ChemMatters

October 2009 Teacher's Guide

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About the Guide

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8. How do diamonds help scientists understand the composition of the Earth’s mantle?
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Answers to Student Questions

Where Do Chemical Elements Come From?

1. **What chemical element is the primary constituent of a young star?**
Hydrogen is the primary constituent of a young star.

2. **Name the astrophysicist who first advanced the idea that the chemical elements originated from hydrogen in stars.**
Arthur Stanley Eddington first proposed the elements originating from hydrogen, in 1920.

3. **Name the stellar process in which the fusion of hydrogen produces other elements.**
The stellar process producing other elements from hydrogen by fusion is called nucleosynthesis.

4. **Why is iron the heaviest element that can be produced in stars?**
Iron is the heaviest element that can be produced in stars because the nucleosynthesis of elements heavier than iron absorb energy rather than release energy. This is because the binding energy of the iron nucleus is very strong.

5. **What are the two opposing forces at work as fusion takes place in stars?**
The two opposing forces are gravity and heat/pressure. Gravity attempts to pull all of the matter in a star into the smallest volume possible and the heat and pressure produced by stellar fusion of gases like hydrogen and helium cause the matter to expand.

6. **What name is given to the explosion of a star?**
Supernova is the term for a star exploding.

7. **Neutron capture produces what kind of elements in a star?**
Elements heavier than iron are produced by neutron capture.

8. **Name the material sent into space by a supernova.**
The matter sent into space by a supernova is called an interstellar cloud.

9. **What does a spectroscope do to light?**
A spectroscope breaks light into its component parts.

What "Uuo"ught to Know About Elements 112–118

1. **How many of the elements beyond 103 were known to exist in 1972?**
According to Moody, only element 104 was suspected to exist in 1972, but even that was just dotted in on the periodic table. Russian scientists had preliminarily claimed its existence. None of the rest of the elements beyond element 103 had yet been discovered/made.

2. **Name the isotope of the element involved in the synthesis of all elements from 113-118, and explain why it was chosen.**
Calcium-48 is the element involved in the synthesis of all elements from 113-118. It was selected because it is a stable nucleus, and it contains a large number of neutrons relative to its number of protons.

3. **Describe the role of the neutron in the actual synthesis of new elements.**
The neutron acts as a heat absorber/transporter. When the neutron is ejected from the nuclear collision, it takes with it large amounts of heat that would render the new element's nucleus less stable if the heat were not removed.

4. **What are the similarities and differences between a “normal” nuclear reactor and the High Flux Isotope Reactor (HFIR)?**
Similarities and differences between a normal reactor and the HFIR are the following:
They both work similarly—through nuclear reactions.
A normal reactor is used to produce electricity—the HFIR is not.
The HFIR produces about 10-20 times more neutrons than a normal reactor.

5. **Describe the process of producing Californium-249 in the lab.**
Producing californium-249 in the lab begins by bombarding curium (isotopes 244-248) with neutrons from the high flux isotope reactor (HFIR). Through a series of neutron bombardments, the mass of the curium isotope changes from Cm-244 all the way up to Cm-249; this then undergoes beta decay, to produce Bk-249. Further beta decay produces californium-249.

6. **What problem do scientists encounter when using the heavier isotopes of elements produced by the HFIR in further experiments?**
The heavier isotopes of the elements produce in the HFIR are radioactive. They quickly decay into other, lighter elements. Scientists must use them quickly, before they decay.

7. **What problem do scientists face once they have succeeded in colliding the ions and target nuclei?**
Once scientists have collided the particles successfully, they then have to detect the new product. Many collisions occur—not just the one they want. Scientists have to be able to detect the new particle by its properties of mass and energy.

8. **What do the “names” of elements 112 through 118 mean?**
The names of elements 112-118 are really just placeholders until the elements’ discoverers are allowed to name the elements. The temporary name is made of the Latin or Greek words that spell out the number. Element 112, for example, is named ununbium (un- one, un- one, bi- two).

9. **Why is it so difficult to give a new element a permanent name?**
It is difficult to give an element a permanent name for two reasons: first, it is a long, tedious process to produce and detect nuclei of the new element, and second, because its production/existence must be confirmed by other scientists (and there are very few labs internationally that have the requisite equipment.

10. **Does element 117 exist?**
The author waits until the very end of the article to hint to us about the existence of element 117 by telling us that Researcher Moody at the Lawrence Livermore National Laboratory is “…actually working on answering that right now.” So the question goes unanswered—for now. (Or students could take that to mean, no, it doesn’t exist yet, as far as scientists have been able to prove.)

Metals’ Hidden Strengths

1. **What basic atomic structural property of metals accounts for thermal and electrical conductivity?**
Metals have freely moving valence electrons that contribute both to electron and thermal transfer.

2. **What is meant by the term metalloid?**
Metalloids have properties intermediate to metals and non-metals.

3. **What are the two most important limitations on silicon as a generator of electricity in a solar cell?**
Silicon can only capture a small fraction of the sunlight’s energy, and the electricity produced is short lived.

4. **How are silicon's limitations, mentioned in Q#3, improved upon or eliminated?**
By making solar cells from plastic with certain metals imbedded, all the visible light from the sun can be captured and used to generate electricity for a longer period of time.
5. **What is the function of tungsten or molybdenum in a plastic-based solar cell?**
These two metals increase the range of the solar spectrum to be captured by a plastic solar cell compared with one that is silicon-based.
6. **How does phosphorescence increase the amount of light absorbed by a plastic solar cell?**
Because phosphorescence is produced after sunlight is absorbed by the plastic material, the emission of light produced by this phosphorescence adds energy that can release more electrons for production of an electric current.
7. **How have research chemists made polycrystalline memory materials responsive to a magnetically-induced strain (elongation)**
Manufacturing techniques have produced a crystalline material that has lots of microscopic holes or voids that allow flexibility, allowing the material to bend or elongate, then return to a previous shape (a type of metal elasticity).
8. **How are the holes or voids created in the metal alloy?**
The metal alloy is melted, and then poured into a porous material of sodium aluminate salt which forms a scaffold for the metals without reacting. Then the salt is removed through the addition of an acid that dissolves or leaches out the salt, leaving behind the small holes in the metal lattice.
9. **What happens electrically to the insulating layer of a silicon-based transistor as it becomes smaller (thinner)?**
As the insulating layer of silicon dioxide becomes thinner, it eventually reaches a thickness that no longer can insulate or prevent electrons from leaking between the top and bottom conducting layers.
10. **How has the problem mentioned in Q#9 been overcome, chemically speaking?**
Adding the compound, Hafnium oxide to the insulating layer allows thinner transistors without having the electron leakage of silicon dioxide.
11. **What are the separate functions of gold and zirconium oxide in converting volatile organic molecules or compounds (VOCs), such as formaldehyde, into carbon dioxide (CO_2) and water (H_2O)?**
The gold acts as a catalyst to the reaction, while the zirconium oxide is merely a structural element that holds the gold.
12. **What additional "ingredient" is needed besides gold to convert VOCs to carbon dioxide and water?**
There must be a form of energy, in this case, visible light. The blue end of the visible spectrum is most energetic and therefore the most productive while the entire spectrum of sunlight is less efficient (64% reduction in the concentration of formaldehyde using just blue light vs. 8 % reduction using sunlight's spectrum).

Graphite Versus Diamond: Same Element but Different Properties

1. **What are the modern day uses of charcoal, an amorphous form of carbon?**
Charcoal is used in briquettes for outdoor grilling and barbecues, in water filters to remove bacteria, and in the form of sticks and powder used as drawing materials in artwork.
2. **What are some uses of graphite?**

A mixture of clay and graphite is the "lead" in pencils. Graphite is also used as a lubricant by adding it to oils and greases and as a molding material in glass manufacture.

3. **List some of the contrasting properties of graphite and diamond.**

Diamond is the hardest natural substance known while graphite is one of the softest. Diamond does not conduct electricity while graphite is a good conductor of electricity. Diamond is the ultimate abrasive while graphite is a good lubricant.

4. **What is the difference in bonding between diamond and graphite?**

In diamond, each carbon is covalently bonding to four other carbon atoms while in graphite each carbon atom is covalently bonded to only three carbon atoms.

5. **Describe the shape of the lattice formed in diamond and in graphite.**

The lattice in diamond is a three-dimensional tetrahedral lattice. The lattice in graphite is a two dimensional sheet-like lattice with the carbon atoms arranged in a hexagonal pattern.

6. **What are the allotropes of carbon called?**

The allotropes of carbon are diamond, graphite, and fullerenes.

7. **Describe the process by which diamonds found in remnants of volcanic eruptions are formed.**

Diamonds form in the Earth's mantle, which starts at approximately 33 kilometers underground and is about 3000 km thick. At a distance of about 150 km pressures are 54,000 times greater than atmospheric pressure and the temperature ranges from 900 C to 1300 C. These are the conditions necessary for the formation of diamonds. Volcanoes that originate in the Earth's mantle bring the diamonds formed deep in the mantle to the surface in a type of rock called kimberlite. The kimberlite is liquid within the mantle and traps diamonds and other minerals. On the surface the kimberlite hardens to a solid with the diamond trapped within its matrix.

8. **How do diamonds help scientists understand the composition of the Earth's mantle?**

Because diamonds form deep within the Earth's mantle, scientists can study the mantle indirectly by analyzing diamonds. Inclusions, impurities found in diamonds give an insight into the composition of the mantle. Studies of these inclusions have shown the mantle to be heterogeneous.

9. **How does the study of diamonds found in meteorites provide clues to the origin of the solar system?**

By determining the age of the meteorites, the age of the embedded diamonds can be determined. In some cases, the diamonds are older than the meteorites. These meteorites must have formed in space and were later captured by asteroids. The diamonds were probably formed in star explosions that predate the formation of our solar system.

10. **List three methods for producing synthetic diamonds.**

Synthetic diamonds may be produced (1) in large high-pressure, high-temperature presses, (2) in explosions which generate very high-pressure shock waves, and (3) by chemical vapor deposition (CVD).

11. **What is the state of production of gem quality diamonds by CVD?**

A lab at the Carnegie Institution in Washington, D.C. recently made a 15-carat (3-gram) diamond by CVD. The lab has also grown 18 millimeter thick single crystals of diamond.

12. **What is "graphene?"**

Creation of graphene sheets is one of the hottest crazes in carbon chemistry. Graphene sheets represent the thinnest substance produced. The graphene sheets are one-atom thick sheets of carbon arranged like atomic scale chicken wire.

Nanotechnology's Big Impact

1. **Just what is nanotechnology?**

Nanotechnology refers to the study of materials which measure between1 and 100 nanometers. Derived from "nanos"—the Greek word for "a small person"—a nanometer is one billionth of a meter.

2. **What is nanotechnology's main appeal?**

One of the main appeals is that nanomaterials do not react the same way as the bulk materials from which they derive.

3. **To what is the difference in properties of nanomaterials attributed?**

The different properties are due to an increase in the surface area of such materials and to their unusual shapes – such as tubes and hollow balls – which can affect how durable they are, how they conduct electricity and heat, and how they absorb light.

4. **What is a nanotube?**

A nanotube is basically a sheet of pure, carbon graphite rolled into a cylinder. Nanotubes are usually a few nanometers in diameter and between 1 and 100 micrometers—one thousandth of a millimeter—in length.

5. **What properties affect the ways nanotubes conduct electricity?**

The nanotube's diameter and how the hexagons in the graphite sheet are arranged on the wall of the tube affect the way the nanotubes conduct electricity.

6. **What are nanowires?**

Solid rods of silicon or other materials that are only a few nanometers wide are called nanowires. A nanowire's length is much longer than its width and it behaves like a wire in which electrons can move, thus conducting an electric current.

7. **What are fullerenes or buckyballs?**

Fullerenes or buckyballs are hollow, soccer-ball-shaped molecules made up of 60 carbon atoms, with each carbon atom bonded to three adjacent carbon atoms. The sphere is about one nanometer in diameter. Other buckyballs exist that contain 70 or 80 carbon atoms.

8. **Why are buckyballs being modified for therapeutics?**

The buckyball-based therapeutics to block inflammation is based on the buckyball's unique ability to trap harmful free radicals which increase inflammation and can damage or kill cells. The buckyballs can neutralize a free radical when its unpaired electron is transferred to the buckyball forming a bond.

9. **How is nanotechnology being used as a better way to deliver therapeutic drugs?**

Buckyballs have a high potential for drug delivery. This approach involves attaching drug molecules to the carbon atoms on the surface of the buckyball. Other chemical groups are added to make the molecules more water soluble. This allows the medicine-loaded buckyball to be absorbed by the bloodstream when swallowed or injected. The buckyball can then release the drug upon reaching a chemical trigger, such as a change in pH or a particular chemical substance (such as those released by cancer cells).

10. **How are nanotubes being used in water purification?**

An array of nanotubes packed side by side in a membrane allow water molecules to pass through the membrane 10,000 times faster than predicted, yet the sodium and chloride ions did not pass through. The water molecules appear to form a chain of one water molecule hydrogen bonded to two others in a head to tail configuration. These chains flow through the nanotubes with nearly no friction. The sodium and chloride ions, surrounded by their hydration spheres, are not able to pass through the membrane.

11. **What is the major challenge facing nanotechnology?**

The major challenge facing nanotechnology is creating better manufacturing methods. Creating the large quantities needed is still time consuming and expensive.

12. **What safety issues are associated with nanotechnology?**

Questions have not been answered concerning the impact of nanomaterials on the environment and on the general public. Inhalation of nanoparticles is of special concern.

ChemMatters Puzzle: A Clue-Less Chemical Crossword

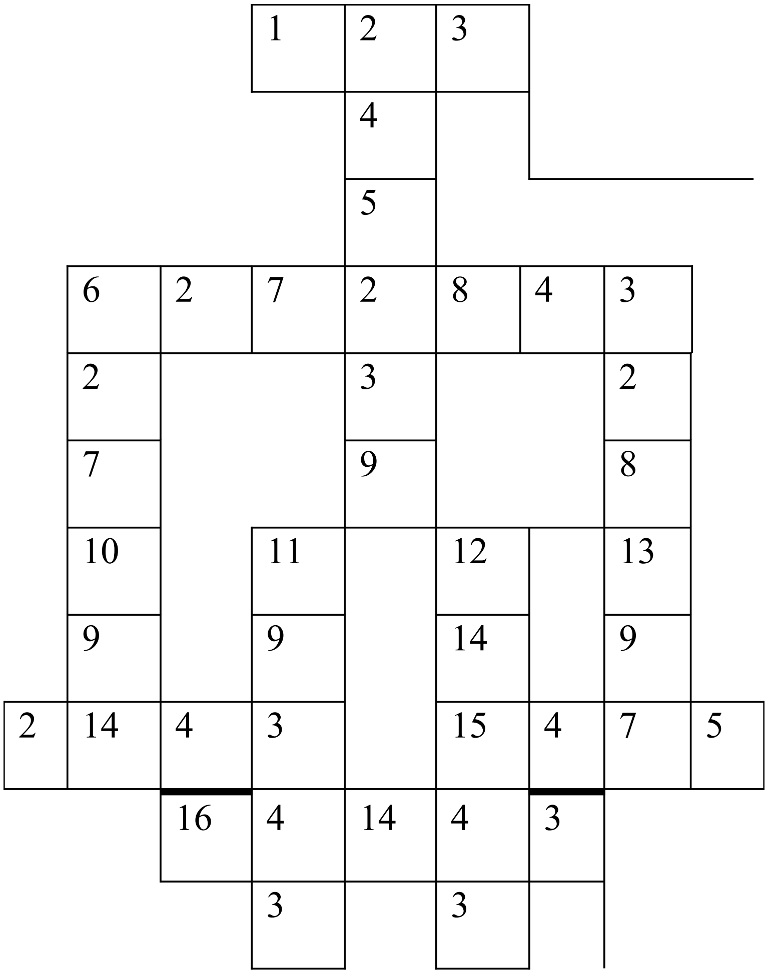
In the cross word-like grid below will be placed letters … but there are no clues provided ! That's because each of the 10 words is the NAME of an element. We're using just 16 alphabet letters; the letters omitted are F,H,J,M,P,Q,U,W,Y and Z. Given the lengths available, the limited letters, and the symmetry imposed, only 18 names are possible, including our ten. (Note the absence of a "u" or "m " . There go dozens of metallic elements !)

We'll suggest two versions for you to tackle.

For a really hard puzzle, try to complete the grid disregarding the numbers in each box, and without using a Table of the Elements. We believe there is a unique solution. Can you find it ?! As a starting hint, the top row is the only row/ column with just three spaces to fill, so must contain the one element with only three letters in its name.

For an easier version, all the boxes that share the same number contain the same letter. So once you deduce one such box, its mates follow.

It should be ELEMENTARY to complete the grid! Give it a try.



Answers to the ChemMatters Puzzle

			1 T	2 I	3 N			
				4 O				
				5 D				
	6 S	2 I	7 L	2 I	8 C	4 O	3 N	
	2 I			3 N			2 I	
	7 L			9 E			8 C	
	10V		11X		12A		13 K	
	9 E		9 E		14 R		9 E	
2 I	14 R	4 O	3 N		15G	4 O	7 L	5 D
		16B	4 O	14R	4 O	3 N		
			3 N		3 N			

NSES Correlation

National Science Education Content Standards Addressed

National Science Education Content Standard Addressed As a result of activities in grades 9-12, all students should develop understanding	**Question from the Classroom**	**Origin of Chemical Elements**	**Elements 112-118**	**Metals**	**Graphite vs. Diamond**	**Nano-technology**
Science as Inquiry Standard A: about scientific inquiry.	✓	✓	✓	✓	✓	✓
Physical Science Standard B: of the structure of atoms		✓	✓	✓		
Physical Science Standard B: of the structure and properties of matter.	✓		✓	✓	✓	✓
Earth and Space Standard D: about the origin and evolution of Earth system.		✓			✓	
Earth and Space Standard D: about the origin and evolution of the universe.		✓				
Science and Technology Standard E: about science and technology.		✓	✓	✓	✓	✓
Science in Personal and Social Perspectives Standard F: of personal and community health.	✓			✓		
Science in Personal and Social Perspectives Standard F: about natural resources.		✓		✓	✓	
Science in Personal and Social Perspectives Standard F: about environmental quality.				✓		✓
Science in Personal and Social Perspectives Standard F: of science and technology in local, national, and global challenges.		✓	✓	✓	✓	✓
History and Nature of Science Standard G: of science as a human endeavor.						✓
History and Nature of Science Standard G: of the nature of scientific knowledge.	✓	✓	✓	✓	✓	✓
History and Nature of Science Standard G: of historical perspectives.		✓				

Anticipation Guides

Anticipation guides help engage students by activating prior knowledge and stimulating student interest before reading. If class time permits, discuss students' responses to each statement before reading each article. As they read, students should look for evidence supporting or refuting their initial responses.

Directions for all Anticipation Guides: ***Before reading***, in the first column, write "A" or "D," indicating your agreement or disagreement with each statement. As you read, compare your opinions with information from the article. In the space under each statement, cite information from the article that supports or refutes your original ideas.

Question from the Classroom

Me	Text	Statement
		1. All colored gases are poisonous.
		2. Steam is gaseous water.
		3. Gaseous water can reach a temperature of more than 200°C.
		4. In its vapor form, water is invisible.
		5. Gaseous water can ignite a match head.

Where Do Chemical Elements Come From?

Me	Text	Statement
		1. The supernova of 1054, which provided enough light to read at night, was described by both Chinese astronomers and the Anasazi in the American Southwest.
		2. For more than 50 years, scientists have been studying the links between chemical elements and how they are created.
		3. Elements lighter than iron are formed from successive nuclear fusion reactions, beginning with hydrogen atoms.
		4. All stars form iron in their cores.
		5. The hydrogen nucleus is the most stable nucleus in nature.
		6. Elements heavier than iron can only be formed in the first few seconds after a supernova's collapse.
		7. The type of elements produced by a star depends on the temperature and pressure of its core.
		8. There are no radioactive isotopes of nickel.
		9. The gas in an interstellar cloud is mostly helium.
		10. All of the elements on Earth, except for hydrogen, were formed in the interiors of stars.
		11. Astronomers use spectroscopes to identify elements in stars because each element produces a unique emission spectrum.
		12. Our sun contains a very small number of gold atoms.

What "Uuo"ught to Know About Elements 112–118

Me	Text	Statement
		1. Superheavy elements can only be discovered through synthesizing them in a laboratory.
		2. Calcium-48 was used to form elements 113-118 because it is stable and neutron rich.
		3. When nuclei in the beam combine with target nuclei, protons carry energy away.
		4. The number of neutrons is unimportant in trying to form a heavy nucleus.
		5. Californium-249 can only be produced in a laboratory through a series of neutron captures, followed by beta decay.
		6. Californium-249 has a half-life of more than 350 years.
		7. Projectile nuclei ions are accelerated in a cyclotron until they have the right energy to be sent toward the target nuclei.
		8. Approximately 10% of the projectiles produced in the cyclotron produce the desired product.
		9. The detector calculates the mass of an ion by measuring the time required for an ion of interest to travel between two grids and the distance between the grids.
		10. As of the writing of this article, all of the elements through element 118 have been discovered or created in a laboratory.

Metals' Hidden Strengths

Me	Text	Statement
		1. Silicon is a metalloid that can cheaply and efficiently convert sunlight into electricity.
		2. Solar cells using silicon can use light with wavelengths corresponding to blue or green light.
		3. Phosphorescence and fluorescence are the same process.
		4. Shape-memory alloys that react to heat have been used for years in dental braces for teeth and other applications.
		5. Shape-memory alloys that react to a magnetic field are new, and the shape is determined by the direction of the magnetic field.
		6. Transistors today use hafnium oxide-based materials for a coating film.
		7. Volatile organic compounds (VOCs) such as formaldehyde can be decomposed into carbon dioxide and water.

Graphite Versus Diamond: Same Element but Different Properties

Me	Text	Statement
		1. Both diamond and graphite have been known for more than 20 centuries.
		2. The differences between diamond and graphite are due to the fact that the carbon atoms in each allotrope bond to different numbers of neighboring atoms.
		3. Diamond will dissolve in strong acids.
		4. Diamonds naturally convert to graphite.
		5. Diamonds may come from Earth's mantle.
		6. Diamonds of gemstone quality are formed in asteroids.
		7. A gigantic diamond has been found in the core of a burned-out star.
		8. Currently there are 3 ways to produce synthetic diamonds.
		9. Graphene, a one-atom thick sheet of carbon, was produced in 2004 using graphite and adhesive tape.

Nanotechnology's Big Impact

Me	Text	Statement
		1. A human hair has a width of about 10 nanometers.
		2. Nanomaterials have a much smaller surface area than ordinary materials.
		3. A nanotube can be rolled only one way.
		4. A "buckyball" may have 60, 70, or 80 carbon atoms.
		5. Buckyballs can trap dangerous free radicals.
		6. In the future, buckyballs may be used to deliver drugs directly to the target organ in the body.
		7. Carbon nanotubes must be at least 2 nanometers across.
		8. Since nanoscale materials are made of carbon, they are relatively inexpensive.
		9. Most people agree that more studies are needed to determine the safety of nanomaterials.
		10. A typical protein such as hemoglobin is about a nanometer in diameter.

Reading Strategies

These matrices and organizers are provided to help students locate and analyze information from the articles. Student understanding will be enhanced when they explore and evaluate the information themselves, with input from the teacher if students are struggling. Encourage students to use their own words and avoid copying entire sentences from the articles. The use of bullets helps them do this. If you use these reading strategies to evaluate student performance, you may want to develop a grading rubric such as the one below.

Score	Description	Evidence
4	Excellent	Complete; details provided; demonstrates deep understanding.
3	Good	Complete; few details provided; demonstrates some understanding.
2	Fair	Incomplete; few details provided; some misconceptions evident.
1	Poor	Very incomplete; no details provided; many misconceptions evident.
0	Not acceptable	So incomplete that no judgment can be made about student understanding

Where Do Chemical Elements Come From?

Directions: As you read, complete the chart below describing the formation of elements.

Elements	**How they are formed** *(Use bullets or number each step.)*
Elements up to and including iron	
What elements are formed by stars less massive than our sun?	
What elements are formed by stars having a mass of one to eight suns?	
What elements are formed by stars having a mass greater than eight suns?	
Elements heavier than iron	“s” process:
	“r” process:
	“p” process:

What “Uuo”ught to Know About Elements 112–118

Directions: As you read, please complete the table below describing what scientists must consider as they create superheavy elements in a laboratory.

Step	**Description**	
Deciding which elements to use	Atomic number	
	Other considerations	
Energy considerations		
Preparing projectile		
Preparing target		
Cyclotron collisions		
Detecting desired element		
Naming element		

Metals' Hidden Strengths

Directions: As you read, please complete the table below describing current and future technologies.

Application	Today	Future	Advantage
Solar Cells			
Shape-Memory Alloys			
Transistors			
Cleaner Air	▨		

Graphite Versus Diamond: Same Element but Different Properties

Directions: As you read, please complete the table below comparing diamond, graphite, and graphene.

Attribute	Diamond	Graphite	Graphene
Physical properties			
Structure			
Uses			

In the chart below, describe natural and synthetic sources of diamonds.

Natural	Synthetic
1.	1.
2.	2.
3.	3.

Nanotechnology's Big Impact

Directions: As you read, please complete the chart below describing different nanomaterials.

Nanomaterials	Description	Current and Future Uses	How they would work
Nanotubes		1.	
		2.	
Nanowires			
Nanoballs		1.	
		2.	

Where Do Chemical Elements Come From?

Background Information

More on the life cycle of stars

In order for students to understand the origin of the elements, they should also have an understanding of basic concepts that might be covered in an advanced astronomy course. The processes that produce the chemical elements are an integral part of the life cycle of stars.

Many students think that there is no matter in space when, in fact, there is. Existing stars themselves are matter, mostly hydrogen. Even in between the stars, in what is called interstellar space, there is matter. It is about 99% gas, primarily hydrogen, and 1% solid. The matter in space is extremely low density, from a few thousand particles per cubic meter to a few hundred thousand particles. When a denser region of interstellar matter becomes unstable, it is usually referred to as a nebula. When the nebula begins to collapse, the life cycle of a star begins.

All stars go through similar stages in their life cycles—nebula, main sequence, and the red giant phase. Then, depending on the mass of the star, the cycles vary. Lower mass stars have longer life cycles. After the red giant phase these stars become white dwarfs and then black dwarfs.

At the beginning of the cycle, gravity causes hydrogen atoms in the star to collapse toward each other, and the mass begins to spin. As it spins, the temperature increases. When the temperature reaches 15 million degrees (C) hydrogen nuclei begin to undergo nuclear fusion to produce helium. The star stabilizes and begins to glow, much like our sun at present. The force of gravity and the pressure of expanding gases are in equilibrium. In stars there is a constant tension between these two factors. Gravity pulls stellar matter toward to star's core and the heat and pressure of newly formed gases tend to expand the matter.

As available hydrogen is used up, helium nuclei undergo fusion to form carbon. When there is sufficient carbon produced by nucleosynthesis (see "More on nucleosynthesis", below), the core of the star collapses a second time due to the increased gravitational attraction, expelling the outer gas layer, resulting in a white dwarf star. When the white dwarf mass cools, the star is considered a black dwarf.

However, if the star's mass is very large, on the order of 8-10 times the mass of our sun (2.0×10^{30} kg, about 333,000 times the mass of the earth), its life cycle is shorter. Following the red giant phase, massive stars become the supernova mentioned in the article. For massive stars, the nucleosynthesis process includes the formation of elements heavier than carbon (oxygen, nitrogen and other elements up to iron, as the article describes). Energy is required to fuse iron nuclei and as a result the core temperature rises quickly to 100 billion degrees. The repulsive force of the iron nuclei is strong enough to overcome gravity and the core matter explodes in what is a supernova. As the iron nuclei in the core are expelled toward the outer layer of the star at such high temperatures, they fuse to form isotopes of elements heavier than iron. In this way, a wide variety of elements results from the processes that take place during a star's lifetime.

Which elements are most often created in stars? As the article states, there are eight elements-- oxygen, carbon, neon, nitrogen, magnesium, silicon, iron, and sulfur. If we use the sun as an example, this list of elements is confirmed. The composition of the sun from spectroscopic analysis (see “More on spectroscopy”, below):

Element	Abundance (% of total number of atoms)	Abundance (% of total mass)
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.030	0.014
Sulfur	0.015	0.040

Hydrogen and helium, which make up most of the mass of the sun by far, are also included on this list. Analysis of other stars confirms that they, too, are mostly hydrogen and helium. Stars are not homogeneous in composition. One way to think about the composition of stars is to think about them as having concentric layers. The outmost layer is made up of hydrogen and helium. The next layer is where hydrogen fusion takes place to produce helium. Moving toward the core of the star, layers are producing carbon, then oxygen, then silicon and finally iron in the core. As you move toward the core the temperature increases, making a wider variety of nucleosynthetic processes possible.

How do these elements get from a star in space to places like the earth? The article describes the explosion-like event in a star that sends matter outward from the star’s core. This matter is expelled with enough force to send it into the interstellar space around the star. This matter is called interstellar medium. Students often think that there is no matter in space, but that is not completely true. There is matter present in space but limited to a density of about 1 atom per mL. This matter is distributed through space by various mechanisms and some of the elements that make up this interstellar medium have ended up in our galaxy and in our solar system and on Earth.

More on nucleosynthesis

The article discusses how heavier elements are produced from lighter elements by means of nuclear fusion reactions in stars. Students should have some background in both isotopes and nuclear reactions and should be able to follow written nuclear equations. If you choose to discuss this area of the article with students, it might be best to limit the discussion of fusion reactions to several examples, since the actual stellar fusion reactions involve sub-atomic particles (positrons, neutrinos, etc.) not usually covered in a general chemistry course.

There are three important basic stellar fusion processes—proton-proton fusion, helium fusion and the carbon cycle. Following are the basic steps in each.

Proton-Proton Fusion—Recall that the environment for these reactions is a high-temperature environment, thus creating high-energy collisions between nuclei. Students may ask about the role of electrons in this process. You can note that the temperature is sufficiently high to ionize the elements present, clearly the way for nuclear reactions. Hydrogen is the most abundant element in stars. A hydrogen nucleus is a single proton. The first step in this process involves the fusing of two hydrogen nuclei, producing a deuterium nucleus and a neutron, which is the result of the transmutation of one of the protons.

$$ {}^{1}_{1}H + {}^{1}_{1}H \longrightarrow {}^{2}_{1}H + {}^{1}_{0}n $$

In the next step a deuterium nucleus fuses with another proton to produce an isotope of helium:

$$ {}^{2}_{1}H + {}^{1}_{1}H \longrightarrow {}^{3}_{2}He $$

Two of these helium nuclei then fuse to produce a He-4 nucleus, and two protons are emitted:

$$ {}^{3}_{2}He + {}^{3}_{2}He \longrightarrow {}^{4}_{2}H + 2\,{}^{1}_{1}H $$

In this cyclic process the two original protons are produced and helium is formed from the original hydrogen. If students can understand that the net result of this process is to produce a helium nucleus from two hydrogen nuclei, they understand how helium nuclei can fuse to produce heavier and heavier elements. Note that each of these steps produces energy.

Helium Fusion—This second basic process illustrates the production of elements heavier than helium. If the core star temperature reaches about 100 million kelvins, helium nuclei fuse to form isotopes of beryllium, and then carbon-12:

$$ {}^{4}_{2}He + {}^{4}_{2}He \longrightarrow {}^{8}_{4}Be $$

$$ {}^{4}_{2}He + {}^{8}_{4}Be \longrightarrow {}^{12}_{6}C $$

Carbon Cycle—At 15 million kelvins, the carbon nuclei produced via helium fusion enter into a fusion process that involves multiple steps and is thought to replace the hydrogen (proton-proton) fusion as the main energy source for the star. In the first step a carbon nucleus fuses with a proton to produce nitrogen-13. A proton in the N-13 transmutates to yield carbon-13. The C-13 fuses with another proton to produce nitrogen-14, which fuses with yet another proton to produce oxygen-15, within which a neutron decays, emitting an electron to produce nitrogen-15. One more fusion between a proton and the N-15 produces oxygen-16, which emits an alpha particle (a helium nucleus) yielding carbon-12 to complete the cycle.

In these three examples of nuclear fusion processes, increasingly heavier elements are produced—helium, beryllium, carbon, nitrogen and oxygen. Other elements in this mass range can be produced from isotopes of the aforementioned elements. These types of processes take place in stars that are relatively light—like our sun. Fusion produces heavier elements—from oxygen to iron—in stars that are more massive. The fusion processes for most nuclei are exothermic. Producing elements heavier than iron, however, requires energy, and it is believed that these heavier elements are formed only during supernova explosions.

Most sources claim that iron is the heaviest element that can be formed by nuclear fusion in stars. The theoretical basis for this is questionable from a binding energy point of view. It is true that elements in “the iron group” have high nuclear binding energies, iron is not the highest. Nickel-62 has the highest binding energy, followed by iron-58 and iron-56. Nuclear binding energy is a measure of how tightly particles in the nucleus are held together. Nuclei with high binding energies are very stable. Binding energy is the energy equivalent of the difference in mass between the masses of the individual nucleons and the total mass of the resulting nucleus. This energy would be required to disrupt the nucleus of an atom. Thus, nuclei like iron’s and those of heavier elements require large amounts of energy, far beyond the energy available in a normal star. However, as the article states, a supernova explosion creates enough energy to fuse nuclei heavier than iron.

The question might arise about the origin of hydrogen in the universe. If it is the simplest element, how did it originate? The most accepted answer is given by the Big Bang Theory. Scientists believe that 13 billion years ago all matter existed in a tightly packed, very dense space. The universe began with a single massive explosion that spread matter over millions of miles at the speed of light, creating what we know as our universe. Scientists believe that the temperature at the time was so intense that only sub-atomic particles existed. Within seconds after the explosion, the expanding matter cooled the universe and these sub-atomic particles formed neutrons and protons, which soon formed the simplest of atomic nuclei—hydrogen and helium. Since a hydrogen nucleus is a single proton, it was available to begin the fusion process described in the article.

In addition to the examples of stellar fusion listed above there are several other processes that create heavy elements under special circumstances. Among them are the s process, the r process, the rp process and the p process.
The s process, discussed in the article, is also known as slow neutron capture. In stars there are a host of processes that produce neutrons. An example is the fusion of carbon-13 with an alpha particle to produce oxygen and a neutron. This availability of neutrons allows heavy elements to absorb one or more neutrons to produce other heavy nuclei.

For example:

$${}^{110}_{48}Cd + {}^{1}_{0}n \dashrightarrow {}^{111}_{48}Cd$$

The Cd-110 absorbs a neutron to become Cd-111. This neutron capture takes place four more times to produce Cd-115, which immediately undergoes beta decay to produce indium-115. In this sequence a higher atomic mass nucleus (indium from cadmium) is produced. The process is call slow neutron capture because it may take thousands of years to occur.

The r process (or rapid neutron capture), also mentioned in the article, operates by much the same mechanism as the s process, but at a much faster rate. It is thought to occur only in a supernova environment where the availability of neutrons is much greater. The s process and r process produce a majority of stellar elements heavier than iron.

The rp (or rapid proton) process produces elements heavier than iron by capturing protons at high stellar temperatures in an environment that is hydrogen-rich. This process is not completely understood, but it is believed that the "seed" nuclei are produced in the carbon cycle, mentioned above.

The p process (or photodisintegration) is a mechanism for producing heavy nuclei in which the proton-neutron ratio favors the protons (hence, the p process). When gamma rays strike a nucleus, neutrons may be ejected from that nucleus, thus disrupting the proton-neutron ratio, which, in turn affects the radioactivity of that nucleus. The p process works in nuclei with more than 100 nucleons (protons and neutrons).

More on supernovas

The article mentions a supernova from the year 1054 and show photos of several more. They are rare events. On average there is one supernova observed in the Milky Way each century. Ancient records suggest that Chinese astronomers saw a supernova in 185 AD, without knowing, of course, exactly what it was. Astronomers now have the ability to trace celestial remnants of ancient supernova and approximate the time the original supernova occurred.

Other notable supernova occurred in 1006 (in the constellation of Lupus), 1054 (in Taurus, observed by Tycho Brahe), in 1572 (mentioned in the article), and one observed by Kepler in the Milky Way in 1604. Most recently in 1987, supernova 1987A was observed in a galaxy near the Milky Way.

"After" and "Before" pictures of Supernova 1987A (NASA)

According to NASA, "Supernovae are divided into two basic physical types:

Type Ia. These result from some binary star systems in which a carbon-oxygen white dwarf is accreting matter from a companion. (What kind of companion star is best suited to produce Type Ia supernovae is hotly debated.) In a popular scenario, so much mass piles up on the white dwarf that its core reaches a critical density of 2×10^9 g/cm^3. This is enough to result in an uncontrolled fusion of carbon and oxygen, thus detonating the star.

Type II. These supernovae occur at the end of a massive star's lifetime, when its nuclear fuel is exhausted and it is no longer supported by the release of nuclear energy. If the star's iron core is massive enough then it will collapse and become a supernova."

Also from NASA, a simple explanation of a supernova: “A supernova explosion will occur when there is no longer enough fuel for the fusion process in the core of the star to create an outward pressure which combats the inward gravitational pull of the star's great mass. First, the star will swell into a red supergiant...at least on the outside. On the inside, the core yields to gravity and begins shrinking. As it shrinks, it grows hotter and denser. A new series of nuclear reactions begins to occur, temporarily halting the collapse of the core. But alas, it is only temporary. When the core contains essentially just iron, it has nothing left to fuse. (Because of iron's nuclear structure, fusing iron does not result in a net yield of energy. Since energy production cannot then be maintained, the star begins to collapse.) Fusion in the core ceases.

In less than a second, the star begins the final phase of gravitational collapse. The core temperature rises to over 100 billion degrees as the iron atoms are crushed together. The repulsive force between the nuclei is overcome by the force of gravity. So the core compresses but then recoils. The energy of the recoil is transferred to the envelope of the star, which then explodes and produces a shock wave. As the shock encounters material in the star's outer layers, the material is heated, fusing to form new elements and radioactive isotopes. The shock then propels that matter out into space. The material that is exploded away from the star is now known as a supernova remnant.
(http://imagine.gsfc.nasa.gov/docs/science/know_l1/supernovae.html)

More on fusion

Most textbooks available to you have information on nuclear fusion so only the basics will be given here briefly.

Fusion is a reaction in which two lighter nuclei join to form a heavier nucleus. In order for two nuclei to join, the repelling force created by their like charge must be overcome. When nucleons are brought close together the nuclear force takes over and the two join. For elements lighter than iron, fusion releases energy. In order to achieve fusion the nuclei must be heated to very high temperatures, temperatures sufficient to accelerate the nuclei to speeds that will allow them to overcome the repulsive force of their like charges. However, when fusion occurs there is enough energy created that we can consider the overall process to be exothermic.

Several examples of fusion equations:

$${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

$${}^{12}_{6}C + {}^{12}_{6}C \longrightarrow {}^{24}_{12}Mg + energy$$

$${}^{16}_{8}O + {}^{4}_{2}He \longrightarrow {}^{20}_{10}Ne + energy$$

Other examples of fusion equations can be found in “More on nucleosynthesis”.

More historical background on stellar nucleosynthesis

The article refers to the now classic paper written by Burbidge, Burbidge, Fowler and Hoyle (often referred to as B^2FH) in 1957 that explained stellar nucleosynthesis. The article also refers to work on the evolution of stars by Arthur Stanley Eddington, and English astrophysicist. Eddington published his theories in a 1926 paper titled “The Internal Constitution of the Stars.”

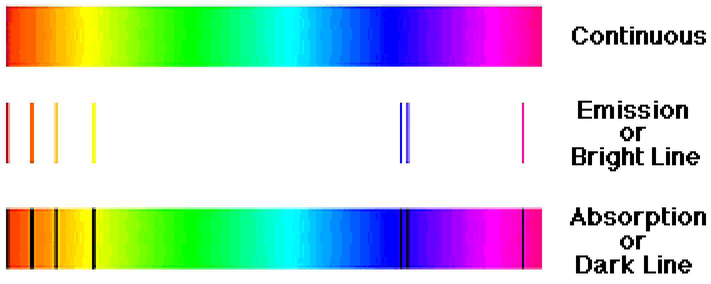
At the time of the B^2FH paper in 1957, prevailing theory about the origin of the elements was that they were all created during the Big Bang and that the relative amounts of the elements remained constant in the universe. The paper, titled "Synthesis of the Elements in Stars," argued that while some lighter elements had been created by the Big Bang, all elements are being continuously created by nuclear fusion in stars. B^2FH also argued that scientists could track new elements being formed in stars by looking at their atomic spectra, which would show both which elements and how much of each element was produced over time.

The net result is that most scientists accepted the idea that some elements were created during Big Bang (big bang nucleosynthesis) and that many elements continued to be created by stellar nucleosynthesis. B^2FH were able to identify specific elements and their isotopes present is stars and in interstellar space. They predicted the s process, the r process and the p process to explain how heavier elements could be produced in stars. The original paper can be found here: http://prola.aps.org/pdf/RMP/v29/i4/p547_1.

The quartet that produced the classic paper included Geoffrey Burbidge, who is a physicist by training with a specialty in particle physics. He became interested in astronomy when he married astronomer Margaret Peachy in 1948. Margaret Burbidge pioneered the study of galaxies by connecting a spectrograph to a telescope. In the 1990's she worked on the Hubble Telescope. Both Geoffrey and Margaret are connected to the center for Astrophysics and Space Science at the University of California, San Diego. Fred Hoyle, an English mathematicians and theoretical physicist, began working on stellar evolution in the 1930's. He established the concept of nucleosynthesis in stars in 1946. He coined the term "Big Bang," but later rejected the theory. William Alfred Fowler gained the most fame of the four authors of the 1957 paper. He shared the Nobel Prize in Physics in 1983 "for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe."

More on spectroscopy

Your students likely know (or will know) a little about spectroscopy from the chapters on electrons in atoms. They will know that there are basically three types of spectra—continuous spectra, emission spectra and absorption spectra. Each of these types of spectra can be used to identify the chemical elements present in a star.



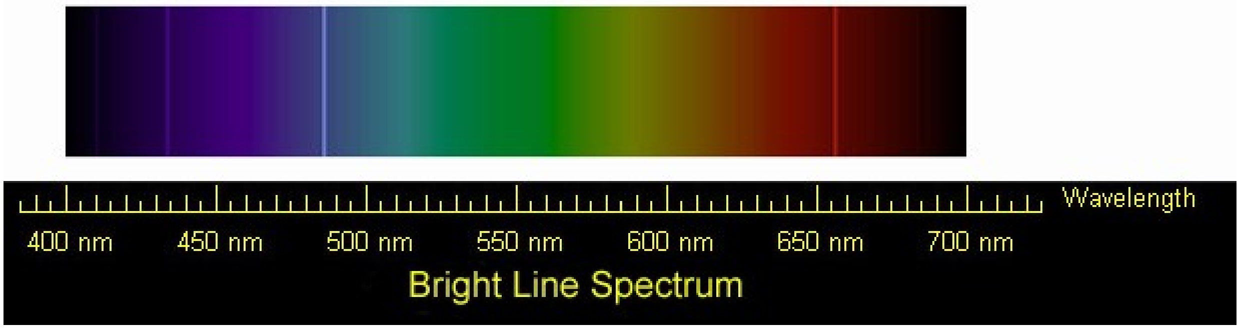
(Image from NASA)

Each element has its own emission spectrum and its own absorption spectrum, which are characterized by either bright lines or dark lines that appear at specific wave lengths (or frequencies) along the electromagnetic spectrum. The pattern of either bright or dark lines is unique for each chemical element. Isaac Newton studied the continuous spectrum of the sun. Later William Wollaston observed dark lines in the sun's spectrum. And still later Joseph von Fraunhofer saw 600 dark lines in the sun's spectrum and established the relationships between continuous, emission and absorption spectra.

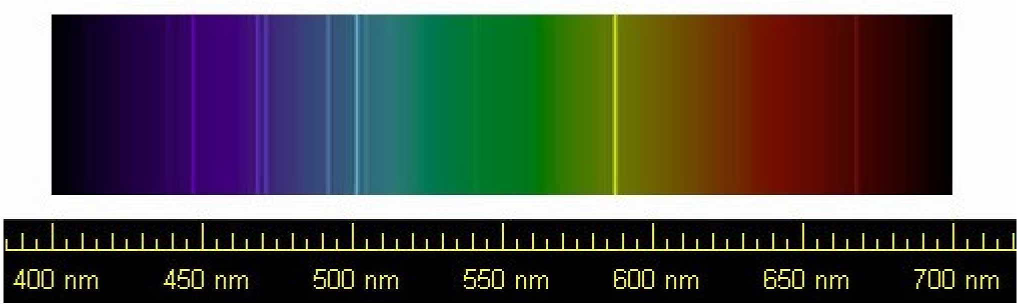
Scientists can use spectral lines in the light being emitted by stars not only to identify the elements present in a star but also the density of the element and the temperature of the star. The table below, which also appears in "More on life cycle of stars" (above), lists the ten most abundant elements in our sun (a table similar to this appears in the article).

Element	**Abundance (% of total number of atoms)**	**Abundance (% of total mass)**
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.030	0.014
Sulfur	0.015	0.040

Below are the bright line spectra for the two most abundant elements in the sun, hydrogen and helium. Most stars, in fact, have a similar composition—about 70% hydrogen, 28% helium by mass and the other 2% being heavier elements.

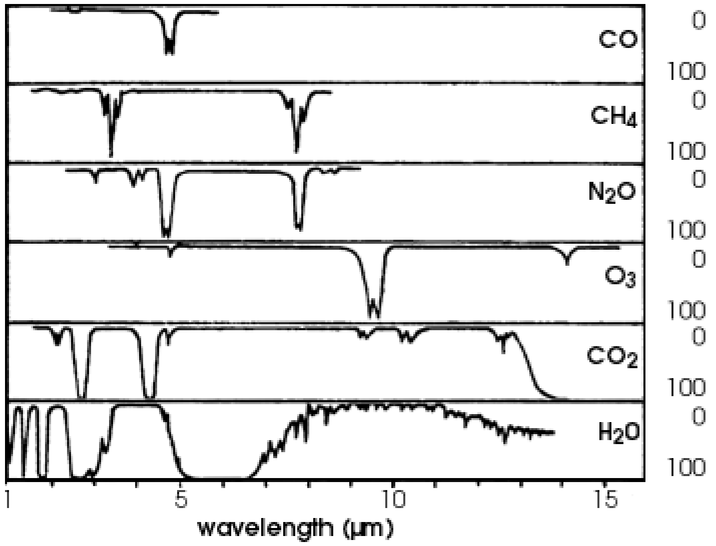


Hydrogen



Helium

In addition to the bright line or emission spectra, scientists can use the absorption spectra to analyze the composition of a star. Absorption spectra show dark lines at wavelengths at which energy is absorbed between the light source and the detecting device. As energy radiates from the core of a star it must pass through the gases and solid matter that make up the star. Each of the elements (the gases and solids) absorbs some of the energy at specific locations along the spectrum. As the energy reaches the earth, science can look at the absorption spectrum and identify elements present in the star by the way the energy was absorbed. Below is an example of an absorption spectrum for substances in the earth's atmosphere.



Connections to Chemistry Concepts

1. **Atomic Structure**—You can connect the ideas in this article to a unit on atomic structure including the nucleus, isotopes and sub-atomic particles.
2. **Nuclear Reactions**—Nuclear reactions may or may not be an important topic in your course, and if it is, you likely concentrate on fission reactions rather than fusion. This article is a chance to introduce fusion to your students.
3. **The Elements**—Obviously, since this article is about the origin of the elements, you could relate it to any part of your courses in which the elements themselves play an important role —elements vs. compounds, the periodic table, atomic structure, etc.
4. **Spectroscopy**—You likely include at least a brief discussion of spectroscopy in your course, probably in connection with the behavior of electrons. You can connect to this article at this point.

Possible Student Misconceptions

1. **"I thought explosions were a form of chemical oxidation. How do stars explode? Is the hydrogen exploding?"** *Some students may think that the sun is actually "burning" hydrogen in a combustion reaction between hydrogen and oxygen to make water. The word "explode" is also often used in discussions of stars and the formation of elements. You should emphasize to students that words like "burning" and "explode" as used in this article (and others) are non-technical use of the words. Burning and explosions are, in fact, chemical processes, while the processes in stars are nuclear processes. Another source of misconception here may be that both burning and many fusion processes are exothermic. Students tend to associate exothermic with burning, but many processes are exothermic.*
2. **"The title of this article fooled me. I thought this article was going to be about where the elements are found in nature."** *The title might lead you to believe that, but it is about how elements heavier than hydrogen are actually created in nature. We don't often think about where elements originate. And we don't often think about how one element can*

be created from another element. That happens only in nuclear reactions like fusion. We do tend to discuss in chemistry where the elements are found in nature—as native elements, in compound form, as solids, liquids or gases, etc., but this discussion is about the chemical properties of the elements—their state at room temperature, their reactivity, etc.

Demonstrations and Lessons

1. This is the site of the NOVA TV show, "The Elements: Forged in Stars." A classroom activity is included. http://www.teachersdomain.org/resource/ess05.sci.ess.eiu.fusion/
2. This activity from the American Museum of Natural History (AMNH) simulates the composition of stars using multi-colored sprinkles. (http://www.amnh.org/education/resources/card_frame.php?rid=1046&rurlid=1003)
3. This activity, also from the AMNH, allows students to determine the actual elemental composition of the sun: http://www.amnh.org/education/resources/card_frame.php?rid=1023&rurlid=1001.
4. A *You Tube* video, narrated by Neil DegrasseTyson, about the origin of the elements can be found here: http://www.youtube.com/watch?v=B-LXUHJmzzc .
5. This computer-based activity allows students to examine x-rays from stars to determine their composition. (Requires download of software) (http://xmm.sonoma.edu/edu/clea/index.html)
6. This is a connected series of activities from NASA on "X-ray Spectroscopy and the Chemistry of Supernova Remnants": http://imagine.gsfc.nasa.gov/docs/teachers/lessons/xray_spectra/spectra_unit.html
7. Another activity from NASA, this one on fusion: http://imagine.gsfc.nasa.gov/docs/teachers/lessons/xray_spectra/activity-fusion.html
8. Students can perform flame tests for elements to illustrate the use of spectroscopy in the lab: http://www.800mainstreet.com/spect/emission-flame-exp.html.
9. Still another activity from NASA on spectroscopy: http://imagine.gsfc.nasa.gov/docs/science/how_l1/spectral_how.html

Student Projects

1. Students can compare the life cycle of a human with the life cycle of a star using images from NASA. (http://btc.montana.edu/ceres/html/LifeCycle/stars1.html)
2. Students can research the history of supernova sightings. The article describes two such sightings. http://www.astro.cornell.edu/academics/courses/astro201/sn_history.htm or http://www.seds.org/MESSIER/more/mw_sn.html
3. Students can research Supernova 1987A, observed on Feb. 23, 1987. One good place for students to begin is the Chandra Observatory site: http://chandra.harvard.edu/photo/2005/sn87a/, or on this timeline site: http://www.google.com/search?q=supernova+1987A&hl=en&sa=G&tbs=tl:1&tbo=u&ei=XXmASvj9BIyCMqWGpekC&oi=timeline_result&ct=title&resnum=15, or the NASA/Hubble site: http://www.spacetelescope.org/news/html/heic0704.html.

Anticipating Student Questions

1. **"If other elements are formed from hydrogen, where did hydrogen originate?"** *The most accepted answer is given by the Big Bang Theory. Scientists believe that 13 billion years ago all matter existed in a tightly packed, very dense space. The universe began with a single massive explosion that spread matter over millions of miles at the speed of light, creating what we know as our universe. Scientists believe that the temperature at the time was so intense that only sub-atomic particles existed. Within seconds after the explosion, the expanding matter cooled the universe and these sub-atomic particles formed neutrons and protons, which soon formed the simplest of atomic nuclei—hydrogen and helium. Since a hydrogen nucleus is a single proton, it was available to begin the fusion process described in the article.*

2. **"Why can't elements heavier than iron be produced by ordinary nucleosynthesis?"** The fusion processes up to the ones that produce iron are exothermic. Processes producing elements heavier than iron are endothermic, and it is believed that these heavier elements are formed only during supernova explosions. Most sources claim that iron is the heaviest element that can be formed by nuclear fusion in stars. The theoretical basis for this is questionable from a binding energy point of view. It is true that elements in "the iron group" have high nuclear binding energies, but iron is not the highest. Nickel-62 has the highest binding energy, followed by iron-58 and iron-56. Nuclear binding energy is a measure of how tightly particles in the nucleus are held together. Nuclei with high binding energies are very stable. Binding energy is the energy equivalent of the difference in mass between the masses of the individual nucleons and the total mass of the nucleus. This energy would be required to disrupt the nucleus of an atom. Thus, nuclei like iron's and those of heavier elements require large amounts of energy, far beyond the energy available in a normal star. However, as the article states, a supernova explosion creates enough energy to fuse nuclei heavier than iron.

3. **"I thought spectroscopy had to do with electrons in atoms. At temperatures in stars, aren't electrons stripped away from their nuclei? If nuclei have no electrons attached to them, how can scientists study the elements using spectroscopic methods?"** While it is true that in the core of stars the temperatures are high enough to create plasma—that fourth phase of matter consisting of ions and electrons, there are at least two other factors to consider. First, even in a plasma, individual atoms vacillate between what we might refer to as ground state and plasma, and back again. That means that for part of the time, a given nucleus has its normal number of electrons. Second, as new elements are produced by nucleosynthesis, they are often moved to parts of the star farther from the core, thus decreasing in temperature. In these regions of the star there is a higher likelihood of finding complete atoms. As light is emitted from the star it passes through the "layers" of the star where there are likely complete atoms. In this way, spectroscopists are able to determine the composition of the star.

References

Thielk, David. "The Birth of the Elements." *ChemMatters*, October, 2000, page 4.

Finkbeiner, Ann. "Star Born: The Origin of the Elements", *ChemMatters*, October, 1984, page 6.

Selbin, Joel. “The Origin of the Chemical Elements,” *J. Chem. Ed*. 1973, 50, 306-10 and 380-86.

Web Sites for Additional Information

More sites on the Big Bang Theory

For background on the Big Bang Theory and the origin of helium and hydrogen see this site from the Exploratorium and CERN: http://www.exploratorium.edu/origins/cern/ideas/bang.html.

More sites on nucleosynthesis

The following sites have additional information about this topic:

The Hyperphysics site has information about the main cycles in nucleosynthesis: http://hyperphysics.phy-astr.gsu.edu/Hbase/Astro/astfus.html#c2.

NASA has a collection of news articles about nucleosynthesis: http://helios.gsfc.nasa.gov/nucleo.html.

Short videos of several processes: http://zebu.uoregon.edu/textbook/energygen.html

A podcast about nucleosynthesis: http://www.universetoday.com/2008/09/29/podcast-nucleosynthesis-elements-from-stars/

Astronomy Cast has a series of links at http://www.astronomycast.com/astronomy/ep-107-nucleosynthesis-elements-from-stars/.

More sites on the life cycle of stars

From NASA’s Imagine the Universe site: http://imagine.gsfc.nasa.gov/docs/teachers/lifecycles/LC_main_p1.html

More sites on supernovas

NASA’s “Imagine the Universe” page has more on this: http://imagine.gsfc.nasa.gov/docs/teachers/lessons/xray_spectra/background-lifecycles.html and at http://imagine.gsfc.nasa.gov/docs/science/know_l2/supernovae.html.

More on the history of supernovas

For a list of notable supernovas see http://www.seds.org/~spider/spider/Misc/sn.html.

More sites on spectroscopy

Spectroscopy basics in detail (http://www.astro.illinois.edu/~jkaler/sow/spectra.html)

Stellar Spectroscopy (http://www.ph.surrey.ac.uk/astrophysics/files/spectroscopy.html#spectrum)

NASA's "Imagine the Universe" page (http://imagine.gsfc.nasa.gov/docs/teachers/lessons/xray_spectra/background-spectroscopy.html)

Here is an excellent page on stellar spectroscopy from Surrey University in England: http://www.ph.surrey.ac.uk/astrophysics/files/spectroscopy.html#spectrum

More sites on historical context of nucleosynthesis

A link to the original B^2FH paper on nucleosynthesis: http://prola.aps.org/abstract/RMP/v29/i4/p547_1

A link to a paper reviewing the origin of theories on nucleosynthesis: http://cococubed.asu.edu/papers/wallerstein97.pdf

More sites on fusion

A complete workbook on fusion, see http://fusioned.gat.com/images/pdf/Workbook.pdf

What “Uuo”ught to Know About Elements 112–118

Background Information

More on the transfermium elements

The transfermium (“beyond fermium”) elements are those with atomic numbers above 100 (fermium is element 100). This group includes the superheavy elements. The transfermium elements are grouped together for several reasons: they are all prepared in the lab; none of them occur “naturally” on Earth; they are very difficult to prepare; and we know very little information about them. (Since they’re so hard to prepare, there aren’t many of them around to study.)

Despite all this, scientists have been eager to study these elements because they allow them to test hypotheses and answer questions about the periodic table. Since the transfermium elements are at the end of the periodic table, studying them can give scientists more information about possible limits on the number of elements we can have or produce. Just how far can the periodic table go?

Here is some basic information about the transfermium elements:

Element	Name	Symbol
101	mendelevium	Md
102	nobelium	No
103	lawrencium	Lr
104	rutherfordium	Rf
105	dubnium	Db
106	seaborgium	Sg
107	bohrium	Bh
108	hassium	Hs
109	meitnerium	Mt

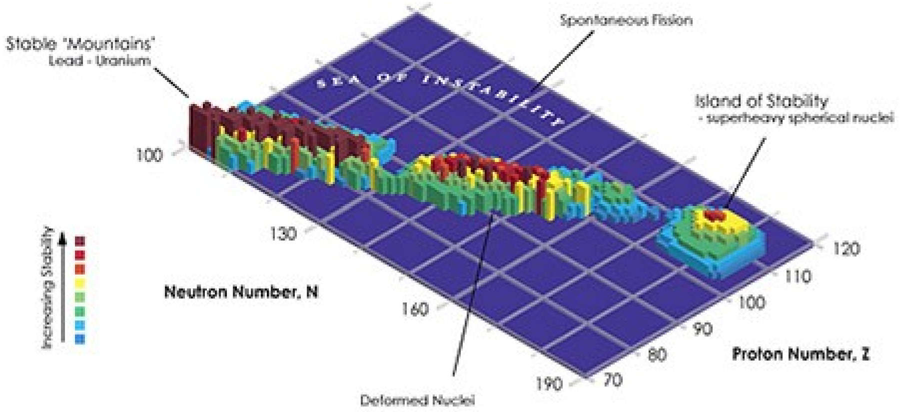
All the transfermium elements are produced in particle accelerators, dubbed “atom smashers”. The isotopes of the transfermium elements produced in these atom smashers are all radioactive, with most having half-lives of a few seconds or less. And the existence of each new element has been identified through the decay series it experiences as its unstable nucleus decays into other, (usually) known elements. Their properties of mass and velocity are used to detect these particles.

The larger an atom is, the more likely it is to be unstable. This instability occurs long before the superheavy elements are reached on the periodic table. It turns out that all elements heavier than bismuth are radioactive. This would suggest that all the elements scientists can produce beyond 109 will be radioactive and unstable. Many scientists believe that is not the case. They have predicted that some elements will be especially stable, starting at element 114. This is considered to be a “magic” number—the number of protons or neutrons that result in a stable atom. Previous magic numbers are 2, 8, 20, 28, 50, and 82. Others beyond 114 are expected to be 120, 126 and 184. Thus the stable isotope of element 114 (114-298, or ${}^{298}_{114}Uuq$) would have 114 protons and could have 184 neutrons. That would give it a double magic number, making it (hopefully) very stable. Thus they could prepare enough of it to actually study its chemical and physical properties, and although it might not have immediate practical applications, it would be exciting for scientists to have it available for study. Uuq-298 has not yet been produced/discovered, although Uuq-289 is believed to have been discovered. Two other yet-to-be discovered, double magic-number elements would be 120-304 (${}^{304}_{120}Ubn$) and 126-310, (${}^{310}_{126}Ubh$).

One special note: the calcium-48 nucleus used by scientists as the "bullet" for many of the newly discovered elements is itself doubly magic—20 protons and 28 neutrons, both magic numbers. That is one reason it was chosen—it should be stable enough to withstand the collision without itself breaking apart upon impact. The second reason is that it is neutron-rich, allowing it to bring into the collision the largest number of neutrons for its atomic number. (As mentioned in the article, heavier nuclei usually need a larger fraction of neutrons for maximum stability.

More on the periodic table and the "island of stability"

Scientists have long speculated about the "Island of Stability" for newly discovered, heavier elements. In fact, Glenn Seaborg, discoverer of ten of the transuranium elements, was the first to propose the idea. This island of stability encompasses isotopes of new elements that exist for relatively long time periods (for radioactive atoms), on the order of a tenth of a second or longer. This compares with many isotopes of transuranium elements, with half-lives of only a tiny fraction of a second. It is proposed that some of these elements will have half-lives on the order of years. And more recent research has indicated that not only does this island of stability exist, but several other islands exist for much higher atomic mass elements. The original island is located at element 114, and the next island of stability is predicted to exist around element 164—far from the superheavy elements now being discovered, in the 110-120 range.



The proposed island of stability
(Source: https://publicaffairs.llnl.gov/news/news_releases/2006/NR-06-10-03.html)

To view a video on a bit of the history of the concept of an island of stability (which came from Glenn Seaborg), go to the Nova Teachers web site to view the Nova "Science Now" video, "Island of Stability". (http://www.pbs.org/wgbh/nova/teachers/programs/3313_02_nsn.html) There is an overview of the 13 minute video included, as well as viewing ideas for the teacher to use with students before and after viewing the video. The video includes an interview with Ken Moody, one of the researchers mentioned in the *ChemMatters* article, and it shows an animated sequence to explain proton-proton and proton-neutron interactions. The video discusses the discoveries of the transuranium elements, and then jumps to element 114, the next element expected on the island of stability.

The idea of the island of stability is based on a hypothesis that the nucleus is made up of shells of protons and neutrons, similar to those of electrons in the atom. Filled shells of protons and neutrons in the nucleus would be separated by relatively large energy gaps from other shells, just like those of electrons. This would result in increased stability, hence longer lifetime for those filled shells than for near-relative isotopes without filled shells.

In addition to the idea of the island of stability, Seaborg also predicted the extension of the periodic table well beyond the then-present number of elements that had been discovered. He suggested that the periodic table would include the elements of the "g" orbital series of electrons. This would require two more energy levels than those presently on most periodic tables at that time (or even today). Wikipedia has an example of this table at http://en.wikipedia.org/wiki/Extension_of_the_periodic_table_beyond_the_seventh_period. It is expected that atoms of elements above atomic number 176 could not exist due to the limitation of the electrons' speeds to that of light. This limitation would not hold for the nucleus, however, so elements' nuclei above 176 could still exist; they would exist as ions, though, not neutral atoms.

For further discussion about how far the periodic table may actually extend, see http://jeries.rihani.com/. This site includes Seaborg's version of the periodic table, numbered to 173, with room all the way up to element 218! Other scientists dispute this claim, and Rihani discusses some of that disagreement.

More on the discovery of the superheavy elements

Element 110 (ununnilium, Uun)

Although element 110 had been discovered first in 1994 by researchers at the Gesellschaft für Schwerionenforschung (the Society for Heavy Ion Research, or GSI) Laboratory in Darmstadt, Germany, and observations by other research teams also saw evidence of element 110, the evidence did not confirm that discovery; instead it was later learned that the other research teams had merely produced different isotopes of the same element; in total, seven different isotopes had been prepared, ranging from 157 neutrons to 171 neutrons. Finally, in 2003, an international team of research scientists confirmed the discovery. The process of preparing 110 involved the bombardment of Pb-208 with Ni-64. The confirmation of the discovery by the international research team involved the production of $^{271}110$ by the same process as that performed by the GSI laboratory. The name "darmstadtium" was given to element 110 in 2003 by the GSI research group, after IUPAC officially recognized them as the discoverers of the element. (http://old.iupac.org/publications/pac/2001/7306/7306x0959.html)

$$^{208}_{82}Pb + ^{64}_{28}Ni \longrightarrow ^{271}_{110}Ds + ^{1}_{0}n$$

Ds-271 then decays into these daughter products:

$$^{271}_{110}Ds \longrightarrow ^{267}_{108}Hs + ^{4}_{2}He$$ and

$$^{267}_{108}Hs \longrightarrow (\square 106\,^{263}Sg + ^{4}_{2}He$$

Both these elements could be confirmed, which in turn confirmed the existence of Uun (later, Ds).

Element 111 (unununium, Uuu)

Element 111 was first discovered at the GSI in Darmstadt, Germany in December, 1994. A one-page report from the GSI of the decay chains that could help to verify the discovery can be found here: http://www.gsi.de/forschung/kp/kp2/ship/el111.html.
The element was prepared by bombarding Bi-209 with Ni-64. Once again, only three atoms were produced, so chemical properties could not be deduced.

$$^{209}_{83}Bi + ^{64}_{28}Ni \longrightarrow ^{272}_{111}Uuu + ^{1}_{0}n$$

Two daughter atoms in the decay chains were ^{268}109 and ^{264}107, two isotopes that had not been identified before.

$$^{272}_{111}Uuu \longrightarrow ^{268}_{109}Mt + ^{4}_{2}He \quad \text{and}$$

$$^{268}_{109}Mt \longrightarrow (\square 107\,^{264}Bh + ^{4}_{2}He$$

IUPAC approved the discovery and the name roentgenium on November 1, 2004 and published their findings here:
http://old.iupac.org/publications/pac/2004/7612/7612x2101.html.

Element 112 (ununbium, Uub)

The GSI lab was also responsible for the discovery of element 112 in 1996. They prepared atoms of this element by bombarding Pb-208 with Zn ions. The first isotopes to be produced were 112-277, with a half-life of 0.2 milliseconds. Five isotopes have been produced; the longest half-life of these is 10 minutes and comes from 112-285. The equation for the reaction is

$$^{208}_{82}Pb + ^{70}_{30}Zn \longrightarrow ^{277}_{112}Uub + ^{1}_{0}n$$

And the equation for the first decay process is

$$^{277}_{112}Uub \longrightarrow (\square 110^{273}Ds + ^{4}_{2}He$$

Element 112's discovery was approved by IUPAC in 2009. View their review official announcement at http://media.iupac.org/publications/pac/2009/pdf/8107x1331.pdf.
Element 112 has been named copernicium (Cp) by the GSI team in Darmstadt, Germany. The name was approved by IUPAC.

Element 113 (ununtrium, Uut)

Ununtrium (element 113) was discovered as a by-product of the decay series of ununpentium, discovered in 2004.

$$^{290}_{115}Uup \longrightarrow \, ^{286}_{113}Uut + \, ^{4}_{2}He$$

Uut was identified by its decay chain (series of alpha decay processes) of daughter particles:

$$^{283}_{113}Uut \longrightarrow \, ^{279}_{111}Uuu + \, ^{4}_{2}He$$ and

$$^{279}_{111}Uuu \longrightarrow \, ^{275}_{109}Mt + \, ^{4}_{2}He$$ and

$$^{275}_{109}Mt \longrightarrow (\square 107^{274}Bh + \, ^{4}_{2}He$$

Although ununpentium atoms only lasted for 90 milliseconds, ununtrium's atoms existed for 1.2 seconds before decaying. This is a long time for these usually very unstable atoms produced by scientists.

An article in the June, 2004 issue of Popular Mechanics cites the discovery of elements115 and 113 by Moody at the Lawrence Livermore Laboratory and Russian scientists at the Joint Institute for Nuclear Research. (http://www.popularmechanics.com/science/research/1282326.html?page=2)

Element 114 (ununquadium, Uuq)

It has been reported that only one atom of element 114, ununquadium has ever been produced, from a fusion of a calcium-48 ion with a plutonium atom, according to the following reaction:

$$^{242}_{94}Pu + \, ^{48}_{20}Ca \longrightarrow \, ^{289}_{114}Uuq + \, ^{1}_{0}n$$

Element 115 (ununpentium, Uup)

The first of the superheavy elements to be discovered (produced) was element 115, ununpentium (Uup). Americium-243 was bombarded with Ca-48 to produce ununpentium, observable only by its decay chain of atoms, one of which was previously undiscovered element 113, ununtrium.

$$^{243}_{95}Am + \, ^{48}_{20}Ca \longrightarrow \, ^{290}_{115}Uup + \, ^{1}_{0}n$$

Ununpentium's 4 atoms (that's all that were produced) decayed by alpha decay after a mere 90 milliseconds into ununtrium, which then further decayed:

$$^{290}_{115}Uup \longrightarrow \, ^{286}_{113}Uut + \, ^{4}_{2}He$$

Element 116 (ununhexium, Uuh)

Four independent international research groups all produced 116-292 (^{292}Uuh) by bombarding Cm-248 with Ca-48 ions, according to the following reaction

$$^{248}_{96}Cm + \, ^{48}_{20}Ca \longrightarrow \, ^{292}_{116}Uuh + \mathbf{4} \, ^{1}_{0}n$$

The Uuh atoms decayed 47 ms later by alpha decay into Uuq atoms by the following reaction:

$$^{292}_{116}Uuh \longrightarrow (\square 114^{288}Uuq + {}^{4}_{2}He$$

Element 117 (ununseptium, Uus)

Element 117 has not yet been discovered.

Element 118 (ununoctium, Uuo)

In 1999, researchers at the US DOE’s Lawrence Berkeley National Laboratory published in *Physical Review Letters* the announcement of their discovery of element 118 and the product of its immediate decay, element 116. Using the 88-inch Cyclotron and bombarding lead-208 with high-energy krypton-86 ions, they believed they had succeeded in producing elements that had gotten them closer to the predicted “island of stability” involving nuclei with approximately 114 protons and 184 neutrons.

$$^{208}_{82}Pb + {}^{86}_{36}Kr \longrightarrow {}^{293}_{118}Uuo + {}^{1}_{0}n$$

According to *Research News*, a publication of the Lawrence Berkeley Laboratory, the isotope of ununoctium, Uuo, they produced was Uuo-293, with 118 protons and 175 neutrons. The atoms of Uuo—only three of which were detected—each decayed within a millisecond by alpha decay into element 116, which also instantly decayed into element 114. (See elements 116 and Element 114, above for examples of these decay reactions.) The chain of alpha decays continued at least until element 106.

The lead researcher partly attributed his team’s new discovery to a newly constructed apparatus, the Berkeley Gas-filled Separator. This separator had supposedly increased efficiency and suppression of background nuclear reactions. The other factor that allowed them to make their discovery was the unique ability of the 88-inch Cyclotron to accelerate ions such as Kr-86 to high energy and high intensity beams. Scientists around the world touted this discovery as a clear sign that the island of stability was real and could be reached.

Unfortunately, their jubilation was short lived. Two years later, in 2001, the same research team reported in a correspondence to *Physical Review Letters* a retraction of their discovery. Re-analysis of the primary data files by the original research team and outside independent experts indicated their reported claims were not evident in the 1999 data. It seems that only one of the original researchers had actually traced their results all the way back to the primary data. (He was later relieved of his position.)

Berkeley’s *Research News* also published a report on the retraction. Both *Research News* references can be seen at http://www.lbl.gov/Science-Articles/Archive/elements-116-118.html.

Try again!

But that’s not the end of the story for element 118! In October, 2006 scientists at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, and Moody’s team at the Lawrence Livermore National Laboratory, published in the journal *Physical Review C*, a journal of the American Physical Society, their discovery (again?) of element 118. In a 5-month period in 2005, they had produced 3 atoms of element 118. They based their findings on the alpha decay chains from 118 to 116 to 114, as had the Berkeley Livermore team in 2001. By this time however, element 116 had already been produced and identified.

Their approach this time was significantly different from the Kr-86 bombardment of Pb-208. This time they bombarded Ca-48 into a californium target.

$$ {}^{249}_{98}Cf \; + \; {}^{48}_{20}Ca \longrightarrow {}^{294}_{118}Uuo \; + \; \mathbf{3}\,{}^{1}_{0}n $$

Here again, decay processes helped the research teams to identify the new element:

$$ {}^{294}_{118}Uuo \longrightarrow (\square 116^{290}Uuh \; + \; {}^{4}_{2}He $$

$$ {}^{290}_{116}Uuh \longrightarrow (\square 114^{286}Uuq \; + \; {}^{4}_{2}He $$

$$ {}^{286}_{114}Uuq \longrightarrow (\square 112^{282}Uub \; + \; {}^{4}_{2}He $$

Element 118 was predicted to be a noble gas, according to its expected electron configuration and its position on the periodic table. As such, it has long been a goal of nuclear chemists and physicists. Now that its discovery/production has been accomplished, scientists are working on producing even heavier elements. And even though some of the superheavy elements have been relatively stable (for radioactive elements), they still decay relatively rapidly.

Element 119 (ununennium, Uue)

Element 119 has not yet been discovered.

Element 122 (?)

But perhaps not all superheavy elements' nuclei are unstable. Researchers at the Hebrew University of Jerusalem reported in 2008 that they had discovered several atoms of element 122 in a small sample of a purified solution of thorium (element 90). By analyzing the solution in a mass spectrometer, they discovered atoms with masses just over 292, when they should have been seeing masses of approximately 232 (for common isotopes of thorium with about 142 neutrons).

Team leader Amnon Marinov of the Hebrew University research team stated that no known naturally-occurring element had a mass as high as the one they observed. He offered the possibility that this previously undiscovered element might be Ubb (unbibium) with 122 protons and 170 neutrons, or even element 124 with 168 neutrons, since there was no way to prove which element they saw. The researchers estimated the element's half-life to be on the order of 100 million (1×10^8) years.

Since the prevailing theories of the time expected either of these elements to have unstable nuclei, decaying in a matter of nanoseconds, other scientists quickly expressed doubt about Marinov's team's research. Elements located in the island of stability mentioned in the article are expected to require 184 neutrons, far more than Marinov's nuclei contained.

The original paper detailing Marinov's findings was posted on a pre-publication server here: http://arxiv.org/abs/0804.3869. You can download the entire article in pdf format at this site.

Bloggers also got into the act, and one in particular showed another interpretation of Marinov's team's mass spectrographs which seems to refute Marinov's claim. You can find a copy of the blog refuting his findings at http://www.chemistry-blog.com/2008/04/29/adressing-marinovs-element-122-claim/. Scientific journals seem to be in concert with the doubters; although Marinov submitted his paper to *Nature* and *Nature Physics*, both journals refused to publish it—even before sending it for peer review. *Chemistry World*, the online reporting arm of the Royal Society of Chemistry, also reports about doubting scientists at http://www.rsc.org/chemistryworld/News/2008/May/02050802.asp.

Attempts have been made to produce element 122, first at Dubna, Russia in 1972 by colliding a U-238 nucleus with a Zn-66 nucleus, and later in Darmstadt, Germany in 2000 (with greater detector sensitivity) by bombarding U-238 with Zn-70. Both attempts failed to produce any atoms of Ubb.

More on the HFIR

The Oak Ridge National Laboratory's (ORNL) High Flux Isotope Reactor (HFIR) is used to produce neutrons for international research on condensed matter. The neutron flux is used for neutron scattering to probe the fundamental particles of condensed matter. In addition to research into the production of new elements, the HFIR is used to study more practical materials. The neutron flux can be helpful in studies to learn more about: the arrangement of molecules in polymers, the special properties of crystalline materials, or the study of various materials in superconductivity, just to name a few. More than 200 research projects are done at the HFIR annually. Some of these projects are highlighted on the ORNL website: http://neutrons.ornl.gov/news/highlights.shtml.

The HFIR began full-power operations in 1966. It is the sole supplier of Cf-252 in the western world. Cf-252 is an isotope used in cancer therapy and detection of pollutants in the environment and explosives in luggage. Operating at 85 megawatts, HFIR is the highest flux reactor-based source for neutrons for research in condensed matter in the United States.

More on particle accelerators

There are essentially two types of particle accelerators—linear accelerators and circular accelerators. In a linear accelerator (linac) the particles are shot like bullets from a gun either into a stationary target, a circular accelerator, or a colliding particle beam from another linear accelerator. In a circular accelerator (also called a cyclotron), an electric field first accelerates charged particles. Then huge electromagnets are used to continually bend the beam of fast-moving charged particles into a circular path. These particles are contained in the magnetic field and eventually collide either with stationary targets or with other particles crossing their path.

Linear accelerators are easier and cheaper and to build, but they usually can't produce energies as large as those in circular accelerators. Circular accelerators are more complex, owing to the array of electromagnets needed to keep the particles going in a circle, and the need for a large diameter (sometimes on the order of kilometers) in order to get those larger energies. This, of course, makes circular accelerators more expensive to build. In addition to the larger energies a cyclotron can produce, the repeated circular path of the accelerated particles results in a much higher probability of collisions with the target particles at the intersection of their paths.

To see a very simple demonstration of a particle accelerator using a ping pong ball, see this 1-1/2 minute YouTube video: http://www.youtube.com/watch?v=EKxzXAQJvB8&eurl=http%3A%2F%2Fvideo%2Egoogle%2Ecom%2Fvideosearch%3Fhl%3Den%26source%3Dhp%26q%3Dparticle%2Baccelerator%2Bexperiment%26um%3D1%26ie%3DUTF%2D8%26ei%3D21uRSu%2D9HImZlAfu0pG1DA%26sa&feature=player_embedded#t=14. If you want to use it in your classroom, but your school blocks YouTube, simply download it at home to your own computer and save it to a flash drive to take to school and put on your school computer.

As the energy needs for the continued production of new elements increased, many of the lower-energy particle accelerators responsible for the discovery of the transuranium elements were decommissioned and have been replaced by new, higher-energy instruments. The latest new US particle accelerator, originally proposed by Michigan State University as the Isotope Science Facility, but later renamed the Facility for Rare Isotope Beams (FRIB), is being planned. The government in 2008 awarded a $550 million grant to Michigan State University for its proposal to develop the instrument. The primary purpose of FRIB is to produce the higher energies needed to accelerate heavier ions into heavier nuclei in order to produce even heavier superheavy elements. All of this will also help scientists better understand the nuclear reactions behind stars and stellar explosions test present theories about the nature of matter, and to help to develop new nuclear technology and medicines. It is expected to take a decade to design and build the facility. Here is the official Department of Energy's Office of Science announcement of the awarding of the grant: http://www.sc.doe.gov/np/program/FRIB.html. And this document contains an illustration of the proposed facility: http://www.orau.org/RIA/frib/frib-facility-description.pdf.

For an example you could use with students, you probably have in your own home an example of a linear particle accelerator—a television or computer monitor with a cathode ray tube (CRT) screen. In the case of the CRT screen, the particles being accelerated are electrons. Electrons are emitted from a heated filament, similar to that of a normal light bulb. The heated filament is the cathode. The negative electrons are attracted (accelerated) through the evacuated picture tube toward the anode, consisting of a focusing anode and an accelerating anode. Two sets of electromagnets deflect the accelerated electrons to control their vertical and horizontal positioning as they collide with your TV screen. Phosphors on the screen then glow when struck by those electrons. In a black-and-white monitor, there is only one phosphor that glows white when impacted; in a color television, there are three phosphors—red, green and blue—that emit light when excited. There are also three individual electron beams that excite the three different phosphor colors to give you composite colors. If you want to know more about how televisions work, see the How Stuff Works web page on "How Television Works" at http://electronics.howstuffworks.com/tv.htm.

More on naming elements (and the role of IUPAC)

Before a new element can be officially named, it must first get official recognition of its existence by the governing body of chemists—the International Union of Pure and Applied Chemistry (IUPAC). IUPAC has formed a Joint Working Party (JWP) with the International Union of Pure and Applied Physics (IUPAP) to judge the claims of the various research teams regarding the discovery of a new element. Their criteria were published in 1991 in IUPAC's official journal, *Pure and Applied Chemistry,* and can be found online at http://old.iupac.org/reports/periodic_table/index.html.

After much debate and criticism in the early 1990s within the chemistry community about the provisional names given to the transfermium elements (atomic numbers 101-109), IUPAC formally specified the names of the transfermium elements in *Pure and Applied Chemistry* in 1997. You can find the publication online at http://old.iupac.org/reports/1997/6912transfermium/index.html.

The official names, from that publication, are:

Element	Name	Symbol
101	mendelevium	Md
102	nobelium	No
103	lawrencium	Lr
104	rutherfordium	Rf
105	dubnium	Db
106	seaborgium	Sg
107	bohrium	Bh
108	hassium	Hs
109	meitnerium	Mt

Only the following three “superheavy” elements have IUPAC-accepted names:

At. No.	New Name	Symbol	Old Name
110	darmstadtium	Ds	ununnilium
111	roentgenium	Rg	unununium
112	Copernicium	Cp	Unbibium

Connections to Chemistry Concepts

1. **Observations**—Scientists use all their senses in their experiments – and when these are insufficient, they use instrumentation to aid their senses. The detectors used to detect the new particles produced in the cyclotron are examples of this.
2. **Periodicity**—[The properties of the superheavy elements do not necessarily follow the “rules” of the periodic table.
3. **Isotopes**—Many examples are noted in the article that could give students practice in (and practical applications for) understanding isotopes.
4. **Equations for nuclear reactions**—Lots of examples of nuclear reactions appear in the article. You can use these for balancing nuclear equations.
5. **Nuclear stability, reactivity and half-lives**—Examples abound of unstable isotopes and the role of neutrons in these reactions.
6. **Nuclear decay**—Beta decay is illustrated in the article; alpha and gamma decay will require further development outside the article.

Possible Student Misconceptions

1. **“Scientists have already discovered all the elements there are to discover.”** Well, the problem with this statement is the word “discover”. Actually, the student making this statement may be right in that scientists aren’t discovering elements anymore; they’re making them. But then again, there may be more elements (of higher atomic mass) out there in space (inside novae, for example) that scientists haven’t yet detected. Any new elements that scientists are “discovering” now are indeed being made by them, and in that sense of the word, there may be (are?) more to come.
2. **“Atoms of one element can’t be changed to atoms of another element that’s what makes it an element.”** *This was the belief of scientists historically, but a better scientific understanding of the natural world in the last 100 years has changed those beliefs. We now know that unstable atoms regularly undergo a change from one element to another as they experience radioactive decay.*
3. **“Scientists can always just shoot a heavier element at the target element to make heavier new elements, one by one.”** *Unfortunately, it’s not that easy, as the article states. Many factors make this an untrue statement, including the relative instability of heavier “bullet” atoms/ions, and the energy required to fuse the two nuclei. Also, scientists in the recent past have believed they’d produced new elements when, in fact, they had not.*
4. **“Atoms can fuse together easily to make new elements, just like atoms combine to make new compounds.”** *Although this would seem to make sense, fusing nuclei together requires much greater energy to overcome the huge repulsion between the nuclei (proton-proton repulsions, with no electron-proton attractions, like those that exist in chemical bonds). In chemical bond formation, the small electron-electron repulsions are more than made up for by the new proton-electron attractions, resulting in a more stable new molecule.*

Demonstrations and Lessons

There truly are no demonstrations/experiments that can be done with the transfermium elements directly (unless perhaps your high school is affiliated directly with the Lawrence Livermore National Laboratory). And there are only a few experiments that can be done involving radioactivity directly. Those are the “old standard” activities, listed in 1), below.
The activities following 1), below are simulations of radioactivity experiments that can be done in the lab. (There are no transfermium simulations found or listed.) These, too, are versions of “old standards”.

1. If you are fortunate enough to have access to nuclear sources (alpha- or beta-sources—and perhaps, gamma-sources as well), you can do the standard experiments involving a) the inverse square law and nuclear radiation intensity, b) nuclear radiation intensity and shielding, and c) half-life determination.
   A standard set of these experiments can be found at the Lawrence Berkeley Laboratory site: http://www.lbl.gov/abc/Contents.html#experiment.

   Another source of real nuclear experiments/demonstrations can be found at the Practical Physics web site. “Alpha radiation: range and stopping” (http://www.practicalphysics.org/go/Experiment_587.html), and “Beta radiation: range and stopping” (http://www.practicalphysics.org/go/Experiment_588.html;jsessionid=aHPdysvpdnm_?topic_id=$parameters.topic_id&collection_id=%24parameters.collection_id. Handling and safety are included in teacher notes.

And this one comes from NASA (2002). “Orbital Space Settlements Online Course” provides “Radioactive Shielding”, an experiment requiring alpha, beta and gamma sources to test shielding effects. (http://www.nas.nasa.gov/About/Education/SpaceSettlement/teacher/course/radioactive_shielding_expe.html)

In Nuclear Experiments You Can Do, a booklet by the Thomas Alva Edison Foundation, students are introduced to nuclear science. The booklet is very dated (1986, last printing), but it does contain an experiment on shielding. And if you’ve ever wanted to build your own Geiger counter, the instructions are included.

2. Half-life activities—Many web sites provide hands-on activities to involve the students in simulations that allow them to discover for themselves what a half-life is. Here are just a few of them:

“Rock of Ages—A Half-life Analog provides a geological view of half-life, complete with radiologic dating with C-14. (http://www.geology.wisc.edu/~museum/hughes/RockAges.html) The reason this version is offered is two-fold: first, it gives a direct application of half-life determination and second, it replaces the decayed atom with its daughter atom to show (more or less) conservation of mass. Most other simulations simply remove the decayed atoms (which is probably more correct in the case of C-14, as it decays into a gaseous nitrogen atom which leaves the system). This lab also includes state (Wisconsin) and national science standards.

“Radioactive Decay: A Sweet Simulation of a Half-life” is one of many candy-based simulations. (http://www.sciencenetlinks.com/lessons.php?DocID=178) The reason this one is chosen is because it provides for teachers an entire lesson script for the activity, while it also provides a student lab sheet. It is one in a series of 3 lessons on radioactivity. (Lesson one is “Isotopes of Pennies” and lesson three is “Frosty the Snowman Meets his Demise: An Analogy to Carbon Dating.” This site is also one of the “ScienceNetLinks” sites, sponsored by the American Association for the Advancement of Science (AAAS).

Suitable for honors chemistry students, a “beefed-up” version of the activity from Westminster College, “Half-Life Simulation with M&Ms”, provides for students to discuss the decay process in terms of the decay constant and the integrated rate law. (http://www.westminster.edu/acad/sim/documents/SHalf-LifeSimulation.MMs.pdf)

Again, for honors (or second-year) students, if you wanted to give individual students access to simulated data, you could go to “Halflife Simulation” (http://chem.lapeer.org/Chem1Docs/Halflife/HalflifeExp.html). There students (or you) can choose from approximately 30 different isotopes. Once an isotope is chosen, data about the original number of atoms and final number of atoms observed, and the number of days observed is given. Unfortunately, the equipment failed before enough data could be gathered. The student must then decide the parameters of the experiment, run the experiment, and determine the half-life. Background radiation is included in the new data, just to confuse things further. It’s an interesting exercise. Every student could get individual data and then plot it.

3. If you would like to just show students a representation of half-life as part of your lesson, you can do that, too.

Visit http://www.lon-capa.org/~mmp/applist/decay/decay.htm. This is a very simple applet (Java required) that shows a large number of dots representing atoms. You can choose the time of the half-life, and when you press “Start”, the dots disappear at the rate for the half-life you choose (times chosen are relative times, not based on real time). A histogram is shown simultaneously for reference purposes.

The University of Colorado’s PhET web site has a simulation on alpha particle decay that shows half-life in animation at http://phet.colorado.edu/simulations/sims.php?sim=Alpha_Decay.

A simple classroom demonstration of half-life using the flipping pennies idea can be found here: http://serc.carleton.edu/quantskills/activities/PennyDecay.html.

4. If you would like more information about typical radioactive decay series, you can find a Java applet, “Radioactive Decay Series”, by Walter Fendt, at http://www.walter-fendt.de/ph14e/lawdecay.htm that shows a chart with step-by-step decays of four radioactive isotopes.
5. A series of 4 lessons, “Nuclear Energy: Nuclear Decay”, can be found at http://www.montgomeryschoolsmd.org/departments/Intern/stp/workshops_shilling.html. The lessons were written for an environmental science class and a link on the site contains background information on nuclear science, and three activities. One is a simulation by Physics 2000, called, simply, “HalfLife” (http://www.colorado.edu/physics/2000/isotopes/radioactive_decay3.html), which takes students through a simulated discussion between two people about what half life really means, and includes an applet that demonstrates atoms decaying and a graph of that phenomenon over time. The second activity involves an interactive link that shows decay chains of with specific steps in each decay process. And the third activity discusses using two different colors of dice to determine the half-life of each (self-contained on the site). Student data tables are included for this activity.

You don’t want to just give this (original) web site to students because a) it’s a lesson plan site for teachers, and b) it contains a hot link that is supposed to take the reader to the site that displays the interactive table of elements and their decay series (second of the three activities), but it goes to a, shall we say, less desirable site (really “hot”). (The site has been taken over since the writing of the lesson plan.) The site the activity should access has changed to http://www.nucleonica.net/unc.aspx, NOT www.nuclides.net.

6. You could give students an idea of how a particle accelerator works by showing them a CRT television or computer monitor, preferably removed from its case so they can see the internal workings. See the last paragraph in “More on particle accelerators” earlier in this Teachers Guide for basic information. A reference web site for an explanation of how the CRT screen works is given there.

Student Projects

1. Students could research individual superheavy elements and report on the history of their discovery (or purported discovery-see element 122).
2. For a list of possible student projects for written reports on nuclear science or societal issues, see http://www.lbl.gov/abc/wallchart/chapters/appendix/appendixb.html.
3. Here is an account of a student project involving the use of a digital camera’s LCD window to view alpha radiation from a readily available radiation source (a smoke detector). (http://www.inventgeek.com/Projects/AlphaRad/overview.aspx)
4. Students could research and report on binding energy within atoms.
5. Students could research and report on the unifying theory of physics, with its
6. While you may not want to encourage this in your own students, it might pay off in the long term. In the March, 2007 issue, Discover magazine carried the (very short) story of Thiago Olson, a high school senior and Boy Scout, who achieved in his basement the fusion of hydrogen to produce plasma. (http://discovermagazine.com/2007/mar/radioactive-boy-scout)

Anticipating Student Questions

1. **"Is there a limit to how large a nucleus can be produced by present methods?"** *Scientists don't really know the answer to this question, although it is becoming more difficult for them to produce heavier and heavier nuclei by this process. But scientists are always working on new methods that may allow them to produce heavier elements.*
2. **"Why would elements 112 and 118 have different properties than anticipated/predicted?"** *Element 112 is expected to be more inert than Hg (directly above Uub on the periodic table), while element 118 is expected to be more active than Rn (directly above 118 on the periodic table). Part of the reason for the predictions is that there are so many protons inside Uub's nucleus that the nucleus would contract the electron cloud and that, to prevent their being pulled into the nucleus, some of the electrons would need to be traveling very close to the speed of light. This had suggested to scientists that it would make the nucleus highly unreactive, like a noble gas. These expectations are also based on spin-orbit interaction within the nuclei. (For more on this phenomenon, you'll need to visit quantum physics theory.)*
3. **"OK, why can't we just test elements 112 and 118 to see if their properties are different than predicted?"** *Unfortunately, only a few nuclei at a time are produced in the cyclotron. Until scientists can create enough of the element and have them remain un-decayed long enough to test them in the lab, we won't be able to determine their gross properties.*
   New information suggests that Uub may actually be much closer in properties to Hg than Rn. This discovery was made even with only two atoms of Uub. See http://www.rsc.org/chemistryworld/News/2007/May/02050703.asp for the details. It's worthwhile to note that at the time of this experiment, the existence of element 112 had not yet been sanctioned by IUPAC. A similar report of the same experiment came from Scientific American *at http://www.scientificamerican.com/article.cfm?id=superheavy-element-ununbium-has-ordinary-chemistry.*
4. **"Where do all these new elements come from?"** *The new superheavy elements are created by scientists; they do not exist in nature (as far as scientists know now). (There may be an exception to this; see the section in "More on superheavy elements", where the possible 2008 discovery of element 122, Ubb, is discussed.*
5. **"Is there an end to the periodic table?"** *Scientists don't know the answer to this question. Although all the superheavy elements to-date have been unstable, some scientists have predicted that elements in the island(s?) of stability may once again be stable. Seaborg predicted elements all the way up to 218.*

Web Sites for Additional Information

More sites on transfermium elements

For a tongue-in-cheek treatment on the discovery of a new element, called governmentium, see http://docstalk.blogspot.com/2008/11/cop-lawrence-livermore-laboratories-has.html.

More sites on the periodic table and the island of stability

For another view of the extended periodic table, this one from ChemEuro.com, see http://www.chemeurope.com/lexikon/e/Periodic_table_(extended)/.

Mark Leach has an extensive coverage of periodic tables of every size and arrangement on his Chemogenesis web site. View the collection at http://www.meta-synthesis.com/webbook/35_pt/pt_database.php?Button=1950-1999+Formulations.

Here is another list of more than 100 variations on the periodic table, as well as a list of sites with lessons related to the periodic table: http://dubber6.tripod.com/whereisit/id52.html.

More sites on the discovery of the superheavy elements

Wikipedia shows you a timeline of the history of the discovery of the elements, including the unconfirmed discoveries of the superheavy elements, at http://en.wikipedia.org/wiki/Timeline_of_chemical_elements_discoveries.

IUPAC has a periodic table of the discovery of the elements, by 50-year intervals. It includes the early transfermium elements, but it does not contain the superheavy elements. You can find it at http://old.iupac.org/reports/periodic_table/index.html.

Professor Bob Bruner's web site contains a wealth of chemistry internet resources, including specific references to the discoveries of some of the superheavy elements. Go here to start: http://bbruner.org/11net.htm#Top.

More sites on particle accelerators

The Lawrence Berkeley National Laboratory has a site which provides students with information about each of the world's eight major accelerators. Information includes schematics, descriptions of what the accelerator is designed to study, and what important discoveries were made at each. You can find the site at http://particleadventure.org/variation.html.

FermiLab's web site includes an animated sequence of the events that transpire to accelerate particles inside their chain of accelerators. The FermiLab accelerators deal with much higher energies (1 trillion electron volts, instead of 1 billion eV) and much smaller particles (protons and antiprotons, rather than large nuclei) than the accelerators discussed in the article, but it does show linear and circular accelerators being used in tandem. It combines colors and sounds to show the changes in energy as a particle is accelerated through the chain of accelerators. View (listen to) it at http://www-bd.fnal.gov/public/index.html.

More sites on naming elements

The International Union of Pure and Applied Chemistry (IUPAC) has published its "Naming of New Elements" document at http://old.iupac.org/publications/pac/2002/pdf/7405x0787.pdf. It restricts what names a discoverer of an element can propose to the categories below.

"In keeping with tradition, elements are named after
- a mythological concept or character (including an astronomical object);
- a mineral, or similar substance;
- a place or geographical region;
- a property of the element; or
- a scientist

To avoid confusion in the literature, when a name has been in unofficial use for a particular element, but a different name is ultimately chosen for that element, then the first name cannot be transferred for use for another element. A case in point is element 105 for which the name hahnium has been unofficially used. Since the name dubnium was chosen for that element, hahnium cannot be used for another as yet unnamed element.

For linguistic consistency, the names of all new elements should end in "-ium".

The site also lists the procedure a scientist must follow to obtain acceptance of the proposed name. And reference is made to "interim" names—those involving the prefixes for their atomic numbers; e.g., Ubb, etc.

In the August 18, 2003 issue of *Chemical and Engineering News*, the American Chemical Society reported on the naming of Darmstadtium (element 110): http://pubs.acs.org/cen/topstory/8133/8133notw1.html.

General Web References

The Nuclear Science Division of the Lawrence Berkeley National Laboratory web site provides a wealth of research data about elements and all their isotopes (mostly for scientists, but also useful for teachers and students) at this site: http://ie.lbl.gov/toi.html. Within this site, there are tables of isotopic data, both real [a pdf file with 21 pages] (http://ie.lbl.gov/toi/pdf/chart.pdf) and theoretical [3 page pdf file] (http://ie.lbl.gov/toipdf/theory.pdf). The site also contains an interactive periodic table, from which you can choose an element and it will show you all the known isotopes for that element (http://ie.lbl.gov/education/isotopes.htm).

If you want more in-depth information on very recent results of studies about sub-atomic particle physics, check out the "Particle Adventure: The Fundamentals of Matter and Force", produced by the Particle Data Group of the Lawrence Berkeley National Laboratory. This web site shows you (or students?) the "standard model" of matter, the present understanding of the four forces of nature, and the building blocks of matter (no, not just atoms, but quarks, hadrons, leptons, etc.). It takes you (them?) on an adventure through the world of the submicroscopic. It also presents a section on particle accelerators and detectors. You can find the site at http://www.particleadventure.org/.

Metals' Hidden Strengths

Background Information

From the periodic table, metals are the most abundant category of elements found on earth (of course in the universe, it is the non-metal hydrogen!). And when one considers the long history of humankind, metals are fundamental to the advance of civilizations, having played a major role in their development, from the crudest of tools made from copper (succeeding stone implements) to present day's plethora of "tools" that depend on metals for their operation. Early history is often divided into ages or epochs based on the types of tools—Stone, Bronze, Iron Ages. If the 21st Century can be considered the era of communications, then, as mentioned in part of the Metals article, we have the ever-shrinking transistor device with its microcircuits constructed from a variety of metals.

We need to distinguish between pure metals (elemental) and the more common mixes of metals (alloys) that produce a multitude of characteristics. The modern "alchemy" turns a collection of individual metals (and non-metals) into a material with characteristics that are not necessarily those of any one element in the mix. Again, the somewhat curious chemical fact is that several elements chemically reacted together lose their elemental characteristic properties. When they react sodium metal and toxic chlorine gas produce the compound sodium chloride (a "salt") that is not metallic, gaseous, or toxic.

Finding the correct blend of chemicals in the modern era of electronics, for instance, becomes both an art and a science. When one looks at something like superconductivity, the varieties of chemical blends that have been developed for the electrical conducting medium are not entirely intuitive. A modern jet engine is constructed from a variety of metallic elements including titanium (38%), nickel (37%), chromium (12%), cobalt (6%), aluminum (5%), niobium (1%) and tantalum (0.02%). Looking at these blends, some of which can be considered alloys, harkens back once again to one of the earlier epochs, the Bronze Age, when harder tools were somehow crafted from a mix of copper and tin. As human technology developed ways to produce hotter fires (use of enclosures—furnaces), iron was removed from its ore by separating the iron from other compounds by hammering (wrought iron) the heated ore or, later, melting out the iron itself ("blast" furnace). In the process, carbon from the charcoal fire or carbon monoxide accidentally added hardness to the soft elemental iron. This altered material (steel) succeeded bronze as the new hard metal for tools and weapons.

More on solar cells (photovoltaics)

The basics of the operation of solar cells, including good diagrams, are found at http://www.howstuffworks.com/solar-cell.htm and http://www.solarbotics.net/starting/200202_solar_cells/200202_solar_cell_physics.html.

Essentially, the chemistry of the materials used in solar cells depends on creating both a source of electrons and some "holes" into which the electrons flow. The majority chemical of choice is silicon, the second most abundant element after oxygen in the Earth's crust. Silicon is a semi-conductor—that means it can be an electron donor and an insulator, the properties of both metals and non-metals. Adding the element germanium to the silicon has been found to increase the efficiency of the electron movement. Displacement of electrons always requires some form of energy which, in this case, would be photons. The materials in the solar cell (a center absorber layer plus two outside layers) act to provide both a source of electrons that moves under an electric field (which produces a voltage or potential difference) as well as a destination for those electrons, known as “holes” within the solar cell. This arrangement includes a path for the flow of displaced electrons, thus creating a current (associated with the movement of electrons).

The two outside layers of a solar cell are labeled N and P. The N-type layer in the cell is “negative” or the source of electrons; the P-type layer is “positive” and the destination for electrons, or the “holes”. To provide a flow of electrons from the N to the P layers, additional chemicals are introduced into the silicon. This is known as doping. Several elements that are often used include phosphorus (and other members of group 5A) in the N layer for electron donation (think five valence electrons). In the P layer, boron or other members of group 3A such as gallium can be used to create electron “holes” (three valence electrons for boron). (See the basics of a semiconductor at http://electronics.howstuffworks.com/diode1.htm and the entire series of articles on semiconductors at http://electronics.howstuffworks.com/diode3.htm)

Thin film solar, as an alternative to silicon-based solar cells is described at http://www.scientificamerican.com/article.cfm?id=solar-power-lightens-up-with-thin-film-cells. An illustration of a commercial product can be found at http://www.globalsolar.com/technology/. Also from the National Renewable Energy Laboratory, NREL, is an update on the efficiency of thin-film solar cells at http://www.nrel.gov/news/press/2008/574.html.

More on shape memory alloys

Shape memory alloys came out of US Naval research by William J. Buechler of the late 1950s, early 1960s. (http://www.americanheritage.com/articles/magazine/it/1993/2/1993_2_18.shtml)

His curiosity was sparked by the change in sound of a particular alloy of nickel and titanium when the metal was heated (cold sound was a thud, and warm metal sound, a bell-like sound). The change in sound with a change in temperature was due to a change in shape. Metals and metal alloys consist of tiny crystallites that have a regular atomic structure. These crystallites are held together through bonds that give a particular orientation. If the structure is heated and a shape is forced onto the structure, the bonding arrangements are changed from that of the colder (room) temperature. Cooling this crystalline structure does not alter the bonding established at the higher temperature—it is locked in.

For the NiTi wire (called Nitinol), the crystalline structure changes, depending on the temperature. At temperatures between 0 and 100 degrees Celsius, there are two important phases or crystal structures called austenite (high temperature) and martensite (low temperature). The austenite phase has the symmetry of a cube and is characterized by hardness and rigidity.

“When the wire is heated, a new shape can be introduced. That shape remains after the wire cools to room temperature. The wire is flexible at the lower temperatures. When the wire is distorted, the stress is absorbed ***within*** the structure of the individual crystallites. At the higher temperature, the crystalline structure is stiff and stresses due to bending are absorbed by the bonds ***between*** the crystallites, as in a normal metal. The ability to change the shape of the material derives from defects or irregularities in the packing of the atoms of the material. The defects, which can be altered at the high temperature of a candle flame where NiTi is in the

austenite phase, are used to create the shape to be "remembered" by forcing groups of atoms to have particular positions relative to one another."
(http://mrsec.wisc.edu/Edetc/modules/HighSchool/memory/Memory_Metal_Overview.pdf)
(http://mrsec.wisc.edu/Edetc/cineplex/NiTi/—a series of videos that demonstrate the behavior of the NiTi wire)

The application of the memory metals utilizes this temperature-dependent transition. For instance, in the case of dental braces, the brace can be shaped into a curve at high temperature that the teeth are supposed to follow. When the brace is at room temperature, it is flexible and can be shaped to fit the mouth around the teeth of the wearer. Then body temperature causes the metal to return to the stiff, preformed shape, exerting pressure on the teeth. This same idea of changing to an original shape at higher temperatures finds applications in valves that will shut off if temperatures of liquids passing through the valve go higher than desired.

Another *ChemMatters* article on how memory metals work at the molecular level (with diagrams) is found in the October, 1993 issue, pp.4-7 (*"Memory Metal")*.

An application of futuristic proportions is the construction of a robot bat that can fly, having flexible wings that, if "distorted", will return to the original shape, using the characteristics of memory metal for muscle function. The distortion in shape of the memory metal, which is highly elastic, is done using heat from an electric current sent to the wires that are the size of a human hair. Heating causes contraction (going to the higher temperature's original shape). Contraction of the wires increases electrical resistance and a change in current flow that can be used as a sensory input to control electronics. Cooling allows the metal to return to another shape or length because of the wire's elasticity.
(http://news.ncsu.edu/news/2009/07/wmsbungetrobobat.php) and
(http://www.heraldonline.com/109/story/1466072.html#)

More on transistors

A description of the hafnium-based transistor (referred to in the Metals article) is found at http://www.scientificamerican.com/article.cfm?id=the-magic-ingredients-in as well as http://www.scientificamerican.com/article.cfm?id=microprocessor-computer-chip. The latter reference describes the method, at the nanoscale, of depositing individual atoms for the N- and P-layers of a transistor that allows for much thinner transistors.

Also, there is a different use for transistors—to control the flow of molecules rather than of electrons, thereby moving molecules themselves without using moving parts such as valves and pumps. The concept is based on the early work of moving ions between electrically charged plates. This technique can be used to analyze molecules such as DNA, proteins, etc. at a nanoscale. (http://www.scientificamerican.com/article.cfm?id=transistor-flow-control)

More on alloys

Alloys come in a variety of mixes (both homogeneous and heterogeneous) that provide a variety of useful characteristics. Something like alloy steels have various small amounts of metals added to iron. These include:

- Chromium for increased hardness and resistance to corrosion
- Tungsten and molybdenum for increased heat resistance
- Nickel adds toughness (as in armor plating)

- Vanadium adds springiness
- Manganese improves resistance to wear

This website,http://www.gcsescience.com/ex28.htm provides information on the various alloys of aluminum, copper, iron, lead, titanium and so-called smart alloys (another term for memory metals such as Nitinol).

More on ores

From where do metals come in nature? Students may not be aware of the idea that metals usually occur in nature as compounds (minerals) in rock (the ore), rather than as a pure substance such as gold and silver. The mining industry and subsequent processes of refining a metal from its ore should be understood in the same way as the fact that milk comes from cows, not from a refrigerator in a store! A variety of compounds of metals can be found in the earth in the physical form of "rocks"!

Examples of ores or minerals from rocks that contain various metal compounds include:

- The mineral wolframite, $FeWO_4$ / $MnWO_4$ is the source of tungsten, element W; (in Danish, tung sten, means heavy stone); W is obtained from wolfram oxide, WO_3 by reduction using carbon or hydrogen.
- Chromium oxide, Cr_2O_3, from which the element chromium, Cr, is isolated by reacting the oxide with silicon (Si)
- Iron oxides, FeO and Fe_2O_3 or hematite, which turns rocks red brown, yield iron through a heating process utilizing carbon (coke) or carbon monoxide for reduction of the iron compound
- Copper occurs in a number of compounds including Cu_2S (chalcocite), $CuFeS_2$ (chalcopyrite), $Cu_2CO_3(OH)_2$ (malachite), $Cu_3(CO_3)_2(OH)_2$ (azurite) and is isolated from the ore by heating in air (roasting)
- Aluminum is isolated from the mineral, hydrated aluminum oxide, Al_2O_3, or bauxite by electrolysis

Explanations with diagrams on electrolysis for extraction of metals can be found at the three related websites here: http://www.gcsescience.com/ex.htm, http://www.gcsescience.com/ex1.htm, and http://www.gcsescience.com/ex2.htm.

The history of mining for gold, including present day methods, is found in another *ChemMatters* article, *"The New Gold Rush";* October 1989, pp. 4-8.

More on the element silicon, a metalloid (semi-metal)

Silicon of solar photovoltaic fame is obtained by melting and reducing the compound, SiO_2, associated with quartz crystals, as found in common sand. Reduction is accomplished through the use of carbon monoxide or elemental carbon:

$$SiO_2\ (\ell) + C\ (s) \rightarrow Si\ (\ell) + 2\ CO_2\ (g)$$

This produces 98% pure silicon. Additional purification of this silicon can be done by using chlorine, Cl_2:

$Si (s) + 2Cl_2 (g) \rightarrow SiCl_4 (\ell)$

The silicon tetrachloride, $SiCl_4$ is repeatedly distilled to yield gaseous $SiCl_4$ which is then reacted with magnesium:

$SiCl4 (g) + Mg (s) \rightarrow 2 MgCl_2 + Si (\ell)$

For use in solar cells, the silicon should have a purity of at least 15% but desired purities above 20% are sought for increased efficiency. Adding the element germanium from the same chemical family also increases the efficiency of electron transfer within the solar cell. Normally the solar cell is cut from essentially a “sausage” of silicon.

More on catalysis of hydrocarbons and beyond

From an article in the August 2008, Scientific American, (“Self-Cleaning Materials”, pp. 88-94) are found two chemically related topics on self-cleaning and self-disinfecting surfaces that provide more details on the surface chemistry involved. The self-disinfecting topic delves into photo-catalysis using titania, which is titanium dioxide. This catalysis is able to split organic compounds into water and carbon dioxide using ultraviolet light as the activator. The details of this particular reaction involve the microscopic surface of titania acting as a semi-conductor with the UV light, creating two mobile charges—a displaced electron and a positively-charged “hole” which acts much like a positively charged particle. There is a very good colored diagram in the article to illustrate the effect. These two mobile charges interact with water and oxygen at the surface of the titania, producing superoxide radical anions (O_2^-) and hydroxyl radicals (OH). These very reactive species can then convert organic compounds into carbon dioxide and water.

Another interesting discovery about titania concerns the ability of a titania layer to again interact with UV light, but now becoming what is known as a surface with multiple types of wetability; i.e., able to absorb not only water but also oil. The mechanism of operation is based on the fact that the UV light removes some of the oxygen atoms of the titania surface, creating a surface at the nanoscale that is able to adsorb hydroxyl groups. In between these hydroxyl-adsorbing surface structures are areas for absorbing oil. This particular surface then acts as a self-cleaning one in which water is able to spread across the entire area, forming a sheet of water that carries away dirt as it flows.

The photocatalytic action of the titania also can act as a deodorizer as well as a disinfectant by breaking down organics and killing bacteria. As such, the technology has been developed to not only incorporate this compound into clothing but also to use in places where disinfecting is needed, such as kitchens and bathrooms (tiles that can be exposed to light). In addition, application of the titania to surfaces of building materials that are hard to access will allow for self-cleaning when exposed to rain or other water sources. Because glass, which absorbs UV, may be between sunlight and a titania surface, it has been found that adding nitrogen or silver to the titania surface (doping, as in silicon-based photovoltaic cells) widens the band of visible light that can activate the photocatalysis of the titania layer.

Connections to Chemistry Concepts

1. **Valence electrons**—Both for the operation of solar cells and other transistor types of electrical devices, metals are providing electrons for conduction, based on the loosely held outer valence electrons.
2. **Metallic Bonding/ delocalized electrons**—With non-directional bonds in metals due to delocalized electrons, metal are able to be good conductors of heat and electricity as well as being malleable to shaping.
3. **Thermal/Electrical Conductivity of Metals**—Because the valence electrons in metals are rather mobile within the metallic crystal, they are easily displaced by an applied voltage. The same is true for thermal conductivity in metals in which higher temperatures produce higher kinetic energies for the electrons, which if moving to cooler regions of the metal, will transfer some of their kinetic energy to the crystal lattice. This is a more rapid transfer than for poor conductors that depend upon vibrations of atoms or molecules about fixed positions in the crystal lattice colliding with adjacent atoms, with a resultant transfer of energy that is slower than for movement of electrons.
4. **Oxidation, Reduction**—Isolation of metals from their parent ores depends on the reduction of the metal in the ore. In the process, oxidation of the reducing agent has to take place as well.
5. **Alloys of metals**—The particular mix of metals provide for a variety of physical characteristics. Brass (copper and zinc) and bronze (a mix of copper and tin) were some of the earliest alloys in the history of tools (between stone and iron). Gold is made harder by adding copper. Melting points of metals can be lowered by creating an alloy. An example is Wood's metal, a mix of bismuth, lead, tin and cadmium, producing a melting point of 70 ° C. Stainless steel combines iron with chromium, nickel and some carbon (for hardness).
6. **Photoelectric effect**—Solar cells depend on the displacement of electrons in metals and metalloids based on the photoelectric effect in which a particular frequency of electromagnetic radiation (visible light as well as infrared and ultraviolet) provide enough energy to displace electrons from silicon atoms into a circuit.
7. **Fluorescence, phosphorescence**—In fluorescence, photons absorbed by molecules cause the emission of photons at a different and usually longer wavelength. In phosphorescence, photons absorption causes re-emission of photons at the same wavelength but with a time delay and a slow release of the photon emission. This extra light production means additional electricity generation in special solar cells that incorporate hafnium oxide into the silicon base.
8. **Polymer**—Polymers, compared with silicon-type glass, allow not only visible light but also infrared and ultraviolet transmission through the material. This additional transparency allows for a broader spectrum of electromagnetic radiations to be absorbed by photovoltaic materials.
9. **Doping**—In order to make a metalloid such as silicon a better conductor, adding additional elements that are either better electron donors or acceptors, contribute to the so-called N and P layers of a transistor. Such elements include Phosphorus as a donor and Boron as an acceptor.

Possible Student Misconceptions

1. **"All metals are magnetic."** *Not all metals have magnetic properties. The so-called ferrous metals that include iron and nickel are attracted to a magnet whereas gold and aluminum are not. Such a distinction can be used in separation techniques in recycling operations.*

2. **“Most metals occur in nature as pure metals—ready for use.”** *Most metals are found in nature as compounds and are called minerals. Various techniques, including the use of heat and acids, are used to separate the metal from its parent compound. A few metals such as gold and silver can be found as a pure substance in nature because these elements do not readily react with other chemicals in the environment, particularly oxygen, which is why these metals are able to retain their metallic luster.*
3. **“Metallic ores and minerals are the same thing.”** *They are not the same thing though they are “related”. The term ore refers to the rock or earthen material that contains metal compounds which are called minerals. So, ores contain minerals.*
4. **“A metal catalyst is one of the reactants in a chemical reaction.”** *A catalyst is a chemical substance that accelerates the rate of a chemical reaction. It may be part of the reaction at one or more stages but it is not permanently altered or consumed, which would be required if it were a reactant. It would have to change chemically.*

Demonstrations and Lessons

1. Students probably do not know the source of metals from the earth, with the possible exception of gold which is not the norm for metals! To illustrate the idea of ores and the minerals they contain, it would be good to have rock samples containing metal compounds (minerals). The copper minerals are particularly attractive and include some of the gemstones with which students may be familiar, such as malachite and azurite. Students will be impressed with the crystalline structures. This could lead to a discussion as to how one goes from these stones to a piece of copper wire, for instance. Several lab exercises listed below can help in illustrating the purifying process.
2. There is a very good video series on the history of metals that explores the ways by which civilization has been shaped through mankind's use of mineral resources. This series, “Out of the Fiery Furnace” is still available either for rent or purchase; there is also a book of the same name. “Out of the Fiery Furnace” originally a PBS product of 1985. Video/C 927-933 is from http://www.lib.berkeley.edu/MRC/Videoseries.html. Also the Nebraska Humanities Center (http://www.nebraskahumanities.org/speakers/hrc.html) has three episodes**,** each 60 minutes. The titles are: a. “Swords and Ploughshares”, b. “Shining Conquests”, c. “The Revolution of Necessity”.
3. Students can perform a reduction process for isolating metals from their ores. With a copper compound, such as copper carbonate, reduction can be carried out using charcoal. Students will observe the color changes associated with ionic vs. elemental copper. Depending on where you are in the curriculum, students also have an opportunity to write redox equations to show the changes occurring. Several lab procedures for both copper carbonate and copper oxide reduction can be found at: http://books.google.com/books?id=DuJLYq4IkL0C&pg=PA183&lpg=PA183&dq=Reduction+copper+carbonate&source=bl&ots=NgXDJBOxdM&sig=DSWO2YhRA9vVDNuvwZckFn_QgAc&hl=en&ei=R1mASuySBJH4NbTo-d0C&sa=X&oi=book_result&ct=result&resnum=9#v=onepage&q=Reduction%20copper%20carbonate&f=false; (basic lab procedure for the reduction of copper oxide including three different sources of reducing agent) Another procedure uses copper oxide (5.0 g) with 3.0 g of carbon (activated charcoal) mixed together, then placed in a crucible with a lid. Strong heating eventually reduces the oxide to orange-brown copper. Carbon dioxide gas forms and escapes. This can also be done in a large Pyrex tube with a delivery tube carrying the carbon dioxide to limewater in which a precipitate of calcium carbonate will form—the classic test for carbon dioxide. Videos showing reduction of copper oxide can be found at http://www.rsc.org/education/teachers/learnnet/videodemos/reduction.pdf; and

http://www.youtube.com/watch?v=6nEt6cW_GSw; A video of copper oxidation can be found at http://www.youtube.com/watch?v=1oVJ5E8kdWs&NR=1.

4. Students can isolate a pure metal (copper) from a metallic compound using electrolysis. This can be done as a quantitative lab. The easiest arrangement is to use a 0.2 M solution of copper (II) chloride in U-tubes, with carbon electrodes (either pencil "lead" or pencils with both ends of the pencil exposed enough to clip wires to the "lead") and a nine-volt battery. Students should observe changes occurring at each electrode, including color and production of gases (odor of chlorine will be evident). Again, depending on where students are in the curriculum, they should write equations to explain what is happening at each electrode.
5. To illustrate the Idea of an alloy such as brass (Cu, Zn), students can do their own "brassing" of a penny by reacting a penny in an alkaline solution of zinc. See lab procedure at http://www.chemistrylecturenotes.com/Brass_Penny_Lab.htm.
6. Catalysts, including enzymes, lend themselves to both good demonstrations as well as lab activities that students can perform. The chemistry behind catalysts involves a study of reaction rates and activation energies for which there is plenty of information in standard chemistry texts. However, as an example of a catalyst demonstration, simply take some 3% hydrogen peroxide (from a drug store), observe, then add a small pinch of manganese dioxide and observe. An additional and more colorful reaction is to show the catalytic action of the iodide ion (I^-) on the decomposition of hydrogen peroxide (30%-be very careful!). (Refer to the equations for this reaction at http://antoine.frostburg.edu/chem/senese/101/kinetics/faq/mechanism-h2o2-iodide.shtml.) The procedure for doing the iodide/hydrogen peroxide reaction is found at http://antoine.frostburg.edu/chem/senese/101/redox/faq/elephants-toothpaste.shtml. For additional succinct information on catalysts, both inorganic and organic (biological) with some mechanisms suggested, see http://antoine.frostburg.edu/chem/senese/101/reactions/faq/examples-of-catalysts.shtml.

Student Projects

1. Obtain cheap solar cells and have students determine to what frequencies of light the solar cell responds. This could be done using filters, as long as the intensity of the light is kept the same. Indirectly, they could be observing the photoelectric effect since a solar cell responds in the infrared as well as the blue-ultraviolet region, not over the entire visible spectrum. They could compare this response to that of chlorophyll, based on absorption spectra of chlorophyll solutions (chlorophyll extracted from spinach- check with biology teacher for lab procedure).
2. Students could investigate and compare properties of metals and metalloids in terms of magnetism, luster, acid reactions, conductivity, malleability, and brittleness.
3. Students could test the basic properties of metals in terms of setting shape in a metal (annealing). Using a hairpin, heat the center section red hot and cool slowly. The pin will be soft and bend easily. This is called annealing. Next, reheat the same pin and quench in water. This process of tempering produces a hardened or tempered metal.
4. Students could research the various methods for extracting metals from ores. The methods vary, depending on the particular metal to be isolated from its ore.
5. Students could research the concept of superconductivity. Superconductivity is dependent on the proper mix of metals, non-metals, and metalloids to produce a material that will conduct electricity with essentially no resistance at very low temperatures. The ability to produce superconductivity means transmission of electricity with very low losses of

power. It also allows for what is known as magnetic levitation or the suspension of a magnetized object above a superconducting material. That concept is currently being used in so-called "maglev" trains that move along at very high speeds with much less electrical energy than normal electric-powered engines. The quest for conductivity has been going on since the first superconductor was produced in 1911. Recently the discovery of iron-based compounds known as pnictides for superconductivity have become the new focus because these compounds can produce superconductivity temperatures higher than previous mixes (in this case, at -223 K). If superconducting materials can be found that operate close to room-temperature, such a spectacular discovery would contribute to the improvement in a large number of electric-based technologies. (ref. Scientific American, August 2009 issue, pp. 62-69; http://www.scientificamerican.com/article.cfm?id=an-iron-key-to-high-temp; and http://www.scientificamerican.com/article.cfm?id=low-temperature-supercond (from April 2005 issue of Scientific American)

6. Students could investigate the whole realm of environmental issues associated with mining of metal-containing ores here in the USA, but especially in poorer countries, such as on the African continent.
7. Students could research the chemistry behind the use of catalytic converters in auto exhaust systems. A starting point for them would be the reference at http://auto.howstuffworks.com/catalytic-converter2.htm which includes labeled photo diagrams. Students could also tie the production of these converters to the mining and processing of the various metals included in the converter, including platinum, rhodium, and/or palladium. Gold is also now included with the other metals because it is cheaper.
8. Students could perform quantitative experiments using enzymes (biological catalysts) such as catalase (available as a powder) and the enzymes contained in yeast cells. Variables to be tested include temperature, concentration and pH. There are ways to quantify the rates of the chemical reaction through the measure of gas production (carbon dioxide). Check with your biology colleagues for some lab procedures that involve floating disks. (see http://www.accessexcellence.org/AE/ATG/data/released/0074-GenNelson/index.php)

Anticipating Student Questions

1. **"Compared with metals, why does a non-metal compound not conduct electricity or possess magnetic properties?"** *Non-metal compounds involve bonding that does not provide for valence electrons that are easily displaced for conduction. Metals have bonding (non-directional) that involves valence electrons that are not as tightly bonded and are easier to displace for conduction (an array of metal cations in a "sea" of electrons). Magnetic properties are dependent on unpaired electrons that are influenced by the orientation of neighboring electrons. In the presence of a magnetic field, the electrons align strongly in the same direction creating a magnetic force in the metal.*
2. **"How does an alloy differ from an amalgam?"** *An alloy is a mix of metals (more than one element)—there are solution alloys, heterogeneous alloys and inter-metallic alloys. An amalgam is a special case of an alloy in which mercury is present as a solvent.*
3. **"Is an ore a rock or a piece of metal ready to melt?"** *An ore is rock material that contains minerals that are metal-containing compounds from which a metal can be extracted using various procedures including heat and electricity.*
4. **"Can a solar cell use light sources other than sunlight?"** As long as the light source provides frequencies of electromagnetic radiation to which a solar cell is capable of responding, the energy will be absorbed. The light does not have to be sunlight.

References

As mentioned, there is a book as well as a video series on the history of developing and using metals in cultures ("the impact of metals on the history of mankind"). The book, "*Out of the Fiery Furnace"* by Robert Raymond is available from The Pennsylvania State University Press, 1984, ISBN 0-271-0041-X (pbk). The video series can be obtained from the Univ. of California (http://www.lib.berkeley.edu/MRC/Videoseries.html).

Web Sites for Additional Information

More sites on solar cells

http://www.scientificamerican.com/article.cfm?id=how-does-solar-power-work (explains the basics of how a solar cell works)

http://www.scientificamerican.com/article.cfm?id=solar-power-lightens-up-with-thin-film-cells (use of thin film to improve transmission/absorption of light)

http://www.scientificamerican.com/article.cfm?id=how-to-use-solar-energy-at-night (use of molten salts to store the heat generated by solar absorption during the day, then use the heat to convert water to steam to power electricity-generating turbines at night)

http://photovoltaics.sandia.gov/docs/PVFSCGallium_Arsenide_Solar_Cells.htm (the basics of solar cells that incorporate the elements of gallium and arsenic to improve efficiency of silicon-based solar cells)

http://www.scientificamerican.com/article.cfm?id=nanoscale-trees-improve-efficiency-plastic-solar-cells (use of nanoscale for solar cell fabrication to improve efficiency)

http://www.scientificamerican.com/article.cfm?id=superefficient-cost-effec

http://www.scientificamerican.com/article.cfm?id=chasing-rainbows (adding tungsten and molybdenum to silicon to increase light absorption over the full range of sunlight, from UV to deep red which silicon alone cannot do.)

http://www.solarbotics.net/starting/200202_solar_cells/200202_solar_cell_physics.html (the physics behind solar cell operations, in case you want more detail)

http://www.solarbotics.net/starting/200202_solar_cells/200202_solar_cells.html (the history behind the development of solar cells)

http://www.solarbotics.net/starting/200202_solar_cells/200202_solar_cell_types.html (explains the difference between single crystal, multi-crystalline, and amorphous-type solar cells)

http://www.vacengmat.com/solar_cell_diagrams.html (more diagrams showing the operational basics of the NP-type of thin-film solar cell) http://www.scientificamerican.com/article.cfm?id=a-solar-grand-plan (This is a must read for understanding the need for an over-arching grand plan for developing a solar-based economy to reduce dependence on carbon-based fuels and drastically reducing greenhouse gas emissions. It includes a unique storage system for the daytime solar generated electricity—compressed air. Find out how and why transmission lines would be DC.

More sites on transistors

http://chemlinks.beloit.edu/Chip/pages/trans_r.html (A glossary related to making a transistor)

http://www.appliedmaterials.com/htmat/animated.html (This is a very complete video with animations to show how transistors are fabricated and how they function. Teacher preview for elaboration will be important in order to help clarify for students what is being shown.)

http://electronics.howstuffworks.com/diode1.htm (This is a good site to show, with diagrams, the construction and workings of a semi-conductor.)

More sites on metal memory foams

http://www.sciencedaily.com/releases/2007/12/071220111513.htm (Explains the production of memory foams, with a micro-photo.)

http://cleantechnica.com/2008/11/09/lightweight-metal-foam-makes-autos-safer/ (An article that discusses the use of metal foams to increase safety and fuel efficiency in autos.)

http://commons.wikimedia.org/wiki/File:Metal_Foam_in_Scanning_Electron_Microscope,_magnification_10x.GIF (Very clear photomicrograph of a metal form)

http://mrsec.wisc.edu/Edetc/cineplex/NiTi/ (A series of videos that show manipulation of memory metal, Nitinol. It could be used in class if you do not have any samples of the metal. Also it is part of a larger project that provides lab activities for chemistry class called Exploring the Nano World) (http://mrsec.wisc.edu/Edetc/index.html)

http://www.stevespanglerscience.com/experiment/00000116 (This is another series of videos showing manipulation of Nitinol wire.)

More sites on superconductivity

Superconductivity is both an interesting topic in the use of metals as well as an important future process that will form the basis for all kinds of technology that revolve around energy efficiency, from electricity generation to electrical energy applications, from transmission to transportation. There is an interesting article related to superconductivity that shows, through the use of electron and X-ray beams (with visual enhancement), orbitals in the metallic bonding of copper. From these orbital pictures, it has been determined that the bonding is not just metallic but also ionic and covalent. This information is part of the research to understand bonding in copper (which is part of various copper-based alloys used in low temperature superconductivity). The goal is to be able to produce superconductivity at temperatures higher than the present that are close to 35 kelvin. Ideally the temperature would be room temperature. (http://www.scientificamerican.com/article.cfm?id=observing--orbitals)

Another interesting connection to superconductivity is the proposal for future energy using what is known as a "SuperGrid". This super grid would deliver both electricity as well as hydrogen fuel. The transmission lines would be cooled with hydrogen gas in order to allow for superconductivity. The hydrogen gas would also be available as a fuel when sent to some terminal. (See http://www.scientificamerican.com/article.cfm?id=a-power-grid-for-the-hydr-2006-07.)

For more references on the topic of superconductivity, go to the suggestions listed under "Student Projects".

General Web References

A useful search tool (with index) in chemistry is found at http://www.gcsescience.com/chemistry-science-index.htm.

More Web Sites on Teacher Information and Lesson Plans

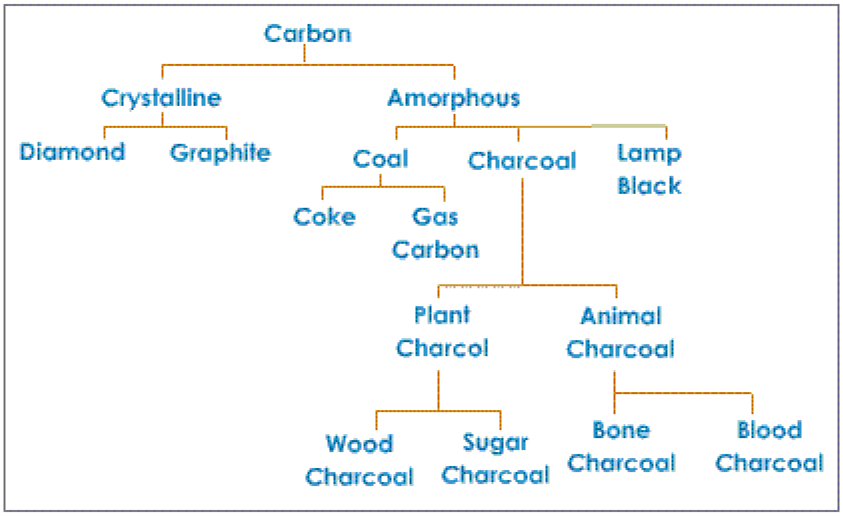
This college website is a very useful reference with all kinds of classroom tools. See http://antoine.frostburg.edu/chem/senese/101/index.shtml.

Graphite Versus Diamond: Same Element but Different Properties

Background Information

More on allotropes

Allotropes are different forms of the same element that result from a different arrangement of its atoms. Common examples are oxygen (0_2 and 0_3), phosphorus (white, red, black and yellow) and the different forms of carbon. The most commonly listed allotropes of carbon are diamonds, graphite, fullerenes and carbon nanotubes. Confusion may arise when the carbon allotropes are listed as crystalline vs. amorphous. Both diamond and graphite are crystalline. Amorphous carbon is the name used for coal, soot and other carbon compounds that are neither graphite nor diamond. The amorphous forms of carbon; e.g., charcoal and lamp black, consist of many groups of small graphite crystals. The chart below lists the most common forms of carbon.



(http://www.tutorvista.com/content/chemistry/chemistry-i/carbon/carbon-allotropy-and-allotropes.php)

A more complete description of all of the allotropes of carbon (the source lists eight) may be found at http://www.nanoscienceworks.org/nanopedia/carbon-allotropes.

Existence of an allotrope depends on the type of bonding associated with the carbon atoms. Diamonds are the result of sp^3 bonding while the other graphite-like allotropes are the result of carbon sp^2 bonding within a plane and delocalized pi bonding between planes.

Graphite and diamonds are always referenced in chemistry textbooks, but buckyballs (buckminsterfullerenes) and carbon nanotubes may get less discussion because of their recent discovery—by Smalley, Kroto and Curl in 1985. Carbon nanofoams, a type of carbon aerogel, were discovered in 1997 by Andrei V. Rode and co-workers. The nanoscienceworks link (above) provides more details. To view an interactive page on the structure of graphite, diamond and buckminsterfullerenes, see http://www.creative-chemistry.org.uk/molecules/carbon.htm.

Other common elements that exist in allotropic forms are phosphorus, sulfur and carbon. Like carbon, the differences in the allotropes can be accounted for by the arrangement of atoms.

Phosphorus—Red phosphorus is a crystalline powder with four atoms of the element arranged in a pyramid. It is stable in air, but still very reactive. It is used in strike anywhere matches, since the heat generated by friction can ignite the allotrope. In black phosphorus, the atoms are arranged in a puckered sheet, somewhat like graphite. It is very unreactive. Compared to the other two, it has a higher boiling point and melting point. White (or yellow) phosphorus is a waxy solid at room temperature. It is very flammable in air. It is stored under water for this reason. It has a garlic-like odor.

Oxygen—Molecular oxygen, 0_2, is made up of two oxygen atoms per molecule, and has the properties students know about. Ozone has three oxygen atoms per molecule and has an acrid odor. Ozone can be formed from oxygen by passing an electric charge through the oxygen. It can be detected in the air after a lightning storm. In very small concentrations it causes breathing problems in humans. So oxygen near the surface of the earth is a pollutant. Ozone higher in the atmosphere has the ability to absorb UV radiation from the sun and acts a protector for the earth.

Sulfur—Based on crystal structure it is possible to identify at least four allotropes of sulfur. Solid sulfur consists of molecules containing eight sulfur atoms joined in a ring, S_8. Such molecules can pack to form more than one crystal. The most stable form of sulfur consists of orthorhombic crystals. If orthorhombic sulfur is heated to liquid and then cooled, the second solid allotrope of sulfur, long needle-like monoclinic crystals, are formed. They will slowly revert to orthorhombic form over time. Both forms are composed of S_8 molecules.

In the liquid phase the allotrope is called lambda sulfur, which is a low viscosity liquid that is soluble in non-polar solvents. If it is heated more strongly the S_8 rings break apart to form long sulfur chains called mu sulfur. Mu sulfur is not readily soluble in common solvents and is a very viscous liquid.

More on graphite

An allotrope of carbon, graphite is usually found as veins, lenses, pockets and in thin layered deposits. It is found often with feldspar, mica, or quartz as impurities. There was no graphite produced in the United States in 2006. Imports came primarily from China, 42%; Mexico, 30%; Canada, 18%; Brazil, 6%; and other, 4%. Much of the graphite in use today is produced synthetically from petroleum coke, the tar residue after crude oil refining.

Physical properties
Density: 1.9 - 2.3 g/mL (compared to diamond at 3.50)
Hardness: 1 - 2 Moh's scale
m.p. = 3652-3697°C (sublimes)
Specific heat = 0.17 cal/g-ºC
Heat of refractoriness (resistance to heat)—up to 3000ºC in an inert atmosphere
Flammability—burns in oxygen at temperatures between 620°C to 720°C.

The crystal structure of graphite is made up of carbon atoms bound covalently to nearby carbon atoms at a distance of about 141.8 pm to form hexagon rings. These rings form sheets of graphite which are loosely bound to each other by weak van der Waals forces. To see the crystal structure in a variety of forms, see the Naval Reserve Laboratory Center for Computational Materials Science site at http://cst-www.nrl.navy.mil/lattice/struk/a9.html.

Uses: According to the United States Geological Service, the major uses of natural graphite in 2006 were refractory (high heat) applications, 27%; brake linings, 15%; and batteries, foundry operations, and lubricants, 8%.

The uses depend on the type of graphite produced: flake, lumpy (crystalline) or amorphous. Flake graphite has low electrical resistivity and so is used in making electrodes and batteries. The flake form is also used to make graphite crucibles by combining the graphite with clay and sand at high temperatures. Such crucibles are used to melt non-ferrous metals like brass and aluminum.

Both amorphous and crystalline graphite are used in lubricants because of their low coefficient of friction. The graphite is suspended in oil to form the lubricant. Amorphous graphite is also the form of choice in pencil manufacture because it is best at leaving residue on paper. The finer the graphite powder is, the darker the streak.

In addition to its use in pencils, graphite is used to make battery electrodes, in composites where strength is important (tennis racquets, golf clubs) helicopter blades, artificial heart valves, lubricants, and as a nuclear power plant moderator.

Again, according to the USGS, "Advances in thermal technology and acid-leaching techniques that enable the production of higher purity graphite powders are likely to lead to development of new applications for graphite in high-technology fields. Such innovative refining techniques have enabled the use of improved graphite in carbon-graphite composites, electronics, foils, friction materials, and special lubricant applications. Flexible graphite product lines, such as graphoil (a thin graphite cloth), probably will be the fastest growing market. Large-scale fuel-cell applications are being developed that could consume as much graphite as all other uses combined."

These uses are interesting because they highlight other properties of graphite. Synthetic carbon can be made into fibers, which are both strong and heat resistant. So this form can be used in places like brake shoes, electric motors and heat-resistant products. Expandable graphite finds uses in fire-resistant structures like fire doors. When the graphite is heated, it expands and reduces the spread of the fire.

Graphite is related to a class of carbon allotropes called fullerenes, which include carbon nanotubes and the more familiar buckyballs. Carbon nanotubes are used where strength is important, in products like fishing rods, golf clubs and bike frames. These materials are often referred to as composites.

More on graphite and pencils

The article mentions the discovery of graphite in England and its use as “lead” in pencils. This particular use represents the most common contact students will have with graphite. Students may wish to learn more about graphite’s use in the manufacturing of pencils. The Oct.

2007 *ChemMatters* Teacher's Guide presents excellent background material. You can access the Teachers Guide for October, 2007, as well as all the other Teacher Guides and selected articles from the last five years at http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_ARTICLEMAIN&node_id=1090&content_id=CTP_005702&use_sec=true&sec_url_var=region1&__uuid=76641e19-0021-4d68-9c9c-177ef2d9edba. For your convenience, some of the pertinent background material is printed below.

> The earliest event that enabled pencil production on a large scale was the discovery of a huge graphite deposit at the Seathwaite Fell site near Borrowdale, Cumbria, England, in 1564. Local sheepherders used it for marking their flock. Chemistry was in its very early stages as a discipline, and the graphite was thought to be a form of lead. Originally it was used to line the molds for cannonball manufacture because of its refractory properties. Pencils were very much a secondary use, and it had to be smuggled out of the mines for use in pencil making. The soft graphite was originally wrapped in sheep skin or string to make a stable pencil.
>
> Wooden housing made the pencil more popular, and for nearly two hundred years, graphite from the Borrowdale mines supplied pencils for England and the rest of Europe. As the Borrowdale deposit began to be depleted, manufacturers looked for other materials to mix with graphite to extend its lifetime. Nicolas-Jacques Conte was the person in France who developed the powdered graphite-powdered clay-water mixture that replaced pure graphite by the late 1700' s. Conte also found that he could vary the darkness of the pencil's markings by varying the ratio of graphite to clay in the mixture. At the time England and France were at war and pure graphite was not available to the French. Conte's method is still the basis for pencil manufacture today.
>
> The world's second big graphite mine was discovered in the 1840s as Jean Pierre Alibert, searching originally for gold, found high quality graphite in Siberia along the Chinese border. Much of this was shipped to Germany where A. W. Faber Pencil Company was on its way to becoming one of the world's largest pencil manufacturers.
>
> By the beginning of the nineteenth century pencils were very popular around the world including in the United States. There were, however, no pencils being manufactured in the U.S. What's more, the War of 1812 shut down pencil imports from England. Of economic necessity, several U.S. entrepreneurs began to manufacture pencils (of lower quality) and several sources of graphite were discovered. Among the manufacturers were William Monroe in Massachusetts, Joseph Dixon in New Jersey and Eberhard Faber in New York City. Also among the early manufacturers was one John Thoreau who lived in Concord, Massachusetts. His brother-in-law, Charles Dunbar had found graphite deposits in New Hampshire. Thoreau's son, Henry David, eventually joined his father, and in the 1820's found the same formula that Conte has used for mixing graphite with clay for the filler for the pencil. It is fairly certain that the younger Thoreau-of Walden Pond fame-made the discovery independent of Conte (even though it was some years later) since the methods of pencil manufacture in Europe were closely guarded secrets.
>
> After the Civil war, four major companies dominated pencil manufacture in the United States-Eagle Pencil Company, Eberhard Faber (brother of the German Faber and an immigrant to the US), the American Lead Pencil Company, and Joseph Dixon Crucible Company.
>
> Joseph Dixon, originally from Massachusetts, experimented as a youth with pencil making. He saw the potential of pencils even though his company w as founded to make graphite crucibles for making steel. In 1847 he moved his company to Jersey City, NJ. Three years later he received patents for the use of graphite crucibles in pottery and

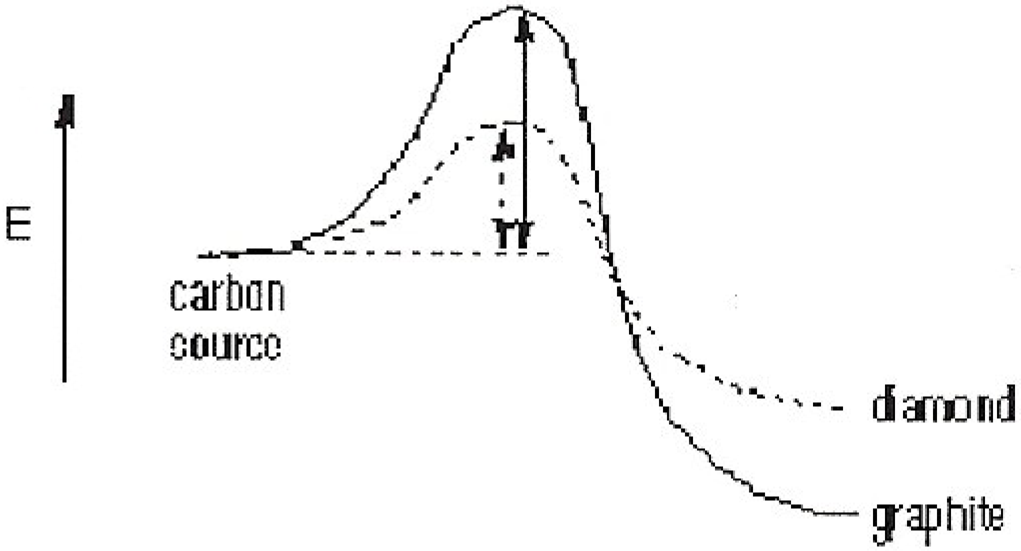
> steel. The company's now famous Dixon Ticonderoga pencils were named for the fort in New York which played a prominent role in the French and Indian War and the Revolutionary War.
>
> By the 1870's over 20,000,000 pencils were purchased per year in the US. By 1912, the figure had grown in the US to be 750,000,000, while world wide the figure was at two billion. The article says that the current U.S. production is 2.8 billion.

Pencils in use today are characterized by a hardness scale of the "lead." The "hardness" of pencils is determined by the ratio of graphite to clay in the mixture. In the United States, a numbering system is used with 1 representing a soft mixture and a 4 being a hard mixture. In Europe letters are used instead of numbers, with B designating soft lead and H meaning hard lead. The common grades are:

U.S.	Europe	Graphite%	Clay%	Wax %
#1	B	71	23	5
#2	HB	68	26	5
#2 ½	F	66	28	5
#3	H	63	31	5
#4	2H	60	34	5

More on Chemical Vapor Deposition (CVD)

This process is briefly described in the article and much research is still being devoted to its improvement. In one simple sense, methane, CH_4, is a "logical" starting material because it has tetrahedral bonds, much like those found in diamond. In the CVD approach, methane is converted into diamond, which is somewhat surprising, since graphite is the more stable allotrope of carbon at the conditions at which the process is run (see Connections to Chemistry Concepts). The reason this can occur is due to the fact that, while graphite may be more thermodynamically stable, it isn't formed as rapidly as diamond; i.e., the kinetics of the process favor the formation of diamond rather than graphite. The activation energy for forming diamond films is lower than that for forming graphite. This is illustrated in the diagram below:



So the trick is to set up the conditions so one forms diamond, but not graphite; i.e., one arranges things so the kinetics of the process dominates over the thermodynamics.

Although the reasons are not yet fully understood, it has been discovered that one can keep graphite from being created by forming the diamond under a constant stream of hydrogen. The role of the hydrogen is thought to be to etch away any graphite that might be formed. There are variations on this process. Sometimes oxyacetylene torches or simple heated tungsten filaments are used instead of a microwave. Recently the methane has been replaced by buckyballs.

More on why graphite isn't easily converted into diamonds

There are a lot of both simple and very complex thermodynamics and kinetics connected to the transformation of graphite to diamond and vice versa. Thermodynamically, graphite is more stable than diamond at room conditions. This means that a diamond will "spontaneously" transform itself into graphite if given enough time. But this obviously doesn't occur, and the reason is fairly simple and common.

One could just as easily ask why a diamond doesn't spontaneously burst into flame, since it is thermodynamically favorable for a diamond and oxygen to transform into carbon dioxide and water. The reason is a very common one for many "spontaneous" chemical reactions. The transformation has a high activation energy barrier. Somewhat simplified, in order for the transformation to take place, the colliding molecules (or atoms) must overcome an energy barrier. If the colliding molecules do not possess enough initial kinetic energy when they collide, they will simply bounce off each other and will not transform into the product molecules.

A similar question might ask why your morning newspaper doesn't spontaneously burst into flame before you can read it. Again, the answer is that the reaction of paper with oxygen, although highly exothermic, requires that the colliding molecules possess enough initial energy to surmount the activation energy barrier. If you provide this energy via a match, some molecules can then react, and the energy released when they react can be used by other molecules to get over the barrier, and the energy they release, etc., etc., etc. Once we get the reaction going, it becomes self-sustaining.

A match will work to ignite a newspaper but will not ignite a diamond. The activation energy for converting a diamond and oxygen gas to carbon dioxide and water is so high that a burning match isn't at a sufficiently high temperature to accomplish this. In fact, if your house burns down, don't rush in to save your diamonds, as they will not burn at the temperature of an ordinary house fire.

Diamonds don't spontaneously convert into graphite at room temperature simply because the activation energy barrier for this conversion is very high.

Although graphite is thermodynamically more stable than diamond, the energy difference is quite small, only about 2.9 kJ per mole of carbon. (The graph above is not drawn to scale.) Then why can't we just take some graphite, put it in an environment without air, get it very hot (so we can surmount the activation energy barrier) and convert it into diamond?

We might just as well ask why we wouldn't be converting a diamond into graphite via this procedure. In fact, this is what would probably happen if we tried it this way. Graphite is thermodynamically favored, so it is more likely that a diamond would convert into graphite, but not the reverse. This was done in a great scene in Philip Morrison's The Ring of Truth series. But at very high pressures diamond becomes more stable than graphite. A diamond is a more compact structure—the atoms are closer together. High pressure favors this structure, so if we apply enough pressure and also get the system to a high enough temperature to surmount the activation energy barrier, the transformation of graphite to diamond can take place.

This is what happens deep in the earth and this is how early artificial diamonds were made.

Connections to Chemistry Concepts

1. **Elements other than carbon exist as allotropes in nature**—Allotropes are forms of a chemical element in which the atoms are arranged differently, producing forms of the same element with different properties. Elements other than carbon with commonly occurring allotropes are (1) oxygen and ozone, (2) red and white (yellow) phosphorus

2. **Tetrahedral bonding in sp^3 and trigonal pyramidal bonding in sp^2, sigma and pi bonding**—Each carbon atom in a diamond is bonded to four other carbons. The bonds are covalent and the angles are all tetrahedral angles of 109° 28’. The carbon atoms in graphite are bonded to each other in a plane. Each carbon is bonded to three other planar carbon atoms with bond angles of 120°. These covalent bonds in both diamond and graphite are classified as sigma bonds. In a sigma bond the electron density of the shared pair is located on a line between the two carbon atoms. The bonding between layers in graphite is called pi bonding. The electrons are delocalized and free to move if an external force is applied. This allows the layers of carbon in graphite to slip easily, making graphite an excellent lubricant and a very good conductor of electricity.

3. **Role of thermodynamics and kinetics in chemical transformations**—Refer to the section "More on why graphite isn't easily converted into diamonds for a more complete explanation.

Possible Student Misconceptions

1. **"Diamonds and graphite can't possibly be made of the same material."** *The difference in properties and appearance can be accounted for by the difference in bonding. How atoms bond is the key to the manifestation of macroscopic properties such as color, hardness, etc.*
2. **"Lead pencils contain lead, not graphite. Otherwise they would be called graphite pencils."** *This is a long standing misconception that the article helps clear up.*
3. **"All meteorites are the same. They fall out of the sky from space."** *The article discusses the importance of carbonaceous meteorites which contain microscopic diamonds. Most meteorites contain iron. The main classification of meteorites is based on the amount of iron in the particular sample.*
4. **"Graphene can be made by rubbing a pencil on paper."** *The statement has some truth to it. Rubbing a pencil on a piece of paper does deposit layers of graphite onto the paper. To become graphene, though, either the pencil would have to leave on the paper only one layer of carbon atoms, or many, <u>many</u> layers of graphite would have to be removed until only one layer of carbon atoms remained. This would be the layer of graphene. Such a layer would be invisible to the naked eye and would require a powerful electron microscope to observe it.*

Demonstrations and Lessons

1. Here is a series of videos and exercises on nanotubes and other forms of carbon (diamond, graphite, buckyballs, and nanotubes. The videos can be used as a class presentation on the individual allotropes. (http://mrsec.wisc.edu/Edetc/cineplex/nanotube/index.html)
2. Obtain a set of mineral samples from an earth science teacher and review the Moh's scale of hardness that the students may have encountered in an earlier course. Graphite and diamond appear at the extremes of the scale. Graphite is grouped with minerals similar to talc and is given a value of 1.5 on the hardness scale. Diamond, on the other hand, is given a value of 10, the highest number used in the scale. Somehow, the same element can present itself either as the softest of minerals or as the hardest of minerals. The two extremes exhibited by allotropic forms of the same element provide a vehicle to stress the importance of chemical bonding on the properties of a pure substance.
3. The following web site is a complete classroom unit of study on the allotropes of carbon: http://www.nsec.northwestern.edu/Curriculum%20Projects/Carbon%20Allotropes.pdf.
4. The following three URL's are videos from the collection at howstuffworks.com. Any one of the three, or all three, could be incorporated into a lesson on carbon/graphite.

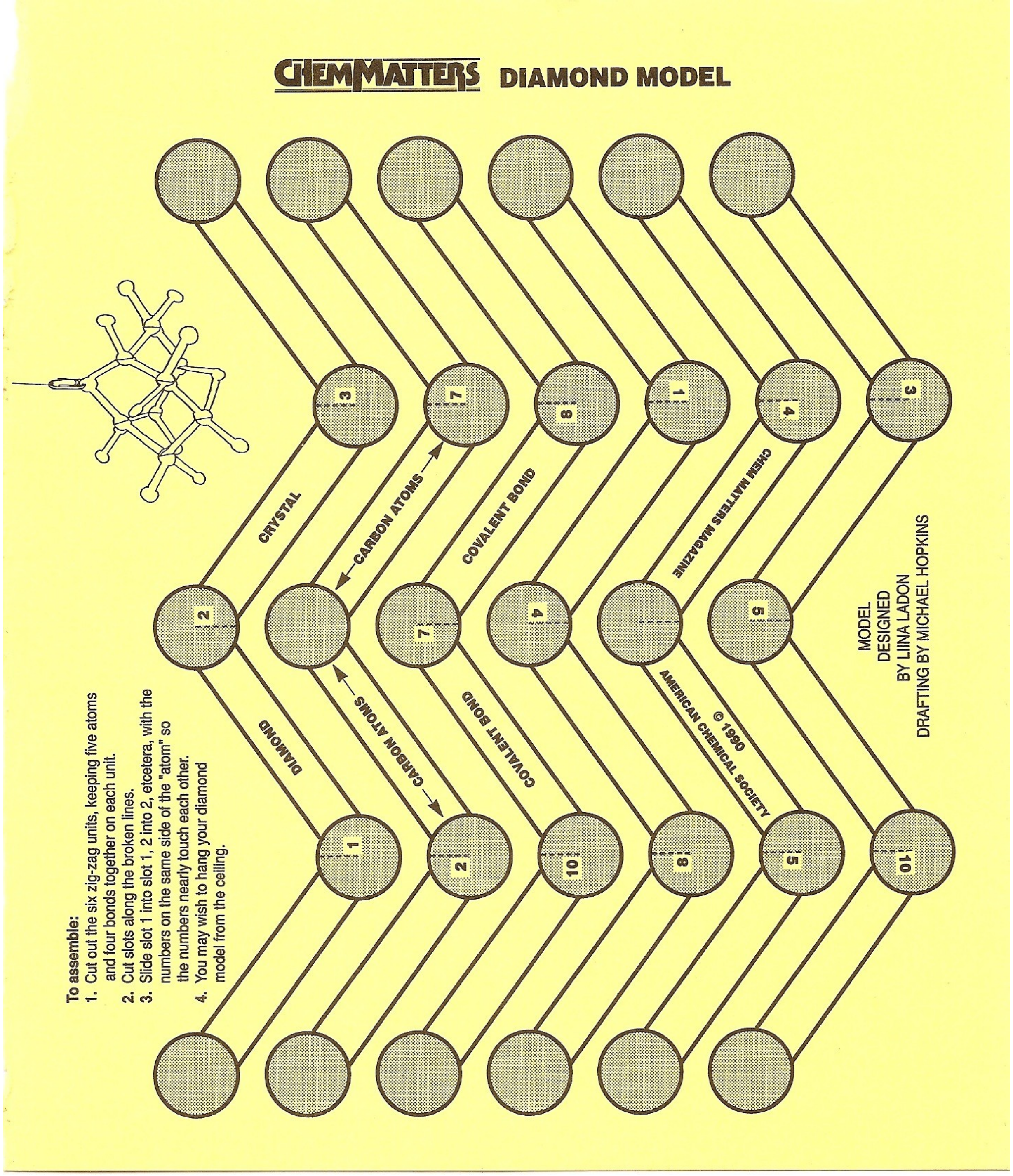
- Physical Science: The Stuff of Diamonds
  http://videos.howstuffworks.com/hsw/12050-physical-science-the-stuff-of-diamonds-video.htm
- Pure Carbon: The Science of Nanotubes

http://videos.howstuffworks.com/hsw/8224-pure-carbon-the-science-of-nanotubes-video.htm

- Pure Carbon: The Chemistry of Diamonds and Graphite
  http://videos.howstuffworks.com/hsw/8222-pure-carbon-the-chemistry-of-diamonds-and-graphite-video.htm

Student Projects

1. Build a diamond model. The April 1990 issue of *ChemMatters* included a template for constructing a diamond model. The template is reproduced below. It may be resized and copied onto stiff paper. Students may use the template to construct individual models, or they may combine templates to construct a much larger model. A series of the individual models could be artistically combined to create a diamond "mobile."



CHEMMATTERS DIAMOND MODEL

To assemble:

1. Cut out the six zig-zag units, keeping five atoms and four bonds together on each unit.
2. Cut slots along the broken lines.
3. Slide slot 1 into slot 1, 2 into 2, etcetera, with the numbers on the same side of the "atom" so the numbers nearly touch each other.
4. You may wish to hang your diamond model from the ceiling.

2. Prepare a report on conflict diamonds. How did the name "conflict" arise? Although diamonds are portrayed as symbols of love, the history of diamond mining paints a much darker picture. Diamonds have fueled conflicts in Angola, Democratic Republic of Congo, Ivory Coast, Liberia, and Sierra Leone. Include a discussion on the Kimberley Process by which diamonds are now certified and distinguished from conflict diamonds.
3. Have a student who is also enrolled in an art course visit an art supply store, or work with the art teacher, to develop a list of the different types of graphite-containing pencils that are available. The student could then correlate the properties and uses of the pencils with

the percent graphite and percent clay (or other filler material) used in the production of the particular pencil.

Anticipating Student Questions

1. **"Why can't coal be squeezed into a diamond, as seen in the movies?"** *The preferred form of coal is graphite if one looks at thermodynamic stability. Coal (graphite) can be coaxed to form diamonds at extremely high pressures and temperatures, conditions not usually found in a traditional lab.*
2. **"Why are pencils called "lead" pencils instead of "graphite" pencils?"** *There is no lead in "lead" pencils. Before graphite was used in the manufacture of pencils, lead, a very soft metal which will leave grey marks when rubbed against paper, was originally used in "pencils."*
3. **"If graphite is so soft, why does it have a melting point almost as high as diamond which is the hardest substance known?"** *Graphite is "soft" because the bonding between layers is weak and consists of a cloud of delocalized electrons. Within each layer of graphite, the carbon atoms are covalently bonded to each other in a hexagonal pattern. It is these strong bonds that give graphite the very high melting point.*

References

Zaugg, Harold. Growing Diamonds. *ChemMatters*. Vol. 8, No.2, April 1990, pp. 10-14. The article includes a center fold out template for constructing a diamond model. A side bar features an Australian high school student, Andrew Good, who developed a new process for growing diamond films. The article is similar in scope to the current one.

Davenport, Derek A. Burning Diamonds and Squeezing Peanuts. *ChemMatters*. Vol. 8, No. 2, April 1990, pp.14-15

Wood, Clair. Buckyballs. *ChemMatters*. Vol. 10, No. 5, Dec. 1992, pp. 7-9. The article includes a template for building a buckyball model.

Ritter, Steve. Pencils and Pencil Lead. *ChemMatters*. Vol. 25, No. 3, Oct, 2007, pp. 11-12. Excellent background article on the manufacture of pencils.

Web Sites for Additional Information

More sites on synthetic diamond manufacturing

This is the Life Gem website. The company makes diamond for families who have lost a loved one. The carbon from the remains of a cremation, or a lock of hair from a burial are incorporated into the materials to create a synthetic diamond. The process is explained in the website. (http://www.lifegem.com/secondary/LGProcess2006.aspx)

More sites on the chemistry of diamonds and graphite

A video comparing and contrasting the differences between diamond and graphite can be found at http://videos.howstuffworks.com/hsw/8222-pure-carbon-the-chemistry-of-diamonds-and-graphite-video.htm.

More sites on graphite

Here is a video describing the properties of graphite: http://videos.howstuffworks.com/discovery/28093-assignment-discovery-graphite-video.htm.

More sites on allotropic forms of carbon

"How Stuff Works presents a video describing the structure of carbon as diamond, the formation of diamonds, and the structure of graphite and its uses: http://videos.howstuffworks.com/hsw/8332-chemistry-at-work-the-many-forms-of-carbon-video.htm.

More sites on carbon-containing meteorites

A video describing the significance of carbonaceous meteorites: http://videos.howstuffworks.com/hsw/8423-cosmic-collisions-carbon-containing-meteorites-video.htm

More sites on diamond crystal structure

A web site featuring the crystal structure of diamond: http://cst-www.nrl.navy.mil/lattice/struk/a4.html

More sites on graphite crystal structure

A web site featuring the hexagonal structure of graphite: http://cst-www.nrl.navy.mil/lattice/struk/a9.html

More sites on diamond structure

A website featuring a crystal model of diamond that can be manipulated: http://newton.ex.ac.uk/research/qsystems/people/sque/diamond/structure/structure.html

More sites on the formation of diamonds

The Nature website which includes an interactive portion on the formation of diamonds: http://www.pbs.org/wnet/nature/diamonds/index.html

More sites on famous cut diamonds

These seven diamonds are among the most rare and valuable in the world. They are being displayed together for the first and only time through the collaborative efforts of the Smithsonian Institution, The Steinmetz Group, and the Gemological Institute of America. The diamonds range from 5.11 to 203.04 carats in weight. All crystallized from carbon atoms deep within the Earth and endured an explosive journey to the Earth's surface. One—the De Beers

Millennium Star—is composed purely of carbon atoms. The others were tinted rare colors as impurities and defects replaced some carbon atoms during growth. (http://www.mnh.si.edu/exhibits/si-gems/)

More sites on diamonds in space

The film documents the efforts of researchers around the world to create synthetic diamonds, some of which have become so indistinguishable from natural diamonds as to fool experts. This segment, "Diamonds in the Sky" (http://www.pbs.org/wgbh/nova/diamond/sky.html), is a part of the full Nova series, "The Diamond Deception" (http://www.pbs.org/wgbh/nova/diamond/).

General Web References

The entry about carbon in Wikipedia offers a wealth of information on carbon. All of the topics covered in the *ChemMatters* article are discussed in the Wikipedia entry. This entry has a very valuable list of references as well as entry points to a variety of carbon related topics. (http://en.wikipedia.org/wiki/Carbon)

Nanotechnology's Big Impact

Background Information

More on the meaning of nanotechnology

The meaning of the term "nanotechnology" has changed since its theoretical capability was stated by Richard Feynman, a physics Nobel laureate, in his now famous remarks, given at the annual meeting of the American Physical Society on December 29th, 1959 during an after-dinner talk, "I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously…The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws: it is something, in principle, that can be done; but in practice, it has not been done because we are too big."

The term "nanotechnology" was popularized by K Eric Drexler in the 1980's. He concentrated on building machines on the scale of molecules. The National Nanotechnology Initiative (NNI) was created by presidential executive order in 2001. The NNI was charged "to accelerate the responsible development and application of nanotechnology in order to create jobs and economic growth, to enhance national security and to improve the quality of life for all citizens."

The Center for Responsible Technology states that "…nanotechnology is the engineering of functional systems at the molecular level. This covers both current work and concepts that more advanced. In its original sense, 'nanotechnology' refers to the projected ability to construct items from the bottom up, using techniques and tools being developed today to make complete, high performance products."

Mihail Roco of the US National Nanotechnology Initiative describes four generations of nanotechnology development: 1) passive nanostructures, 2) active nanostructures, 3) systems of nanosystems, and 4) molecular nanosystems. He presents the information in chart form at http://crnano.typepad.com/.shared/image.html?/photos/uncategorized/4_gen_1.JPG. We are currently entering the third generation. By 2010 Roco speaks of systems of nanosystems that will feature thousands of interacting components. The first generation centered on passive nanostructures. These materials were developed to perform one task. Examples include a) dispersed and contact nanostructures; e.g., aerosols and colloids, and b) products incorporating nanostructures; e.g., coatings, nanoparticle-reinforced composites, nanostructured metals, polymers and ceramics. The second generation, in which we currently find ourselves, centers on active nanostructures—the devices discussed in the article. These can be divided into the following: a) bio-active, health effects; e.g., targeted drugs and biodevices, and b) physico-chemical active devices; e.g., 3D transistors, amplifiers, actuators, and adaptive structures. Roco projects that between 2015 and 2020 we will be working with the first integrated nanosystems functioning much like a mammalian cell with hierarchical systems within systems.

Michael Crichton's novel Prey takes the creation of free-floating assemblers or nanobots to an extreme. The novel does not portray good science, but could act as a discussion point among interested students.

More on the history and production of carbon nanotubes

On a large or macroscopic scale, imagine cutting a soccer ball in half – along its diameter. Then take a sheet of the material from which the soccer ball was made and roll just enough of the material into a tube or cylinder having the diameter of the original soccer ball. Carefully join the end of the tube to the half of the soccer ball. If done properly, the soccer ball will form a cap to a tube whose length can vary depending on the amount of material used. If chicken wire were used instead of the soccer ball material, the structure should look like a chicken-wire tube topped at one end with a chicken wire hemisphere. An enterprising student or group of students might consider creating such a structure out of chicken wire.

Now, instead of the soccer ball, substitute half of a C_{60} buckyball or fullerene molecule. Instead of the soccer ball material or chicken wire, substitute a sheet of graphene. Graphene, as discussed in another article in this issue of *ChemMatters*, is a hexagonally bonded, single-layer sheet of carbon atoms. Roll a sheet of the graphene to create a tube having the diameter of the C_{60} molecule. Attach (bond) one end of the graphene tube to the half of the C_{60} molecule and one has made a carbon nanotube. It certainly is not visible to the naked eye as was the soccer ball structure. It takes a powerful electron microscope to allow one to actually view the nanotube.

The inability to view the carbon nanotubes without the availability of electron microscopes in use today provides the background when trying to determine the history of the carbon nanotubes. The history is not clear and has been the subject of much debate. As early as the 1950’s, Roger Bacon may have synthesized the nanotubes, but without an instrument to view them, he was not given credit for the original discovery. He was the first to describe a tube of atoms that could be capped by a buckyball.

The “National Historic Chemical Landmarks” portion of the American Chemical Society’s website provides a fascinating look at Bacon’s work, especially when a company allows its researchers free reign to work on topic of interest.

> The modern era of carbon fibers began in 1956, when Union Carbide opened its Parma Technical Center just outside Cleveland. The complex was one of the major laboratories of Union Carbide’s basic research program, modeled after the university-style corporate labs that became popular in the late 40s and 50s. They gathered young, bright scientists from a variety of backgrounds and let them loose on their favorite projects, giving them an extraordinary degree of autonomy.
>
> With a freshly minted Ph.D. in physics, Roger Bacon joined the Parma staff in 1956. “I got into carbon arc work, studying the melting of graphite under high temperature and pressures,” Bacon recalls. “I took on the job of trying to determine the triple point of graphite. That’s where the liquid, solid, and gas are all in thermal equilibrium.” The equipment was akin to the early carbon arc streetlamps, only operating at much higher pressures. Small amounts of vaporized carbon would travel across the arc and then deposit as liquid. As Bacon decreased the pressure in the arc, he noticed that the carbon would go straight from the vapor phase to the solid phase, forming a stalagmite-like deposit on the lower electrode. “I would examine these deposits, and when I broke one open to look at the structure, I found all these whiskers,” he says. “They were imbedded like straws in brick. They were up to an inch long, and they had amazing properties. They were only a tenth of the diameter of a human hair, but you could bend them and kink them and they weren’t brittle. They were long filaments of perfect graphite.”
>
> The year was 1958, and Bacon had demonstrated the first high performance carbon fibers. ..Carbon fibers are polymers of graphite, a pure form of carbon where the atoms are arranged in big sheets of hexagonal rings that look like chicken wire. Bacon’s

> graphite whiskers were sheets of graphite rolled into scrolls, with the graphite sheets continuous over the entire length of the filament.
>
> "After studying the heck out of these things, I finally published a paper in the *Journal of Applied Physics* in 1960," Bacon says. The paper has since become a milestone, partially because some have claimed that Bacon may have been the first person to produce carbon nanotubes — hollow cylinders of graphite with diameters on the order of single molecules. Their incredible properties have made nanotubes one of the hottest areas of research in recent years, promising to revolutionize just about every area of science. Sumio Iijima published a paper in 1991 that is often regarded as the first discovery of carbon nanotubes; it reported on a method that produced both tubes and scrolls. The process is similar to Bacon's, suggesting that he too may have prepared nanotubes along with his whiskers, although he didn't know it at the time. "I may have *made* nanotubes, but I didn't discover them," he says.
>
> By producing his high strength and high modulus whiskers, Bacon had demonstrated experimentally something that theoreticians had proposed long ago. But the fibers were still just a laboratory phenomenon, not a practical development. "I estimated the cost of what it took to make them, and it was $10 million per pound," he says. To tap their full potential, manufacturers needed a cheap and efficient way to produce the fibers. Much of the research in the ensuing decades was dedicated to exactly that.
> (http://acswebcontent.acs.org/landmarks/landmarks/carbon/car3.html)

The synthesis of the first single walled carbon nanotubes was confirmed in 1993. Iijima, whom Bacon mentions in the above section, and Donald Bethune, synthesized tubes now known as buckytubes. Russian nanotechnologists also had been working in this area, but their announcement came later and, as a result, Iijima and Bethune are given full credit for the discovery of the carbon nanotube.

In 1993, Dr. Bethune and his IBM Almaden colleagues discovered that transition metals such as cobalt can catalyze the formation of single-wall carbon nanotubes. In 2002, the American Physical Society awarded the James C. McGroddy Prize for New Materials jointly to Bethune and Prof. Sumio Iijima of NEC for their independent discoveries of single-wall carbon nanotubes and methods to produce them, using transition-metal catalysts. In 2004, the American Carbon Society Medal was awarded to Bethune, Iijima and Prof. Moribundo Endo of Shinshu University for their outstanding contributions to the discovery of and synthesis work on carbon nanotubes.
(http://domino.research.ibm.com/comm/research_people.nsf/pages/bethune.index.html)

The lack of a suitable production method to create carbon nanotubes hindered the research on the exciting potential of the carbon nanotubes. Richard Smalley's group at Rice University provided the breakthrough needed to produce nanotubes in quantities large enough to sustain research studies on their properties and potential.

Smalley himself is one of the researchers credited with the discovery of the buckyball in 1985. The discovery of the C_{60} molecule and its structure—an atom-sized soccer ball, is a fascinating story in itself. Richard Smalley and Robert Curl of Rice University, along with Sir Harold Kroto of the University of Sussex in Brighton, UK were awarded the 1996 Nobel Prize in Chemistry for their co-discovery of the fullerenes. The announcement of the Rice University discovery follows:

> Rice researchers have produced defect-free nanoropes in useful quantities, the next step toward bringing products to market made from nanoscale materials.

> For the first time, nanoropes made up of conductive carbon nanotubes, resembling bundles of long drinking straws, can be produced in high yields-more than 70 percent-according to research led by Professor Richard Smalley at the Center for Nanoscale Science and Technology at Rice University.
>
> A key to developing applications based on nanoscale science and technology is having enough material to work with, and until now, nanotube production has been inefficient at producing tubes with few or no defects. The advance allows for a systematic, clean study of the strongest and most conductive class of nanotubes, Smalley says. The nanotube fibers that pack together to make ropes are predicted to be 100 times stronger than steel, and boast an electrical conductivity similar to copper and the thermal conductivity of diamond.
>
> A paper describing the production of uniform diameter single- wall nanotubes, which self-organize into tightly packed ropes, appears in the July 26 issue of Science. "Crystalline Ropes of Metallic Carbon Nanotubes," is authored by a team of researchers led by Smalley, Gene and Norman Hackerman Professor of Chemistry and professor of physics at Rice.
> (http://www.media.rice.edu/media/NewsBot.asp?MODE=VIEW&ID=197&SnID=2)

The process employed in the production of the nanotubes is called laser vaporization. A special nickel-cobalt catalyst is used in a 1200 degree Celsius furnace in which carbon particles are vaporized. The catalyst prevents the carbon tubes that form from being capped, allowing them to grow to great lengths in relatively short periods of time. Over time, the original process has been improved to the point that carbon nanotubes of prescribed lengths and properties can be mass-produced.

Now that single-walled carbon nanotubes and more complicated, larger structures, such as nanoballs, nanocars, and nano drug delivery devices are able to be manufactured, potential uses for the tubes are closer to becoming a reality. The article describes a number of uses, utilizing the unique properties of extremely high tensile strength, electrical conductivity, large surface area, and the ability to open and close the tubes on command. These areas include, but are not limited to, the medical and environmental applications mentioned in the article. Areas not mentioned in the article include the potential of nanotubes to transmit nerve signals in the case of spinal injuries. As semiconductor chips, the potential for smaller, more powerful computers is almost limitless.

In the twenty year history of nanotubes and related materials, no technology holds the potential and promise for helping to solve so many of the world's problems as does nanotechnology.

Connections to Chemistry Concepts

1. **Molecular sizes-metric scale review**—The following chart lists the prefixes used for both small and large numbers within the metric system.

Exponent	Prefix	Number
10^{24}	YOTTA	1,000,000,000,000,000,000,000,000
10^{21}	ZETTA	1,000,000,000,000,000,000,000
10^{18}	EXA	1,000,000,000,000,000,000

10^{15}	PETA	1,000,000,000,000,000
10^{12}	TERA	1,000,000,000,000
10^{9}	GIGA	1,000,000,000
10^{6}	MEGA	1,000,000
10^{3}	KILO	1,000
10^{2}	HECTO	100
10^{1}	DEKA	10
10^{-1}	DECI	.1
10^{-2}	CENTI	.01
10^{-3}	MILLI	.001
10^{-6}	MICRO	.000 001
10^{-9}	NANO	.000 000 001
10^{-12}	PICO	.000 000 000 001
10^{-15}	FEMTO	.000 000 000 000 001
10^{-18}	ATTO	.000 000 000 000 000 001
10^{-21}	ENTO	.000 000 000 000 000 000 001
10^{-24}	FITO	.000 000 000 000 000 000 000 001
10^{-27}	SYTO	.000 000 000 000 000 000 000 000 001
10^{-30}	TREDO	. 000 000 000 000 000 000 000 000 000 001

The nanoscale region includes micelles, proteins, DNA, antibodies, viruses, and ribosomes. Individual atoms and molecules are smaller and fall below the nanoscale region.

2. **Nanoscale limits–defining nanomaterials**—[As stated in other entries, the nanoscale region encompasses materials ranging in size from one nanometer to 100 nanometers.]

Typical Nanomaterials	Size (approx.)	Materials
(a) Nanocrystals and clusters	Diameter 1-10 nm	Metals, semiconductors, magnetic materials
Other nanoparticles	Diameter 1-100 nm	Ceramic oxides
(b) Nanowires	Diameter 1-100 nm	Metals, semiconductors, oxides, sulfides, nitrides
Nanotubes		Metal, layered metal Group VI (16) compounds (chalcogenides)
(c) 2-Dimensional arrays (of nanoparticles)	Several nm^2-μm^2	Metals, semiconductors, magnetic materials
Surfaces and films	Thickness 1-1000 nm	Various materials
(d) 3-Dimensional structures (superlattices)	Several nm in all three dimensions	Metals, semiconductors, magnetic materials

(source: http://www.ece.udel.edu/~baloo/Properties%20of%20nanomaterials.pdf)

3. **Properties of nanomaterials**—Properties are an integral part of any chemistry curriculum.

   a. **Physical properties of nanomaterials**—Increased surface area affects the physical/mechanical properties of nanomaterials. Hardness, scratch resistance, fracture toughness, and energy dissipation are all increased.

   b. **Chemical properties of nanomaterials**—The increase in surface area increases the rate of chemical reactions. Nanoparticles make very effective catalysts.

   c. **Electrical conductivity of nanomaterials**—Nanomaterials can hold a considerably higher charge than conventional materials because of the extremely high surface area of the nanomaterials.

   d. **Magnetic properties of nanomaterials**—The strength of magnets increase with decreasing grain size and specific surface area (surface area per unit volume) of the grains. Higher power magnets can be produced from nanocrystalline materials.

4. **Chemical bonding–free radicals**—Free radicals are atoms or groups of atoms (molecules and ions) that contain unpaired electrons. Such substances tend to be very reactive. In the atmosphere, chlorine free radicals formed from the atmospheric decomposition of chlorofluorocarbons (CFC's) formerly used in the refrigeration industry and as an aerosol propellant were linked to the destruction of the ozone layer. Eliminating most uses of the CFC's led to a "solution" to the ozone depletion. Free radicals are implicated in a number of serious biological conditions. Although necessary in a number of biological processes, free radicals have been associated with the aging process.

   a. **Ionic bonding–hydration shells**—An ion dissolved in water attracts water molecules to itself. Water molecules are polar, with electron density greater near the oxygen end of the molecule. The water molecules orient themselves depending on the charge of the ion. A positive ion attracts the oxygen end of the water molecule while negative ions attract the hydrogen end of the water molecule. The number of molecules and the strength of the attraction depend on the size and charge of the ions. Small highly charged ions produce the greatest attraction for water molecules. The water molecules grouped around the ion are called the hydration shell. The orientation of the water molecules in the hydration shell affects the hydrogen bonding and orientation of water molecules in the vicinity of the ion. These water molecules make up the second hydration cell.

   b. **Covalent bonding in carbon–two- and three-dimensional bonding (graphite and nanotubes)**—Bulk graphite consists of a large number of layers of carbon atoms. Each atom is covalently bonded to three other carbons within the plane. These planes of covalently bonded carbon atoms account for graphite's high melting and boiling points. (With diamond, they represent the highest melting and boiling points of any known materials.) The remaining electron in graphite does not form a single covalent bond. It belongs to a "sea" of delocalized electrons bounded by two covalently bonded layers. These electrons are free to move, and they account for the metallic-like electrical conductivity of graphite. These same electrons also account for graphite's excellent lubricating property. The individual sheets are able to move and slide across each other. The individual planes of covalently bonded carbon sheets are sheets of graphene. Graphite may therefore be considered an extremely large array or layers of sheets of graphene. Individual layers of graphene can be rolled into a cylinder creating the carbon nanotubes described in the article.

5. **Chemical Safety–nanomaterials in the environment**—The manufacture and use of nanomaterials creates safety considerations not covered by traditional safety practices. The extremely small size of the particles introduces personal safety issues surrounding possible ingestion and inhalation of the nanoparticles. Early animal studies indicate that ingested particles are excreted in the urine. Inhaled particles are a more serious concern. Exposure to nanoparticles can trigger allergic asthma symptoms or aggravated symptoms of

pneumonia. Cardiac and circulatory systems may also be affected. Issues in the manufacture and disposal of nanomaterials must also be addressed.

6. **Chemical synthesis or direct combination reactions–building nanomaterials from the bottom up**—Chemical synthesis or direct combination reactions represent the reactions of small particles (atoms) to produce larger structures (molecule or ionic solids). When run in a lab these reactions produce macroscopic quantities of products. The products formed cannot be considered nanomaterials. Bottom-up synthesis begins with individual atoms and molecules to create larger structures, but structures whose size lies between 1 nm and 100 nm. The forces of attraction that exist between the atoms and molecules are key to implementing the process. Electroplating is the traditional approach to bottom-up processing. Chemical vapor deposition is an alternate approach to building nanomaterials from the bottom up. A goal is to design and implement a set of conditions such that the atoms or molecules will self assemble into the desired material.

Possible Student Misconceptions

1. **"Nano materials are simply very small materials—something that requires a microscope for viewing."** *The term "nano" has come to mean particles between 1 nanometer and 100 nanometers in size. Other terms apply to particles that are smaller or larger.*
2. **"Nano materials are dangerous. Just look at the movie industry and popular novels."** *A number of movies have embraced the "nano" theme. Scenes from the movies could be used as introductions to specific nanotechnology topics. Movies employing the "nano" theme include: "Fantastic Voyage" (miniaturized submarine on an emergency medical mission), "Jurassic Park" (bionanotechnology used to resurrect dinosaurs), "Terminator 2" (robot composed of an amorphous structure made up of tiny self assembling nanobots), "I Robot" (the nanobots are called nanites), "Knight Rider" (the car utilized all sorts of adaptive nanotechnology). Other movies on microscaling include "The Incredible Shrinking Man", "The Incredible Shrinking Woman", "Innerspace", "Honey, I Shrunk the Kids", and "Ant Bully".* Prey *by Michael Crichton is perhaps the best known popular novel based on the runaway, self-assembling nanobots. A great story but weak, at best, science!*

Demonstrations and Lessons

1. Have your students take the National Institute of Standards and Technology's "NIST Nano IQ Quiz". The quiz is available at http://www.nist.gov/public_affairs/nanotechquiz.htm?totalQuestions=10&A0=2&A1=4&A2=2&A3=4&A4=3&A5=4&A6=1&A7=4&A8=1&A9=1. Scoring 0-3 correct = Nano Novice, 4-6 correct = Nano Nerd, 7-10 correct = Nano Genius.
2. The Interactive Nano-Visualization in Science & Engineering Education (IN-VSEE) is a consortium of university and industry scientists and engineers, community college and high school science faculty and museum educators with a common vision of creating an interactive World Wide Web (WWW) site to develop educational thrust based on remote operation of advanced microscopes and nanofabrication tools coupled to powerful surface characterization methods. Clicking on "Modules" brings up a list of activities that can be performed in class. The "Links" section contains a wealth of resources. The modules and links section are the most valuable to teachers. Each one includes numerous activities available to teachers and/or students. (http://invsee.asu.edu/invsee/invsee.htm)
3. Cutting it Down to Nano is an exercise with the following objectives: understand the smallness of the nanoscale, appreciate the impossibility of creating nanoscale materials with

macroscale objects, and understand the invisibility of the nanoscale to the unaided eye. http://mrsec.wisc.edu/Edetc/IPSE/educators/activities/cuttingNano.html.

4. The website listed above is located at the University of Wisconsin-Madison Materials Research Science and Engineering Center. A number of other nanoscale activities are included. Topics linked to the website are listed below. Not all deal with the specific topics covered in the *ChemMatters* article, but if the article sparks student interest in nanotechnology, such interest can be channeled to one or more of the activities which follow. Each of the activities listed below includes a materials section, a set of training videos on how to conduct the activity and a "learn more" section providing links to more information on the topic.
5. Balloon Models of Nanotubes (Tabletop) (Build a nanotube made of balloons.)
6. Balloon Models of Nanotubes (Suspended Sculpture) (Similar to #6 above, but this model is suspended from the ceiling.)
7. Cutting it Down to Nano (An activity to help understand just how small a nanoparticle is)
8. Forms of Carbon (Examines the atomic structure of diamond, graphite, fullerenes and carbon nanotubes and helps explain why they have such different properties from each other)
9. Mitten Challenge (simulates the challenge of working with macro tools to manipulate micro materials)
10. Here are more activities that are also on the site, but perhaps less directly related to the article.

a. Amorphous Metal
b. Nanogold Sensors
c. Nanostained Glass
d. Nanosurfaces
e. Probe Microscopy
f. Wheel of Fortune
g. Writing with Light
h. Electric Squeeze
i. Ferrofluid
j. LEDs
k. Liquid Crystals
l. Magic Sand
m. Memory Metal

Student Projects

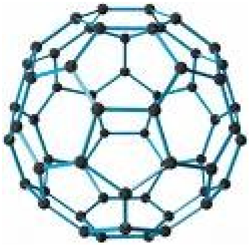
1. "NanoVenture: The Nanotechnology Board Game" explores the connections between science, specifically nanotechnology, and society. In this game, players become leaders of a new country. The leaders are challenged to make decisions regarding their country's use of nanomaterials and nanotechnology for industrial expansion, military application, economic security and basic scientific research, while maintaining a high approval rating from the citizens of the country. These decisions require players to carefully analyze the interplay of technological advances, regulations, public perception and risk, while also learning about the emerging field of nanotechnology. It is best to play with four or five players. However, teams can be used if there are more than six players. An inquiry as to the cost and availability of the game led to the following reply: "Thank you for your interest in our

NanoVenture game. We're still finalizing distribution details with the Institute for Chemical Education (which is the non-profit distributor for all of our kits), but in the mean time, we are selling the kits at cost for $45 each, which includes shipping. The cost will increase once we distribute through ICE to cover their administrative costs and overhead, probably to ~$60, but no guarantees. If you want to direct people to up-to-date information, you can list my email address Greta M. Zenner [gmzenner@wisc.edu], the NanoVenture website (http://mrsec.wisc.edu/Edetc/supplies/nanoventure/index.html), or the ICE website at (www.ice.chem.wisc.edu). NanoVenture isn't up on the ICE website yet, but it will be soon."

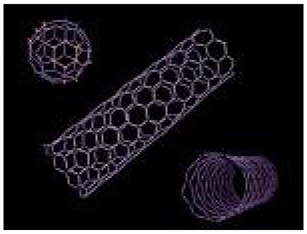
2. "Duck Boy in Nanoland: Big Adventures in a Nanoworld". In this on-line game, "Duck Boy is exploring Nanoland. It is a strange place where not is all that it seems, As Duck Boy explores Nanoland he encounters a strange phenomenon; as he plays Nanoland's games they reduce in size to nano-scale! Playing the game is much harder at nano-scale until Duck Boy is introduced to solutions based in Nanotechnology which help nano-Duck Boy complete the challenges!" The game is suited for all audiences. Students used to online game playing may find the game somewhat unsophisticated, but completing the game does provide one with a series of properties associated with nanomaterials. (http://www.sciencemuseum.org.uk/antenna/nano/nanoland/nanoworld.asp)
3. If a school budget allows, Indigo Instruments offers a series of carbon nanotube models. The models have enough parts to build armchair, zigzag, and chiral nanotubes. Kits run from ~$40-$200. (http://www.indigo.com/models/carbon-nanotube-molecular-model-kits.html)
4. If funds are not available for the purchase of model kits, a model of a nanotube can be constructed from balloons. Complete instructions are given for building two models – a ten-foot model or a table-top model. (http://mrsec.wisc.edu/Edetc/nanolab/balloons/BalloonNanotubes_ProgramGuide.pdf)
5. Another page at the University of Wisconsin-Madison site gives students using this site paper (electronic) models of the three different types of nanotubes that they can build for themselves. A PDF file representing graphene sheets may be reproduced and used in building the models. (http://mrsec.wisc.edu/Edetc/cineplex/nanotube/graphene.pdf) The site also includes videos describing each of the models: (http://mrsec.wisc.edu/Edetc/cineplex/nanotube/index.html)
6. The Exploratorium web site contains a series of Small Talk Podcasts which explore the topics presented in the articles. Podcasts include: Nature's Playing Field: Nanotechnology and Medicine (31 min.), Nanotechnology's Role in Making Cheap Solar Power (26 min.), Consumer Products Using Nanotechnology (37 min.), and Vroom! Nanocars and Nanofactories (28 min), Nanograffiti: Building from the Atoms Up (23 min). (http://www.exploratorium.edu/ti/podcasts/smalltalk.php)
7. The sites listed under "Websites for More Information" offer a wealth of background information for student-produced written, oral, or video class presentations. One project in particular might be of interest to students: Is there a real danger in using sunscreens that contain nanoparticles? Friends of the Earth provides a consumer guide for avoiding nano-sunscreens at http://action.foe.org/content.jsp?key=3060. A more balanced report tracing the history of the use of nanoparticles in sunscreen and results of product testing can be found at http://realizebeauty.wordpress.com/2009/03/27/zinc-and-the-nano-sunscreen-revolution/.

Anticipating Student Questions

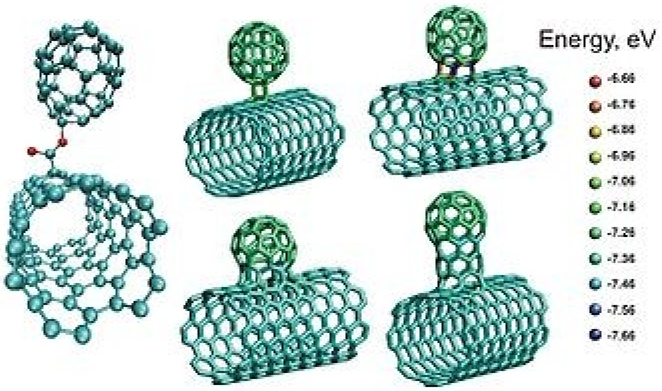
1. **"What are the differences among buckyballs, nanotubes, nanobuds, and nanowires?"** *Buckyballs belong to the family of carbon allotropes called fullerenes, named after the famous architect Buckminster Fuller, who introduced the use of the geodesic dome into architecture. The most common buckyballs are* C_{60} *and* C_{70}*.*



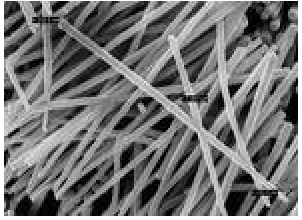
Nanotubes are cylindrical structures of fullerenes. They are usually a few nanometers wide and can be up to millimeters lengths. The tubes can have either open or closed ends.



Nanobuds are structures composed of buckyballs attached to nanotubes that exhibit properties of both.



Nanowires are nanostructures that have incredibly large length to width ratios. Nanowires can be as thin as one nanometer, although the usual width is 60-70 nanometers.



All images are taken from the Wikipedia gallery.

2. ***"Why are people concerned about nanoparticles used in sunscreens?"*** *The older zinc oxide sunscreens provided protection from the UV rays of the sun by completely blocking any UV rays from penetrating the zinc oxide ointment. The zinc oxide came in a variety of colors, but all were opaque and covered the skin. By transforming the zinc oxide into nanosized particles, the sunscreen becomes transparent but still affords the same protection. Concerns have arisen as to the mobility of the zinc oxide particles penetrating the surface of the skin and entering the body. Health effects of the nanoparticles on body tissue are still unknown.*

References

The University of Wisconsin–Madison, Materials Research Science and Engineering Center on Nanostructured Interfaces has produced a comprehensive website covering all areas of nanotechnology. If only one site were to be accessed, this site provides requisite background information, projects, labs, videos, lessons—anything a teacher would need. (http://mrsec.wisc.edu/Edetc/)

Web Sites for Additional Information

More sites on nanotechnology

The Center for Responsible Nanotechnology presents a broad look at various aspects of nanotechnology. Of special interest is the final section of the site: More Background on Nanotechnology. Included in this section are:

- Nanotechnology Basics—For students and other learners
- Managing Magic—A brief overview of the challenges posed by advanced nanotechnology
- Nanotechnology on an Upward Slope—An online PowerPoint presentation
- Turn on the High Beams—An essay published by *Future Brief*
- Nan Simulation—A way to visualize what is meant by molecular manufacturing
- Debating the Future of Nanotechnology—Perspective from the Foresight Institute
- Safe Utilization of Advanced Nanotechnology—One of the founding papers of CRN
- 5-Minute Nanosystems—A quick summary of Eric Drexler's foundational work on nanotechnology
- Nanotechnology Press Kit—Compiled and published by *Nanotechnology Now*.

The Press Kit itself contains a wealth of information. The opening page includes an animated working model of one of the largest nanomechanical devices ever modeled in atomic detail, a parallel-shaft speed reducer gear made up of 15,342 atoms. (http://www.crnano.org/whatis.htm)

The Northwestern University DiscoverNANO site offers a complete introduction to all aspects of the field of nanotechnology. The site includes a history of nanotechnology, a glossary of terms, applications of nanotechnology, societal impact of nanotechnology, a section specifically for teachers, a nano art gallery, and interesting links. The site also offers free registration for future nanotech town hall meetings. Streaming videos of previous town hall meetings are available. (http://www.discovernano.northwestern.edu/index_html)

More sites on carbon nanotubes

This is a site completely dedicated to carbon nanotubes. It contains a superb set of images as well as the specific links that follow the main website.
http://nanotube.com/

Nanomaterials
Fullerenes
Fullerene chemistry
Applications
In popular culture
Timeline
Carbon allotropes
Nanoparticles
Quantum dots
Nanostructures
Colloidal gold
Colloidal silver
Iron nanoparticles
Platinum nanoparticles
See also Nanotechnology

A video on a massive construction project in Japan based on nanotubes:
http://videos.howstuffworks.com/hsw/8224-pure-carbon-the-science-of-nanotubes-video.htm

More sites on carbon fiber prosthetics

In this TED archive video from 1998, paralympic sprinter Aimee Mullins talks about her record-setting career as a runner, and about the amazing carbon-fiber prosthetic legs (then a prototype) that helped her cross the finish line.
(http://www.ted.com/talks/lang/eng/aimee_mullins_on_running.html)

More sites on viewing C-60 in carbon nanotubes and how one visualizes/views atomic sized particles

"*'Reactions in Chemistry'* is an eight-part workshop for the professional development of high school chemistry and physical science teachers. The workshop blends chemistry content, history, and technological applications with a range of classroom lessons to provide teachers with updated knowledge and new approaches to pedagogy. Teachers will see diverse classes doing hands-on lessons and labs and will hear teachers reflect on their own practices. The on-camera teachers meet in roundtable discussions about teaching strategies and the particular challenges of helping students connect the content to their own lives. The programs also present the work of industrial and forensic chemists and researchers."
(http://learner.org/vod/vod_window.html?pid=1812)

"'Workshop 2. Macro to Micro Structures' is the program that deals with the conceptualization of micro processes and environments. It involves teaching chemistry through macro phenomena, which can be observed, and micro processes, which occur on the molecular level, and can only be imagined. Conceptual change must occur in order for students to understand chemical phenomena. Teaching for conceptual change poses a great challenge to teachers, because they must create imaginary and physical models in order to help students visualize microenvironments and processes that occur within them."

More sites on all aspects of nanotubes

The primary purpose of The Nanotube Site is to facilitate the exchange of ideas among researchers by concentrating links to sites dedicated to nanotubes. One of the benefits is to provide an easier (or better structured) electronic access to bibliographical information and preprints. Information about providers of nanotubes is intended to increase the production volume and find new applications for nanotubes. (http://nanotube.msu.edu/)

More sites on nanotube and fullerene simulations

This is the homepage of Nanotech Research in David Tomanek's Group. He states "Research on carbon nanotubes in my group focuses on modeling the self-assembly and electronic properties of these systems. Recent advances in the synthesis of identical carbon nanotubes with a diameter of 1.4 nm, yet hundreds of microns in length, bear high promise for the application of these advanced materials in next-generation electronic nano-devices. Advanced computational techniques, including large-scale parallelizable molecular dynamics simulations of the growth mechanism and first-principles calculations of the electronic structure, are being applied to model the self-assembly and the electronic properties of these structures. Results will elucidate ways to direct and optimize growth conditions, mechanical and thermal stability, and the usefulness of nanotubes as perfect nanoscale conductors." (http://www.pa.msu.edu/~tomanek/nanotubes.html)

More sites on nanotubes and nanostructures

The site includes an interactive database. (http://uminokai.net/nanotube/index.php)

More sites on safety issues and nanotubes

A new study has found that carbon nanotubes—if inhaled—could be as dangerous as asbestos. This is not only problematic for a future of semiconductors that would like to exploit the technology, but also for the goods already on the market now that use nanotubes in composite mixtures, like baseball bats and tennis rackets. Some entrees appear to be of a serious nature, while others are questionable. The site needs to be mined for the valuable nuggets. (http://gizmodo.com/tag/nanotubes) The article of interest is Are Nanotubes the New Asbestos?

More Web Sites on Teacher Information and Lesson Plans

An all inclusive website sponsored by NASA—Nanotech Gallery. The site includes images, Power Point presentations, reports, webcasts and movie clips—all of which would be aids in developing lessons on nanotechnology. The homepage of the site explains why NASA is so interested in nanotechnology. (http://www.ipt.arc.nasa.gov/gallery.html)

The relatively new Microsoft search engine www.bing.com provides a survey of nanotechnology that covers any topic which might be on interest to a teacher. An overview of

each site is accessed by moving the cursor to the right side of the site. Related links at this website are listed below the URL for the main site.
(http://www.bing.com/search?FORM=SOLTDF&q=history+of+nanotechnology)

- **Applications** Of Nanotechnology
- **Define** Nanotechnology
- **Future** Nanotechnology
- **Medical** Nanotechnology
- **Uses** Of Nanotechnology
- **Introduction To** Nanotechnology
- **Military** Nanotechnology
- **Definition** Of Nanotechnology

A complete set of lesson plans on nanotechnology may be found at http://www.bscsd.org/teachers/dvickery/nanotechnology.htm. Sections include:

- What is Nanotechnology?
- Why focus on Nanotechnology?
- Nanotechnology Basics
- Nanotechnology in Tech Valley—What's Going On?
- Industries and Occupations Affected by Nanotechnology
- Helping Tech Valley Students Get a Head Start in Nanotechnology.

The University of Pennsylvania's ITEST-Nano Resource Library contains materials used in their Summer Development Teacher Workshop, 2008. The first two modules Introduction to Nanotechnology I and II are available as PDF versions of the original slides. The third module, Cell Nanosurgery: Delivering Material into Cells and Analyzing Effects fits in perfectly with the article. The two sets of Power Points slides and Support Files are excellent resources and complement the article. The site also includes three PBL units: Nanotechnology and Sunscreen, Nanotechnology and Cancer, and Nanotechnology and Environmental Clean Up, all available as Word files. Each is a complete set of lessons including laboratory activities. (http://www.gse.upenn.edu/itest/resources.htm)