



February 2006 Teacher's Guide

About the Guide	3
Student Questions	4
Answers to Student Questions	5
Dial-A-Compound Puzzle	8
Answers to Dial-A-Compound Puzzle	9
Content Reading Guide	10
National Science Education Content Standard Addressed	10
Anticipation Guides	11
The Chemistry of Digital Photography and Printing	12
Real or Fake: The James Ossuary Case	13
Super Fibers	14
Salting Roads	15
Flaking Away	16
Reading Strategies	17
The Chemistry of Digital Photography and Printing	18
Real or Fake? The James Ossuary Case	19
Super Fibers	20
Salting Roads	20
Flaking Away	22
The Chemistry of Digital Photography and Printing	23
Background Information	23
Connections to Chemistry Concepts	26
Possible Student Misconceptions	26
Demonstrations and Lessons	26
Suggestions for Student Projects	26
Anticipating Student Questions	26
Websites for Additional Information	26
Super Fibers	35
Background Information	35
Connections to Chemistry Concepts	39
Possible Student Misconceptions	39
Demonstrations and Lessons	39
Anticipating Student Questions	40
Websites for Additional Information	40
Salting Roads: The Solution for Winter Driving	42
Background Information	42
Connections to Chemistry Concepts	45
Possible Student Misconceptions	45
Demonstrations and Lessons	45
Suggestions for Student Projects	46
Anticipating Student Questions	46
Websites for additional Information	46

Flaking Away	47
Background Information	47
Connections to Chemistry Concepts	50
Possible Student Misconceptions.....	50
Demonstrations and Lessons	50
Suggestions for Student Projects:.....	51
Anticipating Student Questions	51
Websites for Additional Information.....	52

About the Guide

William Blead and Donald McKinney, TG Editors, created the teacher's guide article material.

bbleam@verizon.net

Susan Cooper prepared the national science education content, anticipation, and reading guides.

coopers@hendry.k12.fl.us

Terri Taylor, CM Administrative Editor, coordinated production and prepared the MS Word and PDF versions of the Guide.

chemmatters@acs.org

David Olney created the puzzle. djolney@rcn.com

Student Questions

The Chemistry of Digital Photography

1. What part of the digital camera records the image?
2. Why is silicon doped for its use in digital photography?
3. Differentiate between *n*-type and *p*-type silicon.
4. How do photosites on the sensor respond to light?
5. How do digital cameras take color photos?
6. How is static electricity employed in the process of laser printing?

Real or Fake? The James Ossuary Case

1. What is patina? How was it used to determine the authenticity of the tablet and bone box?
2. What information led Professor Goren to the conclusion that the inscription was added in recent times?
3. Why did fluorine found in the patina of the bone box indicate that the patina had been faked?
4. How did cleansers use to clean the bone box further confuse matters?

Super Fibers

1. Why are carbon nanotubes able to conduct electricity so efficiently?
2. What other properties make carbon nanotubes promising as future building material?

3. What challenges exist in producing useful nanotubes?
4. How do carbon nanotubes compare to spider silk and Kevlar in terms of strength?
5. What are some potential applications for carbon super fibers?

Salting Roads

1. How does molecular motion change during the freezing process?
2. Why does the presence of a solute, such as salt, cause freezing to occur at lower temperatures?
3. What are the two ways in which salt is used by highway workers?
4. Why don't communities with very cold temperatures use salt on their roads?
5. Why are salts such as $MgCl_2$ and $CaCl_2$ more effective than $NaCl$ at depressing the freezing point?
6. Give one disadvantage to salting roads.

Flaking Away

1. Define oxidation and reduction.
2. What three ingredients are needed for the redox reaction that forms rust?
3. Why is iron the perfect anode for the electrochemical process of rusting?
4. Why does a high abundance of salt favor the formation of rust?
5. Give two ways that corrosion can be prevented.

Answers to Student Questions

The Chemistry of Digital Photography

1. *What part of the digital camera records the image?* The image is recorded on the sensor.
2. *Why is silicon doped for its use in digital photography?* Silicon is a poor conductor of electricity in its purest form. When a small amount of impurity is added, the silicon is able to conduct electricity more effectively.
3. *Differentiate between n-type and p-type silicon.* N-type silicon has been doped with an element that contains more valence electrons than silicon does. These provides extra electrons that are able to move through the material. This type of silicon is called *n*-type because of the negative charge associated with the extra electrons. P-type silicon has been doped with an element that contains fewer valence electrons than silicon does. This creates a deficiency of electrons. This type of silicon is called *p*-type because of the positive charge associated with a deficiency of electrons.
4. *How do photosites on the sensor respond to light?* When photons of light are absorbed, electrons within the photosites are promoted to higher energy levels.
5. *How do digital cameras take color photos?* Filters in red, green, or blue are placed over each photosite on the sensor of the camera.
6. *How is static electricity employed in the process of laser printing?* In laser printing, positively charged toner sticks to negatively charged paper.

Real or Fake? The James Ossuary Case

1. *What is patina? How was it used to determine the authenticity of the tablet and bone box? Patina is a coating that builds up on objects over long periods of time. A technique called ^{14}C dating was performed on patina to determine the approximate age of the tablet and bone box.*
2. *What information led Professor Goren to the conclusion that the inscription was added in recent times? The softness of the patina indicated that it had formed in more recent times. Additionally, the patina in the inscription was different from the surface patina.*
3. *Why did fluorine found in the patina of the bone box indicate that the patina may have been faked? Fluorine was not added to water until modern times. This suggests that the patina was made using tap water from modern times.*
4. *How did cleansers use to clean the bone box further confuse matters? The cleansers that art dealers may have used to clean the bone box had oxygen isotope data identical to the patina in the inscription of the bone box. This means that the oxygen isotope data from the patina that suggested the forged inscription may have come from the cleansers.*

Super Fibers

1. *Why are carbon nanotubes able to conduct electricity so efficiently?* Because every atom in a carbon nanotube shares electrons with the other carbon atoms around it, electricity can be conducted easily.

2. *What other properties make carbon nanotubes promising as future building material?* Carbon nanotubes can also conduct heat efficiently, are strong, and are lightweight.
3. *What challenges exist in producing useful nanotubes?* The combustion reactions that could produce nanotubes lead to the formation of nanotubes with different angles, lengths, and types. This means that the properties of the nanotubes within a given sample can vary dramatically.
4. *How do carbon nanotubes compare to spider silk and Kevlar in terms of strength?* Carbon nanotubes are four times as strong as spider silk and 17 times as strong as Kevlar.
5. *What are some potential applications for carbon super fibers?* Carbon nanotubes can potentially be used as protective garments for law enforcement officers, artificial muscles, and cables for conducting electricity.

Salting Roads

1. *How does molecular motion change during the freezing process?* During freezing, the molecules slow down and settle into fixed positions in a crystal lattice. They are still moving; however the motion is vibrational as opposed to the translational motion that occurs in liquids.
2. *Why does the presence of a solute, such as salt, cause freezing to occur at lower temperatures?* The presence of a solute, such as salt, requires that more energy needs to be removed to get the water molecules organized into the crystal lattice.
3. *What are the two ways in which salt is used by highway workers?* Salt is used to melt ice that is already on the roads and to prevent ice from forming.
4. *Why don't communities with very cold temperatures use salt on their roads?* Below the eutectic temperature, the solution will be too cold to hold the salt which prevents it from freezing.
5. *Why are salts such as $MgCl_2$ and $CaCl_2$ more effective than $NaCl$ at depressing the freezing point?* $MgCl_2$ and $CaCl_2$ dissociate into three particles per formula unit; $NaCl$ is able to dissociate into two particles per formula unit. Three particles require that that even more energy is removed to get the water molecules organized into the crystal lattice.
6. *Give one disadvantage to salting roads.* Salting the roads can increase the corrosion of vehicles, can be damaging to the road and can be environmentally harmful to animals and plant-life.

Flaking Away

1. Define oxidation and reduction. Oxidation is the process by which electrons are lost. Reduction is the process by which electrons are gained.
2. What three ingredients are needed for the redox reaction that forms rust? An anode (to give up electrons), a cathode (to accept electrons) and an electrolyte solution (to complete the circuit).
3. Why is iron the perfect anode for the electrochemical process of rusting? Iron easily loses electrons.
4. Why does a high abundance of salt favor the formation of rust? A high abundance of salt is able to act as the salt bridge in this electrochemical process; this is needed to complete the circuit and to balance the build-up of charged particles.

5. Give two ways that corrosion can be prevented. Corrosion can be prevented by using a noncorroding metal to build cars. Addiitonally, corrosion can be prevented by the use of paint. Paint prevents water from contacting steel; thus decreasing the amount of reactant (iron) available for rust formation.

Dial-A-Compound Puzzle

Shown below is the typical telephone layout. Notice that for each number there are three letters. One can imagine that a baseball player like Roger Clemens might have a phone number of 253-6367, since one can spell out CLEMENS by those numbers; knowing he is a famous pitcher helps out in the identification. Listed below are ten compounds commonly found in chemistry, all spelled with seven letters. Some are organic, some inorganic, some names of minerals. We'll provide for each a "telephone number" and one clue as to its meaning.

For example, given 6 3 8-4 2 6 3 and the clue "simplest alkane:"

The first letter is either M ,N,or O, the second letter D,E, or F, etc.

A little trial-and-error effort yields the answer METHANE, confirmed by the clue

See if you can identify all ten with just this information!

- 2 6 6 - 6 6 4 2 **product of the Haber process**
- 3 8 4 - 2 6 6 5 **solute in grain alcohol**
- 2 2 8 - 9 4 8 3 **ore rich in aluminum**
- 2 5 2 - 6 4 6 3 **one of the amino acids**
- 2 2 5- 2 4 8 3 **a mineral source of calcium carbonate**
- 7 8 2 - 7 6 7 3 **a sugar with 12 carbon atoms**
- 2 2 5 - 6 6 3 5 **Hg₂Cl₂ ; used in some reference electrodes**
- 2 3 3- 6 4 6 3 **one of the organic "bases" in DNA**
- 2 2 3 - 8 6 6 3 **simplest of the ketones and a well-known solvent**
- 7 2 5 - 7 6 3 2 **crystalline sodium carbonate (two words)**

Here's the telephone lay-out

1	ABC	DEF
2	3	4
GHI	JKL	MNO
5	6	7
PRS	TUV	WXY
8	9	
*	0	#

Answers to Dial-A-Compound Puzzle

ANSWERS: ammonia, ethanol, bauxite, alanine, calcite, sucrose, calomel, adenine, acetone, sal soda

Content Reading Guide

National Science Education Content Standard Addressed As a result of activities in grades 9-12, all students should develop understanding	Salting Roads	Chemistry of Digital Photography & Printing	Super Fibers	Flaking Away	Real or Fake?
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.	✓	✓	✓	✓	✓
Physical Science Standard B: of chemical reactions.				✓	✓
Physical Science Standard B: of conservation of energy and increase in disorder.				✓	
Physical Science Standard B: of interaction of energy & matter.		✓	✓		
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: 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 their 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: 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.

The Chemistry of Digital Photography and Printing

Me	Text	Statement
		1. The world's first photograph was made more than 175 years ago.
		2. Instead of film, a digital camera records an image on a sensor that is the size of a fingernail.
		3. Pure silicon is a good semiconductor.
		4. Diodes permit current to flow in two directions.
		5. Silicon doped with gallium has the same charge as silicon doped with arsenic.
		6. The best digital camera available today has more pixels than the human eye.
		7. As more photons are absorbed by semiconductors in the pixels, more electrons are collected at the <i>n</i> side of the diodes.
		8. Sensors in digital cameras record only shades of gray.
		9. Good color printers have at least ten colors of toner.
		10. Laser printers tend to produce better quality photos than inkjet printers.

Real or Fake: The James Ossuary Case

Me	Text	Statement
		1. Forgers use carbon found at ancient archeological sites to make patina to fool scientists who use radiocarbon dating to authenticate pieces.
		2. As a once-living organism decays, the amount of ^{14}C in the remains stays constant.
		3. Oxygen isotope analysis can be used much like ^{14}C dating to determine the age of an artifact.
		4. The amount of ^{18}O is different for calcite formed from hot groundwater than that formed from cold groundwater.
		5. Old patina can be faked by using carbonate from fossils.
		6. Cleansers used to clean artifacts contain chemicals similar to those in patinas.
		7. The scientists involved in this case agree that the bone box and stone tablet are fakes.
		8. James, Joseph, and Jesus were common names in the 1 st century AD.

Super Fibers

Me	Text	Statement
		1. Carbon nanotubes were discovered more than 20 years ago.
		2. Carbon nanotubes conduct electricity but not heat.
		3. Carbon nanotubes are lightweight and strong.
		4. Carbon nanotubes are produced by burning candles.
		5. A mixture of unmatched nanotubes is needed in order to produce consistent properties.
		6. Today's technology cannot produce the long nanotubes needed for many of the uses described in the article.
		7. High-frequency sound waves are used to keep carbon nanotube yarns from bunching together.
		8. Electrical cables made of nanotubes could save electricity.

Salting Roads

Me	Text	Statement
		1. Salt lowers the freezing point of water, but not other solvents.
		2. When salty water freezes, the salt is incorporated into the crystal lattice structure.
		3. Salting the roadways melts ice and prevents ice formation.
		4. Very cold locations do not salt roadways.
		5. Roadways were first salted in the 1950s.
		6. Calcium chloride and sodium chloride have the same effect on the freezing point of water.
		7. Some bridges have deicing sprayers built into the pavement.
		8. The concentration and solute identity affect the freezing point depression of a solvent.

Flaking Away

Me	Text	Statement
		1. Rusting depends on an anode, a cathode, and an electrolytic solution.
		2. Iron is a good anode because it releases electrons readily.
		3. Water aids rusting because the oxygen in water combines with iron to make ferric oxide.
		4. Salt (sodium chloride) aids corrosion for two reasons: it makes water a better conductor, and chloride ions help dissolve iron.
		5. Iron is often found in its elemental state in nature.
		6. Rust is more thermodynamically stable than iron.
		7. The best way to prevent rust on your car is to wash it often.
		8. The Department of Defense invests a great deal of money in antirust research.

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

The Chemistry of Digital Photography and Printing

Complete the chart below to compare photosites found in digital cameras with photograph printers.

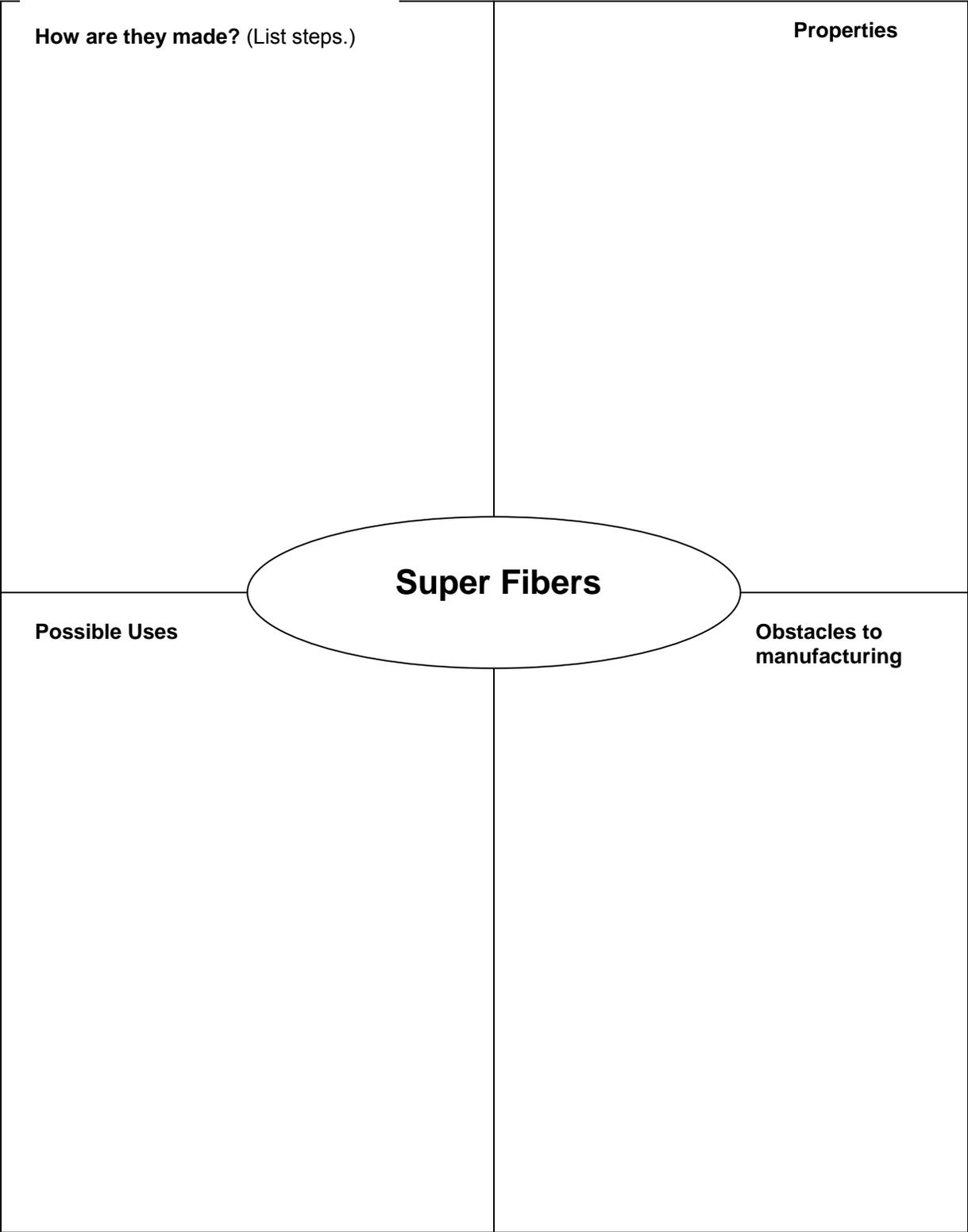
	Photosites	Printers
Chemicals used		
How they work		Laser: Inkjet (2 kinds):
Colors needed		
Other interesting or important information		

Real or Fake? The James Ossuary Case

As you read, find **at least four** pieces of evidence for the authenticity of the bone box and tablet discussed in the article. For each piece of evidence, name the scientist(s), state if the evidence supports a decision of real or fake, and explain why.

Evidence	Scientist(s)	Real or Fake?	Explanation

Super Fibers



Salting Roads

Process	Examples	Why it works	<i>Problems to solve/ Future technology</i>
Freezing Point Depression			
Salting Roads			
Using chemicals other than NaCl for salting roads			
Deicing bridges			

Flaking Away

	Anode	Cathode	Electrolytic Solution
Examples			
Chemical Equation			
How can understanding of this be used to prevent rust?			

The Chemistry of Digital Photography and Printing

Background Information

Digital Camera Sales

According to industry analysts, more than 53 million digital cameras were sold worldwide in 2004. This compares to sales of 5.5 million in 1999, 11.0 million in 2000, 18.5 million in 2001, 30 million in 2002, and 50.0 million in 2003. Estimates of sales by 2008 will top 82 million cameras. Major producers include Canon, Sony, Olympus, Fujifilm and Kodak with a combined market share of three quarters (75%). By comparison, analog camera sales for 2003 were about 57 million units.

More on How Digital Cameras Work

Light coming through the lens of a charge coupled device (CCD) digital camera falls on an image sensor. The image sensor is divided into smaller sections called picture elements, or pixels, which vary in size from about 3-12 microns square. The pixels are arranged in a rectangular array on the surface of the sensor. For example, the sensor in a 4.2 megapixel camera has an array measuring 2400 pixels x 1800 pixels, a measure of the resolution of the digital camera.

Each of these pixels is actually a semi-conductor, as the article describes. When photons of light strike a pixel, electric charge is built up in the semi-conductor that makes up that pixel. This charge is proportional to the intensity of the incoming light. This sequence of events occurs simultaneously in each pixel on the sensor. In the camera is a small microprocessor, an analog-to-digital converter (ADC), which converts the electric charges from each pixel into digital form. The ADC is part of the digital signal processor (DSP).

The essential chemistry of a digital camera is related to the semi-conductors that make up each photosite (or pixel) in the sensor. Silicon is, of course, the basic semi-conductor substance. Silicon exists in the form of a crystal lattice with each silicon atom bonded covalently to four other silicon atoms. This arrangement does not allow silicon to conduct electricity, since all of its valence electrons are involved in bonding. As the article describes, introducing small amounts of other elements into the silicon crystal makes silicon a conductor. The process is called doping.

The doping process replaces some of the silicon atoms in the crystal with atoms of a different element, and usually the elements used as impurities are found in the two groups on either side of silicon on the periodic table. For example, phosphorus and arsenic may be used as dopants. Both phosphorus and arsenic have five valence electrons. But the silicon crystal requires only four bonds per atom. This leaves an extra electron free inside the crystal. Since these extra electrons move through the crystal to carry current, the doped silicon is referred to as *n*-type, since the charge carriers are negatively charged. If elements like boron or gallium are used as dopants, a silicon atom is replaced by an atom with only three valence electrons. This leaves a bond in the crystal incomplete. The incomplete bond is called a "hole," and it too can hop through the crystal to carry current in this *p*-type silicon (*p* for the positive charge associated with the lack of an electron).

Joining these two doped crystals creates a diode. Joining these two doped crystals creates a diode, which has the remarkable property that current will flow readily in one direction, but only with great difficulty in the other. For example, if the positive battery terminal is attached to the *n* side of the diode, it attracts the mobile electrons away from the *p-n* junction, while the mobile holes on the *p* side are attracted to the negative battery terminal. But this is untenable, since it tends to deplete the mobile charge carriers near the junction, creating an essentially nonconducting layer that impedes passing current. In contrast, if the battery is reversed, electrons and holes both flow toward the interface between the *p*- and *n*-type silicon (where they can meet and annihilate each other), and current flows relatively easily.

When light enters the camera and photons strike the diode, energy from the photons promotes electrons in the silicon crystal to a higher energy state, as the article describes. The greater the intensity of light striking the pixel, the more excited electrons accumulate at that location and the higher the charge.

The band theory for solid crystals suggests that valence electrons have energies which fall in a narrow band range as opposed to the energy of electrons in independent atoms, which have discrete values described by quantum theory. In semiconductors, there are two energy bands, the valence band and the conduction band, which are separated in energy by a "band gap", where there are no allowed energy

levels for electrons. In an undoped semiconductor, such as silicon, the valence band is completely filled with electrons and the conduction band is completely empty. Conductivity is poor because valence electrons cannot hop to nearby orbitals, because all nearby orbitals are filled. Doping increases conductivity either by adding electrons to the nearly empty conductivity band (*n*-type) or by opening up free spaces in the valence band by removing electrons (*p*-type). In silicon, the band gap is about 1.1 eV, which means that any photon of visible light has enough energy to promote an electron from the valence band to the conduction band (and so silicon looks black).

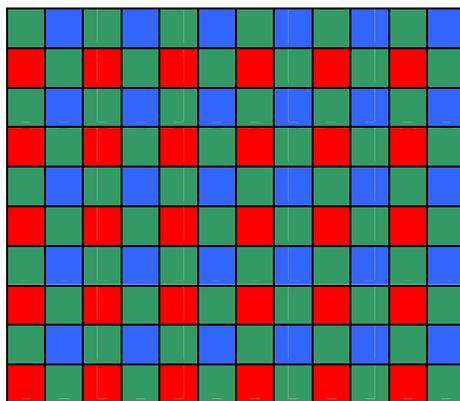
Each pixel on the sensor is actually a capacitor, a device that can store an electric charge. The charge from one pixel is linked to the charge from an adjacent pixel and this chain is passed through the readout register. This sequence of moving charges is the coupling part of the process. Thus, the name of the system is called a charge coupling device (CCD). The process is something like an old-time bucket brigade of fire-fighters passing buckets of water from person to person. The charge from each pixel is sent to the ADC. In a digital camera there is not much “water” (charge) lost in this process since the charge is transferred from pixel to pixel at 99.9% efficiency.

It should be apparent that electrons play a significant role in the operation of a digital camera. Although the electronics involved in a digital camera may not be a topic which you would cover in depth in a chemistry course, it might be worthwhile to trace the path of photons and the resulting energized electrons through a digital camera to reinforce the importance of the chemistry of the camera.

More on How Color Is Produced in a Digital Camera

In the digital camera described in the article the exposure is called “single shot,” which means that the sensor in the camera is exposed to light only once for each picture. (This single CCD system is used in many cameras in order to keep the cost down.) So the photosites (pixels) are exposed to incoming light of varying wavelengths, which should produce an image in color. The problem is that digital camera pixels only respond to the *number* of incoming photons, not their *energy*. So the pixels only “see” in black, white and shades of gray.

To provide color, digital cameras place color filters over each pixel, either red, green or blue (RGB). Each pixel has a single color filter, which means that each pixel is sensitive to one color of light, either red, blue or green. The filters are arranged in what the article describes as a Bayer pattern, sometimes called a mosaic filter. The arrangement is a row of alternating red and green filters then a row of alternating blue and green filters, like this:

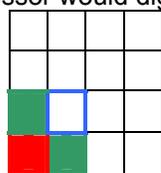


In this array there are twice as many green filters as either red or blue because the human eye is more sensitive to green light than to light of other wave lengths. So, on any surface area of the sensor there are more green pixels than either red or blue. Each pixel in this system is able to recognize and record the intensity of a single color of light, either red, green or blue. In an actual scene recorded by the camera, however, the colors are *not* all either red green or blue. A CCD digital camera is able to obtain colors other than red, green or blue by color mixing, or color interpolation.

Most students will know color by addition from their art class. If red and green are mixed, the result is yellow. Red and blue produce magenta, and green and blue result in cyan. All three produce white. However, if each pixel records only one color, how does the camera determine which colors to mix? The microprocessor in the camera goes through a process called spatial color interpolation. It “looks at” the

color and the intensity of the color in each adjacent pixel and averages the two colors in the appropriate intensity to produce a smoother color gradient in that region of the image.

For example, the pixel in the bottom left corner below has a red filter and has recorded a high electric charge. The pixels above it and to the right with green filters recorded intense green. The blue pixel above it and to the right had no charge and so no color. The microprocessor interpolating color for the bottom left pixel (red), would look at the adjacent pixels and see green. Since red and green produce yellow, the microprocessor would digitize the pixel at lower left as yellow.



This process occurs for all combinations of adjacent pixels. Pixels in the interior of the array interpolate color from each of the eight adjacent pixels. The result is smooth color transitions. Fewer pixels produces more “pixellation” of the image. More pixels produces smoother color transitions.

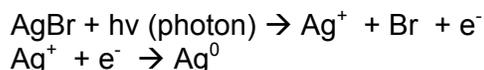
More on CMOS Imaging

Digital cameras that use CMOS (complimentary metal oxide semi-conductor) work in much the same way that CCD cameras do. The difference is in how each pixel captures color. In the CCD camera, each pixel captures either red, green or blue and the other colors are interpolated from them. CMOS cameras employ filters for each of the three primary colors sandwiched on top of each pixel. Thus each pixel captures all colors. In addition, in CMOS cameras the light at each pixel is converted to voltage at that pixel, eliminating the need for more complex circuitry. However, the disadvantage is that transistors are located next to each pixel so some of the incident light strikes the electronics rather than the photosensor. CMOS cameras use much less power than CCD cameras, up to 100 times less. The semiconductor chips in a CMOS camera are manufactured just like most computer chips and so are less expensive. CCD sensor, however, tend to be of higher quality.

More on How Old Fashioned Photography Works

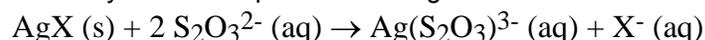
There is much more “wet” chemistry involved in traditional photography than in digital photography. Traditional photographs can be thought of as chemical recordings of images.

When film is exposed to light in a camera, microscopic light-sensitive grains of silver halide salts undergo a photochemical reaction, the most important of which involves the reduction of the silver ion to metallic silver:



Very little metallic silver is produced in this reaction, perhaps just a few atoms per grain of silver halide (the technical term for this bit of silver is a “speck” – believe it or not). This speck is made apparent during development by treating the exposed film with a chemical reducing agent (usually a polyphenol such as hydroquinone, metol, or pyrogallol) under carefully controlled conditions. It turns out that the specks of silver catalyze the reduction of the grains of silver halide, so the tiny amount of silver is amplified tremendously, with exposed grains being reduced entirely to silver metal and unexposed grains not being reduced much or at all. This amplification gives traditional photographic film its exquisite sensitivity, which is still unrivaled by digital photography.

Since phenols are much more powerful reducing agents when they are deprotonated, in basic solution, addition of acetic acid acts as a “stop bath” to halt the development process. Soaking the developed print in a solution of sodium thiosulfate (“hypo”) dissolves the unreacted silver halide grains, because thiosulfate forms a very stable complex ion with Ag^+ :



This leaves behind dark silver metal where the film was exposed to light, and nothing where there was no light, giving the familiar “reversed” black-and-white photographic negative.”

More on Printing Digital Photographs

See “Web Sites for Additional Information” below

Connections to Chemistry Concepts

1. Electrons, energy levels and bonding – This article might be used as a way to illustrate the importance of electrons and energy levels since the behavior of semi-conductors depends on the behavior of electrons. The movement of electrons in semi-conductors is also very much related to the way bonds are formed in the lattice.
2. Uses of elements – The article discusses the importance of several chemical elements that are used in digital cameras. This is an opportunity to remind students that elements have many uses in many parts of their lives.
3. Technology – This article is about a consumer product that is actually a technological device. It is not always clear to students that many devices they use in their lives are actually applications of important chemical concepts.

Possible Student Misconceptions

1. *Where's the chemistry?* Students may not easily understand how an article on digital cameras is connected to chemistry since digital cameras probably seem to students to be electronic devices. It will be important to point out to students that many electronic devices depend upon the application of chemical principles for their operation.

Demonstrations and Lessons

1. Have students examine various kinds of photographs, both digital and traditional, under a microscope or magnifying lens and compare the differences.
2. Students might experiment with the coffee can “laser” printer mentioned in the article.
3. You could borrow color filters from a physics colleague and have students experiment with creating colors using the filters.
4. There are a number of activities that students can do to illustrate electrostatics, which is described in the printing section of the article (rubbed newspaper strips, balloons, etc.)
5. For photography lab activities see <http://wwwchem.csustan.edu/chem2500/labs/sect1.htm>

Suggestions for Student Projects

1. Have students bring in their own digital cameras (or use those belonging to the school, if appropriate) and take pictures, or sponsor a digital photography contest for students.
2. Assign students to research the history of “old-fashioned” photography and the development of digital photography.

Anticipating Student Questions

1. How does the image become a photograph in a digital camera? See “More on How Digital Cameras Work.”
2. How do color cameras produce color? See “More on How Color Is Produced in a Digital Camera”

Websites for Additional Information

For more on how digital cameras work see <http://www.apogeephoto.com/sept2001/digicams092001.shtml> or <http://www.pctechguide.com/19digcam.htm>

For more on the early history of photography see <http://www.rleggat.com/photohistory/>

For more on the chemistry of photography see

<http://www.wellesley.edu/Chemistry/Chem&Art/Topics/Photography/photographys01.pdf>

For More on Human Vision see

http://www.accessexcellence.org/AE/AEC/CC/vision_background.html and be sure to click on the "Activities" link at the bottom of this page.

For a complete description of how color ink jet printer, laser printers and other printers work, see

<http://www.shortcourses.com/how/printers/photoprinters.htm#Color%20Laser%20Printers>

References:

For photography-related *ChemMatters* articles, see:

"Profile: Edwin H. Land," *ChemMatters*, April, 1984.

Real or Fake? The James Ossuary Case

Background Information

More on the Ossuary

In the first century it was common practice among Jews to bury the dead in a burial cave for a year, then transfer the remaining bones to an ossuary. The bones were placed in a stone box and then into the family crypt. Ossuaries were often decorated, usually on one side only, by cutting a design, often a star within a circle, in the box.

The James ossuary came to light in October, 2002, when André Lemaire of Sorbonne University in Paris announced that he had translated the inscription on a 20-inch limestone box, which he believed had held the remains of James, the brother of Jesus. Lemaire had been shown the box by its owner, Oded Golan, a resident of Tel Aviv, Israel. Golan is a collector of antiquities, and he claimed to have purchased the ossuary in 1976. The Israeli Antiquities Authority (IAA) became aware of the potentially historic box only because Golan applied for a permit to send the ossuary to a biblical convention in Canada. Lemaire's translation of the inscription on the ossuary and the resulting article in *Biblical Archaeology Review*, directed attention to the box, and this resulted in still on-going controversy about the authenticity of the box and its inscription. And in January of 2003, a second artifact, a tablet with writing called the Jehoash Inscription, was brought to light.

As the article describes, a panel of experts was named by the IAA to determine if the artifacts were authentic. It concluded in June, 2003, that the box and the tablet were fakes. There were two committees at work, the Writing and Content Committee and the Materials and Patina Committee. The first was charged with analyzing the inscription, and the other committee was asked to determine the authenticity of the box. Assigned to study the physical and chemical properties of the two artifacts were Yuval Goren of Tel-Aviv University, Avner Ayalon of the Geological Survey of Israel, Elisabetta Buaretto, head of the radiocarbon dating laboratory at the Weizmann Institute of Science, Jacques Neguer, head of IAA's stone restoration department, and Orna Cohen, an experienced archaeological restorer. The article describes the work of Goren, Ayalon, Buaretto and Cohen in some detail. Goren and Ayalon found, according to *Archaeology* magazine (June 18,2003):

- "A thin brown veneer of clay and other minerals cemented to the rock surface, presumably rock varnish created by living bacteria or alga over prolonged periods of time.
- A crusty natural coating of patina (this was the "cauliflower") that formed over the rock surface due to the absorption or loss of various elements and minerals.
- The "James Bond": a unique composite material that received this nickname from Goren since it was bonded onto the incised letters of the James Ossuary inscription, but wasn't found at any other place on the ossuary surface—or on any of the authentic ossuaries that the commission members had used as comparative examples."

The thin varnish layer found on the ossuary was likely deposited by bacteria which lived on the limestone surface. The bacteria absorb small amounts of trace metals from the environment and deposit metals compounds, often oxides, in a very thin layer on rock surfaces. The varnish also contains minute clay particles that helped to protect the bacteria.

Goren and Ayalon concluded that although the box and the tablet were authentic first century artifacts, the inscriptions were forgeries, based on the analysis of the patinas on both artifacts. The text of the official letter, as reported in *Archaeology* magazine, June 23, 2005:

"Jerusalem, June 22nd, 2003

Dr. Uzi Dahari
Deputy Director

Antiquity Authority
Jerusalem

Dear Dr. Dahari,

Following the press conference of June 18, 2003 in which the Antiquity Authority announced that the inscriptions known as "James Ossuary" and "Jeoash Tablet" were fake, we wish to clarify the following:

1. The Geological Survey of Israel (GSI) was part of the Scientific Committee established by the Antiquity Authority to determine the authenticity of the two items.
2. The Geological Survey appointed Dr. Avner Ayalon as its representative in the committee.
3. Dr. Ayalon studied the oxygen isotopic composition of the patina covering the letters and surface of the two items, as well as that of authentic ossuaries provided by the Antiquity Authority.
4. The patina covering the letters and surface of the "Jeoash Tablet," as well as the patina in the letters of "James Ossuary," is significantly different from the oxygen isotopic composition on the surface patina of "James Ossuary," and of patina of authentic ossuaries stored in Rockefeller Museum.
5. The carbonate oxygen isotopic composition of "Jeoash Tablet" patina and the "letters patina" of "James Ossuary" reveals that the patina could not have formed under natural climatic conditions (temperature and water composition) that prevailed in the Judea Mountains during the last 2000 years.
6. The above conclusions represents the official and unbiased view of the scientific advisory committee in the GSI that reviewed Dr. Ayalon's work, and as such is the official view of the GSI.

Sincerely yours,
Dr. Amos Bein
Director, Geological Survey of Israel"

In July, 2003, the owner of the James ossuary, Oded Golan, was arrested on forgery charges along with dealing in fake antiquities. In early 2005, Golan and four others were indicted on charges of forgery. Israeli authorities claim the ring had been operating for more than 20 years and had produced other forgeries. The trial, originally schedule for May, 2005, was postponed first until September and then to November. No additional updates were available at press time. The indictment against Golan and the other four can be read here: http://www.bib-arch.org/bswbOOossuary_indictment.pdf

More on the Israel Antiquities Authority Committee

Dr. Elizabetta Boaretto - She is associate staff scientist at the Weizmann Institute and the director of the Institute's radiocarbon dating lab. She is a nuclear physicist. Her report can be read here:

http://www.bibleinterp.com/articles/Boaretto_report.htm

Professor Yuval Goren at Tel-Aviv University - He is an associate professor in archaeology at Tel Aviv University. Areas of expertise include ancient technologies and micromorphology studies. His report:

http://www.bibleinterp.com/articles/Goren_report.htm

Dr. Avner Ayalon is a member of the department of Archaeology and Ancient Near Eastern Cultures at Tel-Aviv University and the committee representative from the Geological Survey of Israel. He is a geologist who is an expert on identification of materials through the study of isotopes in rock

Ms. Orna Cohen is an expert conservator of antiquities, especially on the identification and preservation of ancient patinas. Her conclusions can be read here: <http://www.biblicalarchaeology.org/Cohen.pdf>

Dr. Uzi Dahri is the Deputy Director of the Israel Antiquities Authority. He was the committee chairperson.

Dr. James Harrell, professor of Archaeological Geology at the University of Toledo in Ohio. He disputes the official findings of the AAI committee.

Andre Lemaire, an archaeologist and paleographer from the University of Sorbonne in France

More on Tests Performed on the Ossuary

1. Chemical Analysis

Chalk from the ossuary:

CaCO₃ - 97%
silicon - 1.5%
aluminum - 0.7%
iron - 0.4%
lead - 0.3%
magnesium - 0.2%

Patina from the ossuary:

CaCO₃ - 93%
silicon - 5%
aluminum - 2.5%
iron - 0.3%
lead - 0.4%
magnesium - 0.2%

2. Hardness

There are several ways in which hardness is measured. The most common method is the scratch test using the Mohs scale of hardness. The hardness of minerals is determined by which other minerals are able to scratch the sample. Students may be familiar with the Mohs scale from an earth science course:

Hardness	Mineral
1	talc
2	gypsum
3	calcite
4	fluorite
5	apatite
6	orthoclase
7	quartz
8	topaz
9	corundum
10	diamond

Another method is rebound hardness, which is measured by observing the height to which a weight dropped on the material under test rebounds. A third method is called penetration hardness. In this method a standard tool is used to make an indentation in the sample using a standard force. The Rockwell hardness test is an indentation test.

On archaeological materials, such as the ossuary, microhardness tests are used. Microhardness testing is similar to indentation testing but using much smaller forces. The test specimens are observed under a metallurgical microscope. A microhardness tester can be used to measure the hardness of individual constituents in the microstructure of a material.

3. Density

The density (or specific gravity) of minerals is another property used to identify them. Geologists use a beam balance or jolly balance to measure gross densities (and specific gravities). A jolly balance compares the weight of the mineral sample in air to its weight in water. The sample is attached to a spring scale whose stretch is used as a measure of the sample's weight. The specific gravity is calculated using the equation

$$\text{Specific gravity} = \frac{\text{weight in air}}{\text{weight in air} - \text{weight in water}}$$

A pycnometer is a small container of known volume whose mass is measured when filled with water. The water is replaced with the mineral in question, the mineral is added and the mass again determined. From these masses of equal volumes the specific gravity of the mineral is calculated.

Liquids with greater densities can be used to measure the density (or specific gravity) of a mineral. In this method the mineral is added to a dense liquid. If the mineral floats, its density is less than the density of the liquid. By employing a series of liquids of varying densities, the density of a mineral sample can be determined. The liquids that are used are often bromoform (CHBr₃, SG = 2.88), methylene iodide

(CH₂I₂, SG = 3.33), and monobromonaphthalene (SG =1.49). By combining these or diluting them, liquids of known densities can be prepared. Each of these must be used in a fume hood.

4. Mass Spectroscopy

Mass spectroscopy is the method used in ¹⁶O, ¹⁸O and the ¹³C analysis. The mass spectrometer is useful in determining the relative abundance of elemental isotopes, which is what these studies are about. In the case of the oxygen analysis, the CaCO₃ making up the ossuary is converted chemically to CO₂ (as described in the article) and the oxygen in the CO₂ is analyzed. The carbon is analyzed in a similar manner.

In a mass spectrometer neutral atoms (or molecules) are first ionized and then accelerated through a magnetic field. As the ions pass through the magnetic field, they are deflected from a normal path based on their mass and their charge. Heavier ions are deflected less than lighter ions. Ions with greater charge are deflected more than ions with lower charge. These two factors, mass and charge, are combined into one factor that is characteristic of each ion. The factor is often given as m/z or mass to charge ratio. Since most ions passing through the mass spectrometer have a charge of +1. The m/z is a measure of the relative masses of the ions. The mass spectrograph of an element shows the relative abundance of each isotope of that element. To see an example mass spectrograph for the element molybdenum, along with a complete explanation of how a mass spectrometer works, see <http://www.chemguide.co.uk/analysis/masspec/howitworks.html>

The article describes the analysis of the ossuary box by Dr. Avner Ayalon, using mass spectrometric methods for the isotopes of oxygen. To see a dissenting view of these findings see this analysis by Dr. James Harrell, professor of geology at the University of Toledo in Ohio and a member of the Association for the Study of Marble and Other Stones in Antiquity: http://www.bib-arch.org/bswbOOossuary_flawed.asp

5. Carbon-14 Dating

Many elements exist in isotopic forms. Isotopes are atoms of the same element, but with different masses. Since all atoms of a given element have the same number of protons, isotopes differ in the number of neutrons contained in the nucleus. The element carbon has three possible isotopes, carbon-12, carbon-13 and carbon-14. By far, most atoms of carbon are carbon -12 (98.9 %). About 1 % are carbon-13 atoms, but the percent of carbon-14 atoms is very small, about 0.00000000010%. Carbon-12 and carbon-13 are stable. That is, they do not undergo radioactive decay. Carbon-14, however, does decay, and its half-life is 5730 years

Carbon-14 forms in nature as a result of collisions between cosmic rays and atmospheric atoms. In the collision a neutron is emitted, and if this neutron collides with an atom of nitrogen-14 the nitrogen captures the neutron and emits a proton. This change in the number of protons results in an atom of carbon being formed with a mass of 14 amu—carbon-14. These carbon-14 atoms react chemically in the same way that carbon-12 atoms react to form organic matter, and so become part of living systems. Carbon-14 atoms decay to reform nitrogen-14, but are replaced with other carbon-14 atoms. Thus in nature the percent of carbon-14 atoms in living systems remains rather constant, as long as the system remains alive. Once the plant or animal dies, it stops taking in new carbon-14 atoms, and the carbon-14 decay “clock” begins as carbon-14 atoms undergo beta decay. After 5760 years, half of the carbon-14 atoms in the system have decayed, and so on.

A formula to calculate how old a sample is by carbon-14 dating is:

$$t = [\ln (N_t/N_o) / (-0.693)] \times t_{1/2}$$

where ln is the natural logarithm, N_t/N_o is the percent of carbon-14 in the sample compared to the amount in living tissue, and t_{1/2} is the half-life of carbon-14 (5,700 years).

More on the Ossuary and Tablet Composition

1. Greywacke

Graywacke is a relatively hard type of sandstone, which has quartz, calcite and feldspar as its major components.

2. Arkose

Arkose is also a type of sandstone, often rich in feldspar and calcite.

3. Limestone

Limestone is a type of sedimentary rock made up primarily of the mineral calcite, CaCO_3 . It often contains silica. It varies in color due primarily to the presences of iron oxides.

Connections to Chemistry Concepts

- 1. Chemistry in Other Disciplines** - This article provides an excellent example of the role of chemistry in other disciplines, such as archaeology. The article describes chemical methods that were used to study the ossuary and tablet. Three sources that give more information about chemistry in archaeology are:
 - a. *Traces of the Past* review here: http://www.perseusbooksgroup.com/basic/book_detail.jsp?isbn=0738200271
 - b. *Archaeological Chemistry* review here <http://www.chemsoc.org/networks/learnnet/Archae-book.htm>
 - c. *Accounts of Chemical Research: Archaeological Chemistry* (ACS, 2002, Vol. 35, Issue 8) <http://pubs.acs.org/journals/achre4/special/02/archaeological.html>You may want to use the article as a way to motivate students to become more interested in a career in chemistry or, at least, as a way to let students know about how chemistry plays an important role in their lives.
- 2. Nuclear Reactions** - The dating method described in the article involves nuclear reactions and, therefore, the concept of half life. If you have covered this topic in your course prior to having students read this article, you still may want to review the idea of half life so that students understand how the radiocarbon dating method works. Similarly, the mass spectrometer analysis involves isotopes of elements. You may wish to review isotopes before assigning the article to students. See "Websites for Additional Information" (below)
- 3. Use of Technology** – Chemistry is increasingly dependent on instrumentation, especially for analytical methods. You may not have time or reason to include much on chemical instrumentation in your course, but this article describes results obtained by using the mass spectrometer. You may wish to include a brief explanation of the mass spec as students read this article. See "Websites for Additional Information" (below)
- 4. Geochemical Reactions** -The article can be used to teach students that matter is naturally recycled throughout the environment. You could use the CO_2 example, the carbon example, or the fluorine example. Students often think of recycling as a process that can be used by people to conserve resources, but matter is recycled naturally by means of chemical and physical changes in nature. Chemists understand many of the mechanisms by which matter is naturally recycled over long periods of time, and this understanding allows chemists, like the ones in the article, to use modern methods of analysis to create the history of an archaeological artifact.
- 5. Chemistry and controversy** – It is apparent from the article that chemists (and other types of scientists) do not always agree on the interpretation of experiments. This is not often a topic of discussion in chemistry classes. Students read and see in the media examples of controversies in science. Stem cells and global warming are recent examples. In the case of the James ossuary, the controversy is about the interpretation of a rather narrow set of analytical findings related to the authenticity of the ossuary (as opposed to controversial "big issues" that have non-science overtones). Students might be surprised to find that well-credentialed scientists can disagree about the results of even quantitative research. See "Websites for Additional Information" (below)

Possible Student Misconceptions

- 1. Controversy** – Many students have the idea that chemists (and scientists in general) engage in routine procedures that lead to indisputable results that other chemists are bound to agree on. This article is one example of the way in which the meaning of observations and data are discussed and

disputed in the scientific community. Students might be interested in this aspect of science since it sometimes also leads to scientists testifying in legal matters. You can also make a connection to the forensic applications of chemistry. For another article on the Shroud of Turin, another controversial topic in archaeology, see "Shrouded in Mystery," *ChemMatters*, February, 1989.

2. **Careers in chemistry** – many general chemistry students may have the impression that chemists work only in corporate research labs or in a university setting. Today chemistry is an integral part of many other disciplines, including archaeology. This article gives you an opportunity to make your students aware of the many areas of modern life in which chemistry and chemists play a significant role. In addition, many students have little or no idea of what chemists do. For additional resources on careers in chemistry see two ACS sites, either <http://www.chemistry.org/portal/a/c/s/1/acdisplay.html?DOC=vc2%5C3wk%5Cwk3.html> or <http://www.chemistry.org/portal/a/c/s/1/acdisplay.html?DOC=education%5Cstudent%5Cugcars.html> or AAAS's site http://sciencecareers.sciencemag.org/career_development/looking_for_next_wave
3. **Radiocarbon dating** - Many general chemistry students do not understand the concept of half life, and so cannot understand how it can be used to find the age of an ancient artifact. See "Websites for Additional Information" (below)

Demonstrations and Lessons

1 You might consider setting up lab activities that allow students to perform tests on minerals and identify them. See http://www.minsocam.org/MSA/collectors_corner/id/mineral_id_key1.htm#TOC for specific procedures.

2. A variation on the activity suggested in #1 above is to have students study limestone in the lab. For background and ideas see <http://www.nationalstonecentre.org.uk/euas/appendices/chemlimestone.htm> or <http://www.chemsoc.org/networks/learnnet/jesei/chemlim/home.htm>

Suggestions for Student Projects

1. Since there are a great many articles in print (and on the web) about the James ossuary case, you might divide the class into teams and assign each team to become experts on the findings of the various groups and individuals involved in the case and present their "findings" in a mock court session.
2. As part of #1 above, assign students (or groups) to become technical experts in the scientific methods used to study the ossuary and tablet, such as radiocarbon dating and mass spectrometry, and report on these methods in class.
3. Students can research other ways in which chemistry is used in archaeology. See web sites below for further information.

Websites for additional Information

Articles from *Archaeology* (a publication of the Archaeology Institute of America) tracing the controversy can be read here: <http://www.archaeology.org/ossuary/>

The reports of the committee members that studied the ossuary can be found here: http://www.bib-arch.org/bswbOOssuary_06reports.asp

The actual committee report can be viewed here:

http://www.antiquities.org.il/article_item_eng.asp?module_id=&sec_id=17&subj_id=175&id=266 and here: http://www.bibleinterp.com/articles/Final_committees_reports.htm

A link to an American Chemical Society publication *Accounts of Chemical Research: Archaeological Chemistry* (2002, Vol. 35, Issue 8) can be found here

<http://pubs.acs.org/journals/achre4/special/02/archaeological.html>

<http://www.tfba.org/news.php?newsid=16> GOOD CHEMISTRY
http://www.perseusbooksgroup.com/basic/book_detail.jsp?isbn=0738200271 "Traces of the Past"
<http://www.chemsoc.org/networks/learnnet/Archae-book.htm> "Chemical Archaeology"

For a more detailed explanation of mass spectroscopy see

<http://www.chemguide.co.uk/analysis/masspec/howitworks.html>

For more on radiocarbon dating see [http://www.ndt-](http://www.ndt-ed.org/EducationResources/CommunityCollege/Radiography/Physics/carbondating.htm)

[ed.org/EducationResources/CommunityCollege/Radiography/Physics/carbondating.htm](http://www.ndt-ed.org/EducationResources/CommunityCollege/Radiography/Physics/carbondating.htm)

For an interactive radiocarbon dating calculator see <http://www.101science.com/Carbon14.htm>

References

For other *ChemMatters* articles on archaeology, see:

"Lindow Man—Murders in a Bog," *ChemMatters*, February, 1998.

"Soil Chemistry: Sifting Through the Past," *ChemMatters*, April, 2001.

"King Midas: Leftovers from His Last Feast," *ChemMatters*, December, 2001.

Super Fibers

Background Information

The term “nano” means “billionth”, and nanometer specifically refers to a billionth of a meter. Atom sizes are in the nanometer range, but scientists have not, historically, been able to deal with individual atoms or molecules on that scale. It is only with the advent of instruments such as the scanning tunneling microscope (STM) that we have been able to see such small particles, much less manipulate them. Nanomaterials are generally defined as having a diameter less than 0.1 micron (0.1 μ), 1 ten-millionth of a meter (1 hundred-thousandth of a centimeter). The term nanomaterial derives from any substances that can be measured at the nanometer level, although this does not mean they are only one (or less) nanometer in size. Typical early nanomaterials were on the 100+ nm scale. Many nanomaterials that have established applications today are also on this scale. They have specialized characteristics at these small sizes, but materials down at the 1-20 nm show especially useful properties, such as high electrical conductivity, high heat conductivity, and tensile strength 10-100 times that of steel at one-sixth the weight, etc.

To give students an idea of the sizes under discussion, use the following table.

Object	Approximate Size	Size in nm
Person	1 m	1 x 10 ⁹
Sand grain	1 mm	1 x 10 ⁶
Human hair (diam.)	100 μ m	1 x 10 ⁵
Red blood cell	10 μ m	1 x 10 ⁴
Wavelength of visible light	10 ³ nm	10 ³
Virus	100 nm	100
Atom	0.1 nm	0.1

Information taken from <http://www.physicscentral.com/action/action-00-1.html>

As mentioned in the article, the first report of carbon nanotube formation is attributed to Sumio Iijima, working at NEC, in 1991. Carbon nanotubes are essentially sheets of graphite rolled up into tubes. These tubes are several nanometers in diameter and about a millimeter in length. They can exist as single-walled nanotubes (SWNT's), or multi-walled nanotubes (MWNT's).

Because nanoscale materials are so small, their fabrication is very difficult. Scientists have come to rely on the process of self-assembly, whereby the nanoparticles are formed by the build-up of individual layers of atoms, layer by layer. Chemists are using DNA as the backbone for self-replication processes to design circuits at the nanoscale level.

Carbon/graphite nanotubes are not the only type of nanotubes that scientists can manufacture.

Polymeric nanotubes have been used as the basis for very fine particulate air filters for more than 20 years. The polymeric nanotubes are formed by a process called electrospinning. Very fine webs are created using the electrospin process, and these webs are the basis of the filter. This application uses the nanotubes in a non-woven capacity, as opposed to the reference in the article to nanofibers being woven directly into other fibers in the soldier's clothing.

Another use for carbon nanotubes/nanofibers is in the adsorption of gases, especially hydrogen.

Graphite nanotubes have been shown to adsorb up to 40 weight % of hydrogen. The significance of this is in storage of hydrogen to be used as a fuel in hydrogen-powered automobiles, for example. Carbon-based adsorbents, known generally as activated charcoal, have been known and used for a long time, but

these all require extremely low temperatures to maintain the gas adsorption (little molecular motion, hence reduced gas volume). Nanotube adsorption occurs efficiently at room or slightly reduced temperature. Adsorption in nanotubes seems to be a result of hydrogen getting between the layers of carbon atoms, and actually expanding the layers slightly, thus trapping the hydrogen within the nanotube structure.

More about History

Since they have been discovered so recently, the history of nanotubes is relatively scarce and certainly recent. A brief history of nanotechnology can be gleaned from a few selected articles found in the scientific journals and magazines in recent years:

November, 2000, Scientific American...

"The Tiniest Carbon Nanotubes"

Researchers in Japan and Hong Kong produced carbon nanotubes only 0.4 nm thick, the theoretical limit of "smallness". Very little mention of any applications is made at this time.

December, 2000, Scientific American...

"Nanotubes for Electronics"

Ten years after the discovery of nanotubes by Sumio Iijima at NEC, they have found uses in several electronics applications. Chemists have added carbon nanotubes to plastics in the automotive industry. These plastics can be charged electrically to help car paint stick electrostatically to the plastic. (These nanotube additives were later mentioned to be on the order of 200 nm, far larger than today's true nanoparticles.)

September, 2001, Scientific American

"Little Big Science"

This article reports on what nanoscience is, where carbon nanotubes fit in to nanoscience, and the dreams and the realities of the effects of nanotubes on mankind. Little progress is reported on applications of nanotubes to society – yet.

April 1, 2003, Scientific American Channels: Technology

"Researchers Put Rogue Proteins to Work Assembling Nanowires"

Researchers have used prions (mis-folded proteins responsible for Mad Cow disease, among others) to produce nanoscale wires. The proteins self-assemble fibers on the nanoscale. These fibers are strong and heat-resistant, but they do not conduct electricity. Gold or silver atoms are attached along the filament to make it conductive. These are 80-200 nm in diameter, still large by nanoparticle scale.

September 15, 2003, Scientific American

"Carbon Nanotubes for Solar Cells"

Researchers have teamed carbon nanotubes with ferrocene molecules to produce a substance that moves electrons when stimulated by visible light. These electrons can be harnessed to do work.

January 6, 2004, American Channels: Technology

"Scientists Turn DNA Tubes into Nanowires"

Scientists are using DNA replicating units to produce wires 25 nm in diameter and 20 microns long. Since DNA chemistry is widely understood, scientists expect that these nanowires can be positioned very precisely in larger electronic chips with little external manipulation.

March 15, 2004, Scientific American Channels: Technology

"Lengthy Nanotube Fibers Could Trump Traditional Textiles"

Scientists have pulled long strands of nanotube fibers from a furnace by winding them around another rod-like fiber. This direct-spinning process has resulted in fibers that are much longer than any other process has yet produced. Unfortunately, these fibers have shown no improved qualities over other fibers. Scientists are hopeful that "tweaking" the production process may result in improved qualities of the fibers.

October 12, 2004, Scientific American Channels: Technology

"Nanoparticles Enable Speedy *E. coli* Detection" (reported in *Proceedings of the National Academy of Sciences*, this week)

E. coli is a source of food-borne illness. Early detection of its existence in food products is key to preventing further outbreaks. Old detection methods required lengthy testing and

amplifying of results. Silicon nanoparticles carrying fluorescent molecules on their surface have been used to detect single E. coli bacteria in a food sample without further amplification within minutes of the test. Scientists predict that this process can be used for many pathogens, and may be used to detect any terroristic attempts at mass-poisonings at a very early stage.

[As a follow-up to this article, a new start-up company has recently announced its soon-to-be available water-test kit. The article describing this, "WATER TEST KIT MOVING CLOSER TO MARKET", was published in *The Chicago Tribune*, December 12, 2005 issue. Here's the site: http://www.smalltimes.com/document_display.cfm?section_id=21&document_id=10508

July 26, 2005, Scientific American Channels: Technology
"Nanoparticles Pass Muster as Vectors for Gene Therapy"

Silicon nanoparticles have been used to replace viral vectors in marking neurons in brain cells in mice. The surface of these nanoparticles can be tailored to target specific cells.

August 2, 2005, Scientific American Channels: Technology
"Nanotube-Laser Combo Selectively Targets Cancer Cells, Study Shows"

Carbon nanotubes, when exposed to near-infrared light, quickly emit excess energy as heat. Researchers have shown this process to be viable in killing cancerous cells in a suspension, while not harming normal cells. They hope to use this phenomenon to kill cancerous cells in the body.

August 25, 2005, Scientific American Channels: Technology...
"Branching Is Key to Carbon Nanotube Transistors"

Conventional transistors have been made progressively smaller over the years, now reaching about 100 nm across. Reduced transistor size has resulted in increased speed in various electronics applications. Researchers hope to use carbon nanotubes to reduce this size to just a few nm, thereby increasing electronic speeds even more.

November 10, 2005, Nature magazine...

"Graphite Found to Exhibit Surprising Quantum Effects"

Single atom layers of graphite were found to have electrons on their surface that did not slow down with reduced temperature, implying that these electrons would still be moving, even at absolute zero. This research also showed that these electrons travel much faster than electrons in other semiconductors.

As we move from 2000 to 2005, applications cited in the above articles seem to deal with smaller nanoparticle sizes.

The late Dr. Richard Feynman, the brilliant Nobel Laureate physicist, was one of the first people to recognize the importance of nanoscale materials. In his 1959 lecture, "There's Plenty of Room at the Top", he stated that the properties of materials at the nanometer scale would present great opportunities for the future. He stated that, "...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." For a complete copy of Feynman's speech, go to <http://www.its.caltech.edu/~feynman/plenty.html>, or <http://www.zyvex.com/nanotech/feynman.html>.

Almost 30 years later (in 1986), Eric Drexler wrote a book called, "Engines of Creation: The Coming Era of Nanotechnology", which caused greater public awareness – and perhaps fear – of the new technology. This book is accessible on the web at <http://www.foresight.org/EOC/Engines.pdf>.

In 1985, C₆₀ molecules, buckminsterfullerenes (fullerenes or buckyballs) were discovered by Harold Kroto, James Heath, Sean O'Brien, Robert Curl, and Richard Smalley. These were the first carbon polyatomic molecules discovered. It was recognized that these were essentially graphite molecules wrapped into 3-dimensional shapes. Nanotubes were the next variety of these distorted graphite sheets, discovered by Iijima in 1991.

Richard Smalley's personal papers are now part of the Chemical Heritage Foundation's collection. They are not yet completely catalogued, but they will be in the near future. When they are catalogued, they will be available online at www.chemheritage.org.

The U.S. federal government got in on the nanotechnology revolution in 2001 when it initiated the National Nanotechnology Initiative, a directive that seeks to further nanotechnology research, while keeping an eye on the implications for ethics, health and the environment. You can access the site at <http://www.nano.gov/index.html>

For a timeline of some of the important discoveries in nanoscience, see the following web sites:

<http://www.nanoscience.com/education/chronology.html>, a chronology of scanning probe microscopy, responsible for being able to see materials at the nanoscale, <http://www.msc-nanoscience.tudelft.nl/nanotimeline.html> provides a brief timeline that stops at 2001. <http://www.pa.msu.edu/cmp/csc/nanotube.html> is a 10-year timeline of nanotube discovery, from 1991-2001.

For a succinct history of technology (not in timeline form), visit http://www.nanotech-now.com/Press_Kit/nanotechnology-history.htm

More about Nanotechnology Terms – Glossaries

For a glossary of nanotechnology terms, check the following web sites:

<http://www.nanotech-now.com/nanotechnology-glossary-N.htm> from Nanotechnology Now: Your Gateway to Everything Nanotech

<http://www.crnano.org/crnnglossary.htm> from the Center for Responsible Nanotechnology

http://nano.cancer.gov/resource_center/nanotech_glossary.asp is a site from the National Cancer Institute. The word list is very limited, but from this list you can get an idea of where nanotechnology has affected the medical field, especially in cancer research.

More Information about Nanotechnology Applications

Nanotechnology is responsible for the constant progression of computer electronics, from room-size computers to PDA's.

Nanotechnology is applied in a practical way in stain-repelling fabrics. An example is Eddie Bauer's stain-resistant Nano Care™ khakis. They employ small whisker-like particles to coat the surface fibers of the fabric, which creates a stain-repelling surface. (Other companies have used the same techniques and similar materials.)

Health care firms are marketing antimicrobial bandages that are coated with silver nanocrystals. Silver nanoparticles are also being used to coat appliances to act as antifungal and antimicrobial agents.

Nanocomposites are also being used in the automobile industry to add strength with reduced weight to various car parts. Bumpers made of these materials are 60% stronger, yet more resistant to scratches and dents.

Nanoscale zinc oxide particles are being used as sunscreen. The old version of zinc oxide was a thick white paste. Nanoparticles are actually so small that they're invisible to the naked eye, and so the sunscreen appears transparent. A 2-minute video showing how this nanotechnology works is at <http://www.csiro.au/files/files/ppf8.wmv>.

(Much of the above information was taken from the American Elements web site, at <http://www.americanelements.com/nanotech.htm>.) This company manufactures nanotechnology materials.

Metal Rubber™ is a patented material made by NanoSonic. It is essentially an elastomer (polymer) that can carry an electric current. Potential uses include artificial stents, airplane wings, and muscles for robots. Read more about it at

http://www.sciencentral.com/articles/view.php3?type=article&article_id=218392354.

Nanotechnology will soon find its way to manufacture of golf clubs. The use of nanomaterials to coat the shaft of the club would result in a lighter weight club that would result in greater head speed, sending the ball greater distances. Coating the head with nanomaterials could have an even greater effect.

According to USA Today, <http://www.keepmedia.com/pubs/USATODAY/2005/08/17/970389>, a pound of nanotubes could cost as much as \$700,000, so their price is still too high to be practical for current use, but as soon as the price comes down, we can expect to see their use in this field, as well as other sports areas.

Cornell University, the same organization that created the guitar above, has a large nanotechnology department. For an extensive list of their nanotech accomplishments in each of the last 5 years, visit http://www.cnf.cornell.edu/cnf5_research.html. The list for each year includes applications in the areas of biology, chemistry, electronics, materials, mechanical devices, optics and opto-electronics, and physics and nanostructure physics.

Connections to Chemistry Concepts

1. Bonding within elements – sp^2 bonding orbitals and delocalized electrons in graphite, buckyballs and carbon nanotubes
2. Allotropes of elements – graphite, Buckyballs, nanotubes, and graphene
3. Surface phenomena – adsorption happens on both inside and outside surfaces in open nanotubes
4. Catalysis – most catalysis processes are actually “old” nanotechnology.
5. Quantum mechanics – nanoscale materials display quantum mechanical properties unlike those of “normal” (macroscopic) materials
6. Periodicity – carbon forms nanotubes, so do boron (one electron less than carbon) and nitrogen (one electron more than carbon) together. Similar hybridization exists in carbon and in boron-nitrogen nanoparticles.
7. Science as an ongoing process – students can see through this article that discovery is ongoing – science is not just facts they read in a textbook, but a process that builds on past understanding and technology.

Possible Student Misconceptions

1. Nanotubes are only 1 nm in diameter (long, wide, etc.) Actually the term nanomaterial refers to anything that can be measured on the nanometer scale. Usually it is recognized to mean anything less than 1 micron (1000 nm) in size. Thus nanomaterials can be anything from 1 (or less) nm – the size of 10 hydrogen atoms laid end to end – to 100's of nm. The only limitation is that they be less than 100 nm in one dimension.
2. Carbon is the only element that forms nanotubes. Many elements and compounds form nanostructures. Carbon is a focus because it forms nanotubes relatively easily, because it was known to form fullerenes (Buckyballs) that have special properties, and it is a very abundant element so its nanostructures might be less expensive than those of other, less abundant elements.
3. Applications for nanotubes are still far in the future. Actually, scientists have found many uses for nanotubes already. See “More Information on Applications”, above. The more futuristic uses mentioned in the article may be a little further in the future, however. Most scientists working in the field believe that “the best is yet to come.”
4. We know all there is to know. Science is ongoing and ever-growing. And as we continue to seek understanding, “...our search for knowledge must be unending by its very nature, since as we expand the island of knowledge, the perimeter of our ignorance increases in direct proportion.” – Nick Herbert

Demonstrations and Lessons

1. You could use larger dimensions to represent small sizes of things on a relative scale. See <http://www.microbeworld.org/mlc/gifs/activities/pgs44-47.pdf> for an idea of such a lesson activity. It sets the width of a human hair as 100 m (yes, that's meters – as in a gymnasium or outdoors in a parking lot or on a sidewalk), and scales everything else relative to that. It uses microbes as its main focus, but you could throw in nano-size particles to the mix. This site also gives ideas for ways to adapt the activity for special needs students.
2. Although high school students may not have any means to see atoms and molecules directly, they can still do an experiment to calculate the size of a molecule. This is an old lab experiment that originally (I believe) came from the Physical Science Study Committee (PSSC) Physics curriculum from the '60's. Several sites are listed below with a description of the lab activity.
<http://www.chemheritage.org/EducationalServices/pharm/antibiot/activity/size.htm> This site has both a student version and a teacher's version. It is part of a larger picture dealing with antibiotics and the history of these substances, but the experiment can be used out of context.
<http://www.scienceteacherprogram.org/chemistry/Flomberg00.html> This site apparently does not have a teacher version.

Suggestions for Student Projects:

1. Students could research the history of nanoparticles and prepare a report on same.
2. Interested students might pursue a lab whereby materials of several different known particle sizes are mixed with water and suspended therein. Then the time for them to settle could be measured and plotted against particle size. They could then extrapolate to predict how long nanoparticles would take to settle out.
3. Have students research quantum dots and their relationship to nanotechnology, as well as their applications to the real world. The science gets technical rather quickly, so students may need help.
4. Have students research the atomic force microscope and report their findings. You might suggest they start here: <http://www.nanoscience.com/education/AFM.html>
This site provides a download of a simulated atomic force microscope that would help students report how an AFM works: <http://www.nanoscience.com/education/software.html>
5. You might want to give students the opportunity to debate nanotechnology as the promise of a great future or the “gray goo” (Drexler’s reference to self-replicating nanobots that could destroy life as we know it).

Anticipating Student Questions

1. What gives nanomaterials their special properties? Nanotubes in particular, have a very large surface area (inside and outside the hollow tube) for their size and weight, resulting in their having an extremely low density. The entire surface is a potential reaction site, or at least adsorption site. The surface also has all the delocalized electrons available for reaction.
2. Why are the properties of nanomaterials so different from “normal” size materials made of the same substances? When we get to the atomic level, quantum mechanical properties take over. Electrons can travel faster at these levels, and indeed, seem never to stop. Other quantum mechanical effects are also evident.
3. Are nanotubes just graphite sheets that have been rolled up? Although many newspaper and magazine reports make reference to the fact that nanotubes appear to be just like graphite sheets rolled up, and it is easy to visualize them that way, they are not formed that way. The tubes form themselves at high temperatures.

Websites for Additional Information

Cornell University offers a course in nanotechnology to students. Videos of the lectures from this course are available online at http://www.cnf.cornell.edu/cnf5_courses.html. They may be a little too deep for high school students, but the first one is an introduction to nanotechnology, and the lecturer gives a little history, as well as a few applications of nanotechnology as he begins to discuss quantum mechanical effects at the nanometer level.

Once you have registered and logged into nanohub.org, you or your students can get a series of lectures on nanotechnology, called Nanotechnology 101, at https://www.nanohub.org/index.php?option=com_resources&id=179. This is a series of excerpts from lectures in a course at Northwestern University. This series gives you the audio and PowerPoint slides (or their equivalent) to accompany the lecture.

Images of Nanotechnology

The University of Bristol’s web site gives a good overview of three different carbon nanotubes at http://www.chemsoc.org/exemplarchem/entries/2003/bristol_shanley/carbonallotropes/nanotubes.htm. Other tabs on this site show you the other allotropic forms of carbon.

From October of 2003 to August of 2004, <http://www.nanopicoftheday.org/index.htm> offered a picture each day of a different aspect of nanotechnology. Most are microscope pictures of nanomaterials. You can still access their index of pictures. It is an extensive list.

Scanning Probe Microscope animated images can be found at NanoScience Instruments' Education site, <http://www.nanoscience.com/education/gallery.html>

The Institute of Nanotechnology (IoN) web site offers images of nanoscale materials at:

<http://www.nano.org.uk/images.htm>

This site gives you a choice of scientist/photographers: <http://www.nanotech-now.com/nanotechnology-art-gallery.htm>. Several of the artists have some futuristic views of nanobots and nanotechnology applications, while several have actual scanning force microscope images of nanomaterials.

Vega Science Trust web site contains a large series of video recordings of various famous scientists. A video recording of a television show from Britain that involves a panel discussion on "The Next Big Thing", nanotechnology, is available at <http://www.vega.org.uk/video/programme/3>. This video features Sir Harry Kroto, one of the co-discoverers of buckyballs. The video is worth watching – it gives some background on buckyballs and on nanotubes, and Dr. Kroto's own insights are inspiring. He also shows models of both buckyballs and a single-walled carbon nanotube. The background monitors behind the panel members continually show scanning force microscope images of nanomaterials.

Other Nanotechnology Sites

The American Chemical Society's *Chemical and Engineering News* ran a special edition on nanotechnology in 2003. That issue, and other articles from C & E News focusing on nanotechnology can be accessed at <http://pubs.acs.org/cen/nanotechnology/nanoarchive.html>. Some of the articles on this site may require that you belong to ACS and that you log in with your membership ID.

Another C & E News site, that focuses on business applications of nanotechnology, <http://pubs.acs.org/cen/nanotechnology/7842/7842business.html>, has, at the bottom of the screen (scrolled down), a list of more than 30 businesses that are presently working in the nanotechnology area. Many of them have clickable web sites on this list, in case you or your students want to follow up for more information.

Nanohub offers a wide variety of simulations of nanotechnology at <http://www.nanohub.org/>. Registration is required, but free.

http://science.nasa.gov/headlines/y2005/27jul_nanotech.htm provides an introduction to NASA's interest in nanotechnology, including the "space elevator".

<http://www.google.com/search?hl=en&q=nanotechnology+high+school+experiments&btnG=Google+Search>

If you want to know more about nanotubes, this site, <http://www.pa.msu.edu/cmp/csc/nanotube.html>, has a long list of links to other sites, especially university research sites. The site is several years old, so there's no guarantee that all the links are active, but it's still an impressive list.

<http://www.cns.cornell.edu/TechnologyAndSociety.html#Introduction> is another site that has an extensive list of links to other sites dealing with nanotechnology.

This site, the National Nanotechnology Infrastructure Network (NNIN) is a site sponsored by the National Science Foundation and the NNI. It is relatively new, and promises to offer curriculum materials to get nanotechnology into classrooms. Right now there is nothing there, but the promise...stay tuned.

http://www.nnin.org/nnin_k12teachers.html (It does have some other nano information.)

There's a site at <http://mrsec.wisc.edu/Edetc/LEGO/bookindex.html> that comes from the University of Wisconsin-Madison that shows how Lego models can be used to simulate nanotechnology materials and instrumentation geared for the middle/high school levels. There's a 62-page book written about these applications, and it was sponsored by the NSF.

This slide show from the University of Wisconsin-Madison has a nice assortment of the applications of nanotechnology, as well as the instrumentation devised to manipulate the nanoparticles. It also one slide that shows models of all the allotropes of carbon, and you can manipulate them on the screen. Access it at <http://mrsec.wisc.edu/Edetc/SlideShow/index.html>.

Salting Roads: The Solution for Winter Driving

Background Information

More on Salting Roads

In 2004, more than 16 million tons of salt was used to treat winter highways at a cost of nearly \$389 million. Compare that to the 164,000 tons used in 1940, when salt first became accepted as a winter road treatment. According to the Salt Institute (<http://www.saltinstitute.org/33.html#highways>) the sale of salt for winter highway use since 1960 has increased dramatically:

Salt Sales for Highways

Year	Tons (000)	Year	Tons (000)	Year	Tons (000)
1960	2,220	1975	9,493	1990	10,528
1961	2,127	1976	9,937	1991	9,730
1962	3,060	1977	10,072	1992	10,457
1963	3,707	1978	10,927	1993	17,126
1964	3,975	1979	11,323	1994	18,885
1965	4,536	1980	8,108	1995	14,427
1966	4,133	1981	7,240	1996	20,117
1967	6,500	1982	9,787	1997	16,369
1968	6,750	1983	7,267	1998	10,196
1969	7,550	1984	10,329	1999	15,690
1970	8,855	1985	10,730	2000	18,101
1971	9,584	1986	11,057	2001	16,845
1972	8,721	1987	9,462	2002	13,391
1973	8,420	1988	11,202	2003	19,359
1974	8,629	1989	11,227	2004	16,014

Much of the increased use was due to the expansion of the highway system in the U.S. in the 1960's and the growing expectation on the part of drivers that the roads would be clear and clean soon after major snow storms.

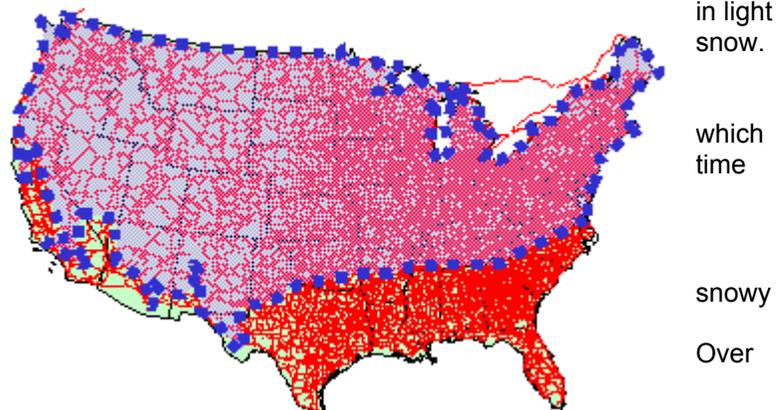
The United States is the world's largest producer of salt for all uses, approximately 44 million metric tons in 2002. Other leading producers of the world's 225 million metric tons of salt include China, Germany, India, Canada and Australia.

The article mentions that using salt for maintaining winter highways began in the 1930's, actually the late 1930's. For an interesting article (with photos) on the history of salting winter roads, written by a former New Hampshire maintenance engineer, see <http://www.betterroads.com/articles/brian01d.htm>.

According to the Federal Highway Administration, "Over 70 percent of the nations roads are located in snowy regions, which receive more than five inches (or 13 cm) average snowfall annually. Nearly 70 percent of the U.S. population lives in these snowy regions. Snow and ice reduce pavement friction and vehicle maneuverability, causing slower speeds, reduced roadway capacity, and increased crash risk. Average arterial speeds decline by 30 to 40 percent on snowy or slushy pavement. Freeway speeds are reduced by approximately 10 percent

in light snow and by 40 percent in heavy snow. Heavy snow and sleet can also reduce visibility. Lanes and roads are obstructed by snow accumulation, reduces capacity and increases travel delay.

"In 2001, nearly 20 percent of weather-related vehicle crashes occurred on or slushy pavement and 13 percent happened during snowfall or sleet. 1,100 people were killed and nearly



95,000 people were injured in vehicle crashes on snowy or slushy pavement that year. In 2001, nearly 790 people were killed and nearly 62,000 people were injured in vehicle crashes during snowfall or sleet.

“Snow and ice increase road maintenance costs. State and local agencies spend more than 2.3 billion dollars on snow and ice control operations annually. Each year, these road agencies spend over five million dollars to repair infrastructure damage caused by snow and ice.” Text and map from:

http://www.ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm

Highway maintenance officials have to do more than just spread salt on snowy highways. They must choose the chemicals that are right for their area. They must know how much to use. If they use too much, the excess will run off and cause pollution. If they use too little deicer, then the snow or ice will not melt properly. They must know when to use it. They must know the best temperatures at which to spread it. As the temperature of the atmosphere decreases, more salt is required to melt ice and snow. For example, one pound of salt can melt five times as much ice at 30°F as it can at 20°F. They must know how to spread it. And they must know how to store it. Other factors which come into play in a real world setting include time of day, pavement temperatures, weather conditions, type of road surface, topography, traffic volume, width of application, and time of chemical application. All of these affect the process of melting snow and ice.

More on Common Deicers

Five chemicals make up about 95% of all deicers: sodium chloride in the form of rock salt, potassium chloride, urea, calcium chloride, and magnesium chloride. Acetates such as calcium magnesium acetate make up the remainder.

Sodium chloride (NaCl) is the most common deicer. It melts ice and snow efficiently with optimum performance at 15-20°F. Dissolved salt lowers the freezing point (see More on Freezing Point Depression) of ice until the salt concentration of the solution reaches 23.3% at which it becomes a eutectic mixture. At this concentration, the freezing point of the solution is -6.02°F, the minimum temperature at which NaCl functions as a deicer. It can be used in solid form or as a 23% brine solution. The application rate for NaCl is typically between 200 and 400 pounds per lane-mile

Calcium chloride (CaCl₂) is the only deicer that dissolves in water exothermically. In its natural state, this chemical is a liquid brine that is then converted into the dry salt when water is removed. One advantage is that because it is hygroscopic it is more effective at lower temperatures. Its practical working temperature is -20°F while its eutectic temperature is -60°F. It can cost three to five times more than rock salt. It also leaves a residue that can be tracked into homes when used on sidewalks.

Magnesium chloride (MgCl₂) is similar to calcium chloride. However, because MgCl₂ is usually sold as the hexahydrate, MgCl₂ · 6H₂O, it is only 50% as effective as CaCl₂. It is usually applied in solution form. It acts very fast to melt ice. It is effective down to -25°C, but its practical working temperature is about 5°F. It is not harmful to concrete or metal.

Potassium chloride (KCl) and **urea** (NH₂CO NH₂) are fertilizers commonly used in combating snow and ice. The practical working temperature for these chemicals range between 20-25° F with a eutectic temperature of between 11-12 °F. They can be as much as five times more expensive than rock salt. Urea is not as corrosive, it's safer on concrete that contains rebar, and is frequently mixed with other deicers

Calcium magnesium acetate (CMA) is a non-corrosive deicer that can be made from biomaterials but is often petroleum based. It is often used for bridges, parking decks and surfaces exposed to air on the underside. Rather than melting ice, it actually prevents ice and snow from aggregating on the road surface. It is often mixed with sodium chloride. It costs four to five times as much as calcium chloride. Its practical working temperature is about 15°F.

The overall mechanism for deicing action is for the deicer to form a localized brine solution, which penetrates the surrounding ice or snow until it reaches the road surfaces. There it breaks the ice away from the road surface and further melts the ice.

More on Freezing Point Depression

The ability of salts, like the deicers described in the article, to lower the freezing point of a solution is called freezing point depression. Freezing point depression is a colligative property, which means that it depends only on the concentration of the solute, not on the identity of the solute. Most chemistry texts include a section on freezing point depression.

Freezing point depression for a solvent can be calculated using this equation:

$$\Delta T_f = K_f m_{\text{sol}} \quad \text{where } \Delta T_f \text{ is the freezing point lowering, } K_f \text{ is the freezing point depression constant and } m_{\text{sol}} \text{ is the molal solute concentration.}$$

In the case of water, which is the solvent involved for snow and ice, the freezing point depression constant has a value of $1.86^\circ\text{C} \times \text{kg/mol}$. This means that for every mole of solute dissolved in 1 kg of water, the freezing point of the resulting solution will be lowered 1.86°C .

The above calculation holds for non-electrolytes. But electrolytes like NaCl, CaCl_2 and MgCl_2 , the common deicers, produce ions in solution. One mole of dissolved NaCl produces *two* moles of ions, one mole of Na^+ ions and one mole of Cl^- ions. This factor which compares the number of moles of particles in solution to the number of moles of dissolved solute is called the van't Hoff factor and is noted with the letter *i*. The van't Hoff factor can be determined by noting the number of ions per formula unit of solute. The van't Hoff factor for sodium chloride would be two and for calcium chloride and magnesium chloride it would be three.

For an electrolyte dissolved in water, then, the freezing point depression is magnified by the van't Hoff factor and the working equation becomes:

$$\Delta T_f = i K_f m_{\text{sol}}$$

At a molecular level, when water and ice are mixed at the freezing point (0°C) the rate at which molecules leave the ice surface and the rate at which molecules in the liquid phase are captured on the ice surface are equal. That is, at 0°C , the system is in a dynamic equilibrium. Adding salt (NaCl) to the mixture alters the equilibrium, however. There are two factors at work. First, the salt particles (the sodium and chloride ions) do not easily fit into the ice crystal lattice. Second, dissolving salt in the water lowers the relative concentration of water molecules in the liquid phase. This, in turn, affects the equilibrium by decreasing the rate at which water freezes. In order to increase the rate of liquid-to-solid transitions, the temperature of the mixture would have to be lowered. Adding salt has the net effect of lowering the temperature at which water freezes. The freezing point of water is lowered, or depressed, by the addition of a solute like salt.

Adding more salt would seem to result in the freezing point being depressed more and more. This is true down to a fixed temperature, called the eutectic temperature. As more salt is added to the mixture, the freezing temperature does decrease. But as the temperature of the solution is lowered, the solubility of the salt is also decreased. The eutectic temperature is the temperature at which the solution becomes saturated (at the lowered temperature). Adding more salt causes the dissolved salt to re-crystallize quickly. As salt is taken out of solution, the freezing temperature of the water rises and ice quickly forms. At the eutectic point the solution becomes a heterogeneous mixture of ice crystals and salt crystals.

More on Dissolving

Deicers in the solid form cannot melt snow and ice. They must first dissolve to form a brine. It might be helpful for students to understand the dissolving process to help them understand how deicers work. There are three basic steps involved in dissolving an ionic solid (most of the common deicers are ionic solids) in water. One step involves the dissociation of the ionic crystal of the solute into its constituent ions. Faster moving water molecules interact with the NaCl crystal to "break off" both Na^+ ions and Cl^- ions. Because water molecules are polar, they attract both positively charged sodium ions and negatively charged chloride ions. Energy is required for this step since ionic bonds must be broken. This step is, therefore, endothermic. A second step involves overcoming the intermolecular forces between the water molecules to make room for the solute particles. Water molecules are attracted to each other by hydrogen bonds, London forces and dipole interactions so this second step is also endothermic. A third step involves the solvation, or hydration, of the solute particles by water molecules. Hydration is always an exothermic process. The heat (enthalpy) of solution is the sum of the heats for these three steps.

More on Environmental Effects of Deicers

Some of the major effects of deicer use on highways include:

- Corrosion of concrete surfaces
- Rusting of cars
- Long-term ecological damage to the terrestrial and aquatic environment (because most deicers are water soluble, they become part of water runoff)
- Reduction of soil permeability

Connections to Chemistry Concepts

1. Change of phase – This article can be used when your class studies change of phase, since the article deals with freezing and melting.
2. Dissolving and solutions – The effect of dissolving a solute in water is of major importance in this article. The article can also be used to illustrate change of phase mechanisms.
3. Thermodynamics of dissolving – see notes above on heat of solution.
4. Colligative properties – Since freezing point depression is a colligative property, the article might be used in connection with this topic.
5. Ionic bonding and crystal structures

Possible Student Misconceptions

1. *In freezing point depression, larger solute molecules should cause a larger depression.* This is not so. The size of the solute particles has no effect on the freezing point, only the number of particles is important.
2. *Using more deicer should produce better results.* To a point this is so. However, at the eutectic point, adding more deicer does nothing since it won't dissolve any further.
3. *All deicers are alike.* The freezing point depression is the same per mol solute, but because the heats of solution of various deicers are different and because the eutectic points are different, deicers do have different properties. Also, different deicers have varying environmental impacts.

Demonstrations and Lessons

1. Students can do freezing point experiments in the lab. See <http://intro.chem.okstate.edu/HTML/SEXP10.HTM> for one procedure.
2. Students can do freezing point depression experiments. See <http://www.woodrow.org/teachers/chemistry/institutes/1986/exp9.html> or <http://chemweb.calpoly.edu/chem/125/125LabExp/FPDepression/>
3. For a lab procedure that illustrates how to purify salt from water by freezing, see <http://www.watercan.com/h2oh/2-2.shtml>
4. For a lab activity that compares deicers, see <http://jchemed.chem.wisc.edu/HS/Journal/Issues/2002/May/clicSubscriber/V79N05/p592A.pdf>
5. For a lab activity on salt as a deicer, see <http://www.saltinstitute.org/42g.html>
6. Most textbooks have a section that includes freezing point depression problems. For more problems see <http://dbhs.wvusd.k12.ca.us/webdocs/Solutions/BP-Elev-and-FP-Lower.html>
7. For a little fun with freezing point depression, students can make ice cream. One procedure is here <http://www.oswego.edu/wscp/ic.htm>

Suggestions for Student Projects

1. Students can read the C&E News article on deicers at <http://pubs.acs.org/cen/whatstuff/stuff/7901scit5.html>.
2. Students might be encouraged to take samples of water near designated roads in your area in the fall, again in late winter and in the spring to attempt to measure the effect of road salt on the environment.
3. Students could compare the various deicers – NaCl, CaCl₂, MgCl₂, KCl, MCA, for effectiveness at lowering the freezing point of water in a series of experiments.

Anticipating Student Questions

1. **How is salt produced?** Salt occurs naturally as the mineral halite in underground deposits. Major salt deposits in the U.S. are located in Texas, Michigan, Kansas and New York. Most halite is mined by blasting out cavernous spaces in the salt deposit, leaving as much as 30% of the salt forming thick pillars that support the dome of the blasted space. The salt is then crushed and screened prior to sale.
2. **How can dissolving a solute in water lower its freezing point?** See “More on Freezing Point Depression.”
3. **Do all deicers affect the environment equally?** No, salt actually has been shown to affect roads and sidewalks less than the other deicers, although salt is possibly worse in terms of plants found along the roadways. This could be due to the fact that NaCl is used in the greatest amounts, so its effect would be greater. (It's also due to the fact that we have to use more of it than CaCl₂ or MgCl₂ because it only produces 2 ions in solution, while the others produce 3 ions, so the colligative effect is less for NaCl.) Magnesium and calcium chlorides corrode concrete more than sodium chloride.

Websites for additional Information

For more on the history of treating roads with deicers, see <http://nsidc.org/snow/shovel.html> .

For more on the use of salt on highways, see <http://www.saltinstitute.org/30.html>.

For more on using salt to melt ice, see <http://antoine.frostburg.edu/chem/senese/101/solutions/faq/why-salt-melts-ice.shtml>.

For more on the latest technology in applying winter road treatments, see

<http://www.betterroads.com/articles/NewProds/jun05bid.htm> and <http://www.cargillsafelane.com/>.

For an article on aircraft deicers, see <http://pubs.acs.org/cen/whatstuff/stuff/7901scit5.html>.

For a complete explanation of the phase diagram for a salt-water-ice mixture see

<http://www.chemguide.co.uk/physical/phaseeqia/saltsoln.html>. Scroll down to the section “Phase Diagram for a Sodium Chloride Solution.”

For a thermodynamic explanation of freezing point depression, see

<http://antoine.frostburg.edu/chem/senese/101/solutions/faq/thermo-explanation-of-freezingpoint-depression.shtml>.

For a two-part article on deicers and the rusting of cars (see “Flaking Away” in this edition of *ChemMatters*) see

http://www.chemistry.org/portal/a/c/s/1/feature_ent.html?id=516b4c7e060811d7f25b6ed9fe800100.

For students with drivers licenses, here are tips on winter driving

http://www.chemistry.org/portal/a/c/s/1/feature_ent.html?id=c373e9080ab0eede8f6a17245d830100.

Flaking Away

Background Information

Cars are actually lasting a lot longer today than they did ten or twenty years ago. This is due in part to better engines and other mechanical parts, but cars' longevity is due in large part to the advances that have been made in protecting its metal surfaces from rust.

History of corrosion

The history of corrosion and the history of corrosion prevention are inseparable. As soon as man recognized corrosion as a problem, he tried to counteract its effects. As early as Greek times, Pliny the Elder and Dioskorides mentioned that copper plates could be protected from corrosion by tinning, coating them with a thin coat of tin.

The great Roman philosopher, Pliny also wrote at length about *ferrum corruptitur*, or spoiled iron, apparently referring to rusted iron.

Early shipbuilders recognized that their wooden hulls could be protected from rotting by coating them with a thin sheath of lead. The coating was usually attached with nails of copper or gold-plating. The lead sheathing by itself was rather slow to corrode, but these nails, being a different metal from the lead, acted upon the lead and increased the corrosion of the lead sheathing, so shipbuilders eventually coated their ships with copper instead. But copper corroded in salt water, too, so in 1823 Sir Humphrey Davy studied the problem and solved it the next year by attaching sacrificial anodes made of iron and zinc to the copper, and later wrote that he preferred cast iron because it lasted longer.

Copper sheathing was fine for wood ships, but eventually, when steel/iron ships were built, the iron itself corroded quickly. A layer of copper wasn't the answer to this problem, however, because the copper touching the iron of the ship's hull set up galvanic reactions between these two dissimilar metals, causing even more corrosion than the iron would have by itself.

Galvanizing is a process whereby iron (as in nails, for instance) is dipped in molten zinc. Since the zinc coats the iron, preventing oxygen from coming in contact with the nail, the iron is protected from corrosion. "The recorded history of galvanizing goes back to 1742 when a French chemist named P.J. Malouin, in a presentation to the French Royal Academy, described a method of coating iron by dipping it in molten zinc.

In 1836, Stanilaus Tranquille Modeste Sorel, another French chemist, obtained a patent for a means of coating iron with zinc, after first cleaning it with 9% sulfuric acid and fluxing it with ammonium chloride. A British patent for a similar process was granted in 1837. By 1850, the British galvanizing industry was using 10,000 tons of zinc a year for the protection of steel." – excerpted from The American Galvanizers Association web site

This site, <http://www.tfsrc.gov/structur/corros/history.htm>, gives a brief history of bridge corrosion. It ties increased rates of corrosion of bridges in the 60's and 70's to the increased usage of salt as a deicer on roads. Although salt's effect on concrete is minimal (surface corroding, called spalling), the dissolved salt seeps through the concrete into the reinforcing bars of steel that are used to add strength to concrete and corrodes them. As they corrode, the iron(III) oxide that forms, causes swelling around the internal reinforcing bars and this eventually causes cracks in the concrete. When one thinks of bridge corrosion, it is normal to think of the girders and support structures, and indeed, these are easily corroded, but this corrosion is visible and therefore usually kept under control. It is the unseen corrosion inside the decking of the bridges that is usually far more severe. (Underwater pilings are also frequently severely corroded, but even these can be viewed by divers and their corrosion can thus be controlled, or at least repaired.) (See also, "Websites for Additional Information", "Bridges", below.)

See also, "Websites for Additional Information", "History", below.

More about rusting (and corrosion in general)

A national study was conducted in 2001 to assess the economic impact of corrosion. The study was run by CC Technologies, Inc., and sponsored by the Federal Highway Association (FHWA) and the National Association of Corrosion Engineers (NACE) International. They discovered that corrosion costs the US approximately \$275 billion per year (extrapolated from their actual data). Only a small portion of that (\$23

billion) is from corrosion to cars, but even that is a significant amount. The report states that cars are being built to be more corrosion-resistant now than they were in the 1970's, and that cars are lasting longer now than they did then. Here's the site: <http://www.corrosioncost.com/home.html>. It contains about 80 pages of actual report and about 300 pages of appendices. The report is replete with tables, graph, and photographs. It is very extensive. Students who look at this site will see the diverse nature of corrosion, and the impact it has on our economy and our society. Beyond the numbers, this report will give students a good overview of the myriad areas that are affected by corrosion, areas they probably never even imagined would be adversely affected by corrosion.

When you access this site, the opening page shows a multi-color pie chart. Clicking on this chart will enlarge the chart, which gives more details within each pie segment, and then you can click on each subsection to get a separate information sheet on that topic.

Here are a few details from the study:

Summary of the Industry Sectors Analyzed in this study (\$138 billion for these sectors):

Infrastructure (16.4%) (\$22.6 billion): Cost in Billions of dollars

Highway Bridges	8.3
Gas and Liquid Transmission Pipelines	7.0
Waterways and Ports	0.3
Hazardous Materials Storage	7.0
Airports	---
Railroads	---

Utilities (34.7%) (\$47.9 billion):

Gas Distribution	5.0
Drinking Water and Sewer Systems	36.0
Electrical Utilities	6.9
Telecommunication	--

Transportation (21.5%) (\$29.7 billion):

Motor Vehicles (Cars & Trucks)	23.4
Ships	2.7
Aircraft	2.2
Railroad Cars	0.5
Hazardous Materials Transport	0.9

Production and Manufacturing (12.8%) (\$17.6 billion):

Oil and Gas Exploration – Production	1.4
Mining	0.1
Petroleum Refining	3.7
Chemical, Petrochemical, Pharmaceutical	1.7
Pulp and Paper	6.0
Agricultural	1.1
Food Processing	2.1
Electronics	---
Home Appliances	1.5

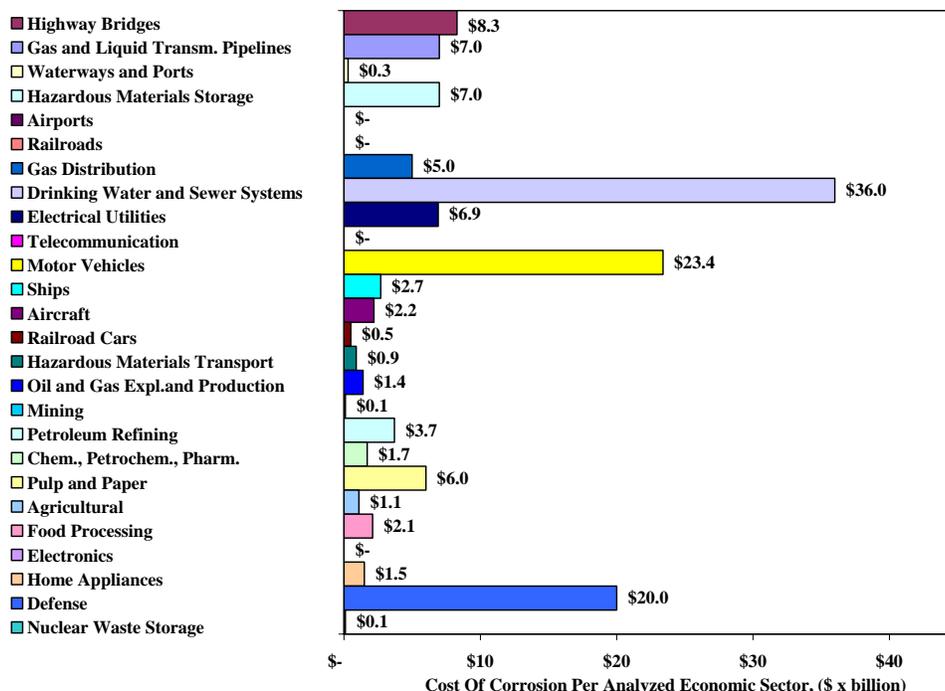
Government (14.6%) (\$20.1 billion):

Defense	20.0
Nuclear Waste Storage	0.1

The chart below is taken from a PowerPoint slide in the presentation about this corrosion cost project.

The PowerPoint presentation can be found at

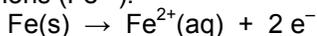
<http://www.corrosioncost.com/downloads/slides/corrosion.pps>



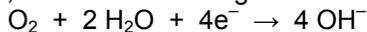
The costs of corrosion to the US are calculated to be anywhere from 1.5% to 3.1% of the total gross domestic product (GDP). That's \$137 billion to 375 billion annually!

More about corrosion as a chemical reaction

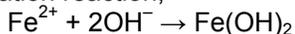
Corrosion is an oxidation-reduction reaction, but it is also an electrochemical reaction. On the exposed surface of a piece of iron, individual electrochemical cells occur wherever the iron comes in contact with water and oxygen from the air, especially at sites that have undergone stress, as at bends or joints. These become the anodes of the reaction. At the anode, oxidation of the iron is taking place, leaving ferrous ions (Fe^{+2}):



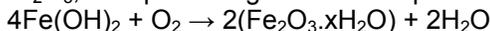
Since iron is a metal, and metals conduct electricity, the electrons can travel through the metal to distances away from the original oxidation. The ferrous ions can also migrate through solution to other areas, where they can react with oxygen to form rust. Thus rust formation can occur at some distance from the original site of oxidation. The sites at which rust forms become the cathodes for the redox reaction, where the following reaction occurs:



The Fe^{2+} (ferrous) ion can then react with the OH^{-} (hydroxide) ions to form $\text{Fe}(\text{OH})_2$ by a direct combination reaction,



and then the $\text{Fe}(\text{OH})_2$ can react further with O_2 in another oxidation-reduction reaction to form a hydrated form of Fe_2O_3 , also producing water in the process.



The color of rust can vary from yellow to reddish-orange to black. The amount of water present as the rusting occurs determines the color of the rust that forms.

So the site where pitting of the metal surface occurs is the anode, and the site where rust builds up is the cathode. They do not necessarily occur at the same place, as has been explained above.

Once students understand that corrosion or rusting is essentially an electrochemical reaction, they should then easily see the effect that salts would have on the reaction – salts dissolve in water and allows the circuit to be completed by balancing the charge imbalance created in solution (positive ions at the anode, negative ions at the cathode). Essentially, the salt in solution acts as a salt bridge, in electrochemical terms.

See “Websites for Additional Information”, “Corrosion Chemistry”, below.

More about salt

See “Salting Roads” elsewhere in this Teacher Guide

Also see “Websites for Additional Information”, “Salt and corrosion”, below

Connections to Chemistry Concepts

1. Oxidation-reduction – corrosion is a great everyday example of oxidation-reduction reactions
2. Reaction rates – discuss factors affecting the rate of corrosion; e.g., moist vs. dry environment, warm vs. cold environment, etc.
3. Activity Series (Electromotive Series) – the series predicts iron should corrode easily as it is high on the series, indicating an active metal (more active than hydrogen).
4. Electrochemistry – corrosion is an electrochemical reaction; voltages can be predicted from the half-reactions involved
5. Thermodynamics – corrosion is a spontaneous reaction; therefore, ΔG must be negative. Calculations could be done here also – for ΔH , ΔS , and ΔG , from half-reactions

Possible Student Misconceptions

1. *Corrosion only happens to iron or steel.* Corrosion happens to almost all metals. The more active the metal, the faster corrosion occurs on that metal’s surface.
2. *There’s nothing we can do about corrosion – it just happens.* Although this might be what the general public believes, it is not true; see “Anticipated Student Questions” number 1, below.

Demonstrations and Lessons

1. Paint as a protective cover stops rust. A long-term demonstration could involve submerging metal strips (some of which have been protected with coatings, and some not) in a salt solution could be set up for students to observe over a period of days, weeks, or even months.
2. Rate of oxidation varies with type of metal. A similar arrangement as above could be done with different metals.
3. The Titanic is a prime example of the corrosion process. A wet lab demonstration as part of a lesson (or series of lessons) about the Titanic can be found at <http://oceanexplorer.noaa.gov/explorations/04titanic/edu/media/Titanic04.Galvanic.pdf>. This site’s lessons are very thorough, including connections to relevant National Science Education Standards, extension activities, and a list of links to other resources. The corrosion occurring on the Titanic’s surface involves “rusticles” that form from anaerobic bacteria and fungi interacting with the iron in the hull. The site differentiates galvanic deterioration from biodegradation. Unfortunately, no chemical reactions are offered for the biodegradation process.
4. Chemical cleaning of pennies is an example of corrosion. See a site that describes how to do this for/with your students at <http://chemistry.about.com/cs/demonstrations/a/aa022204a.htm>. There are several activities here: cleaning pennies, returning a patina to some of them, and copper-plating iron nails – all examples of redox reactions. A nail can be found at <http://chemistry.about.com/gi/dynamic/offsite.htm?zi=1/XJ&sdn=chemistry&zu=http%3A%2F%2Fchemlearn.chem.indiana.edu%2Fdemos%2Fdemocont.htm>. This one, with copper sulfate and a nail, is done more as a classroom demo, with chemical concepts listed, etc. It also has the other demo, with a piece of copper and iron sulfate, so you can show the relative activity of each.
5. You can do the old silver nitrate-copper wire reaction as a demonstration to show a single displacement reaction that is oxidation-reduction. It is written up as a demo for you at

<http://chemistry.about.com/cs/crystallography/ht/silvercrystals.htm#>. One caveat: Do NOT use mercury as described in this link as a possible alternative to copper wire! (I don't understand how that one is still on the web on such a popular web site.)

6. A Project Labs experiment involving several different oxidation-reduction reactions, complete with data tables, is found at http://chemistry.about.com/gi/dynamic/offsite.htm?zi=1/XJ&sdn=chemistry&zu=http%3A%2F%2Fwww.chemistrycoach.com%2FLinks%2520to%2520chemistry_experiments.htm%23Oxidation%2C%2520Reduction.

Suggestions for Student Projects:

1. Students could do a series of experiments to discover what works best at preventing rusting of metal.
2. Students can test the effects of temperature on rusting.
3. Students could research the role rust plays in our national (global?) economy (and how to minimize its impact) and write a report, or prepare a presentation for the rest of the class, on the results of their research. You may want them to start with the national 2001 FHWA/NACE report on corrosion, <http://www.corrosioncost.com/home.html>
4. Students could be given 2 nails and charged with the task of preventing each of them from rusting in a salt solution. One of them can be coated, but the other one must have at least half of the nail uncovered, submerged in the salt solution. More details can be obtained from the British Columbia Ministry of Education web site at <http://www.bced.gov.bc.ca/irp/chem1112/ch1222.htm>. Scroll down to "Suggested Instructional Strategies".
5. Students could research and report on the use of sacrificial anodes in the real world. Details might include: the chemistry behind the process, the specific uses, the costs involved in a) using them and b) in savings compared to what would happen in their absence to the items being protected, difficulties in using them, and present-day research in new applications. This site, <http://www.sescocp.com/tutorial.php>, might be a good place to start, although it is rather technical at places.
6. Students could research differences between corrosion of shallow-water shipwrecks and corrosion of deep sea wrecks (like the Titanic). (Check out "rusticles".)
7. Students might devise their own inquiry experiments involving corrosion; e.g., testing factors that affect corrosion rates. Suggestions for open-ended experiments abound at <http://www.npl.co.uk/ncs/schools/experiments01.html#rates>. This site also contains good diagrams (PowerPoint slides?) of corrosion processes and photographs of corrosion in action on familiar objects, like pipes, oil storage tanks, bridges, and copper roofs.

Anticipating Student Questions

1. Why can't chemists just stop corrosion? The thermodynamics of the corrosion process are favorable. The best chemists (or anyone) can do is to try to slow the process down. We can do that several ways: a) prevent the reactants from coming in contact (use coatings to cover the surface of the metal to separate it from oxygen in the air), or b) prevent the reaction from happening to the specific metal by allowing another metal to react in its place (sacrificial anode). Or chemists can try to slow down the reaction by minimizing the exposure of the metal to the conducting ions in solution needed for the reaction to take place (washing salt off the bottom of cars in the winter time, for example – see http://www.chemistry.org/portal/a/c/s/1/feature_ent.html?id=516b4c7e060811d7f25b6ed9fe800100 for a personal view).
2. Why are cars lasting longer now than they did a few decades ago? a) Car manufactures are using less metal, replacing it instead with polymeric (plastic) materials. b) Paints and coatings are much improved – and they protect the exposed surfaces of the metal so they can't corrode. c) Methods of preparing metal surfaces and applying those improved paints and coatings have themselves been improved, allowing paints to adhere longer than before. All of these reasons keep oxygen from coming in contact with metal parts of the car, thus preventing corrosion.

- Why doesn't gold rust? At normal pH's (close to 7) the oxidation of gold by O_2 is thermodynamically unfavorable. (For a complete – very complete – list of reduction half-reactions [530 of them], see http://www.efunda.com/materials/corrosion/electrochem_list.cfm?sort=&start=1&r1=&e1=&e2=&e3.)
- And what's with silver? Silver corrodes on its surface, just like iron, except we call this corrosion tarnish, instead of rusting, as on iron. The corrosion on silver's surface, though, is mostly silver sulfide, not silver oxide. The sulfur comes from things like mayonnaise (eggs) and rubber products (rubber is cross-linked with sulfur to give it more strength). When the silver combines with sulfur, you get silver sulfide, a black substance. Silver sulfide coats the silver object and, and this coating itself protects the silver metal underneath from continued corroding or tarnishing.

Websites for Additional Information

History

Corrosion-Doctors has a fairly extensive history of electrochemistry, century by century at

<http://www.corrosion-doctors.org/History/History.htm>.

<http://www.corrosion-doctors.org/Cases/Frames.htm> is a part of Corrosion-Doctors' web site that cites about a dozen catastrophes that occurred on a large-scale due to corrosion concerns. The site gives a case study on each one.

Corrosion chemistry

This site by Engineering Fundamentals, http://www.efunda.com/materials/corrosion/corrosion_basics.cfm, gives good chemical background of corrosion, complete with equations.

This C-D site gives a list of more than 20 equations dealing with iron rusting in the presence of water and oxygen. <http://www.corrosion-doctors.org/Thermo/FeReactions%20.htm>.

This site gives a fairly basic coverage of why metals corrode, complete with diagrams:

<http://www.westcoastcorrosion.com/Papers/Why%20Metals%20Corrode.pdf>

<http://www.corrosion-club.com/basictheory.htm> is a site by the Corrosion Club. It is a one-pager, with very basic information. You could use this as an assignment for students to use this site to explain corrosion of iron to other students in the class. It has a few equations, two charts, and a summary of terms. By itself it doesn't **teach** corrosion chemistry, but all the ingredients are there.

<http://www.diracdelta.co.uk/science/source/e/electromotive%20series/source.html> is from an engineering web site that gives a table of the electromotive series. Note that this is an oxidation half-reaction table, listing the elements from those most likely to lose electrons to those least likely to do likewise.

Another page on the Engineering Fundamentals web site has a list of 530 equations for reduction potential half-reactions at

http://www.efunda.com/materials/corrosion/electrochem_list.cfm?sort=&start=1&r1=&e1=&e2=&e3.

The Leeward Community College and Kapi'olani Community College's web site contains a whole course on oxidation-reduction chemistry at http://library.kcc.hawaii.edu/external/chemistry/redox_title.html. They also have a page on this site dedicated to corrosion, at

http://library.kcc.hawaii.edu/external/chemistry/everyday_corrosion.html.

Taken from the *Chem 1 Virtual Textbook*, this

site, <http://www.chem1.com/acad/webtext/elchem/ec7.html#MAP>, contains a lesson on corrosion, several photos of corrosion of common materials, and a concept map of the corrosion process.

Salt and corrosion

The American Chemical Society's Kevin McCue gives us a first hand account of winter storms, cars, and road salt (and their aftermath) at

http://www.chemistry.org/portal/a/c/s/1/feature_ent.html?id=516b4c7e060811d7f25b6ed9fe800100. Part 1 focuses on the role of salt in controlling snow on winter roads, and part 2 focuses on the effect of salt on cars – namely, rusting.

This site, <http://www.saltinstitute.org/publications/saltandenvironment-english.pdf>, provides information re: salt on highways and how it enhances corrosion. This specific subsite deals with corrosion: <http://www.saltinstitute.org/th2020s.html>

Corrosion testing

This is an ASTM (American Society for Testing and Materials) International site that gives a description of one standard for testing the effectiveness of paints and coatings in rust prevention by measuring the amount of “creep” of the rust in a scribed (scratched, marked) area of painted metal:

<http://www.astm.org/cgi-bin/SoftCart.exe/STORE/filtrexx40.cgi?U+mystore+iyfz1993+-L+RUSTING+usr6/htdocs/astm.org/DATABASE.CART/HISTORICAL/D7087-05.htm>. The ASTM standards are acknowledged internationally as the standards for all kinds of testing methods in government and industry. Unfortunately, each standard test has a fee attached. This one, for example, costs \$33.60, and it's only 4 pages (pdf file) long!

Glossaries

A glossary of electrochemical terms: <http://www.corrosion-doctors.org/Dictionary/Dictionary-A.htm>
Corrosion-Club.com again with an extensive clickable glossary of corrosion terms: <http://www.corrosion-club.com/contents.htm>. This is more than just a glossary – it has a page of materials on each term in the list, and appropriate links to more information.

Bridges

This is one of the appendices to the official “cost of corrosion” report. It deals specifically with the corrosion of bridges: <http://www.corrosioncost.com/pdf/highway.pdf>. It shows pictures of bridges and processes being used to minimize corrosion; it also gives the costs of bridge corrosion, and describes the processes and improvements being used to reduce corrosion.

A site with numerous links to various organizations dealing with bridges – construction and testing, including corrosion concerns: <http://abcdpittsburgh.org/links2.html>
<http://www.carolinaprecast.com/index.html> is a site that shows you how to prevent corrosion in concrete, especially rebar, reinforcing steel bars used in reinforced concrete.

Terrific Science, from the University Of Miami, Ohio, has a teaching module on “Corrosion of Steel Structures”. The module includes student and teacher versions of classroom activities, including wet lab activities. It is sold as part of a 5 CD set. The cost is \$20.95, plus shipping and handling. The description can be found on page 1 of their catalog, available online at <http://www.tsbkm.com/pdfs/TSBKM-CAT-WEB.pdf>. The CD is rather new, hence it does not yet appear in the online merchandise descriptions.

Miscellaneous sites

This site, from SESCO, Inc., a corrosion protection engineering firm, gives examples and descriptions of many different types of corrosion:
<http://images.google.com/imgres?imgurl=http://www.sescocp.com/img/pitting.gif&imgrefurl=http://www.sescocp.com/typesofcorrosion.php&h=262&w=192&sz=10&tbnid=AeFTT7iyI80J:&tbnh=106&tbnw=78&start=17&prev=/images?q=pitting+corrosion&svnum=20&hl=en&lr=&ie=UTF-8&newwindow=1&safe=off&sa=G>

And this site, <http://www.cheresources.com/corrosion.shtml>, shows photographs of examples of several of the types of corrosion referred to in the SESCO descriptions, above.

This site gives a complete picture of The Cost of Corrosion in the USA, 2001 – an extensive research project and report done by the Federal Highway Association and NACE, the National Association of Corrosion Engineers: <http://www.corrosioncost.com/downloads/pdf/index.htm> (cited in the body of the Teacher's Guide)