



December 2008 Teacher's Guide

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About the Guide

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Articles from past issues of *ChemMatters* can be accessed from a CD that is available from the American Chemical Society for \$30. The CD contains all *ChemMatters* issues from February 1983 to April 2008.

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Student Questions

Tasteful Chemistry

1. Name the five types of taste cells listed in the article.
2. Name the two cations involved in detecting salty taste.
3. How many types of sweet taste receptors are there on the human tongue?
4. Which of the five tastes are associated with poisons and rotten food?
5. Taste is initiated on the tongue when molecules enter a taste cell via small tunnels. Name these structures.
6. Name the taste that is related to salts of glutamic acid.

Coffee: Brain Booster to Go

1. What is the chemical name for caffeine?
2. What is the chemical formula for caffeine?
3. What characteristic do all the plants that are known to contain caffeine have in common?
4. How does caffeine work in the brain to keep you awake?
5. Is coffee a simple molecule? Explain.
6. What happens to coffee beans as they are roasted?
7. What happens in the Maillard reaction?
8. Can scientists identify all the chemicals responsible for the aroma and flavor of coffee?
9. What is the role of the antioxidants found in coffee?
10. What are nutraceuticals?
11. What are the beneficial effects of drinking a cup of coffee?
12. What are the potentially harmful effects of drinking too much coffee?
13. What's with the dancing goats?

Are Energy Drinks Good for You?

1. Do energy drinks give you energy?
2. How can one calculate the amount of energy?
3. What are the only three food nutrients that can give you calories?
4. What is considered the most "potent" ingredient in energy drinks?
5. What ingredient also found in large concentrations in energy drinks is also a cause for concern?
6. What does one mean by the term "a synergistic effect"?
7. How does one apply the concept of synergistic effect to energy drinks?

Glowing Proteins with Promising Biological and Medical Applications

1. What color of bioluminescent light is produced by jellyfish?

2. What color of light is produced by the reaction of aequorin with calcium ion?
3. What is the relationship between blue light emitted by aequorin and green light emitted by green fluorescent protein (GFP)?
4. What is the difference between the terms bioluminescence and fluorescence?
5. What makes GFP glow or fluoresce?
6. What is the basic design plan or what is required in order to have proteins in cells glow (fluoresce) when exposed to ultraviolet light?
7. What technique was used to duplicate in large quantities the gene responsible for synthesizing the GFP protein in a cell?
8. What are some of the uses of fluorescent proteins (green, red, yellow, blue) in biological research?

The Tale of the Teeth

1. How is it possible that some of the skeletal remains dug up in Campeche, Mexico in 2000 were those of 16th Century Africans?
2. What was the first clue that some of the skeletal remains were of African origin?
3. What was the chemical evidence that supported the initial conjecture that some of the skeletal remains were African in origin?
4. What kind of building was originally built on the foundation excavated in Campeche in 2000?
5. What are isotopes?
6. How can ratios of isotopes of the same element be used to determine the geographical origin of bone or teeth?
7. If a person migrates from one location to another, how is it possible to use the strontium isotope ratios to determine where that person lived in his or her first few years of life?
8. How were scientists able to decide that the African skeletons were not from people who were born in Campeche, Mexico?
9. What historical evidence was used to reinforce the chemical idea that the African skeletons were from people who were brought to Mexico?
10. What three groups of people were the original residents of Campeche and surrounding areas in Mexico?
11. What new chemical markers may help to determine migration origins, routes, and destinations of ancient groups of people?

Answers to Student Questions

Tasteful Chemistry

- 1. Name the five types of taste cells listed in the article.**
The five types of taste cells are sweet, salty, sour, bitter, and Umami (or savory).
- 2. Name the two cations involved in detecting salty taste.**
Sodium (Na^+) and calcium (Ca^{++}) ions are involved in detecting salty taste.
- 3. How many types of sweet taste receptors are there on the human tongue?**
There is only one type of sweet taste receptor on the human tongue, but it is capable of detecting a variety of "sweet" molecules.
- 4. Which of the five tastes are associated with poisons and rotten food?**
Sour and bitter are the tastes associated with poisons and rotten food.
- 5. Taste is initiated on the tongue when molecules enter a taste cell via small tunnels. Name these structures.**
The small tunnels on a taste cell are called taste receptors.
- 6. Name the taste that is related to salts of glutamic acid.**
Umami is related to glutamic acid salts.

Coffee: Brain Booster to Go

- 1. What is the chemical name for caffeine?**
The chemical name for caffeine is 1,3,7-trimethylxanthine.
- 2. What is the chemical formula for caffeine?**
The chemical formula for caffeine is $\text{C}_8\text{H}_{10}\text{N}_4\text{O}_2$
- 3. What characteristic do all the plants that are known to contain caffeine have in common?**
All the plants known to contain caffeine are recognized as brain stimulants.
- 4. How does caffeine work in the brain to keep you awake?**
Adenosine normally binds to adenosine receptors in nerve cells, resulting in your feeling drowsy. Caffeine preferentially binds to the adenosine receptors in the brain, blocking adenosine from binding to those receptors, preventing you from feeling drowsy – at least temporarily, until the caffeine molecules break down and are excreted.
- 5. Is coffee a simple molecule? Explain.**
No, coffee is not a simple molecule. Chemists have identified more than 800 chemicals in coffee beans, including caffeine, sucrose and other sugars, cellulose, amino acids, proteins, citric and tartaric acids, and even formic acid.
- 6. What happens to coffee beans as they are roasted?**
As coffee beans are roasted, some of the original chemicals disappear, even as new ones develop. The beans' color changes from green/blue-green to yellow, to light brown, and finally to dark brown.
- 7. What happens in the Maillard reaction?**
In the Maillard reaction, heated sugars and amino acids in coffee beans react to form hundreds of color and flavor molecules, which break down into even more aromatic chemicals.

8. **Can scientists identify all the chemicals responsible for the aroma and flavor of coffee?**

Scientists still don't know many of the chemicals responsible for the aroma and flavor of coffee. They still don't know precisely what happens in the roasting process.

9. **What is the role of the antioxidants found in coffee?**

Antioxidants help to prevent damage to proteins and to genetic material that can lead to severe diseases such as cancer, coronary heart disease, and stroke.

10. **What are nutraceuticals?**

Nutraceuticals are food extracts that have medicinal effects.

11. **What are the beneficial effects of drinking a cup of coffee?**

Beneficial effects of drinking a cup of coffee include improving one's mood, increasing mental alertness, cognition and reaction speed, and improving one's ability to do simple math problems – but it doesn't make you smarter! Some studies have shown that drinking coffee can have a positive effect on one's health by preventing type-2 diabetes, Parkinson's, liver and Alzheimer's diseases, and even some forms of cardiovascular disease and cancer.

12. **What are the potentially harmful effects of drinking too much coffee?**

Harmful effects of drinking too much coffee include restlessness, irritability, and sleeplessness.

13. **What's with the dancing goats?**

Legend tells of a goat herder who noticed his flock dancing around a bush of red berries. When the goat herder tried some of the berries, he, too, began dancing. A monk walking by noticed the display of exuberance and took some of the berries back to the monastery where he was able to stay awake for all-night prayers by ingesting some of the berries. The rest of the story about coffee is "history".

Are Energy Drinks Good for You?

1. **Do energy drinks give you energy?**

According to the article – absolutely!

2. **How can one calculate the amount of energy?**

The amount of calories in each drink will determine how many calories of energy it provides. Recall that "food" calories are actually "kilo" calories.

3. **What are the only three food nutrients that can give you calories?**

Fats, carbohydrates, and proteins are the only three food nutrients that can give you calories.

4. **What is considered the most potent ingredient in energy drinks?**

Caffeine is the most potent ingredient in energy drinks.

5. **What ingredient also found in large concentrations in energy drinks is also a cause for concern?**

The large sugar content, usually in the form of high fructose corn syrup, is of concern.

6. **What does one mean by the term "a synergistic effect"?**

A synergistic effect is one in which the combined effect of two or more substances is greater than the effect of each of the substances taken separately.

7. **How does one apply the concept of synergistic effect to the energy drinks?**

The combined effect of the many ingredients when mixed together in energy drinks is still an unknown. Long term effects on the body are not known. No one ingredient may be of concern, but when all mixed together, the mixture may pose a problem.

Glowing Proteins with Promising Biological and Medical Applications

1. What color of bioluminescent light is produced by jellyfish?

Bioluminescent light produced by jellyfish is green.

2. What color of light is produced by the reaction of aequorin with calcium ion?

The reaction of aequorin with calcium ion produces blue light.

3. What is the relationship between blue light emitted by aequorin and green light emitted by green fluorescent protein (GFP)?

The blue light produced by the chemical reaction of aequorin with calcium ion (chemiluminescence and bioluminescence if within a living organism) is absorbed by the GFP that in turn produces green light (fluorescence).

4. What is the difference between the terms bioluminescence and fluorescence?

Bioluminescence is light produced by a chemical reaction within a living organism, while fluorescence is light produced when a molecule absorbs light of a particular wavelength and re-emits the absorbed energy at a different, usually visible, wavelength.

5. What makes GFP glow or fluoresce?

GFP gives off light (fluorescence) when the protein absorbs light in the ultraviolet region and re-emits the energy at a different wavelength (green).

6. What is the basic design plan, or what is required in order to have proteins in cells glow (fluoresce) when exposed to ultraviolet light?

The genes that control the production of the proteins that glow must be inserted into a cell's nucleus next to the genes that control the production of proteins that will be "observed" when they are active.

7. What technique was used to duplicate in large quantities the gene responsible for synthesizing the GFP protein in a cell?

The gene controlling synthesis of the GFP protein was inserted into bacteria which, when reproducing, made many copies of the gene which could then be isolated and inserted into whatever organism is being studied (see question and answer for #6).

8. What are some of the uses of fluorescent proteins (green, red, yellow, blue) in biological research?

Fluorescent proteins can be used to trace infections (protein of bacteria), follow the growth patterns of cancer cells in animal tissue (protein in the cancer cells), trace the migration and behavior of viruses in plant tissue, or watch the particular nerve cells (neurons) involved in a particular neuronal activity.

The Tale of the Teeth

1. How is it possible that some of the skeletal remains dug up in Campeche, Mexico in 2000 were those of 16th Century Africans?

Africans were brought to Mexico by colonial Spanish conquerors.

2. What was the first clue that some of the skeletal remains were of African origin?

The first clue was the pointed teeth (filed), a decorative trait of some African tribes.

3. What was the chemical evidence that supported the initial conjecture that some of the skeletal remains were African in origin?

Chemical analysis of the teeth found that the ratios of the two isotopes of strontium, strontium 86 and strontium 87, did not match the isotopic strontium ratios of the soil and rock of Mexico and Central America.

4. What kind of building was originally built on the foundation excavated in Campeche in 2000?

The original building was a Spanish church.

5. What are isotopes?

Isotopes are variants of a given element's nuclear structure in which the number of protons is the same (hence the same element) but the number of neutrons varies, giving differences in weight but not chemical activity.

6. How can ratios of isotopes of the same element be used to determine the geographical origin of bone or teeth?

Because a person's bones and teeth are made from the chemicals in foods that are eaten, the food in turn derives its chemicals ultimately from the earth. Isotopes of a given chemical element are found in specific ratios, depending on the geographical location in the world. As they say, you are what you eat.

7. If a person migrates from one location to another, how is it possible to use the strontium isotope ratios to determine where that person lived in his or her first few years of life?

In the first few years of a person's life, the teeth lock in the strontium that comes from food eaten. The strontium ratios so fixed reflect the strontium ratios of the soil and rock of that region. Some of the strontium becomes part of food ingested by the residents of the area, including animals and humans, who may eat some of the animals as well as some of the plants.

8. How were scientists able to decide that the African skeletons were not from people who were born in Campeche, Mexico?

Scientists knew the African skeletons were not those of Campeche natives because the ratios of strontium-86 and strontium 87 in the skeletal teeth did not match the isotopic ratios in the soil and rock of the Campeche area.

9. What historical evidence was used to reinforce the chemical idea that the African skeletons were from people who were brought to Mexico?

It was known from historical records of the Spanish that they bought slaves from Portuguese traders in West Africa, near the present country of Ghana.

10. What three groups of people were the original residents of Campeche and surrounding areas in Mexico?

The three original resident groups of Campeche were Mayans, Spaniards and Africans.

11. What new chemical markers may help to determine migration origins, routes, and destinations of ancient groups of people?

The analysis of DNA, the genetic material that determines human characteristics, can provide evidence of similarities and differences between people in different parts of the world and their relationship with ancient DNA characteristics.

ChemMatters Puzzle

This puzzle combines the current popularity of Sudoku puzzles with some chemical knowledge. We are indebted to Chem13 news for this format, since they feature such puzzles in each monthly issue.

We've chosen nine symbols of elements. (You'll see the set in alphabetical order at the bottom of the grid).

Your task is to assign unfilled cells a symbol such that each of the nine appears exactly once in each column, row, and 3x3 box, with no duplications or omissions.

One other help: The symbols in the shaded cells in the top row will spell out in order the name (first initials, full last name) of the chemist widely regarded to be father of the metric system and modern chemical nomenclature .

		La	V				Er	F
	O				F		Mt	
I			Mt	Er		Al	La	
F			I					Al
		O	Al	Si	Mt	V		
V					O			Mt
	Er	Mt		I	La			Si
	V		F				O	
O	La				Er	Mt		

The nine symbols used: Al Er F I La Mt O Si V
 For each, once all nine are situated in the grid, you can cross it off.

Now for a bonus
 ! Match the 9
 elements used
 here to these
 descriptions:

Mt	Al	La	V	O	I	Si	Er	F
Er	O	Si	La	Al	F	I	Mt	V
I	F	V	Mt	Er	Si	Al	La	O
F	Mt	Er	I	La	V	O	Si	Al
La	I	O	Al	Si	Mt	V	F	Er
V	Si	Al	Er	F	O	La	I	Mt
Al	Er	Mt	O	I	La	F	V	Si
Si	V	I	F	Mt	Al	Er	O	La
O	La	F	Si	V	Er	Mt	Al	I

A. Highest

electronegativity of any element.

- Has several oxidation states, each with a distinctive color.
- Part of the carbonyl group in organic chemistry.
- The metal that caps the Washington Monument in Washington, D.C.
- The non-radioactive halogen of biggest atomic radius.
- The first of the rare earth elements.
- Element at the heart of many transistors.
- Named in honor of a famous woman chemist / physicist.
- Its value for [atomic weight – atomic number] is 99.

Answers to the ChemMatters Puzzle

The completed grid has these 81 entries

The middle seven letters of row 1 yield the name **A.L. Lavoisier**

The matching to the nine descriptors:

Al The metal that caps the Washington Monument (quite rare and expensive in the 1800's!).

Er Its value for (atomic mass – atomic number) is 99 (for Er, that's 167 – 68).

F Highest electronegativity of any element. (On the Pauling e.n. scale it's 4.0 .)

I The non-radioactive halogen of biggest atomic radius. (All Astatine isotopes are radioactive)

La The first of the “rare earth” elements.(These are often called the Lanthanides and the Actinides.) The Lanthanides have atomic numbers of 57-71, and the actinides 89-103.

Mt Named in honor of a famous woman chemist/physicist (Lise Meitner, co-discoverer of nuclear fission).

O Part of a CARBONYL group in organic chemistry. (C=O, such as in ketones and aldehydes)

Si Element at the heart of many transistors.

V Has several oxidation states, each with a distinctive color.

NSES Correlation

National Science Education Content Standards Addressed

National Science Education Content Standard Addressed As a result of activities in grades 9-12, all students should develop understanding	Tasteful Chemistry	Coffee	Energy Drinks	Glowing Proteins	Tale of the Teeth	Turning the Lens on Chemistry
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.		✓		✓	✓	
Life Science Standard C: about the cell.	✓	✓		✓		
Life Science Standard C: about biological evolution.					✓	
Life Science Standard C: about matter, energy, and organization in living systems.	✓			✓		
Earth and Space Science Standard D: about geochemical cycles.					✓	
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.

Question from the Classroom

Directions: 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.

Me	Text	Statement
		1. Compounds have much different properties from the elements they are composed of.
		2. It is safe to inhale helium from helium tanks because helium is an inert gas.
		3. When you hold your breath, the gasping reflex is triggered by the lack of oxygen in your blood.
		4. Sulfur hexafluoride has six polar bonds, but the molecule itself is nonpolar.
		5. Balloons filled with sulfur hexafluoride deflate more quickly than those filled with helium.

Tasteful Chemistry

Directions: 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.

Me	Text	Statement
		1. There are four taste sensations: sour, salty, bitter, and sweet.
		2. Sweet and sour taste cells work by the same mechanism as other types of taste cells.
		3. We have approximately the same number of each type of taste receptor.
		4. All tastes linger for the same amount of time.
		5. Taste modifiers may change the way a beverage tastes.
		6. Scientists understand how sweet receptors in taste cells work.
		7. Scientists are working on compounds that would make sweet cells more sensitive so that you can use less sweetener in recipes.
		8. Scientists are working on compounds to block the bitter taste of many medicines.
		9. Molecules from food have special shapes that allow them to bond to certain receptors on taste cells.

Coffee: Brain Booster to Go?

Directions: 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.

Me	Text	Statement
		1. Caffeine is used worldwide more than any other mind-altering chemical.
		2. Because of its shape, caffeine blocks the adenosine receptors in your brain, so you feel alert instead of tired.
		3. Coffee beans contain only about 100 different chemicals.
		4. The coffee roasting process changes the chemical composition of coffee.
		5. Roasted coffee beans release oxygen gas.
		6. Coffee contains large amounts of antioxidants which protect cells from damage by molecules that damage DNA.
		7. Research shows that coffee does not help alcoholics.
		8. Research shows that coffee aroma may benefit people who have stress.
		9. Research shows that coffee is bad for your teeth and it encourages bacteria growth in your stomach and lungs.
		10. Beverages with added caffeine have the same effects on your body as coffee.
		11. Coffee is just as addictive as illegal drugs.
		12. Worldwide, more tea is consumed than coffee.

Are Energy Drinks Good for You?

Directions: 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.

Me	Text	Statement
		1. Energy drinks and sports drinks have similar formulations.
		2. Only fats, carbohydrates, and proteins provide your body with calories.
		3. Even seemingly harmless substances can be toxic if consumed quickly in large quantities.
		4. Mixing combinations of substances can be very dangerous to your health.
		5. Vitamin B ₃ and Vitamin B ₆ provide similar benefits to your body.
		6. The elements carbon, oxygen, and hydrogen are found in all in energy drinks.

Glowing Proteins with Promising Biological and Medical Applications

Directions: 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.

Me	Text	Statement
		1. Fluorescent proteins enable scientists to understand how both viruses and tumors work.
		2. Fluorescent proteins were first discovered in fireflies.
		3. Genes from jellyfish can be inserted into the DNA of humans.
		4. Fluorescent proteins have been used to study plant viruses.
		5. Fluorescent proteins are used to study brain diseases.
		6. Fluorescent proteins are being used to develop anticancer drugs.
		7. So far, scientists have found only green fluorescent proteins.

The Tale of the Teeth

Directions: 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.

Me	Text	Statement
		1. Teeth from a 16 th century grave site indicated that all of the people buried there came from Africa.
		2. Isotopes of the same element have the same number of protons but different numbers of neutrons.
		3. Strontium is found in rocks, but it gets into plants from groundwater, so it can be found in human teeth and bones.
		4. All of the soil on Earth has the same ratio of strontium isotopes.
		5. The Earth’s crust in Mexico is older than the crust in Africa.
		6. Big discoveries in archaeology depend on chemistry.
		7. Archaeochemists work on only one project at a time.

Turning the Lens on Chemistry

Directions: 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.

Me	Text	Statement
		1. According to Felice Frankel, loving what you do is more important than being super smart.
		2. Frankel learned how to photograph chemicals from a chemist.
		3. Chemistry helps explain the optics of reflection.
		4. Ferrofluids are very colorful and fun to photograph.
		5. Scientists often look for visual images as an afterthought, after they have written their papers for publication.
		6. Curiosity is crucial to Frankel’s success.

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

Tasteful Chemistry

Directions: As you read, please complete the table below with information about different tastes.

Taste sensation	How the taste cells work	How we recognize them	Interesting information
Sweet			
Sour			
Salty			
Bitter			
Umami			

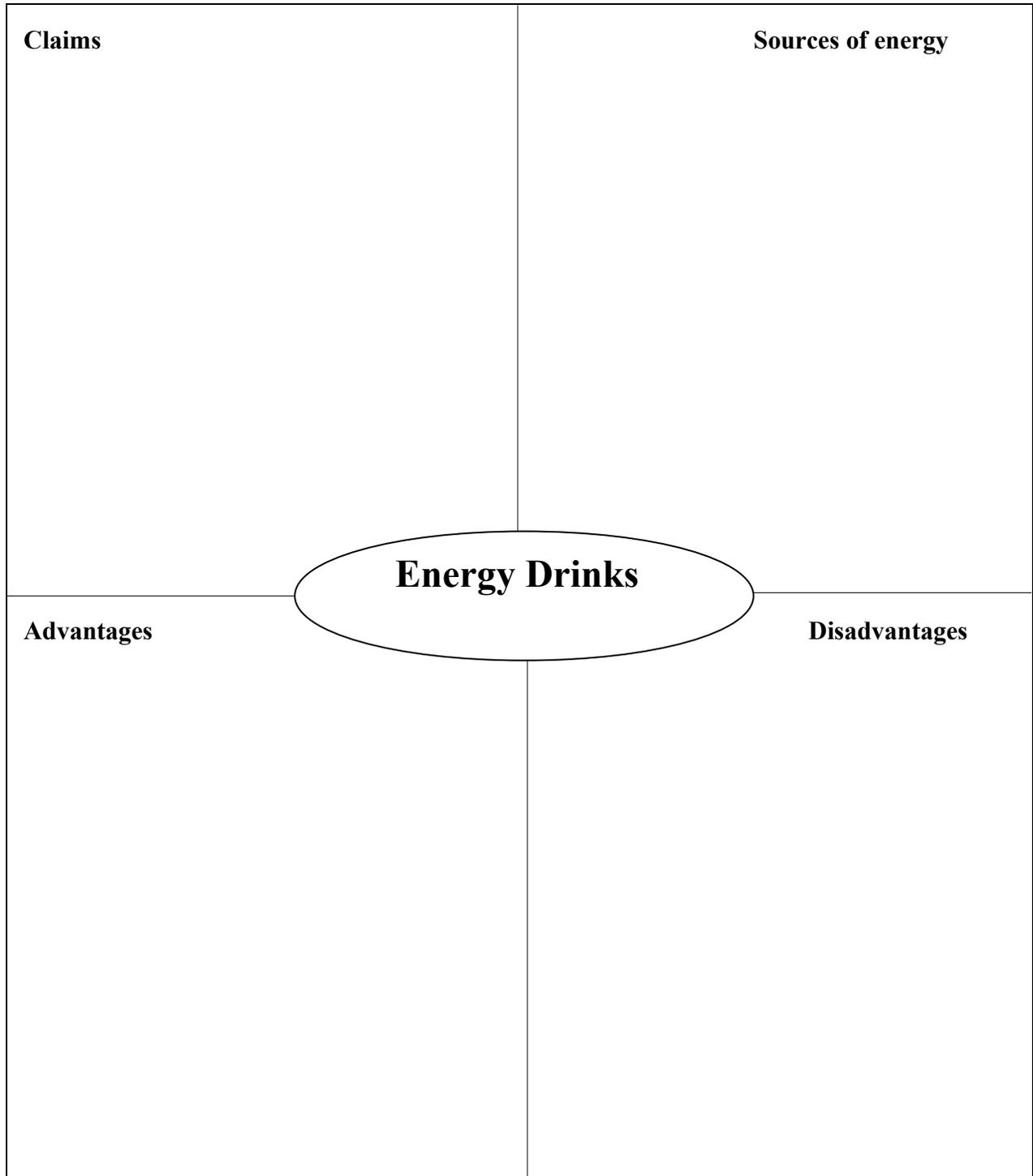
Coffee: Brain Booster to Go?

Directions: As you read, please complete the chart below describing the work of scientists who study coffee and its compounds.

Scientist(s) and Institution	Chemical(s) studied	Health claim(s) and Evidence

Are Energy Drinks Good for You?

Directions: As you read the article, complete the chart below. Use bullets for each new idea.



Glowing Proteins with Promising Biological and Medical Applications

Directions: As you read, please complete the chart below about fluorescent proteins.

Discovery	Who? Where? When?	How?
Use as tracers	Who? Where?	How?
Use to prevent plant diseases	Who? Where?	How?
Use to cure brain diseases	Who? Where?	How?
Use to battle cancer	Who? Where?	How?

The Tale of the Teeth

Directions: As you read, please complete the chart below regarding the investigation of the teeth found in Mexico.

Problem	
Hypothesis	
Procedure	
Claim	
Evidence	
Background information	
Conclusion	

Turning the Lens on Chemistry

Directions: As you read, please complete the diagram below about Felice Frankel.

Felice Frankel	
Background before she began her current career	How she began her current career
What she enjoys about her career	Why she believes her work is important

Tasteful Chemistry

Background Information

“An effective way to deal with predators is to taste terrible.” —Unknown

It is likely that the sense of taste, like smell, became developed billions of years ago. Scientists know that bacteria have receptor cells on their surface which are able to detect the difference between potential nutrients and potential toxins. Jellyfish have these receptors as do nematodes. Honeybees follow odor to find nectar. About half of the land snail’s brain is connected to odor and taste. It has one antenna to detect molecules in the air and a second which it dips in potential food to test it before consuming.

Higher animals separate the sense of smell from the sense of taste, with a separate organ for each, but the two senses are intertwined. Both seem to have developed in order to detect the difference between nutrients and toxins, just like bacteria. What we taste is predominantly the result of odor. Students can test this for themselves by holding their nose and chewing foods of similar consistency, like an apple and a potato, or a variety of jelly beans.

Humans, even with a diminished sense of smell compared to cats or dogs, for example, can smell thousands of separate odors. There are, on the other hand, only the four (or five) tastes as the article suggests—sweet, sour, salty and bitter, with the fifth being umami. The limited tastes provide us with a simple screening technique to decide if we should ingest something or not. Taste, therefore, is related to survival, and not just to a sense of pleasure.

More on Sense of Taste

In humans the sense of taste consists of taste buds, receptor cells, and taste nerves. Taste buds are located on the tongue on small bumps of skin called papillae. Taste buds themselves are too small to see, but the papillae are clearly visible, especially if you place a drop or two of blue food coloring on the tongue. There are about 10,000 taste buds in humans.

The article describes a taste bud being made up of bundles of taste cells, and on the surface of these taste cells are taste receptors. There are typically 50-150 taste cells per taste bud. On any taste bud there are receptors for all five tastes. The receptors respond to molecules of food or drink by triggering chemical changes that eventually send signals to the brain, which the brain interprets as some kind of taste.

Within each taste bud there are receptors cells for each of the five types of taste—sweet, sour, salty, bitter and umami. Each of these receptors cells can detect and respond to potentially hundreds or thousands of individual molecules in food and drink. Current research has found that taste has a genetic base with specific genes producing specific proteins that act within the receptors. These proteins are described in families such as T1R (sweet tastes) or T2R (bitter tastes). Receptor cells are replaced in humans about every ten days.

Interspersed between receptors cells are nerve cells which eventually transmit impulses to the brain. The process begins when a molecule binds to a receptor. This causes the cells to depolarize, which in turn activates the taste nerves. Two substances involved in the neurotransmission are neuropeptide Y (NPY) and cholecystokinin (CCK).

Underlying this complex neurobiology are three simpler chemical concepts—solubility, electrolytes and molecular polarity. When food is first ingested, saliva in the mouth begins the digestive process. Molecules in food dissolve in the water, which brings molecules in contact with taste receptors. If the dissolved molecules are polar, the resulting electrolyte ions play a role in the taste process. Polar molecules bind with the receptors, which triggers a micro-potential difference in nearby nerves, thus sending signals to the brain via one of three cranial nerves—the facial nerve, the vagus nerve, and the glossopharyngeal nerve. Ions like Na^+ and Ca^{++} play an important role in taste. Nonpolar solutes create taste sensations by entering the taste cell itself where a potential difference is created to send signals to the central nervous system

The intensity of a specific taste is directly related to the concentration of dissolved solute. The greater the number of dissolved molecules coming in contact with taste receptors, the more intense the taste. Receptors also have thresholds for taste. If the solute concentration is too low, there will be no taste reported. Below are some examples of threshold concentrations for various tastes:

Taste	Compound	Concentration (Molarity)
Salty	NaCl	0.01
Sour	HCl	0.0009
Sweet	Sucrose	0.01
Bitter	Quinine	0.000008
Umami	Glutamate	0.0007

It should be noted that many chemicals can produce the same taste. Within a given taste there are different thresholds for different chemicals. For example, sucrose, 1-propyl-2 amino-4-nitrobenzene and lactose all taste sweet, but the range of threshold concentrations of these three varies by a factor of 15,000.

As the article states, there are four traditional tastes—sweet, sour, bitter and salty—and one more recent addition to the list—umami. Each of these is believed to have a specific role. For example, sweet taste lets a person know that what they are ingesting is probably rich in energy. The salty taste is important in humans in order to maintain an electrolyte balance. And bitter and sour tastes raise the alarm about foods that are rotten or poisonous.

More on sweet taste

Students will be interested in the fact that a wide variety of organic molecules have a sweet taste. In addition to the carbohydrates like sucrose, fructose and glucose, many aldehydes and ketones taste sweet. Some amino acids, like alanine, glycine and serine taste sweet. Plants produce natural sweeteners like glycyrrhizin, stevioside and thaumatin. Glycyrrhizin makes licorice taste sweet and is 30 times sweeter than sucrose.

Some inorganic compounds taste sweet. Among them are beryllium chloride and lead acetate, which was probably involved in lead poisoning in ancient Rome. A favorite Roman drink called sapa was prepared by boiling sour wine in lead vessels. The acetic acid and the lead reacted to produce the sweet-tasting lead acetate.

In addition to natural compounds, there are a number of synthetic compounds with a sweet taste—chloroform, nitrobenzene and ethylene glycol, for example. Because the latter, the ingredient in antifreeze, has such a sweet taste, pets often ingest the toxic substance. The Humane Society estimates that 10,000 pets die annually from ingesting antifreeze.

Another class of “sweet” compounds are artificial sweeteners—saccharin ($C_7H_5NO_3S$), cyclamate ($NaC_6H_{12}SNO_3$), aspartame ($C_{14}H_{18}N_2O_5$), acesulfame potassium ($C_4H_4KNO_4S$), sucralose ($C_{12}H_{19}Cl_3O_8$), alitame ($C_{14}H_{25}N_3O_4S$) and neotame ($C_{20}H_{30}N_2O_5$). These compounds are better known by their commercial names:

Saccharin—Sweet ‘N Low

Cyclamate—Sucaryl

Aspartame—Equal and NutraSweet

Acesulfame potassium—Acesulfame K or SweetOne

Sucralose—Splenda

Alitame—Aclame

The sweet receptor on the tongue is geared for glucose but will respond to other compounds as well. The mechanism by which the tongue senses sweet taste is that the molecule binds with one or more proteins called T1R2 or T1R3. These are coupled with G proteins that trigger a series of biochemical reactions in the cells that registers taste in the brain.

Since teenage obesity has been in the news so much recently, this article might be an opportunity to discuss calories and diet as part of this section on sweet taste. More information can be found at the National Center for health Statistics site at http://www.cdc.gov/nchs/products/pubs/pubd/hestats/overweight/overwght_child_03.htm.

More on bitter taste

Bitter taste is triggered in the same way as sweet taste. Different receptors bind with bitter molecules and G proteins begin the “chain reaction” of chemical signals that inform the brain. There are many more bitter receptors than sweet because there are so many more compounds with bitter tastes. The T2R family of proteins is also involved with bitter taste.

Compounds that have a bitter taste include quinine ($C_{20}H_{24}N_2O_2$), caffeine, phenylthiocarbamide ($C_7H_8N_2S$) and humulone ($C_{21}H_{30}O_5$). Phenylthiocarbamide has the unusual property of either tasting very bitter, or being virtually tasteless, depending on the genetic makeup of the taster. The test to determine PTC sensitivity is one of the most common genetic tests on humans. Humulone derives from the hops that are used in making beer. Bitter foods include olives, lemon peel, unsweetened chocolate, cabbage, cauliflower, turnip and radish and broccoli.

Bitter taste, unlike sweet, is often undesirable in food and drink. So researchers have looked for ways to “turn off” the ability to taste bitter compounds. One such “bitter-blocker” is adenosine monophosphate (AMP). For example, canned chicken noodle soup contains large amounts of salt to mask the bitter taste resulting from processing the soup. AMP could be added to soup, block the bitter taste and allow manufacturers to use less salt. It could also be used to mask the bitter taste of children’s cough syrups, antihistamines and antibiotics.

More on sour taste

Chemistry books tell students that acids taste sour. That is the basis for all of sour taste. Sour is registered on the tongue when hydrogen ions (H^+) reach receptor cells on the tongue and enter the taste cell. The PKD2L1 molecule is the likely receptor molecule. This action changes the Ca^{++} concentration in the cell and triggers the impulses that lead to the brain. The article describes the basic mechanism that leads to the brain’s registering a sour taste.

Among familiar foods that have a sour taste are: Lemon, grapefruit, lime, tamarinds, fermented dairy products, vinegar-based salad dressing, pickle, apple, apricot, crab apple, grape, grapefruit, kumquat, litchi, mandarin orange, mango, olive, peach, pineapple, plum, raspberry, strawberry, tangerine, tomato, and vinegar.

More on salty taste

The salt taste is the result of the presence of NaCl. Other alkali halides also produce saltiness, but only NaCl and LiCl produce a salty taste above concentrations of about 0.10 M. Specifically, it is Na⁺ ions that elicit the taste. You can note to students that within the alkali metal family saltiness of the ions decreases as atomic number increases. It is believed that the salty taste evolved as a way to find salt-containing foods in order to maintain the body's electrolyte balance.

The American Heart Association recommends that humans consume not more than 2,300 mg of salt per day. That is about 1 teaspoon of salt. Many dietary experts estimate that Americans consume almost 4,000 mg per day.

The article describes the mechanism for the salt taste. Sodium ions enter the taste receptor cells, which permit calcium ions to enter the taste cell, and that event triggers the biochemical reactions that send impulses to the brain.

Dietary sodium has also been a health concern. For more information on sodium, see this information from the National Institutes for Health:
<http://www.nhlbi.nih.gov/hbp/prevent/sodium/sodium.htm>.

More on umami taste

According to the Umami Information Center, "Taking its name from Japanese, umami is a pleasant savory taste imparted by glutamate, a type of amino acid, and ribonucleotides, including inosinate and guanylate, which occur naturally in many foods including meat, fish, vegetables and dairy products. As the taste of umami itself is subtle and blends well with other tastes to expand and round out flavors, most people don't recognize umami when they encounter it, but it plays an important role making food taste delicious."

"Glutamate is naturally present in most foods, such as meat, poultry, seafood and vegetables. Two kinds of nucleotides that contribute most to the Umami taste, inosinate and guanylate, are also present in many foods. Inosinate is found primarily in meat, whereas guanylate is more abundant in plants. Another nucleotide, adenylate, is abundant in fish and shellfish. " Umami-rich foods include mackerel, tuna, cod, squid, oysters, shellfish, beef, pork, chicken, tomatoes, soybeans, potatoes, sweet potatoes, and carrots.

More on flavor

Flavor of food is the sensation produced by food in the mouth, resulting primarily from the senses of taste and smell. Other factors that affect flavors experienced by humans include aroma, fullness, texture, temperature, glossiness, color, shape and sound.

The major nutrients—fats, carbohydrates and proteins--have no flavor compounds. However, amino acids (protein), sugars (carbs) and fatty acids (fats) do have hundreds of flavor compounds that elicit one of the five tastes. The major nutrients develop flavor compounds when they are heated to 250-500F. Likewise, heating increases the number of flavor compounds in amino acids, sugars and fatty acids. Fermentation also increases the number of flavor compounds in many foods.

The Department of Food Science Technology at Ohio State University provides this list of flavors:

Flavor Class	Subdivision	Representative Example
Fruit flavor	citrus-type flavors	grapefruit, orange
	berry-type flavors	apple, raspberry, banana
Vegetable flavors		lettuce, celery
Spice flavors	aromatic	cinnamon, peppermint
	lachrymogenic	onion, garlic
Beverage flavors		hot pepper, ginger
	unfermented flavors	juices, milk
	fermented flavors	wine, beer, tea
	compounded flavors	soft drinks
Meat flavors	mammal flavors	lean beef
	seafood flavors	fish, clams
Fat flavors		olive oil, coconut fat, pork fat,
		butter fat
Cooked flavors		broth beef bouillon
		vegetable legume, potatoes
		fruit marmalade
Processed flavors	smoky flavors	ham
	broiled, fried flavors	processed meat products
	roasted, toasted, baked	coffee, snack foods, processed
		cereals
Stench flavors		cheese

(Taken from <http://class.fst.ohio-state.edu/fst820/820-1.pdf>)

The flavor industry is a major industry in the United States. Chemical flavors and additives are produced for almost every food on the market. In addition to isolating and identifying natural flavor compounds, the industry also produces synthetic flavor compounds for a wide variety of uses.

Connections to Chemistry Concepts

1. **Electrolytes**—Although not mentioned in the article directly, electrolytes are an important chemistry concept for this article. Major steps in the recognition of tastes depend on food ingredients being dissolved in water and in ion form. In addition, the salty taste is an important factor in humans ingesting foods that maintain their electrolyte balance.
2. **Concentration of food ingredients**—Molecules that elicit tastes must be present in threshold concentrations in order to elicit a response.
3. **Senses**—Taste is one of the five senses, the basis for all observing in science. Both taste and smell are thought of as “chemical senses” because the mechanism by which they operate is through a series of chemical interactions and reactions. However, it important to note that a basic rule in chemistry is not to taste anything in the lab.

4. **Biochemicals**—Often, it is difficult for students to understand that most biological processes—like taste—are essentially chemical processes. This article provides an opportunity to pursue that discussion with students.

Possible Student Misconceptions

“Aren’t there specific areas of the tongue for each taste? I did an experiment in elementary school that showed this.” This age-old idea has been shown to be a myth. For an online article from 2006 explaining the new concept of taste see http://www.livescience.com/health/060829_bad_tongue.html.

Demonstrations and Lessons

1. Students can experiment with the sense of taste using a procedure like the one found here: <http://faculty.washington.edu/chudler/taste.html>.
2. The Franklin Institute has several activities related to the sense of taste at <http://sln.fi.edu/qa97/me12/me12.html>.
3. Several more taste activities are here: <http://faculty.washington.edu/chudler/chtaste.html>.
4. Although this taste activity is designed for younger students, chemistry students will benefit as well. From the Exploratorium in San Francisco: http://www.exploratorium.edu/snacks/your_sense_of_taste/index.html.
5. This activity relates taste buds with the intensity of taste experienced: <http://faculty.uca.edu/~jmurray/baw2004/taste.pdf>.
6. This activity allows a class to determine its favorite type of taste: <http://www.sedl.org/scimath/pasopartners/senses/lesson6.html>.
7. The relationship between taste and genetics is explored in the PTC activity: <http://genetics-education-partnership.mbt.washington.edu/cool/tools/ptcpaper.html>.

Student Projects

Many of the artificial sweeteners have had controversial histories. Assign teams of students to do research on one of the artificial sweeteners.

Anticipating Student Questions

“How can there be only five tastes? Most times when I taste food the taste isn’t just one of the five listed in the article.” *The taste of any given food is a mix of several factors. One of them, and the most important, is the basic taste—sweet, salty, etc. But what we taste is also due to our sense of smell, the texture of the food, the temperature of the food, the mood we are in, and other factors. So for any given food there will be nuances of taste.*

References

ChemMatters, April, 1995, “The Taste Effect of Sodium Lauryl Sulfate”, p. 14.

ChemMatters, December, 1992, "Salt", p. 4.

ChemMatters, February, 1988, "Artificial Sweeteners", p. 4.

ChemMatters, April, 1987, "Chocolate", p. 16.

NOVA has a video for sale, titled "Mystery of the Senses: Taste" and is available online at <http://www.shoppbs.org/sm-pbs-nova-mystery-of-the-senses-taste-dvd--pi-2583949.html>.

Web Sites for Additional Information

More sites on electronic senses

<http://www.washingtonpost.com/wp-dyn/content/discussion/2008/03/06/DI2008030603254.html>

More sites on taste and smell

http://www.starsandseas.com/SAS%20Physiology/Neurology/Realm_Chemical.htm

More sites on being a food or flavor chemist

http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_ARTICLEMAIN&node_id=1188&content_id=CTP_003389&use_sec=true&sec_url_var=region1

The American Chemical Society provides information on a career in flavor chemistry at <http://pubs.acs.org/cen/employment/84/8404employment.html>.

More sites on flavor chemistry

For details on flavor chemistry, see this site from Ohio State University: <http://fst.osu.edu/min/Flavor%20Chemistry.htm>

More sites on coffee flavoring

For a *Chemical & Engineering News* article on coffee flavors see <http://pubs.acs.org/cen/science/85/8538sci1.html>.

More sites on the chemical senses

The Monell Chemical Senses Center in Philadelphia does important research on the sense of taste and smell. Check out their web site at <http://www.monell.org/>.

Coffee: Brain Booster to Go

Background Information

More on the history of coffee

The goatherd legend mentioned in the sidebar is but one of many legends that abound about the origins and development of coffee as a global drink. Recent scientific research indicates that the first use of coffee beans might have begun on the plateaus off central Ethiopia and was then brought to Yemen. Although coffee is primarily a drink today (and has been such throughout history), Ethiopian tribesmen used the coffee bean as a food item, mixing the ground up berries with animal fat to produce an energy boosting food.

There is some disagreement about specific times for the development of the coffee industry, but some sources state the actual small-scale cultivation of coffee as a crop for drinking purposes began sometime in the 12th century, and by the 17th century it was a global enterprise. Early on, Yemen became a center for this agribusiness. Mocha, a port of Yemen, became a center of trade of coffee, including trade with Constantinople and Alexandria. The actual export of the beans was very closely guarded, as no live plants or fertile seeds of the coffee bean were allowed to leave the country. This was done to maintain the “monopoly” the Arabian countries had on the coffee plant and hence the value of the country’s export crop. The coffee that was exported was in the form of boiled or parched coffee beans (the seeds of the plant), and these were no longer fertile.

Since wine was forbidden for Moslems, coffee became an essential part of Arabian society. It was so engrained in their culture that an Arabian man could be divorced by his wife should he not provide her with coffee. (It was “grounds” for divorce.) It also became the norm for Arabian merchants to share coffee with traders from other countries, who then took coffee beans back with them to their own countries. This increased the spread of coffee drinking to other parts of the world.

Venetian trade merchants were the first to bring coffee to the European continent. At first, Venetian apothecaries offered coffee to citizens only with a prescription. Coffee became a beverage of choice in many European countries. Even though it was gaining popularity, not everyone thought coffee was a good idea (sounds like today, eh?). Some tried to get the Pope to ban coffee outright for all Christians, citing it as the “devil’s cup” and saying it was the beverage of choice of the Ottoman Empire. Unfortunately (for the detractors), Pope Clement VII tried coffee before he made his decision, and he liked it so much that he baptized it, so it actually became a sanctioned drink for all Catholics.

Entrepreneurs began setting up coffeehouses in cities throughout Europe. These coffeehouses were frequented by artists, scholars, bankers and merchants, and deep discussions often ensued therein. The shops were referred to as “penny universities”, since a penny was charged for admission and a cup of coffee. Edward Lloyd’s coffeehouse opened in 1688. It eventually became Lloyd’s of London, the internationally recognized insurance company.

The African and Arab countries’ tight export security of their coffee beans and live plants apparently paid off, as no large-scale agriculture of coffee trees occurred outside Africa and

Arabia until the 17th century. Then an Indian pilgrim, Baba Budan, left Mecca with seven fertile seeds strapped to his mid-section under his clothing. He began growing them in the hills of Mysore, India, and he began a huge coffee industry in India.

Dutch traders bought some of Budan's coffee plants and shipped them to distant Dutch colonies in Indonesia and Ceylon, where new coffee industries blossomed. (Java, one of the islands where coffee was grown gave birth to coffee's present-day moniker, "java".) These new coffee plantations spelled the death knell for the Arabian monopoly of coffee trade, and ushered in a new era for coffee drinking around the world.

Coffee plants found their way to the Americas by the 1700s by a French soldier who took care of one coffee plant on his sea voyage from Europe to Martinique in the Caribbean. That one plant became the ancestor of more than 19 million coffee plants within 50 years.

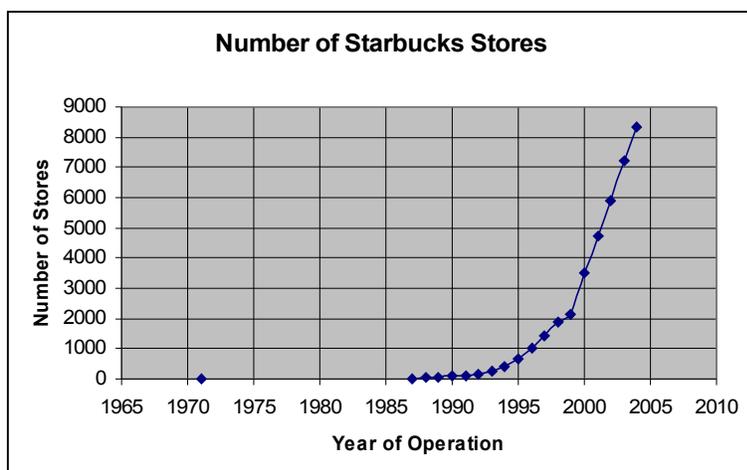
The Continental Congress in the (soon to be) United States declared coffee the national drink due to the harsh tax on tea levied by Britain.

The first decaffeinated coffee was produced in 1903 by a German research team after Ludwig Roselius gave them a batch of ruined coffee beans to reclaim. Their process was not the first to decaffeinate coffee, but it was the first time the coffee was decaffeinated without losing the flavor of the coffee. In 1923 Ludwig marketed the coffee as Sanka® (a contraction of "sans caffeine").

Satori Kato, a Japanese-American chemist was the first to invent soluble coffee, but the first person to market instant coffee was George Constant Washington. He was an English chemist living in Guatemala. He noticed a fine dark powder on the spout of his wife's silver coffee pot. He deduced it had come from coffee vapors condensing on the spout. In 1906 he began experimenting and in 1909 he marketed the soluble coffee product as Red E Coffee.

Nestle developed freeze-dried coffee after Brazil asked them to help find a solution to their coffee surpluses (in good years). It was marketed first in Switzerland as Nescafé®. Instant coffee got a boost after 1956 when commercial television came on the scene. It seems commercial breaks were too short to brew a cup of tea, but long enough to make a cup of instant coffee. The large coffee companies, realizing a huge opportunity, advertised their instant coffees during these breaks. Tea companies recovered by marketing tea bags, which were a new development, since loose tea or tea balls were the norm up to that time.

Starbucks opened its first coffee shop in Seattle, WA, in 1971. In 2004, the latest year for which the company provides data, it had approximately 8,340 stores. Here's a graph of the year vs. number of stores.



Data for the plot was obtained from Starbucks' own web site, <http://www.starbucks.com/aboutus/timeline.asp>.

More on the coffee plant and coffee beans

Coffee plants are really trees, although they are typically pruned to look more like shrubs to increase yield and make harvesting easier. Coffee beans are really not beans at all, but are the seeds of the fruit of the coffee plant. The fruit is called a coffee cherry or berry, and the coffee beans are the seeds inside the coffee cherry. The cherry starts out dark green, but turns yellow and, when ripe, is bright red and pulpy, while the seeds are green or blue-green. They turn to the familiar brown color upon roasting.

You can view photos of coffee trees and their fruit at <http://www.bijlmakers.com/fruits/coffee.htm>. You can also view a short video clip about coffee growing and processing from Newton's Apple at <http://www.newtonsapple.tv/video.php?id=1407>. Be aware that the very end of the clip shows the narrators talking to a group of elementary students, which may be a turnoff to high school students. There is, however, no indication that this is an elementary level talk until that point. A teacher's guide is also available on the site, but this is geared to perhaps middle level students.

The coffee tree reaches maturity in about 5 years after planting, and can be expected to produce good yields for 15-20 years. Each tree produces approximately one-half a kilogram of coffee each year.

Coffee beans come from several varieties of coffee plant. One is the Arabica plant, *Coffea arabica* L, of the Rubiaceae family. The second most popular coffee plant is *Coffea canephora*, also known as *Coffea robusta*. Both are evergreen shrubs, and economically they are the most important members of the family.

Arabica coffee bushes have a relatively deep root system and grow to a height of about 4 meters (12 feet), although they are typically pruned shorter for easier harvesting of the berries. It is the most widely used coffee variety, accounting for about 70% of all coffee grown worldwide. Arabica beans mature in about 9 months, and they are flat beans. The Arabica plant is more susceptible to a number of plant pests and diseases. Arabica coffee has greater acidity

and less bitterness than *C. robusta* coffee. *C. arabica* coffee is grown primarily in South America, Central and East Africa, India, and, to a lesser extent, in Indonesia.

Robusta coffee trees grow to a height of about 10 meters (33 feet), although they are typically pruned to lesser heights for easier harvesting. They have a shallow root system. They produce flowers regularly and take about 11 months for the coffee cherries to ripen to produce oval beans. Robusta beans account for about 20% of the global coffee market. The *C. robusta* plant produces a greater yield than Arabica and is less susceptible to plant pests and diseases. Thus it is usually much less expensive than Arabica and is often used as a filler in cheaper blends. The flavor of *C. robusta* tends to be more earthy and more bitter than Arabica. This extra flavor is useful in blends to give them greater “strength” and “finish”, particularly for the Italian coffee culture. Robusta coffee is grown in western and central Africa, Southeast Asia and, to a lesser extent, in Brazil.

More on roasting coffee

There are four aspects to the taste characteristics of coffees: acidity, aroma, body and flavor. The International Coffee Organization lists 18 terms for types of aroma, 5 for flavor (one of which is “acidity”), and two for “mouth feel” (one of which is “body”).

Roasting of coffee beans occurs at about 400F. At these temperatures, the sugars and other carbohydrates in coffee beans caramelize and form what is called the coffee oil. Since it's water soluble, this substance is not really an oil; nevertheless, it is this “oil” that gives coffee its aroma and flavor. The amount of coffee oil that rises to the surface of the bean is related to the amount of roasting time.

Light roast beans produce coffee with a sharper, more acidic taste, and therefore are not usually used for espresso. The light roast beans may appear cinnamon to light tan in color. Darker roast beans, on the other hand, will vary from medium chocolate brown to almost black, and they will be very shiny due to the coffee oil on their surface. They will have a fuller flavor, approaching bittersweet. As roasting time is increased, caffeine and acidity decrease. The darker the roast, the more char taste will come through, rather than bean taste.

Hundreds of volatile compounds are produced in the roasting process, and these must be allowed to dissipate for a day or two before the optimal flavor of the beans can be realized.

Roasts, from light to dark are typically classified as: Cinnamon, Medium High, City, Full City, French, and finally, Espresso or Italian roast. (Note that on the west coast of the United States, French roast is generally understood to be the darkest roast.)

More on how coffee works in the brain

Caffeine is known to restrict blood vessels in the brain. It also causes the release of adrenaline into the body, resulting in the body remaining alert and active, not sleepy. A third effect is to produce dopamine in the brain, giving the coffee drinker a temporary “high”. In these three respects, caffeine acts similarly to heroin and cocaine, two addictive drugs. Like these two drugs, a person addicted to caffeine will experience withdrawal symptoms, although they will be much less severe than those from the other drugs.

Adenosine typically slows down neural activity when it binds to its receptors, thus aiding sleep. It also dilates the blood vessels, possibly to ensure cellular oxygenation during sleep.

Caffeine replaces adenosine on the receptors, but it does not reduce neural activity; in fact, neural activity is increased. This increased neural activity also causes the pituitary gland to secrete hormones that cause the adrenal glands to produce more adrenaline, providing the individual with increased energy.

Functional magnetic resonance imaging (fMRI) studies provide evidence that coffee affects the brain's prefrontal cortex to improve short-term memory and speeds up reaction times. Caffeine primarily affects "executive memory," which is involved in attention, concentration, planning and monitoring. (Reference: <http://www.newscientist.com/article.ns?id=dn8401>)

More on the chemicals in coffee

Here is a list of some of the chemicals found in coffee, by type of compound:

Carbohydrates

Polysaccharides (glycans) 50% by weight (of dried beans)

Trisaccharides

Disaccharides

(sucrose) 8% (dry weight)

Monosaccharides

Mannose

Galactose

Glucose

Arabinose

Nitrogenous Components

Alkaloids

Caffeine 1-2% (dry weight)

Trigonelline 1% (dry weight)

Proteins

Chlorogenic Acids 7% (dry weight)

Quinic acid

Caffeic acid

Volatile Components 655 volatile compounds in 18 different groups have been identified by GCMS.

Carboxylic Acids (>30 aliphatic acids, including 15 non-volatiles, C1 – C10, rest are volatile

Citric acid

Malic acid

Oxalic acid

Tartaric acid

< 2%(dry weight)

Information above was taken from "Jamaican Coffee" web site at <http://wwwchem.uwimona.edu.jm/lectures/coffee.html>.

List of chemicals found in *Coffea arabica* ("Seed" or "leaf" indicates where chemical is found, and if numbers are present, they represent parts per million. "Tr" means trace amount.)

2,3,5-TRIMETHYLPHENOL *Seed*
2-ETHYLPHENOL *Seed*

2-METHOXY-4-ETHYLPHENOL *Seed*
24-METHYLENE-CYCLOARTENOL *Seed*

24-METHYLENEPHENOL *Seed*
 3,4-DICAFFEOYL-QUINIC-ACID *Seed*
 3,5-DICAFFEOYL-QUINIC-ACID *Seed*
 4,5-DICAFFEOYL-QUINIC-ACID *Seed*
 4-ETHYLPHENOL *Seed*
 4-METHOXY-4-VINYLPHENOL *Seed*
 5-AVENASTEROL *Seed*
 7-STIGMASTEROL *Seed*
 ACETALDEHYDE *Seed*
 ADENINE *Seed*
 ALLANTOIC-ACID *Leaf*
 ALLANTOIN *Leaf*
 ALPHA-TOCOPHEROL *Seed*
 ARABINOGALACTOSE *Seed*
 ARABINOSE *Seed*:
 ARACHIDIC-ACID *Seed*
 ASH *Seed* 37,400 ppm
 ASPARAGINE *Seed*
 ASPARTIC-ACID *Seed*
 BETA-CAROTENE *Leaf* 20 - 25 ppm
 BETA-TOCOPHEROL *Seed*
 CAFESTEROL *Seed*
 CAFESTOL *Seed*
 CAFFEIC-ACID *Leaf*
 CAFFEINE *Seed* 600 - 32,000 ppm
 CAFFEOL *Seed*
 CAFFEYOYL-3-QUINIC-ACID *Seed*
 CAFFETANNIC-ACID *Seed* 84,600 ppm
 CAHWEOL *Seed*
 CALCIUM *Leaf* 19,000 - 20,406 ppm, *Seed*
 1,200 - 1,281 ppm
 CAMOESTANOL *Seed*
 CAMPESTEROL *Seed*
 CAPRINIC-ACID *Seed*
 CARBOHYDRATES *Leaf* 666,000 -
 712,000 ppm, *Seed* 600,000 - 728,000 ppm
 CARNAUBIC-ACID *Seed*
 CELLULOSE *Seed*
 CHLOROGENIC-ACID *Seed* 50,000 -
 100,000 ppm
 CHOLESTANOL *Seed*
 CHOLESTEROL *Seed*
 CHOLINE *Seed* 300 ppm
 CITRIC-ACID *Seed*
 CITROSTADIENOL *Seed*
 COFFEASTEROL *Seed*
 CYANIDIN *Plant*
 CYCLOEUCALENOL *Seed*
 CYSTEINE *Seed*
 CYSTINE *Seed*
 DATURIC-ACID *Seed*
 DEXTRINS *Seed* 8,700 ppm
 DIHYDROLANASTEROL *Seed*
 DIHYDROSITOSTEROL *Seed*
 DIMETHYL-5-ALPHA-CHOLEST-7-EN-3-
 BETA-OL *Seed*
 DIMETHYL-5-ALPHA-CHOLEST-8-EN-3-
 BETA-OL *Seed*
 ENT-16-KAUREN-19-OL *Plant*:
 EO *Seed* 1,000 - 2,000 ppm
 EUGENOL *Seed*
 FAT *Leaf* 55,000 - 59,000 ppm, *Seed*
 74,000 - 170,000 ppm
 FIBER *Leaf* 175,000 - 187,000, ppm *Seed*
 229,000 - 244,000 ppm
 FUFURYL-ALCOHOL *Seed*
 FURFURALDEHYDE *Seed*
 GALACTAN *Seed*:
 GALACTOMANNAN *Seed*
 GAMMA-SITOSTEROL *Seed*
 GAMMA-TOCOPHEROL *Seed*
 GLUCOGALACTOMANNAN *Seed*
 GUAIACOL *Seed*
 GUANOSINE *Seed*
 HEMICELLULOSE *Seed*
 HOMOCCELLULOSE *Seed*
 HYDROGEN-SULFIDE *Seed*
 HYPOXANTHINE *Seed*:
 IRON *Leaf* 966 - 1,032 ppm, *Seed* 29 - 31
 ppm
 ISOCHLOROGENIC-ACID *Seed*
 ISOEUGENOL *Seed*
 LANOSTEROL *Seed*
 LIGNOCERIC-ACID *Seed*
 LINOLEIC-ACID *Seed*
 LINOLENIC-ACID *Seed* 33,300 - 72,000
 ppm
 M-CRESOL *Seed*
 MANNAN *Seed*
 MANNOSE *Seed*
 METHIONINE *Seed*
 METHYL-1-5-ALPHA-STIGMAST-7-EN-3-
 BETA-OL *Seed*
 MYRISTIC-ACID *Seed*
 N-NONACOSANE *Seed*
 NIACIN *Leaf* 52 - 56 ppm, *Seed* 13 - 14
 ppm
 NITROGEN *Seed* 16,000 - 23,000 ppm
 O-CRESOL *Seed*
 O-XYLENOL *Seed*
 OBTUSIFOLIOL *Seed*
 OLEIC-ACID *Seed* 5,920 - 12,800 ppm

OXALIC-ACID *Fruit 154 ppm*
P-COUMARIC-ACID *Plant*
P-CRESOL *Seed*
P-XYLENOL *Seed*
PALMITIC-ACID *Seed 23,680 ppm*
PECTIN *Seed*
PENTOSANE *Seed*
PENTOSANS *Seed*
PHOSPHORUS *Leaf 1,700 - 1,816 ppm,*
Seed 1,780 - 1,900 ppm
PROTEIN *Leaf 99,000 ppm, Seed 98,700 -*
140,000 ppm
PUTRESCINE *Seed*
RAFFINOSE *Seed*
RHAMNOSE *Seed*
RIBOFLAVIN *Leaf 2 ppm, Seed 1 ppm*
SACCHAROSE *Seed*
SCOPOLETIN *Seed*
SINAPIC-ACID *Plant*

SPERMIDINE *Seed*
SPERMINE *Seed*
SQUALENE *Seed*
STACHYOSE *Seed*
STEARIC-ACID *Seed 5,920 - 12,800 ppm*
STIGMASTEROL *Seed*
SUGAR *Seed 4,300 ppm*
TANNIC-ACID *Seed*
TANNIN *Seed 90,000 ppm*
TETRACOSIC-ACID *Seed*
THEOBROMINE *Leaf, Seed 18 ppm*
THEOPHYLLINE *Leaf, Seed:*
THIAMIN *Seed 2 ppm*
TRIGONELLINE *Seed 3,000 - 13,000 ppm*
WATER *Seed 60,000 - 100,000 ppm*
WAX *Seed 10,000 - 14,000 ppm*
XANTHINE *Seed*
XYLAN *Seed*

List above from "Dr. Duke's Phytochemical and Ethnobotanical Databases" at <http://www.ars-grin.gov/cgi-bin/duke/farmacy2.pl?289>.

More on antioxidants in coffee

Antioxidants are used by the body to react with and neutralize free radicals. Free radicals can do cellular damage and can cause cancer and heart disease. The human body already contains some antioxidants, but we need to augment our supply from foods in our diet. Plants are known to contain phenols, which have shown strong antioxidant activity *in vitro*. It is hypothesized that they will have these same properties *in vivo*, allowing them to protect cellular DNA, lipids and proteins from free-radical initiated damage in living cells.

According to a study done at the University of Scranton, PA in 1985, and reported at the 230th American Chemical Society Annual Meeting, coffee is the primary dietary source by which adults in the U.S. obtain their antioxidants. Joe Vinson, Ph.D. and lead scientist in the study, says that "Nothing else comes close." And it doesn't seem to matter whether the coffee is "regular" or "decaf". It beats out fruits and vegetables, known to be good sources of antioxidants. The study took into account both antioxidant quantity per serving size and the frequency of consumption. Coffee beat out more than 100 food items, including fruits (even blueberries and cranberries) and vegetables, nuts, oils and other common beverages. Dates actually were found to contain the most antioxidants on a per serving basis, but dates are not consumed very frequently or in large quantities, so they lost out to coffee.

The availability of antioxidants in coffee, however, doesn't necessarily translate into high levels of antioxidants in the body. Levels in the body depend on how they are absorbed and used in the body, and those processes are not well understood at this time. Antioxidants have been connected to many potential health benefits, including protecting us from cancer and heart disease.

Vinson also suggests drinking black tea if you don't like coffee. Black tea came in second in his study, although black tea has only one-fourth as much antioxidant as coffee (294

mg for tea versus 1299 mg for coffee). Tea is followed in the study by bananas (76 mg), dry beans (72 mg) and corn (48 mg), as third through fifth in the rankings, respectively. A report of the report of these findings can be accessed at <http://www.physorg.com/news6067.html>.

There are approximately 4,000 known antioxidant compounds in plants. Their purpose in plants is to reduce free radicals occurring from UV light exposure. Coffee is somewhat unique in that it doesn't have a lot of different antioxidants. And that is a bit of the problem for humans. There's no evidence yet that the antioxidants found in coffee are the ones we need to maintain our health. That's why we still need to eat our fruits and vegetables, to make sure we're getting what we need in our diets. (http://news.nationalgeographic.com/news/2005/08/0831_050831_coffee.html)

More on health effects of drinking coffee

A WebMD video, "The Truth about Coffee", at <http://www.webmd.com/video/truth-about-coffee> cites findings from many studies that show the benefits of drinking coffee. Nineteen thousand studies have studied health effects of coffee over the years. The video highlights a few of these. According to some recent studies, the potential health benefits of coffee have been linked to protection from colon and liver cancers, Parkinson's disease, and type 2 diabetes.

Chemicals in coffee have been shown to reduce cavities in teeth; reduce the risk of colon cancer, gallstones, cirrhosis of the liver, diabetes and Parkinson's disease (all from antioxidants in coffee); increase athletic speed and endurance, and reduce muscle fatigue. It also improves mood and stop headaches. Scientists still don't know what specific chemicals are responsible for the beneficial effects, and this is a prime reason coffee isn't prescribed to remedy specific health concerns.

A recent study reported in the June 17, 2008 issue of the journal *Annals of Internal Medicine* states that people may actually extend their lives by drinking coffee. The slight increase in longevity was attributed to fewer deaths from all causes in a long-term study of female nurses and a separate one involving male health professionals. After eliminating other risk factors, such as diet, weight, smoking and diseases, the study concluded that coffee drinkers were less likely to die than those who didn't, and that this was due primarily to a lower risk for heart disease-related death. You can find WebMD's report about it at <http://www.webmd.com/heart/news/20080616/drinking-coffee-may-extend-life>.

Drinking too much coffee, however, can lead to stomach distress and nervousness, and some studies have shown elevated heart rates and blood pressure from drinking coffee in excess. Vinson recommends no more than two cups of coffee a day. He also recommends eating fruits and vegetables because, even though they can't match coffee's antioxidant levels, they provide nutrition that coffee can't—specifically fiber, minerals and vitamins.

Coffee made from boiling the beans, called the French press method, has been shown to increase the amount of LDL, bad cholesterol, in the blood. It has also been shown to make drinkers jittery and increase their blood pressure or heart rate, particularly in those with previous heart problems.

More on caffeine

Caffeine's chemical name is 1,3,7-trimethylxanthine. It is the most widely consumed food or beverage (that is pharmacologically active) in the world. The major effect of caffeine is the stimulation of the central nervous system. Caffeine is a member of the alkaloid family of plant chemicals. It is found in more than 60 plant species, including coffee, tea and cocoa beans. Several closely related substances—theophylline, 1,3-dimethylxanthine, and theobromine, 3,7-dimethylxanthine—are found in a variety of plants, also.

Caffeine is absorbed rapidly in the gastrointestinal tract and is practically complete within about 45 minutes of ingestion. Peak plasma caffeine concentration occurs between 15 and 120 minutes of ingestion. Half-life for caffeine in plasma varies from 2.5-4.5 hours in men, increasing substantially (to 80 hours) in infants. Metabolism of caffeine varies from species to species. In humans, about 80% of caffeine demethylates to paraxanthine, and about 16% converts to theobromine and theophylline in the liver. Urates and uracil derivatives are formed upon further demethylation and oxidation. The paraxanthine is even more potent than caffeine itself, so a large portion of the “buzz” people get from drinking coffee is actually due to the formation of the paraxanthine, not the caffeine itself. More than 10 caffeine metabolites can be recovered in urine, but very little (<3%) of ingested caffeine is detected.

As mentioned in the article, physiological concentrations of caffeine antagonize the effects of adenosine. (Adenosine, a member of the family, as is caffeine, has a chemical structure similar to caffeine.) Thus, competition between caffeine and adenosine at adenosine cell receptors leading to changes in the intracellular concentration of AMP is likely to be the mechanism behind the physiological effects of caffeine. (Reference: <http://www.cosic.org/background-on-caffeine>) You can see an animated sequence of the adenosine molecule bonding to the receptor with and without caffeine present at http://thebrain.mcgill.ca/flash/i/i_03/i_03_m/i_03_m_par/i_03_m_par_cafeine.html#drogues.

Caffeine is actually a poison, and it can even be lethal. The lethal dose is about 10 grams. This amount of caffeine would require a person to drink about 60-80 cups of coffee at one time. This is not likely, but an injection of the same amount of caffeine would probably be deadly. The poisonous aspect of caffeine helps to explain why the body responds to caffeine by trying to eliminate it from the system, by breaking it down to the demethylated metabolites.

Connections to Chemistry Concepts

1. **Separation by filtering**—Coffee grounds are usually filtered out before you drink the liquid—a physical separation based on particle size.
2. **Heating to dryness**—Roasting is essentially heating the coffee beans to remove water and alter the flavor/taste of the bean. This is similar to what is done in the lab to dry a substance in a quantitative analysis experiment.
3. **Organic chemistry**—Caffeine, sugars, carbohydrates and many other substances contained in the coffee bean are organic molecules.
4. **Reaction time/rate**—Caffeine has a limited useful “life” in the body. Its effects last only several hours. This is related to reaction kinetics.
5. **Chemical structures**—Caffeine has a structure similar to several other plant chemicals; theophylline and theobromine, and to adenosine. Its similarity to adenosine explains why it is able to bond with the adenosine receptors. Since it is a slightly smaller

molecule than adenosine, it actually bonds more tightly to the receptor than adenosine does. The products of the metabolism of caffeine in the body are also very similar to the original molecule, and these products have similar effects in the body.

6. **Phase diagrams**—One of the decaffeination processes uses carbon dioxide in its supercritical fluid state. The phase diagram for CO₂ can be used in your discussion of phase diagrams in classes. (See *ChemMatters*, April, 1999, pp. 12-13, available on *ChemMatters* 25-year CD.)

Possible Student Misconceptions

1. **“The ‘buzz’ I get from caffeine is harmless.”** While this statement may generally be true, but maybe not, depending on the individual’s health.
2. **“You can’t get addicted to coffee/caffeine.”** On the contrary; people become dependent upon caffeine, just as they do to other addicting drugs. The effects of withdrawal are less severe for coffee/caffeine partly because the original enhancing effects are themselves less severe.
3. **“Coffee is good for you; research proves that.”** Coffee in moderation doesn’t seem to do any permanent harm to the body; nevertheless, dependency does occur, and results of scientific studies are not always clear and do not always agree. Most studies involving moderate coffee drinking show mainly beneficial effects, but those involving greater amounts of coffee ingested show some deleterious effects as well. Also, individuals react to stimuli differently, and studies can only give average effects. If drinking coffee adversely affects an individual, he/she should stop drinking it.
4. **“Energy drinks have more caffeine than coffee.”** This is false. Point 1: caffeine content varies from drink to drink. Point 2: Red Bull, advertised as the most “potent” energy drink re: caffeine, contains 80 mg of caffeine, but the average cup of coffee contains about 100 mg of caffeine.
5. **“I thought antioxidants were only in foods we eat.”** The article tells students that coffee contains chlorogenic acid and other antioxidants, and that coffee is probably the primary source of antioxidants for most people, since we drink so much of it.

Demonstrations and Lessons

1. You can use the filtering of coffee as an example of the process when you first introduce filtration in the lab. Ask students on the basis of what property does filter separate substances. (Answer: particle size) As a follow-up to demonstrating filtration of coffee, you could ask students how they could separate the component compounds of aqueous coffee (as a complete group, not individually) from the solution. (Answer: evaporation)
2. Can a suspect be convicted on the basis of the coffee he left behind? Ok, so this can’t stand alone as evidence, but with other evidence and tests, there’s a whole unit of curriculum, called “Forensic Science in High School Chemistry” that uses coffee and pH as a way of testing evidence to see who committed the evil deed. (Coffee actually plays a very small role in this unit.) Find it at <http://www.chatham.edu/pti/2005%20Units/Law%20and%20Order/Zanetti%20unit.pdf>.
3. To answer the age-old question, “Does your coffee cool faster if you add the cream to your coffee right away and drink it later, or if you take the cream along and add it just before you want to drink it?”, you might want to go to the Newton’s Apple video clip, “Coffee and Cream”, here: http://www.newtonsapple.tv/video_only.php?id=3022. This is a somewhat

light-hearted, yet scientific approach to the experiment. There appears to be a definitive answer here related to kinetic molecular theory. You might want to show the experiment a second time and have students look for uncontrolled variables in the experiment, or ways to improve on the experimental design.

4. While this isn't exactly a chemistry lesson per se, this site shows a coffee maker for sale that is somewhat unique and could be used for a lesson on gas pressure or boiling.

http://www.kitchenware.co.uk/browse_4911&big=1. The apparatus is called a vacuum coffee maker, and it consists of a lower glass pot and a separate top "reactor" piece. You fill the bottom pot with water. The top part looks like a large thistle tube (anyone remember those?), only larger and with a short tube reaching down into the bottom pot. The top vessel also has a filter across its base. Coffee goes into this top "reactor". The top piece fits snugly (think rubber stopper-type fitting) into the bottom pot. You place the completed apparatus on the stove and begin heating the bottom pot. The water begins to boil and builds up (steam and air) pressure inside the bottom pot. This forces very hot water (but not quite boiling) through the stem up into the top part, where it mixes with the coffee. As long as the water continues boiling in the bottom, pressure builds and hot water is forced up to the top part. When the water is all forced into the top, you turn off the heat. The cooling of the bottom pot lowers the ambient pressure inside (hence the name, "vacuum" pot, although that's not exactly true). Outside air pressure forces the coffee solution down through the filter back into the decreased-pressure bottom pot and, voila! Your coffee is finished. In chemistry classes, you could use this apparatus/demonstration to illustrate phase changes, pressure-temperature relationships in gases, or solubility. And when the demonstration is over, you have your daily fix of caffeine already prepared! (You may want to do this demonstration frequently during the year.) ;-)

5. You might want to reproduce the above cited vacuum coffee maker on a smaller scale, using chemistry laboratory glassware. Of course, the problem with this is that you should not drink the results. (Too bad, eh?)

6. Coffee filters can also be used in classes to show filtering (no surprise here, eh?), and to show how chromatography works.

7. Coffee cups also have a use in chemistry labs to serve as the calorimeter in thermochemistry experiments.

8. For anyone with access to a mass spectrometer, IR spectrometer, or high performance liquid chromatography (HPLC) (at a local university, perhaps), there are many web sites describing the extraction and analysis of caffeine from coffee. One complete package for this activity, which uses a virtual mass spec, is described at <http://mass-spec.chem.cmu.edu/VMSL/Caffeine/Caffeine.htm>. Although the site is geared for college-level studies, the Webmaster, Joe Grabowski, provides ancillary materials to high school teachers for their students' use, provided teachers show evidence of their status as an instructor.

9. Ideas for lessons about coffee for an advanced level high school chemistry course could come from the following article from the NSTA's *Journal of College Science Teaching*, Volume XXX, No. 2. "Javametrics 101: Introducing Non-science Majors to the Chemistry Laboratory", on pages 106-108, describes a two-week 3-hour/day multi-disciplinary mini-course of coffee. The course "...integrates the art, literature, history and music of coffee with experiments that emphasize the scientific method." You can access the article, which includes a list of the eight experiments included in the course, at http://www.campbell.edu/faculty/bryan/CHEM441/coffee_chemistry.pdf.

10. You might want to demonstrate liquid carbon dioxide in the classroom as an analogy for supercritical carbon dioxide. You can find a description of the process using a Beral pipet and dry ice. The source: Becker, R. Wet Dry Ice. *J. Chem. Educ.* **1991**, 68(9), pp 782-783.

Student Projects

1. You might ask students to predict the number of stores operated by Starbucks in the intervening years, 2005-2008, and ask them to explain whether they think the trend can/will continue during those years. Then have students do research to discover how many stores Starbucks was actually operating in the years 2004-2008. (Starbucks had 16,226 coffee stores operating in 2008.) Then ask students to explain any differences between their predictions and the actual numbers.
2. Since many students believe that “coffee is good for you”, you might want them to research and report to the class the latest findings of scientific research. You might want them to begin with these web sites: <http://coffeeisgoodforyou.com/>, obviously a web site touting the benefits of coffee drinking, but it lists the results of many studies. On the negative side, they can view a report from the Mayo Clinic, at <http://www.mayoclinic.org/news2007-mchi/3910.html>. You have to read pretty far down the article to find any bad effects. This article from the BBC, <http://news.bbc.co.uk/2/hi/health/3759948.stm>, says one cup a day may be risky. Another site, this one from MSNBC, lists benefits of drinking coffee, as well as the risks and ill effects off drinking too much coffee: <http://www.msnbc.msn.com/id/8375407/>. And Another MSNBC site discusses coffee drinking as a serious risk for people with a specific gene for slow metabolism of caffeine. See <http://www.msnbc.msn.com/id/11713660/>. Students can find lots more information at other sites.
3. Perhaps a debate between those espousing the benefits of coffee drinking and those who believe coffee is deleterious to one' health would be an interesting way to spend a class period. Students could use the sites cited in 2) above.
4. Students could research the methods involved in separating caffeine from coffee and the economic impact of each of the methods in the production off decaffeinated coffee.
5. Students may want to track their daily caffeine consumption, given that so many drinks and other foodstuffs contain caffeine.
6. Have students investigate supercritical carbon dioxide, one of the methods used to decaffeinate coffee, in terms of its chemical relevance to the chemistry course.
7. Students might investigate the relationship between weather and coffee prices. They might start with Brazil's weather, since Brazil produces such a large percentage of the entire world's coffee crop.
8. Have students investigate caffeine content of coffees purchased at various stores in your area. They might try a gas station/convenience food store, a coffee shop, a fast-food restaurant, a “normal” restaurant.

Anticipating Student Questions

1. **“How does caffeine give me all that energy?”** *As mentioned above in the section, “More on how coffee works in the brain”, caffeine works 3 ways: 1) it blocks adenosine on adenosine receptors. This prevents the adenosine from slowing down neural activity when it binds to its receptors, thus aiding sleep and dilating blood vessels, to ensure cellular oxygenation during sleep. 2) Caffeine replaces adenosine on the receptors, but it does not reduce neural activity; in fact, neural activity is increased, resulting in a more wide-awake feel. 3) This increased neural activity also causes the pituitary gland to secrete hormones*

that cause the adrenal glands to produce more adrenaline, providing the individual with increased energy.

2. **“Can coffee replace all those energy drinks?”** Coffee does contain caffeine—and lots of it! But it doesn’t contain all the other ingredients of energy drinks, like amino acids and sugars, so it can give you a buzz and keep you alert, but that doesn’t last long. It may be safer—and healthier for you than energy drinks; the jury’s still out on that one. (See “Energy Drinks” article in this same issue of ChemMatters.

3. **“Why do so many people drink coffee?”** [Millions of people drink coffee, probably for the extra energy they feel they get from it.

4. **“Why is caffeine able to replace adenosine so easily on the adenosine receptors?”** As the article mentions, both caffeine and adenosine have similar shapes, so they both “fit” on the receptors, but caffeine is slightly smaller molecule, so it actually “fits” better than adenosine. It beats adenosine at its own game, so to speak.

5. **“What causes the pressure that makes the coffee beans pop?”** Steam builds up inside the green (moist) beans as they are heated, much like what happens in kernels of popping corn when they are heated to make popcorn. In addition, the breakdown of some of the organic molecules inside the beans when they are heated produces carbon dioxide, which also increases the pressure inside the beans. The combination of these gases forming and increasing in kinetic energy as the beans are heated eventually gets the beans to the point where their shells can no longer withstand the pressure and they “explode”.

References

Coffee Flavor Chemistry, Ivon Flament, Yvonne Tessière-Thomas, John Wiley & Sons, 2001.

“Our Everyday Cup of Coffee: The Chemistry behind Its Magic”, Marino Petracco, *Journal of Chemical Education*, Vol. 82 No. 8 August 2005, pp. 1161-1167. Also available, with subscription, at <http://jchemed.chem.wisc.edu/Journal/Issues/2005/Aug/abs1161.html>

More articles from ChemMatters (CM) archives

The references below are all articles that have appeared in past issues of ChemMatters. They are all contained on the “ChemMatters CD: 25 Years of ChemMatters” (covering years 1983 through 2003). The CD is obtainable from ACS for \$30 (or a site/school license is available for \$105) at this site: [ChemMatters CD](#) (click on CD on right of screen). If this site is invalid, search online for ChemMatters. The ChemMatters CD can also be purchased by calling 1-800-227-5558.

“The Case of the Missing Caffeine”, pp. 12-13, April, 1999, tells about the two major decaffeination processes.

“A Supercritical Clean Machine”, pp. 14-15, April, 2000, describes using supercritical carbon dioxide in dry cleaning processes. The Teachers Guide for the same issue gives background on CO₂’s phase diagram and how to read phase diagrams in general. It also describes and gives a reference for the process of preparing liquid carbon dioxide as a demonstration for students.

Web Sites for Additional Information

More sites on the history of coffee

The National Geographic Society has a somewhat light-hearted look at the history of coffee at <http://www.nationalgeographic.com/coffee/ax/frame.html>. The site includes a global map that shows where the major coffee producers are located, as well as their output (in 60-kg bags) and a brief history of how coffee came to be produced in each of the countries.

For a timeline of the history of coffee, go to <http://www.2basnob.com/coffee-history.html>. This site cites a timeline in an article by Mark Schapiro, "Muddy Waters", in the *UTNE Reader*, Nov/Dec, 1994 issue. (There are some typos in the rewritten timeline, so its veracity may be in question.)

More sites on coffee

The pan-European Coffee Science Information Centre (CoSIC) provides scientific information on coffee, caffeine and health. Its goal is "...to provide accurate, balanced and consistent information to all audiences across Europe who have an interest in coffee, caffeine and health. The objective is to bring balance to the coffee and health debate." CoSIC maintains and updates a scientific database of thousands of published research studies, and provides extensive scientific information about coffee and caffeine. You can find the site at <http://www.cosic.org/>. [Note that this site is run by a consortium of coffee growers/distributors who have a vested interest in the continued distribution and consumption of coffee. While its scientific information may be beyond reproach, CoSIC may present a somewhat biased view on several key issues; e.g., caffeine addiction (called "habituation" by their site), and physiological benefits of drinking coffee (deleterious effects are typically not mentioned, or played down).

Starbucks'® web site has quite a bit of information about coffee, including history, growing regions, growing, harvesting and preparing coffee and, of course, its coffee menu. Find it at http://www.starbucks.com/ourcoffees/coffee_edu1.asp?category%5fname=coffee+education.

More sites on coffee bean and coffee plant

You can find images of coffee plants and coffee beans on the tree and by themselves on the Britannica web site at <http://www.britannica.com/EBchecked/topic-art/124337/859/Turning-coffee-beans-for-even-drying-in-the-Costa-Rican#assembly=url~http%3A%2F%2Fwww.britannica.com%2FEBchecked%2Ftopic-art%2F124337%2F4925%2FTurning-coffee-beans-for-even-drying-in-the-Costa-Rican&tab=active~checked%2Citems~checked>

The Food and Agriculture Organization (FAO) of the United Nations has a web site describing their work with coffee plantations on Myanmar. The site is replete with diagrams and pictures of growing and processing of coffee beans, including the machinery needed to do it. It includes pictures and diagrams of the internal structure of the coffee cherry and the beans inside. You can find the site at <http://www.fao.org/docrep/008/ae938e/ae938e03.htm#TopOfPage>.

More sites on antioxidants in coffee

MSNBC has another article about the Vinson antioxidant study at the University of Scranton at <http://www.msnbc.msn.com/id/9105892/>. The article is titled, "Coffee a top source of healthy antioxidants: But beverage is still no substitute for fruits and vegetables".

WebMD has a video about the virtues of coffee at <http://www.webmd.com/video/truth-about-coffee>.

The Coffee Science Information Centre discusses the role of antioxidants in coffee on health-related issues at <http://www.cosic.org/coffee-and-health/antioxidants>. This is fairly detailed information.

More sites on caffeine

"Coffee and Caffeine Chemistry" is a short 4-1/2 minute video clip that shows basic information about coffee via simple Flash® animations. It is available for purchase (for \$9.00) or for viewing (for \$2.00) from Goalfinder: The Knowledge Makers at <http://www.goalfinder.com/product.asp?productid=94#>. You can view a less-than-a-minute clip of the clip for free at the site.

To see simplistic structural formulas of compounds with structures similar to that of caffeine, see http://www.erowid.org/chemicals/caffeine/caffeine_chemistry1.shtml. This site also cites four articles dealing with analogs of caffeine.

More sites on chemicals in coffee

Coffee Research.org's Web site has a table of chemical compounds responsible for the aroma of coffee. You can find it here: <http://www.coffeeresearch.org/science/arommain.htm>.

Bitterness in coffee can be attributable to specific chemicals. See the explanation and list of chemicals at the Coffee Research Institute's web page on bitterness at <http://www.coffeeresearch.org/science/bittermain.htm>.

Acidity of coffee is actually a valued quality. See a list of the acids present in coffee at the Coffee Research Institute's web page on acidity at <http://www.coffeeresearch.org/science/sourmain.htm>.

General Web References

Coffee Research Institute hosts an extensive web site, covering coffee from plant to cup, at <http://www.coffeeresearch.org/science/sourmain.htm>.

An arm of the National Coffee Association, "Coffee Science Source", maintains a web page at <http://coffeescience.org/>. Information on this site overlaps some of that on the Coffee Research Institute's site, cited above.

The International Coffee Organization hosts a web site replete with information about coffee, caffeine and decaffeination processes at <http://www.ico.org/>

Are Energy Drinks Good for You?

Background Information

More on the history of energy drinks

The first “energy” drink can be attributed to the Japanese. The drink, Lipovitan-D, was produced by Taisho Pharmaceuticals in 1962. Vitamins B1, B2, and B6 and niacin and taurine were the key ingredients in the drink. The drinks were supposed to give a boost in energy and provide the body with vitamins at the same time.

Based on the increasing popularity of the drinks in Asia, Dietrich Mateschitz, an Austrian, took the “tonic” drink concept, added sugar and caffeine, and produced Red Bull for the European market in 1987. Red Bull continues to be one of the best sellers and most recognized names in the energy drink market.

With so many drinks currently on the market, each trying to capture a small part of the craze sweeping the U.S., Europe, and Asia, marketing is the key element for success. Red Bull spends approximately 30% of its revenues on marketing. Larger established companies like Coca Cola spend about 9%.

More on the “suspected dark side to these beverages”

Rohrig cites two cases of a suspected connection between the energy drinks and the illness of four Florida teens and the death of an Irish basketball player. One could initiate an interesting class exercise on how to scrutinize web-based information. The Urban Legends web site at Snopes.com addresses the issue of the dangers of Red Bull and specifically mentions the case of the Irish basketball player. (<http://www.snopes.com/medical/potables/redbull.asp>)

Even though the player drank three cans of Red Bull prior to the game, his death on the court was attributed to thickened arteries and sudden adult death syndrome. The London Daily Telegraph reported the incidents referred to in the Urban Legends web site. Links to the article are listed below. <http://www.telegraph.co.uk/news/newstoppers/politics/health/1374291/Student-died-after-sharing-three-cans-of-Red-Bull.html> and <http://www.telegraph.co.uk/news/worldnews/europe/sweden/1333884/Red-Bull-under-investigation-after-link-to-three-deaths.html>

More on what America drinks

The Beverage Marketing Corporation (<http://www.ameribev.org>) provides statistics on beverage consumption for the average (non-existent) American. This average person “needs liquids, wants liquids, and drinks liquids.” The information may be useful when discussing the specific consumption of energy drinks. According to the BMC:

Total U.S. Beverage Consumption in 2005

Carbonated Soft Drinks	28.3%
Bottled Water	10.7%
Milk	10.9%
Coffee	9.0%
Beer	11.7%
Fruit Beverages	4.7% (fruit beverages and fruit drinks)

Sports Drinks	2.3%
Tea	3.8%
Wine	1.3%
Distilled Spirits	0.7%
All Others	15.3% (tap water, vegetable juice, powders, and miscellaneous drinks)

(Source- <http://www.ameribev.org/all-about-beverage-products-manufacturing-marketing--consumption/what-america-drinks/index.aspx>)

More on adverse effects of the consumption of energy drinks

A number of sources list health concerns related to the consumption of energy drinks. A well-referenced study at the University of California—Davis noted that caffeine consumption of up to 400 mg per day for a healthy adult did not appear to have any adverse effects. At-risk groups such as children and women of reproductive age should limit consumption to 300 mg per day. Caffeine consumption greater than 100 mg per day may trigger a rise in blood pressure in adolescents. The study concludes that “pregnant or nursing women, adolescents, and children” should not consume energy drinks.

The addition of guarana to energy drinks increases the caffeine content in the drinks. Drinking more than one energy drink on any one day will also greatly increase the caffeine ingested. Consumption of more than 400 mg per day may lead to “nervousness, irritability, sleeplessness, increased urination, abnormal heart rhythm (arrhythmia), decreased bone density levels, and stomach upset.” The high sugar levels found in many energy drinks also pose potentially serious health problems, especially when combined with the other ingredients.

The addition of herbal supplements to the caffeine in energy drinks, combined with claims made by the energy drinks manufacturers, prompted the Center for Science in the Public Interest to propose that the FDA enforce stricter standards for energy drinks. A hearing held by the FDA on Dec. 5, 2006 targeted not only claims made by energy drink manufacturers but also claims made for what are called “functional” foods. Examples include claims made by Rockstar energy drink—“party like a rockstar”—and the label on Monster Energy drink that states that, “We went down to the lab and cooked up a double shot of our killer energy brew. It’s a wicked mega hit that delivers twice the buzz of a regular energy drink.”

No long term studies are available on the lasting effects of energy drinks. A number of studies on college campuses and in Europe are beginning to collect data. The references listed below provide added information on the health effects and the studies.

<http://www.cspinet.org/new/200612051.html>,
<http://anrcatalog.ucdavis.edu/10325/8265.aspx>,
http://www.boston.com/yourlife/health/fitness/articles/2007/01/29/are_energy_drinks_bad_for_you/, and
http://seattletimes.nwsourc.com/html/health/2002430338_healthenergy10.html

Connections to Chemistry Concepts

1. **Conversion of food Calories to chemical calories/kilocalories**—Students learn that one calorie is the amount of energy needed to raise the temperature of one gram of water by one Celsius degree. Food calories listed on food labels use a capitalized “C” for the

calorie. The food “calorie” is actually one thousand of the chemical calories. Therefore, a product that contains 100 C actually contains energies of 100,000 cal or 100 kcal.

2. **Chemical formulas and structures**—The bulk of the article consists of the chemical ingredients of four of the most popular energy drinks: Red Bull, Monster, Rock Star, and Amp. The web references at the end of the Teacher’s Guide provide the students with three dimensional molecular models. Students may select the type of view—from ball and stick to space filling. The molecules may also be rotated. For students who have a basic knowledge of organic chemistry, the models serve as an excellent tool for review and enhancing knowledge of complex organic molecules.

Possible Student Misconceptions

1. **“Energy drinks provide even better benefits than sports drinks.”** *This is a popular misconception that can have dire consequences. Some student athletes have been known to consume energy drinks before and during vigorous exercise. The role of the sports drink is to re-hydrate the body and replace spent electrolytes and fluids. The caffeine in the energy drink provides a rush by increasing heart rate and blood pressure. This apparent boost in energy is short-lived. The loss of water (body fluids) through perspiration and the diuretic effects of the caffeine can leave the athlete severely dehydrated. As a result, the athlete is not able to perform at a peak level for the duration of the game/event.*
2. **“It is OK for high school athletes to drink energy drinks as long they do it in moderation.”** *Not known to many high school athletes is that the NCAA has banned the high levels of caffeine and some of the other ingredients found in energy drinks. Concentrations of caffeine exceeding 15 micrograms per liter are banned by the NCAA. Other ingredients found in the drinks may be banned in any amount. Synephrine is a banned stimulant found in Speed Stack and Ripped Force distributed by ABB as well as in the Worldwide Extreme Thermo Rush drink. NCAA rules do not apply to high school athletes. As a result, habits formed in the high school years may have serious repercussions during the college years. A complete list of substances banned by the NCAA may be found at <http://www.ncaa.org/wps/ncaa?ContentID=283>.*

Demonstrations and Lessons

The data on caffeine content and sugar content of various energy drinks can be used as an exercise to review graphing techniques utilizing Excel or Fathom. The data can be found at the following sites: <http://www.energyfiend.com/the-caffeine-database>, and http://en.wikipedia.org/wiki/List_of_energy_drinks.

Student Projects

1. Since caffeine is the main ingredient in sports drinks, students may wish to research the amount of caffeine in each of the energy drinks now on the market. How the information is presented is left to the students’ ingenuity and creativity. The following web sites list the analyses of the caffeine and other ingredients in the drinks: <http://www.energyfiend.com/the-caffeine-database> and http://en.wikipedia.org/wiki/List_of_energy_drinks.

2. The above study could be expanded to include sugar, also a primary ingredient, as well as some of the other additives.
3. Students can set up a display of cans of the different beverages. The cans can be grouped by the quantity of caffeine in the drink, or by the total number of calories in the drink.
4. A study of the websites of each of the drinks can afford the students to examine marketing techniques and the selection of a target audience. The websites are listed in the “General Web References.”
5. The Urban Legends articles on refuting the claims that an ingredient in Red Bull causes brain tumors is worth investigating if someone is not familiar with the Snopes or Urban Legends site. A history of the assertion as well as information confirming or refuting the assertion is presented with a comprehensive list of references. The reference list in turn serves as a starting point for further research.
<http://www.snopes.com/medical/potables/redbull.asp>

Anticipating Student Questions

1. **“What are the percentages of each ingredient in each of the energy drinks?”** *Percent values are not required on the drink labels. Instead, the ingredients are listed in decreasing order of percent content in the drink. The gaps in percent between one ingredient and the other are not the same.*
2. **“The main ingredients in the energy drinks appear to be similar. Why are there so many energy drinks on the market?”** *The popularity of energy drinks and the potential monetary profits from sales of energy drinks has caused the large number to flood the market. Each drink has its own marketing ploy to grab the attention and purchase by its intended audience. Energy drinks will most likely fall into the “fad” category of so many products that have made it to market and have been replaced by the next fad.*
3. **“What are the effects of water, sports drinks, soda, and energy drinks on the body?”** *Water replenishes loss of fluids from the body. The sports drinks not only replace fluid levels in the body, but they also replace electrolytes lost during heavy exercise. Sports drinks can be considered to be flavored “sweat” or “perspiration.” They are most effective following strenuous exercise. Regular sodas contain high levels of sugar in the form of high fructose corn syrup with caffeine, in many cases. Sodas appear to boost energy and concentration because of the two main ingredients. Sugar free and non-caffeinated drinks are consumed for their taste preferences with little energy impact on the body. The typical energy drink, with its high level of caffeine and sugar, provides a relatively quick but short-lived energy boost. As stated earlier, energy drinks should not be used in place of the sports drinks during or after strenuous exercise because they do not rehydrate the body. They act as diuretics.*
4. **“How do the caffeine levels in energy drinks compare to other drinks?”** *A study of energy drinks by the University of California—Davis presents the following general information: “The caffeine content of a single serving of an energy drink (8 to 12 fl oz) can range from 72 to 150 mg; however, many bottles contain 2 to 3 servings, raising the caffeine content to as high as 294 mg per bottle. In comparison, the caffeine content per serving of brewed coffee, tea, or cola beverages (8 fl oz) ranges from 134 to 240 mg, 49 to 175 mg, and 22 to 46 mg respectively.” (Heneman, Karrie and Zidenberg-Cherr, Sheri. “Energy Drinks.” Nutrition and Health Info Sheet, Publication 8265. University of California—Davis) (<http://anrcatalog.ucdavis.edu/10325/8265.aspx>)*

References

Graham, Tim. "Sports Drinks: Don't Sweat the Small Stuff". *ChemMatters*. February, 1999. Pp 11-13.

"Raging Bull: Health warnings over popular drink being brushed off?" <http://www.cbc.ca/consumers/market/files/health/redbull/index.html> from CBC News, Toronto

Web Sites for Additional Information

More sites on molecular structures: The focus of the article is on the chemicals that make up the various formulations of energy drinks. Students might be interested in viewing and manipulating molecular structures of the various ingredients found in energy drinks. The following web sites provide structures that can be manipulated, rotated, or converted from ball and stick to space filling models.

Caffeine: <http://www.3dchem.com/3dmolecule.asp?ID=138>

Glucose: <http://www.3dchem.com/molecules.asp?ID=423#>

Sucrose: <http://www.3dchem.com/molecules.asp?ID=59#>

Taurine: <http://www.3dchem.com/molecules.asp?ID=22#>

Vitamin B₂: <http://www.3dchem.com/molecules.asp?ID=63>

Vitamin B₃: <http://www.3dchem.com/molecules.asp?ID=64#>

Vitamin B₆: <http://www.3dchem.com/molecules.asp?ID=65#>

Vitamin B₁₂: <http://www.3dchem.com/molecules.asp?ID=66#>

Calcium Pantothenate: <http://www.chemblink.com/products/137-08-6.htm>

Citric Acid: <http://www.chemblink.com/products/5949-29-1.htm>

Benzoic Acid: <http://www.chemblink.com/products/65-85-0.htm>

Sodium Citrate: <http://www.chemblink.com/products/68-04-2.htm>

More sites on other ingredients found in energy drinks

The following five ingredients found in energy drinks are not compounds which can be represented by a single molecular formula. The nutrasanus Web site referenced below contains a natural health library where the reader can obtain up-to-date information on herbs, vitamins and other health supplements.

Ginkgo Biloba Extract: [<http://www.health-marketplace.com/Ginkgo.htm> or <http://www.nutrasanus.com/ginkgo-biloba.html?search=ginkgo%20biloba>]

Guarana Seed Extract: [<http://www.nutrasanus.com/guarana.html>]

Inositol: <http://www.nutrasanus.com/inositol.html?search=inositol>

Milk Thistle Extract: <http://www.nutrasanus.com/inositol.html?search=inositol>

Panax Ginseng Root Extract: <http://www.nutrasanus.com/panax-ginseng.html?search=panax%20ginseng>

More sites on Red Bull's ingredients

<http://www.redbullusa.com/#page=ProductPage.Ingredients>

General Web References

A Listing of energy drink production web sites:

http://www.dmoz.org/Business/Food_and_Related_Products/Beverages/Sport_and_Energy//.

A listing of reviews of individual energy drinks: This web site consists of a photographic table of 161 energy drink bottles/containers. One simply clicks on a particular bottle to be given a written review of the energy drink. A summary text list of the reviews is also available: <http://www.screamingenergy.com>.

A web site providing general and specific information on energy drinks: The website provides a history of energy drinks, claims and criticisms of energy drinks, common energy drink ingredients, and an energy drink directory: <http://www.energysip.com/sitemap.html>

A well documented nutrition and health information sheet on energy drinks: The University of California—Davis' Publication 8265 provides a wealth of well documented nutrition and health information on energy drinks. Tables within the information sheet list caffeine and sugar content of a number of energy drinks, unusual ingredients and what they claim to do, support for the claims, and, finally, safety of consumption of the ingredients: <http://anrcatalog.ucdavis.edu/10325/8265.aspx>.

Glowing Proteins with Promising Biological and Medical Applications

Background Information

More on Bioluminescence

Bioluminescence in animals (single-celled to multicellular) can be used to attract mates, as in fireflies. The reaction in fireflies, and a variety of biological organisms from single cell algae to fish, is based on a reaction using molecules called luciferins that are involved in bioluminescence. They include luciferin in bacteria, dinoflagellates, fish, and fireflies among other examples. Each type of luciferin has a very different structure. (To see these molecular structures, go to <http://www.lifesci.ucsb.edu/~biolum/chem/detail2.html>.) Luciferin is activated with adenosine triphosphate (ATP) to form a complex. This complex, in the presence of oxygen, some ions, as well as the enzyme luciferase at a given pH, undergoes a redox reaction with some of the chemical potential energy converted to light. As the concentration of ATP increases, so does the light that is produced.

The light is considered to be “cold” light; little heat is generated, which suggests an efficient system of energy conversion in the chemical reaction. An interesting aside is the fact that luciferin from fireflies (ground up firefly tails) is actually used as an analytical tool to determine the concentration of ATP in biological tissue. It is also available as a synthetic chemical for use in the same type of ATP assays. The light emitted is measured with a sensitive light meter and correlated to known concentrations of ATP. Another interesting historical fact is that, during World War II, soldiers used dried sea fireflies (*Cypridina hilgendorffii*) to produce dim nightlight by simply crushing the organisms in sand and water. This is a luciferin-luciferase system that does not require ATP for bioluminescence. (A kit can be purchased from Carolina Biological Supply for use in the classroom. There are also firefly bioluminescent kits available for purchase).

Bioluminescence (chemiluminescence in a living organism) has to be distinguished from fluorescence. The former requires enzymes and chemical reactions whereas the latter involves the absorption of radiant energy that is re-emitted at a different wavelength due to changes in the position of valence electrons. A good visual of this can be found at <http://www.lifesci.ucsb.edu/~biolum/chem/>. Interestingly enough, in the Glowing Protein article, the special bioluminescence associated with jellyfish has two stages. A calcium-dependent bioluminescent protein named *aequorin* emits blue light from a chemical reaction. This blue light is then absorbed by a second protein (named GFP) that produces fluorescence in the green band of light. This combination of reactions is the basis for light production (final stage being green fluorescence) in jellyfish. As mentioned in the article, the key to the eventual use of fluorescence in locating individual tissue cells (a biological marker) was the incorporation into a cell's nucleus of the genetic material (DNA) that controls the production of the GFP protein that is attached to other protein-controlling DNA. Again, because the GFP produces fluorescence, it does so only when it is stimulated by a specific wavelength of light, in this case in the ultraviolet region. An extensive reference to fluorescent proteins, complete with many photomicrographs, is found at the Nikon Microscopy website, <http://www.microscopyu.com/articles/livecellimaging/fpintro.html>.

This tool of fluorescent proteins is useful, not only to locate specific proteins within a cell, but to see their activity (e.g., synthesis) in real time. In particular, the study of the nervous system in action, based on protein synthesis, as in memory activation for instance, proves to be a non-invasive tool. In the past, studies of the nervous system in action (depending on the size of the animal studied) required the introduction of electrodes into the nervous system to record nerve activity. Such intervention runs the risk of modifying or even damaging the nerve cells themselves. With the use of the GFP incorporated into the individual nerve cells, one merely has to have a light stimulus in the UV region and some recording device for detecting emission of light in the green region. Depending on the subject (fruit flies, worms), both the absorption of the stimulus light and the emission of the fluorescent light can be done with the animal intact

Because there are now fluorescent proteins that emit other colors besides green, mapping of the nerve tissue can be done with multiple colors tracing different neurons (different functions or enervations). The protein material within a neuron can be genetically modified so that the luminescence emitted does so in response to a number of different changes in a neuron including voltage or calcium associated with signaling within a cell, as well as the release of neurotransmitters that allow for passage of neural “signals” between nerve cells.

A very good reference to elaborate on this concept of viewing neural activity in real time as well as actually controlling cellular functions (which would be useful if you want to get a cell to secrete a particular chemical at a specific time) is found in Scientific American magazine, <http://www.sciam.com/article.cfm?id=three-color-coral-protein> and <http://www.sciam.com/article.cfm?id=neural-light-show> (in print as “Lighting Up the Brain” in the October, 2008 edition of *Scientific American*, pp. 52-59).

Additional useful material on fluorescent proteins, with many color photographs, can be found at the website of a research professor from Connecticut College, <http://www.conncoll.edu/ccacad/zimmer/GFP-ww/GFP-1.htm>. As used by living organisms, see <http://www.bio.davidson.edu/Courses/anphys/1999/Cody/Cody.htm> for photographs of mostly marine organisms.

[NOTE: On October 8, 2008 the Nobel Prize in chemistry was announced. It was awarded to the three principle investigators responsible for the isolation and elucidation of the Green Fluorescent Protein (GFP). The winners are Osamu Shimomura (Japan), and Americans, Martin Chalfie and Roger Tsien. You can read about the awards in *Chemical and Engineering News*, October 13, 2008 issue, page 7, or online at <http://pubs.acs.org/cen/news/86/i41/8641news1.html>.]

More on Protein

Proteins perform many important functions in living organisms. These include:

- Regulation of gene expression (control of cell growth and reproduction; control of hereditary information in terms of how much is used at any given time)
- Motion (contraction and expansion of muscle results from interactions between specialized protein molecules, actin and myosin)
- Structural tissue as well as cell components such as the cell membrane
- Enzymes providing catalysis in biochemical reactions
- Receptors for nerve impulses in the nervous system; these receptors also respond to stimuli from hormones as well as light, as in photosynthesis

- transport within a circulatory system by specialized proteins; examples include hemoglobin-carrying oxygen. Myoglobin stores oxygen in tissue. Other proteins assist in transport of molecules across cell membranes.

Proteins are polypeptides that consist of amino acids linked together. They have well-defined three-dimensional shapes. The behavior of proteins depends not only on the order of the amino acids but also on the secondary, tertiary, or quaternary structures, i.e., the folding arrangements of these long chains of amino acids. Failure to fold properly means a malfunctioning molecule. And the insertion of just one or two incorrect amino acids in the sequence may mean a malfunctioning of the molecule, which could lead to an inherited disease.

Proteins are formed by condensation reactions of amino acids. For humans there are 20 different amino acids that can be used to make protein. The chemical differences between these amino acids are determined by side chain or R group of the molecule. Amino acids are the same in that they all have an amine group (-NH₂) bonded to a carbon (the α carbon), which is in turn bonded to a carboxylic acid (-COOH) group—hence the name amino acid. The α carbon in amino acids is also attached to one hydrogen and to a second group, which differs in the different amino acids.

In a condensation reaction to form a polypeptide, bonds are formed between amino acids using the amine group and the carboxyl group and splitting out a molecule of water. While the overall sequence of the protein is held together by strong covalent bonds, the way the strand is arranged in space (the “fold” of the protein) is determined by much weaker interactions between the side chains of the strand, such as hydrogen bonds or van der Waals interactions. These interactions can be easily broken and if the protein misfolds, it may not work properly.

More on Deoxyribonucleic Acid (DNA)

One of the key techniques for putting fluorescent proteins into an animal's cell depends on the insertion into the functioning cell of specific genes that control the formation of fluorescing proteins. These genes contain the information that dictates how these proteins are to be formed from specific sequences of amino acids. Genes are composed of deoxyribonucleic acid (DNA), a polymer-type structure consisting of repeating units called *nucleotides*. The nucleotides consist of a nitrogen base connected to a sugar (either ribose or deoxyribose) by a covalent bond. These two entities (called a *nucleoside*) are linked to a phosphate group, creating what is called a nucleotide. These nucleotides can be made from four different bases, which when linked together begin to establish a specific sequence that becomes genetic information.

There is plenty of visual information available on the structure of the units that make up a nucleotide. A very good collection of molecular visualizations can be found at <http://www.accessexcellence.org/RC/VL/GG/>. From a chemical standpoint two things are of interest here. When you see the structure of DNA or RNA, you will notice that the structural units, the nucleotides, are held together in a double helix by hydrogen bonds.

One way to think about this double helix is as follows. If you imagine taking a ladder and slicing it in half vertically (through the rungs), and then twisting it into a corkscrew shape, then that's a fair image of DNA. The rungs of the ladder are the bases, the posts holding the rungs are the sugar-phosphate backbones. It is called a “double” helix because both strands of DNA (both sides of the hacked-apart ladder) are in a helical form.

This is very important because if the DNA is to be replicated, it has to “unzip” itself physically, and this occurs down the middle of the helix where the two halves are held together by the “weaker” hydrogen bonds (compared with covalent bonds).

The second point is that the so-called bases in the nucleotides are of only four types. They link up across from each other in these long strands only in specific pairs, using the hydrogen bonding. When replication occurs at the “unzipping” points, the base pairing determines which new bases are added to each “unzipped” strand to make a new, exact copy of the original DNA. This is a simple but elegant system. And the order of multiple sequences of the four bases along any one strand can be “read” as a code to control the synthesis of specific proteins. Details can be found at http://www.accessexcellence.org/RC/AB/BC/Reading_Messages_in_Genes.php.

A collection of essays on the History of DNA discoveries and applications can be found at <http://www.accessexcellence.org/RC/AB/BC/1953-1976.php>.

Connections to Chemistry Concepts

1. Light emissions and electrons in chemical reactions

a. **Chemiluminescence**—If a reaction is sufficiently exothermic, there may be enough energy produced to make the final product in an electronically excited state—in which one electron is occupying a higher-energy orbital than it normally would. If this electron relaxes back down to its normal orbital, this may be accompanied by emission of light.

b. **Fluorescence**—The basis for identifying or locating a particular protein depends on the protein being able to absorb radiant energy (often high energy ultraviolet light), which in turn excites certain electrons that briefly occupy a higher potential energy position, then fall back down to a lower energy level, giving off that energy in the form of light.

2. **Oxidation-reduction**—The conversion of luciferin to oxyluciferin under enzyme control (luciferase) is a redox reaction; energy changes in the oxyluciferin produce light rather than heat in this reaction.

3. **Organic chemistry**—Amines and carboxylic acids are topics covered in a “light” coverage of organic chemistry in chemistry classes.

4. **Catalysts (Enzymes)**—Proteins that are very specific to a substrate that is affected. Interaction between enzyme and substrate is based on points of matching molecular surfaces.

5. **Energetics of reaction**—Chemical reactions always involve energy changes, but they don’t exclusively involve heat; the energy changes could be in the form of light also, in either endogonic or exergonic reactions.

6. **Condensation reactions**—The splitting out of a water molecule from the reaction of an amine and a carboxylic acid is also a topic of organic chemistry sections in first-year chemistry curricula.

7. **Reactions—Protein synthesis**—Long chains of amino acids are linked through the amine and carboxyl groups (formation of water from loss of a hydrogen atom and a hydroxyl from the amine and carboxyl groups respectively). The sequence of these amino acids produces distinctive protein molecules.

Possible Student Misconceptions

1. **“For light to be produced in a chemical reaction, electricity is involved.”**

Depending on the type of light, electrons are involved but not as electricity in the sense of conductivity, or transfer of electrons from atom to atom. Rather, as in fluorescence, valence electrons of atoms that absorb radiation are displaced to a higher potential energy level, then drop to some lower potential energy level or position, emitting energy in the form of electromagnetic radiation in the visible or invisible range (UV, IR).

2. **“Light from a chemical reaction means there’s fire.”**

Fire implies a reaction of a fuel with oxygen, with the subsequent emission of light and heat. Light emanating from a chemical reaction without heat means there is a difference in energy between the reactants and products (products have lower energy than reactants, just as in exothermic reactions). This energy can be emitted directly by the electron energy jumps of the reacting particles. No reaction with oxygen is necessary for this type of chemical reaction.

Demonstrations and Lessons

1. Activities that investigate the factors that affect chemiluminescence can be done with either a luminol solution or light sticks. One can investigate the effect of temperature on rate of the reaction with light sticks. For a luminol solution, effects of temperature as well as substrate (an enzyme-catalyzed reaction) can be demonstrated or done as a student activity. See science supply companies or even the Dollar Stores that sell light sticks as “bracelets”. A good reference for these activities is found at <http://scifun.chemi.wisc.edu/HomeExpts/Chemilum.html>. The chemistry behind the Light Sticks can be found at <http://chemistry.about.com/od/howthingsworkfaqs/a/howlightsticks.htm>. Another reference that describes the use of luminol in demos as well its preparation is found at http://www.chem.leeds.ac.uk/delights/texts/Demonstration_24.htm. You could also use luminol to detect the presence of blood. This is a very old tool used in forensics. Check any high school forensics textbook for the activity that includes the preparation of the solution. Kits are available from science supply companies. Another *ChemMatters* article illustrates this forensic technique in the December, 2001 issue, p. 12.
2. Enzymes are an important aspect of reactions involving bioluminescence. The enzyme catalase readily found in a variety of fruits and vegetables such as potatoes and other tubers is also available as a dry powder that can be measured for use in experiments that investigate a variety of factors that influence the rate of a catalyzed reaction, including temperature, concentration of substrate, and pH of the reacting solution. A detailed description of this kind of experiment can be found at <http://www.accessexcellence.org/AE/ATG/data/released/0074-GenNelson/index.php>
3. A somewhat “wacky” experiment that demonstrates production of light by the quick crushing of a spearmint-containing hard candy can be done as a demonstration. Something like a Lifesaver® can be made to produce light by a quick hammer blow or by crushing the candy with a pliers, all done in a dark room. You might also be successful by having a student break the candy with their teeth. The reaction is referred to as *triboluminescence*. The following reference is a guide:

<http://www.madsci.org/experiments/archive/860029125.Ch.html>. An explanation of the changes in electron positions within the atom is given at the following reference: the *Journal of Chemical Education*, American Chemical Society, Volume 56, No.6, June 1979, pp. 413, 414. This activity is also found in *ChemMatters*, October issue, 1990, p. 10 (“Light Your Candy”).

4. A redox reaction that produces very bright light can be done with the burning of magnesium. You can also investigate the chemistry behind this reaction, including the testing of the ashen product (the oxide) for its alkaline properties since magnesium is an alkaline earth metal—a good way to add emphasis to its classification name on the periodic table.
5. Students could try the commonly used technique for separating out the different amino acids in a protein, electrophoresis. Commercial kits for the classroom are available at <http://www.carolina.com/category/life+science/biotechnology+kits+%26+materials/protein+analysis+%26+elisa.do>.
6. Students can also easily isolate and see a mass of DNA by extracting the important macromolecule from ordinary plant material such as onions, strawberries and carrots. Directions for doing this activity can be found at http://www.accessexcellence.org/AE/AEC/AEF/1994/dollard_onionDNA.php. Commercial kits are also available.
7. Students can do an actual insertion of a fluorescence-controlling gene using bacterial transformation techniques. Success of the transfer to bacteria can be tested, using UV light to produce fluorescence. Complete student kits are available at the following catalog address (the BioRad company): http://www.bio-rad.com/B2B/BioRad/product/br_category.jsp?BV_SessionID=@@@@0896623597.1222710821@@@@&BV_EngineID=ccceadeffjkkgmcfngcfkmdhkkdfm.0&divName=Life+Science+Education&categoryPath=%2fCatalogs%2fLife+Science+Education%2fClassroom+Kits%2fpGLO+Bacterial+Transformation+Kit&loggedIn=false&lang=English&country=HQ&catLevel=4&catOID=-18873&isPA=false&serviceLevel=Lit+Request.
8. A paper activity to construct a gene with 8 pairs of DNA triplets related to normal RBC hemoglobin can be found at <http://www.accessexcellence.org/AE/AEPC/WWC/1993/hemoglobin.php> also at http://www.accessexcellence.org/AE/AEPC/WWC/1995/simulation_amino.php.

Student Projects

1. Isolation of DNA from common sources such as carrots, strawberries and onions can be done without elaborate equipment. (See http://www.accessexcellence.org/AE/AEC/AEF/1994/dollard_onionDNA.php.)
2. If you have the equipment, students can work with electrophoresis to separate small portions of DNA and identify.
3. Students can do what is known as a bacterial transformation that involves the transfer of the genes involved in fluorescence. The test for successful transfer is to expose the bacterial cultures to UV light! Again reliable kits are available from educational supply companies. The best site for this is from the Bio-Rad company at http://www.bio-rad.com/B2B/BioRad/product/br_category.jsp?BV_SessionID=@@@@0896623597.1222710821@@@@&BV_EngineID=ccceadeffjkkgmcfngcfkmdhkkdfm.0&divName=Life+Science+Education&categoryPath=%2fCatalogs%2fLife+Science+Education%2fClassroom+Kits

[%2fpGLO+Bacterial+Transformation+Kit&loggedIn=false&lang=English&country=HQ&catLevel=4&catOID=-18873&isPA=false&serviceLevel=Lit+Request.](#)

4. Students could research the literature that supports the theory of migration of human ancestors out of Africa. Some of the evidence for this theory comes from both the study of markers on DNA and, interestingly enough, the roots of language. For the DNA studies, students could begin their search with the background articles listed below:

(References for Migration History of Humans Using DNA Markers)

- <http://www.sciam.com/article.cfm?id=the-migration-history-of-humans>
- <http://www.sciam.com/article.cfm?id=the-modern-human-origins>
- <http://www.sciam.com/article.cfm?id=genomic-time-machine-may>
- <http://www.sciam.com/article.cfm?id=dna-from-ancient-australi>

Anticipating Student Questions

1. **“What is the difference between bioluminescence and fluorescence?”** *The difference is that bioluminescence, which is chemiluminescence in a living organism, is a light-producing chemical reaction. Fluorescence is the emission of light after something absorbs light of a particular frequency or wavelength, then re-emits the energy from the absorbed light at a different wavelength of electromagnetic radiation (EMR). In the latter, there is no chemical reaction involved in the production of the emitted EMR.*

2. **“Are the Fluorescent Proteins that emit light part of a cell’s nuclear DNA?”** *No, Fluorescent Protein is found elsewhere in the cell, not in the DNA of the nucleus. In a structure called the ribosome a particular type of protein is synthesized under the indirect control of a portion of the DNA in the cell’s nucleus. This portion of the controlling DNA is known as a gene (translate to ‘location’).*

3. **“Why is ultraviolet light needed to activate a fluorescent protein and not some other wavelength of electromagnetic radiation (EMR)?”** *As mentioned previously, the fluorescent protein must absorb the ultraviolet light in order to fluoresce (which occurs when the excited electrons within the protein molecule give up some of the absorbed energy at a different wavelength of light). The molecule absorbs in the UV because those energies of light are appropriate to promote an electron to a higher-lying empty orbital. The molecule then loses some of the energy it absorbed by vibrational relaxation before the electron falls back to its ground state. So the emitted light is of lower energy (longer wavelength) than the absorbed light.*

References

Older issues of *ChemMatters* about luminescence include the following:

- “Light Your Candy”, Oct. 1990, p.10
- “Luminol—Casting a Revealing Light on Crime”, Dec.,2001, p.12
- “Chemiluminescence, the Cold Light”, October, 1995, p.12

Older issues of *ChemMatters* about genes and enzymes include:

- “Abnormal Insulin”, Feb. 1988, p. 18
- “Blood Markers”, April 1992, p.13
- “The Dog Ate My Homework and Other Gut-Wrenching Tales”, April 2006, p.4

All the above articles can be found on the new, complete 25-year compilation of *ChemMatters* articles CD, available from the American Chemical Society for \$30 for an individual copy, or \$105 for a school-wide site license. Find out more at [ChemMatters 25-Year CD](#).

Web Sites for Additional Information

More sites on bioluminescence

A well-illustrated website on the famous Green Fluorescent Protein is found at <http://www.conncoll.edu/ccacad/zimmer/GFP-ww/GFP-1.htm>.

A useful site on Marine Animal Bioluminescence from a college professor's website, again well illustrated is <http://www.bio.davidson.edu/Courses/anphys/1999/Cody/Cody.htm>.

Molecular structures (illustrated with descriptions of function) of the various forms of luciferin are found at <http://www.lifesci.ucsb.edu/~biolum/chem/detail2.html>.

Want to know all about luminescent earthworms but were afraid to ask? Check out <http://www.bmb.uga.edu/wampler/biolum/worm/index.htm> (includes class handouts).

An entire article from Scientific American magazine, Sept. 2008, on the complete study of the functioning brain using bioluminescent proteins is found at the following website: <http://www.sciam.com/article.cfm?id=neural-light-show>.

An interesting aside to the use of bioluminescence in tracking biological activity, in this case, transferring DNA from an extinct animal into a mouse, is found at <http://www.sciam.com/article.cfm?id=life-after-extinction-tiger>.

Use of fluorescence in cancer detection is found at <http://news-service.stanford.edu/news/2005/august24/med-probe-082405.html>.

More sites on chemiluminescence

A wacky but real use of chemiluminescence down on the farm (breeding markers) is found at <http://www.bovinebeacon.com/>. Enjoy, though you may not be able to use in class!

A very teacher-friendly website on chemiluminescence is found at <http://www.chm.bris.ac.uk/webprojects2002/fleming/intro.htm>.

A collection of videos on chemiluminescent demonstrations, including luminol, is found at http://www.shsu.edu/~chm_tgc/chemilumdir/chemiluminescence2.html.

The Tale of the Teeth

Background Information

More on Archaeology

Archaeology might be characterized as the study of “who, what, when, where”. The business of archaeology is basically a search for answers to a collection of remains that once belonged to a particular human culture. The word “archaeology” has its roots in Greek, the word *archaios* that refers to “primal, ancient, or old”. The suffix “-logy” refers to “the study of—”, in this case, human cultures. It is a scientific study of the life and culture of past people through the excavation and examination of their settlements, relics, and artifacts. Archaeological sites can be many things from the past—habitation sites, ceremonial sites, even trash heaps.

Often these physical remains can become buried through natural processes such as flooding or subsequent human activity. So, careful excavation of a site becomes a type of science in its own right. Information that is generated from an archaeological site includes artifacts (any object made or changed by human beings) and site features; i.e., features at the site that cannot be easily transported back to a laboratory. Examples include foundations, postholes, and trash pits. Sites do not always have to be excavated to be discovered—their existence can be detected through the use of radar.

More on Analytical Tools in Archaeology

Examining the artifacts that are discovered at an excavation site makes use of a whole host of tools, including chemical, biological and physical analytical devices. In some respects many of the tools of modern forensic investigations, including piecing together the “evidence”, fit right in with the work of archaeologists. As an example, in the present excavations at colonial Jamestown, Virginia, a fragment of skull bone was unearthed that, upon examination, provided many reliable clues about the original “owner” of the fragment! For instance, the bone thickness indicated the person was a mature adult. The types of attachment points for muscle indicated the person was male. There was an incomplete attempt to drill a hole in the skull, possibly to relieve pressure on the brain after the person had been hit with a blunt instrument. That the drilling was never completed suggests the patient died from his injuries. Chemical analysis revealed high levels of lead that can be attributed to the use of pewter eating utensils. (You can find lots of useful information about the Jamestown excavations, complete with interactive features and good photographs of many artifacts, at www.historicjamestowne.org)

The article’s basis for establishing the origins of the people who possessed the teeth depended on the ratio of two isotopes of strontium, Sr-86 and Sr-87. These ratios vary depending on where they are found. Further, these chemicals can become part of both plant and animal material that may be ingested as food by people. In turn, these two isotopes become part of bone and teeth. The ratio of the two isotopes in teeth is fixed early in life. Depending on the food source, the ratios have different values, giving clues about people’s mobility—assuming analysis is done on soil, rock and faunal remains for suspected areas from which the migrants may have come. There is also interest in not only strontium, but also barium. Sampling of prehistoric bone from many different locations in the world for strontium and barium has produced a data base from which inquiry and comparisons can be made about paleodiet,

paleoclimate and even provenience (origin). For example, different barium levels indicate marine versus terrestrial resources in the diet.

Composition of clay can be analyzed using what is known as an ion-extraction method that is highly sensitive in determining the composition of the clay “paste” originally used. It can also be used to determine the firing temperature of the clay to make the ceramic. Broken pieces of ceramic (potsherds) can be accurately matched based on the analysis, as can the clay from which the ceramic was made. More importantly, archaeological finds of ceramics, if analyzed with this ion-extraction method, can help to trace the evolution of various ceramic traditions within or across cultures.

Another tool that can be used effectively in determining the composition of ceramic material is a technique called Instrumental Neutron Activation Analysis (INAA).

More on Instrumental Neutron Activation Analysis (INAA)

When using INAA to examine a sample of material, the object is subjected to a large stream of neutrons, generated by a nuclear reactor. A uranium fuel source emits a beam of neutrons that penetrate a piece of pottery, for instance, converting the various elements in the clay into radioactive nuclides. These nuclides emit gamma radiation of varying intensities that are detected and recorded (computer). From these patterns of energy intensities, one can determine the abundance of each element present in a pottery sample. The various elements in a clay material are unique for a given geochemical history, producing a singular chemical composition that is related to a particular geological and geographical location in the world. As a result, analysis can produce a chemical profile that is used to compare with the chemical values obtained from soil, clay and pottery waste (shards) found at archaeological kiln excavations, which are obviously site specific.

A similar technique called Proton-Induced X-Ray Emission (PIXE) uses beams of protons rather than neutrons to displace electrons in individual atoms. The displaced electrons, returning to a more stable state, emit x-rays rather than gamma rays. Again, these x-ray patterns are specific for a particular element, similar in principle to visible atomic emission spectra. In both the use of Neutron Activation and Proton-Induced X-Ray Spectrometry analysis, the spectra produced can be used to identify specific elements present in an archaeological artifact, and the ratio of those elements. A computer printout of these recorded patterns is essentially a fingerprint of that sample of material that can be compared with the source of the chemicals (e.g. clay from a specific soil and its location). Obviously, if the soil sample is from another distant location, then the migratory history of that clay or pottery might be established or related to human migration, if that is of archaeological interest.

More on Carbon-14 Dating

If dating of an object that has a biological origin (bone, wood, cloth) is important to an archaeological investigation, then one of the techniques for determining the age of such a class of objects is to use carbon-14 dating. Carbon that is part of once living organic material becomes incorporated into an object either from photosynthesis (atmospheric carbon dioxide converted to simple sugars) or cellular metabolism (sugars converted to structural molecules such as muscle protein or bone complexes). Elemental carbon has at least three isotopes: carbon-12, carbon-13, and carbon-14. Carbon-14 is made in the upper atmosphere from nitrogen-14 and energetic neutrons formed from cosmic rays. The ratio of C-14 to C-12 is nearly constant both on earth and in the atmosphere. The C-14 that becomes part of animal and plant

tissue is constantly undergoing radioactive decay. In dead organisms, no more radioactive C-14 enters the tissue and the ratio of C-14 to C-12 begins to change because of radioactive decay of the C-14 at a predictable rate. By comparing the amount of C-14 in a dead organism to that of the C-14 in living tissue, the age of the dead organism can be calculated, using the following formula:

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

where $\ln (N_f/N_o)$ = the natural logarithm of the percent carbon-14 in the sample compared to the percent carbon-14 in living tissue, and

$t_{1/2}$ = the half-life of carbon-14 = 5,700 years.

If you wanted to date a fossil, first you would determine the percent carbon-14 it contained compared to a living sample. Imagine your sample contained 20% of the carbon-14 found in a living plant leaf. Then,

$$t = [\ln (0.2) / (-0.693)] * 5,700 \text{ years}$$

$$t = [(-1.609) / (-0.693)] * 5,700 \text{ years}$$

$$t = [2.322] * 5,700 \text{ years}$$

$$t = 13,238 \text{ years old}$$

(Reference is

<http://www.acad.carleton.edu/curricular/BIOL/classes/bio302/Pages/CarbonDatingBack.html>.)

Carbon-14 has a half-life of about 5,730 years. This half-life restricts its usage to artifacts that are less than 50,000 years old—a period of 8 to 9 half-lives, after which less than 1% of the original C-14 remains un-decayed. For fossils older than that, other isotopes with longer half-lives are used, including those in the following table:

Isotope	Half-Life
Potassium-40 (found in your body at all times)	1.3 billion years
Uranium-235	704 million years
Uranium-238	4.5 billion years
Thorium-232	14 billion years
Rubidium-87	49 billion years

Another useful and more extensive (advanced) reference on the C-14 analytical method with applicable examples is found at <http://www.c14dating.com/int.html>.

More on Electron Microprobe Analysis in Archaeology

Another analytical tool used in archaeology to determine some of the characteristics of artifacts is called Electron Microprobe Analysis (EMPA), also known as Electron Probe Microanalysis (EPMA). This technique employs a combination of scanning electron microscopy (SEM) and x-ray spectrometry for compositional analysis. Often used as an analytical technique in geology, it has not been as commonly used in archaeology, even though that area of study involves some of the same materials (think ceramics from clay, glass from sand, metallic objects). An extensive collection of examples of EMPA used in the analysis of a wide range of artifacts is clearly presented (with photographs of artifacts) in the reference,

<http://archaeology.about.com/gi/dynamic/offsite.htm?zi=1/XJ/Ya&sdn=archaeology&zu=http%3A%2F%2Fweb.mac.com%2Felleryfrahm%2FiWeb%2FMicroprobe%2FElectron%2520Microprobe%2520Analysis%2520in%2520Archaeology%2FElectron%2520Microprobe%2520Analysis%2520in%2520Archaeology.html>.

More on Archaeological Evidence for Human Migration

One of the side issues associated with documenting the origins of archaeological artifacts is the history of a civilization that made the artifacts. It also includes both the migration of the artifact and its creators. Again, an artifact's specific chemical composition can sometimes help to determine the geological source of the chemicals, if it came from earth materials. But there is also another technique that in recent years has been applied not only to determine the origins of human culture but to follow the migration of these early ancestors to other parts of the world. This evidence is being produced through the analysis of DNA in various races of people. Some correlation can be obtained by the location of human and pre-human fossils. Some of this migrational evidence is also corroborated or reinforced to some degree by the study of root languages.

It is thought that the ancestors of the present human race migrated out of East Africa some 50,000 to 60,000 years ago. They migrated north, crossing the land at a location where presently the Red Sea flows into the Indian Ocean. Scientists believe that these ancestors settled in South America via Asia by migration through the Bering Strait into North America, then migration south into South America. These ancestors may have migrated out of Africa and then split to go either to Europe or to Asia (from where they migrated to America).

These wanderings are confirmed to some degree by fossilized bones or spearheads. But there are many gaps in this migratory story that, in the next 20 years, may be filled in through the investigations of population geneticists. They are studying the DNA of modern humans. It is known that 99.9 percent of human DNA is the same in every person (some three billion nucleotides that make up the human genome). But the remaining 0.1 per cent of the DNA varies from person to person. And it is this variable 0.1 percent that contains the information for determining origins (location) of this DNA fragment in ancient ancestry. Hundreds of thousands of nucleotides scattered throughout an individual genome can be analyzed.

What is done currently is to take advantage of the fact that mutations in the genetic material associated with cell mitochondria take place at a relatively predictable rate. The number of mutations that have occurred between two groups of people (lineage) allows for the construction of a genetic tree that works backward in time to a common ancestor (the number of mutations or ticks is like the radioactive decay of an isotope). One comes out with ages for two comparative lineages from different geographical regions, which in turn produce a timeline for the migration of these groups from a common origin. There is a question that is raised by some geneticists that present day *Homo erectus* may not have evolved from just one original stock but in fact includes genetic material from several other older ancestral *Homo* species through cross breeding. There are also other issues related to refining this genetic sleuthing including the effect of random mutations (genetic drift) and the effect of natural selection as migrants adapted to their new homes. A detailed discussion of these genetic issues can be found at <http://www.sciam.com/article.cfm?id=the-migration-history-of-humans>.

Connections to Chemistry Concepts

1. **Isotopes**—Isotopes as a general term in chemistry is often associated with radioisotopes, those isotopes that are radioactive. As such, radioisotopes are widely used as markers in both biological and non-biological materials.
2. **Radioactivity and half-life**—Radioisotopes used as markers in materials are the same radioisotopes students study about in chemistry classes. Half-life calculations are part of the curriculum. Now students have a real-life example of using those calculations to decide the age of human bones and other artifacts.
3. **Bonding**—DNA, a macromolecule, contains a number of different types of bonding, including covalent and hydrogen, the latter responsible for weak bonding between so-called nucleotides and tertiary bonding of the “twisted” strands of DNA, the so-called double helix.

Possible Student Misconceptions

1. **“Isotopes of a given element have different chemical characteristics.”** *Isotopes of a given element have different masses but the same chemical characteristics. This is due to the fact that the isotopes have different numbers of neutrons in the nucleus, producing different masses. But the number of protons in the nucleus is the same, producing the same chemical characteristics.*
2. **“Isotopes of a given element are radioactive.”** *Isotopes of a given element may or may not be radioactive. Those that are radioactive are called “radioisotopes”. Usually radioactivity is associated with elements with heavier nuclei that are unstable because of the large number of neutrons and protons. All isotopes of elements with atomic numbers larger than that of Bismuth (83) are radioactive. Fewer elements of lower atomic number, such as potassium and rubidium, have naturally occurring isotopes that are also radioactive.*

Demonstrations and Lessons

1. It is possible for students to do a simulation of isotopes, using pennies with different masses. Pennies minted before 1982 have a different mass than pennies after 1982. Provide ten pennies of the two types in different ratios in a container such as a film canister. Students should mass a pre- and a post-1982 penny for later reference and calculation. The mass of the individual empty containers should be done by the teacher and provided to the students. The containers with the individual mix of ten pennies should be sealed. Students will find the mass of the sealed container of pennies. Students will then calculate the mass and number of pennies of each type in the container. To do that, use the equation:

TOTAL Mass of pennies = (X x mass of pre-1982 pennies) + [(10-X) x mass of post-1982 pennies]. Solve for X and (10 - X) to determine number of pennies of each type. From this information, calculate the percent of each “isotope”.

2. The concept of radioactive decay that is associated with radioisotopes can be simulated also with pennies. Place 80 pennies in a box (with a lid), all with HEADS UP. Close the box and shake vigorously. Each shaking period is a half-life. The pennies can be shaken up and down once, each shake representing a half-life. Open the box and remove all pennies that are “decayed”, i.e., that are now “tails” up. Repeat the process three more times. Record the

number of pennies of each type (heads, tails) after each shaking. The data can be graphed, showing a curve like that of radioactive decay, a random event just as penny-flipping. Pooling all the class data will provide a more reliable graph. (Reference for activities #1 and #2 can be found in the American Chemical Society's textbook, "*Chemistry in the Community*" or *ChemCom*. The textbook includes the lab activities.)

3. The idea that bones or teeth accumulate chemicals that originate in soil might be a new idea to students. Students, and even adults, may not really make the connection between soil and food and the old adage, "We are what we eat". Chemical analysis of soil can be done for a sampling of chemical characteristics such as pH, and some important chemicals taken up by plants (think "fertilizer") including iron, calcium, chloride, sulfate, phosphate and nitrate ions. There are soil-testing kits readily available at local garden centers. You can also use chemical testing kits for freshwater aquaria. Students should be provided with different types of soil including sandy, loam, clay, and forest soils. Students could also be asked to bring in soil samples from their own yards. The role of these ions in humans could also be studied as a follow-up to the lab exercise. The whole realm of folklore-based nutrition could use some clarification through basic chemistry. What is the real difference between organic and commercial fertilizers as far as a plant is concerned or as far as food consumption and nutrition are concerned?

Student Projects

1. Students could do an extended chemical analysis of soil and rock material, focusing on school property if there are different biomes readily available. Since water becomes a "solution" from land runoff (as solids in soil dissolve in the water), there are a variety of chemical analyses that could be done on several different bodies of water that collect runoff water. Look for several different land topographies that drain into a body of water, including forest, lawns, and parking lots, among others. The categories of analysis could be extended beyond the chemicals listed in #3 of "Demonstrations and Lessons" above to include biological activity (flora and fauna of the water system), temperature, dissolved oxygen, and water hardness.

2. For students who have an interest in biology and human cultures, they could do an extended research project into understanding how DNA is used to trace possible migration routes of our human ancestors out of Africa. This would require an understanding of the basic structure of DNA, the idea of mutations and the rate of mutations over time. A starting reference for this is <http://www.sciam.com/article.cfm?id=the-migration-history-of-humans>.

Anticipating Student Questions

1. **"How do you distinguish between the different isotopes of a particular element?"** *The most basic analysis for determining the existence of a particular isotope would be to determine its mass and percentage by mass in a sample. This is done most readily through mass spectrometry. Essentially, individual atoms in a sample are converted to a gas, ionized with high-energy beams of electrons, and then subjected to a magnetic field that causes the ions of different masses to separate out at different locations on a detector surface that registers the ion's impact.*
2. **"How does carbon-14 dating work?"** *Carbon-14 dating depends on the presence of radioactive carbon that is part of all living or once living material (bone, paper, wood,*

cotton). This radioactive carbon “decays” at a regular rate. This decay is a change from one element to another element. In this case, carbon-14 undergoes a radioactive decay to form nitrogen-14. The time it takes for half the chemical to change is known as its half-life which, for C-14, is about 5730 years. For objects more than 50,000 years old, carbon dating will not work because most of the original C-14 has decayed. Measuring the ratio of C-14 to all carbon in a sample (must be dead!) and comparing that to the isotopic ratio in present day samples containing carbon will allow one to determine how much carbon-14 has decayed. Knowing the rate of decay for C-14 (the half life) allows the use of an equation to calculate the age of the sample being analyzed.

3. **“Why would you determine the ratio of strontium isotopes in soil or rocks in order to identify the geographical origin of the owner of the teeth containing the strontium isotopes?”** The isotopes found in rock, soil, and even water, can be taken up and deposited in the teeth when a person eats food that has grown in soil or water (that includes, plants, land animals and fish). These food sources absorb and incorporate all kinds of chemicals that are eventually passed on to humans who consume the food.

References

Chemistry in the Community, 5th Edition, 2006; ISBN 0-716-78919-1, W.H. Freeman Co., San Francisco CA (Chapter 7, “Atoms” about nuclear chemistry, with appropriate lab exercises)

Web Sites for Additional Information

More sites on Jamestown archaeology

Two very useful articles (both by the same author) that are very descriptive of the archaeological investigations at Jamestown can be found at the Chemical Heritage Foundation website, www.chemheritage.org. The specific article references are: http://www.chemheritage.org/pubs/ch-v25n2-articles/feature_jamestown.html and http://www.chemheritage.org/pubs/ch-v25n2-articles/feature_archaeology.html. The first article makes for a very interesting read on the sleuth work of “archaeological” chemists in analyzing copper to determine whether the early settlers were involved in mining and processing copper ore or were simply reworking copper from mother England. It could be used with students as a study in obtaining and using evidence to answer a question, in this case a historical one.

More sites on Proton-Induced X-Ray Emission (PIXE)

More information on how PIXE works and examples of how it is used in analyzing archaeological artifacts is found at http://masca.museum.upenn.edu/pixe_spectrometry.html. This reference describes the work at the Univ. of Penna. Museum of Applied Science Center for Archaeology (MASCA). If you go to their website, you will find a description of specific tools used for analysis with examples, from the evidence for beer brewing in 8th C. BC Turkey and China, to the composition of the famous Phoenician Royal Purple made from Mediterranean mollusk shells (that was eventually imitated by William Perkin with purple mauve or mauveine, a synthetic of 19th C. England). See additional references for analysis at MASCA: <http://masca.museum.upenn.edu/archaeochem.html> and <http://masca.museum.upenn.edu/archaeometallurgy.html>.

More sites on chemical analysis of archaeological substances

For additional short references to chemical analysis on such things as red wine in King Tut's tomb, go to <http://www.sciam.com/article.cfm?id=king-tut-drank-red-wine-r>.

Other examples of chemical analytical tools, this time for evidence of Chinese brewing 7,000 years B.C., can be found at <http://www.sciam.com/article.cfm?id=chemical-tests-confirm-an>.

The use of fluorescent activation to make invisible writing visible on ancient wine bottles is found in a short article at <http://www.sciam.com/podcast/episode.cfm?id=5D382AE6-E7F2-99DF-3CA3BB09D70357D0&print=true>.

Another reference to an exhibit on "Origins and Ancient History of Wine" at the Univ. of Penna. Archaeological Museum can be found at http://www.museum.upenn.edu/new/exhibits/online_exhibits/wine/wineegypt.html.

More sites on Neutron Activation Analysis (NAA)

A very extensive website that completely describes how NAA works can be found at <http://archaeology.about.com/gi/dynamic/offsite.htm?zi=1/XJ/Ya&sdn=archaeology&zu=http%3A%2F%2Fmicro5.msc.huji.ac.il%2F%257Emsjan%2Fneutron.htm>. As part of this website you will find many examples of using this analysis with good photographs of the artifacts that are being analyzed at <http://archaeology.about.com/gi/dynamic/offsite.htm?zi=1/XJ/Ya&sdn=archaeology&zu=http%3A%2F%2Fweb.mac.com%2Felleryfrahm%2FiWeb%2FMicroprobe%2FElectron%2520Microprobe%2520Analysis%2520in%2520Archaeology%2FElectron%2520Microprobe%2520Analysis%2520in%2520Archaeology.html>.

A complementary reference to the above is found at <http://www.lbl.gov/Science-Articles/Archive/nuclear-archaeology.html>.

If you want to learn more about archaeological analysis at the molecular level, refer to the following website: <http://archaeology.about.com/gi/dynamic/offsite.htm?zi=1/XJ/Ya&sdn=archaeology&zu=http%3A%2F%2Fwww.bradford.ac.uk%2Facad%2Farchsci%2Fdepart%2Fresgrp%2Fmolarch%2Fmolarch.html>.

More sites on carbon-14 dating

<http://www.acad.carleton.edu/curricular/BIOL/classes/bio302/Pages/CarbonDatingBack.html> is a clear and straight-forward website from Carleton College that provides background information on the dating technique with some discussion on how one knows that the C-14 tool is accurate. Another more extensive reference on radiocarbon dating is found at <http://www.c14dating.com/int.html>. Included in this reference is some history behind developing the technique as well as a list of carbonaceous samples that have been dated, with links.