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**October/November 2015 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 DVD that is available from the American Chemical Society for $42. The DVD contains the entire 30-year publication of *ChemMatters* issues, from February 1983 to April 2013.

The *ChemMatters* DVD also includes Article, Title and Keyword Indexes that covers all issues from February 1983 to April 2013.

The *ChemMatters* CD can be purchased by calling 1-800-227-5558.

Purchase information can be found online at [www.acs.org/chemmatters](http://chemistry.org/chemmatters/cd3.html)

# Student Questions (from the articles)

**Eating with Your Eyes: The Chemistry of Food Colorings**

* 1. Why is green-colored ketchup not found on supermarket shelves?
  2. Why do people often avoid multicolored food?
  3. What is the reason for adding food coloring to hot dogs?
  4. Describe a property of beta-carotene that makes it suitable for use as a coloring agent for dairy products.
  5. What makes anthocyanin molecules water-soluble?
  6. What groups on anthocyanin molecules are responsible for their water solubility?
  7. Why did Starbucks remove cochineal dye from its strawberry flavored products?
  8. Why do manufacturers prefer artificial- to natural-coloring substances for their products?
  9. How do the elements that compose the molecular formula of Red No. 3 differ from the elements present in the other formulas shown in Table 1?
  10. What is the base material currently used to produce most synthetic food dyes?
  11. What happens when food-coloring molecules dissolve in water?
  12. In what ways do food scientists claim that eating involves more than just taste?

**Tooth Decay: A Delicate Balance**

* 1. Name the three main constituents of the hard parts of the tooth.
  2. What is hydroxyapatite?
  3. Why does the author say the hydroxyapatite in your teeth “is dynamic”?
  4. What are the products of the demineralization of hydroxyapatite?
  5. How does pH differ between that of the mouth and that of the body?
  6. How do the lungs help to control blood pH (e.g., after exercising)?
  7. How does saliva maintain the pH of the mouth after bacteria produce acid from the carbohydrates we’ve consumed?
  8. What happens next to maintain equilibrium?
  9. What are the results of a consistently low pH in the mouth?
  10. What are the two main materials used to fill a decayed tooth, once the decay has been removed?
  11. Name three problems with the use of amalgams for filling teeth.

**Probiotics: Good Bacteria, Good Health**

1. What do the terms probiotic and microbiome mean?
2. What are some of the benefits that some think may be provided to our bodies by some of our gut bacteria?
3. Who first researched the role of probiotics in maintaining health?
4. Name some foods that contain probiotics.
5. According to the UN World Health Organization, how are probiotics defined?
6. Explain what is meant by probiotics acting as miniature chemical factories.
7. In addition to energy, what are the chemical products of bacterial fermentation?
8. What are two different mechanisms by which certain probiotics may control or reduce obesity in mice?
9. We usually associate the term pasteurization with milk, but for which drink did Louis Pasteur actually begin his research to kill bacteria with heat?
10. How might certain bacteria known as *Lactobacillus rhamnosus* reduce anxiety in mice?
11. What mechanism is thought to reduce anxiety when mouse gut bacteria, *Bifidobacteria*, are increased in numbers?

**Dirt? Who Needs It? How Hydroponics Is Poised to Change the World**

1. What is the predicted population of the world in 2030? Why is this important?
2. What is hydroponics?
3. What is the per cent composition of most plants?
4. What is the source of nutrients for plants that are grown hydroponically?
5. Name the two main chemicals needed for plant growth.
6. Who first introduced the term “hydroponics”?
7. What is the difference between macronutrients and micronutrients?
8. Name three plant macronutrients.
9. What solution condition is crucial for adequate delivery of nutrients to plants?
10. List two drawbacks to growing hydroponic plants, and one way these can be minimized.

**Light in the Cellar of the Sea**

1. List three (3) ways marine organisms emit light.
2. How does the midshipman fish hide from its prey?
3. Explain why so many red and black fish exist in the twilight zone of the ocean?
4. Why is there no red light below 6 meters in the ocean but there is blue light at 35 meters?
5. Based on Figure 1, which wavelengths of light fade fastest underwater?
6. Explain why white objects appear white and black objects appear black.
7. Name the three chemical substances required to produce bioluminescence.
8. What event caused Edith Widder to decide to study bioluminescence?
9. Why did Karen Osborn name the nearly transparent worm *Swima bombiviridis*?
10. Explain how Dr. Widder uses bioluminescence to detect water pollution.
11. List three (3) characteristics of mantis shrimp’s vision.

# Answers to Student Questions (from the articles)

**Eating with Your Eyes: The Chemistry of Food Colorings**

* + 1. **Why is green-colored ketchup not found on supermarket shelves?**

*Although green colored ketchup has existed, consumers prefer red because this color matches the color they associate with the flavor of ketchup (and tomatoes).*

* + 1. **Why do people often avoid multicolored food?**

*People avoid multicolored food because it looks like it might be moldy and should not be eaten.*

* + 1. **What is the reason for adding food coloring to hot dogs?**

*Without the addition of food coloring, hot dogs would be gray and unappealing to customers.*

* + 1. **Describe a property of beta-carotene that makes it suitable for use as a coloring agent for dairy products.**

*Beta-carotene is fat soluble so it will dissolve in fatty dairy products such as butter giving them color.*

* + 1. **What makes anthocyanin molecules water-soluble?**

*The polar nature of anthocyanin molecules makes them water-soluble.*

* + 1. **What groups on anthocyanin molecules are responsible for their water solubility?**

*It is the –OH groups that make the anthocyanin molecules polar.*

* + 1. **Why did Starbucks remove cochineal dye from its strawberry flavored products?**

*Starbucks removed cochineal dye from its strawberry flavored products in response to customer complaints about eating bugs***.**

* + 1. **Why do manufacturers prefer artificial- to natural-coloring substances for their products?**

*Manufacturers prefer artificial- to natural-coloring substances because they are cheaper and can be mass produced.*

* + 1. **How do the elements that compose the molecular formula of Red No. 3 differ from the elements present in the other formulas shown in Table 1?**

*The molecular formula of Red No. 3 contains iodine (I) and does not contain sulfur (S) which is present in all the other molecular formulas.*

* + 1. **What is the base material currently used to produce most synthetic food dyes?**

*The base material currently used to produce most synthetic food dyes is petroleum or crude oil.*

* + 1. **What happens when ionic food-coloring molecules dissolve in water?**

*Ionic food-coloring molecules dissolve in water when the ions that form the solid become associated with the partial negative and partial positive charges on polar water molecules.*

* + 1. **In what ways do food scientists claim that eating involves more than just taste?**

*Food scientists claim that the smell, sound, feel and sight of food are just as important as its taste.*

**Tooth Decay: A Delicate Balance**

* + 1. **Name the three main constituents of the hard parts of the tooth.**

*The three main constituents of the hard parts of the tooth are mineral, proteins and water.*

* + 1. **What is hydroxyapatite?**

*Hydroxyapatite is the mineral that makes tooth enamel hard. Its formula is Ca5(PO4)3(OH).*

* + 1. **Why does the author say the hydroxyapatite in your teeth “is dynamic”?** *The author mentions that the hydroxyapatite in your teeth “is dynamic” because there is an equilibrium occurring between demineralization and mineralization of the hydroxyapatite, as food is eaten which reduces pH that increases the rate of demineralization, and the subsequent release of saliva with a slightly higher pH that increases the rate of mineralization.*
    2. **What are the products of the demineralization of hydroxyapatite?**

*The products of the demineralization reaction of hydroxyapatite are calcium ions (Ca2+), phosphate ions (PO43–) and hydroxide ions (OH–).*

* + 1. **How does pH differ between that of the mouth and that of the body?**

*The pH in the body differs from that in the mouth in that the blood pH is closely controlled at a slightly alkaline value of 7.4, while the pH of the mouth can vary between 6.2 and 7.4.*

* + 1. **How does the body control blood pH (e.g., after exercising)?**

*When exercising, lactic acid is produced in the muscles, adding H+ ions to the bloodstream. To relieve this equilibrium shift, according to Le Chatelier’s Principle, bicarbonate ions react with the H+ ions and produce carbonic acid. Then the carbonic acid build-up causes an increase in the amount of carbon dioxide and water (which is exhaled through the lungs). This returns the body to a new state of equilibrium and a normal pH.*

* + 1. **How does saliva maintain the pH of the mouth after bacteria produce acid from the carbohydrates we’ve consumed?**

*Saliva maintains the pH balance in the mouth by secreting bicarbonate ions, produced in the salivary ducts, which combine with and neutralize the H+ ions produced in the fermentation process.*

* + 1. **What happens next to maintain equilibrium?**

*As the excess H+ ions from the previous question are consumed, the amount of carbonic acid builds up. To maintain the right amount of carbonic acid in the mouth, some of the excess carbonic acid breaks back down into carbon dioxide and water. The excess carbon dioxide then diffuses out from the saliva.*

* + 1. **What are the results of a consistently low pH in the mouth?**

*Consistently low pH in the mouth results in small holes or pits to form in the enamel of the tooth, which eventually exposes the dentin below the enamel. Dentin, being less resistant to acid than enamel (only 70% hydroxyapatite vs. 96% for enamel), is more quickly and easily demineralized, resulting in more rapid tooth decay.*

* + 1. **What are the two main materials used to fill a decayed tooth, once the decay has been removed?**

*The two main materials used to fill a decayed tooth are composite resins and mercury amalgams.*

* + 1. **Name three problems with the use of amalgams for filling teeth.**

*Three problems with using amalgams to fill teeth are:*

* + - * 1. *More of the healthy part of a tooth must be removed in order to pack the amalgam into the cavity in such a way that it ensures no movement of the filling,*
        2. *Amalgams block X-rays, making it more difficult for the dentist to obtain a useful 3-dimensional panoramic picture of your entire mouth, and*
        3. *Amalgams need to be properly disposed of, since they contain hazardous mercury.*
        4. *(Not mentioned in article: Amalgam fillings appear silver or black, making them obvious and not very attractive.)*

**Probiotics: Good Bacteria, Good Health**

* + 1. **What do the terms probiotic and microbiome mean?**

*The term probiotic refers to “…live strains of bacteria similar to the ones that live naturally in the human gut.” The microbiome is the name for all the bacteria living inside our body.*

* + 1. **What are some of the benefits that some think may be provided to our bodies by some of our gut bacteria?**

*Different bacteria in the gut are essential to digestion, provide energy, back up the immune system and synthesize chemicals that our body can use.*

* + 1. **Who first researched the role of probiotics in maintaining health?** *Russian physiologist and Nobel Prize winner Elie Metchnikoff first studied the effects of probiotics on people’s health in Bulgaria.*
    2. **Name some foods that contain probiotics.**

*Some foods containing probiotics include yogurt, sauerkraut, pickles, Kefir (a fermented milk drink), kimchee, kombucha, cottage cheese (with added probiotics), and buttermilk.*

* + 1. **According to the UN World Health Organization, how are probiotics defined?**

*Probiotics are defined as “… live microorganisms administered in adequate amounts which confer beneficial health effects on the host.”*

* + 1. **Explain what is meant by probiotics acting as miniature chemical factories.**

*Probiotics provide chemical reactions that convert carbohydrate molecules into alcohols or acids as they release energy through the chemical reaction, fermentation.*

* + 1. **In addition to energy, what are the other chemical products of bacterial fermentation?**

*Carbon dioxide and either lactic acid or ethanol are produced in bacterial fermentation, in addition to the energy.*

* + 1. **What are two different mechanisms by which certain probiotics may control or reduce obesity in mice?**

*It is thought that “… certain genetically modified probiotics can produce a hunger-suppressing compound which signals the brain to want less food. Other probiotics stimulate the release of a hormone called GLP-1 which also causes a reduction in food intake.”*

* + 1. **We usually associate the term pasteurization with milk, but for which drink did Louis Pasteur actually begin his research to kill bacteria with heat?**

*Louis Pasteur began his research on killing bacteria using wine, which neighboring winemakers had found was turning sour. They asked him to help them find out why.*

* + 1. **How might certain bacteria known as *Lactobacillus rhamnosus* reduce anxiety in mice?**

*When mice are fed the bacterium, Lactobacillus rhamnosus, it was found that the mice had half the normal amount of a stress hormone called corticosterone in their brains. This is due to the fact that the bacteria secrete a neurotransmitter, GABA (gamma aminobutryric acid), which influences the brain as an anti-stress compound, travelling from the intestine to the brain via the vagus nerve.*

* + 1. **What mechanism is thought to influence a number of different brain perceptions when mouse gut bacteria, *Bifidobacteria,* are increased in numbers?**

*With an increase in this particular bacterium in the gut of mice, there was a matching increase in a protein called brain-derived neurotrophic factor. This factor in turn increases the production of another chemical called serotonin which is involved in mood regulation, pain perception, and perception of hunger and satiety (feeling full).*

**Dirt? Who Needs It? How Hydroponics Is Poised to Change the World**

1. **What is the predicted population of the world in 2030? Why is this important?**

*The article says the predicted world population in 2030 is 8–9 billion. The reason this is important, according to the article, is that the land available for agriculture may not be sufficient in 2030 to adequately feed that population.*

1. **What is hydroponics?**

*“Hydroponics is the agricultural technique of growing plants in water instead of soil.”*

1. **What is the per cent composition of most plants?**

*The article says that most plants are made up of “72% water, 24% organic material and 4% inorganic material, such as nitrogen and phosphorus.”*

1. **What is the source of nutrients for plants that are grown hydroponically?**

*The nutrient source for hydroponic plants is a water solution containing the chemical nutrients (ions) that plants require for growth.*

1. **Name the two main chemicals needed for plant growth.**

*Carbon dioxide and water are the essential chemicals for plant growth.*

1. **Who first introduced the term “hydroponics”?**

*William Gericke, a scientist working at the University of California, Berkeley in the 1930s first coined the term.*

1. **What is the difference between macronutrients and micronutrients?**

*According to the article, macronutrients are those chemicals that plants need in large amounts, while micronutrients are needed in smaller amounts.*

1. **Name three plant macronutrients.**

*Potassium, nitrogen, phosphorus, and calcium are the plant macronutrients listed in the article.*

1. **What solution condition is crucial for adequate delivery of nutrients to plants?**

*The pH of the solution is the condition important for nutrient delivery.*

1. **List two drawbacks to growing hydroponic plants, and one way these can be minimized.**

*Growing plants hydroponically requires a light-controlled environment and water must flow constantly through the system, both of which are energy-intensive. One way to minimize this impact is to use solar panels (possibly as both the source of light and of energy to pump the water).*

**Light in the Cellar of the Sea**

1. **List three (3) ways marine organisms emit light.**

*Marine organisms emit light by*

* + - 1. *flashing or flickering,*
      2. *emitting sparkles (“light bombs”), and*
      3. *glowing.*

1. **How does the midshipman fish hide from its prey?**

*The light produced by the midshipman fish helps to hide it from prey. The glow “radiates from its belly and blends in with a hint of moonlight, masking the shadow and silhouette of the fish.”*

1. **Explain why so many red and black fish exist in the twilight zone of the ocean.**

*Since red light does not penetrate very far beneath the surface of the ocean there is no red light to reflect off of the red fish so they appear black in the black water as do the black fish. These fish are not visible at depths associated with the twilight zone.*

1. **Why is there no red light below 6 meters in the ocean but there is blue light at 35 meters?**

*Red light has the longest wavelength, the least energy of visible light, and is filtered out first. Blue light, with the shortest wavelength, penetrates the ocean water best.*

1. **Based on Figure 1 which wavelengths of light fade fastest underwater?**

*Based on Figure 1, Infrared and ultraviolet light fade away first.*

1. **Explain why white objects appear white and black objects appear black.**

*“White objects appear white because they reflect all colors of light in the visible spectrum. Black objects appear black because they absorb all colors of light [in the visible spectrum].”*

1. **Name the three chemical substances required to produce bioluminescence**

*The three chemical substances required to produce bioluminescence are*

* + - 1. *luciferin,*
      2. *oxygen, and*
      3. *luciferase.*

1. **What event caused Edith Widder to decide to study bioluminescence?**

*The event that convinced Edith Widder to study bioluminescence was when she dove in a one-person submersible. During that dive she was so impressed by the bioluminescent light show that she decided to study the phenomenon.*

1. **Why did Karen Osborn name the nearly transparent worm Swima bombiviridis?**

*When Karen Osborn gently pinched the nearly transparent worm it shot out tiny bombs that burst into brilliant green light. Swima bombiviridis is Latin for “green bomber.”*

1. **Explain how Dr. Widder uses bioluminescence to detect water pollution.**

*To detect water pollution, Dr. Widder mixes glowing bacteria with mud samples from the Indian River Lagoon in Florida. When the water is toxic the glowing solution is dimmer. The toxic substances in the water are killing the bacteria, which is indicated by the dimmer glow.*

1. **List three (3) characteristics of mantis shrimps’ vision.**

*The mantis shrimp eyes*

* + - 1. *have four times as many specialized photocells in their retinas as humans,*
      2. *have three pupils, and*
      3. *can see polarized light (which humans cannot see).*

# *ChemMatters* Puzzle: Word Search

We offer a few word-search puzzles, but with an unusual twist. We have taken a pithy quotation about chemistry and alphabetized its individual words to form a *word list*. Your task is to generate the original quote, based on a set of hints. Puzzle 1 is a warm-up.

PUZZLE 1

**World list** (12 words in alphabetical order )

and Chemistry comings electrons. goings is

of science studies the the that

**Hints**

* Note which list-word is capitalized, and which ends with a period.
* “ studies “ is a verb, not a noun in this puzzle.
* The only two-letter preposition is found in the second half of the quote.
* The third-to-last word in the quote has as many letters in it as *any* carbon atom has protons.

PUZZLE 2

The quote is from the noted astronomer/cosmologist Carl Sagan. The word list contains 15 words which we give you below in alphabetical order, not reading order. Can you generate the original quote?

a a body is is it knowledge. more

much of of Science than thinking way

**Hints**

* Note the only word that is capitalized,
* The longest word ends the quote.
* The second word is a verb.
* The two words beginning with the letter m appear consecutively.
* The only 8-letter word appears in the first half of the quote.
* Starting with word #9 in quote the next six words all have 4 or less letters.

Good luck with your search!

# Answers to the *ChemMatters* Puzzle

PUZZLE #1

“Chemistry is the science that studies the comings and goings of electrons.”

It is a paraphrase of a Henry Bent quote in his textbook.

PUZZLE #2

“Science is a way of thinking much more than it is a body of knowledge.”

It is a quote from Carl Sagan.

# Correlations to the Next-Generation Science Standards

|  |  |
| --- | --- |
| **Article** | **NGSS** |
| **Eating with Your Eyes: The Chemistry of Food Colorings** | |  | | --- | | **HS-PS1-3.**  Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.  **HS-ETS1-3.**  Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts. |   **Crosscutting Concepts:**   * Patterns * Structure and Function   **Science and Engineering Practices:**   * Constructing explanations (for science) and designing solutions (for engineering)   **Nature of Science:**   * Scientific knowledge assumes an order and consistency in natural systems. * Science is a human endeavor. * Science addresses questions about the natural and material world. |
| **Tooth Decay: A Delicate Balance** | |  | | --- | | **HS-PS1-6.**  Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium.  **Crosscutting Concepts:**   * Structure and Function * Stability and Change   **Science and Engineering Practices**:   * Developing and using models. * Constructing evidence (for science) and designing solutions (for engineering)   **Nature of Science**:   * Scientific knowledge is based on empirical evidence. * Scientific knowledge assumes an order and consistency in natural systems. | |
| **Probiotics: Good Bacteria, Good Health** | |  | | --- | | **HS-LS1-3.** Plan and conduct an investigation to provide evidence that feedback mechanisms maintain homeostasis. |   **Crosscutting Concepts:**   * Stability and change * Systems and System Models   **Science and Engineering Practices:**   * Constructing evidence (for science) and designing solutions (for engineering)   **Nature of Science:**   * Science models, laws, mechanisms, and theories explain natural phenomena. * Science addresses questions about the natural and material world. |
| **Dirt? Who Needs It? How Hydroponics Is Poised to Change the World** | |  | | --- | | **HS-PS2-6.** Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.  **HS-ETS1-3.**  Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.  **Crosscutting Concepts:**   * Structure and Function * Systems and system models   **Science and Engineering Practices:**   * Developing and using models * Constructing evidence (for science) and designing solutions (for engineering)   **Nature of Science**:   * Science is a human endeavor. | |
| **Light in the Cellar of the Sea** | |  | | --- | | **HS-ETS1-3.**  Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts. | | **Crosscutting Concepts:**   * Cause and effect: mechanism and explanation * Systems and system models   **Science and Engineering Practices**:   * Asking questions (for science) and defining problems (for engineering) * Constructing explanations and designing solutions * Obtaining, evaluating, and communicating information   **Nature of Science**:   * Scientific knowledge is based on empirical evidence. * Science is a human endeavor. * Scientific knowledge assumes an order and consistency in natural systems | |

# Connections to Common Core State Standards

**RST.9-10.1** Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.

**RST.9-10.2:** Determine the central ideas or conclusions of a text; trace the text's explanation or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.

**RST.11-12.1** Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.

**RST.11-12.2:** Determine the central ideas or conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.

***In addition***, the teacher could assign writing to include the following **Common Core State Standards**:

**WHST.9-10.2** Develop the topic with well-chosen, relevant, and sufficient facts, extended definitions, concrete details, quotations, or other information and examples appropriate to the audience’s knowledge of the topic.

**WHST.9-10.2F**: Provide a concluding statement or section that follows from and supports the information or explanation presented (e.g., articulating implications or the significance of the topic).

**WHST.11-12.1E:** Provide a concluding statement or section that follows from or supports the argument presented.

**WHST.11-12.2**  Develop the topic thoroughly by selecting the most significant and relevant facts, extended definitions, concrete details, quotations, or other information and examples appropriate to the audience’s knowledge of the topic.

# Anticipation Guides

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

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

## Eating with Your Eyes: The Chemistry of Food Colorings

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

|  |  |  |
| --- | --- | --- |
| **Me** | **Text** | **Statement** |
|  |  | 1. About 30% of the diet of the average U. S. resident is from processed foods. |
|  |  | 1. People have used natural food dyes for centuries. |
|  |  | 1. All anthocyanins have the same molecular structure. |
|  |  | 1. Some red food dye comes from insects. |
|  |  | 1. Synthetic food dyes are more expensive than natural food dyes. |
|  |  | 1. Most synthetic food dyes are made from petroleum. |
|  |  | 1. Food coloring molecules are usually nonpolar solids. |
|  |  | 1. Blue dye absorbs mostly red, orange, and yellow light. |
|  |  | 1. Food coloring molecules usually have alternating single and double bonds that allow electrons to be excited at relatively low energy. |
|  |  | 1. Natural products are always healthier than artificial ones. |

## Tooth Decay: A Delicate Balance

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

|  |  |  |
| --- | --- | --- |
| **Me** | **Text** | **Statement** |
|  |  | 1. The enamel in the outer layer of your tooth is the hardest substance in your body. |
|  |  | 1. The mineral that makes up tooth enamel is made of sodium and carbonate ions. |
|  |  | 1. Your saliva contains buffers that resist a change in pH. |
|  |  | 1. When teeth are exposed to low pH for extended periods of time, an unstable equilibrium causes tooth decay. |
|  |  | 1. The pH in your mouth causes the pH in your body to change. |
|  |  | 1. In a chemical equilibrium, the concentration of molecules on both sides of the chemical equation are the same. |
|  |  | 1. Food increases the pH in your mouth. |
|  |  | 1. Carbon dioxide is involved in maintaining equilibrium in your mouth. |
|  |  | 1. Composite resins made of polymers are usually used to fill holes in tooth enamel. |
|  |  | 1. One drawback to using amalgams to fill teeth is that the hole drilled for the filling removes healthy tissue. |

## Probiotics: Good Bacteria, Good Health

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

|  |  |  |
| --- | --- | --- |
| **Me** | **Text** | **Statement** |
|  |  | 1. Probiotics are similar to bacteria that live naturally in your gut. |
|  |  | 1. There are fewer than 100 species of bacteria living inside you. |
|  |  | 1. The idea of adding probiotics to your diet is only about 30 years old. |
|  |  | 1. All probiotics are made from dairy products |
|  |  | 1. Very specific rules have been established by authorities in the United States for commercial probiotics. |
|  |  | 1. The chemical process of fermentation releases the energy that was stored in plants through photosynthesis. |
|  |  | 1. As much as 10% of the energy you need daily may come from fermentation inside your body. |
|  |  | 1. In a healthy person, there are about twice as many beneficial bacteria as harmful bacteria. |
|  |  | 1. Because of pasteurization, store-bought milk can’t be used to produce probiotics like sour milk. |
|  |  | 1. There is a nerve that goes from your abdomen to your brain. |

## Dirt? Who Needs It? How Hydroponics Is Poised to Change the World

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

|  |  |  |
| --- | --- | --- |
| **Me** | **Text** | **Statement** |
|  |  | 1. Hydroponics is the fast growing field in agriculture. |
|  |  | 1. People have been growing plants without soil for about a hundred years. |
|  |  | 1. The solutes in a hydroponic solution include nutrients such as copper, calcium, and potassium. |
|  |  | 1. Plants require only sunlight and water to grow. |
|  |  | 1. The nutrients plants need in small amounts are called micronutrients. |
|  |  | 1. The pH of a hydroponic solution should be slightly basic. |
|  |  | 1. Ions that have precipitated out of solution are unavailable cannot be taken up by plant roots. |
|  |  | 1. Most people can easily taste the difference between hydroponically grown tomatoes and those grown in soil. |
|  |  | 1. The term “hydroponics” was coined by Walt Disney for the hydroponic garden at Disney World’s Epcot Them Park. |
|  |  | 1. Hydroponic farms require a lot of energy to maintain. |

## Light in the Cellar of the Sea

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

|  |  |  |
| --- | --- | --- |
| **Me** | **Text** | **Statement** |
|  |  | 1. Very few deep-sea creatures emit light. |
|  |  | 1. The sun’s rays penetrate the ocean to a depth of about 100 meters. |
|  |  | 1. Red light penetrates water better than blue light. |
|  |  | 1. A red fish reflects red light and absorbs all other colors. |
|  |  | 1. Bioluminescence is a chemical reaction requiring oxygen. |
|  |  | 1. When excited electrons return to their original energy levels they absorblight energy. |
|  |  | 1. Students can contribute to keeping track of marine life on citizen science websites. |
|  |  | 1. Bioluminescence can be used to detect water pollution. |
|  |  | 1. Cancerous tissue reflects light differently than healthy tissue. |
|  |  | 1. Mantis shrimp’s eyes are much more complex than those of any other animal. |

Reading Strategies

These graphic organizers are provided to help students locate and analyze information from the articles. Students’ 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 |

***Teaching Strategies:***

1. Links to **Common Core Standards for Reading**:
   * ELA-Literacy.RST.9-10.5: Analyze the structure of the relationships among concepts in a text, including relationships among key terms (e.g., force, friction, reaction force, energy).
   * ELA-Literacy.RST.11-12.4: Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 11-12 texts and topics.
2. Links to **Common Core Standards for Writing**:
   * ELA-Literacy.WHST.9-10.2F: Provide a concluding statement or section that follows from and supports the information or explanation presented (e.g., articulating implications or the significance of the topic).
   * ELA-Literacy.WHST.11-12.1E: Provide a concluding statement or section that follows from or supports the argument presented.
3. **Vocabulary** and **concepts** that are reinforced in this issue:
   * Solution chemistry
   * Chemical equilibrium
   * Acids and bases
   * pH
   * Buffers
   * Molecular structures
4. The infographic about autumn leaves on page 19 will engage students with more information about some of the natural dyes found in “Eating With Your Eyes.”
5. To help students engage with the text, ask students which article **engaged** them most and why, or what **questions** they still have about the articles. The Background Information in the *ChemMatters* Teachers Guide has suggestions for further research and activities.

## Eating with Your Eyes: The Chemistry of Food Colorings

**Directions**: As you read, complete the graphic organizer below to compare and contrast natural and artificial food dyes. You could include information found in the infographic on page 19 of this issue of *ChemMatters*.

|  |  |  |
| --- | --- | --- |
|  | **Natural Food Dyes** | **Artificial Food Dyes** |
| **Examples, including colors** |  |  |
| **Advantages** |  |  |
| **Disadvantages** |  |  |
| **How they work** |  |  |

**Summary:** After reading this article, will you notice the dyes in your food? Explain your reason(s) on the back of this paper.

## Tooth Decay: A Delicate Balance

**Directions**: As you read the article, complete the graphic organizer below to describe how chemistry helps us understand each topic listed.

|  |  |  |
| --- | --- | --- |
|  | **Chemicals** | **Chemical Structure and/or Chemical Equation** |
| **Tooth enamel** |  |  |
| **Dentin** |  |  |
| **Acids & Bases in your body** |  |  |
| **Acids & Bases in your mouth** |  |  |
| **How tooth decay is treated** |  |  |

**Summary**: On the back of this paper, write a sentence to explain how chemical equilibrium helps prevent tooth decay.

## Probiotics: Good Bacteria, Good Health

**Directions:** As you read the article, complete the graphic organizer below to describe probiotics.

How are they made?

What are they?

Probiotics

How do they work?

What are some of their advantages?

**Summary:** On the back of this sheet, describe probiotics you might try after reading the article, and why you might eat them.

## Dirt? Who Needs It? How Hydroponics Is Poised to Change the World

**Directions:** As you read the article, complete the graphic organizer below to describe what you learned about hydroponics.

|  |  |  |
| --- | --- | --- |
| 3 | **New things you learned** |  |
| 2 | **Ways an understanding of chemistry helps farmers grow plants hydroponically** |  |
| 1 | **Question you have about hydroponics** |  |
| Contact! | **What would you like to tell others about hydroponics?** |  |

## Light in the Cellar of the Sea

**Directions**: As you read the article, complete the graphic organizer below using your own words to describe how each sea creature uses light in the deep ocean.

|  |  |
| --- | --- |
| **Sea creature** | **How it uses light** |
| **Midshipman fish** |  |
| **Cookiecutter shark** |  |
| **Female anglerfish** |  |
| ***Swima bombiviridis*** |  |
| **Mantis shrimp** |  |
| **Add a creature not mentioned above** |  |

* **In the graphic organizer below, tell how two scientists are studying deep-sea organisms to improve human life:**

|  |  |  |
| --- | --- | --- |
| **Scientist** | **Organism studied** | **How the study helps humans** |
|  |  |  |
|  |  |  |

* **Summary:** On the back of this paper, write a sentence describing something you learned from the article, and why the information is important to you.

# Eating with Your Eyes: The Chemistry of Food Colorings

## Background Information (teacher information)

**More on the discovery of synthetic coloring agents**

In the Middle Ages, only royalty could wear the color purple. Tyrian purple dye was first used by the Phoenicians in 1570 BC. It was extracted from small snails and was valued because it did not fade. The cost was prohibitive because 12,000 snails had to be smashed to yield 1.5 grams of dye, enough to dye only one handkerchief! Laws prohibited commoners from inordinate expenditures on clothing, so only royalty was permitted to wear this color.

William Henry Perkin (1838-1907) is credited with the discovery of the first synthetic organic chemical dye. Perkin was only 15 years old when he began studying at the Royal College of Chemistry in London. At 18, Perkin was working on the synthesis of quinine from bark of the cinchona tree found in Bolivia and Peru. Quinine is used to cure malaria.

Perkin was working in a crude laboratory in his apartment, when he accidentally discovered that mauveine (also known as aniline purple) could be extracted with alcohol to produce an intense purple dye that would neither wash out nor fade from silk material. His discovery provided the foundation for the discovery of many colorful aniline dyes.

(<http://www.humantouchofchemistry.com/william-henry-perkin.htm>)

(<http://perryponders.com/2015/04/23/a-chemist-accidentally-discovered-purple-when-looking-for-a-cure-for-malaria/>)

**More on links between the brain and food color**

Charles Spence, an Oxford experimental psychologist says, "Half the brain is visual in some sense, versus just a few per cent for overall taste senses. So in cortical real estate, vision is always going to win." This, he explains, is why color helps us decide if a food is fit for consumption as well as what flavor we will expect.

Spence has found that the package may also affect expected flavor. His research showed that people could be confused into thinking that salt and vinegar potato chips tasted like cheese and onion flavored when he switched the chip bags. He theorized that our brains make quick association shortcuts. We look at the color of the bag and expect the taste of the chips to match the color of the familiar bag. (<http://www.theguardian.com/lifeandstyle/wordofmouth/2013/mar/12/how-taste-different-colours>)

**More on the association of color with taste**

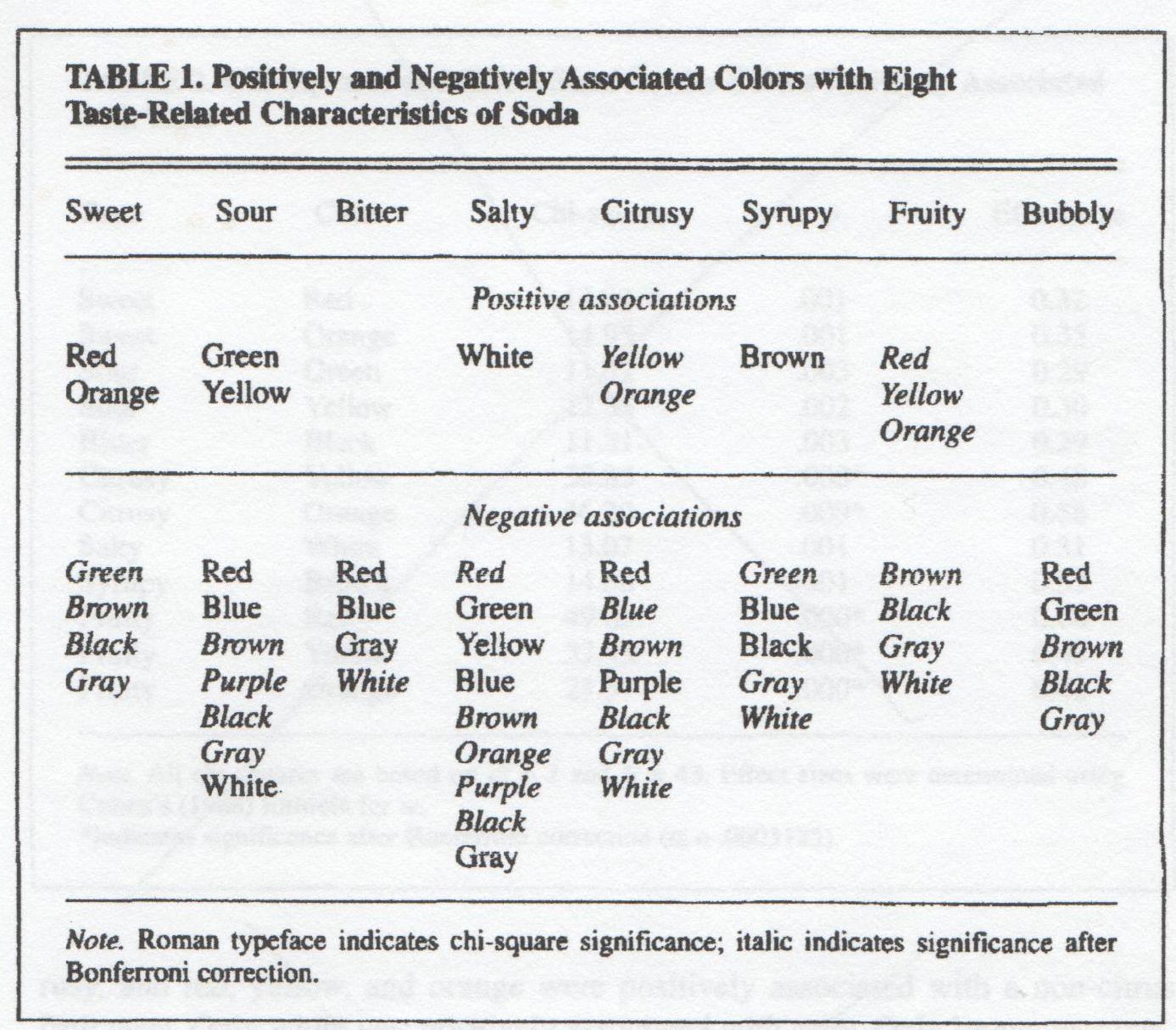
This research is usually done with colored liquids and solid gelatin solutions. The following studies were cited in “Preconceptions of Taste Based on Color”. In this paper published in *The Journal of* Psychology, 2003, 137 (3), pp 233–242, Christopher Koch of the Department of Psychology, George Fox University, and Eric Koch, Department of Business Administration, Texas Tech University, describe the results of several studies, including a description of their own findings from a questionnaire administered to 45 college students. Data from two of the studies are described below. A description of the Koch findings follows this information.

(<http://digitalcommons.georgefox.edu/cgi/viewcontent.cgi?article=1034&context=psyc_fac>)

In 1997, C. Strugnellinvestigated “Colour and its role in sweetness perceptions.” In his tests, he first asked participants to rank liquids by their sweetness. In the second stage of the tests, he kept the concentration of sweetness constant but changed the colors of the liquids. He found that participants ranked red colored liquids the sweetest and blue liquids the least sweet on their sweetness scale. **(**<http://www.ncbi.nlm.nih.gov/pubmed/9134097>)

1998 studies by R. L. Alley and T. R. Alley used sucrose solutions of four different colors in both liquid and solid gelatin form with a colorless solution as the control. Rebecca L. Alley (D. W. Daniel High School Central, South Carolina) gave 50 junior high school students ten samples of each solution. Overall the students ranked the liquids sweeter than the solids and the colored solutions sweeter than the colorless. The color did not seem to make a difference. The results of their studies were published in the *Journal of Psychology* in September 1998. (<http://www.ncbi.nlm.nih.gov/pubmed/9729847>)

Studies done by the Kochs, mentioned above, in 2003 at the University of Oregon involved 45 student volunteers. They investigated the “role of color in perceived taste using soft drinks as target beverages”. Soft drinks were chosen due to prior studies that found that people associate certain colors with these drinks. They used ten colors (red, green, yellow, blue, brown, orange, purple, black, gray and white) and eight tastes associated with soft drinks (sweet, sour, bitter, salty, citrusy, syrupy, fruity and bubbly). Their questionnaire contained 80 questions asking students to rank both colors and tastes on a   
1–10 scale. For example, “On a scale of 1 to 10 with 10 being the sweetest, how sweet is the color red?” Data was displayed by ranking of the colors as positively or negatively associated with each taste. For example, the table at right shows red and orange positively associated with sweet and red negatively (seldom) associated with sour, bitter, salty, citrusy and bubbly.



*(*[*http://digitalcommons.georgefox.edu/cgi/viewcontent.cgi?article=1034&context=psyc\_fac*](http://digitalcommons.georgefox.edu/cgi/viewcontent.cgi?article=1034&context=psyc_fac)*)*

**More on connections between taste and color**

In summarizing the research on connections between taste and color completed in the 1980s through 2003, Koch and Koch claim that

* Most colors are not associated with a particular taste.
* Color is commonly considered a taste enhancer.
* Color probably affects the desirability of food. As suggested in the Rohrig food dyes article, off-color may indicate that food is moldy and should not be eaten.
* A pink color may indicate that beef or chicken is undercooked.
* Former associations between certain colors and food may influence taste.

Additional research is suggested to determine if a person’s perception of taste can be changed by varying familiar color/taste combinations. Another problem to investigate is the possible connection between the package color and label with the taste of its contents.

(<http://digitalcommons.georgefox.edu/cgi/viewcontent.cgi?article=1034&context=psyc_fac>)

**More on launching black cheese burgers**

In September 2014, Burger King announced the introduction of black colored cheese burgers complete with black buns, black sauce and black cheese. The “Kuro Burger”, translated as “Black Burger”, was a tremendous hit in Japanese establishments. The buns and cheese are colored with bamboo charcoal; the sauce is made of garlic, onions, and squid ink; and the hamburger patty is generously spiced with black pepper before grilling. A cooking video with complete directions can be found in this teachers’ guide suggested as an “Out-of-Class Activity”.



The Japanese Kuro Burger at Burger King

*(*[*http://kotaku.com/in-japan-burger-king-has-a-black-cheese-burger-1632883542*](http://kotaku.com/in-japan-burger-king-has-a-black-cheese-burger-1632883542)*)*

The Black Burgers were not as welcome in North America. Hayley Peterson, a reporter for *businessinsider*, says, **“**Burger KingJapan's black burgerslook unbelievably gross in real life.” (<http://www.businessinsider.com/burger-kings-black-burgers-look-gross-2014-9>)

Somewhat similar but more descriptive comments came from Josh Elliott of *Canadian CTVNews*. Josh said, “People have certain expectations when it comes to food and drink. Corn is yellow, coffee is black and chicken is white. But would you try teal corn, red chicken or blue coffee?” Burger King did not attempt to introduce the black burgers to the Canadian market. (<http://www.ctvnews.ca/business/black-burgers-the-newest-offering-in-crazy-coloured-food-1.2004111>)

Eva Hyatt studies food preferences as a marketing professor at Appalachian State University. When interviewed by *The Atlantic*, she said, “The Japanese are used to eating black seaweed, fermented black bean-paste-based foods, black walnut powder, squid ink, and a lot of gray, muted-colored foods, so a black burger bun and cheese would not seem too alien to them.” (<http://www.theatlantic.com/health/archive/2014/09/food-color-trumps-flavor/380743/>)

**More on Burger King and McDonald’s competition**



Burger King’s Aka Samurai Beef Burger *(*[*http://www.today.com/food/burger-king-japan-sell-red-burgers-t27256*](http://www.today.com/food/burger-king-japan-sell-red-burgers-t27256)*)*

McDonald’s quickly produced a black burger knockoff, so rival Burger King introduced the “Aka Burger” (aka means red in Japanese). Beginning in July 2015, Aka Burgers were available in Samurai Beef and Samurai Chicken with a red bun and red cheese.



The Burger King Kuro Shogun

*(*[*http://blogs.wsj.com/japanrealtime/2015/06/17/burger-king-japan-to-sell-red-burgers/*](http://blogs.wsj.com/japanrealtime/2015/06/17/burger-king-japan-to-sell-red-burgers/)*)*

The *Wall Street Journal* reports that the aka burger is served with a red hot sauce made from miso and red hot peppers. Also, to keep ahead of the curve, Burger King will add deep-fried eggplant to its black burger producing the new “Kuro Shogun” (at right) which was to debut on August 21, 2015.

**More on processed foods**

The Rohrig food dyes article reports that about 70% of our diet is processed foods. What does “processed” mean? There is no legal definition of “processed”. The International Food Information Council Foundation (IFICF) defines food processing as, “Any deliberate change in a food that occurs before it's available for us to eat.” Manufacturers are currently not required to provide processing information on labels. There are some strong movements to require labeling of products that use genetically modified crops (GMOs). The IFICF “Fact Sheet: Common Food Production Practices and Their Unique Contributions to the Food Supply” contains much information on modern food production systems and government regulation. (<http://www.foodinsight.org/Content/3843/Final_Food_Production_Fact_Sheet_5.11.pdf>)

The term “Processed Food” is very broad and frequently conveys a negative connotation. Using the IFICF definition of food processing, food is considered processed even if it is only chopped, frozen or dried. The table below contains a few examples of the processing that certain types of food undergo before they reach our tables.

|  |  |
| --- | --- |
| **Type of Food** | **Examples** |
| Foods that require little processing or production (also called “minimally processed”). | Washed and packaged fruits and vegetables; bagged salads; roasted and ground nuts and coffee beans |
| Foods processed to help preserve and enhance nutrients and freshness of foods at their peak. | Canned tuna, beans and tomatoes; frozen fruits and vegetables; pureed and jarred baby foods |
| Foods that combine ingredients such as sweeteners, spices, oils, flavors, colors, and preservatives to improve safety and taste and/or add visual appeal. (Does not include “ready-to-eat” foods listed below.) | Some packaged foods, such as instant potato mix, rice, cake mix, jarred tomato sauce, spice mixes, dressings and sauces, and gelatin |
| “Ready-to-eat” foods needing minimal or no preparation. | Breakfast cereal, flavored oatmeal, crackers, jams and jellies, nut butters, ice cream, yogurt, garlic bread, granola bars, cookies, fruit chews, rotisserie chicken, luncheon meats, honey-baked ham, cheese spreads, fruit drinks and carbonated beverages |
| Foods packaged to stay fresh and save time | Prepared deli foods and frozen meals, entrées, pot pies and pizzas |

*(*[*http://www.foodinsight.org/sites/default/files/what-is-a-processed-food.pdf*](http://www.foodinsight.org/sites/default/files/what-is-a-processed-food.pdf)*)*

**More on labeling foods as “Natural”**

Since the U.S. Food and Drug Administration (FDA) does not define “natural”, no restrictions are placed on its use in product labeling. Thus, you will often see packages labeled “natural” to simply imply healthful, nutritious contents. In general this label usually means the absence of artificial food coloring or synthetic flavoring. Meat and poultry labeling, under the auspices of the U.S. Department of Agriculture (USDA), is much stricter. Under USDA rules a meat product can bear the “natural” label only if it is free of “artificial flavorings, coloring, ingredient, or chemical preservative” and the food processing is no more than minimal.

(<http://www.foodinsight.org/Content/3843/Final_Food_Production_Fact_Sheet_5.11.pdf>)

Although there is no overall legal definition, natural food colorings are considered to be materials that are found in nature and prepared with minimal processing. Pigments extracted directly from plants, minerals and animals are considered natural. Natural materials contain no petroleum products. DDW – The Colour House offers the following descriptions of some frequently confused terms:

**Naturally derived colouring**

1. sources from substance that occurs in nature. Its origin is natural - whether vegetal (plant), microbiological, animal or mineral.
2. results from traditional food preparation processes

**Nature identical colouring**

1. meets none of the above criteria
2. through chemical synthesis replicates molecular structure to become identical to the naturally derived colouring.

(<http://www.ddwcolor.com/colorant/carotenoids/beta-carotene/>)

**More on food color poisoning**

In ancient times natural food coloring was not always safe for the consumer—particularly when the colorant came from minerals. Early legislation in Europe attempted to regulate the use of food coloring. In 1396 the French banned coloring in butter; in 1574 pastry coloring was added to this law; and in 1531 any German accused of using saffron as a colorant could be sentenced to death by burning!

In the 1820s, sweets were colored with a variety of colorful and frequently toxic compounds. Mercury sulfide, red lead, white lead, yellow lead chromate and a mixture of copper salts including copper arsenate caused frequent food poisoning and death. When William Henry Perkin (see the first section of the Background Information for this Teacher’s Guide) discovered artificial dyes, some manufacturers used them to cover and thus disguise poor quality or rotten food. In 1860, following the poisoning of about 200 people in England, the British government began to regulate the use of food coloring.

The U.S. Food and Drug Administration (FDA) was established in 1927 to investigate the toxicology of artificial colorants. In 1951 many children were poisoned after eating popcorn colored with Orange #1. In response the FDA revisited its approval list of sixteen artificial colorants. In 1960, this list was reduced to the seven currently approved artificial colorants. These are listed in Table 1 of the Rohrig article.

**More on** **natural food coloring**

**Carotenoids**

Carotenoids are a large class of pigments that can be extracted from plants, algae and photosynthetic bacteria. The human body synthesizes vitamin A, essential for vision, the immune system and growth, from carotenoids present in the fruits and vegetables of a normal diet.



Various foods containing carotenoids

*(*[*http://www.ddwcolor.com/colorant/carotenoids/beta-carotene/*](http://www.ddwcolor.com/colorant/carotenoids/beta-carotene/))

DDW – The Colour House claims that the natural beta-carotene that they extract (and sell) is far superior to the synthetic version. They find that the natural pigment readily dissolves as a very slightly cloudy solution, contains vitamin A, and does not form a sediment or stain the bottle as does the synthetic colorant.

As stated in the Rohrig article, excessive amounts of beta-carotene can color your skin. Drinking excessive amounts of carrot juice, eating too many yellow-orange vegetables and taking beta-carotene supplements can cause *carotenosis*. This is a condition where the skin on your nose, the palms of your hands and the soles of your feet turn yellow-orange because you are feeding your body more beta-carotene than it can use to make vitamin A. Once you reduce your intake of these vegetables and supplements, the color will fade and leave no harmful side effects.

The body stores fat-soluble beta-carotene and uses it only as needed to make Vitamin A (also called retinol). However, some people take excessive Vitamin A supplements as a “cancer cure”. Since the Vitamin A molecule is also fat soluble, excess amounts are retained primarily in the liver. The American Cancer Society reports that while vitamin A is important for your health, consuming excessive amounts of supplements can lead to a serious medical condition, hypervitaminosis A. If, in addition to color changes in the skin, the vision is blurred along with dizziness and bone pain, hypervitaminosis A can be fatal. A fact sheet from the National Institutes for Health (NIH) reports several studies:

**Carotene and Retinol Efficacy Trial (CARET)**: This U.S. trial examined the effects of daily supplementation with beta-carotene and retinol (vitamin A) on the incidence of lung cancer, other cancers, and death among people who were at high risk of lung cancer because of a history of smoking or exposure to asbestos. The trial began in 1983 and ended in late 1995, 2 years earlier than originally planned. Results reported in 1996 showed that daily supplementation with both 15 mg beta-carotene and 25,000 International Units (IU) [retinol](http://www.cancer.gov/Common/PopUps/popDefinition.aspx?id=CDR0000046057&version=Patient&language=English) was associated with increased lung cancer and increased death from all causes (all-cause mortality) ([13](http://www.cancer.gov/about-cancer/causes-prevention/risk/diet/antioxidants-fact-sheet#r13)). A 2004 report showed that these adverse effects persisted up to 6 years after supplementation ended, although the elevated risks of lung cancer and all-cause mortality were no longer statistically significant ([14](http://www.cancer.gov/about-cancer/causes-prevention/risk/diet/antioxidants-fact-sheet#r14)). Additional results, reported in 2009, showed that beta-carotene and retinol supplementation had no effect on the incidence of prostate cancer ([15](http://www.cancer.gov/about-cancer/causes-prevention/risk/diet/antioxidants-fact-sheet#r15)).

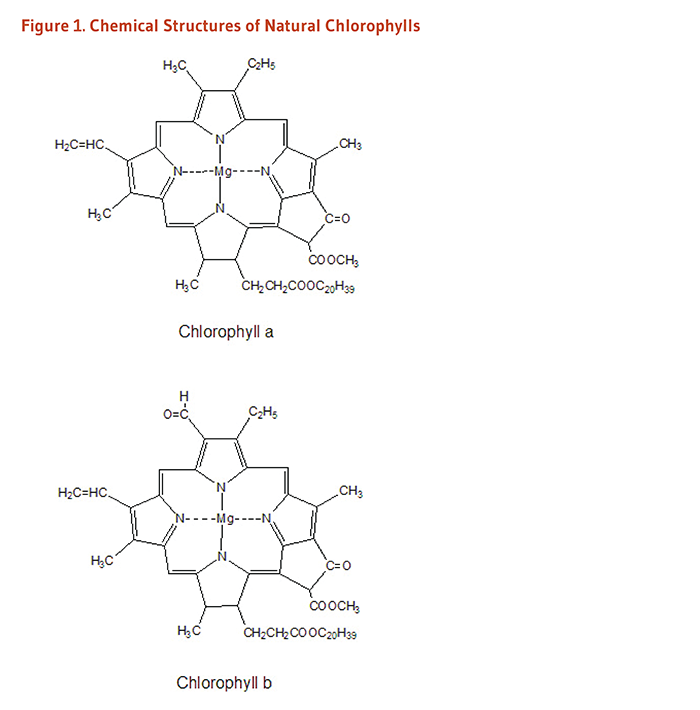
* 1. Omenn GS, Goodman GE, Thornquist MD, et al. Effects of a combination of beta carotene and vitamin A on lung cancer and cardiovascular disease. *New England Journal of Medicine* 1996;334(18):1150-1155.
  2. Goodman GE, Thornquist MD, Balmes J, et al. The Beta-Carotene and Retinol Efficacy Trial: incidence of lung cancer and cardiovascular disease mortality during 6-year follow-up after stopping beta-carotene and retinol supplements. *Journal of the National Cancer Institute* 2004;96(23):1743-1750.
  3. Neuhouser ML, Barnett MJ, Kristal AR, et al. Dietary supplement use and prostate cancer risk in the Carotene and Retinol Efficacy Trial. *Cancer Epidemiology, Biomarkers & Prevention* 2009;18(8):2202-2206.

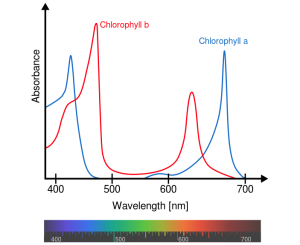
(<http://www.cancer.gov/about-cancer/causes-prevention/risk/diet/antioxidants-fact-sheet>)

**Chlorophyll**

Natural chlorophyll, extracted from plants such as alfalfa, is heat- and light-sensitive and insoluble in water because the molecule is nonpolar. Therefore, for food use it must be mixed first with a small amount of vegetable oil.

The two major photoreceptors located in plant leaves are chlorophyll type A and chlorophyll type B. These are the molecules responsible for photosynthesis. Note the similarities in their structures shown below:

*(*[*http://lpi.oregonstate.edu/mic/dietary-factors/phytochemicals/chlorophyll-chlorophyllin*](http://lpi.oregonstate.edu/mic/dietary-factors/phytochemicals/chlorophyll-chlorophyllin)*)*

 Both types are large molecules with a central (porphyrin) ring where magnesium is complexed to four nitrogen atoms. Their colors differ slightly: type a is blue-green; type b is yellow-green. The two structures show functional group differences: structure a has a methyl

(–CH3) side chain and b has an aldehyde (–CHO) as seen on the upper left of the structures above. Type a chlorophyll is essential for photosynthesis to occur. It serves as reaction centers for photosynthetic processes. Chlorophyll b is an accessory pigment that absorbs at wavelengths where chlorophyll a is less effective and transfers this energy to chlorophyll a. (<http://dyna-gro-blog.com/the-difference-between-chlorophyll-a-b-and-photosynthesis-overview/>)

A plot of the absorption spectra for chlorophyll A and B is shown above.

*(*[*https://commons.wikimedia.org/wiki/File:Chlorophyll\_ab\_spectra2.PNG*](https://commons.wikimedia.org/wiki/File:Chlorophyll_ab_spectra2.PNG)*)*

In 1997 Frank S. Lisa Sagliano at the University of Florida developed a procedure for freeze drying liquid chlorophyll extracted from spinach leaves. This was the first stable natural chlorophyll product. It can be purchased in powdered form.

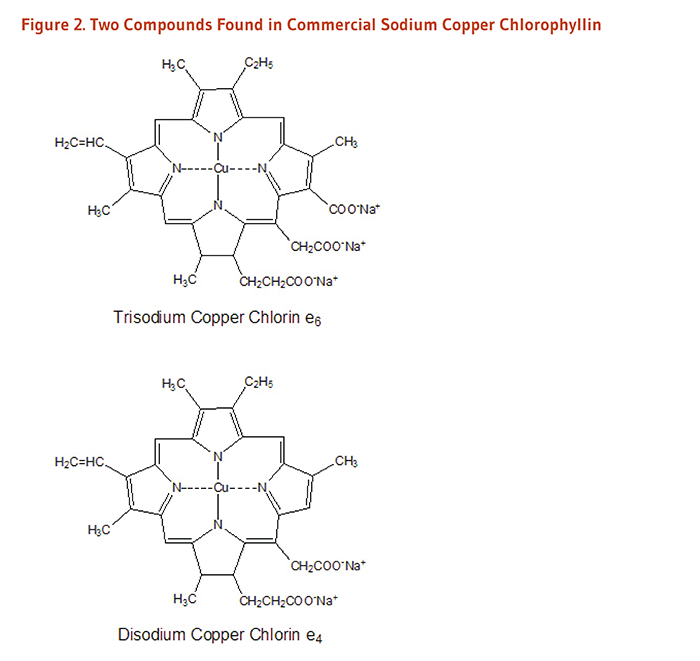
To form a stable synthetic compound, the magnesium in the middle of the molecule is replaced by copper. The synthesized colorant (sodium copper chlorophyllin) is a stable, water soluble molecule, approved for use as a food colorant by the European Union (EU). An oil soluble version is also available. The USA permission for food use is restricted for use as a colorant for “dry citrus beverage mixes” such as colorings for orange, lemon or lime flavored powdered beverages and gelatins.

(<http://www.ddwcolor.com/colorant/chlorophyll-chlorophyllin/>)

On November 30, 1999, Kraft Foods, Inc. received patent number US 5993880A for the use of sodium copper chlorophyllin: “Non-staining, acid-stable, cold-water-soluble, edible green color and compositions for preparing acidic foods and beverages”.(<http://www.google.com/patents/US5993880>)

Chlorophyll types a and b found in plant leaves are fat-soluble compounds, as are their copper chlorophyllin salts. The copper salt can be saponified with sodium hydroxide to form sodium copper chlorophyllin, a water-soluble compound shown in the structures below. Note the three sodium ions on the trisodium compound and two sodium ions on the disodium indicate polarity and thus water solubility.

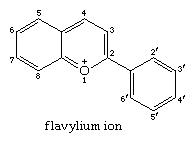
(<https://books.google.com/books?id=MiLSBQAAQBAJ&pg=PA517&lpg=PA517&dq=how+do+you+make+an+oil+soluble+version+of+sodium+copper+chlorophyllin&source=bl&ots=Q8FbQep5fx&sig=vr5SAbf4K4jL4hAMM0fm_i5wgVk&hl=en&sa=X&ved=0CB4Q6AEwAGoVChMIkdjf8PnKxwIVyNGACh2r5woC#v=onepage&q=how%20do%20you%20make%20an%20oil%20soluble%20version%20of%20sodium%20copper%20chlorophyllin&f=false>)



*(*[*http://lpi.oregonstate.edu/mic/dietary-factors/phytochemicals/chlorophyll-chlorophyllin*](http://lpi.oregonstate.edu/mic/dietary-factors/phytochemicals/chlorophyll-chlorophyllin)*)*

**Anthocyanins**

Red cabbage, beets, blueberries and radishes are some sources of anthocyanin pigment. The concentration of anthocyanins varies within each plant source, and their chemical structure depends upon the pH of the soil. The parent structure of anthocyanins is the flavylium cation, described in the Rohrig article and pictured below.



*(*[*http://www.britannica.com/science/heterocyclic-compound/Six-membered-rings-with-one-heteroatom#ref1004954*](http://www.britannica.com/science/heterocyclic-compound/Six-membered-rings-with-one-heteroatom#ref1004954)*)*

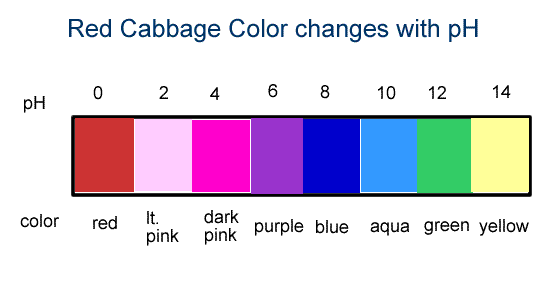
The molecular structure of these pigments changes as the pH of the solution or soil changes. From acidic to basic, the structures show color shifts from red to purple to blue. The molecular structure of anthocyanins is reversible; a pH change from basic to acid results in structural changes that present colors from blue to purple to red. Students may be familiar with red cabbage juice and know that the colors of some flowers such as violets and pansies depend upon the soil pH.

As weak organic acids, anthocyanin molecules donate protons to a solution. The pigment color depends upon the number of ionizable protons attached to the structure. Note that the molecule and ions shown below reflect light differently, thus producing color changes as the pH changes. The Rohrig article says that over 500 different anthocyanins have been identified in plants. The Web site for DDW—The Color House shows three structures for an anthocyanin, the molecule and two ions, plus the color reflected. Note that “B-L” stands for Bronsted-Lowry acid-base theory. The discussion column on the right explains that the second ion is the conjugate base of the molecule and the third ion is the conjugate base of the second ion.

|  |  |
| --- | --- |
| antho2 | Molecule 1 represents the anthocyanin with two protons (the 2 red H) to donate - a B-L acid.  **The molecule reflects red light.** |
| antho1 | Molecule 2 represents the B-L conjugate base of molecule 1, but it still has one proton to donate.  **The molecule reflects blue light.**  This molecule can either act as a B-L conjugate base and accept a proton - changing its color back to red - or act as a  B-L acid and donate its other proton. |
| antho0 | Molecule 3 represents the B-L conjugate base of molecule 2, with no more protons to donate.  **The molecule reflects greenish-yellow light.**  This molecule can no longer donate protons, but as a B-L conjugate base it can accept protons. Accepting 1 proton changes its color back to blue - while accepting 2 protons changes its color back to red. |

*(*[*http://www.ddwcolor.com/colorant/anthocyanins/*](http://www.ddwcolor.com/colorant/anthocyanins/)*)*

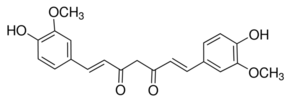
Anthocyanins serve well as food colorants because they are nearly flavorless and odorless. They can also be used as pH indicators. (See the “In-Class Activities” section of this Teacher’s Guide for a suggested student investigation.) As seen in the chart at right, their solution color varies from red in acidic solutions to blue in slightly basic solutions and almost colorless in very basic solutions.



*(*[*http://www.coolscience.org/*](http://www.coolscience.org/)*)*

**Turmeric**

The spice turmeric has three curcuminoids, the active pigments that give Indian curry and mustard their deep yellow color. Turmeric comes from the rhizomes of the curcuma longa plant which grows in southwest India, China, South America, and the East Indies. The bulb-like roots are ground to produce turmeric.



Curcuma longa (curcumin)

*(*[*http://www.sigmaaldrich.com/catalog/product/sigma/c1386?lang=en&region=US*](http://www.sigmaaldrich.com/catalog/product/sigma/c1386?lang=en&region=US)*}*

Various healing properties have been attributed to turmeric for at least 4000 years. While some have been substantiated, many are not based on reliable data. The University of Maryland Medical Center reports that many of the studies do not involve humans, and others use an injectable form of curcumin. Their Web site summarizes some of the benefits and risks.

Curcumin is a powerful antioxidant, inflammation reducer and blood thinner. It has also been known to assist in the treatment of ulcers, indigestion, osteoarthritis, heart disease, inflammation of the iris, and cancer. Curcumin may interact with other medications. Long term use may cause ulcers, gallstones, and low blood sugar. Details of these studies can be found on their site, (<http://umm.edu/health/medical/altmed/herb/turmeric>).

**Carminic acid from bugs**

The Aztecs were coloring their garments with the vibrant red extract from the female cochineal bug before Europeans arrived in South America in the 1500s. This small bug is found on prickly pear cactus in Mexico, Peru and the Canary Islands. Students may be familiar with the leaves (pads) of this plant because “nopales” are frequently used in Mexican cuisine. Sun drying and crushing thousands of bugs was required to produce the powdered dye.



Cochineal infestation on prickly pear cactus

*(*[*http://www.thecactusdoctor.com/CochinealEradication.html*](http://www.thecactusdoctor.com/CochinealEradication.html)*)*

(<http://www.livescience.com/36292-red-food-dye-bugs-cochineal-carmine.html>)

The female cochineal bug

*(*[*http://www.vegparadise.com/news13.html*](http://www.vegparadise.com/news13.html)*)*



The white clumps on the nopales of the cactus plant shown above are clusters of microscopic cochineal bugs. They are considered a pest on this highly infected plant. The average female chochineal bug is only about five millimeters long.

**More on hypersensitivity to natural food colorings**

As stated in the Rohrig article, some people suffer minor to severe allergic reactions from contact with carmine in cosmetics such as eye shadow and lipstick. Especially susceptible are those who work with carmine in industrial settings. Allergic response can lead to dermatitis, asthma and anaphylactic response, a severe life-threatening allergic response. Additional details are available on this Web site:

(<http://www.inchem.org/documents/jecfa/jecmono/v46je03.htm>).

As of January 5, 2011, the U.S. Food and Drug Administration (FDA) requires that product labels for all foods and cosmetics containing cochineal extract (red dye from cochineal beetles) and/or carmine (red pigment made from dye of cochineal beetles) must notify consumers that they contain these pigments. This information is stated in “Guidance for Industry” on the FDA Industry Web site, below. This government site also includes frequently asked questions (FAQs) with answers regarding this regulation. (<http://www.fda.gov/ForIndustry/ColorAdditives/GuidanceComplianceRegulatoryInformation/ucm153038.htm>)

 Although not considered major food allergens, some people may experience hives or asthma from other natural coloring agents such as carotenoids, annatto (seeds of fruit from the achiote tree), and saffron (red stigmas of the flower) used to color and flavor rice for Italian risotto and Spanish paella. Additional information is located on these sites: (<https://en.wikipedia.org/wiki/Annatto>) and (<http://www.drugs.com/npp/saffron.html>).



Annatto is produced from seeds from the achiote tree.

*(*[*http://www.npr.org/sections/thesalt/2015/02/19/387319835/chocolate-makeover-nestle-dumps-artificial-colorings*](http://www.npr.org/sections/thesalt/2015/02/19/387319835/chocolate-makeover-nestle-dumps-artificial-colorings)*)*

Saffron color is concentrated in red stigmas of the flower.

*(*[*https://en.wikipedia.org/wiki/Saffron*](https://en.wikipedia.org/wiki/Saffron)*)*

**More on commercial response to public demands—natural colorants**



In March 2012 Starbucks responded to complaints from vegetarians, vegans and those whose religious beliefs prohibit consumption of animals by removing cochineal extract from its strawberry frappuccinos. The chain replaced the powdered bugs with lycopene, a tomato based coloring. Purple sweet potatoes can also be used as a natural cochineal extract replacement.

(<http://www.businessinsider.com/how-cochineal-insects-color-your-food-and-drinks-2012-3>)

 Other manufacturers have not followed suit. For example, Dannon will not remove cochineal extract from its strawberry yogurt. In July 2013, Elaine Watson, editor of FoodNavigator-USA, quotes Dannon, “Carmine is a safe natural food color, and we label it clearly on pack”. (<http://www.foodnavigator-usa.com/Suppliers2/Dannon-rejects-calls-to-remove-crushed-bugs-from-its-yogurts-Carmine-is-a-safe-natural-food-color-and-we-label-it-clearly-on-pack>

*(Photo:* [*http://www.vegparadise.com/news13.html*](http://www.vegparadise.com/news13.html)*)*

 *Vegetarians in Paradise: News from the Nest* also warns vegetarians and others who want to avoid animal products that Tropicana’s “Season's Best Ruby Red Grapefruit Juice” and their “Pure Premium Orange Strawberry” drinks show cochineal extract on their labels.

The label on the Strawberry drink reads, “made from fresh oranges, not concentrate, 100% pure squeezed orange juice with calcium and strawberry and natural flavors and ingredients." Ingredients listed: “100% pure squeezed pasteurized juice, Fruit Cal (calcium hydroxide, malic acid, and citric acid), banana puree, white grape juice concentrate, strawberry juice concentrate, natural flavors, and **cochineal extract** [editor emphasis] (color)”. Note that in response to allergic reactions and personal diet objections, FDA approves the use of natural cochineal extract as long as it is listed on the label. (<http://www.vegparadise.com/news13.html>)

*(*[*http://www.vegparadise.com/news13.html*](http://www.vegparadise.com/news13.html)*)*

**More on** **synthetic food coloring**

“FD&C” from the table in the Rohrig article is the acronym for the U.S. Federal Food, Drug, and Cosmetic Act (FD&C Act). This set of laws was passed by Congress in 1938. This legislation gave the FDA authority to oversee the safety of food, drugs and cosmetics.

**The 1938 Food, Drug, and Cosmetic Act**

More consumer-oriented than its predecessor, the 1938 Food, Drug, and Cosmetic Act was a watershed in US food policy. In contrast to the limited health-based standards that the Ministry of Health proposed in Britain during the Depression, the US, largely through the efforts of women’s groups, pioneered policies designed to protect the pocketbooks of consumers, and food standards were enacted to ensure the ‘value expected’ by consumers. [46] The 1938 Act eliminated the ‘distinctive name proviso’ and required instead that the label of a food ‘bear its common or usual name’. The food would be misbranded if it represented itself as a standardised food unless it conformed to that standard. The law provided for three kinds of food standards: 1) standards (definitions) of identity, 2) standards of quality, and 3) standards regulating the fill of container. Regulators had the discretionary authority to set standards ‘whenever in the judgment of the Secretary such action will promote honesty and fair dealing in the interests of consumers’.[47]

[46]Legislative History, vol. 2, p. 93.  
[47]Pub. L. No. 75-717, 52 Stat. 1040 (1938)

(<http://www.fda.gov/AboutFDA/WhatWeDo/History/ProductRegulation/ucm132818.htm>)

These are the two additional food colorings that The FDA added (with restrictions) to the seven listed in the Rohrig article.

* Citrus Red 2, orange color, C18H16N2O3: for use on the rind of early season ripe oranges when there was insufficient cold weather to produce the natural color. At high levels, this colorant is a suspected carcinogen. (<https://en.wikipedia.org/wiki/Citrus_Red_2>)
* Orange B, red color, C22H16N4Na2O9S2: for use only on hot dogs and sausage casings with a limit of 150 ppm of the final product weight. The only U.S. supplier of Orange B has ceased producing it, but the colorant still remains on the limited use list. (<https://en.wikipedia.org/wiki/Orange_B>)

**More on how dyes produce visible color**

The following university Web sites provide information for students who are studying how food coloring is produced at the particle level. University students are performing laboratory experiments designed to study and determine how certain organic compounds absorb light of ultraviolet or visible wavelengths, the UV-Vis range. These articles provide an excellent source of information to augment the material in the Rohrig article.

The University of Massachusetts Amherst Web site article, “A Brief Discussion of Color”, uses experimental test results to explain the electromagnetic energy involved in the production of color in the visible spectrum. Structural formulas are used to show the conjugated (alternating single and multiple bonds) that allow the absorption of visible light.

(<https://people.chem.umass.edu/samal/269/color.pdf>)

Dartmouth University provides free access to an explanation of “The Spectra of Conjugated Dyes and Investigation of Beer's Law”. This piece was written to augment a college-level laboratory exercise and MAY be suitable for AP chemistry students. Quantum mechanical theory is developed to explain light scattering. The article is written for university students learning to calculate the amount of energy involved in light scattering in food dyes. It uses “The Quantum-Mechanical Particle-in-a-box” theory to “predict the wave functions and energy levels of the electrons responsible for the visible wavelength transitions and therefore the color of the dye” in Kool-Aid and Gatorade. Colorimetry and Beer's Law, paper chromatography and the structural formulas of food dyes are illustrated and explained.Students will be analyzing a solution of the drink to determine whether the colored drink is composed of one or more colorants.

(<https://www.dartmouth.edu/~chemlab/chem6/dyes/full_text/chemistry.html>)

**More on lake pigments**

The label on a package of M&Ms lists: “coloring (includes Blue 1 Lake, Red 40 Lake, Yellow 6, Yellow 5, Red 40, Blue 1, Blue 2 Lake, Yellow 6 Lake, Yellow 5 Lake, Blue 2”. Lake colors are synthetic food colorants. They are insoluble in water and they disperse in oil making them a preferred color for coating candies such as M&Ms.

Lake pigments are organic compounds that have been precipitated with an inert (nonreactive) binder that is usually colorless, tasteless, odorless and insoluble. Barium or calcium sulfates and aluminum hydroxide or oxide can serve as neutral binders. The organic compound determines the wavelength of light absorbed and reflected by the precipitate. (<http://www.foodadditivesworld.com/lakes.html>)

Natural Red 4 can be produced by boiling carminic acid (the natural extract is produced by the female cochineal bug) in a basic sodium carbonate solution containing a small amount of ethanol and precipitating it with aluminum or calcium cations. The dye is pH sensitive as seen in the pH and color ranges below:

**CARMINE COLOR**

**Differs with pH of Solution**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| resized_300x282_web-cochineal | |  |  |  | | --- | --- | --- | | Shade | pH 3.0  pH 4.0  pH 7.0 | orange to red or purple  red or purple  red or purple | | Acceptable pH Range | 3.5 - 9.0 | | | Stability | heat  light  acid | excellent  excellent  excellent | | Forms | powder, liquid | | | Solubility | dispersible in water or oil | | |

*(*[*http://www.foodcolor.com/carmine-color*](http://www.foodcolor.com/carmine-color)*)*

The carmine precipitate is a "lake" known as Natural red 4. Once dried, the powder contains approximately 50% carminic acid. It is insoluble in oil but soluble in an alkaline water solution. The solution is stable above pH 6.

(<http://www.colormaker.com/natural-ingredients_carmine.html>)

**Natural Red 4**



*(*[*http://www.ddwcolor.com/colorant/carminic-acid-carmine-cochineal/*](http://www.ddwcolor.com/colorant/carminic-acid-carmine-cochineal/)*)*

**More on the difference between dyes and lakes**

Both dyes and lakes are used for food coloring. Dyes are produced in either light powder or granular forms. To be FD&C certified, they must undergo a rigorous premarket approval by the FDA. The manufacturer submits a petition with data demonstrating that the dye is safe for human consumption and appropriate for use as a food dye. Subsequently each batch must be certified by the FDA. Dyes are water soluble so they can be used to color products that contain sufficient water for dissolution such as drinks and baked goods. (<http://www.fda.gov/ForIndustry/ColorAdditives/RegulatoryProcessHistoricalPerspectives/>)

Lakes are insoluble compounds made from dyes. They color fats and oils by dispersion. For food use, a lake must be prepared from an FDA certified food dye. A lake pigment is named for its metallic salt binder. For example, Red No. 40 can be used as the base material to produce Red No. 40 aluminum lake. This comes in two dilutions: a low dye which is 15–17% pure Red No. 40 and a high dye containing 36–42% of the original dye. Lake colors do not readily dissolve so they are the best choice for coating M&Ms and coloring lipstick.

<http://www.ifc-solutions.com/color_guide.html>)

**More on commercial response to public demands—synthetic colorants**

The *Berkeley Wellness* newsletter (November 2014) states, “According to the Institute of Food Technologists, natural colors outsold artificial ones globally in 2011 for the first time ever.” (<http://www.berkeleywellness.com/healthy-eating/food-safety/article/food-coloring-goes-natural>)

On January 20, 2015 the supermarket chain, Whole Foods, announced on their blog,

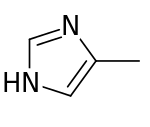
“Our Quality Standards: No Artificial Colors or Flavors”.

The blog adds that, since natural coloring agents are not as intense as the artificial ones, the product cost is greater for both the manufactures and the consumers.

(<http://www.wholefoodsmarket.com/blog/our-quality-standards-no-artificial-colors-or-flavors>)

The compound 4-methylimidazole (4-MEI) is a brown-colored byproduct formed during cooking procedures such as caramelizing (oxidizing) sugar, grilling meats and roasting coffee. “Caramel coloring” on a label may not indicate that 4-MEI is the coloring agent. See additional information in next section, “More on caramel coloring”, of this Teacher’s Guide. The FDA does not consider that the current data shows short-term danger from its consumption. Both the FDA and the European Food Safety Authority (EFSA) find current exposure levels below a danger threshold for human consumption. Yet, the FDA is continuing to monitor data on its use. (<http://www.fda.gov/food/ingredientspackaginglabeling/foodadditivesingredients/ucm364184.htm>)

4-methylimidazole (4-MEI)



*(*[*https://en.wikipedia.org/wiki/4-Methylimidazole*](https://en.wikipedia.org/wiki/4-Methylimidazole))

Public response to the use of 4-MEI has been extremely negative and politicians in California as well as Whole Foods have listened. In 2011, California listed 4-MEI as a carcinogen in Proposition 65. The food coloring gives cola drinks their characteristic brown color. This legislation requires that a cancer warning be placed on the label of every product containing 4-MEI sold in the state. In response, Coca Cola and Pepsi changed their formulas eliminating 4-MEI. The FDA does not restrict its use, citing that one would have to drink 1000 cans of soda per day to reach the threshold of cancer in rodents.

This comes from the January 23, 2015 The American Beverage Association report on 4-MEI:

**Statement:**

First and foremost, consumers can rest assured that our industry's beverages are safe. Contrary to the conclusions of Consumer Reports, FDA has noted there is no reason at all for any health concerns, a position supported by regulatory agencies around the world. In fact, FDA has noted that a consumer ‘would have to drink more than a thousand cans of soda in a day to match the doses administered in studies that showed links to cancer in rodents.’ However, the companies that make caramel coloring for our members' soft drinks are now producing it to contain less 4-MEI, and nationwide use of this new caramel coloring is underway. (<http://www.ameribev.org/news-media/news-releases-statements/more/324/>)

**More on caramel coloring**

When a product lists “caramel coloring”, this may mean that the food is colored by Class I or Class II Caramel Coloring rather than 4-MEI. Class I coloring is made by oxidizing sugar (caramelization) and the Class II process uses sulfite compounds (see table below). Some people may suffer allergic reactions to sulfites.

Internationally, the United Nations Joint Food and Agriculture Organization/World Health Organization Expert Committee on Food Additives ([JECFA](https://en.wikipedia.org/wiki/JECFA)) recognizes four classes of caramel color, differing by the reactants used in their manufacture, each with its own [INS](https://en.wikipedia.org/wiki/International_Numbering_System) and [E number](https://en.wikipedia.org/wiki/E_number), listed in the table below.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Class** | **INS No.** | **E Number** | **Description** | **Restrictions on preparation** | **Used in**[[7]](https://en.wikipedia.org/wiki/Caramel_color#cite_note-7) |
| I | 150a | E150a | Plain caramel, caustic caramel, spirit caramel | No ammonium or sulfite compounds can be used | Whiskey and other high proof alcohols |
| II | 150b | E150b | Caustic sulfite caramel | In the presence of sulfite compounds but no ammonium compounds  can be used | Cognac, sherry and some vinegars |
| III | 150c | E150c | Ammonia caramel,  baker's caramel, confectioner's caramel, beer caramel | In the presence of ammonium compounds  but no sulfite compounds  can be used | Beer, sauces, and confectionery |
| IV | 150d | E150d | Sulfite ammonia caramel,  acid-proof caramel,  soft-drink caramel | In the presence of both  sulfite and ammonium compounds | Acidic environments such as soft drinks |

[7] <http://www.ddwcolor.com/select-your-class-class-i-caramel/>

([*https://en.wikipedia.org/wiki/Caramel\_color*](https://en.wikipedia.org/wiki/Caramel_color))

Additional information about caramel coloring Classes I and II is located on: <http://www.sethness.com/caramel_color_products/classI.php>.

**More on restaurant and food manufacturers’ removal of artificial colors**



*(*[*http://www.nestleusa.com/media/pressreleases/nestl%C3%A9-usa-commits-to-removing-artificial-flavors-and-fda-certified-colors-from-all-nestl%C3%A9-chocolate-candy-by-the-end-of-20*](http://www.nestleusa.com/media/pressreleases/nestl%C3%A9-usa-commits-to-removing-artificial-flavors-and-fda-certified-colors-from-all-nestl%C3%A9-chocolate-candy-by-the-end-of-20)*)*

The following are just a few of the major food producers who are jumping on the bandwagon to remove synthetic colors, as evidenced by this February 17, 2014 announcement: “Nestlé USA Commits to Removing Artificial Flavors and FDA-Certified Colors from All Nestlé Chocolate Candy by the End of 2015.” Natural annatto will replace the synthetic Red dye No. 40 and Yellow dye No. 5.

(<http://www.nestleusa.com/media/pressreleases/nestl%C3%A9-usa-commits-to-removing-artificial-flavors-and-fda-certified-colors-from-all-nestl%C3%A9-chocolate-candy-by-the-end-of-20>)

In April 2015 the Kraft Foods Group announced that Kraft Macaroni & Cheese customers may find their product a bit less colorful when they remove Yellow dyes No. 5 and No. 6 from their recipe. The company will begin replacing these synthetic dyes with natural paprika, annatto and turmeric in January 2016. The Web site below contains a 1:37 Mac and Cheese video that your students may find interesting.

(<http://www.usatoday.com/story/money/2015/04/20/kraft-macaroni--cheese-mac--cheese-artificial-preservatives-dyes/26073081/>)

On May 15, 2015 Panera Bread announced that they are the first restaurant chain to eliminate artificial coloring from their foods. To quote from their Web site: ”Beginning today, Panera bakery-cafes nationwide will offer new “clean” salad dressings that are made without artificial sweeteners, colors, flavors and preservatives.” In addition to salad dressings, Panera announced plans to have removed artificial coloring from 85% of their menu items by 2016. (<https://www.panerabread.com/panerabread/documents/press/2015/no-no-list-release%205-5-15.pdf>)

*The* May 26, 2015 *The Wall Street Journal* reports that Yum Brands’ Pizza Hut (by the end of July) and Taco Bell (by the end of the year) will remove artificial colors from their foods. Doritos Locos Tacos will be the one exemption because best-selling Doritos Chips is owned by PepsiCo, Inc. (<http://www.wsj.com/articles/taco-bell-to-remove-artificial-flavors-coloring-1432638320>)

In June 2015 General Mills (Trix, Lucky Charms, Cheerios, Reese’s Puffs …) announced that it will remove artificial colors from its cereals by the end of 2017. The dyes will be replaced by fruit and vegetable juices and natural vanilla will replace artificial vanilla. (<http://www.theatlantic.com/health/archive/2015/06/general-mills-to-phase-out-artificial-cereal-dyes/396536/>)

"People eat with their eyes, and so ... the trick is, how can we maintain an appealing look, just not using the artificial colors?" said Jim Murphy, the president of General Mills’ cereal division. "People don't want colors with numbers in their food anymore."

(<http://www.washingtonpost.com/news/wonkblog/wp/2015/06/22/the-real-reason-general-mills-is-cutting-fake-flavors-from-trix-lucky-charms-and-other-cereals/>)



[*http://www.washingtonpost.com/news/wonkblog/wp/2015/06/22/the-real-reason-general-mills-is-cutting-fake-flavors-from-trix-lucky-charms-and-other-cereals/*](http://www.washingtonpost.com/news/wonkblog/wp/2015/06/22/the-real-reason-general-mills-is-cutting-fake-flavors-from-trix-lucky-charms-and-other-cereals/)

NOTE: No plans were announced to reduce the sugar on their flakes!

*Chemical and Engineering News (*June 29, 2015, p. 15) announced General Mills’ plans to use only natural food coloring in 40% of its cereals. Picture at right shows Trix before (left) and after (right) the removal of artificial coloring.

## Connections to Chemistry Concepts (for correlation to course curriculum)

1. **Solubility (at the particle level)**—The use of a particular colorant depends on its solubility in the material to be colored. For example, the beta-carotene molecule is nonpolar so it is an appropriate choice for coloring nonpolar margarine or butter. In contrast, the food coloring dyes that color the coating of Skittles candy are water soluble. This article provides the opportunity to discuss solubility as a competition between three forces (or energies): the strength of attraction between the particles of

* the solute
* the solvent
* the solute and the solvent.

If the attraction between particles of the solute and the solvent is strongest, the attractions between the solute and solvent particles can be broken and solubility will occur.

1. **Solubility of ionic and covalently bonded substances**—This presents an opportunity to reinforce the understanding of the difference between the properties of water-soluble ionic compounds and water-soluble covalently bonded molecules at the particle level. The dissolving of a soluble salt in water involves the release of hydrated ions into a solution. In contrast, dissolving sugar involves the release of hydrated covalently bonded sugar molecules into the solution.
2. **Intermolecular forces**—The structural formula of the anthocyanin molecule, Figure 2 of the Rohrig article, shows exposed hydroxyl groups that can readily hydrogen bond with water molecules. This provides the opportunity to discuss the water solubility of this molecule in terms of intermolecular forces, the strength of the hydrogen bonding force between anthocyanin and water molecules.
3. **Molecular structure**—The molecular structures of beta-carotene and anthocyanin provide the basis for understanding how structure determines the physical and chemical properties of a molecule.
4. **Organic structural diagrams**—Students may need help interpreting the figures of organic molecules. Organic chemists have developed a shorthand method to facilitate the drawing of large molecules while showing bond angles. Carbons are assumed to be present at each junction of two lines in the drawing and the correct number of hydrogen atoms required to complete an octet are also assumed. Other atoms and functional groups are written into the structure.
5. **Bronsted-Lowry acid-base theory**—While discussing acids and bases, the ability of anthocyanins to reflect light of different colors can provide a connection between conjugate acid/base theory and the background of students who experienced red cabbage indicator experiments in elementary school. Students will be surprised to see yellow colored turmeric turn a bright red in a basic solution.
6. **Atomic emission spectra and basic quantum theory**—Alternating double and single bonds decreases the energy required to excite electrons and promote transitions between the ground state and higher energy levels, thus scattering light in the visible spectrum and giving color to our food. This provides a chemical explanation of a real world phenomena.
7. **Electromagnetic spectrum**—Salt and sugar molecules can only absorb and emit light in the ultraviolet range, wavelengths that our eyes cannot detect, in contrast to the visible range colors absorbed and transmitted by organic dye molecules.

## Possible Student Misconceptions (to aid teacher in addressing misconceptions)

1. **“My cousin told me that to make my diet healthy I should stop eating processed foods.”** *Food processing just means making a deliberate change in the food before it is placed on the supermarket shelves. Even whole fruits crushed in a blender to make a fresh fruit smoothie and frozen broccoli have been processed. Your cousin might correctly suggest that you avoid the processed foods that are sweetened with high fructose corn syrup and preserved with nitrites, sodium and oils.*
2. **“I will gain weight if I eat processed foods.”** *Probably not. You will gain weight if you eat more calories than your body uses. The excess calories may be stored as fat.*
3. **“I’ll be certain to eat foods that use natural dyes because they’re safe.”** *Not all natural dyes are risk free. Some people experience allergies from natural dyes such as carmine, annatto and saffron.*
4. **“From biology I know that a sugar molecule contains 12 atoms of carbon, 22 atoms of hydrogen and 11 atoms of oxygen. For each molecule of sugar that dissolves in water, 45 separated atoms are mixed into the solution.”** *The 45 atoms of a sugar molecule are tightly bound by covalent bonds. The molecule stays as a unit, attracted to water molecules by intermolecular forces of attraction between molecules.*
5. **“I plan to include a lot of carrot juice in my diet so that my vision will become super sharp.”** *Unless you are malnourished, your normal diet contains sufficient beta-carotene to produce as much Vitamin A as needed for your vision. Additional beta-carotene will not improve your vision.*
6. **“The anthocyanin molecule contains hydrogen bonds between the hydrogen and the oxygen in the –OH group.”** *Hydrogen bonding is an intermolecular force of attraction between the —H atoms of the water molecules and the —OH on the anthocyanin molecules. A covalent bond holds the hydrogen and oxygen together within the anthocyanin molecule.*
7. **“Blue means basic, so blueberries must be very basic.”** *An acid-base indicator is a chemical compound that changes color at different levels of hydrogen ion concentration (pH). There are many acid-base indicators with different color changes. Litmus is a commonly used indicator that turns blue in basic solutions, as is universal indicator. Blueberries contain anthocyanin that has a color range that differs from litmus and universal indicator. In anthocyanin, blue indicates slightly basic (pH = 8) and yellow indicates a strong basic solution (pH = 14).*

## Anticipating Student Questions (answers to questions students might ask in class)

1. **“Why has the FDA only approved seven synthetic dyes?”** *The Federal Food, Drug, and Cosmetic Act (FD&C Act) identifies a substance that imparts color as a color additive and thus is subject to rigorous premarket approval requirements. This involves testing and presentation of data that certifies the safety and suitability of the additive for food use. In addition, each batch of the colorant must be evaluated to be certain that it is safe for human consumption.*
2. **“Where can I buy colorless Pepsi?”** *“Crystal Pepsi” was introduced in 1992, then removed from shelves when it did not sell well. But following 34,000 written requests by cult-like followers interested in a Pepsi without color additives, the company is considering a reintroduction of their caffeine free product. Additional information can be found in the June 11, 2015 issue of* Fortune Magazine*. (*[*http://fortune.com/2015/06/11/pepsi-crystal/*](http://fortune.com/2015/06/11/pepsi-crystal/)*)*
3. **“What is the meaning of the Rs shown on the molecular formula for anthocyanin?”** *Rs are an organic chemist’s abbreviation for the location of possibly different functional groups attached to the molecule. In Figure 2 of the Rohrig article, the R3 is identified as the location of a sugar molecule.*
4. **“What is anaphylactic shock? How can it be fatal?”** *Anaphylactic shock is a very severe, sudden-onset, allergic reaction for example to foods, drugs or an insect sting that may result in a severe asthma attack, shown to be fatal in as many as two percent of cases.*
5. **“Do food color additives cause hyperactivity in children?”** *According to the FDA, current data does not show a definitive link between Attention Deficit/Hyperactivity Disorder (ADHD) and FDA certified food coloring additives.*
6. **“Do natural food coloring agents add nutritional value to foods?”** *The primary purpose of food colorants is to improve and maintain the appearance of food as it is processed and prepared for the table. Although the natural colorant may be obtained from healthy foods such as vegetables, only small amounts are needed to color foods so the health benefit is minimal.*
7. **“Why should we be concerned about allergic reactions? Why doesn’t the government just ban all artificial food colorants?”** *Artificial food colorants usually maintain their color longer than natural ones because their color is not affected by high temperatures and humidity. They can be used as water soluble dyes or chemically changed into lakes that can be dispersed in oil based foods. There is more opportunity for different colors that make food appealing and fun. And, they are much cheaper because they can be mass produced.*

## In-Class Activities (lesson ideas, including labs & demonstrations)

1. Prepare a mini-lab on solubility for students. Each student group will need a petri dish, clear plastic or glass dish (or even an aluminum pie plate) with 1 cm depth of half-and-half dairy product, 4 different food colors, toothpicks and small amount of liquid detergent. Tell students to place one drop of each food color 90o apart near the edges of the cream; dip a toothpick into the detergent and gently touch to the center of the cream; observe, play and record observations. Following the lab, ask students to explain their observations in a discussion of solubility, polar, nonpolar, hydrophobic, etc. Tie the discussion to the properties of food coloring agents and interactions with the food that is dyed.

A similar experiment is described at <http://chemistry.about.com/od/chemistryhowtoguide/a/magicmilk.htm>. College-level chemistry explanations can be found on this University of Colorado, Boulder site: <http://www.colorado.edu/MCEN/flowvis/galleries/2011/Team-1/Reports/Velasquez_Gary.pdf>; and a good two minute video showing reactions can be found here: <https://www.youtube.com/watch?v=rqQSlEViNpk>.

1. The properties of lakes are investigated in the *Chemistry in the Community* (*ChemCom*) 6th edition lab 7D.7 “Analyzing Food Coloring Additives”. Food coloring dyes are compared to the dyes in the coatings of M&Ms and Skittles.

This 1988 article from *J. Chem. Educ.*, “Theideal solvent for paper chromatographyof food dyes” describes experimental data showing that the ideal solvent for paper chromatography of food dyes such as the colored coating on M&M candies is a 0.1% sodium chloride solution. You might want to give students the chance to discover this for themselves by replicating parts of the experiment in your own classes. (Markow, P. Theideal solvent for paper chromatographyof food dyes. *J. Chem. Educ.*, 1988, *65* (10)*,* pp 899–900; abstract only here: <http://pubs.acs.org/doi/abs/10.1021/ed065p899>. The article is available only to subscribers at this same URL.)

1. Ask students to draw a picture of how they would see salt dissolving in water at the particle level. Then, show a short video on the solubility of an ionic compound. For example: *How Water Dissolves Salt,* a video from the Canadian Museum of Nature (English and French). (<https://www.youtube.com/watch?v=xdedxfhcpWo>).

The PhET (Physical Education Technology) project has been expanded beyond physics to include simulations appropriate for computer interactive activities for chemistry, biology, earth science and mathematics students. These simulations on solubility are good. Teachers have developed lesson plans and activities for specific simulations. These are two that may provide appropriate enhancement as you teach solubility: (<http://phet.colorado.edu/en/simulation/legacy/soluble-salts><http://phet.colorado.edu/en/simulation/sugar-and-salt-solutions>) This simulation specifically shows the difference between salt and sugar as they dissolve in water. Caveat – the sugar molecule is small relative to salt. The strength is that it shows molecules vs. ions separating. A PhET simulation on light absorption by molecules is found at this URL: (<http://phet.colorado.edu/en/simulation/molecules-and-light>).

1. Make and use red cabbage juice indicator. Complete basic and advanced laboratory directions and a detailed description of the acid-base chemistry involved are located on this site: <http://www.coolscience.org/CoolScience/Teachers/Activities/CabbageJuice.htm>.

Flinn Scientific has produced a video (8:56 min.) showing how to make and test red cabbage indicator. (<https://www.youtube.com/watch?v=nEQ4uOoIx0s>)

1. A Khan video (9:36 min.) shows basic information about light. This video does not discuss light-scattering effects. (*Introduction to Light, Light and Electromagnetic Radiation:* <https://www.khanacademy.org/science/cosmology-and-astronomy/universe-scale-topic/light-fundamental-forces/v/introduction-to-light>)
2. This site shows a picture of brightly colored ice cones (below). As an introduction to the discussion of the impact of color on taste, ask students what flavor they associate with each cone. Compare and discuss the reasons for their choices. (<http://www.theguardian.com/lifeandstyle/wordofmouth/2013/mar/12/how-taste-different-colours>)



(Kathryn Russell Studios/Getty Images)

1. Making hand lotion provides a good way to show the dispersion of an oil (nonpolar substance) in water (polar substance) using an emulsifier to keep the oil dispersed. Students can experiment changing their lotion from the oil to the water phase by adding additional water to the solution. They can also identify the stage (water or oil) with the addition of food coloring. A lake can be used to color lotion in the oil phase; a dye will color in the water phase. (<http://www.laney.edu/wp/pinar-alscher/files/2014/09/14-Preparation-of-a-Hand-Cream.pdf>)
2. These two laboratory investigations published in *The Journal of Chemical Education* were designed for high school students to extract and analyze FD&C dyes:
   1. ”Extraction and separation of FD&C dyes from common food sources: Their separation utilizing column chromatography” was written as a high school laboratory experiment by E. W. Bird and F. Sturtevant and published in 1992. (Bird, E.W. and Sturtevant, F. Extraction and separation of FD&C dyes from common food sources: Their separation utilizing column chromatography. *J. Chem. Educ.,* 1992, *69* (12), p 996; abstract only here: <http://pubs.acs.org/doi/abs/10.1021/ed069p996>. The article is available only to subscribers at this same URL.)
   2. Analysis of FD&C food dyes in powdered drink mixes using a spectrophotometer is described as a high school laboratory experience in a 2004 *J. Chem. Educ.* article, “The Quantitative Determination of Food Dyes in Powdered Drink Mixes. A High School or General Science [College] Experiment”. In this experiment, students determine the total amount of dye present, the quantity per serving and the mass percent of dye in a sample, as well as construct calibration curves from their data. The lab requires two to three hours. (Sigmann, S. and Wheeler, D. The Quantitative Determination of Food Dyes in Powdered Drink Mixes. J. Chem. Educ., 2004, 81 (10), p 1475; abstract only available here: <http://pubs.acs.org/doi/abs/10.1021/ed081p1475>. The article with complete laboratory instructions is available only to subscribers at this same URL.) A free version of the experiment can be found here: <http://www.wfu.edu/chemistry/courses/jonesbt/280L/Experiment%205/Dyes%20in%20Kool-Aid.pdf>.
3. Here is another high school student activity, labeled as AP, to use paper chromatography to identify the FD&C dyes present in various commercial food colors. (<http://staffweb.psdschools.org/rjensen/aplabs/chromatography_of_food_dyes.doc>)
4. Several commercial companies sell kits for investigating food dyes:
   1. Flinn Scientific
      1. AP level “Analysis of Food Dyes in Beverages - Advanced Inquiry Laboratory Kit”, investigation 1, allows students to study the concentration of Blue No. 1 dye in sports drinks. This link provides the abstract and lab kit purchase information: <http://www.flinnsci.com/store/Scripts/prodView.asp?idproduct=22576>.
      2. AP level “Separation of a Dye Mixture Using Chromatography - Advanced Inquiry Laboratory Kit”, investigation 5, allows students to separate mixtures of the seven FDA-approved food dyes. Students relate nature of successful solvents to intermolecular forces and the structures of the dyes. These links provide the abstract and lab kit purchase information: <http://www.flinnsci.com/store/Scripts/prodView.asp?idproduct=22582>.
      3. “Food Dye Chromatography—Student Laboratory Kit” allows first-year students to experiment with the 7 FDA-approved food dyes to learn more about polarity and paper chromatography. (<http://www.flinnsci.com/store/Scripts/prodView.asp?idproduct=22213>)
      4. Quantitative Determination of Food Dyes—Student Laboratory Kit helps students determine how much food dye is in dry powder drink mixes. (<http://www.flinnsci.com/store/Scripts/prodView.asp?idproduct=22222>)
   2. Vernier Software provides this experiment: “Visible Spectra of Commercial Dyes:   
      the Forensic Version”, which has students experiment using a visible spectrometer to determine which of several sports drinks has been tainted by a CuSO4 solution which poisons an athlete, by establishing spectral curves for the approved food dyes and CuSO4, and then comparing these to the curves for the sports drinks found at the scene of the “crime”. (<http://www.vernier.com/innovate/food-dye-forensics-experiment-using-the-spectrovis-plus/>)
   3. Ward’s Science’s “Kool Column Chromatography & Spectrophotometric Analysis Kit” uses a spectrophotometer to obtain spectral curves for FD&C dyes and then uses liquid chromatography to separate the dyes in grape Kool-Aid. (<https://www.wardsci.com/store/catalog/product.jsp?catalog_number=6730973>)
   4. Carolina Scientific provides this activity: “Carolina ChemKits®: Food Dye Chromatography” does approximately the same thing as the Ward’s activity cited above, except that it uses paper chromatography and not liquid chromatography for the separation. (<http://www.carolina.com/chromatography/carolina-chemkits-food-dye-chromatography/FAM_840644.pr?question>=)

## Out-of-Class Activities and Projects (student research, class projects)

1. The information in the following table was taken from the food dyes article. Check the Internet to research additional natural food coloring pigments. Add them to this list:

|  |  |  |
| --- | --- | --- |
| **Natural Food Coloring Pigment** | **Color** | **Food Use** |
| chlorophyll | Green | mint or lime flavored candy or ice cream |
| anthocyanin | deep purple/blue | blue corn chips, colored soft drinks, grape jelly |
| turmeric | deep yellow | mustard, Indian foods (curry) |
|  |  |  |
|  |  |  |
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|  |  |  |
|  |  |  |

1. Ask students to investigate natural food dyes and the possible health risks that they might pose. Suggest they begin with the ones listed in the article: cochineal, annatto and saffron.
2. Assign a student recipe project such as making natural food colorings. Their findings with photos of their products could become part of an electronic recipe book for the class. A 4:39 video clip, “How to Make Natural Food Coloring - Concentrated Color Recipe”*,* provides detailed instructions. Teacher warning: this video begins by telling the audience that, “synthetic dyes are poison and can harm your body” so you may need to discuss misconceptions before students begin the project. (<https://www.youtube.com/watch?v=Q0dhvWA5iq4>) The *Food Network* produced a similar video without the “danger warning”. This site provides printed instructions to accompany the video with the suggestion to freeze the pigment in ice cube trays for later use to color cookies and icing. (<http://blog.foodnetwork.com/fn-dish/2014/12/how-to-make-homemade-food-coloring/>)
3. A recipe for making at home a “healthy” blueberry-cabbage juice drink, loaded with anthocyanins, is located at: <http://www.eatingwell.com/recipes/blueberry_cabbage_power_juice>.
4. “Who can make the best black burger” could take the form of a class challenge. The YouTube video (15:55) shows how to blacken dough with bamboo charcoal for the black buns, use soy and squid ink to blacken the sauce and generously season the hamburger with black pepper. (<https://www.youtube.com/watch?v=0dRBroR36nI>)

The complete recipe can be found at <http://a-nutritionist-mom.blogspot.com/2013/11/very-good-bamboo-charcoal-rotiboy-bun.html>. For a recipe for homemade American cheese blackened with squid ink go to <http://www.browneyedbaker.com/diy-american-cheese/>. Amazon sells food grade activated bamboo charcoal and Alma Gourmet sells squid ink. (<http://www.almagourmet.com/store/>)

1. A possible link between color additives and attention deficit/hyperactivity disorder (ADHD), can provide the prompt for a research project culminating in a class debate regarding the claim that this link exists. WebMD states that after 30 years of study, “To date, no conclusive evidence has been found to show that food coloring causes [ADHD](http://www.webmd.com/add-adhd/default.htm).” However, several Internet sites provide dire warnings for parents. This site along with the one from Mayo Clinic below provides an excellent opportunity to help students evaluate the reliability of their information sources. The FDA strongly advises that research continue to investigate the claims expressed on some Web sites. (<http://www.webmd.com/add-adhd/childhood-adhd/food-dye-adhd>).

This topic is rich with controversy and misconceptions about the scientific process of collecting and analyzing data as opposed to making claims based on anecdotes. John E. Huxsahl M.D. of the Mayo Clinic says, “There's no solid evidence that food additives cause attention-deficit/hyperactivity disorder (ADHD).” Although some studies have found a possible link between food coloring and ADHD, the FDA Advisory Committee states that the data is not sufficient to establish this connection. (<http://www.mayoclinic.org/diseases-conditions/adhd/expert-answers/adhd/faq-20058203>)

## References (non-Web-based information sources)



**30 Years of *ChemMatters***

Available Now!

**The references below can be found on the *ChemMatters* 30-year DVD (which includes all articles published during the years 1983 through April 2013 and all available Teacher’s Guides, beginning February 1990). The DVD is available from the American Chemical Society for $42 (or $135 for a site/school license) at this site:** [http://ww.acs.org/chemmatters](http://www.acs.org/chemmatters)**. Click on the “Archive” tab in the middle of the screen just under the *ChemMatters* logo. On this new page click on the “Get 30 Years of ChemMatters on DVD!” tab at the right for more information and to purchase the DVD.**

**Selected articles and the complete set of Teacher’s Guides for all issues from the past three years are available free online at the same Web site, above. Simply access the link and click on the aforementioned “Archive” tab.**

Darrow, F. W. Analyzing Colors. *ChemMatters*,1994,*12* (4), p 3. Teacher’s Guide. Full directions are given for using paper chromatography procedures to analyze the color pigments in M&M candies. This procedure could be modified to include Skittles candies and commercial synthetic food coloring.

McKone, H. T. The Unadulterated History of Food Dyes. *ChemMatters*, 1999,*17* (4), pp 6–7. Some of the interesting and tragic history of food dye toxicity is presented as an introduction to our current laws and procedures that certify the safety of food color additives. Students may find the historical vignettes about the effects of food dyes quite colorful (no pun intended).

The April 1999 *ChemMatters* Teacher’s Guide for the McKone food dyes article discusses the Delaney Clause that “prohibits the approval of a food additive if it has been found at *any level* to induce cancer in experimental animals or humans.”

McKone, H. T. Chewing Gum—Sticking to the Story. *ChemMatters*, 2000, *18* (4), pp 14–15. While the focus of this article is on the manufacture and forensics of chewing gum, during production “a touch of safe food coloring” is added. This provides an opportunity to point out to students that gum bases are waxes and paraffins thus the food coloring must be a lake that is produced from a certified food dye.

Hersey, J. and Heltzel, C. Your Colorful Food. *ChemMatters*, 2007, *25* (1), pp 12–15. This article includes many of the topics addressed in the Rohrig Food Dyes article. Both the article and its Teacher’s Guide can be used to enhance student research on the history, toxicity (including possible behavior problems in children linked to food dyes), natural and synthetic food dyes and how we connect colors with foods.

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Garfield, S., *Mauve: How One Man Invented a Color that Changed the World;* W. W. Norton and Company: New York, 2000. Perkins’ discovery led to the coloring of our blue jeans! This book recounts the fascinating story of Perkins’ life and the impact of his serendipitous discovery.

This 1988 article from *J. Chem. Educ.*, “Theideal solvent for paper chromatographyof food dyes” describes experimental data showing that the ideal solvent for paper chromatography of food dyes is a 0.1% sodium chloride solution. (Markow, P. Theideal solvent for paper chromatographyof food dyes. *J. Chem. Educ.*, 1988, *65* (10)*,* pp 899–900; abstract only here, <http://pubs.acs.org/doi/abs/10.1021/ed065p899>. The article is available only to subscribers at this same URL.)

Koch, C. and Koch, E. C. Preconceptions of Taste Based on Color. *The Journal of Psychology: Interdisciplinary and Applied,* 2003,*137* (3), pp 233–242. The article contains a table of positive and negative associations between color and taste. The abstract is available here: (<http://www.tandfonline.com/doi/abs/10.1080/00223980309600611?src=recsys&>; only subscribers can access the full article.)

## Web Sites for Additional Information (Web-based information sources)

**More sites on the role of visual information and flavor perception by humans**

This government site has compiled information from many studies relating to the impact of visual information including color clues on the perception of flavor by humans. Discussions include the effect of previous experiences with food that serve as a basis for our preconceptions. (<http://www.ncbi.nlm.nih.gov/books/NBK92852/>)

Kantha Shelke, a food chemist and spokeswoman for the Institute of Food Technologists, says, “Would we really want to ban everything when only a small percentage of us are sensitive?” She describes how our brain’s response to color, “actually overrides the flavor of our food”. (<http://www.foodrenegade.com/the-color-of-food-artificial-vs-natural/>)

An article from the Kochs, “Preconceptions of Taste Based on Color”,contains an interesting table of positive and negative associations between color and taste. It was originally published in *The Journal of Psychology: Interdisciplinary and Applied,* 2003,*137* (3), pp 233–242. It is available without subscription from the George Fox University in Oregon.

(<http://digitalcommons.georgefox.edu/cgi/viewcontent.cgi?article=1034&context=psyc_fac>)

**More sites on natural food colorants**

This *Scientific American* article is one of the “Selected references” listed for the Rohrig article. The focus is on natural sources of blue dye, including the history and some concerns. (<http://www.scientificamerican.com/article/where-does-blue-food-dye/>)

Regular packets of M&Ms contain blue candies, but blue colors are not present in original packages of Skittles. A limited edition was announced in January 2015. (<http://www.talkingretail.com/products-news/confectionery/blue-skittles-launching-limited-edition-packs/> )

An article in the *Washington Post* suggests that if you switch to natural food colorings, you will probably have to adjust to foods that have less vibrant coloring. Also, you must choose your source carefully. The amount of onion used to obtain a desired hue, may change the flavor of your food. (<http://www.washingtonpost.com/lifestyle/wellness/replace-artificial-food-coloring-with-natural-options/2014/11/11/e4bae6ee-6071-11e4-91f7-5d89b5e8c251_story.html>)

The Linus Pauling Institute at Oregon State University conducts extensive research on carotenoids. Their site provides easy access to specific information through links to the biological activity, disease prevention, health issues, and safety and toxicity of various carotenoids. There are tables for specific carotenoids showing food source, serving size and milligrams of carotenoid per serving. (<http://lpi.oregonstate.edu/mic/dietary-factors/phytochemicals/carotenoids>)

This site from *Business Insider* shows pictorially how cochineal bugs are “planted”, harvested and processed to produce carmine red: <http://www.businessinsider.com/how-cochineal-insects-color-your-food-and-drinks-2012-3?op=1>.

**More sites on** **how to write structural formulas of organic compounds**

Well-presented information and illustrations of the shorthand used by organic chemists is located here: (<http://www.harpercollege.edu/tm-ps/chm/100/dgodambe/thedisk/chrom/org.htm>)

The Khan Academy has a series of four videos that show students how to write structural formulas and bond-line formulas for isomeric forms of simple organic compounds:

1. *Condensed Structures* (6:49 minutes)
2. *Bond-Line Structures* (12.57 minutes)
3. *Three-Dimensional Bond-Line Structures* (10:58 minutes)
4. *Structural (constitutional) Isomers* (9:52 minutes)

For students who understand the basics, you may want to begin with the fourth video clip.

(<https://www.khanacademy.org/science/organic-chemistry/gen-chem-review/bond-line-structures>.)

**More sites on a general summary of the use of food additives, including colorants**

This is an excellent, clearly written reference that covers many of the frequently asked questions about the use of both natural and artificial food coloring. It was prepared under a partnering agreement with the FDA. (<http://www.foodinsight.org/Food_Ingredients_Colors>)

**More sites on current government regulations**

The official FDA site is a good place to keep up to date and find answers to student questions about government regulations regarding the use of food additives and colorants. The material can be printed in brochure format, a nice piece for student reading and/or research. (<http://www.fda.gov/Food/IngredientsPackagingLabeling/FoodAdditivesIngredients/ucm094211.htm>)

**More sites on** **black burger battles**

*USA Today Network* features an October 5, 2014 presentation by Jessica Durando about the Burger King and McDonald’s competition for burger sales in Japan. Your students may find this an interesting real-world market competition involving food coloring.

(<http://www.usatoday.com/story/news/nation-now/2014/10/02/mcdonalds-japan-black-burger-burger-king/16571975/>)

*The Atlantic* discusses acceptance of the black burger in the USA. *Color Trumps Flavor* can be found at (<http://www.theatlantic.com/health/archive/2014/09/food-color-trumps-flavor/380743/>).

# Tooth Decay: A Delicate Balance

## Background Information (teacher information)

To begin this discussion, it might be nice to think about the teeth as part of a larger structure. This excerpt is from a 2000 *ChemMatters* article:

The mouth is like the entrance to a deep cave. Inside are minerals, a steady trickle of water, and living creatures! Teeth line the upper and lower jaws like stony stalactites and stalagmites composed of protein (collagen) and a hard smooth mineral called hydroxyapatite, Ca5(PO4)3OH. Along the inner walls of the mouth are glands that secrete saliva, a watery solution that flows into the mouth at 1 to 3 mL per minute at mealtimes but slows to barely a trickle during sleep.

Inhabiting the mouth are millions of living bacteria residing on the tongue, in the soft tissue of the gums, and inside the cracks and crevices of our teeth. Many of the metabolic wastes of these bacteria are both corrosive and sticky with a pH low enough to cause harm to teeth and gums. Dissolved in saliva is bicarbonate (HCO3–). Bicarbonate acts as a buffer to keep the watery solution at a fairly constant pH by balancing the relative amounts of hydrogen ions (H+) and hydroxide ions (OH–) in solution. A healthy pH for the mouth environment is a nearly neutral 6.8.

Saliva is saturated with enzymes, the specialized proteins that act as organic catalysts for a variety of chemical reactions in the body. Alpha amylase is a digestive enzyme in saliva that catalyzes the breakdown of starch. Starch—a natural polymer consisting of thousands of tiny sugar molecules linked together like boxcars on a train—is rapidly uncoupled by amylase to release these sugars in the mouth.

Sugar is food. We—and the bacteria that we harbor—obtain life-sustaining energy from the breakdown of this hydrocarbon fuel. Unfortunately for us, bacteria convert some of this sugar into harmful acids. Saliva acts to dilute and neutralize some of this acid, but bacteria living in teeth fissures or crevices may be protected from this cleansing.

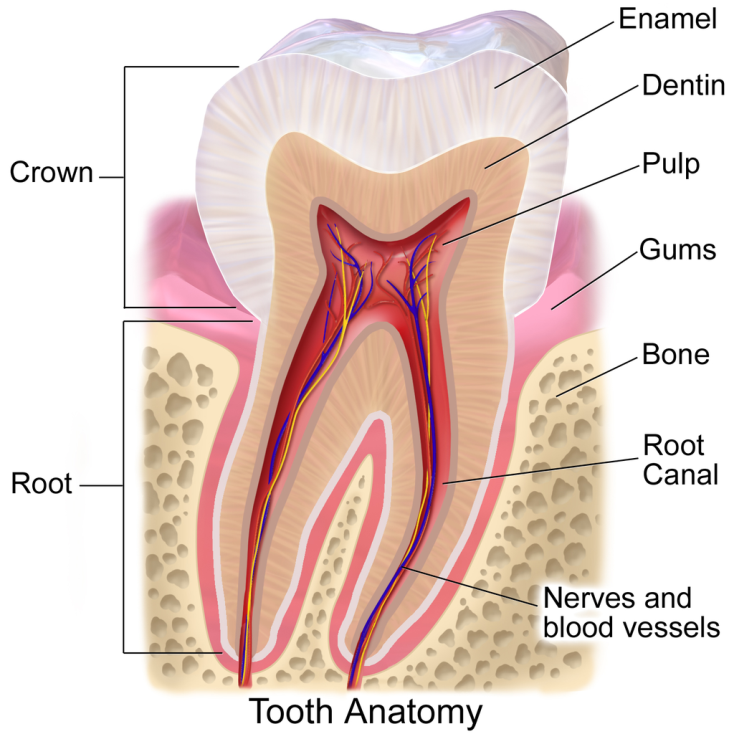
(McClure, M. The Straight Story on Braces. *ChemMatters,* 2000, *18* (1), pp 7–8)

Now that we’ve got the “big picture”, we can proceed with some of the details of tooth decay.

**More on the structure of the tooth**

The tooth consists of three areas: the crown, the neck and the root. (The neck is the area where the crown meets the root, missing from the diagram below.) The internal structure of the tooth is composed of four parts: enamel, dentin, cementum and pulp.

The enamel is located on the surface of the crown. The dentin, which lies just under the enamel, extends through the crown, neck and root, as does the pulp. Cementum surrounds the root. What follows is a description of each of these parts.



*(*[*https://en.wikiversity.org/wiki/Wikiversity\_Journal\_of\_Medicine/Blausen\_gallery\_2014#/media/File:Blausen\_0863\_ToothAnatomy\_02.png*](https://en.wikiversity.org/wiki/Wikiversity_Journal_of_Medicine/Blausen_gallery_2014#/media/File:Blausen_0863_ToothAnatomy_02.png)*)*

**Enamel**

Enamel is the very hard outer surface of the tooth. It is the surface we see when we look at teeth. It appears white, but it is really translucent. The dentin (see below) that shows through the enamel gives the tooth its color.

The role of enamel is to provide the rigid surface needed for mastication—grinding and crushing food by chewing—and to protect the rest of the underlying layers of the tooth from decay. It owes its rigidity to its structure of hydroxyapatite, a crystalline calcium phosphate compound. Although it is a hard substance, it is susceptible to decay through erosion due to exposure to acid. It also serves to insulate the nerves in the tooth from exposure to extremes of hot and cold thus preventing discomfort or pain.

Enamel is also subject to cracking or chipping when exposed to stress, leading to one’s feeling pain, especially when eating hot or cold or sugary foods.

(<https://www.humana.com/learning-center/health-and-wellbeing/healthy-living/tooth-enamel>)

And, lest we oversimplify the enamel in tooth structure, this short paragraph from a *ChemMatters* Teacher’s Guide seeks to set us straight.

The structure and composition of a human tooth is perhaps somewhat more complex than the relatively basic structure and composition presented …. The outer enamel is indeed the hardest material found in the human body, as it is for any mammal that has teeth. It is highly mineralized, but not entirely made of calcium phosphate. It consists of about 95-98% inorganic material by mass. About 90-92% of this inorganic matter is a slightly modified form of calcium phosphate called hydroxyapatite. The formula for hydroxyapatite is Ca5(PO4)3OH. There are also trace amounts of other minerals. The remainder of the enamel consists of about 1% protein and 4% water by mass. The proteins that are contained in tooth enamel are not found anywhere else in the human body. These proteins are called enamelins and amelogenins.

(*ChemMatters* Teacher’s Guide, December 2003, p 29)

**Dentin**

Dentin, part calcified tissue (hydroxyapatite crystallites), part organic material (mainly collagen), and part fluid (mainly water), surrounds the pulp cavity, just under the enamel. It serves several purposes: to absorb the impact of mastication on the tooth enamel, to protect the pulp from infection from the outside (from bacteria in the bacteria-infested mouth), and to provide toughness to the tooth structure, preventing or, at least, minimizing tooth fractures. (Note that enamel, even though it is very hard, is also rather brittle, so it can fracture rather easily.)

Dentin contains dentinal tubules, which are permeable, that radiate outward from the center to the enamel. Mineral buildup surrounds these tubules. Their permeability allows for transfer of the sensations of heat and cold to nerves in the pulp which can, in turn, become sensations of pain. The dentinal tubules also help to prevent tooth fractures by absorbing some of the stress that might normally propagate through and fracture the enamel, forming microfractures within the tubules that prevent a major crack from propagating through the brittle enamel.

It has been noted that older adults seem to be more susceptible to tooth fracturing than younger people. This has been researched and is presently believed to be caused by subtle changes in the behavior of dentin in older teeth, resulting in its becoming more brittle with age. This paper describes current (2008) research: <https://str.llnl.gov/str/JanFeb08/pdfs/01.08.3.pdf>.

**Cementum**

Cementum is the surface layer of the tooth root. It is calcified material that covers the root of the tooth. Slightly softer than dentin, it consists of 45–50% inorganic material (hydroxyapatite) and 50–55% organic matter and water, by weight. Collagen and proteoglycans comprise the majority of the organic matter.

Cementum is the part of the periodontium that attaches the tooth to the alveolar bone. Because some of the cementoblasts, the cells that actually excrete the cementum, are entrapped within the cementum, becoming cementocytes, cementum is able to repair itself to a limited extent.

**Pulp**

Dental pulp serves two main roles. First, it produces odontoblasts, cells that can form dentin. The dentin surrounds and protects the pulp. The second role is to supply nutrients to, and remove waste from, the pulp via blood vessels contained in the pulp cavity. Other functions include signaling the brain (with pain) when trauma, temperature extremes, pressure or tooth decay has reached the dentin or pulp, areas containing nerves, and forming secondary dentin to help protect the pulp.

Dental pulp fills with an increased amount of collagen fibers with age, resulting in the decrease in the ability of the pulp to regenerate. This causes the recession of the pulp cavity, possibly due to an increase of secondary dentin within the pulp cavity, which results in the reduction in sensitivity in older teeth. Thus older adults may not need local anesthesia when undergoing dental restorations.

The web source for the diagram at the beginning of this section also contains a 3-D diagram of the tooth and a brief (0:50), narrated video clip on the anatomy of a tooth. (<http://blausen.com/?Topic=2106>) (Source of diagram above and video clip: Blausen.com staff. "[Blausen gallery 2014](https://en.wikiversity.org/wiki/Blausen_gallery_2014)". *Wikiversity Journal of Medicine*. DOI:[10.15347/wjm/2014.010](http://dx.doi.org/10.15347/wjm/2014.010). ISSN [20018762](http://www.worldcat.org/issn/20018762). - Own work)

**More on the chemical structure of tooth enamel**

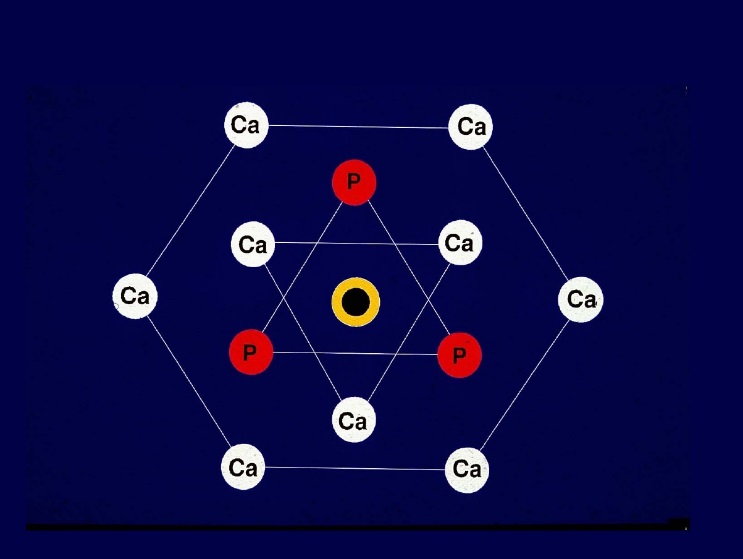
Tooth enamel, as mentioned in the article, is the hardest substance in the human body. The enamel is composed of 96% minerals, primarily hydroxyapatite; the remaining 4% of the enamel is primarily water and organic material. Apatite, the primary constituent of tooth enamel, has a hardness of 5 on the 1–10 Mohs scale of mineral hardness.

The central oxygen atom in the unit cell diagram at right is part of one of the   
–OH groups in the hydroxyapatite formula, Ca10(PO4)6(OH)2 [the dimer of Ca5(PO4)3OH]. In fluorapatite, the fluorine atom replaces that oxygen atom (part of   
–OH) in the center of the hexagonal unit cell.

**©C. Robinson Oral Biology**

The structure of calcium hydroxyapatite.

([*https://www.academia.edu/1732481/Dental\_Enamel\_Chemistry*](https://www.academia.edu/1732481/Dental_Enamel_Chemistry))

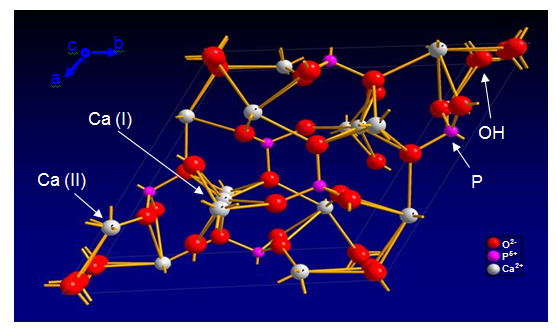


The following passage describes the structure of hydroxyapatite.

The term "apatite" applies to a group of compounds (not only at calcium phosphates) with a general formula in the form M10(XO4)6Z2, where M2+ is a metal and species XO4 3- and Z- are anions. The particular name of each apatite depends on the elements or radicals M, X and Z. In these terms, hydroxyapatite (HAp) has the molecular structure of apatite, where M is calcium (Ca2+), X is phosphorus (P5+) and Z is the hydroxyl radical (OH-). This is known as stoichiometric hydroxyapatite and its atomic ratio Ca/P is 1.67. Its chemical formula is Ca10(PO4)6(OH)2, with 39% by weight of Ca, 18.5% P and 3.38% of OH.

Hydroxyapatite crystallizes in a hexagonal system … Figure 1 shows the unit cell of hydroxyapatite.

HAp structure is formed by a tetrahedral arrangement of phosphate (PO43-), which constitute the "skeleton" of the unit cell. Two of the oxygens are aligned with the c axis and the other two are in a horizontal plane. Within the unit cell, phosphates are divided into two layers, with heights of 1/4 and 3/4, respectively, resulting in the formation of two types of channels along the c axis, denoted by A and B.



**Figure 1.** Crystalline structure of hydroxyapatite.

The walls of channels A type are occupied by oxygen atoms of phosphate group and calcium ions, called calcium ions type II [Ca (II)], consisting of two equilateral triangles rotated 60 degrees relative to each other, at the heights of 1/4 and 3/4, respectively. Type B channels are occupied by other ions of calcium, called calcium ions type I [Ca (I)]. In each cell there are two such channels, each of which contains two calcium ions at heights 0 and 1/2. In the stoichiometric HAp, the centers of the channels type A are occupied by OH radicals, with alternating orientations. …

Despite being taken to the stoichiometric hydroxyapatite as a model, it is noteworthy that hydroxyapatites produced biologically are much more complicated, they are not stoichiometric, have an atomic ratio Ca/P <1.67 and does not contain only ions and radicals of the HAp but also traces of CO3, Mg, Na, F and Cl. These amounts vary according at the specific type of tissue, which is related to the properties and bioactivity of it.

One aspect that is important to note is that, the closer the value of Ca/P to 1.67, the greater the stability of the material inside the human body as they tend to be inert, and on the other hand, if this value decreases (deficient HAp), the better the bioactivity.

Another aspect we must consider is the degree of crystallinity. It has been observed that the crystallinity in the tissues for the tooth enamel is very high, while in the cases corresponding to dentin and bone, it is very poor. This means that the reactivity depends on the degree of crystallinity, since the reactivity in dentin and bone is higher than in tooth enamel.

(Eric M. Rivera-Muñoz (2011). Hydroxyapatite-Based Materials: Synthesis and Characterization, Biomedical Engineering - Frontiers and Challenges, Prof. Reza Fazel (Ed.), ISBN: 978-953-307-309-5, InTech, DOI: 10.5772/19123; <http://www.intechopen.com/books/biomedical-engineering-frontiers-and-challenges/hydroxyapatite-based-materials-synthesis-and-characterization>)

**More on tooth decay vs. tooth erosion**

There seems to be general agreement that two distinct processes occur involving adverse effects on teeth, tooth erosion and tooth decay.

**Tooth erosion**

Tooth erosion occurs primarily due to acids you ingest from outside sources, such as sodas and citrus fruit drinks. These provide acid directly to the tooth, which increases the rate of demineralization of the tooth enamel, which eventually leads to erosion of tooth surfaces and may or may not produce individual caries (cavities).



Microscopic view of erosion on tooth enamel surface.

*(*[*http://www.webmd.com/oral-health/healthy-teeth-14/slideshow-enamel-erosion*](http://www.webmd.com/oral-health/healthy-teeth-14/slideshow-enamel-erosion)*)*

(<https://en.wikipedia.org/wiki/Acid_erosion>)

Frequency and duration of exposure of teeth to these drinks is viewed as more important factors than total intake. These should be drunk, not sipped. Many dentists even recommend using straws to drink these, as then the liquid does not come in direct contact with teeth. Enamel corrosion can even occur in babies if they are allowed to drink fruit juices from a bottle over long periods as a way of quieting them down at bedtime.

The following table, gathered from numerous sites, summarizes the types of acids found in various types of drinks.

|  |  |  |  |
| --- | --- | --- | --- |
| **Type of Drink** | **Type of Acid in Drink** | **Natural or Added** | **Purpose/Use** |
| Soda/Pop | Carbonic  Phosphoric  Citric (perhaps) | Added  Added  Added | Fizz, “bite”  Tartness, preservative  Fruity taste |
| Fruit Juices | Malic  Citric  Ascorbic (vitamin C)  Tartaric | Natural  Natural/Added  Added  Added | In most fruits, tartness  Citrus flavor  Preservative  Acidity, tartness |
| Juice Drinks | Citric  Ascorbic  Fumaric | Natural/Added  Added  Added | Citrus flavor  Preservative  Tartness |
| Sports/Energy Drinks | Carbonic  Citric | Added  Added | Fizz, “bite”  Citrus flavor |
| Wines | Tartaric  Malic  Lactic  Citric | Natural  Natural  Added  Added | Stability, acidity, tart taste  Tartness, apple flavor  “Milky” flavors  Boosts overall acidity |
| Beers | Carbonic | Natural | Fizz, “bite” |

The phosphoric acid is corrosive, but actually the acid concentration in soda pop is lower than that in orange juice or lemonade. Try submerging identical strips of magnesium (or iron staples) in each of these beverages overnight. Which beverage dissolves more metal? Which dissolves the metal fastest?

Fruit juices and drinks are also tart, but they don't use phosphoric acid as a flavor additive. Phosphoric acid would cause many ions present in fruit juices to settle out as insoluble phosphates. These beverages get their tang from citric acid, a substance found in oranges, limes, lemons and grapefruits. Malic acid, found in apples and cherries, is added to many fruit juices. Fumaric acid is used in noncarbonated soft drinks, and tartaric acid gives grape-flavored candies a subtle sour flavor. All of these substances impart only tartness, without overpowering other flavors present.

(<http://antoine.frostburg.edu/chem/senese/101/consumer/faq/why-phosphoric-acid-in-soda-pop.shtml>)

Tartaric acid isn't added to grape-flavored beverages because of the low solubility of some of its salts:

"... tartaric acid gives a very true flavor, but Mother Nature does not intend for tartrates to stay in solution long. When KH-tartrate precipitates out of a juice, looking very much like glass or metal shavings, and the consumer passes their bottle of juice to the FDA, one really does not care about "true" flavor. We in the juice industry usually use malic or a malic citric blend."

(<http://antoine.frostburg.edu/chem/senese/101/consumer/faq/why-phosphoric-acid-in-soda-pop.shtml>)

Chemists know that it’s acid strength, not just the amount of acid, that really matters. That’s why colas are more likely to cause dental erosion than other sodas; colas contain phosphoric acid, with a higher acid dissociation constant (see table, below) than any of the other acids listed in the drinks from the above table. That means that phosphoric acid provides more H+ ions in solution than other acids. These ions then interact with enamel hydroxyapatite, resulting in the formation of Ca2+ and PO43– ions dissolved from the tooth surface. Unless the saliva in the mouth quickly raises the pH and replenishes the lost calcium and phosphate ions, the tooth enamel surface will remain thinner where those ions were removed by the acid, subject to further degradation with the next cola drink.

|  |  |  |  |
| --- | --- | --- | --- |
| **Acid** | **1st Ka** | **2nd Ka** | **3rd Ka** |
| Phosphoric acid | 7.5 x 10–3 | 6.2 x 10–8 | 4.8 x 10–13 |
| Fumaric acid | 9.3 x 10–4 | 2.9 x 10–5 | --- |
| Tartaric acid | 9.2 x 10–4 | 4.3 x 10–5 | --- |
| Citric acid | 8.4 x 10–4 | 1.8 x 10–5 | 4.0 x 10–6 |
| Malic acid | 3.5 x 10–4 | 8.0 x 10–6 | --- |
| Lactic acid | 1.4 x 10–4 | --- | --- |
| Ascorbic acid | 7.9 x 10–5 | 1.6 x 10–12 | --- |
| Carbonic acid | 4.3 x 10–7 | 4.7 x 10–11 | --- |

(Table of Kas gathered from numerous sources)

Notice that the Ka for carbonic acid is the smallest of any of the first dissociation constants for the acids in the above table. This substantiates the notion that it’s not the carbonic acid in sodas that really causes the problems with dental erosion but, rather, phosphoric acid. This can be shown by testing the pH of a freshly-opened soda and one that has been allowed to go “flat”. Carbon dioxide has escaped from the flat soda, upsetting the CO2 – H2CO3 equilibrium, thereby removing most/all carbonic acid from the drink (Le Châtelier’s principle). Yet both sodas will have approximately the same pH, showing that carbonic acid contributed very little or nothing to the acidity of the drink.

While brushing teeth is a good way to minimize tooth erosion, care must be taken as to *when* brushing is done.

Tooth brushing is a way to keep a good oral hygiene. Hard tissue loss after erosion and tooth brushing is significantly greater than erosion alone … However, after intra-oral periods of 30 and 60 min, wear was not significantly higher in tooth brushing than in unbrushed controls. It is concluded that keeping tooth unbrushed for at least 30 min after an erosive attack is necessary for protecting dentin …

(<http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2676420/>)

You may have heard this myth circulating, possibly on the Internet. “Soda is so acidic it can dissolve a tooth overnight.” This is not quite true (at all).

This myth got its start from a nutritionist who made the claim in the 1950s. Sodas contain acids, such as phosphoric, citric, and carbonic acid. But their concentrations are lower in soda than in natural drinks, such as orange or cranberry juice. When left in soda, a tooth will not completely dissolve overnight, or even over a few days. Also, when we drink soda, we don’t tend to hold it in our mouths for long periods of time, and the saliva in our mouths helps protect the enamel.

But this does not mean that soda is harmless to teeth. High-sugar drinks can contribute to tooth decay, and acidic drinks can erode tooth enamel over time. The reason is that although enamel is hard, the substance that makes up most of it, hydroxyapatite [Ca5(PO4)3OH], is in equilibrium with its dissolved form, like any ionic solid in the presence of water. At equilibrium, most of hydroxyapatite is in solid form:

Ca5(PO4)3OH (*s*) ⇌ 5 Ca2+ (*aq*) + 3 PO43– (*aq*) + OH– (*aq*)

But when an acid is added, its free hydrogen ions (H+) neutralize some of the hydroxide ions (OH–), as follows:

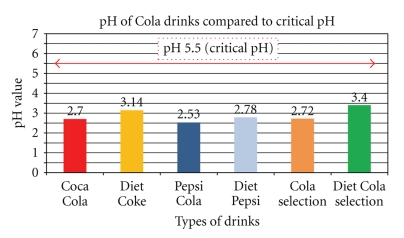
H+ + OH– ➞ H2O

This shifts the hydroxyapatite equilibrium reaction to the right to replace the hydroxide ions removed by the acid, causing more hydroxyapatite to dissolve, thus eroding the tooth enamel.

(Tinnesand, M. Open for Discussion: A Healthy Dose of Skepticism; Soda is so acidic it can dissolve a tooth overnight. *ChemMatters*, 2015,*33* (1), p 4)

Here is another reference to this same myth: <http://io9.com/5903310/the-scientific-myth-that-soda-will-dissolve-your-teeth>.

Before we leave the topic of soda, we should look at its pH. The table below was taken from this 2010 report: “Pop-Cola Acids and Tooth Erosion: An *In Vivo*, *In Vitro*, Electron-Microscopic and Clinical Report.” The report, published in the *International Journal of Dentistry*, provides information on the pH of various colas. Note that all values are in the 2.5–3.5 range, well below the pH of 5.5, which is the pH at which (or below which) tooth enamel is eroded by an acid. Thus all of these colas (and other sodas as well) will cause enamel erosion; indeed, that is the conclusion of the report, as well.



*(*[*http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2997506/?tool=pubmed*](http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2997506/?tool=pubmed)*)*

And, as the title suggests, the study tested cola’s effects on teeth *in vivo*, within the mouth of living test subjects, and *in vitro*, in laboratory settings. And microscopic pictures of the teeth studied *in vitro*, taken by the researchers show definite evidence of erosion by the colas. An interesting note: their study groups were divided into those with teeth (average age, 22) and those without teeth (average 52), ostensibly those with dentures. The tests done on those without teeth (and those with teeth) consisted of determining levels of calcium and phosphate in the mouth after swishing with the various colas (and with water as a control).

(<http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2997506/?tool=pubmed>)

OK, so now we know it’s best to avoid sodas to avoid cavities. But sodas and other acidic drinks, known as *extrinsic* sources of acids (taken in from outside the body), aren’t the only way for tooth enamel to be exposed to acidic environments. Intrinsic sources (as the name implies) also may account for further exposure.

Acid reflux and GERD (Gastroesophageal reflux disease) can cause stomach acid (HCl) to be regurgitated up the esophagus back into the mouth. This exposes the enamel of teeth to the highly corrosive mix, which increases the severity of enamel erosion.

*(*[*http://www.dentalcare.com/en-US/dental-education/continuing-education/ce301/ce301.aspx?ModuleName=coursecontent&PartID=8&SectionID=2*](http://www.dentalcare.com/en-US/dental-education/continuing-education/ce301/ce301.aspx?ModuleName=coursecontent&PartID=8&SectionID=2)*)*

**Erosion caused by chronic vomiting in bulimia.**

Image source: Copyright © 2003 Lippincott Williams & Wilkins



Another area of concern related to tooth erosion is eating disorders like anorexia and bulimia. Repeated vomiting by sufferers of these disorders exposes tooth enamel to the highly acidic environment of the hydrochloric acid in stomach acid. If this were to occur on a regular basis, it can result in severe damage to tooth enamel—long-lasting damage that can’t be undone, even long after the disorder has been effectively treated.

Note in the photo above the almost complete lack of enamel on parts of the teeth. The yellow color is the dentin showing through what’s left of the enamel. Also note that the primary area of erosion is on the posterior surfaces, where the regurgitated stomach content is most likely to come in contact with the teeth.

**Friction and erosion**

And acids aren’t the only problems our teeth face in their quest to maintain the hydroxyapatite equilibrium and avoid cavities. We also create some of our own problems that erode our teeth. Normal (and abnormal) chewing can wear down teeth, as can bruxism—grinding your teeth, especially at night. Here are some other ways we erode our teeth.

* **Attrition.** This is natural tooth-to-tooth friction that happens when you clench or grind your teeth such as with bruxism, which often occurs involuntary during sleep.
* **Abrasion.** This is physical wear and tear of the tooth surface that happens with brushing teeth too hard, improper flossing, biting on hard objects (such as fingernails, bottle caps, or pens), or chewing tobacco.
* **Abfraction.** This occurs from stress fractures in the tooth such as cracks from flexing or bending of the tooth.
* **Corrosion.** This occurs chemically when acidic content hits the tooth surface such as with certain medications like aspirin or vitamin C tablets, highly acidic foods, GERD, and frequent vomiting from bulimia or alcoholism.

(<http://www.webmd.com/oral-health/guide/tooth-enamel-erosion-restoration#2>)

While these causes of tooth erosion result in the wearing down of tooth surfaces, they don’t usually result in dental caries, as they generally only erode already exposed areas of enamel, like the bite surfaces of teeth; they don’t usually penetrate the enamel down to the dentin, where cavities can really go wild. (In extreme cases, these processes can result in opening areas to bacterial infection, particularly along the gum line.)

**Tooth decay**

OK, so if you stay away from acidic drinks, *and* don’t grind your teeth, you can avoid tooth decay, eh? Not so fast. While all of that may minimize tooth erosion, we haven’t even begun to talk about what actually makes teeth decay—*Streptococcus mutans*. *S. mutans* is a bacteria that lives in your mouth and absolutely loves sugars, especially sucrose. This bacteria attaches as individual cells, produces a slime-like material to help it adhere to the tooth, and then reproduces on the enamel surface to form a biofilm consisting of hundreds of cells.

The biofilm is extremely resistant to being removed. The *S. mutans* bacteria within this biofilm are able to cleave sucrose, a disaccharide, (from food we eat) into the monosaccharides glucose and fructose. *S. mutans* ferments the fructose for use as an energy source for its own growth. The glucose is polymerized into the slime- or glue-like material that attaches to teeth and becomes the biofilm base for dental plaque—the growth of colonies of bacteria.

Subsequent depolymerization of the dextran polymer within the biofilm by the bacteria can result in fermentation of the glucose monosaccharide to produce lactic acid. Some of this acid is trapped within the plaque matrix, confined close to the tooth enamel, where saliva can’t reach to wash the acid away, exposing the enamel to relentless erosion. And note that the Ka for lactic acid is 1.4 x 10–4, more acidic than either citric or carbonic acids. (Bad news for tooth enamel) (<http://microbewiki.kenyon.edu/index.php/Streptococcus_mutans>)

And then, just when you thought there was only one species responsible for tooth decay, here comes another one (or, actually, more).

While streptococci family bacteria (e.g. *Streptococcus mutans*) are the main cause of tooth decay, other varieties of microbes can cause dental caries, but to a lesser extent. For example, although considered beneficial, some *Lactobacillus* species have been associated with dental caries. The *Lactobacillus* count in saliva has been used as a "caries test" for many years. This is one of the arguments used in support of the use of fluoride in toothpaste. Lactobacilli characteristically cause existing carious lesions to progress, especially those in coronal caries. The issue is, however, complex as recent studies show probiotics can allow beneficial lactobacilli to populate sites on teeth, preventing streptococci pathogens from taking hold and inducing dental decay.

(<https://en.wikipedia.org/wiki/Lactobacillus>)

Lactobacilli, like *S. mutans*, produce lactic acid in their fermentation of simple sugars, adding that acid to the stores of acid produced by other bacteria and tucked away in dental plaque, waiting there to cause tooth decay.

Left unchecked (or unbrushed), erosion of tooth enamel will eventually lead to an opening (cavity or carie) in the enamel which will continue to grow until it reaches the dentin. At this time, one may feel twinges of pain when hot or cold drinks hit the cavity. Also at this point, the rate of decay progresses rapidly, as dentin is softer and more susceptible to the effects of acid (and bacteria). By this time, one will probably begin to feel more prolonged (but possibly still mild) pain. Ultimately, the decay will reach the pulp of the tooth, at which point the pain may be unbearable. An abscess may form within the pulp and dentin, making the whole area of the mouth near the tooth painful. To avoid this scenario, one must practice good oral hygiene.

**More on tooth decay & hydroxyapatite equilibrium**

It is interesting to note that tooth formation and decay is almost identical in animals to that in humans. The functions of all the parts of the tooth are identical in both, with slight variations in the enamel. Dogs typically suffer from tooth decay much less frequently than humans because saliva in dogs has a much higher pH than in humans. The less acidic environment in dogs’ mouths results in less demineralization of the enamel.

Teeth are in a constant state of demineralization and remineralization. Acidic conditions increase the rate of demineralization, leading to cavities or dental caries. At a pH of 5.5 or lower, demineralization occurs at a more rapid rate than remineralization. Many foods are in this range of pH, so without remineralization, eating these foods would automatically result in tooth decay.

The constant battle between demineralization and remineralization can be considered chemically to be an equilibrium system which is under constant stress.

The enamel of teeth is made of hydroxyapatite (also called hydroxylapatite), empirical formula Ca5(PO4)3OH. The formula is usually written as a dimer, Ca10(PO4)6(OH)2, to denote that the unit cell contains two empirical formula units. Hydroxyapatite forms a 3-dimensional crystal structure which is very hard and durable.

Demineralization of hydroxyapatite occurs in acidic conditions; e.g., when bacteria produce acids from their metabolism of ingested sugars. The primary acid produced is lactic acid, along with smaller amounts of formic, acetic and succinic acids, all of which act to dissolve the enamel of teeth.

Ca10(PO4)6(OH)2(*s*) + 8 H+(*aq*) → 10 Ca2+(*aq*) + 6 HPO42–(*aq*) + 2 H2O(*l*)

In a less acidic (more basic) environment, remineralization occurs:

10 Ca2+(*aq*) + 6 HPO42–(*aq*) + 8 OH–(*aq*) → Ca10(PO4)6(OH)2(*s*) + 6 H2O(*l*)

Demineralization and remineralization occur at different rates throughout our lives. In children, remineralization occurs more rapidly than demineralization. In adults, the two reactions occur at roughly equal rates (equilibrium), while in older adults, demineralization can occur faster than remineralization, resulting in the slow loss of tooth enamel and the subsequent possible loss of the tooth. Of course, at any point in our lives when we have significant plaque build-up, we may suffer increased rate of demineralization.

As shown above, lower pH (higher acidity) enhances demineralization. When plaque builds up, the bacteria in the plaque supply H+ ions in close proximity to the enamel. The H+ ions react with the OH- ions from the hydroxyapatite, resulting in destruction of the crystal structure, weakening the tooth enamel. And as the OH- ions are consumed, they reduce the rate of the remineralization reaction (Le Châtelier’s principle), furthering the effect.

Normal pH in the mouth is about 6.8. Demineralization becomes the dominant process when the pH drops below 5.5. This can occur within minutes of drinking a sugar (or high fructose corn syrup) based soft drink and can last for about 10 minutes. Saliva will gradually wash away the acidic material and return the mouth environment back to normal within about an hour. Of course, that means that teeth are exposed to an acidic environment for most of that time, promoting demineralization. Brushing teeth right after eating can remove the acid and return the mouth to its normal pH immediately.

(*ChemMatters* Teacher’s Guide. October 2011, pp 59–60)

**More on effects of brushing and flossing**

Brushing teeth (if done right) effectively removes the sugars, acids, plaque and bacterial build-up that would otherwise ensure dental erosion and caries formation. Thus it is an effective weapon against cavity formation. But, as noted above, timing of brushing is important. Acidic drinks can leave the enamel softened for some time after drinking them. So, it’s important to wait, perhaps ½ to 1 hour after drinking, before brushing.

It’s also important not to brush too hard, or particles of the enamel might be ground away by the bristles of the brush. Likewise, it’s better to use a soft bristle toothbrush, for the same reason.

And you need to be sure to use a toothpaste that is not too abrasive, so that it does not remove enamel when you brush. Another ingredient to be concerned about is the sweetener used to make the tooth paste palatable (but not too palatable, or it might be swallowed).

“Toothpaste ingredients do typically include a sweetener. However, because of the process described above, sucrose is not a reasonable choice. Toothpastes commonly use two of the artificial sweeteners … saccharin and aspartame. Some products specifically advertise that they do not use artificial sweeteners. One substitute is the use of essential oils, such as spearmint.”

(*ChemMatters* Teacher’s Guide. October 2011, p 73)

One much overlooked—and underrated—procedure that can contribute significantly to decay prevention is flossing. Dentists almost invariably ask patients whether they floss regularly, because they know the importance of this tool in the oral health arsenal. Flossing essentially picks up where tooth brushing leaves off.

Brushing cleans plaque off the anterior and posterior surfaces, as well as the “nooks and crannies” available to its bristles; however, the brush can’t clean surfaces between the teeth, or the tooth surfaces down at the gum line. So brushing only cleans about 60–65% of enamel surfaces in your mouth. The other 35–40% of the enamel, where the tooth brush can’t reach, is susceptible to plaque build-up, which continues to erode the enamel (remember, bacteria in the plaque produce acid), and that plaque eventually becomes calcareous tartar. This hard material can only be removed by the dentist scraping your teeth, a process called scaling. So, flossing can prevent acid erosion between your teeth and along the gum line, and it can prevent your needing this somewhat painful professional scaling procedure.

As you know, plaque on teeth results in the tooth enamel being held in constant contact with acid produced by bacteria in the plaque, hastening enamel erosion. Along the gum line, those same bacteria can also cause infection resulting in gingivitis, an inflammation of the gums and, eventually, if not treated, to periodontal disease which could lead to teeth loss.

Is gum disease really worrisome? Studies have shown a link between gum disease and serious medical conditions, such as heart disease and stroke, and low birth-weight in babies. So, anything we can do to prevent gum disease seems to be worthwhile, and flossing is high on that list.

According to Rockside Family Dental Care, there are 10 reasons one should floss daily.

In less than one minute per day you can accomplish the following health benefits:

**10 Reasons to Floss!!**

1. Prevent Decay
2. Prevent gum disease
3. Fresher breath
4. Whiter smile (less stain)
5. Younger smile (less gum recession)
6. Less dental expense
7. Less dental pain
8. Less time away from work or family life
9. Healthier Heart (bacteria from gum disease has been linked to certain types of heart disease).
10. Maintains health/condition of dental restorations

(<http://rocksidefamilydentalcare.com/10-reasons-to-floss.html>)

OK, so you’ve seen the light; flossing is important and you will do it from now on. What’s the right way, floss before or after brushing? It really doesn’t matter, but dentists point out that if you floss first and then use a fluoride toothpaste to brush, the fluoride has a better chance of finding its way to the enamel between your teeth and at the gum line to better protect your teeth from decay.

And let’s not forget about mouthwashes. These decay-preventers help by killing the germs that cause plaque and acid erosion. Most mouthwashes also contain fluoride, which helps to remineralize tooth enamel and make it stronger (fluorapatite is more stable than hydroxyapatite). So mouthwashes pack a “double whammy” for tooth decay prevention.

**More on fluoride treatment of teeth**

This excerpt from an earlier (1986) *ChemMatters* article discusses the use and benefits of using fluoride mouthwash, including the hydroxyapatite equilibrium and fluoroapatite addition to tooth enamel.

One of the best ways you can … strengthen your teeth—is by using mouthwash, which kills the bacteria in your mouth. One key ingredient in many mouthwashes is fluoride, which is known to strengthen tooth enamel (Fig. 6). Fluoride (F–) is the ionic form of fluorine. It forms when a fluorine atom gains an electron. Fluoride does not exist by itself, but it can be found in compounds, such as sodium fluoride (NaF), which is present in many toothpastes and mouthwashes. When this compound is dissolved in water, the fluoride ions are free to move.

Fluoride ions prevent tooth decay by strengthening the enamel. The primary compound found in tooth enamel is a strong, insoluble mineral called hydroxyapatite [Ca5(PO4)3(OH)]. Hydroxyapatite contains positive ions (Ca2+) and negative ions (PO43– and OH–), which are attracted to each other to form the crystalline structure of hydroxyapatite.

The bacteria present on our teeth produce acids that cause hydroxyapatite to break apart—a process called demineralization:

**Ca5(PO4)3(OH) 🡪** **5 Ca2+ + 3 PO43– + OH–**

A certain amount of demineralization is normal. But it is also normal for the reverse process, remineralization, to occur:

**5 Ca2+ + 3 PO43– + OH– 🡪**  **Ca5(PO4)3(OH)**

If too much bacterial acid is produced, demineralization can outstrip mineralization, leading to a cavity. How does this happen? When acids are present in a solution, they dissolve to produce hydrogen ions (H+). In the mouth, as bacteria produce acids, the amount of hydrogen ions builds up. These ions combine with the hydroxide ions produced during demineralization to form water:

**H+ + OH– 🡪**  **H2O**

But hydroxide ions are essential to remineralization, so their neutralization by hydrogen ions causes remineralization to slow down. The hydroxyapatite on the surface of the teeth keeps dissolving, ultimately leading to tooth decay. Fluoride ions present in mouthwashes help the enamel to remineralize. They accumulate on the surface of the enamel, thus creating a barrier that prevents bacterial acids from reaching the enamel. Also, the fluoride ions attract calcium ions, ultimately changing hydroxyapatite into fluoroapatite [Ca5(PO4)3F], which is stronger than the original hydroxyapatite.

(Rohrig, B. Demystifying Gross Stuff. *ChemMatters*, 2011, 29 (3), pp 13–14)

“The fluoride ion takes the place of the OH– during the remineralization process…

The modified enamel, called fluorohydroxyapatite, is more resistant to acid. The F– does not substitute for all of the OH–; even a small uptake of fluoride makes the enamel less susceptible to decay.”

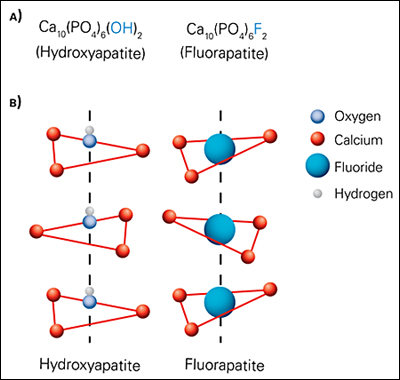
(Yohe, B. Tooth Paste. *ChemMatters,* 1986, *4* (1), pp 12–13)

Fluoride, present either through fluoridated water or through fluoride-enhanced toothpaste or mouthwash, becomes important in the demineralization/remineralization equilibrium because when fluoride ions enter the equilibrium, they produce fluorohydroxyapatite (fluoroapatite), which is harder, more stable and more resistant to acid decay than naturally-occurring hydroxyapatite.

10 Ca2+(*aq*) + 6 HPO42**–**(*aq*) + 6 OH**–**(*aq*) + 2 F**–**(*aq*) → Ca10(PO4)6F2(*s*) + 6 H2O(*l*)

Here’s why fluoride ions are so successful at replacing hydroxide ions in hydroxyapatite.

*(*[*http://www.dentalcare.com/en-US/dental-education/continuing-education/ce410/ce410.aspx?ModuleName=coursecontent&PartID=2&SectionID=1*](http://www.dentalcare.com/en-US/dental-education/continuing-education/ce410/ce410.aspx?ModuleName=coursecontent&PartID=2&SectionID=1)*)*



1. **Fluoride ions (F–) replace hydroxyl groups (OH–) in hydroxyapatite to form fluorapatite in the tooth enamel.**
2. **A portion of the apatite crystal lattice is depicted showing the replacement of hydroxide for fluoride.**

Adapted from: Posner, 1985[20](http://www.dentalcare.com/en-US/dental-education/continuing-education/ce410/ce410.aspx?ModuleName=additionalreference&PartID=-1&SectionID=-1#20)

Fluoride ions are very similar chemically to the hydroxide ion. Their sizes are similar, as are their chemical reactivities. (Recall oxygen and fluorine positions on the periodic table, and their atomic structures.) This makes it easy for the fluoride ion to replace the hydroxide ion in hydroxyapatite [see diagram at right]. And the fluoroapatite produced is actually more stable than the original hydroxyapatite.

In addition to its role in the remineralization process, fluoride also reduces/ prevents cavities by targeting the metabolic processes of bacteria to actually reduce the amount of acid secretions by bacteria in the mouth. This has the effect of reducing the amount of food consumed and thus the amount of acid produced by the bacteria. With a less acidic environment, there is less demineralization. This process seems to be secondary to fluoride’s role in the remineralization process and the formation of fluoroapatite in tooth enamel, however.

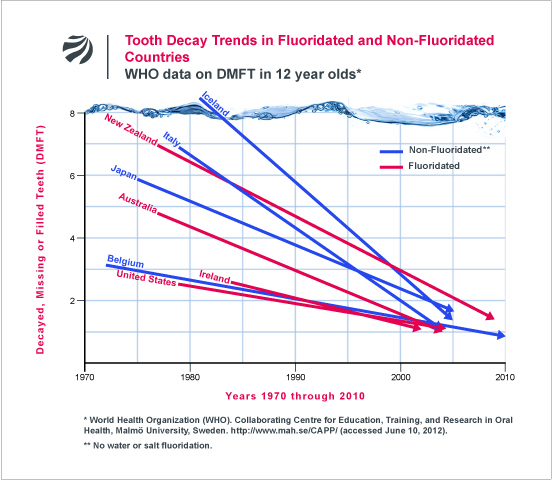
Research has shown that treatment of tooth enamel, bone and calcium phosphate with fluoride all result in lower solubility than just the associated calcium compounds. It is believed that this lower solubility in fluoroapatite is the main (and possibly, the only) factor in the slower rate of demineralization of fluoride-treated enamel. Studies with people exposed to fluoridated water supplies have shown reduced incidence of cavities.

Studies have also been done that also show that fluoride has a greater effect on areas of the tooth enamel already subject to cavity formation—areas of teeth where demineralization has already begun—than in areas where the surface remains intact. This makes sense, since areas of demineralization are areas where the crystal structure has already been compromised and therefore is more prone to rebuilding as fluoride ions come in contact with the greater surface area of “jagged” edges of tooth enamel. These areas of greater fluoride uptake (measured at twice the fluoride concentration of intact enamel) were tested and shown to be much less soluble than intact enamel in the same teeth.

(<http://journals.cambridge.org/action/displayFulltext?type=1&fid=784036&jid=PNS&volumeId=22&issueId=01&aid=784028>)

When enamel is exposed to fluoride, it is also possible to form calcium fluoride, CaF2. Calcium fluoride is less soluble than sodium or stannic fluorides, so it precipitates on the enamel. This can act as a source of fluoride ions, especially in acidic conditions, when demineralization would normally occur. Then the fluoride ion would be right there to join with the hydroxyapatite structure to form fluoroapatite. It can also increase the concentration of fluoride in the saliva, thereby reducing the bacterial metabolism of sugars, the acidity of the environment and hence, demineralization. (<http://www.intelligentdental.com/2011/08/28/fluoride-toothpaste/>)

(The above quote, pp 16–18, was reproduced from *ChemMatters* Teacher’s Guide, October 2011, p 60)

[](http://www.fluoridealert.org/articles/50-reasons/who_data01/)A common means of adding fluoride to our “diet” in the U.S. is by the fluoridation of municipal water supplies. But not everyone believes that water fluoridation is a good idea, including many European countries. The Fluoride Action Network provides some compelling data (in this graph) that they claim refutes the idea that water fluoridation helps fight tooth decay. The data was gathered from the World Health Organization (WHO). *(*[*http://fluoridealert.org/studies/caries01/*](http://fluoridealert.org/studies/caries01/)*)*

(<http://fluoridealert.org>)

[Note: DMFT means decayed, missing or filled teeth.]

The graph shows that the general trend across all countries is that the number of DMFTs is decreasing, even in those countries that do NOT fluoridate their water. The Fluoride Action Network claims that this substantial decrease is due to fluoridation of toothpastes and mouthwashes, and they argue therefore that fluoridation of water systems is not warranted.

The <http://fluoridealert.org> Web site provides more data on specific countries, and actively advocates for the removal of fluoridation from our water supplies.

**More on the effect of too much fluoride**

OK, fluoride helps prevent tooth decay, but is fluoride safe?

The oral LD50 value of sodium fluoride, the active ingredient in toothpaste, is 31 mg/kg. This substance is considered highly toxic and is classified as a poison, yet we put it into our mouths every day. But we swallow such small amounts that it causes no harm. It has been estimated that small children (ages 2–4) ingest about 0.3 g of toothpaste every time they brush their teeth and that adults tend to ingest about 0.04 g per brushing.

(Rohrig, B. How Toxic is Toxic? *ChemMatters,* 2014, *32* (4), p 7)

And fluoride is not without its problems, as this brief article from a 1932 J. Chem. Educ. article shows*:*

**Fluorine proved cause of mottled teeth**

Dogs with mottled teeth, an endemic condition of the enamel produced by the presence of fluorine in drinking water, have been achieved experimentally by Dr. Margaret Cammack Smith of the home economics department at the University of Arizona.

Six months ago, Dr. Smith completed her experiments with the drinking water at St. David, Arizona, and determined that fluorine in the drinking water at that place was responsible for the existence of mottled teeth.

At first the mottled condition was only produced experimentally in white rats but now for the first time this condition has been givento the larger animals. The mottled condition has been produced after a six months' feeding experiment.-*Science Service*

(Fluorine proved cause of mottled teeth.J. Chem. Educ., **1932**, 9 (5), p 858)

**More on ways diet can help to prevent tooth decay**

Diet can play a major role in preventing caries formation. These recommendations come from the article “Sugar and Dental Caries” by Riva Touger-Decker and Cor van Loveren, published in the *American Journal of Clinical Nutrition* in 2003:

*1*) eat a balanced diet rich in whole grains, fruit, and vegetables and practice good oral hygiene—particularly the use of fluoridated toothpastes—to maximize oral and systemic health and reduce caries risk.

*2*) eat a combination of foods to reduce the risk of caries and erosion; include dairy products with fermentable carbohydrates and other sugars and consume these foods with, instead of, between meals; add raw fruit or vegetables to meals to increase salivary flow; drink sweetened and acidic beverages with meals, including foods that can buffer the acidogenic effects.

*3*) rinse mouth with water, chew sugarless gum (particularly those containing sugar alcohols, which stimulates remineralization), and eat dairy product such as cheese after the consumption of fermentable carbohydrates.

*4*) chew sugarless gum between meals and snacks to increase salivary flow.

*5*) drink, rather than sip, sweetened and acidic beverages.

*6*) moderate eating frequency to reduce repeated exposure to sugars, other fermentable carbohydrates, and acids.

*7*) avoid putting an infant or child to bed with a bottle of milk, juice, or other sugar-containing beverage.

(Touger-Decker, R. and van Loveren, C. Sugar and Dental Caries. *Am J Clin Nutr,* 2003, 78 (suppl), 881S–92S; <http://ajcn.nutrition.org/content/78/4/881S.full.pdf+html>)

It has been suggested (and studies show) that chewing gum helps to prevent tooth decay. That, apparently, depends on the type of gum and how long it is chewed. It seems logical that chewing gum stimulates the flow of saliva in the mouth, and that can help to neutralize acids produced by plaque bacteria.

On the other hand, sugared gum tends to coat your teeth with sugar, which can lead to tooth decay, the build-up of plaque and the proliferation of bacteria. This is especially true if the gum is removed soon after the flavor is gone. But if gum is chewed for 10-20 minutes, some experts hold that it will then act to decrease tooth decay. One study showed that after chewing gum for 10 minutes each waking hour for two weeks, participants in the study increased their salivary flow, the pH of their saliva, and its buffering capacity, all of which would tend to neutralize some of the acid produced by mouth—the cause of tooth decay.

Sugar-free gum may actually pose more potential problems if not chewed in moderation. Sugar free gums contain hexitols, sorbitol and mannitol as sugar substitutes. The ingestion of these substances can cause diarrhea, as they are not absorbed, but instead pass into the small intestine and colon. It only takes about 10 grams of sorbitol to produce this effect in many individuals. One flight attendant, who had been experiencing abdominal pain and diarrhea for over seven years was given a wide range of diagnostic tests to no avail, but upon questioning, it was found that she had been consuming about 60 sticks of sugar-free chewing gum a day, representing about 75 grams of sorbitol. Upon ceasing to chew gum, her symptoms disappeared.

But then again, there are studies which indicate that one artificial sweetener, Xylitol (e.g. Xylifresh gum) can act to reduce tooth decay if chewed in moderation—two pieces of gum three to five times daily for at least five minutes per chewing session.

*(ChemMatters* Teacher’s Guide, Dec 2000, Chewing Gum)

Research is being done on other foods to see if they might have decay-preventative properties. Score one (more) for the benefits of drinking coffee!

Coffee may also protect teeth. Farah, Gazzani, and Beatriz Gloria, a chemistry professor at the Universidade Federal de Minas Gerais, Belo Horizonte, Brazil, have shown that chemicals in roasted—but not green—coffee inhibit the growth of bacteria that cause tooth decay.

The scientists found a variety of different antibacterial chemicals which killed or inhibited the growth of *Streptococcus mutans,* the major cause of dental decay in humans. Also, Gazzani and colleagues applied roasted coffee to hydroxyapatite, a component of tooth enamel—the hard white substance covering a tooth—and showed that small molecules present in coffee prevented *S. mutans* bacteria from binding to it.

(Haines, G.K. Coffee: Brain Booster to Go. *ChemMatters*, 2008. *26* (4), p 9)

**More on fillings**

A 1929 article in the *Journal of Chemical Education* by a professor from a dental school discusses the needs of dentists in terms of dental fillings and cements needed to hold them in place, and the then-state-of-the-art developments in dental materials, made by chemists. The requirements listed below have not changed in the interim, although the materials available (thanks to chemists) have come a long way.

**Requirements of Filling Materials**

The dentist continues to seek new and improved materials for filling teeth. Few of the materials now available can be regarded as perfect from his standpoint.

A list of the requirements of a perfect filling material is about as follows-:

1. The material should be indestructible in the fluids of the mouth. It must be remembered that saliva is ordinarily somewhat acid and all cements and even some amalgams are slowly dissolved out in the mouth.
2. The material should have adaptability to the walls of the tooth cavity, *i.e.,* the dentist should be able to mallet or tamp it to place.
3. It must be free from shrinkage or expansion after placing in the tooth.
4. It must be hard enough to resist the attrition and wear of mastication.
5. It must be strong and tough to prevent fracture or displacement by the stresses of mastication.
6. The material should have a good color and appearance. If possible it should be available in shades to match the color of tooth structure.
7. It is highly desirable that the filling material should be a non-conductor of thermal changes-heat and cold.
8. It must be remembered that filling material is placed in a living tooth and it must have no toxic effect on the pulp or "nerve."
9. The material should be easy to manipulate, not only readily prepared or mixed, but, if plastic, it should harden promptly when inserted in the tooth.

No material available today for filling teeth possesses all of these desirable qualities. Some materials, like the gold inlay and silver amalgam, possess enough of these properties to make them satisfactory: some, like the cements, are used because nothing better is available.

(Brightfield, L. The Dentist’s Problem—Satisfactory Material for Restoring Teeth. J. Chem. Educ., **1929**, 6 (2), p 308)

The author also discusses at length the state of the art with regard to dental cements used to hold the fillings in place. He concludes his article by saying that

It is likely that some of these dental requirements will be difficult to meet.

But the dentist is confident that the chemist will continue to study dental cements and eventually give him a formula that will answer most if not all his requirements. The dentist's greatest problem has always been that of finding satisfactory materials for restoring teeth and with the aid of the chemist his problem is on the way to satisfactory conclusion.

(Ibid; p 313)

Here is a similar list from 1999, 70 years later:

Ideally, a dental restorative material should be perfectly compatible with the oral environment and should fulfill the criteria set out below:

easily mixed and placed as an unset paste

short working and setting times

rapid buildup in mechanical properties on setting

match of thermal and expansion properties with the tooth

high resistance to erosion and degradation by oral fluids/saliva, brushing, and flossing

biologically inert or bioactive

achieves a hermetic seal with the surrounding tooth tissue

color and translucency to match the tooth

high strength (tensile and compressive)

inexpensive

(Nicholson, J.; Anstice,H. Chemistry Everyday for Everyone: The Chemistry of Modern Dental Filling Materials. *J. Chem. Educ*., 1999, *76* (11), pp 1497–1501; abstract available online at <http://pubs.acs.org/doi/abs/10.1021/ed076p1497>; article available to subscribers only at this same URL)

Comparing the two lists, we have:

|  |  |
| --- | --- |
| **Desirable Physical Properties of Dental Fillings** | |
| **Brightfield, 1929** | **Anstice, 1999** |
| Indestructible in the mouth | High resistance to erosion by saliva, etc. |
| Adaptable to walls of tooth, tampable, malleable | Achieves hermetic seal with surrounding tooth tissue |
| Free from shrinkage | Match expansion properties of tooth |
| Hard – resistant to wear and chewing | High strength |
| Strong and tough to prevent fracture | High tensile and compressive strength |
| Good color and appearance | Color and translucency to match tooth |
| Non-conductor of thermal heat or cold | Match of thermal properties of tooth |
| Non-toxic to root or nerve | Biologically inert or bioactive |
| Easy to manipulate; harden quickly in place | Easily mixed–short working and setting time–rapid buildup in mechanical properties on setting |
|  | inexpensive |

The list from 1999 would be relatively unchanged, even to present times. As you can see, the two lists have not changed in 70-plus years, although the means to achieving these properties has changed significantly, with the invention of the mercury amalgam and, now, composite polymeric materials.

**More on dental amalgams & mercury**

There is no question that there is controversy surrounding the use of mercury amalgam fillings. And yet, almost all professional dental organizations worldwide say that, at the present time, they find them to be safe to use. Here is some background information about amalgam fillings.

Dental amalgam is a dental filling material used to fill cavities caused by tooth decay. It has been used for more than 150 years in hundreds of millions of patients around the world.

Dental amalgam is a mixture of metals, consisting of liquid (elemental) mercury and a powdered alloy composed of silver, tin, and copper. Approximately 50% of dental amalgam is elemental mercury by weight. The chemical properties of elemental mercury allow it to react with and bind together the silver/copper/tin alloy particles to form an amalgam.

Dental amalgam fillings are also known as “silver fillings” because of their silver-like appearance. Despite the name, "silver fillings" do contain elemental mercury.

When placing dental amalgam, the dentist first drills the tooth to remove the decay and then shapes the tooth cavity for placement of the amalgam filling. Next, under appropriate safety conditions, the dentist mixes the powdered alloy with the liquid mercury to form an amalgam putty. (These components are provided to the dentist in a capsule as shown in the graphic.) This softened amalgam putty is placed and shaped in the prepared cavity, where it rapidly hardens into a solid filling.

(U.S. Food and Drug Administration (FDA): <http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DentalProducts/DentalAmalgam/ucm171094.htm>)

 Here is another description of the amalgam capsule, from a previous (1996) *ChemMatters* article.

A dental amalgam capsule contains two chambers that keep the ingredients separate. When the ingredients are mixed, they form a paste that begins to harden into solid metal in just a few minutes. For this reason, the final mixing must be done in the dentist's office, just before the drilled cavity is filled. The capsule is placed in a machine that shakes it back and forth vigorously. The vibration ruptures the barrier between the two compartments and thoroughly mixes with [sic] mercury with the powdered metals.

(Graham, T. Nightmare on White Street. *ChemMatters,* 1996, *14* (4), pp 9–11)

People worried about mercury in their mouth/body often ask if they should have amalgam fillings removed and replaced with composite fillings. According to the FDA, “If your fillings are in good condition and there is no decay beneath the filling, FDA does not recommend that you have your amalgam fillings removed or replaced. Removing sound amalgam fillings results in unnecessary loss of healthy tooth structure, and exposes you to additional mercury vapor released during the removal process.” (U.S. Food and Drug Administration: <http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DentalProducts/DentalAmalgam/ucm171094.htm>)

The following quote from a 2009 white paper updates the FDA position on the use of mercury amalgams: “It is concluded that there is insufficient evidence to support an association between exposure to mercury from dental amalgams and adverse health effects in humans, including sensitive subpopulations.” (<http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DentalProducts/DentalAmalgam/ucm171117.htm#6>)

Here is a list, from the Department of Health and Human Services, Public Health Service, of advantages and disadvantages of mercury amalgam in dental fillings:

|  |  |
| --- | --- |
| **Table 1.  Comparison of the Advantages and Disadvantages of  Dental Amalgam as a Restorative Material** | |
| **Advantages** | **Disadvantages** |
| * Durable * Least technique sensitive of all restorative materials * Applicable to a broad range of clinical situations * Newer formulations have greater long-term resistance to surface corrosion * Good long-term clinical performance * Ease of manipulation by dentist * Minimal placement time compared to other materials * Initially, corrosion products seal the tooth-restoration interface and prevent bacterial leakage * One appointment placement (direct material) * Long lasting if placed under ideal conditions * Often can be repaired * Economical | * Some destruction of sound tooth tissue * Poor esthetic qualities * Long-term corrosion at tooth-restoration interface may result in "ditching" leading to replacement * Galvanic response potential exists * Local allergic potential * Concern about possible mercury toxicity * Marginal breakdown |

([*http://web.health.gov/environment/amalgam1/amalgamu.htm*](http://web.health.gov/environment/amalgam1/amalgamu.htm))

Lest the reader think that “any old” amalgam will do, dentists early on discovered the need for exact amounts of the components and precise measurement of the mixture, in order to ensure a tight fit and good seal when the amalgam is placed in the newly drilled cavity, and thereafter. The hardened metal alloy used in fillings has a coefficient of expansion very different from that of tooth dentin and enamel. Thus it will change volume within the tooth when exposed to temperature changes. When the filling’s temperature increases, with hot food or drink, it expands, more than the tooth; when the temperature drops with cold food or drink, it shrinks, again, more than the tooth.

The tooth is strong enough to withstand the expansion component, but when the filling shrinks, it could possibly open the sides of the cavity, between the tooth material and the amalgam, exposing it to bacterial infestation and infection. Thus it must be “pre-expanded”, so that future temperature-related shrinkage does not result in re-opening the cavity.

Chemists long ago experimented with varying amounts of the metals in the amalgam mix, until they discovered the best mix for this purpose, per the dental association’s parameters of 3–13 micrometers per centimeter of amalgam. The carefully measured mix of ingredients in the amalgam increases its volume slightly as the alloy is hardening, and thus it somewhat forcefully seals shut the cavity. This slight expansion of the alloy as it hardens within the cavity results in a slight compression of the material within the tooth, allowing for slight shrinkage when cold food or drink lowers its temperature, but not enough to open the cavity.

(Philips, R. Dental Amalgam: A Reaction Involving Measurement of Minute Dimensional Change. J. Chem. Educ., 1945, *22* (3), p 117; first page at <http://pubs.acs.org/doi/abs/10.1021/ed022p117>, entire article available to subscribers only at same URL)

**More on composite fillings**

Composite fillings are made primarily of polymeric materials, which exist in the composite resin material as oligomers, short-chain organic molecules, in a matrix. Some of the most used materials include:

… a [bisphenol A-glycidyl methacrylate](https://en.wikipedia.org/w/index.php?title=Bisphenol_A-glycidyl_methacrylate&action=edit&redlink=1) (BISGMA) or [urethane dimethacrylate](https://en.wikipedia.org/w/index.php?title=Urethane_dimethacrylate&action=edit&redlink=1) (UDMA), and an inorganic filler such as silicon dioxide ([silica](https://en.wikipedia.org/wiki/Silica)). Compositions vary widely, with proprietary mixes of resins forming the matrix, as well as engineered filler [glasses](https://en.wikipedia.org/wiki/Glasses) and [glass ceramics](https://en.wikipedia.org/wiki/Glass_ceramics). The [filler](https://en.wikipedia.org/wiki/Filler_(materials)) gives the composite wear resistance and translucency. A coupling agent such as [silane](https://en.wikipedia.org/wiki/Silane) is used to enhance the bond between these two components. An initiator package (such as: [camphorquinone](https://en.wikipedia.org/w/index.php?title=Camphorquinone&action=edit&redlink=1) (CQ), [phenylpropanedione](https://en.wikipedia.org/w/index.php?title=Phenylpropanedione&action=edit&redlink=1) (PPD) or [lucirin](https://en.wikipedia.org/w/index.php?title=Lucirin&action=edit&redlink=1) (TPO)) begins the [polymerization](https://en.wikipedia.org/wiki/Polymerization) reaction of the resins when external [energy](https://en.wikipedia.org/wiki/Energy) (light/heat, etc.) is applied. A [catalyst](https://en.wikipedia.org/wiki/Catalyst) package can control its speed.

(<https://en.wikipedia.org/wiki/Dental_composite>)

Advantages of composite fillings include:

* Esthetics—composite fillings are typically white, or tooth-colored, rather than the silver or black of amalgam fillings
* Less tooth damage—more healthy tooth material must be removed for amalgam fillings in order to ensure a tight lock-and-key fit for the amalgam; in composites, the filling is glued (bonded) in place, so less tooth is removed
* Bonding to tooth—amalgams are mechanically held in place, but composites are actually bonded to the tooth material chemically, ensuring a stronger bond and, hence a stronger tooth
* Possible prevention of tooth removal—if large portions of a tooth are decayed, it may be too much to allow an amalgam filling, but composites may still be used to preserve and strengthen the tooth
* Versatility—composites can be used to repair cracked or chipped teeth, not possible with amalgams
* Maintainability—minor damage to a composite filling may be repaired using additional composite material laid down over top of the original filling; amalgam filling damage would require removal of the old filling and replacing it with an entirely new filling
* Environment—no mercury in the body, no mercury in the dentists’ offices, no mercury in wastewater

But of course nothing has only advantages; here are some disadvantages of composite fillings:

* Durability—composites may not last as long as amalgams, especially in large cavities, and where they bear the brunt of chewing
* Shrinkage—composites shrink a bit more than amalgams, leaving the areas around the filling, next to tooth material, subject to microleakage which can lead to secondary caries; new formulations of composites reduce the shrinkage factor
* Chipping—exposed edges of composite fillings can chip off
* In dentist’s office—placing composites requires more training, skill and talent than needed for amalgams; placing composites takes more time to do than for amalgams; a completely dry environment is needed to place composites, not so for amalgams
* Cost—because they take longer to do, composites are more costly to place than amalgams, so dentists may charge more for composites; because composites are more costly, insurance companies frequently do not cover entire cost of composite filling

Composites were developed as an improvement over amalgam fillings, which they seem to be in most cases. And they certainly pose less of an environmental and health hazard than mercury amalgam fillings. Nevertheless, their safety has been questioned due to the fact that some composites can emit bisphenol-A (BPA), a known endocrine-disruptor, when they are placed in a filling. The emission seems to last only a short while (<1 hour) after they are placed, so exposure is not chronic, as is the case with mercury.

This emission could be from leftover BPA used in the monomer/oligomer resin that was not polymerized into the matrix, or as the result of the degradation of some of the resin after polymerization. Some studies have shown that the amount of BPA released is insignificant.

**More on possible new developments in preventing/treating tooth decay**

**Here’s a possible new treatment to accelerate remineralization of a dental cavity. According to** Dr. Margaret Culotta-Norton, a dentist in Washington, D.C., and former president of the D.C. Dental Society, this would eliminate the need for dental fillings which, she says, generally require repair or replacement, often several times over a lifetime.

Culotta-Norton said that a new treatment for cavities may be on the horizon. A process called electrically accelerated and enhanced remineralization (EAER) is being developed in London. She explained that this process "accelerates the natural movement of calcium and phosphorous minerals into the cavity to repair it. This process would eliminate drills and injections. It emits tiny electrical currents into the tooth to push the minerals into the repair site. It encourages the tooth to repair itself." According to [The Guardian](http://www.theguardian.com/society/2014/jun/16/fillings-dentists-tooth-decay-treatment), this new process could be available by 2017.

(<http://www.livescience.com/44223-cavities-tooth-decay.html>)

On a similar note, news (as of May 2012) from the University of Maryland School of Dentistry tells us about a nanomaterial that acts as an antibacterial agent is being added to existing—and new—composites to control the growth of bacteria in a cavity that has been prepped for a filling. It is very difficult, even impossible, to remove 100% of the decay in a cavity. Leftover bacteria are able to continue growing and reproducing—and producing acids that will continue to eat away at the enamel and dentin in the cavity—even after the filling has been placed, increasing the likelihood that the filling will eventually fail.

The new material is composed of existing composites and quaternary ammonium and silver nanoparticles, at a high pH (which helps to neutralize acid produced by bacteria). Another key feature is the addition of amorphous calcium phosphate, which helps to remineralize the tooth. This combined material is used primarily in the primer used by dentists to prepare the drilled-out cavity, and in the adhesive used to coat the cavity surface to help the composite filling stick to the remaining surface of the tooth. (<http://www.sciencedaily.com/releases/2012/05/120501182830.htm>)

This study shows that adding hydroxyapatite (HAP) nanofibers to existing composite resins effectively reinforces the composites and significantly improves biaxial flexural strength of the composites. (<http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3422879/>)

And here’s a somewhat novel approach, to genetically engineer a non-stick strain of bacteria that will adhere to tooth enamel so that *S. mutans* can’t!

**No cavities!**

Through genetic engineering, strains of harmless bacteria have been altered to carry desirable traits into plants, making them disease and insect resistant. Other strains have been altered to be tiny factories for otherwise very expensive proteins, insulin and human growth hormone, to name just two. Soon a new strain of Salmonella may be used as an anticavity vaccine, and tooth decay may become only a bad memory The bacteria *Streptococcus mutans* form plaque on teeth, where they convert sugars in food to acids. Once these acids dissolve tooth enamel, teeth decay rapidly. Dr. Roy Curtiss of Washington University in Missouri discovered how *Streptococcus mutans* bacteria stick to teeth. One of the proteins on the surface of the bacteria, called "SpaA," attaches to tooth enamel first, then other surface proteins convert the loose hold to a much tighter one.

The human body forms antibodies against foreign proteins, and should do so against SpaA as well, if enough is present. If surface SpaA were attacked, the bacteria couldn't attach themselves to teeth! Animal experiments on rats and monkeys have been promising, but because *Streptococcal* bacteria are implicated in heart and kidney damage, great caution is needed.

The antibody response cannot be created directly from the bacteria. SpaA is believed safe enough itself, so a harmless strain of Salmonella bacteria was genetically altered to produce SpaA. When injected in a vaccine, the Salmonella attach themselves to lymph nodes of the small intestine and go to work, producing lots of SpaA, enough to trigger the production of lymphocytes (produce antibodies). They migrate through the lymph system to the salivary glands, where the lymphocytes protect against new SpaA and give a permanent protection against *Streptococcus mutans.* Even if an anti-decay vaccine becomes a reality, you will still have to brush and floss regularly. No one wants to kiss someone with rotten gums and bad breath.

(ChemComments: No Cavities! *ChemMatters,* 1990, *8* (2), p 16)

I have to wonder what ever happened to this idea, since 25 years have elapsed. …

## Connections to Chemistry Concepts (for correlation to course curriculum)

1. **Precipitation**—This refers to the chemist’s precipitation, not the meteorologist’s term. Precipitation, the formation of a solid, certainly applies to the process of mineralization, the formation of tooth enamel via the deposition of hydroxyapatite on the surface of the tooth.
2. **Dissolving and dissolution**—The dissolving of a solid into solution occurs in demineralization, the process whereby hydroxyapatite dissolves off the tooth’s surface due to increased acidity in the mouth.
3. **Equilibrium**—The equilibria discussed in this article, acid-base interactions in the mouth and those in the body, are great examples of chemical equilibria at work in nature.
4. **Le Châtelier’s Principle and factors affecting equilibrium**—The article shows how eating food and exercise can be stresses to equilibrium systems within the body.
5. **Acid-Base chemistry**—Although the article focuses primarily on acids, specifically lactic and carbonic acids, this information is a nice segue into the effects of bases on these equilibrium systems, and it offers the teacher a chance to show the interrelatedness of acids and bases in chemical reactions.
6. **pH**—The article reinforces the importance of pH in our study of acids and bases.
7. **pH, Kas, pKas**—The acidity of the mouth with/without food, and its role in enamel/dentin decay could be used in a class discussion of acid strength.
8. **Minerals**—Minerals are usually thought of as materials that are mined from or just under the Earth’s surface, but we frequently forget that they can also be found in living organisms, as in teeth and bones in animals.
9. **Fluorine/fluoride chemistry**—Students don’t get many opportunities to discuss fluorine’s chemical reactivity. The application of fluoride treatments in the prevention of tooth decay gives them one example.
10. **Adsorption**—Fluoride used to prevent tooth decay is adsorbed onto the tooth surface, protecting the enamel from acids produced in the mouth by bacteria, or ingested from outside food/drink sources.
11. **Biochemistry**—Almost all of biochemistry involves rather complex organic chemistry; this article provides a few simple, easy-to-understand (for first year chemistry students) inorganic reactions that affect myriad biochemical reactions in the body.

## Possible Student Misconceptions (to aid teacher in addressing misconceptions)

1. **“Chemical reactions are irreversible—they only go one way, ‘left to right’.”** *Early in the academic year, all equations representing chemical reactions are written for students with the arrow pointing exclusively to the right, giving the student the illusion that reactions only go one way. It isn’t until we reach the topic of equilibrium that most students finally see that chemical reactions can be reversed, or can go in both directions simultaneously.*
2. **“It doesn’t matter when I eat sweet snacks, they’re always bad for my teeth.”** *Current research in tooth decay shows that sweets eaten with a meal are less likely to cause tooth decay than sweets eaten by themselves between meals, primarily because the residual sugars that feed the bacteria that reside in the mouth are washed away with the rest of the food and beverage during a meal. And saliva produced from the foods eaten during the meal helps buffer the effects of the acids produced. Also, you’re more likely to brush your teeth after meals than after between-meal snacks.*
3. **“If I use fluoride toothpaste, I won’t get any cavities.”** *While fluoride treatment does provide another level of protection for your teeth, it does not prevent food materials from getting stuck to teeth. Plaque can still build up on tooth surfaces, resulting in bacterial decay of the enamel that eventually will lead to cavities. Good oral hygiene is still critical—see next misconception.*
4. **“If I use a fluoride mouth rinse and my dentist puts fluoride stuff on my teeth, I don’t have to brush them.”** *While both these procedures will reduce tooth decay, nothing works as well as brushing after meals (and snacks). The fluoride in mouth rinses and dental treatments makes tooth enamel more resistant to acids produced by bacteria as they digest sugars. (see “More on fluoride treatments”, in the Background Information section, above) Fluoride does not, however, make teeth impervious to those acids. So it’s critical that you remove the foodstuff and bacteria by brushing and flossing regularly.*
5. **“Mercury in amalgam fillings is dangerous and dentists should stop using them.”** *There is much controversy today about the use of mercury amalgam fillings, but there is little scientific evidence that the mercury leaches out of the amalgams into the bloodstream, and the American Dental Association and the Federal Food and Drug Administration have not banned their use.*
6. **“If I have mercury amalgam fillings, I should go to my dentist right away and have them removed.”** *If your fillings are in good condition and there is no decay beneath the filling, FDA does not recommend that you have your amalgam fillings removed or replaced. Removing sound amalgam fillings results in unnecessary loss of healthy tooth structure, and exposes you to additional mercury vapor released during the removal process.” (*[*http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DentalProducts/DentalAmalgam/ucm171094.htm*](http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DentalProducts/DentalAmalgam/ucm171094.htm)*)*

## Anticipating Student Questions (answers to questions students might ask in class)

1. **“How do acids attack tooth enamel?”** Essentially, the H+ ion from the organic acids produced by bacteria digesting food reacts with the hydroxyl group (OH–) from hydroxyapatite, as well as with the phosphate groups (PO43-). See “More on tooth decay” in the Background Information section, above.
2. **“What is it about sweets that makes them so bad for our oral health?”** *Sweets contain sugars, and sugars are the main food source for bacterial metabolic processes. Bacteria metabolizing these sugars results produce organic acids, which are responsible for demineralizing tooth enamel.*
3. **“What is the other 4% of the enamel layer of teeth?”** *The remaining 4% of tooth enamel is organic material and water.*
4. **“Is carbonic acid a ‘strong’ acid? Is that why it’s bad for our teeth?”** *Carbonic acid is not a particularly strong acid, as acids go; in fact, it is a rather weak acid, compared to laboratory acids like sulfuric and hydrochloric acids. But even weaker acids can, over time, affect the dissolution of hydroxyapatite from tooth enamel. Acidic foods, such as citrus fruit and spaghetti sauce, also contain weak acids. Actually, strong acids cannot be used in foods, as they would react adversely with organic material in the body. Think battery acid, or concentrated hydrochloric acid from the lab.*
5. **“Is the carbonic acid involved in the chemical equilibrium equations in this article the same carbonic acid as the stuff found in sodas (or ‘pop’)?”** *Yup. See following question.*
6. **“Why is drinking soda (pop) so bad for your teeth?”** *See previous question. But it’s not only (or even primarily) the carbonic acid found “naturally” in carbonated beverages that is responsible for the acidic erosion of tooth enamel, rather it is the extra, stronger acids added to sodas—phosphoric acid and/or citric acid that are added to increase the “sharp” or tingly taste in sodas. In addition, sodas typically contain high fructose corn syrup (HFCS), a simple sugar “loved” by bacteria, enabling them to produce more organic acids that attack enamel. This bacteria food source and the additional acid provided by the dissolved carbon dioxide in soda and the other added inorganic acids, plus all the organic acids produced by the ebullient bacteria, provides a double whammy for your teeth. But don’t think for a moment that diet sodas are off the hook. Although they do not contain HFCSs, they still contain phosphoric and/or citric acids that will erode tooth enamel over time. So, although they’re better than sodas in terms of enamel erosion, they still contribute to the process.*
7. **“Does fluoride really help fight cavities?”** *Many studies have shown the positive effect fluoride has on tooth decay. Chemically, it greatly aids the remineralization of tooth enamel.*
8. **“Is it true that fluoride in drinking water will stain your teeth?”** *Yes and no. It is true that at concentrations higher than 1 ppm fluoride in drinking water can definitely produce stained, or what are referred to as “mottled” teeth. In fact, the discovery that fluoride in drinking water can reduce the incidence of cavities in teeth came about when early in this century it was noted that people who lived around Colorado Springs had a very high incidence of stained or “mottled” teeth, but at the same time had a very low incidence of dental cavities. Both effects were eventually connected to high concentrations of fluoride in the local drinking water. But at concentrations below 1 ppm this staining does not occur to any significant degree.*
9. **“Are mercury amalgams dangerous?”** *This question has been argued over for decades, and the debate continues even today. See “More on treating tooth decay” in the Background Section above. There are definitely drawbacks to using amalgams—problems obtaining a useful 3-dimensional panoramic x-ray picture, the need to cut away extra, healthy tooth to accommodate the shaping of the filling to ensure an immobile fit, and the need for proper disposal due to the mercury content—all as mentioned in the article. In addition, many people believe that some of the mercury itself can leach out of the amalgam and travel through the bloodstream and cause nerve damage within the body. Studies to-date have not supported that belief, and the American Dental Association and other professional groups have not seen the need to ban the use of amalgams, although composite resin fillings are certainly becoming more prevalent and popular.*
10. **“If I have mercury amalgam fillings, should I ask my dentist to remove them and replace them with composite resin fillings?”** *“If your fillings are in good condition and there is no decay beneath the filling, FDA [U.S. Food and Drug Administration] does not recommend that you have your amalgam fillings removed or replaced. Removing sound amalgam fillings results in unnecessary loss of healthy tooth structure, and exposes you to additional mercury vapor released during the removal process.” (U.S. Food and Drug Administration:* [*http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DentalProducts/DentalAmalgam/ucm171094.htm*](http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DentalProducts/DentalAmalgam/ucm171094.htm)*)*

## In-Class Activities (lesson ideas, including labs & demonstrations)

1. The following experiments/demonstrations can be used to investigate dissolution of solids, as in demineralization of tooth enamel. All the following use either egg shell or bone to represent teeth (although some use actual teeth):
   1. Dissolve CaCO3 in HCl or vinegar—egg shell, limestone or even marble dissolving in the acid. Although tooth enamel is notexactly analogous to CaCO3, you could use this as an example of what happens to a calcium-based mineral when it is exposed to acid secretions. Put an egg into vinegar and observe it over several days. The acid will dissolve the shell, similar to what happens when acid attacks tooth enamel, although that is a much slower process.
   2. This simple experiment uses chicken bones (allegedly akin to tooth material) and vinegar to show erosion. It misses the chance to use soda as the acid. Students could check pKas of relevant acids (acetic, phosphoric, citric, malic, carbonic) to predict effects on bones and do the experiment to test their hypothesis. (<http://healthyteeth.org/acid-attack/>) (perhaps they can also draft revised experiment with improved procedure)
   3. You could have students design an experiment using actual citric and phosphoric acids in varying concentrations acting on extracted teeth (obtained from a local dentist, perhaps?) to test their effects. (See this site for a science fair experiment, as an example: <http://www.selah.k12.wa.us/SOAR/SciProj99/ElisaSciProj.html#TOP>.)
   4. Here’s a simple demonstration to show fluoride’s protective effect on teeth (or similar substance, at least): <http://healthyteeth.org/power-of-fluoride/>.
   5. This student science fair project tests various liquids, mostly sodas, to see their effect on the decay of egg shells, chosen to represent real teeth: <http://mwvsciencefair.wikispaces.com/Teeth+Decay+in+Liquids>. You could have students evaluate the project in terms of how well it simulates tooth decay, and how well it was designed/executed, to test their understanding of the process of science.
2. You can show examples of precipitation to simulate the remineralization of hydroxyapatite on tooth surfaces using solutions of 0.1 M CaCl2 in Na2CO3 or CaCl2 & NaOH.
3. To show students how an equilibrium works, you could do the standard equilibrium demonstration or lab activity involving iron(III) nitrate (KNO3) and potassium thiocyanate (KSCN). This site presents a nice visual description of the very simple lab showing the effects of stresses on this equilibrium: <http://www.chem.uiuc.edu/chem103/equilibrium/iron.htm>. And this one provides some nice questions as follow-up to the activity: <http://www.chalkbored.com/lessons/chemistry-12/Le-Chatelier-lab.pdf>.

And this one provides a bit more chemistry at a slightly higher academic level: <http://faculty.scf.edu/GambinC/CHM%202046/CHM%202046%20Lab/Le%20Chatelier%27s.doc>

This 7:40 YouTube video clip shows various stresses on the iron-thiocyanate equilibrium: <https://www.youtube.com/watch?v=xT43fdoT_4w>

1. Or you can do one of many other demonstrations of equilibrium, such as this one:
   1. This 3:04 YouTube video clip shows an instructor simulating a chemical equilibrium system using a “reaction” (water being transferred between two aquaria) approaching and reaching equilibrium: <https://www.youtube.com/watch?feature=player_embedded&v=_QnRt7PYzeY>
   2. This 14:51 Flinn video has Irwin Talesnick teaching teachers how to do the equilibrium demonstration discussed in a: <https://www.youtube.com/watch?feature=player_embedded&v=ksGWvU8KaGE>.
   3. You could also do this demonstration using clear cups as the reservoirs and straws (of differing diameters) to transfer the water between the cups. Remember to color the water to make it more obvious to your audience and be sure you have a one-color background behind the cups—or the aquaria.
2. You can show pH change using Universal indicator in the reaction of baking soda (NaHCO3) in HCl or vinegar; or test the pH of a colorless soda, like 7 Up or Sprite.
3. Almost all of the acidity of soda pop comes from the phosphoric acid and not from the carbonic acid from the dissolved CO2. You can verify this by measuring the pH of fresh and flat soda pop (minus the CO2 and, hence the carbonic acid); there's very little difference in pH. The phosphoric acid is corrosive, but actually the acid concentration in soda pop is lower than that in orange juice or lemonade. Try submerging identical strips of magnesium (or iron staples) in each of these beverages overnight, including soda pop. Which beverage dissolves more metal? Which dissolves the metal fastest? (<http://antoine.frostburg.edu/chem/senese/101/consumer/faq/why-phosphoric-acid-in-soda-pop.shtml>)
4. Vernier Software’s “Chemistry with Vernier” lab manual, experiment 35 has students determine the phosphoric acid content of various sodas. This site provides an evaluation copy of the activity, but it includes a statement that it is an incomplete document, lacking safety instructions, preparation of materials, etc.; they provide the link for you to buy the lab manual. (<http://www2.vernier.com/sample_labs/CWV-35-COMP-phosphoric_acid.pdf>)
5. Show pH change—e.g., Universal indicator, baking soda & HCl or vinegar
6. If you teach an AP or second-year level class, this lab that describes using infrared spectroscopy (830 nm) to experimentally determine the amount of phosphorus (from phosphoric acid) in cola soft drinks may be of interest: Lozano-Calero, D.; Martin-Palomeque, P. Determination of Phosphorus in Cola Drinks. J. Chem. Educ., 1996, 73 (12), p 1173. The abstract of the article is available online at <http://pubs.acs.org/doi/abs/10.1021/ed073p1173>. The pdf is available to subscribers only at this same URL.
7. Have kids design an experiment to test the acidity of various sour candies. Here’s a sample from Mensa for Kids: <http://www.mensaforkids.org/teach/activity-plans/the-science-of-candy/>. Students can review this procedure to determine its efficacy. After discussion of this test, they can devise their own, hopefully improved procedure. (You can download a pdf of the activity for classroom distribution.) This is a list of candy products and their corresponding pH levels: <http://www.drokeefe.com/pages/candy-ph.htm>.
8. Here’s another science experiment testing sugar and dental erosion: <http://scijourner.org/index.php?option=com_content&view=article&id=236:experiment-sports-drinks-possible-cause-of-tooth-erosion>.
9. Have students make their own toothpaste. Here’s an article from *J. Chem. Educ.* that provides the student and teacher versions of the lab activity: Trantow, A. JCE Classroom Activity #47: Brushing Up on Chemistry. *J. Chem. Educ*., 2002, *79* (10), pp 1168A–1168B; abstract available online at <http://pubs.acs.org/doi/abs/10.1021/ed079p1168A>, pdf of entire article available only to subscribers, at this same URL.
10. This *Journal of Chemical Education* article provides five questions (and answers) that students of AP, second year or IB courses could be asked to solve regarding fluoride in dental applications, to give them applications of chemistry to the real world. Chemistry topics included in these questions are: “stoichiometry, concentration units, resonance in polyatomic ions, bond order, bond length, geometry of polyatomic ions, and treatment of water.” (Resources for Student Assessment. Pinto, G. Fluorine Compounds and Dental Health: Applications of General Chemistry Topics. J. Chem. Educ., **2009**, 86 (2), p 185; abstract available at <http://pubs.acs.org/doi/abs/10.1021/ed086p185>; the pdf of the article is also available to subscribers at this same URL)
11. You can have students research and debate the water fluoridation controversy. “Pros” can start with information from the Fluoride Information Network, <http://fluorideinfo.org/>, while “cons” can begin with information from the Fluoride Alert Network, this source: <http://fluoridealert.org/>. Perhaps a more balanced view can be found at the Centers for Disease Control (CDC) Web site, here: <http://www.cdc.gov/fluoridation/benefits/index.htm>
12. As mentioned in the “More on saliva and equilibrium in the mouth” section, amylase is one of the enzymes in saliva that helps digest starches.
13. There is a standard activity that shows amylase activity on starch. The student chews on a carbohydrate and tests the result with tincture of iodine. (simple: <http://www.coolscience.org/CoolScience/KidScientists/IodineStarch.htm>) and

(a bit more complex: <http://www.juliantrubin.com/encyclopedia/biochemistry/saliva_amylase.html>)

1. Or you can use amylase by itself. Here’s a YouTube video clip (7:13) that shows the process in detail, and then the result after several minutes: <https://www.youtube.com/watch?v=cZyq4koUCNM>.
2. And here is an inquiry-based student activity from *The Science Teacher*, “Enzyme Inquiry”, to take the previous student activity a step further: <http://science.kennesaw.edu/~mdias/SCED%204415/Biology%20Teaching%20Resources/Enzyme%20Inquiry.pdf>.
3. Another activity showing saliva’s effects is to test mouth pH before and after eating. “Wait at least two hours after eating or drinking to ensure that the food consumed does not alter test results. Cleanse the mouth by filling the mouth with saliva and then swallowing or spitting. Fill the mouth again with saliva and place a small amount on a pH strip. The strip will change colors based on the results.” <http://www.livestrong.com/article/192281-what-is-ph-of-saliva/>
4. In this student activity (college-level, but not that difficult), students measure the “amylase number”, a relative value that reflects the individual’s amount of amylase and its ability to break down starch. They then compare class results. (<https://www.apsu.edu/sites/apsu.edu/files/chemistry/SP11_1021_BREAKING_DOWN_STARCH_USING_SALIVARY_ENZYMES.pdf>)
5. You may want to use the idea of the photo-initiated catalysts to begin the polymerization process in materials used for composite fillings as an example of light’s effects on chemical reactions. The light used in this process is usually a blue, or even ultraviolet light. You can ask students why a blue light is used, rather than a red or green light, for example.
6. Depending on the level of your students, you might want to have them do the following calculations to show the difference in solubility between hydroxyapatite and fluoroapatite.

Exercise: SOLUBILITY and SOLUBILITY PRODUCT

Tooth enamel is composed of the mineral hydroxyapatite, Ca5(PO4)3OH   
(Ksp = 6.8 x 10-37). The presence of acids, i.e. acidic fruits and fruit juices or acids that are formed when various sugars are metabolized by bacteria, will react with the hydroxyapatite, thus leading to tooth decay. Fluoride is often added to toothpaste and water treatment plants in some communities add fluoride to drinking water to prevent tooth decay. The fluoride reacts with the Ca5(PO4)3OH to form the more decay resistant fluorapatite, Ca5(PO4)3F (Ksp = 1.0 x 10-60). These measures have resulted in a dramatic decrease in the number of cavities among children. Calculate the solubility of Ca5(PO4)3OH and Ca5(PO4)3F in water.

1. Write a chemical equation for the reaction of hydroxyapatite with acids (H+):

2. Calculate the solubility of Ca5(PO4)3OH in water

[*ICE* tables—samples are given on the site below to show how to solve this problem]

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | *Ca5(PO4)3OH* | *Ca2+* | *PO43-* | *OH-* |
| ***I***nitial |  |  |  |  |
| ***C***hange |  |  |  |  |
| ***E***quilibrium |  |  |  |  |

3. Calculate the solubility of Ca5(PO4)3F in water

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | *Ca5(PO4)3F* | *Ca2+* | *PO43-* | *F-* |
| ***I***nitial |  |  |  |  |
| ***C***hange |  |  |  |  |
| ***E***quilibrium |  |  |  |  |

(<http://wc.pima.edu/~skolchens/C152OL/Ch19/Ksp.htm>)

## Out-of-Class Activities and Projects (student research, class projects)

1. Students can research and debate the mercury-in-amalgam fillings issue. Anti-amalgam groups abound online. Here is one set of documents said to support the anti-amalgam position: <http://www.flcv.com/dams.html>. Here is another: <http://www.thenaturalrecoveryplan.com/research.php>. Students must be made aware of the bias inherent in some of these sites. Pro-amalgam positions include the ADA <http://www.ada.org/en/about-the-ada/ada-positions-policies-and-statements/statement-on-dental-amalgam>), the FDA (<http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DentalProducts/DentalAmalgam/ucm171094.htm>) and FDI World Dental Federation (<http://www.fdiworldental.org/media/11351/Safety-of-dental-amalgam-2007.pdf>). It is enlightening to see how one group can cite specific scientific studies that support its position, while the group espousing the opposite position uses the same study to support their position. (reminiscent of global warming, er … I mean, climate change) Wikipedia’s page on the dental amalgam controversy can be found here: <https://en.wikipedia.org/wiki/Dental_amalgam_controversy>.

Also see “Web Sites for Additional Information” below for more sites on amalgam fillings.

1. Students can research and debate the fluoride treatment issue.
2. Students might be able to obtain teeth from their dentist on which to do long-term research re: dental caries formation and prevention.
3. Students can research and report on other equilibrium systems at work in the body.
4. Students can research and report on acidic and basic foods and their effects on tooth erosion/decay.
5. Students can research and report on types of acid contained in various candies (from food labels) and seek a correlation between type of acid and level of tartness/sourness. Here is a sample, very rudimentary experiment: <http://www.education.com/science-fair/article/candy-ph/>. Although rudimentary, it requires melting of each of the candies, perhaps a painstakingly slow process. This one dissolves the candies instead (although no chocolates were tested): <http://cascience6isp.wikispaces.com/file/view/Emily%20K2013.pdf/415709538/Emily%20K2013.pdf>. It also uses a pH meter, rather than pH paper, as in the first experiment.
6. Students can investigate this study on tooth erosion as it relates to Gatorade imbibement, and comment on the scientific rigor of the experiment, possibly suggesting ways to improve the procedure. (<http://www.webdental.com/profiles/blogs/why-gatorade-erodes-teeth>)
7. Interested students can test their own saliva before and after eating, to show changes in pH as a result of ingested food. The standard way of testing pH of saliva is the following: Wait at least two hours after eating or drinking to ensure that the food consumed does not alter test results. Cleanse the mouth by filling the mouth with saliva and then swallowing or spitting. Fill the mouth again with saliva and place a small amount on a pH strip. The strip will change colors based on the results. (<http://www.livestrong.com/article/192281-what-is-ph-of-saliva/>) Varying the times following eating can show changes in pH. Be sure to include a test after brushing the teeth.
8. If you’re not planning to do a debate on the role of water fluoridation in reducing tooth decay in your classes, students can research the pros and cons of this topic and write a report/make a class presentation. See the reference in the “In-Class Activities” section, above, for links to sites to begin their online research. Note: you may NOT want to give them this site: <http://www.debate.org/debates/Water-fluoridation-is-safe/1/>, as it contains an already-established debate. Alternatively, you may want to restrict the debate to one aspect of the controversy, as the debate above does, focusing on the safety of fluoride in the diet.

## References (non-Web-based information sources)



**30 Years of *ChemMatters***

Available Now!

**The references below can be found on the *ChemMatters* 30-year DVD (which includes all articles published during the years 1983 through April 2013 and all available Teacher’s Guides, beginning February 1990). The DVD is available from the American Chemical Society for $42 (or $135 for a site/school license) at this site:** [http://ww.acs.org/chemmatters](http://www.acs.org/chemmatters)**. Click on the “Archive” tab in the middle of the screen just under the *ChemMatters* logo. On this new page click on the “Get 30 Years of ChemMatters on DVD!” tab at the right for more information and to purchase the DVD.**

**Selected articles and the complete set of Teacher’s Guides for all issues from the past three years are available free online at the same Web site, above. Simply access the link and click on the aforementioned “Archive” tab.**

This article from 1986 provides a brief history of tooth decay prevention and discusses the role tooth paste plays in preventing tooth decay and the ingredients of present-day tooth pastes. The author also discusses demineralization and re-mineralization of tooth enamel. (Yohe, B. Tooth Paste. *ChemMatters,* 1986, *4* (1), pp 12–13)

OK, fluoride is used to prevent cavities, but where does fluorine come from? Here’s a brief history of the trials and tribulations of the search for and discovery/isolation of the element fluorine. (Davenport, D. The Back Burner: Going Against the Flow: The Isolation of Fluorine. *ChemMatters,* 1986, *4* (4), pp 13–15)

This 1988 article discusses sugar and artificial sweeteners. It shows their structures and discusses a “triangle of sweetness” (a 3-sided structure containing corners of a hydrogen bond donor site, a receptor site, and a hydrophobic site) to which all sweeteners must relate chemically and by shape. At the end of the article is a 2-page insert form that contains paper molecular models of glucose and cyclamate that can be cut out and then used to show how they relate to the triangle of sweetness. (Emsley, J. Artificial Sweeteners. *ChemMatters,* 1988, *6* (1), pp 4–8, plus 2-page insert)

Author Owsley relates the story of a horrific murder in which the body was burned and crushed, leaving almost no traceable evidence. But small bone and tooth fragments left behind were enough to test using forensic apparatus. In this case, amalgam fillings finally led to the solving of the case. (Owsley, D. Fragments of Murder. *ChemMatters*, 1996, *14* (2), pp 12–15)

In this article, author Baxter investigates mouthwashes and their effectiveness at reducing bad breath and tooth decay. (Baxter, R. Mouthwash: What’s in it for You? *ChemMatters*, 1996, *14* (4), pp 6–8)

Author Graham describes the mysterious deaths of 4 family members after a fire. He describes the symptoms of the family members and the investigation done by scientists to establish mercury poisoning—from the refining of contaminated metals from unused mercury-amalgam dental capsules. A sidebar explains the chemistry behind the toxicity of mercury. (Graham, T. *Mystery Matters*: Nightmare on White Street. *ChemMatters,* 1996, *14* (4), pp 9–11)

This is an early article on whitening of teeth that briefly discusses the history of tooth whitening, and the present-day use of carbamide peroxide as a source of hydrogen peroxide to bleach teeth. (Ruth, C. Teeth Whitening. *ChemMatters*, 2003, *21* (4), pp 7–9)

The December 2003 *ChemMatters* Teacher’s Guide accompanying the “Teeth Whitening” article above contains more on the history of whitening agents and toothpaste. It even offers a “toothbrush timeline”.

Here’s another, more recent article on artificial sweeteners. (Brownlee, C. The Skinny on Sweeteners. *ChemMatters*, 2011, *29* (3), pp 15–16)

The October 2011 *ChemMatters* Teacher’s Guide has lots more information on artificial sweeteners.

This article discusses bodily functions that result in bad smells or less-than-flattering appearance (acne, bad breath and flatulence). In his coverage of bad breath, author Rohrig discusses tooth decay as an offshoot of bad breath. He describes demineralization and remineralization and the role of fluoride in tooth decay. (Rohrig, B. Demystifying Gross Stuff. *ChemMatters*, 2011, *29* (3), pp 12–14)

The October 2011 *ChemMatters* Teacher’s Guide has lots more information about tooth decay and fluoride water treatment to combat decay.

The topic of tooth whitening is discussed in this article. It includes the safety of whitening methods used today. (Sitzman, B.; Goode, R. Open for Discussion: Teeth Whiteners. *ChemMatters,* 2013, *31* (1), p 5)

## Web Sites for Additional Information (Web-based information sources)

**More sites on the structure of the tooth**

A good black-and-white diagram of a tooth’s structure can be found at <http://www1.us.elsevierhealth.com/SIMON/Bird/modern/EIC/graphics/7627_04_24.jpg>.

This 2007 paper, “An Overview of the Dental Pulp: Its Function and Responses to Injury,” describes the role of dental pulp in maintaining healthy teeth: <http://www.ada.org.au/app_cmslib/media/lib/0704/m70470_v1_633112728503963750.pdf>.

This paper, “The Role of Dentin in Tooth Fracture”, reports on studies using scanning electron microscopes (SEM) that show that the softer-than-enamel dentin absorbs some of the stresses of mastication on the enamel, thus preventing propagation of microfractures through the enamel, which would result in cracking the enamel: <https://str.llnl.gov/str/JanFeb08/pdfs/01.08.3.pdf>.

**More sites on the chemical structure of tooth enamel**

A May 2006 article in the *Journal of Chemical Education*, “Calcium Phosphates and Human Beings” by Sergey V. Dorozhkin discusses at length the naturally-occurring crystalline varieties of apatite (calcium phosphate) in rocks and minerals, and its role in mammals, especially humans, in their bones and teeth. (Dorozhkin, S. Calcium Phosphates and Human Beings. J. Chem. Educ., **2006**, 83 (5), p 713) The abstract of the article is available online at <http://pubs.acs.org/doi/abs/10.1021/ed083p713>; the pdf of the article is available only to subscribers *of J Chem. Educ.* at this same URL.

A series of 32 slides from Prof. Colin Robinson of the Leeds Dental Institute, UK, provides information on tooth enamel. His slides aim

* To recognise the structure of calcium hydroxyapatite, the main mineral component of the dental tissues
* To understand apatite structure in terms of foreign ion substitutions and their effect in relation to enamel behaviour
* To recognise the variations in chemical composition of dental enamel in relation to disease and eventually development

The slides illustrate the chemical content and structural arrangement of hydroxyapatite, and the varying chemical content of tooth enamel in various locations on the tooth. (<http://www.academia.edu/1732481/Dental_Enamel_Chemistry>)

This page from webmineral.com provides the unit-cell structure of apatite. This page requires Java to work, and you probably will need to add this site to your “exceptions list” in Java, otherwise security prevents you from viewing it. The Java structure is rotatable, it can be animated to rotate, and you can change the appearance to include/exclude atoms, bonds, polyhedral structures, labels, etc. (<http://webmineral.com/jpowd/JPX/jpowd.php?target_file=Apatite-%28CaOH%29.jpx#.Ve3uWM-FNOQ>)

**More sites on tooth decay**

Simplyteeth.com provides a wealth of basic information about teeth, from anatomy to decay causes, prevention, and treatment: <http://simplyteeth.com/>.

This site discusses the dental erosion experienced by a man who drank 1.5 liters of cola per day for several years. It offers a detailed medical description of his case. It also includes photos of his teeth. (<http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2676420/>)

This PubMed site provides a very detailed 2010 report discussing tests done with colas to show their effects on teeth and the environment of the mouth: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2997506/?tool=pubmed>.

This webmd.com site discusses the various causes of dental erosion: extrinsic, intrinsic and environmental: <http://www.webmd.com/oral-health/guide/tooth-enamel-erosion-restoration>.

This site provides a brief table of Kas and pKas of various common acids (with names and formulas), including carbonic, phosphoric and citric acids: <http://2012books.lardbucket.org/books/principles-of-general-chemistry-v1.0/s31-appendix-c-dissociation-consta.html>.

Here’s a site that covers rather extensively “Acidity, Basicity, and pKa”. This might be most useful as a teacher introduction/review of the topics, although portions (or maybe all for a better student) could be used by students. <http://www.columbia.edu/~crg2133/Files/CambridgeIA/Chemistry/AcidityBasicitykPa.pdf>

Here is a set of 9 sessions from the Khan Academy on acid-base equilibria: <https://www.khanacademy.org/science/chemistry/acids-and-bases-topic/copy-of-acid-base-equilibria>.

The American Chemical Society publication *Chemical and Engineering News* (*C&EN*) frequently publishes “What’s That Stuff?”, one-page articles on specific useful items. This article focuses on fluoride toothpaste and fluoridated water, and the sources for the fluoride in both: <http://pubs.acs.org/cen/whatstuff/stuff/7916sci4.html>, available to all.

You can access a rather detailed description of how enamel forms and how it demineralizes, as well as photomicrographs of tooth enamel, with and without fluoride, at <http://www.dimensionsofdentalhygiene.com/ddhright.aspx?id=5620>.

This site discusses what causes tooth decay, and how to prevent it. Its focus is on the role played by foods we eat. (<http://www.human-health-and-animal-ethics.com/health/dental-care/tooth-decay.php#How%20to%20prevent%20tooth%20decay>)

This site from Virtual Chembook describes the process of food, saliva and *S. mutans* mixing in the mouth, most likely resulting in dental cavities: <http://chemistry.elmhurst.edu/vchembook/548toothdecay.html>.

Dentist Brian Palmer’s site contains 3 pdf documents (among others) that discuss abfraction of teeth. Apparently, some dentists believe this theory and some do not. (<http://www.brianpalmerdds.com/hypothesis_abfractions.htm>)

**More sites on food’s effects on tooth decay**

This site from the Mayo Clinic discusses artificial sweeteners and sugar substitutes: <http://www.mayoclinic.org/healthy-lifestyle/nutrition-and-healthy-eating/in-depth/artificial-sweeteners/art-20046936>.

This 2003 paper from the *American Journal of Clinical Nutrition* reports on research done on the relationship between food intake and dental caries worldwide. (Touger-Decker, R. and van Loveren, C. Sugar and Dental Caries. *Am J Clin Nutr,* 2003, 78 (suppl), 881S–92S; <http://ajcn.nutrition.org/content/78/4/881S.full.pdf+html>)

**More sites on effects of brushing and flossing**

Here’s a site from “Save Your Smile”. Everything You Wanted to Know about Toothpaste: <http://www.saveyoursmile.com/toothpaste/toothpaste-a.html>.

This 1978 article from *J. Chem. Educ.*, Chem I Supplement: Chemistry in Oral Health describes the four main ingredients in oral dentifrices. (Chemistry in Oral Health. J. Chem. Educ., 1978, 55 (11), p 736; abstract only, <http://pubs.acs.org/doi/abs/10.1021/ed055p736>. The article is available at this same URL only to subscribers.)

**More sites on fluorine and fluoride treatment of teeth**

This page from the *Journal of Chemical Education* discusses fluorine’s history of discovery and uses: Banks, A. What’s the Use? Fluorine. *J. Chem. Educ.* 1990, *67* (5), p 373; abstract here: <http://pubs.acs.org/doi/abs/10.1021/ed055p736>; article available to subscribers at this same URL.

Another article from *J. Chem. Educ*. Discusses fluoride: its history, natural source, various compounds used in dental materials, and chemistry in preventing caries. (Rakita, P. Chemistry for Everyone: Dentifrice Fluoride. *J. Chem. Educ.,* 2004, *81* (5), pp 677–679; abstract online at <http://pubs.acs.org/doi/abs/10.1021/ed081p677>; article for subscribers at same URL.

An article in the 1963 Proceedings of the Nutrition Society titled, “Theories on the Mode of Action of Fluoride in Reducing Dental Decay,” presents an in-depth treatment of the role of fluoride in prevention of tooth decay, at <http://journals.cambridge.org/action/displayFulltext?type=1&fid=784036&jid=PNS&volumeId=22&issueId=01&aid=784028>.

The 1963 paper “Theories on the Mode of Action by Fluoride in Reducing Dental Decay” from the Proceedings of the Nutrition Society discusses then-recent research into the ways that fluoride aids in cavity-reduction: <http://journals.cambridge.org/download.php?file=%2FPNS%2FPNS22_01%2FS0029665163000227a.pdf&code=6b757e835089bfe0cc1b3917051f9ad5>.

Here is a 2006 very brief, 2-page flyer from the Centers for Disease Control (CDC) on the benefits of water fluoridation: <http://www.cdc.gov/fluoridation/pdf/natures_way.pdf>.

And a 69-page 2005 document, “Fluoridation Facts”, from the American Dental Association (ADA) provides detailed answers and facts to substantiate their answers to more than 50 commonly-asked questions about water fluoridation. The document also contains more than 350 references (vast majority of references are not linked to World Wide Web). (<http://www.ada.org/~/media/ADA/Member%20Center/FIles/fluoridation_facts.ashx>)

This is a 2013 video clip (9:09) from an Australian (Queensland [Qld]) ABC television news show that discusses the pros and cons of water fluoridation: <http://www.abc.net.au/catalyst/stories/3821248.htm>. Viewing this might be a good way to begin a research study/debate on the controversy, as it presents some of both sides of the issue.

This site from the Fluoride Action Network provides 50 reasons NOT to fluoridate drinking water: <http://fluoridealert.org/articles/50-reasons/>.

And from the same organization comes the document “The Case Against Fluoride”, with 40 ways to rebut claims from pro-fluoridation groups: <http://www.fluoridealert.org/wp-content/uploads/proponent_claims.pdf>

From the National Academy of Sciences (NAP), you can download a pdf copy of the 507-page 2006 National Research Council’s document “Fluoride in Drinking Water: A Scientific Review of EPA’s Standards” at <http://www.nap.edu/openbook.php?record_id=11571>. The document is replete with detailed information on all known aspects of fluoride effects on health, and only a small portion is concerned with fluoride in teeth. You can download chapter by chapter or the entire document. You can register with NAP, or you can download a copy as a guest. NAP has many very useful documents available for purchase or for free download, so it might be useful to register.

**More sites on saliva and equilibrium in the mouth**

This site from the European Food Information Council (EUFIC), “Saliva—more than just water in your mouth”, provides much information on the role of saliva in preventing tooth erosion. It includes material on inorganic erosion (providing calcium and phosphate ions), as its effects on bacteria (preventing bacterial build-up on enamel via its slipperiness, attracting bacteria to it instead of to enamel, thus subsequently being swallowed, and actually killing bacteria via lysozyme). (<http://www.eufic.org/article/en/artid/Saliva-more-than-just-water-in-your-mouth/>)

**More sites on treating tooth decay—mercury amalgam fillings**

The National Capital Poison Center has an extensive, well-documented Web page describing fillings in general and amalgam fillings in particular, especially relative to their safety. (<http://www.poison.org/current/dentalamalgamsandmercury.htm>)

This 116-page pdf document comprises the complete FDA 2008 final ruling on “Dental Devices: Classification of Dental Amalgam, Reclassification of Dental Mercury, Designation of Special Controls for Dental Amalgam, Mercury, and Amalgam Alloy. It includes more than 80 references the FDA used in its study/decision to change dental amalgams from Class I to Class II devices. (<http://www.fda.gov/downloads/MedicalDevices/ProductsandMedicalProcedures/DentalProducts/DentalAmalgam/UCM174024.pdf>)

This site from the European Commission, Health & Consumer Protection, Consulate-General’s Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), presents information on amalgam fillings, and alternative materials used for fillings, through a simple series of Q & As. The document is distributed via GreenFacts.org. (<http://ec.europa.eu/health/opinions/dental-amalgam-l1_en.pdf>)

This 74-page 2008 document from the European Commission, Health & Consumer Protection, Consulate-General’s Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) provides detailed information on their research and findings regarding the safety of mercury amalgams. This is the complete document from which the preceding source was taken and reformatted. (<http://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_016.pdf>)

Here is a 4:26 video clip close-up of a cavity and its repair via an amalgam restoration: <https://www.youtube.com/watch?v=ehFUq2t5O-U&feature=player_embedded>

<http://www.azom.com/article.aspx?ArticleID=8081>

The online source “Dental Amalgam: A Scientific Review and Recommended Public Health Service Strategy for Research, Education and Regulation” is an extensive report published in 1993 of research done and compiled by the Subcommittee on Risk Management of the Committee to Coordinate Environmental Health and Related Programs, of the Public Health Service. <http://web.health.gov/environment/amalgam1/ct.htm>.

This 6-page pdf document discusses the history, production and use of mercury amalgam in tooth fillings: <http://prospect.rsc.org/metalsandlife/9.16b.pdf>.

This site on the FDA Web site provides a passionate plea by doctors, dentists, and researchers, backed up by much evidence, asking the FDA to ban mercury in the United States: <http://www.fda.gov/downloads/advisorycommittees/committeesmeetingmaterials/medicaldevices/medicaldevicesadvisorycommittee/dentalproductspanel/ucm236379.pdf>.

The article “Toxic Teeth: Are Amalgam Fillings Safe?” from the Dr. Oz television show, discusses amalgam fillings: <http://www.doctoroz.com/article/toxic-teeth-are-our-amalgam-fillings-safe>.

**More sites on treating tooth decay—composite fillings**

Webmd.com provides a 7-page Web site detailing the work dentists do on fillings. Page 2 in particular lists advantages and disadvantages of each type of tooth filling: cast gold, mercury amalgam, and composite: <http://www.webmd.com/oral-health/guide/dental-health-fillings>.

The bisphenol-A.org Web site provides much information about bisphenol-A (BPA) in general, and this page specifically deals with the topic of BPA leaching from composite fillings and dental sealants: <http://bisphenol-a.org/human/dental.html>. Going to their “Myths about BPA” page (<http://bisphenol-a.org/about/bpa-myths/index.html>) gives the discerning reader a better understanding on their position concerning the health effects of BPA.

# Probiotics: Good Bacteria, Good Health

## Background Information (teacher information)

**More on** **the science of probiotics**

The term probiotics is a general one which requires the specific names of bacteria and the chemicals they emit that may produce a variety of effects mentioned in the *ChemMatters* article. In general parlance, the role of probiotics often strays from documented evidence of what these substances can do. This is particularly true when non-scientific publications report on the properties of the probiotics. The present state of affairs hints at what these organisms might be capable of doing. What is badly needed is scientific documentation (i.e., isolation) of the particular chemicals that are produced by various probiotics and specifically what biological targets respond to these chemicals. As mentioned in a government report by NIH (National Institutes of Health), “…it is important to stress that the biological effects of probiotics are strain specific and the success or failure of one strain cannot be extrapolated to another strain. Thus proper identification using novel molecular and based technologies is imperative.” (<http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4053917/>).

Then again, some of the functions of the microbiome in the human digestive tract are well documented.

Research suggests that the relationship between gut flora and humans is not merely commensal (a non-harmful coexistence), but rather a mutualistic relationship. Though people can survive without gut flora, the microorganisms perform a host of useful functions, such as fermenting unused energy substrates, training the immune system, preventing growth of harmful, pathogenic bacteria, regulating the development of the gut, producing vitamins for the host, such as biotin and vitamin K, and producing hormones to direct the host to store fats. In return, these microorganisms procure within the host a protected, nutrient-rich environment in which they can thrive….Not all the species in the gut have been identified because most cannot be cultured, and identification is difficult.

*(*[*https://en.wikipedia.org/wiki/Gut\_flora*](https://en.wikipedia.org/wiki/Gut_flora)*)*

The standard bacteria used for making yogurt, an oft-cited source of probiotics, have been well studied for years. They are considered to be probiotics because they help lactose-intolerant people digest yogurt by breaking down the sugar lactose, which these people cannot do because they lack the enzyme lactase. However, these bacteria—*Lactobacillus delbrueckii* subspecies *bulgaricus* and *Streptococcus thermophilus*—don't make it through the intestines alive. That's why many yogurt producers add other probiotics that can survive in the gut. Lactic acid bacteria (LAB) are the most common microbial genera used in probiotics.

(<http://www.livescience.com/46298-the-lowdown-on-probiotics.html>)

Research shows that feeding mice with yogurt containing probiotics does not produce colonization of the cultures in the gut. But ingesting the bacteria directly does produce beneficial effects related to obesity and possibly sugar metabolism (i.e., reducing insulin resistance in diabetes). VSL#3, a commercial product name, has been shown to increase probiotic bacteria, which in turn reduce certain circulating inflammatory cytokines that are related to inflammation associated with diabetes.

Research scientists suggest certain criteria for probiotic bacteria.

The bacterial strains that are selected for probiotic milk products by the culture supplier should fulfill the following requirements:

1. Survive the gastric acidic conditions (pH 1–4).
2. Be resistant to the action of bile salts.
3. Resist degradation by digestive enzymes present in the intestines (e.g. lysozymes).
4. Survive action of toxic metabolites, primarily phenols, produced during the digestion process, antibiotics and phage, anaerobic growth conditions and storage conditions of the food carrier.

(<http://www.nature.com/icb/journal/v78/n1/full/icb200012a.html>)

What other things can probiotics do that have some scientific validity? Scientists have already demonstrated that the gut microbiome is importantly involved in the development of the human immune system, and that abnormalities in microbial diversity are correlated with several inflammatory diseases. Some probiotics have been shown to be effective or possibly effective in preventing pediatric antibiotic-associated diarrhea, necrotizing enterocolitis in preterm infants, and upper respiratory tract infections. They have been shown to be effective or possibly effective in treating acute infectious diarrhea and persistent diarrhea in children. To date, probiotics, such as *L. acidophilus* (found in yogurt) have not been shown to be effective against bacterial vaginosis, ulcerative colitis, Crohn’s disease, or preterm labor. These conclusions are based on reports from the National Center for Biotechnology Information. (<http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3859987/>)

Additionally, many studies have shown that different probiotics can impact immune function in different ways. But, because the effects of probiotic strains can vary broadly, and immune-system effects are incredibly diverse, an international panel of researchers have decided that an immune-system boost should not be considered a core benefit of probiotics,

And from an article by one of the medical authorities at Tufts University, Joel Mason, who is a physician and senior scientist at the Jean Mayer USDA Human Nutrition Research Center on Aging and a faculty member at Tufts School of Medicine and the Friedman School:

Many advertisements and Internet postings say probiotics are effective for the treatment of asthma, dermatitis, irritable bowel syndrome and other conditions. At best, there is marginal evidence that probiotics help these conditions.

Where they have been convincingly shown to be beneficial is in the treatment or prevention of certain kinds of diarrhea, as well as in ulcerative colitis and with certain problems that can accompany fat malabsorption….Many people eat yogurt because it contains probiotics, but studies looking at the potential usefulness of probiotics in a rigorous scientific manner have generally used pure preparations, not yogurt. So whether the helpful bacteria you get by eating yogurt are really as effective as pure probiotics is up in the air right now.

(<http://now.tufts.edu/articles/can-probiotics-keep-gastrointestinal-health#sthash.S9ekHblO.dpuf>)

The *ChemMatters* article mentioned a number of probiotic food products that contain live bacteria. Researchers feel that these foods should not be labeled as containing probiotics unless the bacterial cultures have been shown to provide health benefits as probiotics. Rather they should be labeled as sources of particular bacteria and not sources of probiotics. Three of the products (Asian), Kefir, kimchee, and kombucha have not been shown to have any beneficial effects other than being of nutritional, rather than probiotic, value. And one of them, kombucha, presents some health risk, according to the Mayo Clinic. On the other hand, combining yogurt with kefir, both fermented milk products, create a symbiotic situation, in that the two contain live bacteria and the fuel they need to thrive.

A basic problem with identifying these beneficial bacteria is that not all the species in the gut have been identified because most cannot be cultured. So this fact limits identification. Bacteria make up most of the flora in the colon and up to 60% of the dry mass of feces. Somewhere between 300 and 1000 different species live in the gut, with most estimates at about 500. However, it is probable that 99% of the bacteria come from about 30 or 40 species. Fungi, protozoa, and archaea also make up a part of the gut flora, but little is known about their activities. (<https://en.wikipedia.org/wiki/Gut_flora>)

A healthy gut is mostly composed of bacterial species that fall within two different groups of bacteria: the phyla Bacteroidete*s* and Firmicutes.

A large, government-funded project known as the Human Microbiome Project is in operation to determine the genetic markers on the many bacteria in the body. The purpose of the Human Microbiome Project is to collect all the microorganisms living in association with the human body. These communities consist of a variety of microorganisms including eukaryotes, archaea, bacteria and viruses. An understanding of what microbes exist in the body as well as their genetics and biochemical activity could lead to the development of pharmaceuticals that can either control their behavior (think antibiotics) or enhance their beneficial functions. To date, “… the Human Microbiome Project has published an analysis of 178 genomes from microbes that live in or on the human body. The researchers discovered novel genes and proteins that serve functions in human health and disease, adding a new level of understanding to what is known about the complexity and diversity of these organisms.” (<http://www.sciencedaily.com/releases/2010/05/100520141214.htm>)

**More on** **the role of certain gut bacteria in affecting obesity and insulin-resistant diabetes.**

Another idea about a gut bacterium producing some product related to reducing obesity comes from research done at Vanderbilt University. The design of the research is described in a press release published by the American Chemical Society. ([www.acs.org/content/acs/en/pressroom/newsreleases/2015/march/special-microbes-make-anti-obesity-molecule-in-the-gut.html](http://www.acs.org/content/acs/en/pressroom/newsreleases/2015/march/special-microbes-make-anti-obesity-molecule-in-the-gut.html))

Related to the idea of weight or obesity reduction is the discovery of a lipid produced by certain gut bacteria that reduces feeling of hunger. A chemical called N-acyl-phosphatidylethanolamines (NAPEs) is produced in the small intestine after a meal and is quickly converted into N-acyl-ethanolamines (NAEs), potent appetite-suppressing lipids. Researchers have been able to genetically alter certain probiotic bacteria to produce NAPE. Then they have special mice, bred to gain weight on a regular diet, ingest these altered bacteria. Compared with controls, these mice do not gain excess weight (in fact, a weight *reduction* of 15%) while on their normal diet. In addition, these mice do not show the usual development of fatty livers and diabetes.

One study shows that the use of a commercial product (one of many) called VLS#3 which contains viable probiotics both reduces or controls obesity gains as well as reducing the development of insulin-resistance in mice. The manner in which this product works is that it causes an increase in a short chain fatty acid, butanoic acid, which in turn stimulates the production of an appetite-suppressing hormone called GLP-1 that reduces food intake and improves glucose tolerance.

The VLS-#3 product contains eight different bacterial strains which are able to survive in the gut. The mix of bacteria Include:

4 strains of *Lactobacilli:*

*L. acidophilus,*

*L. paracasei,*

*L. delbrueckii subsp. bulgaricus,*

*L. plantarum*) and

3 strains of *Bifidobacteria:* (*B. breve, B. infantis, and B. longum*) and

1 strain of *Streptococcus thermophiles*

Four formulations are available including capsules with 112.5 billion live bacteria, packets with 450 billion live bacteria, double strength packets and junior packets, each with 225 billion bacteria. A commercial description of VLS#3 can be found at <http://www.vsl3.com/discover/about-probiotics/>. And drugs.com provides a fact sheet on VLS#3 here: <http://www.drugs.com/mtm/vsl-3.html>.

**More on preventing intestinal infections with probiotics**

There is increasing evidence that probiotics can benefit the human host by acting as a first line of defense against disease-causing pathogens by improving the intestinal microflora. Biologically effective probiotic bacteria exert their influence by inhibiting the growth of enteric pathogens through the production of lactic acid and antimicrobial peptides, known as bacteriocins.

Lactobacillus acidophilus and bifidobacteria exert antagonistic effects on the growth of pathogens such as *Staphylococcus aureus, Salmonella typhimurium, Yersinia enterocolitica* and *Clostridium perfringens*. Probiotic bacteria enhance resistance against intestinal pathogens via antimicrobial mechanisms. These include competitive colonization and production of organic acids, such as lactic and acetic acids, bacteriocins and other primary metabolites, such as hydrogen peroxide, carbon dioxide and diacetyl. By competitive colonization, probiotic bacteria inhibit the adhesion of gastrointestinal pathogens to the intestinal mucosa. Production of organic acids, such as lactic and acetic acids, by probiotic bacteria lowers intestinal pH and thereby inhibits the growth of pathogens.

(<http://www.nature.com/icb/journal/v78/n1/full/icb200012a.html>)

And probiotics can provide Immune enhancement at the gut level.

The epithelial lining of the gastrointestinal tract offers a vast surface area for the absorption of molecules and presents a barrier to the countless number of extraneous antigens that may pass through the gut. The exclusion or elimination of potential foreign antigens is mediated by the gut immune system, known as the gut-associated lymphoid tissue (GALT). It is well known that a variety of dietary antigens and commercial and pathogenic micro-organisms can cross the gut mucosal barrier and cause disease or stimulate an immune response. … (A researcher) has reported that there is sufficient evidence to suggest that lactic acid bacteria exert their immunity enhancing effects by augmenting both non-specific (e.g. phagocyte function, NK cell activity) and specific (e.g. antibody production, cytokinase production, lymphocyte proliferation, delayed-type hypersensitivity) host immune responses.

(<http://www.nature.com/icb/journal/v78/n1/full/icb200012a.html>)

Another function of probiotics, in terms of the gut mucosal barrier, is to restore the integrity of the intestinal mucosa if it loses its ability to block passage of pathogenic bacteria because of intestinal inflammation. Ingesting probiotic bacteria that then establish themselves (colonize) in the intestine have been shown to effectively treat patients with intestinal disorders including rotavirus diarrhea in children, persons with food allergies, and patients undergoing pelvic radiotherapy. All these health conditions have their etiology in a disturbed intestinal mucosa and altered gut permeability.

**More on fecal transplants**

One infectious condition that can be cured using gut bacteria is *clostridium difficile* infection, CDI. Fecal Microbiota Transplant (FMT) is a procedure in which fecal matter, or stool, is collected from a tested donor, mixed with a saline or other solution, strained, and placed in a patient, by colonoscopy, endoscopy, sigmoidoscopy, or enema. *Clostridium difficile* is a very serious infection, and its incidence is on the rise throughout the world. The CDC reports that approximately 347,000 people in the U.S. alone were diagnosed with this infection in 2012. Of those, at least 14,000 died. Fecal transplant is considered to be an inexpensive and low risk treatment for a clostridium infection. (<http://thefecaltransplantfoundation.org/what-is-fecal-transplant/>)

CDI infections are considered a very serious health situation for the elderly (those over 65). This population segment develops complications with the disease and attended relapses, compared with the under-65 group of patients. These patients often are missing certain gut flora, most likely due to antibiotic usage. It is thought that some kind of signaling takes place between healthy bacteria and the mucosa of the gut, and without that signaling, *C. difficile* can take over. Restoring the missing flora seems to be the key. And that is what happens when fecal transplants are done. It has been shown that patients having undergone a fecal transplant are cured within 24 hours to several days. This research is from respected health organizations such as the Mayo clinic; it is not anecdotal information. (<http://www.mayoclinic.org/medical-professionals/clinical-updates/digestive-diseases/quick-inexpensive-90-percent-cure-rate>)

On the other hand, there is interest in using the fecal transplant procedure for treating a number of other disease conditions such as irritable bowel syndrome (IBS), celiac disease and ulcerative colitis as well as rheumatoid arthritis, obesity, and diabetes. These are some of the same medical conditions that are being investigated for links to specific probiotic control. But the situation is still in the anecdotal stage—sound data is difficult to come by at this point.

**More on using gut bacteria for weight loss**

The previous section described using a transplant of fecal bacteria to change the gut biota (bacterial) to cure a serious infection due to *Clostridium difficile.* The same idea or technique is now being considered to reduce obesity rather than using the surgical procedure called gastric bypass.

A bypass operation separates off a small part of the stomach and connects that directly to the intestines. Recipients tend to feel less hungry, fill up more quickly and burn more calories at rest, and they often lose up to 75% of their excess fat. Counter-intuitively, this is thought to be caused by a change in metabolism, rather than by the reduced size of the stomach. Gut microbes are thought to be part of this picture. People who have had bypasses are known to experience changes in the selection of microbes in their guts. Fat people have been shown to host a different selection of gut bacteria from people who are obese, and transferring the gut bacteria of fat mice into thin ones can cause the thin mice to pack on extra weight. But no one knew whether the microbes in bypass patients changed because they got thin, or if the patients got thin because the microbes changed.

(<http://www.scientificamerican.com/article/gut-microbe-swap-helps-weight-loss/> )

In experiments done at Massachusetts General Hospital, two sets of mice were set up, one having had bypass surgery. The other group was specially bred mice that lacked any gut flora. Fecal bacteria from the bypass mice were introduced into the mice that lacked gut flora. As a result, this recipient group of mice lost 5 % of their body weight. That these mice did not lose as much weight as the surgical group suggests that there are other factors involved in weight loss. The amount of weight loss however is considered significant. Should this technique be refined, it will require methods to keep the special gut flora intact and not be replaced by other, perhaps harmful, gut bacteria. The next step in the research is to isolate the four different types of bacteria that were instrumental in affecting weight change and introduce them into obese mice or people.

**More on** **the relationship between certain gut bacteria and autism**

While the occurrence of autism remains a big mystery as to its etiology, some studies suggest a link between certain bacterial types and their possible influence on the nervous system.

A ... 2013 study from Mazmanian’s lab found that a mouse model with some features of autism had much lower levels of a common gut bacterium called *Bacteroides fragilis* than did normal mice. The animals were also stressed, antisocial and had gastrointestinal symptoms often seen in autism. Feeding *B. fragilis* to the mice reversed the symptoms. The group also found that the mice with these symptoms had higher levels of a bacterial metabolite called 4-ethylphenylsulphate (4EPS) in their blood, and that injecting that chemical into normal mice caused the same behavioral problems.

(<http://www.nature.com/news/gut-brain-link-grabs-neuroscientists-1.16316>)

These same bacteria influence the body’s use of vitamin B-6 which is associated with the normal development of nerve and muscle cells. In autism there are reports that there is an alteration of these bacteria resulting in gastrointestinal problems which, in turn, influence behavior. One test for autism is based on certain end products from bacterial metabolism. (The B vitamins including B-6, folate, and riboflavin are synthesized by lactic acid bacteria and bifidobacteria in the gut.)

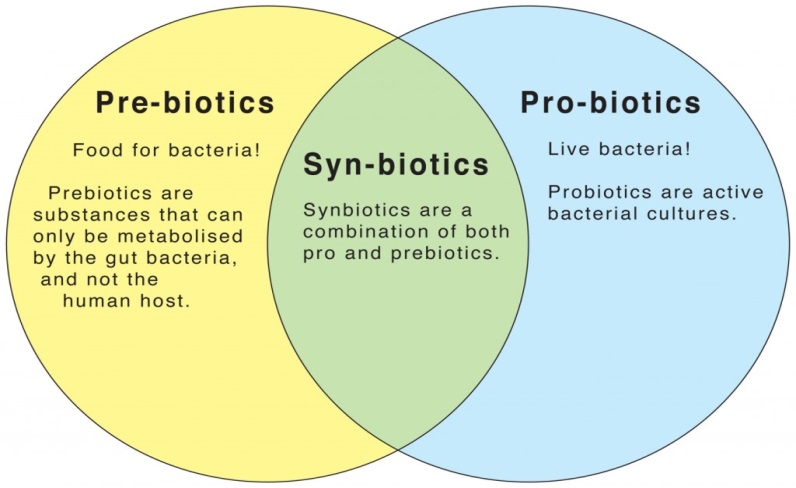
## Connections to Chemistry Concepts (for correlation to course curriculum)

1. **Bond breaking and reforming**—Fermentation and respiration reactions both involve the rearrangement of bonds within molecules.
2. **Chemical Thermodynamics**—The breaking and reforming of chemical bonds in the cellular respiration process could be used to illustrate, with chemical equations (see article for these equations), exothermic reactions in which the energies for bond breaking are less than the energy resulting from bond formation. Students can be asked to calculate the energy changes in these reactions.
3. **Alcohols**—The specific alcohol, ethanol, a product of probiotic activity in the gut and part of fermentation is a great example for alcohols in organic chemistry.
4. **Organic acids**—In the gut, probiotics produce organic acids such as lactic acid due to their metabolic activity to generate energy. Lactic acid is a byproduct, as are butyric, propionic, and acetic acids. These are relatively simple organic acids to illustrate the carboxyl group in organic chemistry.
5. **Carbohydrates**—These organic compounds are formed in plants through photosynthesis and are used by other organisms to produce energy. Carbohydrates are good examples to use in class discussions involving bond breaking and reforming and the accompanying energy changes, and in developing structural formulas in organic chemistry,
6. **Fermentation**—This is an important energy-generating process (exothermic), used by bacteria and fungi. This process could be used in the chemistry curriculum to illustrate energy changes (exothermic, endothermic) in chemical reactions.

## Possible Student Misconceptions (to aid teacher in addressing misconceptions)

1. **“All probiotics are basically the same.”** *Some probiotics have a single strain of organisms, while others contain multiple strains. Different strains of the same species may even be different, and could have different effects on health.*
2. **“Probiotics can be used in place of medications.”** *Although some people may prefer natural treatments, probiotics have typically been studied in conjunction with medications—not as a substitute for them.*
3. **“Most yogurts are generally a good source of probiotics.”** *Just because it is yogurt does not mean it contains probiotics. If probiotics are present in yogurt, the container label will say “live and active cultures”. All yogurts with live bacteria contain Lactobacillus bulgaricus and Streptococcus thermophilus, but some manufacturers add other probiotic bacteria after pasteurization, such as L. acidophilus, L. bulgaricus, L. rhamnosus and L. casei.*
4. **“Taking probiotics might help prevent colds.”** *There is no solid evidence that probiotics either prevent or mitigate the severity or length of time for the illness.*
5. **“Single strain probiotics are as effective as multiple strain probiotics.”** *Because different locations in the gut provide different microenvironments for different probiotic organisms, a single strain approach will not obviously cover all the different loci in the gut for the cultivation and activity of any one probiotic.*
6. **“Diet does not play a part in the effectiveness of a probiotic.”** *In fact, depending on the components of a particular diet, the effectiveness of a probiotic is definitely enhanced by the contents of a meal or snack. For instance, consuming certain amino acids such as lysine and methionine (found in fish and whey protein [e.g., tofu]) provide nutrition for certain probiotics. The same is true for the sugar galactose that supports probiotic metabolism.*
7. **“You need to take probiotics every day like a multivitamin.”** *Various studies suggest that you take the probiotic daily for about two weeks to establish cultures in the gut. After that, taking the probiotics just twice a week seems sufficient to maintain good colonies of probiotic bacteria.*

## Anticipating Student Questions (answers to questions students might ask in class)

1. **“What is the difference between a prebiotic and a probiotic?”** *A prebiotic is non-biological, most often a carbohydrate of the fructo-oligosaccharide category. These are plant sugars as found in cereals, fruit, and vegetables. They are consumed as a fiber which means they can reach the intestine without being degraded (digested) before aiding the probiotics’ growth and activity. A combination of the two is known as synbiotics.*

([*http://sitn.hms.harvard.edu/flash/2015/the-human-microbiome-and-media-confusion/*](http://sitn.hms.harvard.edu/flash/2015/the-human-microbiome-and-media-confusion/))

1. **“Since probiotics are actually bacteria, are they really safe to add to our body?”** *Probiotics are generally safe. But they may cause problems for young children, seniors, and those with a serious illness or a weak immune system. Always check with your doctor.*
2. **“For how long does one have to take probiotics?”** *Depending on what reason you are taking a probiotic source, the time span for the probiotic will vary. The effects of supplements last for just a few weeks after you stop taking them.*
3. **“What other available foods contain probiotics besides those mentioned in the article?”** *Certain juices and cereals have probiotics added to them. Other sources include the Japanese Miso soup, tempeh (Indonesian meat substitute), soy-based foods, pickled cabbage (other than sauerkraut) such as kimchi, curtido, and choucroute, brine pickles and olives.*
4. **“What is the difference between live cultures and probiotics?”** *Live cultures are microbes associated with foods, often as food fermentation agents. Many of these have not been directly tested for health benefits. Probiotics are live microbes that have been shown to have a health effect.*
5. **“Can dead bacteria function as a probiotic?”** *No, by definition probiotics must be alive when ingested.*

## In-Class Activities (lesson ideas, including labs & demonstrations)

1. The fermentation process is an energy-generating process which some bacteria and certain fungi use. Students can study fermentation as a chemical process, evaluating the various components that determine both rate of the process including the specific substrate, its concentration, pH, and the temperature of the reacting medium.
2. There are several different lab procedures for doing this activity, including electronic monitoring of products using software and hardware from companies like Pasco or Vernier, if you have such. The Web site for the lab book for Vernier’s activities can be found here: <http://www.vernier.com/products/books/bio-i/>, while the Pasco lab book is described here: <http://www.pasco.com/prodCatalog/PS/PS-2870_biology-through-inquiry-teacher-guide/index.cfm>.

The Pasco site provides brief descriptions of the activities, while the Vernier site allows you to see evaluation copies of each of the activities.

The Vernier fermentation experiments ask students to research the various parameters of the fermentation reaction, then decide on a particular lab procedure to measure carbon dioxide production or ethanol production over time, plotting the data using Vernier software.

The Pasco activity has students study the process under aerobic and anaerobic conditions and at different temperatures.

Both of these lab books and their lab activities require company-specific software and hardware.

1. A less technical approach to measuring the rate of the fermentation process by measuring volumes of gas production over time is found at <http://www.math.unl.edu/~jump/Center1/Labs/FermentationExercisesforTeachers.pdf>.
2. Instead of using balloons to determine volume of generated gas, a respirometer using a pipette in the fermenting solution can be used. Refer to <https://www.google.com/search?q=Fermentation+lab+exercise&ie=utf-8&oe=utf-8>.
3. A college-level reference on fermentation as a lab activity is found at <http://www.instruction.greenriver.edu/kmarr/biology%20211/Labs%20and%20ALEs/B211%20Labs/B211%20Labs/5%20_Lab%205_Alc%20Ferm%20in%20Yeast_F2009.pdf> . Included in this reference are ideas about yeast metabolism, the experiment design (the variables to be considered), and the chemistry involved, including equations. At the very least, teachers will find this a useful background resource if not used directly by students.
4. Another lab on fermentation which includes using distillation to isolate the alcohol product is found at <http://www.nuffieldfoundation.org/practical-chemistry/fermentation-glucose-using-yeast>.
5. A very informative and practical series of lab activities on fermentation, involving a large variety of foods, is found at the National Centre for Biotechnical Education (UK), at <http://www.ncbe.reading.ac.uk/NCBE/PROTOCOLS/fermentation.html>. There is a student lab manual here as well as a teacher guide that can be downloaded.
6. Another interesting exercise for students is to make yogurt. Again the lab exercise can be used to illustrate the control of variables in the design of the experiment—temperature, types of bacteria cultures if listed on the inoculation source (other yogurts). Does adding sugar make any difference in the yogurt-forming process? Guidelines for making yogurt with suggestions for making the exercise a bit of an investigation are found at <http://www.math.unl.edu/~jump/Center1/Labs/FermentationExercisesforTeachers.pdf> (same reference noted above for fermentation of sugar).

There’s another lab for making yogurt at this college site: <http://biology.clc.uc.edu/fankhauser/Cheese/yogurt_making/YOGURT2000.htm>.

Students might be able to examine the yogurt culture for bacteria before and after the yogurt-making process (see <http://www2.mrclmb.cam.ac.uk/microscopes4schools/yoghurt.php>).

1. Students could also read the labels of different yogurt products for any information about added probiotics, whether pasteurized or not (dead bacteria are not of any value as a probiotic source!), and how effective a given yogurt product is in terms of being the inoculating source for starting a yogurt culture. Students can compare their yogurt-making process to that of commercially prepared yogurt. The details associated with the commercial yogurt-making process are found at <http://milkfacts.info/Milk%20Processing/Yogurt%20Production.htm> and <http://science.howstuffworks.com/innovation/edible-innovations/yogurt1.htm>.

## Out-of-Class Activities and Projects (student research, class projects)

1. For students who would like to combine their interest in biology and chemistry, an involved series of experiments using lactic acid-producing bacteria (LABs) requires the experimenter(s) to collect this category of bacteria from a variety of common sources, then examine the conditions for cultivation of these bacteria. Students will monitor three parameters: growth (as determined by culture turbidity), culture diversity (as determined by microscopy), and pH. For a complete guide to this activity, consult <http://serc.carleton.edu/microbelife/k12/LIMW/lactic_acid.html>. Because of the need for specialized equipment and teacher oversight, this activity is best done in school.
2. Students could research the literature that supports the ideas for the influence of gut microbe metabolites on the nervous system, particularly the brain, and a person’s mood or behavior. A starting read for students is found in an article from the *Atlantic* magazine, titled “When Gut Bacteria Change the Brain”. Refer to <http://www.theatlantic.com/health/archive/2015/06/gut-bacteria-on-the-brain/395918/>.

Here’s a research article that details an experiment done to test the idea that certain gut microbes influence behavior (in mice): <http://www.nature.com/news/gut-brain-link-grabs-neuroscientists-1.16316>. This research report illustrates for students how some of the ideas about microbes come about through scientific investigating.

## References (non-Web-based information sources)



**30 Years of *ChemMatters***

Available Now!

**The references below can be found on the *ChemMatters* 30-year DVD (which includes all articles published during the years 1983 through April 2013 and all available Teacher’s Guides, beginning February 1990). The DVD is available from the American Chemical Society for $42 (or $135 for a site/school license) at this site:** [http://ww.acs.org/chemmatters](http://www.acs.org/chemmatters)**. Click on the “Archive” tab in the middle of the screen just under the *ChemMatters* logo. On this new page click on the “Get 30 Years of ChemMatters on DVD!” tab at the right for more information and to purchase the DVD.**

**Selected articles and the complete set of Teacher’s Guides for all issues from the past three years are available free online at the same Web site, above. Simply access the link and click on the aforementioned “Archive” tab.**

An article from a 1989 issue of *ChemMatters* describes the history of yogurt making (including a modern recipe for making yogurt), as well detailing the important bacteria present in yogurt. This includes the important role of these yogurt bacteria in changing 25–50% of the disaccharide lactose (milk sugar), found in milk products, into glucose and galactose so that lactose-intolerant people will not have as serious a digestive problem eating yogurt compared with other milk products. (Evan, G.D. Yogurt. *ChemMatters,* 1989, *7* (3), pp 9–12.

Another article from this 2013 issue is all about lactose intolerance and its relationship to digestion of milk products in the gut. Tests for lactose intolerance and ways around the problem using foods without lactose or taking a pill containing the missing enzyme, lactase, are described. Refer to Rohrig, B. Not Milk? Living With Lactose Intolerance. *ChemMatters,* 2013, *31* (2), pp 18–19.

## Web Sites for Additional Information (Web-based information sources)

**More sites on** **probiotics**

A useful summary article about probiotics in terms of what probiotics can and cannot do is found at <http://www.livescience.com/46298-the-lowdown-on-probiotics.html>.

A second general article on the balanced view about the potential of probiotics is found at <http://www.theguardian.com/lifeandstyle/2014/nov/30/probiotics-myth-or-miracle-prebiotics>.

A scientific article that elaborates on separating myth from medical evidence about the role of probiotics in human health is found at <https://www.mja.com.au/journal/2008/188/5/probiotics-sorting-evidence-myths>.

A handout for patients to answer their possible questions about probiotics and their use is provided by the University of Wisconsin School of Medicine at <http://www.fammed.wisc.edu/sites/default/files/webfm-uploads/documents/outreach/im/handout_probiotics_patient.pdf>. Among other things is a listing of probiotic-containing products and the specific bacteria that are present. Naturally one needs to know what bacteria are needed, which may not be known to the patient unless suggested by a knowledgeable clinician.

**More sites on** **gut bacteria effects**

A useful site that describes the various types of bacteria and their functions in the human body, other than those of the probiotic type (“5 Ways That Gut Bacteria Affect your Health”), is found at <http://www.livescience.com/39444-gut-bacteria-health.html>.

A generalized article from *The Atlantic* magazine that describes the various studies on the possible effects of gut bacteria on the brain and certain behaviors is found at <http://www.theatlantic.com/health/archive/2015/06/gut-bacteria-on-the-brain/395918/>.

Recent research has suggested that certain vaccines are more effective if specific bacteria are present in the gut. Specifically, a link has been established between the effectiveness of a vaccine used to treat infant diarrhea caused by rotavirus and certain flagellated bacteria of the Proteobacteria group. A description of the problem and potential solution is found at the *Scientific American* Web address, <http://www.scientificamerican.com/article/gut-microbes-may-help-determine-our-immune-response-to-vaccines/>.

A very scientific but informative article on all aspects of probiotics, in particular, their therapeutic potential and survivability, is found at <http://www.nature.com/icb/journal/v78/n1/full/icb200012a.html>.

Another different but interesting approach involving the gut and body bacteria is to use their metabolic end products to diagnose both the healthy as well as the disease state in humans. The body and its intestinal flora produce chemicals with hidden health information according to one investigator, Jeremy Nicholson. Someday, treating disease may mean treating those bacteria associated with different disease states, including neurological conditions. Knowing the chemical byproducts of bacteria would contribute to understanding their metabolism, from which pharmaceuticals could be designed. The story behind Nicholson’s research is found at <http://www.scientificamerican.com/article/jeremy-nicholsons-gut-instincts/?page=2>.

**More sites on informed and critical reporting of scientific research**

In part, the *ChemMatters* article illustrates how scientific research, particularly in the realm of medical issues, can be misrepresented to the public. One day coffee is dangerous (excess causes chromosomal damage), the next day, so to speak, it is found to be a good thing (a source of antioxidants). A cautionary note to explain the issue is provided by a Harvard researcher at <http://sitn.hms.harvard.edu/flash/2015/the-human-microbiome-and-media-confusion/>. One of the concerns is that some of the research (and results reported) is funded by a variety of commercial entities with an investment in positive outcomes for their product’s effectiveness.

A related article expressing caution about what probiotics can and cannot do is found at <http://now.tufts.edu/articles/can-probiotics-keep-gastrointestinal-health>.

A useful Web site that reports on the science behind news reports is found at <http://sitn.hms.harvard.edu/>. This Web site is run by graduate students in the sciences and reports on current science topics that garner both general interest and criticism. Among other topics is the much maligned and misunderstood topic of Genetically Modified Organisms, GMO’s. (<http://sitn.hms.harvard.edu/signal-to-noise-special-edition-gmos-and-our-food/>)

**More sites on probiotics and control of obesity**

For a complete description of the experimental procedure to determine the relationship between probiotics and their influence on controlling the development of obesity and diabetes, refer to <http://www.nutraingredients-usa.com/Research/Probiotics-may-counter-obesity-and-diabetes-NIH-study>. It could be used with students to illustrate both the design of an experiment and how data is generated and what the limits are to “cause and effect” conclusions.

A more recent experimental approach for controlling obesity without involving probiotics focuses on cellular metabolism through the lipid-controlling hormone leptin (the “thin” hormone) and a chemical called celastrol, isolated from a plant called the Thunder God vine. Normally, leptin suppresses food intake. Second, it increases energy expenditure by altering metabolic rate; both effects reduce calorie build-up or storage. The research is clearly described at the Harvard Web site <http://sitn.hms.harvard.edu/flash/2015/the-skinny-on-celastrol-a-potential-future-anti-obesity-drug/>. The content requires careful reading to understand. But it does illustrate what is involved in trying to discover connections in the complicated biological but chemically-dependent systems at the cellular level.

**More sites on the Human Microbiome Project**

The purpose of the Human Microbiome Project is to collect all the microorganisms living in association with the human body. For a complete description of this government project, refer to this Web site at Tufts University: <http://now.tufts.edu/articles/microbiome>.

**More sites on the life and work of Elie Metchnikoff**

Ilya Ilyich (Elie) Metchnikoff, who can be considered the “father” of the probiotics idea back in the beginning of the 20th century, was a pioneer in the field of human physiology, immunology, and medicine, winning the Nobel Prize in Immunology or Medicine in 1908. Teachers, as well as some students, might find Metchnikoff an interesting person to research, learning that there were creative scientists long before the age of computers and sophisticated lab technology! A starter reference is found at <https://embryo.asu.edu/pages/ilya-ilyich-mechnikov-elie-metchnikoff-1845-1916#sthash.EZ3K0di0.dpuf>.

A second biography about Metchnikoff comes from the Nobel Prize Web site. Refer to <http://www.nobelprize.org/nobel_prizes/medicine/laureates/1908/mechnikov-bio.html>.

## General Web References (Web information not solely related to topic)

As mentioned above, there is a Web site that elaborates on a wide range of science topics that are reported in the press, providing critical information that gives both perspective and validation (or not!) of ideas that are being promulgated for public consumption. This is a good reference for teachers to consult when students bring up a variety of questions about such topics as global warming, the “dangers” of GMO’s (genetically modified organisms), cell phones and cancer, and the like. Refer to <http://sitn.hms.harvard.edu/>.

# Dirt? Who Needs It? How Hydroponics Is Poised to Change the World

## Background Information (teacher information)

**More on agricultural** **land and water use**

The development of hydroponic and aquaponic agriculture today is a function of a decreasing supply of arable land and a parallel decrease in water available for irrigation. In the U.S., for example, about twenty per cent of the land is used for growing crops. However, according to the U.S. Environmental Protection Agency:

In spite of a growing population and increased demand for agricultural products, the land area under cultivation in this country has not increased. While advanced farming techniques, including irrigation and genetic manipulation of crops, has permitted an expansion of crop production in some areas of the country, there has been a decrease in other areas. In fact, some 3,000 acres of productive farmland are lost to development each day in this country. There was an 8% decline in the number of acres in farms over the last twenty years. In 1990, there were almost 987 million acres in farms in the U.S., that number was reduced to just under 943 million acres by 2000, and then reduced to 914 million acres in 2012 (\*1).

Development pressure on farmland at the rural-urban interface is posing long-term challenges for production agriculture and for the country as a whole. This is especially significant since about two-thirds of the total value of U.S. agricultural production takes place in, or adjacent to, metropolitan counties (NRCS). About 1/3 of all U.S. farms are actually within metropolitan areas, representing 18% of the total farmland in this country (1992 – 1997 NRCS Report) (\*3).

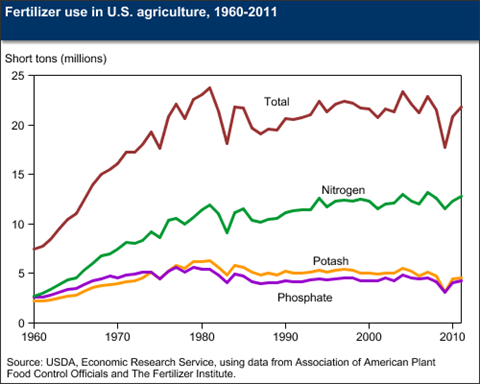
<http://www.epa.gov/agriculture/ag101/landuse.html>

In order to produce ever-increasing amounts of food for the growing population, farmers have had to resort to the use of pesticides and herbicides, artificial fertilizers and genetically-modified crops. The first two have had negative consequences for the environment and GMOs remain controversial. In 2014, the U.S. Department of Agriculture (USDA) reported that:

Pesticides—including herbicides, insecticides, and fungicides—have contributed to substantial increases in crop yields over the past five decades. Properly applied, pesticides contribute to higher yields and improved product quality by controlling weeds, insects, nematodes, and plant pathogens. In addition, herbicides reduce the amount of labor, machinery, and fuel used for mechanical weed control. However, because pesticides may possess toxic properties, their use often prompts concern about human health and environmental consequences. The examination of pesticide use trends is critical for informed pesticide policy debate and science-based decisions.

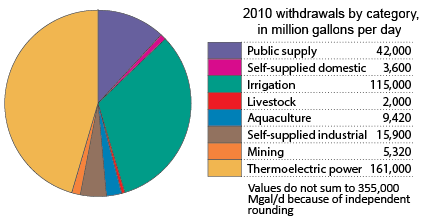
(<http://www.ers.usda.gov/media/1424195/eib124_summary.pdf>)

Similar USDA reports indicate that fertilizer use began its steady increase in the 1960s, and reached nearly 25 million tons by 1980. The graph below shows overall usage in addition to tracking potash (potassium), nitrogen and phosphate consumption individually.

**

*(*[*http://www.ers.usda.gov/topics/farm-practices-management/chemical-inputs/fertilizer-use-markets.aspx*](http://www.ers.usda.gov/topics/farm-practices-management/chemical-inputs/fertilizer-use-markets.aspx)*)*

These kinds of data lead us to search for a method of farming that is not dependent on land use. Similarly, water use for farm irrigation is another important factor in the increase in hydroponics. Agriculture is a major user of ground and surface water in the United States, accounting for approximately 80 percent of the nation's water use and over 90 percent in many western states. The chart below shows the major uses of water in the United States with water for irrigation second only to its use in electric power plants.



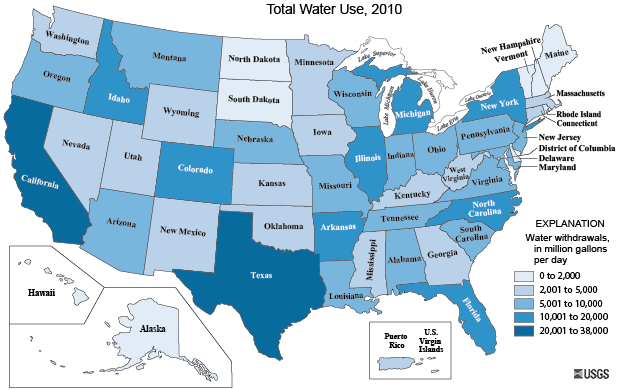
*(*[*http://water.usgs.gov/watuse/wuto.html*](http://water.usgs.gov/watuse/wuto.html)*)*

According to the United States Geologic Survey:

For 2010, total irrigation withdrawals were 115,000 Mgal/d, which accounted for 38 percent of total freshwater withdrawals. Withdrawals from surface-water sources were 65,900 Mgal/d, which accounted for 57 percent of the total irrigation withdrawals. Groundwater withdrawals for 2010 were 49,500 Mgal/d.

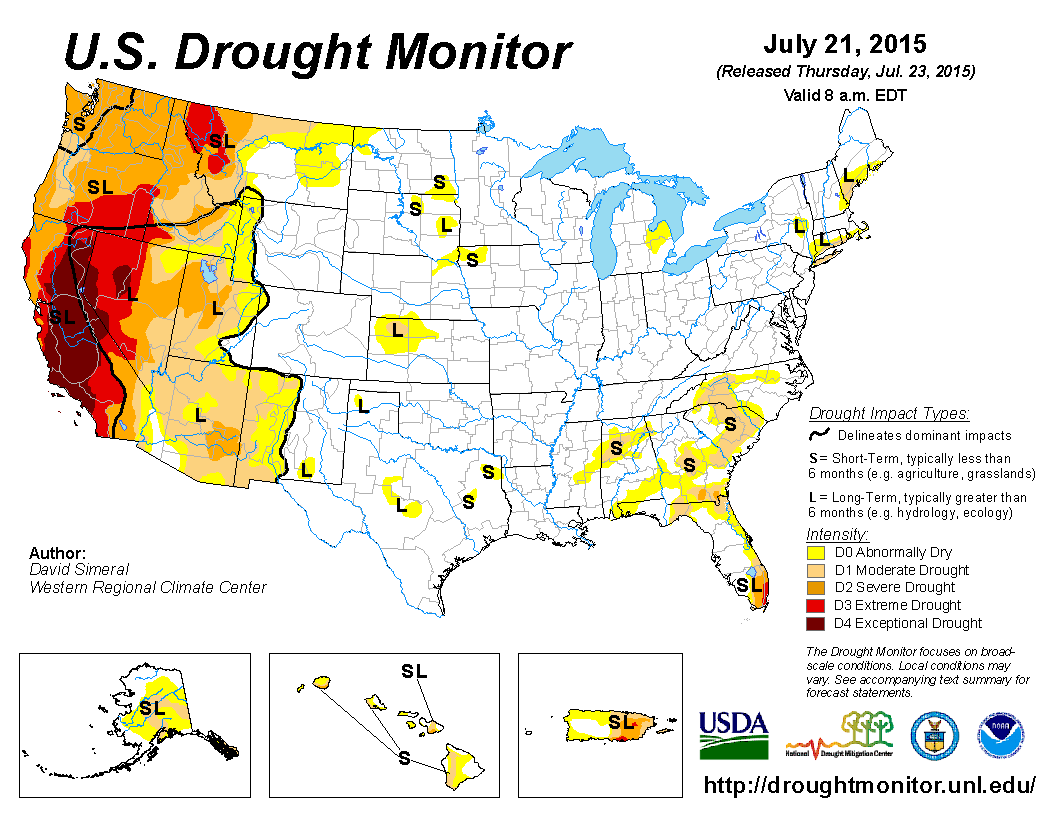
About 62,400 thousand acres were irrigated in 2010, 31,600 thousand acres (51 percent) with sprinkler systems, 26,200 thousand acres with surface (flood), and 4,610 thousand acres with micro-irrigation systems. The national average application rate for 2010 was 2.07 acre-feet per acre.

The map below shows the pattern of water use in the United States, by state. Note the highest use is in California which is currently experiencing a four-year drought.



*(*[*http://water.usgs.gov/watuse/wuto.html*](http://water.usgs.gov/watuse/wuto.html)*)*

This map shows the current drought conditions in the United States. Western states, many of which are agricultural states, are most severely affected.



*(*[*http://droughtmonitor.unl.edu/*](http://droughtmonitor.unl.edu/)*)*

In summary, then, as the number of acres of agricultural land decreases and drought conditions are observed in more and more parts of the world, hydroponic growing becomes an attractive alternative to traditional agriculture.

**More on** **how plants grow**

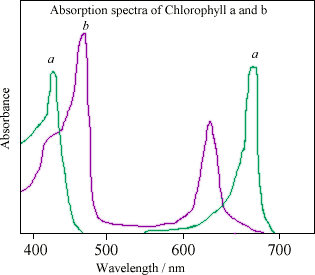
The article indicates that soil is not necessary for plant growth. What, then, do plants need and how do they grow? If students understand the growth process for plants, then they will be able to better understand hydroponic farming.

Plants need air, light, warmth, water and nutrients to be healthy along with certain inorganic nutrients. These are generally classified as macronutrients and micronutrients.

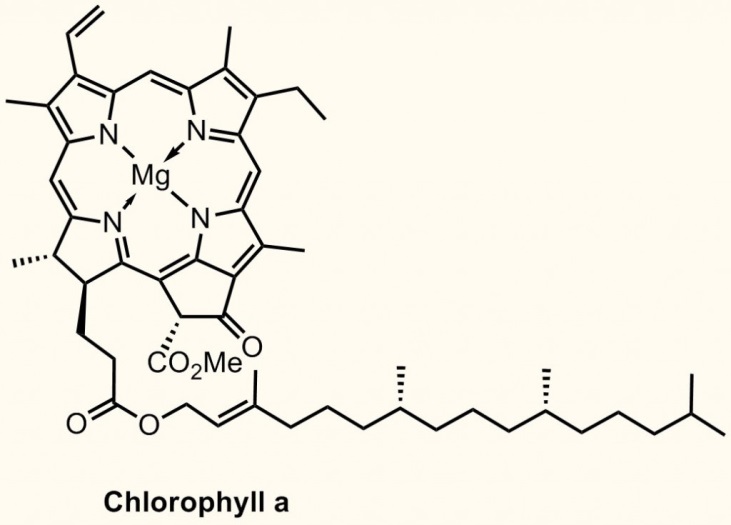
Green plants grow by means of three processes—photosynthesis, respiration and transpiration. Photosynthesis accumulates the sun’s energy in the bonds of molecules like sugars and starches, and respiration uses that energy in order for plants to function. The basic chemistry of both processes should be well known to your students, but to review, the basic photosynthesis equation is:

6 CO2 + 6 H2O + energy 🡪 C6H12O6 + 6O2

The chemical requirements for photosynthesis, then, are carbon dioxide and water along with energy in the form of light. Theprocess takes place in the chloroplasts of plants. The chemical involved is chlorophyll, the pigment that makes plants green. The molecule takes several forms but the predominant form is chlorophyll a, which absorbs light primarily in the red-orange range and the blue range of visible light (chlorophyll a reflects light in the green range, thus accounting for the green color of plants). The complementary form is chlorophyll b, which absorbs light that chlorophyll a cannot. The diagram at right shows the absorption pattern for each form. The photons of light excite electrons in the molecule that trigger a complex process that results in sugars and oxygen.



*(*[*http://www.webexhibits.org/causesofcolor/7A.html*](http://www.webexhibits.org/causesofcolor/7A.html)*)*



The structure of the chlorophyll a molecule appears at the left. The large ring-like structure, left side of the diagram, is a chelate with magnesium at the center of a four nitrogen atoms arranged in a square-planar structure. This entire large ring structure is referred to as a porphyrin. The long hydrocarbon side chain is connected to the ring component by an ester bond, at lower left in the diagram.

*(*[*http://brsmblog.com/woodward-wednesday-3-chlorophyll-a/*](http://brsmblog.com/woodward-wednesday-3-chlorophyll-a/)*)*

The second process involved in plant growth is respiration. In this process the glucose produced by photosynthesis is oxidized to produce carbon dioxide, water and energy. The equation should look familiar:

C6H12O6 + 6O2 🡪 6 CO2 + 6 H2O + energy

This is the reverse of the photosynthesis equation. Oxygen is taken into the plant via the stomata and the roots. Carbon dioxide is expelled via the stomata and water not needed by the plant is eliminated via transpiration, the third process in overall plant growth. In plants the rate of photosynthesis is greater than the rate of respiration resulting in a net gain in plant biomass. Respiration occurs in all plant cells, not just in chloroplasts.

Transpiration is the process by which plants lose water. About 90% of the water that enters a plant is lost by transpiration. Only 10% is used in chemical reactions and in the transport of minerals through the plant tissue.

So, we find that the chemical requirements for plant growth are oxygen, carbon dioxide, water and mineral nutrients. Is soil necessary for plant growth? In conventional agriculture, soil supplies a set of mineral nutrients, as described in the article. The three main mineral nutrients, known as primary nutrients are potassium (K), nitrogen (N) and phosphorus (P). Plants use these three in large quantities (macronutrients), which is why these mineral elements are principal components of fertilizer.

These and all other mineral nutrients must be present in the soil in water-soluble form in order to be of use to plants. So the mineral nutrients in the soil are ions present in water-soluble compounds. Phosphorus is usually found in soil in the form of the phosphates H2PO4 – and HPO4–2.

The phosphorus originally comes from the weathering of the parent material, which releases phosphate ions into the soil solution. This phosphate is adsorbed onto soil constituents, forming "reservoirs" of various types and capacities, some of which release phosphate ions into the soil solution easily, while others strongly bind phosphate. Nitrogen is fixed by certain bacteria into either nitrates, NO3– or ammonium ion, NH4+. And potassium is often found in the soil in the form of feldspar, KAlSi3O8, or biotite, K(Mg,Fe)3(AlSi3O10)(F,OH)2. Other secondary mineral nutrients like calcium, magnesium and sulfur are also available to plants as soluble ions. Likewise, the micronutrients boron, copper, iron, chlorine, manganese molybdenum and zinc are all present as ions. The soil in traditional farming acts as a medium or carrier for these mineral nutrients.

To summarize this section, we see that of the plant growth requirements described above, only soil is expendable. Air and water can be supplied easily. The wavelengths of light needed for growth can be produced artificially. And as long as mineral nutrients are supplied as part of an aqueous solution, soil is not necessary. Plants that are grown under these conditions are grown hydroponically. Hydroponics is the topic for the next section.

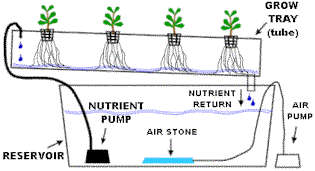
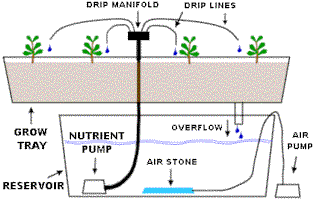
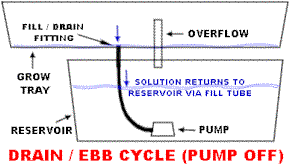
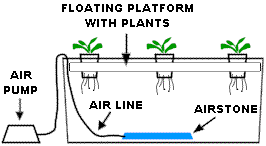
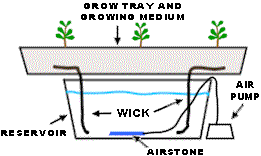
**More on hydroponics**

Hydroponic growing emerged as a result of increased greenhouse agriculture. The earliest forms of greenhouse growing appeared in the 1600s but it was not until post World War II and the advent of inexpensive plastics that greenhouse farming became popular. Hydroponics developed within this environment of growing crops under controlled conditions, but it was limited by the initial higher costs of constructing concrete growing beds. When polyethylene became the material of choice for growing beds in the late 1940s, hydroponics experienced growth in popularity. However, the oil shortages in the 1970s made hydroponics more expensive and less popular, but by the 1990s it regained its place as an alternative to traditional agriculture.

Hydroponics is a system of growing crops that delivers water and nutrients to plants that are supported by a growing medium along with an aeration system and lighting system. The required nutrients are dissolved in water to form a solution. Plants may be in direct contact with the nutrient solution or the solution may be delivered to the plant roots by some pumping mechanism. The water that dissolves the nutrient compounds may be reused or not. Often an aeration system is built into the system to supply oxygen to the roots. And if the system is totally indoors, artificial lighting is included along with a means of pollination.

There is a wide variety of hydroponic growing systems. Each one meets the requirements listed above but in a slightly different way. What follows is a brief description of each, along with a diagram. The source of the diagrams in this section is <http://www.simplyhydro.com/whatis.htm>.

**Water culture—**In this system, a platform made of a low-density material (like Styrofoam) floats directly on the nutrient solution. An air pump at the bottom of the solution supplies the needed oxygen to the plant roots. If you are just beginning to create hydroponic systems with your students, this is a good system for starters. You can see a video that shows how to build a large water culture system at <https://www.youtube.com/watch?v=bzgDI8Hk0Kg>.

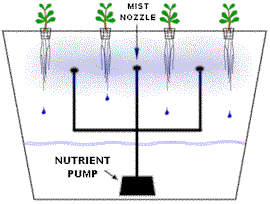


**Wick system—**This is a passive system of nutrient delivery. Nutrients are delivered to the plants by a wicking system. The nutrient solution rises up a wick by means of capillary action and, therefore, nutrients are supplied slowly to the plants. A variety of growing media may be used—among them Perlite, Vermiculite or Pro-Mix. This system works best for smaller plants, since larger plants may absorb nutrients faster than the wick can supply the nutrient solution.

**Ebb and Flow system—**This is a versatile system in which the nutrient solution is pumped into the grow tray (where the plant roots are) to a significant depth. An overflow pipe (see diagram) then allows the solution to return to the reservoir below. The pump cycles on and off several times a day depending on the crops being grown.

**Drip system—**A pump submerged in the nutrient solution sends the solution to a network of small drip lines located near each plant. Small volumes of solution are dripped onto the plant roots and in most cases the excess solution is returned to the reservoir for re-use. In fewer cases the nutrient solution is used only once.

**Nutrient Film Technique (NFT)—**In this simple system even though plants are supported in a grow tray of some kind, there is no support medium for plant roots, only air. Plant roots extend downward into a constantly flowing film of nutrient solution pumped into the grow tray. The solution is returned by gravity.



**Aeroponic system—**Like NFT above, this system suspends plant roots in air and supplies nutrients to the plant roots by means of a misting spray which pumps the solution into the misting system.

There are both advantages and disadvantages to all types of hydroponic systems. Below is a list of general advantages and disadvantages.

Some of the advantages of hydroponics include:

* Elimination of soil also eliminates soil-borne disease.
* Less water is used because it is used more efficiently.
* More plants can be grown in smaller areas.
* Plants grow more rapidly because they are fed efficiently.
* Hydroponic systems can be set up anywhere.
* These do not require use of pesticides or fertilizers.
* Nutrients can be recycled, thus preventing run-off into the environment.

Disadvantages include:

* Many hydroponic systems are energy-intensive and, therefore, expensive.
* Initial costs can be high.
* Technical knowledge is required to monitor systems.
* They are susceptible to power outages.

You will note as you read about the individual hydroponic setups that there are several general ideas underlying them, ideas that you can emphasize to your chemistry students as they read about the various hydroponic systems. The main ideas here are 1) hydroponics requires no soil; 2) mineral nutrients are supplied by a carefully prepared solution of compounds containing the required nutrient; 3) the pH of this solution is important because it affects the availability of nutrients; and 4) in indoor hydroponic systems, artificial lighting is required.

The major difference between hydroponics and conventional agriculture is the absence of natural soil in the growing process. As described above, in conventional agriculture, plants are grown in soil. But as we have also described above, soil serves only as a support medium for plants. In some hydroponic system, however, soil-like media—Perlite or vermiculite, for example—are used. All hydroponic systems have some method of supporting the plants as they grow but there is no soil involved. That is the basic premise of hydroponics—soilless growing.

The second idea that can be emphasized in hydroponics is the use of a nutrient solution to feed plant growth. Detailed knowledge of plant growth chemistry is applied here so that the plants being grown receive the exact amount of nutrient elements at the correct time and under the right conditions for efficient growth. Compounds are dissolved in water in exact concentrations so that nutrients are taken up in plants efficiently. The nutrient solution may be delivered to the plant roots in one of several ways, described above, but in all cases this solution is a key factor in successful hydroponic growing. The solution may be thought of as a replacement for soil or at the same time a replacement for chemical fertilizers, but it delivers nutrients in a more efficient way than any soil-fertilizer combination can do. And, in most of the delivery systems, the nutrient solution is recycled through the system as long as concentration ranges are maintained.

The nutrient solution is critical to hydroponic farming. Optimal and adequate concentrations of dissolved ions are very important. In typical nutrient solutions, these are the ions present along with their concentrations:

**Ion absorbed Common Concentration**

**Element by plant (ppm = mg/L)**

Nitrogen NO3– 100–250

NH4+

Phosphorus H2PO4–

HPO4–2 30–50

PO4–3

Potassium K+ 100–300

Calcium Ca+2 80–140

Magnesium Mg+2  50–70

Sulfur SO4–2 50–120

Iron Fe+2

Fe+3 1.0–3.0

Copper Cu+2 0.08–0.2

Manganese Mn+2 0.5–1.0

Zinc Zn+2 0.3–0.6

Molybdenum MoO4–2 0.04–0.08

Boron BO3–2

B4O7–2 0.2–0.5

Chlorine Cl– < 75

Sodium Na+ < 50

Of course, different plants require different amounts of nutrients, and so the concentration of the solutions used needs to be altered. For example, compare the nutrient needs for tomatoes and cucumbers:

**Crop Concentration (ppm)**

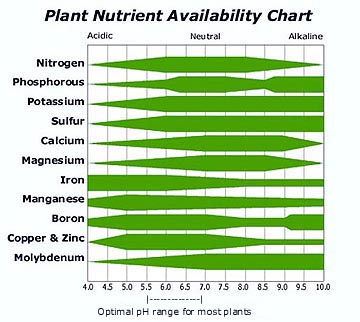
Nitrogen Phosphorus Potassium Calcium Magnesium

Tomato 190 40 310 150 45

Cucumber 200 40 280 140 40

This topic is an opportunity to discuss units with your students. Because the concentration of most hydroponic nutrient solutions is very low, the unit, ppm, or parts per million, is used. Parts per million is equivalent to milligrams of dissolved solute per liter of water. Units like parts per million (ppm) and parts per billion (ppb) are often used in environmental settings or when concentrations are very low. Mole-based units like molarity (M) will be more familiar to your students.

In most hydroponic systems the concentration of dissolved solids is determined electrically by measuring conductivity. The electrical conductivity (EC) of the nutrient solution reflects the total amount of dissolved solids (TDS) in solution and not the concentration of any specific nutrient. EC also includes any impurities in the source water. Frequent waster testing in hydroponics is very important.

A third idea to be emphasized for a chemistry class is the pH of the nutrient solution. The optimal pH range for hydroponic nutrient solutions varies with the nutrient array. The reason that pH is so important here is that it affects the availability of nutrients to be absorbed by plant roots. Many of the ions involved in nutrient solutions are part of a complex set of equilibria, both within the solution and between the solution and the environment. For example, iron uptake in plants occurs best at a pH of 7.3, but if the pH of the solution were to climb to 8.0 the ion precipitates out of solution, most likely as Fe(OH)2. With the Fe now in a solid, Fe ions are not available to be absorbed by plants roots.

The chart at right illustrates pH ranges in which respective nutrients are more or less available. The wider the green band in the diagram, the more available that nutrient is at the corresponding pH.

*(*[*http://www.smart-fertilizer.com/articles/hydroponic-nutrient-solutions*](http://www.smart-fertilizer.com/articles/hydroponic-nutrient-solutions)*)*

Since different plants require different nutrient levels, the best pH levels for plants also differ. The chart below provides a sample of some recommended pH values:

**Plant Recommended pH**

Asparagus 6.0–8.0

Broccoli 6.0–6.5

Cabbage 6.4–7.5

Celery 6.0–7.0

Lettuce 6.0–6.5

Peas 6.0–6.8

Peppers 5.5–7.0

Radishes 6.0–7.0

And the final idea to be emphasized is lighting. If the system is located indoors, artificial lighting may be required. Plants in the vegetative growth stage need 15–18 hours of light and 10–12 hours in the bloom stage. The choice of lighting method for indoor plants is important for two reasons—intensity and correct color range for photosynthesis and respiration. Lighting systems that seem to be recommended are called high intensity discharge (HID) lights, which produce light by arcing electricity between two electrodes, creating an intensely bright light. Mercury, sodium, or metal halide gas acts as the conductor. These are the lights you often see in parking lots and indoor sports arenas. There are two types of HID lights. Metal halide lights produce lighting in the blue region of the spectrum, which is essential for photosynthesis. High-pressure sodium lamps emit light in the orange range which supports fruiting and flowering. The light intensity of common lighting methods are compared below:

**Type Intensity (lumens/watt)**

100 watt light bulb 17.5

40 watt fluorescent tube 22

1000 watt metal halide 125

1000 watt high-pressure sodium 140

**More on setting up a hydroponic system in your class**

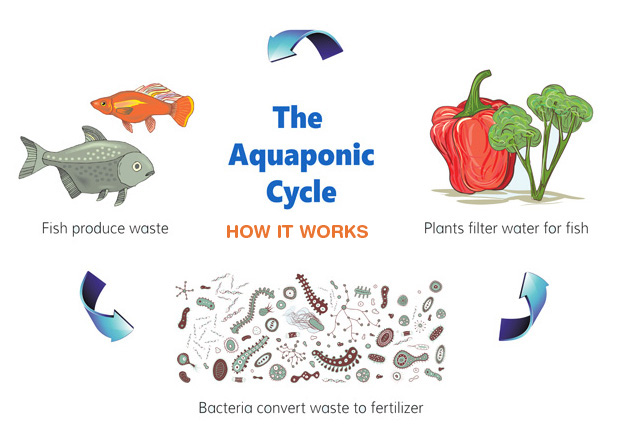
The article does not describe how to set up your own classroom hydroponic system, but there are a great many resources to give you guidance. Following is a brief overview of the elements you will need to create a hydroponic growing system for use with students in your classroom. Refer to “More on hydroponics” section above.

You will need a growing chamber or tray in which the plant roots will grow and where the roots are exposed to the nutrient solution. This may be made of a variety of materials from PVC pipe to a wall-paper tray to a Styrofoam container to a 2-liter soda bottle. It is important, however, that the tray is designed so that light does not get to the plants roots in order to prevent possible mold and algae growth, which would damage the roots. In addition, you will need a reservoir for the nutrient solution and a method to transport the solution to the growing tray. This may be done using a wick system, tubing, a pump, or the roots may extend down into the solution. A second pump, an air pump, will be needed in most cases in order to aerate the system and provide oxygen to the roots. You will also need a light source for growing and a timer to control the amount of light your plants receive. If possible, use natural lighting.

In addition, here is a link to a short summary of how to begin hydroponics in a classroom <http://www.saps.org.uk/attachments/article/83/hydroponics_in_the_classroom.pdf>. You can also refer to “More sites on setting up a hydroponic system,” below.

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Another related alternative growing system is aquaponics. It combines aquaculture (growing fish) with hydroponics. In an aquaponics system, both fish and plants are grown in a symbiotic relationship. In a typical aquaculture system fish are raised in a closed system with the water re-circulated. In this kind of system filters are needed to remove the fish waste products and other toxic substances. However, in an aquaponics system the waste is treated by beneficial bacteria (and/or worms) that convert the waste, primarily compounds of ammonia, into substances that serve as plant nutrients. When plant roots absorb the nutrients, the water in the system is purified and can be recycled. The figure below shows a diagram of a typical aquaponics system.

*(*[*http://www.evofarm.com/aquaponics/*](http://www.evofarm.com/aquaponics/)*)*

Both hydroponics and aquaponics are soil-less methods of growing crops. In an environment where both available land and water are under stress, these methods are becoming increasingly popular.

## Connections to Chemistry Concepts (for correlation to course curriculum)

1. **Biochemistry—**Since this article is about plant growth, this provides an opportunity to discuss with students the role of chemistry in living systems.
2. **Photosynthesis**—This topic is usually studied in biology class, so students may already know about the process, but it is an important chemical reaction essential to plant growth—and life on earth.
3. **Respiration**—Like photosynthesis, respiration is fundamental to plant growth. The chemical reaction involved in respiration is another important chemical reaction.
4. **Solutions**—The unique feature of hydroponics is the use of a nutrient solution to feed plants. The nutrient solution is an easy way for you to illustrate to students an application of solution properties and concentration.
5. **Acid-Base and pH**—One of the most important conditions affecting the efficiency of the nutrient solution is its pH. The article provides an opportunity to show how pH is important in the context of nutrient uptake in plants.
6. **Precipitates and solubility**—The low solubility of iron hydroxides that prevents their being available for plant uptake in solution is an application of solubility and the nature of solid precipitates vs. ions in solution.
7. **Concentration—**One of the skills needed to practice hydroponics successfully is calculating the concentration of solutions. You can apply this idea to your study of molarity and other methods of expressing concentration.
8. **Electromagnetic spectrum**—Plants require light of specific frequencies in order to grow. This article is a chance to preview or review the electromagnetic spectrum and the frequencies of light essential for plant growth.

## Possible Student Misconceptions (to aid teacher in addressing misconceptions)

1. **“Plants need soil to grow.”** *This is a common misconception since we are so used to plants growing in soil. But soil is not necessary in order to grow plants. Soil is simply the support for plants and source for plant nutrients. As the article describes, plants can be supported in other ways and the required nutrient delivered by a solution of dissolved nutrients so that soil is not needed.*

## Anticipating Student Questions (answers to questions students might ask in class)

1. **“Can any plant be grown hydroponically?”** *Yes, it is possible to grow any type of plant hydroponically. However, some plants like pumpkins or watermelons, for example, might present problems in supporting the weight of the crops.*
2. **“The article says that among the nutrients dissolved in the hydroponic solution are elements like nitrogen, phosphorus, potassium and calcium. Nitrogen is a gas and both potassium and calcium react with water. How can they be in solution?”** *The way the article represents these elements is simply by naming them. However, these elements are present in solution as ions that are part of soluble compounds. So, for example, the nitrogen is present as the nitrate ion (NO3–). The compound that is dissolved is likely potassium nitrate. In solution, the ions dissociate and both the potassium and the nitrate are absorbed by plants.*

## In-Class Activities (lesson ideas, including labs & demonstrations)

1. Students can construct their own passive hydroponic system using directions like those found here: <http://tlc.peoriaud.k12.az.us/Enviromental%20and%20Agriculural/Hydroponics/extensions.htm>.
2. Working with hydroponic systems will likely bring up any number of questions that can be answered by students designing an experiment to find the answer. Some example questions include:

* How do plants grown in a soil-based (geoponic) system differ from those grown in a hydroponic system?
* What might happen if we leave out a specific plant nutrient, or put in too much of another?
* Can we use houseplant fertilizers for hydroponic growing?
* How does the growth of plants grown with different amounts of aeration compare?
* Can we simulate a pond or other wetland environment using what we know about hydroponics?

1. A hydroponics activity for high school students can be found here: <http://www.kidscom.com/pdf_files/HS_Sci_Hydroponics.pdf>.
2. A 10-lesson hydroponics unit from the Cornell University Extension Service can be found here. Lesson topics include building a hydroponics unit, plant growth, nutrient solution, data collection, etc. (<https://ecommons.cornell.edu/bitstream/handle/1813/9506/Grow%20with%20the%20Flow.pdf;jsessionid=626A4C806A9FE1E1D9F9BF421C16EA1C?sequence=2>)
3. Here is a hydroponics setup and activity from NASA: <http://quest.nasa.gov/smore/teachers/act3.html>.
4. There are dozens of research and classroom project ideas on this site that are related to the science of hydroponics: <http://americanhydroponics.com/images/stories/comm/pdfs/Classroom_education1.pdf>. The site is produced by American Hydroponics, a commercial company. Many of these activities can also be done outside of class.

## Out-of-Class Activities and Projects (student research, class projects)

1. There are dozens of research and classroom project ideas on this site that are related to the science of hydroponics: <http://americanhydroponics.com/images/stories/comm/pdfs/Classroom_education1.pdf>. The site is produced by American Hydroponics, a commercial company. Many of these activities can be done outside of class.
2. Students can be assigned to research the history of hydroponics.
3. Students can be assigned to research William Gericke, mentioned in the article as a key scientist in the history of hydroponics.
4. Interested students can be encouraged to set up a simple hydroponics system at home, grow a specific plant and bring the results into class to share with other students.

## References (non-Web-based information sources)



**30 Years of *ChemMatters***

Available Now!

**The references below can be found on the *ChemMatters* 30-year DVD (which includes all articles published during the years 1983 through April 2013 and all available Teacher’s Guides, beginning February 1990). The DVD is available from the American Chemical Society for $42 (or $135 for a site/school license) at this site:** [http://ww.acs.org/chemmatters](http://www.acs.org/chemmatters)**. Click on the “Archive” tab in the middle of the screen just under the *ChemMatters* logo. On this new page click on the “Get 30 Years of ChemMatters on DVD!” tab at the right for more information and to purchase the DVD.**

**Selected articles and the complete set of Teacher’s Guides for all issues from the past three years are available free online at the same Web site, above. Simply access the link and click on the aforementioned “Archive” tab.**

Fruen, L. Soil Chemistry—Sifting Through the Past. *ChemMatters*, 2001, *19* (2), pp 6–7. The emphasis in this article is on analyzing ancient soils but includes information about the chemicals in most soils.

Michalovic, M. Ancient Soil Chemists of the Amazon. *ChemMatters*, 2009, *27* (1), pp 7–9. This article contains information about soil used for growing plants and the nutrients required.

Nolte, B. Nitrogen from Fertilizers: Too Much of a Good Thing. *ChemMatters*, 2010, *28* (2), pp 5–7. Although this article is about nitrogen, one of the macronutrients for plant growth, it contains information relevant to the hydroponics article.

## Web Sites for Additional Information (Web-based information sources)

**More sites on** **plant growth**

Colorado State University has a simple but complete review of the processes involved in plant growth. (<http://www.ext.colostate.edu/mg/gardennotes/141.html#photosynthesis>)

This site from the Royal Society of Chemistry provides a more detailed explanation of the biochemical reactions involved in plant growth: <http://www.rsc.org/Education/teachers/Resources/cfb/photosynthesis.htm>.

**More sites on** **mineral nutrients**

Three of the ten lessons on this site produced by Hydroponics Online are related to nutrients required for plant growth. See lessons # 4, #5 and #7. **(**<http://www.hydroponicsonline.com/lessons/table-of-contents.htm>)

The role of nutrients and plant growth is explained in detail on this site by a commercial supplier of nutrients, Manic Botanix. (<http://www.manicbotanix.com/sitemap/38-hydroponic-nutrient-fundamentals.html>)

Texas A & M Agricultural Extension Service provides nice data on nutrient solutions at this site: <http://aggie-horticulture.tamu.edu/greenhouse/hydroponics/solutions.html>.

Cornell University produces this set of “recipes” for nutrient solutions for various plants: <http://www.greenhouse.cornell.edu/crops/factsheets/hydroponic-recipes.pdf>.

**More sites on** **hydroponics**

For a PowerPoint overview on hydroponics see this site from the University of Florida: <http://www.conference.ifas.ufl.edu/aitc/presentations/Session%204/Hydroponics%20in%20the%20Classroom/Hydroponics%20in%20the%20Classroom%20PowerPoint%20Presentation.pdf>.

This Growth Technology site provides information on the types of hydroponic systems in use: <http://www.growthtechnology.com/growtorial/what-is-hydroponic-growing/>.

From the University of Arizona School of Agriculture comes this extensive, and somewhat technical overview of hydroponics: <http://ag.arizona.edu/ceac/sites/ag.arizona.edu.ceac/files/Merle%20overview.pdf>.

The University of Oklahoma Cooperative Extension Service publishes this short summary of hydroponics that includes an interesting flow chart comparing soil-grown plants with those grown hydroponically: <http://osufacts.okstate.edu/docushare/dsweb/Get/Document-6839/HLA-6442web.pdf>.

The University of Arizona summarizes the advantages and disadvantages of hydroponics, along with plant requirements and types of hydroponic systems at this site: <http://ag.arizona.edu/ceac/sites/ag.arizona.edu.ceac/files/pls217nbCH5_1.pdf>.

How Stuff Works gives eight Web pages of information on hydroponics in a non-scientific style. (<http://home.howstuffworks.com/lawn-garden/professional-landscaping/alternative-methods/hydroponics.htm>)

There are links to multiple sources on hydroponics on this site from the U.S. Department of Agriculture National Agricultural Library: <https://afsic.nal.usda.gov/aquaculture-and-soilless-farming/hydroponics>.

Aquaponics is the topic on this site from a trade group called Agricultural Marketing Resource Center. It looks at set-ups, methods, and advantages, with photos. (<http://www.agmrc.org/commodities__products/aquaponics/>)

**More sites on how to build a hydroponic system**

The University of Florida produced this video on how to construct a simple floating hydroponic system: <https://www.youtube.com/watch?v=bzgDI8Hk0Kg>.

A commercial company, Home Hydro Systems, publishes this guide to setting up a home hydroponics system. Note the link to design plans at the bottom of the page. (<http://www.homehydrosystems.com/hydroponic-systems/systems.html>)

This page on the How Stuff Works site explains what you need to set up a hydroponic system: <http://home.howstuffworks.com/lawn-garden/professional-landscaping/alternative-methods/hydroponics4.htm>.

This 29-minute YouTube video clip shows how to start your own aeroponic growing system using mostly household materials: <https://www.youtube.com/watch?v=8eMt3kCUYnw&feature=player_embedded>.

**More sites on setting up a classroom hydroponic system**

Kids Gardening provides several simple hydroponic setups for classroom use. (<http://www.kidsgardening.org/node/3799>)

The University of Florida provides setup instructions and accompanying activities at this site: <http://www.conference.ifas.ufl.edu/aitc/presentations/Session%202/Hooked%20on%20Hydroponics%20in%20the%20Classroom/Chybion%20(all%20files%20combined)handout.pdf>.

Heliospectra, a commercial company selling grow lights, describes how to set up a hydroponic system and get started. (<http://www.heliospectra.com/blog/led-grow-lights-classroom-cultivating-hand%E2%80%99s-learning>)

Another commercial company, Home Hydro Systems, has links for several setups on this page: <http://www.homehydrosystems.com/system_plans/free_plans.html>.

A search on Pinterest reveals plans for hydroponic systems: <https://www.pinterest.com/pin/287174913715653750/>.

Here is a YouTube video clip (8:24) on setting up an ebb and flow/flood and rain system, which you could adapt for classroom use: <https://www.youtube.com/watch?v=8WfRmFp6vk8>.

The ideas in this 9:18 YouTube video clip on hydroponics for beginners can be adapted for your classroom: <https://www.youtube.com/watch?v=Ah3zrGRmx80>.

# Light in the Cellar of the Sea

## Background Information (teacher information)

**More on** **Bioluminescence**

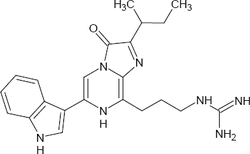
Bioluminescence is a type of chemiluminescence, which is light produced by a chemical reaction. In Bioluminescence the chemical reaction occurs in a living organism. Chemiluminescence and bioluminescence is considered “cold light” because less than 20% of the light produces heat. This makes it very efficient since energy is not lost as heat. Bioluminescence is found both on land as well as in the sea, however it is far more common in the ocean. It is the result of the chemical reaction between luciferin and luciferase, as reported by National Geographic:

The chemical reaction that results in bioluminescence requires two unique chemicals: luciferin and either luciferase or photoprotein. Luciferin is the compound that actually produces light. In a chemical reaction, luciferin is called the substrate. The bioluminescent color (yellow in fireflies, greenish in lanternfish) is a result of the arrangement of luciferin molecules.

(<http://education.nationalgeographic.com/education/encyclopedia/bioluminescence/?ar_a=1>)

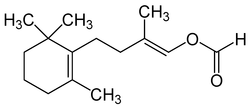
Although the general method of the bioluminescent reaction is similar, there are more than a dozen different mechanisms used by different organisms. This leads scientists to believe that bioluminescence may have evolved separately among different organisms.

It should be noted that luciferin in not one substance or even a class of compounds. Luciferin is a name given to a compound in a living organism that has the special property of producing light when it loses electrons. Look at the figures below for several different examples of luciferins:



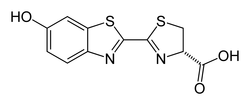
*Crustacean luciferin*

*(*[*http://bioluminescenceintromarinebio.weebly.com/uploads/3/8/6/0/38600933/844757951.png?250*](http://bioluminescenceintromarinebio.weebly.com/uploads/3/8/6/0/38600933/844757951.png?250)*)*



*Latia luciferin of a freshwater snail*

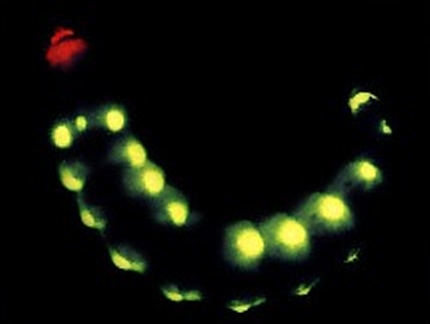
*(*[*http://bioluminescenceintromarinebio.weebly.com/uploads/3/8/6/0/38600933/237999759.png?250*](http://bioluminescenceintromarinebio.weebly.com/uploads/3/8/6/0/38600933/237999759.png?250)*)*



*Firefly luciferin*

*(*[*http://bioluminescenceintromarinebio.weebly.com/uploads/3/8/6/0/38600933/834434594.png?250*](http://bioluminescenceintromarinebio.weebly.com/uploads/3/8/6/0/38600933/834434594.png?250)*)*

Luciferase is an enzyme/catalyst that reacts with the substrate to oxidize the luciferin and produce light. Most organisms produce light with the luciferin/luciferase chemical reaction system, but some use photoproteins instead of the luciferase. Photoproteins combine with the luciferin, oxygen and generally a cation like calcium to produce light. Photoproteins have just recently been discovered and are still being studied by chemists to understand their properties.

Many living organisms produce their own luciferin while others must absorb it from food or other oragnisms. Not all bioluminescence is the same color and depends on the organism and their habitat. Most marine organisms produce light in the blue- green (475 nm–510 nm) part of the visible spectrum. This light is most readily seen in the deep oceans since it travels well through water without being absorbed. Many land organisms also produce blue-green light, but many also glow in the yellow (570 nm) region of the spectum. Fireflies for example glow in the yellow region. There are a few organizims that produce more than one color of light. The “railroad worm,” which is a larva of a female beetle, produces red light on its head and its body glows green. Diffferent luciferins cause the variety of colors produced by different organisms.

*Railroad worm (*[*http://bogleech.com/nature/beetle-glowworm.jpg*](http://bogleech.com/nature/beetle-glowworm.jpg)*)*

There are many different types of bioluminescence and they serve many different purposes, some of which scientest do not understand and some they can only speculate about. The following table outlines some of the varied functions of bioluminescence.

|  |  |
| --- | --- |
| **Purpose/Explanation** | **Examples** |
| Communication: Used especially when locating a mate | Fireflies, ostracods (small shrimplike crustaceans) |
| Illumination: In the depths of the ocean some species of fish use bioluminescence to locate their prey | Flashlight fish, dragonfishes |
| Attracting prey: Some use light to lure their prey. | Anglerfishes, cookie cutter shark |
| Camouflage or Counter-illumination: Many ocean predators hunt from below. They look for where the sunlight creates a shadow below the prey. The biolumination camouflages the shadow. | Hatchetfish, squid |
| Self-defense: Some animals release a bioluminescent cloud when threatened. Others flash a bright light to blind their predators. | Dinoflagellates, some jelly fish, vampire squid |

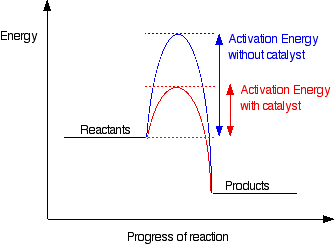
(This table was created using information from the following sites: <http://animals.howstuffworks.com/animal-facts/bioluminescence2.htm>,

<http://biolum.eemb.ucsb.edu/functions.html>, and

<http://education.nationalgeographic.com/education/encyclopedia/bioluminescence/?ar_a=1>.)

**More on catalysts and enzymes**

A catalyst is a substance that increases the rate of a chemical reaction but is not consumed in the reaction. An enzyme is a type of catalyst. For a reaction to occur the particles must collide and collide with sufficient energy to break bonds. The minimum energy required to break bonds is known as the activation energy. In order to increase the rate of a reaction the number of successful collisions must be increased. One way to accomplish that is to lower the activation energy. A catalyst provides an alternative mechanism for the reaction which has a new, lower activation energy requirement, thus speeding up the reaction.



*(*[*http://chemwiki.ucdavis.edu/@api/deki/files/15862/*](http://chemwiki.ucdavis.edu/@api/deki/files/15862/)*)*

Enzymes are biological catalysts, meaning they are organic substances produced by a living organism. Just like non-enzymatic catalyst, enzymes speed up a reaction by lowering the activation energy but do so more dramatically than do other catalysts. A comparison of properties are given in the table below.

|  |  |  |
| --- | --- | --- |
| **Feature** | **Non-biological Catalyst** | **Enzyme** |
| Specificity | Not specific | Highly specific |
| Molecular weight | Low molecular weight substances | High molecular weight globular proteins. |
| Rate of reaction | Increases rate by a factor of 103–106 | Increases the rate only a fraction of that of enzymes |
| Chemical nature | Metal and nonmetal inorganic substances | Organic substances, generally proteins |
| Side reactions | Occur | Do not occur |
| Conditions where effective | High temperatures, high pressures | Mild temperatures and pressures |

(This table was created using information from the following sites:

<http://www.diffen.com/difference/Catalyst_vs_Enzyme> and

<http://www.yourarticlelibrary.com/biology/enzyme/comparison-between-enzymes-and-non-biological-catalysts/33694/>.)

**More on light and the ocean**

Light is electromagnetic radiation and is actually properly referred to as visible light. Visible light has wavelengths between 400 and 700 nanometers. Each wavelength produces a different color; the longest wavelength is red and the shortest is violet. The higher the energy the shorter the wavelength and the higher the frequency.

When light strikes a substance it can do one of three things. It can be reflected, refracted or absorbed. In reflection the light bounces off a smooth surface, like a mirror. The reflected ray bounces off at the same angle at which it hit the smooth surface. If the surface is not smooth the light is reflected in a variety of different angles and it is scattered. When light passes from one transparent medium to another, such as from air to water, it is refracted. The light changes speed and the light ray bends when this happens. In opaque objects light is absorbed, either wholly or just certain wavelengths, and the energy is converted into heat.

When sunlight hits the ocean only 2% of it is reflected and most is transmitted into the water. In the water the speed of light is slowed to 2.25×108 m/s (in air light it travels at 3.0 x108 m/s). This sunlight transmitted to the ocean is important because it heats the surface layer of water, provides energy for phytoplankton, and is used for navigation by animals near the surface. Under the right conditions light may travel 1000 meters into the ocean but in reality there is very little light beyond 200 meters.

The ocean is divided into three zones based on depth and light level. The upper 200 meters (656 feet) of the ocean is called the euphotic, or "sunlight," zone. This zone contains the vast majority of commercial fisheries and is home to many protected marine mammals and sea turtles.

Only a small amount of light penetrates beyond this depth.

The zone between 200 meters (656 feet) and 1,000 meters (3,280 feet) is usually referred to as the “twilight” zone, but is officially the dysphotic zone. In this zone, the intensity of light rapidly dissipates as depth increases. Such a miniscule amount of light penetrates beyond a depth of 200 meters that photosynthesis is no longer possible.

The aphotic, or “midnight,” zone exists in depths below 1,000 meters (3,280 feet). Sunlight does not penetrate to these depths and the zone is bathed in darkness.

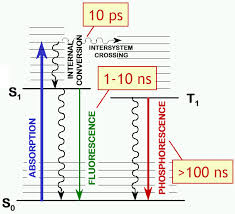
(<http://oceanservice.noaa.gov/facts/light_travel.html>)

The white sunlight striking the ocean contains all the color of the visible spectrum, red, orange, yellow, green, blue and violet. Red has the longest wavelength and therefore the least amount of energy. Red light penetrates the water the least. As the wavelength shorten the light is better able to penetrate the water, so blue light penetrates the ocean best. Since all the red light is absorbed by the water oceans appear blue.

**More on luminescence, light emitting processes, luminol and light sticks**

**Luminescence** is the emission of light that is not the result of high temperatures (e.g., incandescence). It is what is referred to as cold body radiation and occurs after a substance absorbs energy from a source such as electromagnetic radiation, electron beams, chemical reactions, or friction. The absorbed energy lifts an electron from its ground state to a higher energy state, an excited state. Since the excited state is unstable, the electron undergoes other transitions to return to the ground state. Some of the absorbed energy is then released in the form of light.

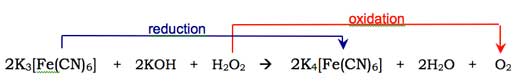
*(*[*http://people.bridgewater.edu/~koverway/courses/CHEM445/ppts/I\_Chapt15Fluorescence.pdf*](http://people.bridgewater.edu/~koverway/courses/CHEM445/ppts/I_Chapt15Fluorescence.pdf)*)*



**Light Emitting Processes:** The table below provides a list of some common light emitting processes.

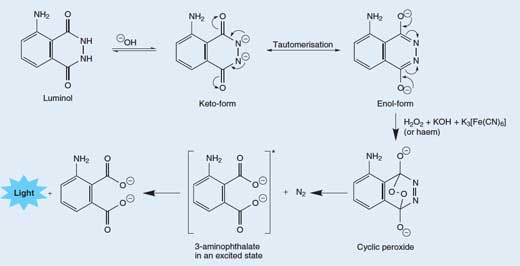
|  |  |  |
| --- | --- | --- |
| **Source** | **Explanation** | **Example** |
| Bioluminescence/ chemiluminescence | Light produced by a chemical reactions | Fireflies, flashlight fish, light sticks |
| Fluorescence | An object absorbs electromagnetic radiation of one frequency and immediately reemits light of a different frequency | Fluorescent lights |
| Phosphorescence | Similar to fluorescence but light is emitted over a longer period of time | “glow in the dark” minerals |
| Incandescence | An object is heated until it produces electromagnetic radiation including visible light | Incandescent light bulb, candle flames |
| Triboluminescence | Light caused by the excitation of electrons during the rubbing, crushing, or tearing of a material | Crushing of sugar crystals |

**Luminol** is a common chemiluminescent material. It is used by forensic scientists to detect blood at crime scenes. The iron in the blood serves as the catalyst for the luminol reaction. The production of light from luminol is a fairly complex redox reaction. In an alkaline solution luminol exists in equilibrium with its anion. The anion exists in two forms with the negative charges delocalized on either the oxygen atoms, the enol form, or the nitrogen atoms, the ketol form. Oxygen will react with the enol form and oxidizes it to a cyclic peroxide. The oxygen is produced in the decomposition reaction of hydrogen peroxide in the presence of a catalyst such as an iron compound.

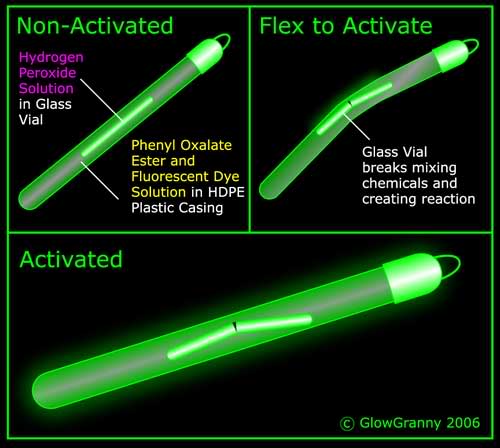


*(*[*http://www.scienceinschool.org/2011/issue19/chemiluminescence*](http://www.scienceinschool.org/2011/issue19/chemiluminescence)*)*

The cyclic peroxide is very unstable and immediately decomposes with the loss of nitrogen to produce 3-aminophthalic acid with electrons in an excited state. Energy is released as blue light when the electrons return to the ground state.



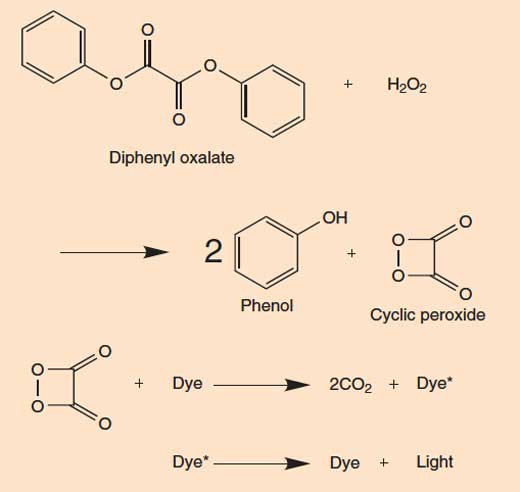
*(*[*http://www.scienceinschool.org/2011/issue19/chemiluminescence*](http://www.scienceinschool.org/2011/issue19/chemiluminescence)*)*

**Light sticks**, also known as glow sticks, are used as entertainment and as toys but they are also used as light sources and light markers by the military, campers and divers. The chemiluminescent light they produce is also a result of an oxidation/reduction reaction. Light sticks are composed of two separate compartments each containing different chemical solutions.

The inner compartment is made of a thin glass tube containing hydrogen peroxide. The outer plastic tube contains a mixture of diphenyl oxalate and a dye, whose identity varies, depending on the desired color. The separate compartments keep the solutions from mixing and reacting. Bending the light stick breaks the inner glass tube releasing the hydrogen peroxide and starting the redox reaction.

*(*[*http://i288.photobucket.com/albums/ll176/cheerleaderchick2856/How-Glow-Sticks-Work-Image-.jpg*](http://i288.photobucket.com/albums/ll176/cheerleaderchick2856/How-Glow-Sticks-Work-Image-.jpg)*)*

The hydrogen peroxide oxidizes the diphenyl oxalate and produces phenol and a cyclic peroxide (1,2-dioxetanedione). The new, cyclic peroxide is unstable and quickly decomposes into carbon dioxide, releasing energy in the process. The energy is absorbed by the dye molecule causing electrons in the dye molecule to be excited. When the electrons return to the ground state the energy is relased as a photon of visible light.



*(*[*http://www.scienceinschool.org/2011/issue19/chemiluminescence*](http://www.scienceinschool.org/2011/issue19/chemiluminescence)*)*

**More on Edith Widder**

Edith Widder was born in Arlington, Massachusetts in 1951 to Dr. Vera Widder and Dr. David Widder. Both parents were mathematicians. Her father was a professor at Harvard University. Edith Widder received her Bachelors of Science degree in biology from Tufts University (1973) where she graduated Magna cum laude. She earned her M.S. degree in biochemistry (1977) and her PhD in neurobiology (1982) from the University of California, Santa Barbara.



*Dr. Edith Widder*

*(*[*http://oceanexplorer.noaa.gov/edu/oceanage/04widder/widder1.jpg*](http://oceanexplorer.noaa.gov/edu/oceanage/04widder/widder1.jpg)*)*

Dr. Widder became certified as a Scientific Research Pilot for Atmospheric Diving Systems. She is qualified to dive the deep diving suit WASP, a self-contained hard suit that incorporates propulsion units. She also became certified to dive in the single-person, untethered submersibles DEEP ROVER and DEEP WORKER. As a result of the dives she took, she became fascinated with bioluminescence.

From 1989–2005, Dr. Widder was a senior scientist and director of the Bioluminescence Department at Harbor Branch Oceanographic Institution in Florida. In 2005 Edith Widder co-founded the Ocean Research & Conservation Action (ORCA). ORCA is a non-profit organization dedicated to the protection and restoration of marine ecosystems and the species found there. According to the ORCA Web site they “have achieved exciting progress in using the latest technologies to develop low-cost solutions for analysis of our polluted waterways.” (<http://www.teamorca.org/cfiles/about_orca.cfm>)

In 2006 Dr. Widder was awarded the MacArthur Fellowship from the John D. and Catherin T. MacArthur Foundation. “The MacArthur Fellowship is a five-year grant to individuals who show exceptional creativity in their work and the prospect for still more in the future.” (<https://www.macfound.org/fellows-faq/>)

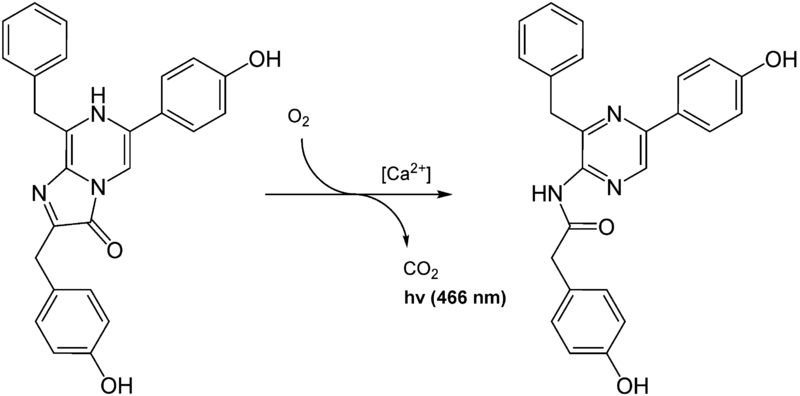
As a specialist in bioluminescence Dr. Widder has been instrumental in the invention and development of equipment to unobtrusively investigate the deep sea. According to her biography on the ORCA Web site,

Working with engineers, she has conceived of and built several unique devices that enable humans to see beneath the waves in new ways, including HIDEX, a bathyphotometer which is the U.S. Navy standard for measuring bioluminescence in the ocean; important information for keeping submarines hidden from above. Edie also built LoLAR, an ultrasensitive deep-sea light meter that measures light in the deep ocean, both dim down-welling sunlight and bioluminescence – both important determinants of animal distribution patterns. Most recently, Widder created a remotely operated deep-sea camera system, known as ORCA’s Eye-in-the-Sea (EITS), which, when deployed on the sea floor, automatically detects and measures the bioluminescence of nearby organisms. EITS has produced footage of rare sharks, jellyfish, and discovered a new species of large squid (over six feet in length), all in their natural habitats.

(<http://www.teamorca.org/cfiles/about_edie.cfm>)

**More on the green fluorescent protein**

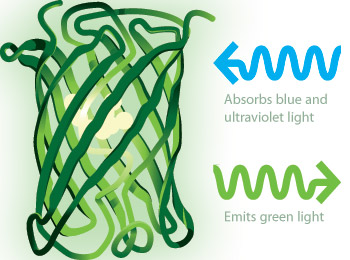
In 2008 Martin Chalfie, Osamu Shimonura and Roger Tsien received the Nobel Prize in chemistry for their discovery and development of the green fluorescent protein. Although this protein has been around for over 150 million years it was not studied until 1961 when Osamu Shimomura decided to study what made the crystal jellyfish (Aequorea victoria) glow. Working out of the Marine Biological Laboratory in Woods Hole, Mass. he identified a molecule in the emitted blue light when in the presence of calcium ions, Ca2+, but the jelly fish emitted green light.



*Aequorin in the presence of calcium ions*

*(*[*https://upload.wikimedia.org/wikipedia/commons/thumb/8/8b/CoelenterazinTOCoelenteramid.png/800px-CoelenterazinTOCoelenteramid.png*](https://upload.wikimedia.org/wikipedia/commons/thumb/8/8b/CoelenterazinTOCoelenteramid.png/800px-CoelenterazinTOCoelenteramid.png)*)*

They eventually (1974) found the green fluorescent protein, GFP, in the jelly fish. The GFP absorbed the blue light produced by the aequorin and emitted the green light in response.



*Green Fluorescent Protein*

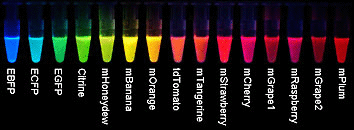
*(*[*http://www.nobelprize.org/nobel\_prizes/chemistry/laureates/2008/che\_illpress\_2008\_gfp\_protein.jpg*](http://www.nobelprize.org/nobel_prizes/chemistry/laureates/2008/che_illpress_2008_gfp_protein.jpg)*)*

In 1987 Douglas Prasher thought it might be possible to attach the GFP to specific proteins such as virus or cancer cells. By 1992 Prasher cloned the GRP gene, which was the first step in using GFP as a tracer chemical. Unfortunately Prasher lost the funding for his grant and was forced to leave Woods Hole. Before he left he gave the gene to his colleagues Chalfie and Tsien.

Martin Chalfie inserted the gene into bacteria and within a month saw a green glow under a microscope that demonstrated that the GFP could be inserted into an organism. This became a powerful research tool. Roger Tsien continued the research with the GFP and was responsible for much of the understanding of how the GFP works. He was able to modify the GFP gene and create mutants of GFP. These mutants start fluorescing faster than the natural type. They are also brighter and with different colors. This made it possible for researchers to track more than one protein at a time by attaching different mutant fluorescent proteins to different proteins in a cell.

*Tsien’s different fluorescent proteins*

*(*[*http://www.conncoll.edu/ccacad/zimmer/GFP-ww/images/tsien2.gif*](http://www.conncoll.edu/ccacad/zimmer/GFP-ww/images/tsien2.gif)*)*

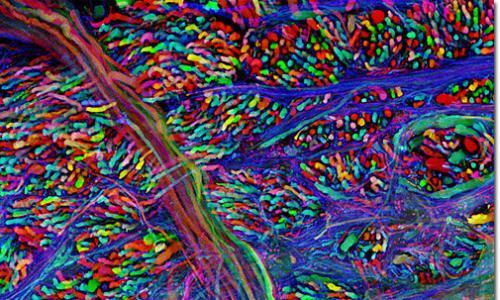


**Applications of GFPs**

The discovery of the GFP and its mutations has led to many scientific applications and discoveries. Jeff Lichtman and Josua Sanes, professors at Harvard University in the Brain Center, inserted yellow, cyan and red fluorescent proteins inside the DNA of the brain cells of mice. The cells then produce enough of the protein to glow.

Each cell glowed in a different color based on how many yellow, cyan and red fluorescent proteins were produced in that cell. This way, the scientists were able to produce a mouse brain in which cells glowed in nearly 90 different colors. The scientists called these mice “Brainbow mice”.

The distinct colors of Brainbow mice can help researchers see individual cells and sort out how they connect with one another. By comparing brain samples from healthy mice with those of mice in which diseases are induced, the scientists hope to better understand what goes wrong in people with debilitating diseases such as Alzheimer’s and Parkinson’s diseases.



Brainstem – Brainbow mouse.

*(*[*http://cbs.fas.harvard.edu/science/connectome-project/brainbow*](http://cbs.fas.harvard.edu/science/connectome-project/brainbow)*, picture 11)*

(Zajac, L. Glowing Proteins with Promising Biological and Medical Applications. *ChemMatters,* 2008, *25* (4), pp 12–14)

This technique allows for the mapping of the neural circuits of the brain since individually colored neurons will help define the complex tangle of neurons in the brain and the nervous system.

Using fluorescent proteins researchers at the University of Cambridge have studied the cause of water retentions and constipation during pregnancy. Fruit flies experience the same problems so Dr. Irene Aliaga and her colleagues created genetically modified fruit flies with intestinal neurons that light up when they are used.

According to the fluorescent intestinal neurons and fruit fly poop analysis it's the fruit fly dad who is responsible for that bloated feeling experienced by the pregnant mom. During copulation he passes along his sperm as well as some hormones. One of the hormones switches on a set of intestinal neurons that are responsible for slowing down the gut emptying rate, resulting in constipation, and so even though pregnant fruit flies are eating more food during pregnancy the contents of their intestines become more concentrated. This allows the pregnant mother to absorb the maximum amount of nutrition. The same hormones also result in water retention and bloating

Similar behavior is observed in humans. And the color-coding of the neurons in fruit flies actually helps us understand it. So if you are pregnant, bloated and constipated, it might be good to know that the food you crave isn't responsible for your discomfort, it's a healthy dose of evolution and sex hormones ensuring that the fetus maximizes its nutritional absorption.

(<http://www.conncoll.edu/ccacad/zimmer/GFP-ww/cooluses26.html>)

The study of cancer has been advanced by the use of fluorescent proteins. Robert Hoffman, professor at the University of California at San Diego, developed imaging techniques using fluorescent proteins that are used in cancer research. Cancers that contain fluorescent proteins can be implanted into mice. The cancer cells can easily be observed and monitored in the live mice. Researchers can observe how the cancer cells grow and migrate in the blood vessels, how they bind to healthy cells and how the cancer cells change DNA. In addition researchers can monitor how drugs affect the cancer cells, allowing for the design of better drugs to fight cancers.

## Connections to Chemistry Concepts (for correlation to course curriculum)

1. **Light and the spectrum**—Not only is bioluminescence described as the production of light by a chemical reaction in a living organism, but the absorption and reflection of light is discussed in this article. The article also explains how various colors of light travel through the ocean.
2. **Organic chemistry**—The luciferin and the luciferase are organic structures.
3. **Enzymes/Catalyst**—Luciferase is the enzyme that catalyzes luciferins to produce bioluminescence.
4. **Oxidation-reduction**—Luciferin is oxidized and oxygen is reduced which produces energy in the form of light.
5. **Technology**—The application of bioluminescence to trace disease, detect pollution and detect cancer is described in this article.

## Possible Student Misconceptions (to aid teacher in addressing misconceptions)

1. **“Bioluminescence is the same as fluorescence.”** *This is not true. Bioluminescence is the result of a chemical reaction between two or more substances. Fluorescence occurs when an object absorbs light of one frequency and immediately reemits light of a different frequency.*
2. **“Fireflies really are flies.”** *Fireflies are not flies but beetles. They are nocturnal members of Lampyridae, a family of insects within the beetle order Coleoptera, or winged beetles.*
3. **“Bioluminescence is produced by bacteria.”** *Some bioluminescence is produced by bacteria and some organisms do have bacteria in their light organs, but the majority of bioluminescent animals produce their light with chemicals stored in their bodies.*

## Anticipating Student Questions (answers to questions students might ask in class)

1. **“What are some other potential uses of bioluminescence?”** *The potential use of bioluminescence is only limited by the imagination of scientists. In a* National Geographic *article two such examples are given: “Other uses are more experimental. Bioluminescent trees, for instance, could help light city streets and highways. This would reduce the need for electricity. Bioluminescent crops and other plants could luminesce when they needed water or other nutrients, or when they were ready to be harvested. This would reduce costs for farmers and agribusiness.”* ([*http://education.nationalgeographic.com/encyclopedia/bioluminescence/*](http://education.nationalgeographic.com/encyclopedia/bioluminescence/))
2. **“Are there any plants that are naturally bioluminescent?”** *There are no true naturally occurring bioluminescent plants. Dinoflagellates, single-celled marine algae, produce light but they are not true plants. There are researchers that are trying to engineer plants that will glow which today are not “natural”, but may be considered natural one day. (*[*http://inhabitat.com/glowing-plant-project-kickstarter-campaign-creates-bioluminescent-plants-for-natural-lighting/*](http://inhabitat.com/glowing-plant-project-kickstarter-campaign-creates-bioluminescent-plants-for-natural-lighting/) *)*
3. **“Does bioluminescence occur in fresh water?”** *There are only a few bioluminescence organisms in fresh water and most of these are larvae of creatures that are terrestrial as adults. The most commonly cited luminous creature is a freshwater limpet, which is like a snail, called Latia and found in New Zealand. There are also a few bioluminescent bacteria that live in fresh water.*

## In-Class Activities (lesson ideas, including labs & demonstrations)

1. A wonderful extension to this article that you might want to use in classes is the TED video (17:19) called Glowing Life in an Underwater World. In the video Edith Widder discusses her exploration of bioluminescence in the deep sea and includes images of her voyages. (<http://www.ted.com/talks/edith_widder_glowing_life_in_an_underwater_world?language=en>)
2. This activity investigates the properties of light and color in ocean waters. Students examine how the wavelength of light determines its ability to penetrate seawater and how deep sea organisms use the properties of light to help them survive.

(<https://www.montereybayaquarium.org/-/m/pdf/education/curriculum/light_in_the_deep_sea.pdf>)

1. The following activities investigate the differences between chemiluminescence, fluorescence, phosphorescence and triboluminescence:
2. The first one is a lesson geared to 7th–8th grade life or physical science students. The focus of the lesson is on light-producing processes and organisms in deep-sea environments. It includes complete explanations of the light producing process for teachers and relates it to the bioluminescence organisms in the ocean.
3. (<http://oceanexplorer.noaa.gov/explorations/09bioluminescence/background/edu/media/ds_09_deeplights.pdf>)  
   This activity was included in the *Journal Chemical of Education* in 2005. Students investigate the luminescent properties of common items and classify them as fluorescent, phosphorescent or triboluminescent. The site includes both teacher information and a student activity sheet.  
   (<http://www.chem.ufl.edu/~kschanze/outreach/h4.pdf>)
4. At this Science Friday site, the activity is appropriate for students in 6th–8th grades. It begins with a video of Edith Widder explaining her explorations and bioluminescence. The students then investigate activities involving chemiluminescence, phosphorescence and fluorescence.  
   (<http://www.sciencefriday.com/blogs/09/23/2010/illuminating-luminescence.html>)
5. A student can further investigate bioluminescence at the following NOAA site. It has a short explanation of bioluminescence, a video of bioluminescent animals and a series of questions relating to the video pictures. (<http://oceanexplorer.noaa.gov/edu/learning/6_deepsea_benthos/activities/bioluminescence.html#activity>)
6. There are numerous activities that use light-sticks to investigate chemiluminescence. The most common experiment is to investigate the temperature effect on the rate of the chemical reaction. These two sites give clear instructions and provide good follow-up questions and information about the reaction.

(<http://scifun.chem.wisc.edu/homeexpts/chemilum.html> and

<http://www.stevespanglerscience.com/lab/experiments/light-sticks-the-science-of-liquid-light>)

1. Luminol demonstrations provide an excellent example of chemiluminescence and are fun and easy to do. There are many excellent demonstrations available. The following site is an example of one. It not only provides the procedure for several luminol demonstrations but provides good explanations of the chemistry and video references as well.

(<http://ncsu.edu/project/chemistrydemos/Light/Luminol.pdf>)

1. There are many teacher demonstrations using either light-sticks or luminol to demonstrate chemiluminescence at this site: (<http://www.acs.org/content/acs/en/education/students/highschool/chemistryclubs/activities/lightsticks-and-luminescence.html>)
2. Triboluminescence can be observed using simple materials. The following Web sites describe these activities. The first one uses wintergreen lifesavers or sugar cubes. The second one uses duct tape.

(<http://www.coolscience.org/CoolScience/Teachers/Activities/TriboLum.htm> and

<http://chemistry.about.com/od/glowinthedarkprojects/a/duck-tape-triboluminescence.htm>)

## Out-of-Class Activities and Projects (student research, class projects)

1. Students could obtain and grow dinoflagellates at home. They are as easy to grow as houseplants as reported by The Bioluminescence Web Page. A journal of the process could be kept by the students and then the progress could be reported back to the class. There are several sites that provide information on how to grow the bioluminescence algae. The following are two such sites:

<http://biolum.eemb.ucsb.edu/> and

<http://www.wikihow.com/Grow-Bioluminescent-Algae-at-Home>

Here are several sources to purchase dinoflagellates:

<http://seafarms.com/html/products.html#anchor> and

<http://www.carolina.com/algae/dinoflagellates/FAM_153240.pr>

1. Students could investigate the properties of light sticks at home as well as in the classroom. They could design their own experiments and report out their findings.
2. Students could investigate the unusual uses of bioluminescence, such as in art.
3. Edith Widder and others have developed special cameras to observe bioluminescence in the deep ocean. Students could research these technologies and report on them and/or build a model of the cameras.

## References (non-Web-based information sources)



**30 Years of *ChemMatters***

Available Now!

**The references below can be found on the *ChemMatters* 30-year DVD (which includes all articles published during the years 1983 through April 2013 and all available Teacher’s Guides, beginning February 1990). The DVD is available from the American Chemical Society for $42 (or $135 for a site/school license) at this site:** [http://ww.acs.org/chemmatters](http://www.acs.org/chemmatters)**. Click on the “Archive” tab in the middle of the screen just under the *ChemMatters* logo. On this new page click on the “Get 30 Years of ChemMatters on DVD!” tab at the right for more information and to purchase the DVD.**

**Selected articles and the complete set of Teacher’s Guides for all issues from the past three years are available free online at the same Web site, above. Simply access the link and click on the aforementioned “Archive” tab.**

Sweeting, L. Light Your Candy. *ChemMatters,* 1990, *8* (3), pp 10–12. This is an article on triboluminescence.

Scott, D. Designer Catalyst. *ChemMatters,* 1994, *12* (2), pp 14–15. This is an excellent article on catalysts and enzymes. It provides an analogy to explain the chemistry involved with catalysis.

Marsella, G. Chemiluminescence, the Cold Light. *ChemMatters,* 1995, *13* (3), pp 12–15. This is an earlier *ChemMatters* article on bioluminescence and chemiluminescence. The article explains the production of light in general terms, describes how light sticks work and compares it to the light produced by living organisms. It also explains how bioluminescence is used to diagnose tuberculosis.

Rosenthal, A. Ocean Biolights. *ChemMatters,* 2004, *22* (4), pp 10–12. Rosenthal describes the bioluminescence of dinoflagellates and explains the process of bioluminescence in this article. He also compares bioluminescence to fluorescence and explains the function of bioluminescence by various living organisms.

The December 2004 *ChemMatters* Teacher’s Guide for the above article elaborates on bioluminescence. The guide explains “Red Tides” and also provides a list of bioluminescent organisms.

Zajac, L. Glowing Proteins with Promising Biological and Medical Applications. *ChemMatters,* 2008, *25* (4), 12–14. This article discusses the discovery, the chemistry and the uses of the green fluorescent protein.

The December 2008 *ChemMatters* Teacher’s Guide for the above article provides additional information on bioluminescence as well as additional ideas for activities and demonstrations.

## Web Sites for Additional Information (Web-based information sources)

**More sites on** **bioluminescence**

The Bioluminescence Web Page has a wealth of information on bioluminescence. It includes its chemistry, its functions, myths about bioluminescence, and various organisms that exhibit bioluminescence and their photos. (<http://biolum.eemb.ucsb.edu/>)

The Scripps Institute of Oceanography site has a section on bioluminescence. It includes, among other things, information on dinoflagellates, a question and answer section, and information on popular accounts citing bioluminescence. (<https://scripps.ucsd.edu/labs/mlatz/bioluminescence/>)

Extensive information on bioluminescence can be found at this site: <http://animals.howstuffworks.com/animal-facts/bioluminescence.htm>.

This Smithsonian National Museum of History site not only has good explanations about bioluminescence but also has beautiful pictures of various living creatures. (<http://ocean.si.edu/bioluminescence>)

This site describes bioluminescence, light production and provides information on luciferins. (<http://bioluminescenceintromarinebio.weebly.com/>)

The National Geographic site not only has useful information on bioluminescence but also beautiful pictures. (<http://education.nationalgeographic.com/encyclopedia/bioluminescence/>)

This Science Friday video (4:32) discusses the bioluminescence of fireflies. (<http://www.sciencefriday.com/video/07/03/2014/in-a-flash-firefly-communication.html>)

**More sites on** **catalyst and enzymes**

Catalysts and their relationship to the activation energy are clearly explained at this site: <http://www.chemguide.co.uk/physical/basicrates/catalyst.html>.

These two sites describe enzymes and their function:

<http://chemwiki.ucdavis.edu/Biological_Chemistry/Catalysts> and

<http://www.microtack.com/html/enzyme1.htm>.

A comparison of catalysts and enzymes can be found at these sites: <http://www.diffen.com/difference/Catalyst_vs_Enzyme> and

<http://www.yourarticlelibrary.com/biology/enzyme/comparison-between-enzymes-and-non-biological-catalysts/33694/>.

This video (8:50) provides an excellent explanation of enzymes. It is clearly presented, provides good analogies and has easy to understand graphics. (<https://www.youtube.com/watch?v=Of1Ix22ytCI>)

**More sites on luminescence, light emitting processes, luminol and light sticks**

The site given below is a great source of information on luminescence and various light emitting processes. It defines luminescence, explains the process, compares luminescence to incandescence and provide some history surrounding these processes. It also explains the various light emitting processes. (<http://www.britannica.com/science/luminescence>)

A brief explanation of the various light emitting process is given at this site: <http://www.scienceclarified.com/Io-Ma/Luminescence.html>

This is another site that fully describes luminescence and light emitting processes. (<http://www.leica-microsystems.com/science-lab/basic-principles-of-luminescence/>)

The Fluorescent Mineral Society site provides a simple explanation of many light emitting processes. (<http://uvminerals.org/fms/luminescence>)

The Compound Interest site not only describes the chemistry of a light stick but also explains the difference colors of light sticks. At this site there is a great poster that can be downloaded that shows the chemistry of light sticks. (<http://www.compoundchem.com/2014/10/14/glowsticks/>)

This article describes chemiluminescence, the chemistry and uses of luminol and light sticks in student friendly language. It includes easy to understand graphics as well. (<http://www.scienceinschool.org/2011/issue19/chemiluminescence>)

“What’s That Stuff?” from *Chemical and Engineering News*, provides a site describing light sticks: <http://pubs.acs.org/cen/whatstuff/stuff/7703scit4.html>.

**More sites on light and the ocean**

Information on visible light, color, absorption, transmission and reflection can be found at the Physics Classroom site. (<http://www.pthysicsclassroom.com/class/light>)

The wavelength of various colors of light is given at this site: <http://science-edu.larc.nasa.gov/EDDOCS/Wavelengths_for_Colors.html>.

A technical article on light in the ocean and the absorption of light is given in this article: <http://oceanworld.tamu.edu/resources/ocng_textbook/chapter06/chapter06_10.htm>.

Edith Widder discusses on this page the absorption of light in the ocean and the effect of the light absorption in the deep ocean. She compares the vision of humans to the deep water fish as well as the ability of these animals to make their own light. (<http://oceanexplorer.noaa.gov/explorations/04deepscope/background/deeplight/deeplight.html>)

This short NOAA article explains why there are so many red fish: <http://oceanexplorer.noaa.gov/facts/red-color.html>.

This site provides a nice graphic showing the distance light travels in the ocean: <http://oceanservice.noaa.gov/facts/light_travel.html>.

A thorough description of light in the ocean can be found at this site: <http://www.whoi.edu/oceanus/feature/shedding-light-on-light-in-the-ocean>.

**More sites on Edith Widder**

This site provides a brief biography of Edith Widder. It is the staff biography from the ORCA organization. (<http://www.teamorca.org/cfiles/about_edie.cfm>)

A series of questions and answers that provide information about Edith Widder can be found at this Web site: <http://oceanexplorer.noaa.gov/edu/oceanage/04widder/welcome.html>.

This article written by Edith Widder provides information about her explorations and her inventions especially the Eye in the Sea: <http://oceanexplorer.noaa.gov/explorations/09bioluminescence/background/eyeinsea/eyeinsea.html>.

This article describes Edith Widder when she received the MacArthur Fellowship award: <https://www.macfound.org/fellows/794/>.

This Wikipedia site provides a brief biography of Dr. Widder: <https://en.wikipedia.org/wiki/Edith_Widder>.

**More sites on the green fluorescent protein (GFP)**

A concise description of the history and discovery of the green fluorescent protein can be found at this Nobel Prize site: <http://www.nobelprize.org/nobel_prizes/chemistry/laureates/2008/illpres.html>.

This article is a brief description of the GFP and its uses. The article contains nice graphics that show the structure of the GFP. (<http://www.rcsb.org/pdb/101/motm.do?momID=42>)

A description of the discovery of the GFP and how it is used are given in this article: <http://www.livescience.com/16752-gfp-protein-fluorescent-nih-nigms.html>.

The Green Fluorescent Protein site contains information on its uses, its history including a timeline, the Nobel Prize, and its structure and the research involving GFP. The Web site is loaded with beautiful photos as well. (<http://www.conncoll.edu/ccacad/zimmer/GFP-ww/GFP-1.htm>)

This video (4:42) describes the use of the GFP to map the neurons in the brain. Analogies and clear explanations make this video very student friendly. (<https://www.youtube.com/watch?v=WP4wW4dC30Q>)