ChemMatters

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Teacher's Guide Table of Contents

About the Guide

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Student Questions

The Forensics of Blood

1. What are two examples of tests that can be done to detect blood at a crime scene?
2. How can an investigator distinguish between human and non-human blood?
3. What makes the difference between blood samples of type A, type B, AB or O?
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7. What is the difference (in terms of function) between a red blood cell and a white blood cell?
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How Chemistry Helps Make Blood Transfusion Safer

1. Why can’t human blood simply be transferred from one person to any other person?
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3. What is the difference in storage life for blood that is at room temperature versus refrigerated blood versus frozen blood?
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6. What is the difference between the function of red blood cells and platelets?
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2. What does your body do with the inhaled air?
3. What percentage of the air in each breath we inhale is consumed oxygen?
4. What percentage of the oxygen we inhale is consumed in each breath?
5. What is the role of carbonic acid in respiration?
6. What causes acidosis?
7. What are the symptoms of acidosis?
8. What are the components of a rebreathing apparatus?
9. What can go wrong with a rebreather?
10. In this article, what do divers and astronauts have in common?

The Not So Simple Life of Filters

1. What size particles can be retained by a filter paper of a fine grade?
2. What is the name given to the mass of glass formed in the production of a glass filter?
3. What material is used to make a ceramic filter?
4. Name the phenomenon that occurs when particles that are being filtered bind with the filter’s surface.
5. Pressure is required in what kind of filtering system?

“Follow the Carbon.” Follow the *What*?

1. What is an organic compound?
2. What is the simplest organic compound?
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5. Did the Viking probes find any organic compounds on Mars?
6. How many protons and how many neutrons does an atom of carbon-12 have?
7. How many protons and how many neutrons does an atom of carbon-13 have?
8. What does GCMS stand for?

Answers to Student Questions

The Forensics of Blood

1. **What are two examples of tests that can be done to detect blood at a crime scene?**
   The presence of blood can be detected through luminescence (Luminol test), by the Kastle-Meyer test using phenolphthalein and hydrogen peroxide.
2. **How can an investigator distinguish between human and non-human blood?**
   Using the precipitin test, antibodies against human blood developed in a rabbit are used to test a sample of crime scene blood. A positive test is the formation of a precipitate from the antibody-antigen reaction.
3. **What makes the difference between blood samples of type A, type B, AB or O?**
   Red blood cells of the different blood types contain surface antigens that are different for each of the blood types.
4. **What test is used to identify blood types? What principle is utilized to make the test?**
   The test is based on the idea that blood type is determined by a particular antigen on the red blood cell. Introducing antibodies against that particular antigen will give a positive test which is clumped and precipitated blood cells.
5. **Why is blood so sticky?**
   Blood is a colloid containing many suspended particles that create a large surface area for intermolecular bonding.
6. **What is the difference between plasma and whole blood?**
   Plasma is the liquid part of the blood that does not include the blood cells and platelets. Together, the plasma plus blood cells and platelets constitute "whole" blood.
7. **What is the difference (in terms of function) between a red blood cell and a white blood cell?**
   Red blood cells, which are essentially non-living and do not have a cell nucleus, carry oxygen and some carbon dioxide to the body's living tissue cells. White blood cells, which are living and contain a nucleus, act as destroyers of foreign, disease-producing substances such as bacteria, viruses, and other objects that do not normally belong in the blood, thereby controlling the extent of various disease-producing conditions. They also produce antibodies.
8. **Is a platelet a cell like red and white blood cells? What is the function of platelets?**
   A platelet is a non-living substance, without a nucleus. Compared with red and white blood cells, it is a cell fragment. Platelets along with a series of chemical reactions aid in the clotting of blood.

How Chemistry Helps Make Blood Transfusion Safer

1. **Why can't human blood simply be transferred from one person to any other person?**
   Blood varies in its compatibility from one person to another. Among other things, there are four basic differences or blood types known as A, B, AB and O. The letters refer to antigens (special proteins that coat the red blood cells) that can cause the equivalent of an allergic reaction when a particular blood type is introduced into another person who does not have the same blood type.
2. **What are the advantages of plastic bags for collecting and storing blood (compared with glass bottles that used to be used)?**

Plastic bags are non-breakable, chemically inert, disposable, and easily sterilized. They can be mass produced at lower cost than glass.

3. **What is the difference in storage life for blood that is at room temperature versus refrigerated blood versus frozen blood?**
   Blood at room temperature does not last more than five days because of chemical change in the platelets. Refrigerated blood lasts about 42 days before the red blood cells become non-functional. Frozen blood lasts up to 10 years with several special chemicals added.
4. **How are viruses detected that may be present in donated blood?**
   If viruses are present in the donated blood, the body of the donor would have produced antibodies to the virus in the blood. These antibodies can be detected, indicated that viruses are also present.
5. **What determines blood types A, B, AB and O?**
   These blood types are based on the presence of either so-called antigen "A", "B", both antigen A and B in "AB" blood or no antigens as in the case of blood type "O".
6. **What is the difference between the function of red blood cells and platelets?**
   Red blood cells transport oxygen and some carbon dioxide, while platelets are responsible for clotting blood in conjunction with several other chemicals.
7. **How might nitric oxide gas be used to monitor the age and quality (condition) of donated blood?** *Nitric oxide in the body is associated with increasing blood circulation by causing blood vessels to dilate. But there seems to be a correlation between the age of blood and the amount of nitric oxide present in the blood. The amount of nitric oxide decreases in a blood sample over time. Therefore it could be used, on a comparative basis, to determine if the blood is fresh enough for use, since the presence of enough nitric oxide seems to mean that this chemical will help to increase blood flow rates due to blood vessel dilation.*

Rebreathers

1. **What is the function of a rebreather?**
   A rebreather recycles the unused oxygen in our exhaled air, while removing the carbon dioxide we exhale.
2. **What does your body do with the inhaled air?**
   The human body uses the oxygen in inhaled air for cellular respiration.
3. **What percentage of the air in each breath we inhale is consumed oxygen?**
   Only 4 % (1L in 25 L) of the air we inhale is oxygen consumed in our body.
4. **What percentage of the oxygen we inhale is consumed in each breath?**
   Twenty % (20 %) of the oxygen we inhale is consumed by our body.
5. **What is the role of carbonic acid in respiration?**
   Carbonic acid helps to regulate blood pH.
6. **What causes acidosis?**
   Acidosis is caused by too much carbon dioxide in the blood.
7. **What are the symptoms of acidosis?**
   The symptoms of acidosis are shortness of breath, easy fatigue, chronic cough, and respiratory failure.
8. **What are the components of a rebreathing apparatus?**
   A rebreather is made of two gas tanks—one oxygen, one a diluent gas, the counterlung that holds the gas when it is not in the diver's lung, and the scrubber which chemically removes the carbon dioxide from the gas system.
9. **What can go wrong with a rebreather?**

1) If the absorbent is not packed correctly, carbon dioxide can pass through/around the absorbent and reenter the counterlung.
2) The absorbent can be used up, rendering the scrubber useless until it is repacked.
3) If the scrubber gets wet, the diver can get the toxic hydroxide scrubber mixture in his mouth.

10. **In this article, what do divers and the Apollo XIII astronauts have in common?**
Both divers and the Apollo XIII astronauts need(ed) to use self-contained breathing apparatus, and they use(d) rebreathers to scrub the air of its carbon dioxide content so they can rebreathe the unused oxygen.

The Not So Simple Life of Filters

1. **What size particles can be retained by a filter paper of a fine grade?**
Particles as small as 1-2 μm can be retained by a fine grade filter paper.
2. **What is the name given to the mass of glass formed in the production of a glass filter?**
The mass of glass formed in the production of a glass filter is called a frit.
3. **What material is used to make a ceramic filter?** *The material that is used to make a ceramic filter is porcelain.*
4. **What is the name the phenomenon that occurs when particles that are being filtered bind with the filter's surface?**
Fouling is the name of the phenomenon that occurs when particles that are being filtered bind with the filter's surface.
5. **Pressure is required in what kind of filtering system?**
Reverse osmosis requires pressure to force the water molecules from the more concentrated side to the more dilute side of the semi-permeable membrane.

"Follow the Carbon." Follow the *What*?

1. **What is an organic compound?**
An organic compound is a compound which contains carbon, hydrogen, and sometimes other elements.
2. **What is the simplest organic compound?**
Methane is the simplest organic compound.
3. **How is this compound produced on Earth?**
Methane is normally produced by the decomposition of biodegradable materials in wetlands and landfills and as a byproduct of digestion in humans and other animals.
4. **How might this compound be produced on Mars?**
Living things might produce the methane found on Mars, it may have been delivered to Mars by meteorites, volcanoes may have produced it, or the weathering of rocks might cause the hydration of certain minerals to produce methane.
5. **Did the Viking probes find any organic compounds on Mars?**
No, the Viking probes did not find any organic compounds on Mars.
6. **How many protons and how many neutrons does an atom of carbon-12 have?**
A carbon-12 atom contains 6 protons and 6 neutrons.
7. **How many protons and how many neutrons does an atom of carbon-13 have?**
A carbon-13 atom has 6 protons and 7 neutrons.
8. **What does GCMS stand for?**
GCMS stands for gas chromatography/mass spectrometry.

ChemMatters Puzzle: DIAL-A-COMPOUND

Shown below is the typical telephone layout. Notice that for each number there are three letters. It's easy to imagine that baseball player Roger Clemens might have the telephone number 254-6367, since one can spell out CLEMENS by those numbers. Knowing that he is a famous pitcher helps out in this identification.

Listed below are ten chemical COMPOUNDS whose names all have seven letters. None are classes of compounds, but rather a specific chemical name. Some are from organic chem., some from inorganic, and a few are names of important minerals. They are in no special order.

We'll provide their "phone number" and one clue that sets them apart.
For example, 776-7263 contains the letters PROPANE, with "barbeque gas" as a clue.
See if you can identify all ten with just this information. But if you need extra help we'll provide a list of chemical FORMULAS used… but scrambled!

Good luck with your phoning; don't get any wrong numbers!

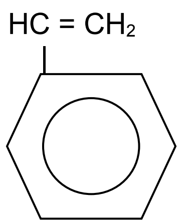
782-7673	**a disaccharide**
228-9483	**ore rich in aluminum**
266-6642	**has three s-sp^3 bonds and a lone pair of electrons**
384-2665	**when" denatured", this compound is quite poisonous**
223-8663	**the simplest ketone**
225-2483	**deposited by marine organisms**
225-6635	**often used in reference electrodes**
277-4746	**acetyl salicylic acid**
258-6462	**helps protect surfaces of element #13 from corroding**
789-7363	**monomer of an important plastic**

Here's the telephone lay-out

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

The scrambled list of formulas:

C_2H_6O
$C_3H_6\ O$
$C_9H_8O_4$
$C_{12}H_{22}O_{11}$
Al_2O_3
Al_2O_3 hydrated
$CaCO_3$
Hg_2Cl_2
$N\ H_3$



Answers to DIAL-A-COMPOUND

SUCROSE
BAUXITE
AMMONIA
ETHANOL
CALCITE
CALOMEL
ASPIRIN
ALUMINA
STYRENE

NSES Correlation

National Science Education Content Standard Addressed

National Science Education Content Standard Addressed As a result of activities in grades 9-12, all students should develop understanding	**Question From the Classroom**	**The Forensics of Blood**	**Chemistry Makes Blood Transfusion Safer**	**Rebrea-thers**	**The Not So Simple Life of Filters**	**"Follow the Carbon"**
Science as Inquiry Standard A: the abilities necessary to do scientific inquiry**.**	✔					
Science as Inquiry Standard A: about scientific inquiry.	✔	✔	✔	✔	✔	✔
Physical Science Standard B: of the structure of atoms.						✔
Physical Science Standard B: of the structure and properties of matter.	✔	✔	✔		✔	✔
Physical Science Standard B: of chemical reactions.		✔	✔	✔		✔
Physical Science Standard B: of interaction of energy & matter.		✔				✔
Life Science Standard C: of matter, energy, and organization in living systems.			✔	✔		✔
Science and Technology Standard E: about science and technology.	✔	✔	✔	✔	✔	✔
Science in Personal and Social Perspectives Standard F: of personal and community health.		✔	✔	✔	✔	
Science in Personal and Social Perspectives Standard F: of natural and human-induced hazards.		✔	✔	✔		
Science in Personal and Social Perspectives Standard F: of science and technology in local, national, and global challenges.		✔	✔	✔	✔	✔
History and Nature of Science Standard G: of science as a human endeavor.		✔	✔	✔		✔
History and Nature of Science Standard G: of the nature of scientific knowledge.	✔	✔	✔	✔	✔	✔
History and Nature of Science Standard G: of historical perspectives.			✔	✔		✔

Anticipation Guides

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

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

The Forensics of Blood

Me	Text	Statement
		1. Since the early 1900s, police investigators have used tests to confirm that what looks like blood at a crime scene really is blood.
		2. When luminol is sprayed on even small amounts of blood, it glows, but similar results can be obtained using horseradish and other substances.
		3. Tests that can determine what kind of animal the blood came from depend on creating antibodies for that type of animal.
		4. The four human blood types are defined by the proteins present on the surface of white blood cells.
		5. Blood is sticky and viscous, producing patterns that provide clues in solving crimes.
		6. Blood consists of about 55% red blood cells, 40% plasma, and 5% white blood cells.
		7. Blood type can be determined by identifying antigens or antibodies.

How Chemistry Helps Make Blood Transfusion Safer

Me	Text	Statement
		1. Blood transfusions have been safely done for several centuries.
		2. Donated blood is mixed with chemicals that prevent clotting and preserve blood for more than a month.
		3. Donated blood is stored in PVC bags.
		4. Viruses, including HIV, can be detected by measuring the presence of specific antibodies.
		5. People with type AB blood may receive only type AB blood in a transfusion.
		6. After a blood transfusion, platelets help regulate blood pressure.
		7. Synthetic blood is currently being used for blood transfusions in many hospitals in the United States.
		8. The blood needed after an emergency may be donated after the emergency occurs.
		9. Thanks to hemoglobin, red blood cells can carry up to one liter of oxygen per minute throughout the body.

Rebreathers

Me	Text	Statement
		1. Divers use rebreathers to breathe in the air they breathe out.
		2. We use about 1% of the available oxygen we inhale.
		3. Too much carbon dioxide in the blood increases the blood pH, leading to alkalosis.
		4. SCUBA divers exhale into the water.
		5. Nitrogen produces narcotic effects at depths approaching 30 meters.
		6. When CO_2 is absorbed in the scrubber of a rebreather, water and heat are produced.
		7. The absorbents in rebreathers are hydroxides which can dissolve in water.
		8. The Apollo 13 command module and lunar module both used the same chemical (LiOH) and the same cartridges, so astronauts were able to switch from one to the other.

The Not So Simple Life of Filters

Me	**Text**	**Statement**
		1. Filters may be made of glass.
		2. Changes in the density or thickness of filters changes the size of particles retained by filters.
		3. Ceramics filters have holes in them that allow passage of the substance being filtered.
		4. Radioactive sources may be used to put holes in polymer membranes.
		5. There is no way to increase filtration efficiency of a given filter.
		6. No filters can filter out bacteria.
		7. Reverse osmosis filters may have membranes that can remove charged particles.

“Follow the carbon.” Follow the What?

Me	Text	Statement
		1. The Sample Analysis at Mars (SAM) suite of instruments will collect and analyze soil and atmospheric samples for carbon on Mars beginning in mid-2010.
		2. Methanogens are single-celled organisms that require oxygen to live.
		3. Carbon was found on the Martian surface by the Mars Exploration Rovers in 2004.
		4. Carbon in meteoritic material has a lower carbon-13/carbon-12 ratio than carbon made by organisms on Earth.
		5. A spectrometer vaporizes a sample to analyze the light absorbed, emitted, or scattered by a material.

Content Reading Guides

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

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

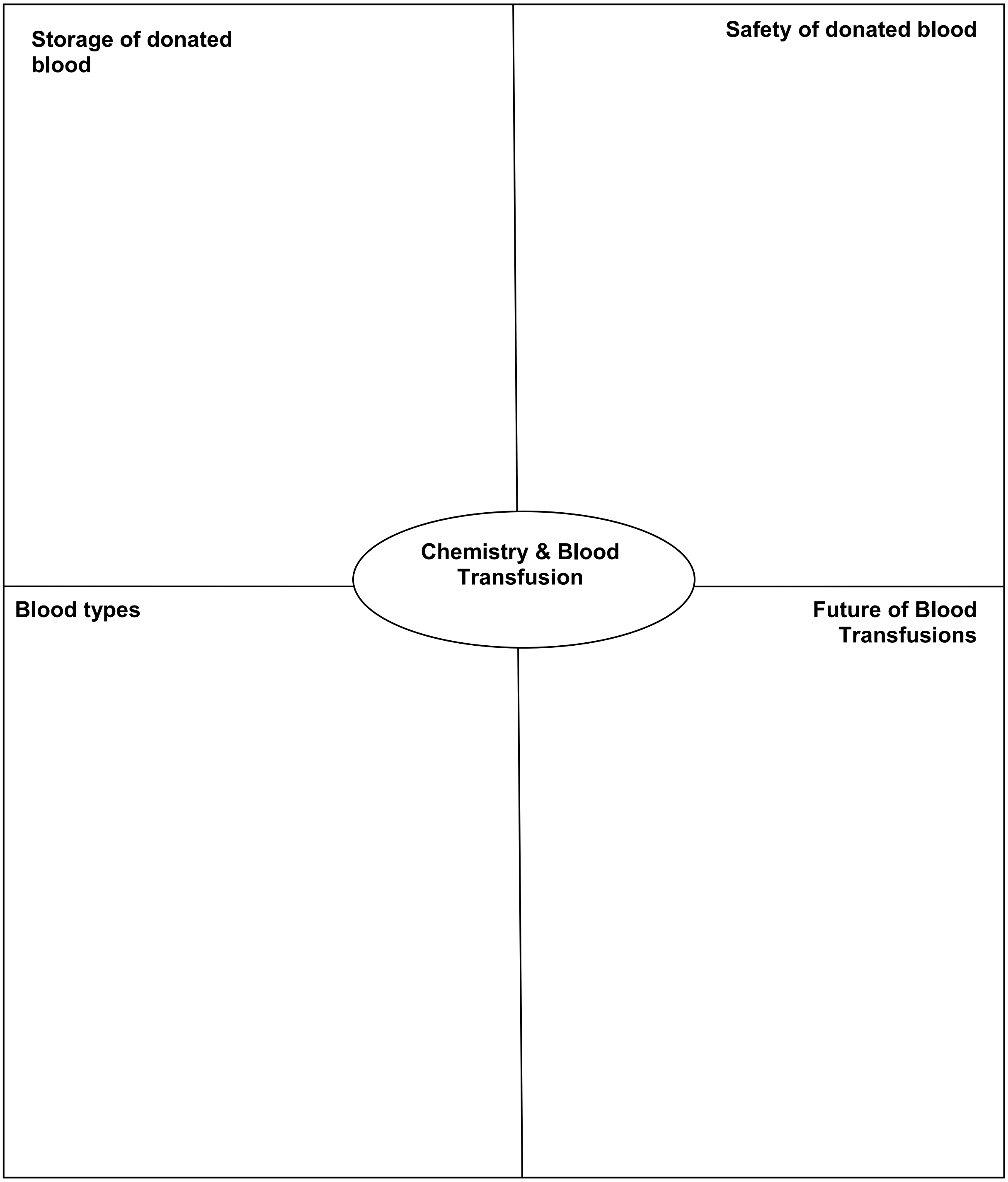
The Forensics of Blood

Use information from the article to describe the purpose and explain each test used by police investigators.

Test	Purpose	Chemical explanation
Luminol		
Kastle-Meyer		
Precipitin		
Blood type		
Bloodstain pattern		

How Chemistry Helps Make Blood Transfusions Safer

In the chart below, describe the **chemistry** involved in each issue related to blood transfusions.



Rebreathers

Find the chemical equation for each process named in the table and tell where in the body or in a rebreather the process occurs.

Description	Chemical Equation	Where does this occur, or where is it found?
Cellular respiration		
Formation of carbonic acid		
Formation of carbonic acid/bicarbonate ion buffer		
Nitrox composition	List percent composition here. There is no chemical equation.	
Heliox composition	List percent composition here. There is no chemical equation.	
Removal of carbon dioxide	Write three equations here.	

The Not So Simple Life of Filters

As you read the article, complete the table below describing each type of filter.

Type of Filter	Description	Uses (if given)
Paper		
Glass		
Ceramic		
Polymer		
Nanofilters		
Reverse Osmosis		

"Follow the carbon." Follow the What?

Complete the chart below using information from the article.

	Definition and examples, if given	Why important in the search for carbon on Mars?
SAM		
Organic compound		
Methanogen		
GCMS		
Carbon isotopes		
Chondrite		

The Forensics of Blood

Background Information

More on Blood Testing and Blood Properties

Testing for the presence of blood as documented in the student version of *"The Forensics of Blood*" is dependent on several properties of the particle content of blood—hemoglobin in red blood cells, antibodies, antigens (A and B, Rh factor) as found on the surface of red blood cells. An additional substance that can be analyzed to determine ownership of the blood is DNA. DNA that is extracted from white blood cells (since red blood cells don't have nuclei) can be replicated to increase the size of the sample, then put through the procedure of electrophoresis in order to identify the order of the purines and pyrimidines on the DNA, the genetic "fingerprint" of an individual. For additional information on the properties of blood, the following will prove useful:

http://www.pbs.org/wnet/redgold/resources.html
http://www.daviddarling.info/encyclopedia/B/blood.html
http://en.wikipedia.org/wiki/Blood

Today, there are many textbooks for high school students that present a very complete forensics learning program, including laboratory activities. There are also several science supply companies that provide a variety of kits for investigating a mock crime scene. These kits include blood facsimiles for testing, so there are no safety issues with handling real, human blood.

More on Forensic Investigation Procedures

As mentioned, there are useful high school textbooks in forensics that provide all the background information on the professional techniques for investigating a crime scene with advice for the teacher on how to set up mock crime scenes of various kinds. The following references are from professional websites to further strengthen the background material in a textbook.

http://www.practicalhomicide.com/research.htm is a primary site for a collection of articles on crime scene investigations.

http://www.practicalhomicide.com/articles/PhyEv.htm features specific crime scene investigation procedures.

http://www.practicalhomicide.com/research/LOmar2007-2.htm#top deals with blood stain pattern analysis.

One of the common chemical tests for detecting the presence of blood is known as the Kastle-Meyer test. It is based on the idea that hemoglobin increases the ability of hydrogen peroxide to act as an oxidant. In the presence of hemoglobin, a molecule of hydrogen peroxide (H_2O_2) oxidizes another molecule of hydrogen peroxide, forming bubbles of oxygen, as follows:
$2H_2O_2$ =======> O_2 (g) + 2 H_2O (l)

In the early 1900's, Dr. Kastle developed a presumptive test for hemoglobin using phenolphthalein's color change in the presence of oxygen. In this test, the phenolphthalein is reduced and pre-dissolved in alkaline solution, giving it a faint yellow color. Then, in the presence of hydrogen peroxide in alkaline solution, the hemoglobin catalyzes the oxidation of this form of phenolphthalein to its normal form, which results in a color change of the phenolphthalein from yellow to intense pink. More details are provided in the original article and in the following reference: http://www.geocities.com/a4n6degener8/kastle.htm.

The various standard crime scene tests that can easily be done in the classroom/lab are available both as kits and with lab procedure instructions for the student and are available from the different science supply companies.

More on Blood Tests Using Luminol and the Chemistry of Luminescence

http://www.chm.bris.ac.uk/webprojects2002/fleming/intro.htm This site is a starting point for information not only about luminescence but also fluorescence and phosphorescence with links to other information including the following URL: http://www.chm.bris.ac.uk/webprojects2002/fleming/mechanism.htm This website provides complete information on the luminol reaction—equations, mechanisms and even a video of the luminol reaction.

In addition to using luminol to detect the presence of blood, several other chemical reactions are used. For example, the Takayama test involves addition of sodium hydroxide, pyridine, and glucose to a suspected blood stain. If blood is present, the hemoglobin will react to form crystals of hemochromogen. Another test, called the Teichmann test consists of adding sodium chloride and then glacial acetic acid to a blood stain, which, if blood is present, will produce crystals of hemin.

Another commercial product called *Hematest* relies on the hemoglobin in a blood stain to activate hydrogen peroxide—formed from the reaction of water with solid strontium peroxide—and the activated hydrogen peroxide oxidizes another chemical component of the tablet, tetramethylbenzidine, which produces a blue color. The Hematest device is used to test for normal medical conditions such as detecting blood in feces as a possible sign of cancer.

Connections to Chemistry Concepts

1. **Chemiluminescence**—This phenomenon occurs when a particular chemical reaction causes electrons in one of the reactants to cascade down an energy gradient after first gaining energy, giving off energy in the form of light rather than heat. * Luminol in an alkaline solution with hydrogen peroxide in the presence of iron or copper[1], or an auxiliary oxidant[2], produces chemiluminescence. The luminol reaction is

   luminol + H_2O_2 → 3-APA[◊] (excited) → 3-APA + light

   (3-APA is Amino Phthalic Acid.)
2. **pH Indicators**—These are molecules that act as an acid in solution producing color changes because of change in the indicator's molecular structure when donating a proton. For phenolphthalein, the donation of two protons occurs at a pH of 8.2 In an alkaline solution, phenolphthalein changes as follows:

   $C_{20}H_{14}O_4 \rightarrow C_{20}H_{12}O_4^{-2} + 2\ H^+$
3. **pH**—The numerical range of acidity through alkalinity is important to the structural integrity of molecules and is an important chemical environmental condition for the function of enzymes.

4. **Organic compounds**—Any chemical that contains carbon (excepting carbon monoxide and carbon dioxide and metallic carbonates) is considered an organic compound. Because of the bonding based on the carbon atom, organic compounds have an infinite number of configurations with important "functional" groups attached. Something like a hemoglobin molecule is considered to have a large molecular weight (64,500), with about 5000 atoms indicating a large molecule. Because the molecule is so large, it folds into a specific shape based on the four individual peptide chains that are linked by both ionic and hydrogen bonds. The size of organic compounds is wide ranging. It is thought that a truck tire made of vulcanized rubber —which consists of polymer molecules linked to each other by atomic bridges—is a single molecule!
5. **Viscosity**—Defined as resistance to flow, the viscosity of a liquid is determined by molecular structure and resulting intermolecular forces that are possible through polarity. In organic compounds, hydrogen bonding is common, particularly involving the hydroxyl group (-OH). Differences in viscosity between organic alcohols, such as glycerol and 1-propanol (both three carbon alcohols), are produced by the number of –OH groups. Propanol, the least viscous, has only one hydroxyl group and glycerol, with three hydroxyls, is the most viscous of the several three carbon alcohols possible. Blood has many more intermolecular bonding sites producing a higher viscosity yet.
6. **Amino Acids**—Amino acids are organic acids that contain the functional amine group ($-NH_2$) as well as the carboxyl group (-COOH) and are fundamental to the various structures of living organisms. Amino acids are linked together through the carboxyl and amine groups (a peptide bond) to form very long chains that are known as polypeptides and/or proteins. Through hydrogen bonding between various points on the polypeptide, various shapes of a molecule can be produced which are specific enough to provide "identification" within living systems (think enzymes, pharmaceuticals, allergens, antibodies, DNA, among other things).
7. **Colloid**—A colloid or colloidal dispersion is a type of homogenous mixture. A colloid consists of two separate phases: a dispersed phase and a continuous phase. In a colloid, the dispersed phase is made of tiny particles or droplets that are distributed evenly throughout the continuous phase. The size of the dispersed-phase particles is between 1 nm and 100 nm in at least one dimension.

Possible Student Misconceptions

1. **"Using a blood sample and testing for blood type can identify a particular suspect with the same blood type."** *If a blood typing test matches that of a suspect, it does not prove he or she is the criminal. It simply eliminates all others who have a different blood type.*
2. **"DNA for testing can only come from sperm or egg cells where DNA is reproduced."** *DNA can be extracted from the nucleus of a cell for replication and analysis using electrophoresis.*
3. **"When using the Kastle-Meyer test to detect the presence of human blood, a positive test is conclusive proof the "spot" is blood."** *Because the reduced phenolphthalein can change color in the presence of several other non-blood substances including potato and horseradish, the color change may not be due to blood. This is known as a false positive.*

Demonstrations and Lessons

In essence, a teacher has many opportunities to do forensics in the classroom these days and to use the program to teach many basic concepts from chemistry, biochemistry and even physics. Rather than produce a variety of standard forensic activities and demonstrations from one of these high school textbooks, it would be better to simply obtain the textbook that usually contains the labs as well as the reading. See what is listed separately in the References section below (the listing is not an endorsement of any particular textbook or publisher).

1. The following four websites are connected to the same main website at the Univ. of Western Australia, but they include a variety of activities and reading material in forensics that can be used in the classroom. http://www.clt.uwa.edu.au/asistm
   To use this site (Univ. of Western Australia), you must type in words related to forensics in the search box. The next three URLs are connected to classroom activities in forensics prepared by UWA for teachers. They include School Break In, Entomology (use of insects to determine how much time has elapsed since the body died), and Blood Splatter patterns.
   http://www.clt.uwa.edu.au/asistm/forensic_investigations/primary_school_breakin
   http://www.clt.uwa.edu.au/asistm/forensic_investigations/bloodstain_pattern_analysis
   http://www.clt.uwa.edu.au/asistm/forensic_investigations/forensic_entomology
2. A standard list of forensic experiments and activities that are supported by science supply companies (see, for example, Ward's, www.wardsci.com) include the following:
   - Staging Crime scenes
   - Documenting Crime Scenes
   - Fingerprinting Evidence
   - Impression Evidence
   - Hair/Fiber/Trace Evidence
   - Entomological Evidence
   - Skeletal Remains
   - Ballistics
   - Trajectory Determinations
   - Blood Evidence
   - DNA Evidence
   - Pathology
   - Toxicology
   - Documents and forgeries
   - Crime Scene Investigation
3. Blood (synthetic form, not human, from science supply companies) can be tested for type (A, B, AB, O and Rh +/-). Instructions are available to prepare "suspect" blood samples and animal samples as well. It is a good exercise in gathering data with limited conclusions. The same is true for the Kastle-Meyer test. Students become aware of "false positive" test results.
4. Separation techniques using paper chromatography as well as electrophoresis can be done to detect particular amino acids as well as DNA patterns (assuming you have electrophoresis equipment, either self-made or commercial)
5. A unit on fibers provides many activities that challenge the chemical knowledge of students. There are a variety of tests that are done on fibers to identify them including burn test, thermal decomposition, chemical tests, absorption characteristics, use of refractive index, fluorescence in dyes, and chromatography.

6. The whole realm of drug testing related to forensics has natural appeal to students! A reference for drug information can be found at www.drugabuse.gov/NIDAHome.html

Student Projects

1. Students could do research to discover how DNA has been used in recent years to free "falsely accused" convicts.
2. Students could trace the history of DNA discoveries, from the 1930s to the 1960s of Watson-Crick to the important polymerase replication technique, PCR that takes a tiny fragment of DNA and replicates it to get a large enough sample to put through electrophoresis.
3. Suggested lessons in numbers 2, 4, and 5 in the Teacher Demonstrations and Lessons section, above, could also be used as student projects

Anticipating Student Questions

1. **"How is DNA detected in bodily fluid?"** *The bodily fluid must contain some kind of body cells in order to be able to isolate, through laboratory procedures, the genetic material (chromosomes) that contains the DNA.*
2. **"How can a chemical test be both positive and negative (=false positive)?"** *Although a chemical test may be used to detect a particular substance, other substances can produce exactly the same results (e.g., a color change). So the result was positive for the chemical reaction (that produced the color change) but was caused by a chemical other than the one being sought. An example of this is the luminol test that is used to detect blood. But various metal ions and bleach can also produce chemiluminescence, hence a false positive.*
3. **"How do investigators determine the height and sex of an individual if only a few bones are found?"** *There is a whole science to reconstructing a person with an incomplete skeleton. Depending on what bones are found, these bone lengths can be plugged into very simple formulas to determine height. Men and women have different proportions for certain bones related to a calculated height. Determining sex (other than through chromosome information) with bones requires the existence of the hip bone, particularly what is known as the Os Pubis part of the hip bone which is different between male and female. Skeletal bones, particularly the skull, can also be used to determine approximate age.*
4. **"What is the basic chemistry behind detecting alcohol on the exhaled breath of a person?"** *The actual detection of alcohol (ethanol) in exhaled breath can be done several ways. The old way was to collect a sample of exhaled breath and allow it to react with orange dichromate which is reduced in the presence of ethyl alcohol (ethanol) and changes to a green color. The new methods use infrared (IR) spectrophotometry. Ethanol absorbs the infrared at very specific wavelengths. Comparison of the input energy to the output energy (the amount of IR that is not absorbed and passes through the detector) allows a calculation, using what is known as the Beer-Lambert law that relates concentration to absorption. A device uses a fuel cell that generates a current from the oxidation of ethanol. Concentration is related to the amount of current that is produced by the oxidation of the alcohol.*

References

"*Forensic Science for High School",* Deslich & Funkhouser: Kendall Hunt Publishing Co., 2006 (www.kendallhunt.com/forensics); ISBN 0-7575-1825-7

Saferstein, R. *Criminalistics: An Introduction to Forensic Science* (9th Ed). Prentice-Hall, 2006 (text; paper back lab manual of same name is 7th Ed, 2003)

Web Sites for Additional Information

The following is a reliable Web site concerning all the properties of blood, good diagrams of the hemoglobin molecule and the circulatory system, the attitudes/beliefs of various religions and cultures about blood, various charts containing numerical information about blood and its constituents, as well as additional science journal references, links and websites: http://en.wikipedia.org/wiki/Blood.

How Chemistry Helps Make Blood Transfusion Safer

Background Information

More on Properties of Blood

Blood as a mixture is a complicated chemical concoction that, over evolutionary time, has performed a variety of functions vital to the existence of many different types of organisms, including humans. As a mixture, it contains a variety of suspended particles, some as large as the red blood cell with a diameter of 5 microns. There are also many specific chemical compounds that help to maintain a necessary equilibrium when the internal environment of an organism is subjected to a variety of changes from the surrounding external environment. Think in terms of temperature, pH, and amount of dissolved gases including oxygen, salts, viruses and bacteria, among others. There is also a variety of protein-based compounds and larger molecules with specific structural shapes that tie directly to their mode of operation. One such large molecular structure is hemoglobin whose primary, though not sole, function is to transport oxygen from the exterior to the interior of an organism at the cellular level.

Hemoglobin consists of four peptide chains (made from amino acids) that enclose a structure known as *heme* which consists of a central ferrous ion (Fe^{2+}) that is bound covalently to the heme, but the heme unit itself is bound noncovalently to the peptide chain that encloses it (see figure on p. 10 of the magazine). The four hemes do not bind oxygen independently. When an oxygen molecule (O_2) binds to one of the hemes, the three other hemes adopt a different structure, making them more accessible, and they each bind to an oxygen molecule relatively easily. It is important for the oxygen not be too tightly bonded; otherwise, the transfer of oxygen between the blood environment and the cells would be difficult.

Why couldn't a simple water solution be used to transport oxygen instead of a special structure like hemoglobin? One has to look at the amount of oxygen that can dissolve in water compared with hemoglobin. One way to look at this issue is to realize, that in human blood, 98.5% of the oxygen is carried by the hemoglobin and only 1.5% is in simple solution. Affinity as well as efficiency is at work here! (See the reference, http://en.wikipedia.org/wiki/Blood, p.16)

A second gas that is transported by blood is carbon dioxide that is produced in the metabolic process known as respiration. Again, the blood is nicely designed chemically to handle carbon dioxide. First, carbon dioxide is much more soluble in plasma and water than oxygen is. Second, there is a specific enzyme (catalyst), carbonic anhydrase, that increases the rate of dissolving for carbon dioxide in water, producing an important ion, the bicarbonate ion ($HCO3^-$) which is highly soluble and which also plays a part in buffering the blood to maintain a fairly steady pH of around 7.2 ($CO_2 + H_2O \rightarrow HCO_3^{-1} + H^{+1}$). But the blood uses the bicarbonate ion to move what was originally carbon dioxide from the cells to the lungs or functionally equivalent structure. And the same enzyme is used when it is necessary to convert the bicarbonate ion back to CO_2 gas for diffusion out of the blood into a lung or the external environment.

In nature, it seems as if metal complexes (metal ions bonded to molecules) such as hemoglobin are found in such variations as chlorophyll molecules where the iron ion is replaced by magnesium (Mg). In the oxygen-carrying proteins of some arthropods (such as horseshoe crabs) and in some mollusks, the job of binding oxygen falls to copper rather than iron. The copper ion is part of a protein called hemocyanin which is colorless without oxygen and dark blue when oxygenated. Hemocyanin carries oxygen in extracellular fluid rather than within cells (red blood cells).

Color changes in blood containing hemoglobin also are due to the amount of oxygen present. Arterial blood is higher in oxygen and brighter red because of the oxygen bound to the iron of the heme. Venous blood (deoxygenated) is darker red. Other conditions in which hemoglobin changes brightness of color include carbon monoxide and cyanide poisonings. In carbon monoxide poisoning, the carbon monoxide molecule binds more strongly to the heme than oxygen and is very difficult to remove. It forms a carboxyhemoglobin which is brighter red than normal hemoglobin. In cyanide poisoning, the oxygen in the blood is not able to be utilized (the cyanide interferes with certain enzymes necessary for cellular respiration). As a result, the venous blood turns brighter red than normal.

A medical condition known as sickle cell anemia is an example of a genetic error that affects protein synthesis (the order of amino acids) that makes for abnormal hemoglobin. In this particular instance, just one amino acid called valine is incorrectly utilized in the hemoglobin chain instead of the normal one, glutamic acid. The glutamic acid is a charged (-1) molecule whereas the valine is neutral. This difference seems to make part of the hemoglobin chain less soluble and causes precipitation of the hemoglobin within the red blood cell. This in turns changes the shape of the red blood cell from circular to curved ("sickle" shape). This structural change means that the blood cells have a difficult time circulating in the tiny blood vessels, the capillaries, which in turn essentially clogs up the blood vessels, creating pain and reduced oxygen-carrying capacity for the victim. Long term, the sickle cell condition can become both debilitating as well as fatal. The only good aspect of sickle cell anemia is that individuals with the condition are less prone to malarial infection and attacks for reasons not fully explained.

Another interesting medical condition involving the synthesis of the heme portion of hemoglobin is known as porphyria. There is a sequence of eight steps in the synthesis of the heme molecule, each catalyzed by a separate enzyme. If any step fails because of a genetic mutation or an environmental toxin, the chemical chain of events is interrupted with a back-up of what are known as porphyrin intermediates. These porphyrins can accumulate to toxic levels. Exposed to light (as in the skin), these compounds can turn caustic, destroying tissue. (They also can be excreted in feces and urine, turning to a purple [port wine] color.) That said, these porphyrin compounds have a potentially beneficial use, attacking tumors for instance. The effectiveness of this particular application again depends on the porphyrin being exposed to light. For more on the condition of porphyria and some interesting history that includes werewolves and vampires, refer to the following two articles:
"New Light on Medicine"; by Nick Lane, *Scientific American,* January 2003;
http://www.sciam.com/article.cfm?articleID=000B4130-5C6C-1DF7-9733809EC588EEDF and
http://www.sciam.com/article.cfm?id=born-to-the-purple-the-st

Another interesting facet of blood is the existence of some animals, particularly fish, some frogs, as well as some insects, which have evolved some chemical additives to their blood that act as an anti-freeze compound to survive in very cold environments, both on land and in water. In these different organisms, the anti-freeze substances are special proteins (antifreeze proteins, AFP) that prevent the formation of ice crystals within the animal's cells, thereby preventing the puncturing of the cell membrane and the fatal loss of the cells' liquid contents. (See http://www.gi.alaska.edu/ScienceForum/ASF15/1560.html and
http://news.nationalgeographic.com/news/2007/02/070220-frog-antifreeze.html

With blood acting as the transport medium for gases, particularly oxygen and carbon dioxide, mammalian bodies have adaptive mechanisms for certain stressful conditions that are potentially hazardous. But these adaptations in some instances make use of the blood circulatory system. One such adaptation actually occurs in the unborn child in which dissolved oxygen levels from mother to fetus (at the exchange point, called the placenta) are not as high as needed. As a result, the fetus has available a modified hemoglobin called "hemoglobin F" that has a higher affinity for oxygen. Under low oxygen conditions for adults, as in high altitude situations, the adult is not able to produce this hemoglobin "F". Two other adaptations however are possible. One is the production of more red cells which usually takes several days to accomplish once the person is in a lower oxygen situation. The other adaptation, a genetic one, is found in certain populations who are born and live in high altitude conditions. An example is the Sherpas of Tibet. Living at altitudes averaging 4500 meters (3 miles!) above sea level, these people do not suffer from the condition known as altitude sickness because they are able to increase their blood flow rate through the production of nitric oxide (NO) in the linings of their blood vessels. The nitric oxide dilates the blood vessels, allowing for large volumes of blood flow in the arteries and capillaries. More information on this topic can be found in Scientific American magazine: http://www.sciam.com/article.cfm?articleID=ED53255A-E7F2-99DF-36FFDF78DD9F2F36.

More on Blood Transfusions

There is a wealth of information including timelines back to the days of the Greeks that highlights the development of the techniques for transfusing blood, testing the blood for various diseases, discovering various additives that can take the place of whole blood including the need for modified blood for hemophiliacs.
(http://www.pbs.org/wnet/redgold/resources.html)

Also, some basics about the information found on a blood-collecting bag (with illustration) as well as some issues related to collected blood can be found in the *Scientific American,* Nov. 2007, pp. 108-109. This article can be accessed electronically at the following website: http://www.sciam.com/article.cfm?id=blood-cells-for-sale.

There are many "actors" in this saga of perfecting the art of blood collection (anticoagulation) and transfusion. One American scientist, Dr. Charles Drew, pioneered the development and operation of the blood bank based on all his research into the properties of blood that could be utilized to develop storage procedures.
(http://www.redcross.org/museum/history/charlesdrew.asp)
(http://www.pbs.org/wnet/redgold/innovators/index.html)

More on Artificial Blood and Blood Substitutes

A substantive series of articles on artificial blood can be found in one place, Scientific American's site called "Ask the Experts": http://www.sciam.com/article.cfm?id=how-do-scientists-make-ar. Included in this website are additional references primarily from scientific journals rather than popular texts. The second article in this series discusses why modified hemoglobin extracts must be part of artificial blood and what the complications are for using straight hemoglobin. Included in this discussion are the bioengineering techniques used to modify hemoglobin. The reason for trying to find ways to incorporate stable forms of hemoglobin into synthetic blood mixtures is because hemoglobin can carry much more dissolved oxygen than something like the perfluorochemicals. Therefore, the use of perfluorochemicals has some limitations (and some advantages as well) unless a way can be found to increase oxygen-carrying capacity.

At the following Web site, you can find a video-based program on blood substitutes from the PBS "*Wired Science*" series: http://www.pbs.org/kcet/wiredscience/video/196-additional_thoughts_on_blood_substitutes.html

In addition, how artificial blood is made, complete with background, history, design, raw materials and manufacturing techniques can be found at http://www.madehow.com/Volume-5/Artificial-Blood.html.

There is also a discussion about the results of recent field tests of one blood substitute called "Polyheme" at ABC News Videos (3 videos in the series) (http://abcnews.go.com/search?searchtext=Artificial%20Blood%20controversy&type=)

Another view of the issues regarding both effectiveness and hazards of blood substitutes is found at http://www.sciam.com/article.cfm?id=blood-substitutes-hemoglobin-anemia&print=true

Also, *ChemMatters* published an article on synthetic blood: "Synthetic Blood: Supply from a Different Vein," by Bruce Goldfarb, *ChemMatters*, April 1998, pp. 13-15.

Connections to Chemistry Concepts

1. **Polymers**—Large molecules made from joining together many smaller molecules are particularly useful in the biological world, where such things as hair, skin, and various proteins (known as polypeptides), some of which act as catalysts, are all polymers. Much of the large size of polymers depends upon the extensive bonding (networks) that is possible because of carbon atoms. The plastics of blood collection bags are polymers and are carbon-based.
2. **Organic compound**—Any chemical that contains carbon (except carbon monoxide, carbon dioxide and metal carbonates) is considered an organic compound. Because of the bonding based on the carbon atom, organic compounds have an almost infinite number of configurations with important "functional" groups attached. The size of organic compounds is wide ranging. It is thought that a truck tire of synthetic or natural rubber, a polymer, is a single molecule!
3. **Gas solubility**—Solubility is a property of gases that is dependent on both the molecular structure of the gas and the chemical properties of the solvent in which the gas dissolves. For biological organisms, the solvent is usually water. Both temperature and atmospheric pressure affect the extent of dissolving and escaping of the gases.
4. **Enzyme**—Enzymes are organic catalysts that accelerate rates of biochemical reactions. One example is the use of the enzyme carbonic anhydrase to accelerate the rate at which carbon dioxide dissolves in the blood or is removed from the blood through the formation of the bicarbonate ion (HCO_3^{-1}).
5. **Amino Acids**—Organic acids which contain the functional amine group ($-NH_2$) as well as the carboxyl group (-COOH) and are fundamental to the various structures of living organisms are called amino acids. These acids are linked together through the carboxyl and amine groups (a peptide bond) to form very long chains that are known as polypeptides and/or proteins. Through hydrogen bonding between various points on the polypeptide, various shapes of a molecule can be produced which are specific enough to

provide “identification” within living systems (think enzymes, pharmaceuticals, allergens, antibodies, DNA, among other things).

6. **pH**—pH is the term given to the numerical range of acidity through alkalinity that is important in the biological world. Among other things, certain enzymes will only function in a narrow pH range (think enzymes in the acid environment of the stomach vs. the alkaline environment of the intestine). For the blood, a pH in the range of 6.8-72 is necessary and is maintained through the use of buffers, including the bicarbonate ion, HCO_3^{-1}.
7. **Polymers and cross-linking**—In polymer-like materials including thermal plastics and proteins like hemoglobin, linkage between several chains of atoms can be produced through covalent bonding of atoms such as sulfur between the chains, as in the vulcanization of rubber.

Possible Student Misconceptions

1. **“A person who donates blood runs the risk of acquiring AIDS.”** *The equipment used to remove blood from a donor is sterile and is kept sealed until applied to the donor’s vein for collection. The equipment will not be contaminated with the AIDS virus so the donor will not get the AIDS virus.*
2. **“Plasma is not real blood.”** *Plasma is part of blood and therefore is real.*
3. **“Blood inside our bodies is blue, but it turns red when exposed to air.”** *No, blood is always red. It only looks blue in the veins close to our skin (at the wrists, for instance) because shorter wavelength red light can penetrate farther into the skin than longer wavelength blue light. If blood in veins is just far enough beneath the surface of the skin, the red light is absorbed by the blood, while the blue light is reflected back to our eyes before it reaches the blood. The reflected light is what we see coming back at us; hence, the blood in that vein appears blue. While this isn’t a scientific site, it offers a simple explanation of the phenomenon: http://www.colourlovers.com/blog/2007/07/26/color-in-science-is-my-blood-really-blue/. Here’s a more scientific explanation from Discover Magazine, for the naturally curious: http://discovermagazine.com/1996/dec/theskinnyonblueb954.*

Demonstrations and Lessons

1. The effect of both temperature and pressure on the solubility of gases in solution can be demonstrated with the use of carbonated beverages, particularly colorless club soda. Setting up a glass delivery tube with stopper that fits 1-liter soda bottles will allow for gas collection by water displacement when you change the temperature of the soda. Immerse the soda bottle system in a large beaker or pan of water that can be heated. For pressure effects, simply releasing the cap on an unopened bottle of soda will clearly show loss of gas from a lowered pressure (the inverse of increasing gas solubility from an increase in pressure).
2. Students can test the idea of incompatibility of blood because of different antigen-antibody reactions by using special blood testing kits that are available from science supply companies. These kits do not contain real blood, so as to avoid the possibility of exposing students to any human blood that may be contaminated.
3. A most unusual and fascinating project for students combines religious history, miracles, and “mysterious” chemistry. The project is based upon the martyred death of a Saint Januarius and the annual celebration of his blood turning from a gel to a liquid on the anniversary of his death more than 1600 years ago. The blood (in a vial kept in Naples

Italy) is supposed to be that of Saint Januarius. Some Italian chemists have tried to determine if this is real blood or not by trying to make a concoction known as a thixotropic mixture. The formula for making this mixture that goes from solid (gel) to liquid by shaking is found in the Feb. 1993 ***ChemMatters*** (p.15) along with the story behind this religious miracle and the chemical sleuthing done by the three Italian chemists (pp.12-14). It makes for an interesting bit of chemistry for students.

4. The information on the history of blood from the PBS program, *"Red Gold"* that can be found at http://www.pbs.org/wnet/redgold/resources.html is a treasure trove of information for students to use in a variety of writing projects, including the history of and the characters involved in discovering various things about the human body's circulatory system and its many components, particularly blood itself. The site includes video clips with some of the scientists talking about their work. There are also useful timelines with short biographies attached of various scientists.
5. Students could get into forensic science, particularly that part that involves detecting blood at a crime scene. There are many high school textbooks with lab activities about forensic science. There are also science supply companies that have a variety of kits for detecting the presence of blood, the type of blood, blood spatter pattern analysis, and comparing blood from different animal species. There is also the important detection of DNA at a crime scene and various procedures to examine, by electrophoresis, the content of the DNA, then try to match the banding patterns against various "suspects'" DNA that is provided.

Student Projects

1. Students could investigate the development of synthetic blood and write/give a report on their findings.
2. See above suggested projects #'s 2- 5 for students under Teacher Demonstrations and Lessons for more project ideas.

Anticipating Student Questions

1. **"If iron is found in blood (in the heme part of hemoglobin), why doesn't blood show signs of rust?** *In blood, ferrous ion Fe^{2+} is readily oxidized by oxygen to form ferric ion Fe^{3+} (which can form rust if it reacts with oxygen). But each ferrous ion in blood is tightly bound to a heme and is not readily removed as it would have to be to form iron oxides.*
2. **"How can a red blood cell function if it has no nucleus?"** *It is true that a red blood cell lacks a nucleus as found in other biological cells. But the red blood cell essentially operates through a variety of chemical reactions, the principle one being the binding of oxygen molecules to the ferrous ion in the heme portion of the hemoglobin found in the red blood cell. The gain and loss of the oxygen is dependent on the partial pressures of oxygen within the cell and the partial pressures of oxygen outside the red blood cell. The oxygen gas diffuses from the higher partial pressure to the lower (lungs to blood). A nucleus is not needed to control such a function.*
3. **"How can synthetic blood fight disease?"** *Actually it can't. The primary function of synthetic blood is to carry oxygen and carbon dioxide. It is made to act primarily as a substitute for red blood cells.*
4. **"Why can't you just use a water-based solution containing salts as a blood substitute since sea water has oxygen dissolved in it and fish do just fine**

'breathing'?" *It is a question of how much oxygen will dissolve in a water-based solution compared with how much oxygen can be attached to hemoglobin ("dissolved") for exchange at the cell membrane barrier. And for the amount of oxygen needed by a blood-carrying animal, not enough would simply dissolve in a water-based liquid compared with how much attaches to hemoglobin. In the blood, more than 95 % of the oxygen attaches to the hemoglobin compared with 2% found dissolved in the plasma (water-based) portion of the blood.*

Web Sites for Additional Information

http://www.daviddarling.info/encyclopedia/B/blood.html This website is a science encyclopedia with emphasis on the biological. One can find various topics using the alphabet tool bar.

http://www.sciam.com/article.cfm?id=what-is-thalassemia This Web site discusses another genetic disease involving defective hemoglobin synthesis called thalassemia or Mediterranean anemia (compare with porphyria). Included in the article is a good "color-coded" picture of normal hemoglobin's structure (alpha and beta chain positions).

http://www.sciam.com/article.cfm?id=000B4130-5C6C-1DF7-9733809EC588EEDF&page=2 This reference in Scientific American makes a good read for students who are interested in seeing the connections between basic biochemistry and specialized applications of biochemistry for treating medical conditions. The specifics involve the use of certain organic compounds, particularly porphyrins, which are altered by exposure to light, subsequently creating toxic products that might be useful in treating cancer, as an example. It is related to the reference to the condition known as porphyria mentioned in the teacher's guide.

http://www.sciam.com/article.cfm?id=blood-substitutes-hemoglobin-anemia This reference deals in detail with one specific blood substitute including the issues involved in its manufacture and the problems in its use.

Rebreathers

Background Information

More on the history of rebreathers

According to Wikipedia, in 1620 Cornelius Drebbel may have unknowingly made the first rebreather. He constructed an oar-powered submarine and included the burning of saltpeter to provide oxygen for breathing. The sodium or potassium nitrate when it reacted would have produced oxides or hydroxides of the metal, and these would have absorbed carbon dioxide from the air, creating a rebreathing apparatus by default.

The next person in the history of rebreathers is Theodor Schwann, the same person responsible for cell theory in biology. This web site shows copies of his original designs from 1853 for two types of rebreathers: http://www.therebreathersite.nl/Zuurstofrebreathers/German/theodore_schwann.htm. His models were designed for use in mining and other incidents, not for underwater use, and it seems that a mining accident in 1876 prompted him to resurrect his inventions. He showed his design in Paris in 1878. Unfortunately, he never patented his designs, and in 1878 Henry Fleuss patented his own version of the rebreather. There may have been some disagreement among the inventors at the time about who should get credit for the invention.

In 1910 Sir Robert Davis invented the Davis Submerged Escape Apparatus for use as an emergency escape apparatus on submarines. It was also used for diving and for industrial breathing uses. Davis' apparatus used barium hydroxide in its scrubber. The apparatus was designed to retain enough oxygen/air to act as a flotation device once the person reached the surface. The devices were used with limited success in rescuing sailors from at least three submarines prior and during WWII.

Italian sport spearfishers in the 1930s were the first people known to use rebreathers specifically for diving. During World War II, captured Italian frogmen's rebreathers affected the design of British rebreathers.

Dr. Christian Lambertsen developed US Navy rebreathers in the 1940s. They were designed for underwater warfare. There are very few photographs of these as they were designed under top secrecy during the war.

More recently, innovations in rebreather design have come primarily from advances in electronics, both in sensors and control devices, and in automated systems.

More on the advantages of rebreathers

1) The main advantage of using a rebreather that is discussed in the article is that of efficiency. Only 20 % of the available oxygen in air is actually used in each breath. That means that 80 % of the oxygen is unused—and could be reused (and is reused in a rebreather). According to the article, "…the ratio of oxygen consumed compared to how much is breathed in is about 1 liter per 25 liters of air during moderate exercise. Since air is made of about 21% oxygen, the ratio of consumed to available oxygen is only 20%. That means that most of the available oxygen that we breathe is not being used." In case students have difficulty following the math here, think of it this way:

The oxygen content of air is 21% or approximately 1 L O_2 in every 5 L air,
or 5 L O2 available / 25 L air inhaled

$$\frac{1\ \text{L}\ O_2\ \text{consumed}}{\cancel{25\ \text{L air inhaled}}} \times \frac{\cancel{25\ \text{L air inhaled}}}{5\text{L O2 available}} = \frac{1\ \text{L}\ O_2\ \text{consumed}}{5\text{L O2 available}} = \frac{20\ \%\ O_2\ \text{used}}{100\%\ \text{O2 available}}$$

So the 80 % unused oxygen is available, after going through the rebreather scrubber, for reuse in subsequent breaths. This advantage results in divers being able to remain submerged for much longer periods of time with smaller air/oxygen tanks. It might also mean the difference between being able to stage a dive or not, if the dive would take longer than a normal scuba tank would last, or would require tanks that are too large or heavy for the diver to carry.

2) Another advantage of rebreathers is that they don't release the air into the water, so that, at the end of the dive, the diver can recapture much of the inert gases, like helium, that are typically used for deeper dives. These relatively expensive gases can then be reused for future dives. Also, because it is a closed-circuit system, a lower partial pressure of the inert gas is needed, allowing a greater partial pressure of oxygen, and this helps to minimize decompression times upon ascent from the dive.

3) The exothermic reaction within the scrubber warms the air before it is returned to the diver, resulting in better temperature control and more comfortable conditions for the diver in cold water.

4) Water is produced in the scrubber reaction, and this helps divers to avoid dry mouth and general dehydration, which are prevalent in scuba divers.

5) The final advantage is that rebreathers produce far fewer bubbles than scuba gear, since the gas isn't released, but recycled through the scrubber. This could be important in military usage where secrecy is important. It could also help divers who are trying to get close to marine life without having bubbles scare it off, or who are trying to photograph underwater activity, where bubbles would get in the way of the photographs. In cave diving, the bubbles might cause turbulence in the water that could result in very greatly decreased visibility, which could be hazardous. (Information was derived from http://www.divesafety.net/Rebreather_Advantages.html.)

More on the chemistry of rebreathers

Industries that produce large amounts of carbon dioxide as a result of chemical processes frequently use CO_2 scrubbers to sequester the CO_2 as metallic carbonates, most frequently $CaCO_3$. Two other chemicals that industry uses to remove CO_2 are monoethanolamine (MEA for short), and Ascarite II. Unfortunately, MEA is corrosive and highly toxic, even in small amounts, and Ascarite II is simply asbestos, covered with sodium hydroxide. The use of Ascarite produces sodium carbonate, Na_2CO_3.

It seems that the chemistry behind rebreathers may become increasingly important throughout the world as levels of carbon dioxide continue to rise dramatically, and all nations are trying to reduce carbon dioxide emissions to much lower levels than those presently occurring. (Even the US has finally gotten aboard the CO_2 reduction bandwagon in international talks, as of the writing of this Teacher Guide.) Of course, some industrial plants do presently use CO_2 scrubbers to remove carbon dioxide from their waste products, and these scrubbers use some of the same technology as rebreathers.

More on the CO_2 / HCO_3^{1-} / H_2CO_3 blood buffer system

Our bodies use the CO2 / H2CO3 equilibrium to control blood pH. The normal range of pH of our blood is very limited—it can only vary between 7.15 and 7.35 before we suffer physiological consequences. Thus if carbon dioxide builds up in our blood, our response is to breathe faster, trying to remove CO_2 to regain our pH balance in the blood.

For more information on the blood's buffer system, see the Teachers Guide on "How Chemistry Makes Blood Transfusions Safer" in this issue of the *ChemMatters Teachers Guide*.

Connections to Chemistry Concepts

1. **Acids and bases**—The reaction within the rebreather (metal hydroxide and CO_2) is an acid-base reaction. The carbon dioxide/water/carbonic acid equilibrium system is an acid-base reaction.
2. **Buffers**— The carbon dioxide/hydrogen carbonate ion/carbonic acid equilibrium is an example of a biological buffer system.
3. **Gas laws**—Two of the gas laws commonly taught in a high school chemistry class are alluded to in this article. These show students direct applications of these laws in real-life situations.
   i. Gas concentration at various depths—Boyle's law.
   ii. The variation of partial pressures of oxygen/carbon dioxide as the chemicals in the rebreather are used up—Dalton's law.
4. **Partial pressures**—Dalton's law of partial pressures
5. **Breathing/Cellular Respiration**—The equation showing the combustion of glucose gives chemistry teachers the opportunity to show an example of a biological reaction in an otherwise essentially inorganic course.
6. **Exothermic reactions**—Metallic hydroxides reacting with carbon dioxide are all exothermic reactions.
7. **Chemical equations/reaction types—**Several types of chemical reactions are represented in this article:
   1. CO_2 + H_2O reacting to produce carbonic acid is a synthesis or direct combination reaction;
   2. H_2CO_3 acting as an acid is a decomposition reaction;
   3. metal hydroxides reacting with CO_2 to produce carbonates and water represent double replacement (or neutralization) reactions; and
   4. The cellular respiration equation is an example of a combustion reaction (albeit a slow one).

8. **Stoichiometry—**The person packing the rebreather scrubber needs to make sure he/she packs enough
of the metal hydroxide to full react with the air/oxygen contained in the gas tank. This is a matter of which is the limiting reagent.

9. **Periodicity/Families of elements**—All the metals in the metal hydroxides are either alkali metals or alkaline earth elements. Their use in scrubbers shows that the compounds of families of elements all have similar properties, just like the elements themselves.

Possible Student Misconceptions

1. **"When we breathe, we exhale only carbon dioxide."** *This is what many students believe, but reading the article carefully should dispel this misconception. Since 79% of the air we breathe is nitrogen, and nitrogen is essentially inert in our lungs, we exhale all of that gas. The rest of the air we inhale is essentially oxygen (~20%). And, as is mentioned in the article, we only use about 4% of the oxygen we inhale to convert to carbon dioxide, so that means about 16% of our exhaled breath is still unused oxygen that could be recycled through a rebreather. The other 4% is carbon dioxide, which must be removed from a diver's next breath.*
2. **"Since we only use about 4% of the oxygen in the air each time we inhale and exhale, then we can re-breathe that air directly until all the oxygen is gone."** *No, because as mentioned in the article, although lots of oxygen might remain, the carbon dioxide level in that exhaled air would increase with each exhalation, and that becomes a problem in our respiration cycle. We can only re-breathe the air as long as the scrubber successfully removes the carbon dioxide before we inhale that air again.*
3. **"I guess rebreathers can be used indefinitely, right?"** *No, they will eventually 1) run out of air/oxygen, if the scrubber contains sufficient hydroxides, or 2) they will run out of scrubbing capacity if the metal hydroxides in the scrubber tank are completely used up, or if the packaging is not done properly and the gases can circumvent the scrubber material.*
4. **"So, Titan Hall really exists, eh?"** An online search *showed no evidence that Titan Hall as it is portrayed in the article/movie exists, at least not in Romania; however, this Wikipedia web site may indicate the source of inspiration for the story. Titan Cave in Castleton, Derbyshire, UK is a mammoth cave approximately 140 m (450 ft.) tall. It is part of a much larger cave system. (Is this sounding familiar yet?) The real Titan Cave was discovered on January 1, 1999 (off by only 6 years from the movie's cavern). It is part of a series of mines that had been in use for several centuries. The cave system exceeds 14 km in length (not quite 90 miles like in the movie, but it's still huge). Find references to the real Titan cave at http://en.wikipedia.org/wiki/Titan_%28cave%29. Be sure to check out the external links at the bottom of the article and visit the photos of the cave at http://www.daveclucas.com/titangallery/index.html to get the full effect of the size of this cave.*

Demonstrations and Lessons

1. You can show how acid anhydrides work, simply by bubbling carbon dioxide gas through water as you monitor its pH. You can monitor the pH either by using a pH meter or pH probe, or by using an acid-base indicator ("universal indicator" works well). You can also relate acid anhydrides to acid rain and acidic lakes and streams. You can get the same effect by allowing small chunks of dry ice to sublime in a water/universal indicator solution. You can also demonstrate the change in pH with CO_2 concentration by placing some club soda with a little universal indicator added into a large syringe (about half full). Force the air out, stopper and allow CO_2 to bubble out into the syringe. The gas pressure build-up should force the plunger back. Have students observe the original color of the indicator. Remove the seal and force that gas out of the syringe. Reseal the syringe and repeat the process, allowing the CO_2 to force the piston back, or you may have to pull the piston back, changing the equilibrium to allow more CO_2 out of solution. You may have to repeat the procedure many times before enough CO_2 has escaped to effect the color change. Have students observe any color change that takes place. The color should change from orange/yellow (it

probably won't be acidic enough to get to red) through green as the CO_2 escapes from the soda.

2. The carbon dioxide/hydrogen carbonate ion/carbonic acid equilibrium is a good one to use in a discussion of le Châtelier's principle. You can use this system to show students the effects of stresses on the equilibrium. Addition of too much of either "end" of the equilibrium equation has a specific effect on the human body.
3. You could use the information from this article as an application of the periodic trends in families of elements. All the metal hydroxides cited in the scrubbers were either alkali metal or alkaline earth metals. These compounds all behave similarly chemically.
4. Some of the demonstrations and lessons discussed in the Teachers Guide accompanying "How Chemistry Makes Blood Transfusions Safer" may also be applicable in this article.
5. Many teachers use the short video clip from the Ron Howard/Tom Hanks "Apollo XIII" movie as an introduction for their students to the problem-solving process. It vividly shows students the processes by which scientists and engineers go about solving seemingly insurmountable problems.
6. You might want to use the rebreather as a segue into the far grander process of removing carbon dioxide from the atmosphere to mitigate the effects of global warming due to the ever-increasing production and distribution of greenhouse gases due to global industrialization.
7. You can demonstrate the ability of a hydroxide to remove carbon dioxide from the air by doing the classic limewater breath test. Have a student blow through a straw into limewater, aqueous $Ca(OH_2)$. The clear solution will turn cloudy as CO_2 from the student's exhaled breath reacts with the $Ca(OH)_2$ to produce low-solubility $CaCO_3$. You can filter the liquid to remove the solid $CaCO_3$.
8. Another demonstration that shows CO_2 being removed from air is to draw some aqueous sodium hydroxide solution into a syringe containing CO_2. The plunger will be drawn in by the reaction that uses up the gas and produces sodium carbonate. (Thanks to Bruce Mattson and Michael Anderson for this idea from their ChemEd 2007 presentation.)

Student Projects

1. Students could research the history of rebreathers and prepare a report/lesson for their classmates. Wikipedia might be a good place to begin research: http://en.wikipedia.org/wiki/Rebreather.
2. Students could, with the teacher's supervision, experiment with one of the hydroxides to see how efficiently carbon dioxide is removed from a closed system. Variables such as method of packing, amount, concentration of CO_2, and ambient temperature could all be tested.
3. If any students have experience with rebreathers, or know anyone who has experience, they could be asked to talk to your class(es) about their experiences with them.
4. Students might want to research the similarities and differences between scuba gear and rebreather gear and report on same. They could begin their research here: http://www.bishopmuseum.org/research/treks/palautz97/rb.html.
5. Students may choose to do research on global carbon dioxide emissions, and carbon capture, storage and sequestration as ways to mitigate the problem. This topic is only tangentially related to rebreathers, but it is a topic of utmost importance to the continued existence of man on Earth. Students could start their research at the US Department of Energy carbon sequestration web site: http://www.fossil.energy.gov/programs/sequestration/. They may obtain data for their research here: http://www.eia.doe.gov/environment.html.

They can also check out this site, http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/7b1.pdf, for a detailed paper by three scientists on the use of calcium hydroxide as the scrubber of choice for an economically-feasible, global-scale carbon dioxide capture and recovery system.

Anticipating Student Questions

1. **"Did the divers make it out of the caves OK?"** (Not exactly a question you had hoped they'd ask, eh?) The article doesn't tell us, except for the one diver "repairman" who was killed early in the story*; students will just have to watch the movie. [Ed. Note: My assumption is that some did, some didn't.]*
2. **"If they are so potentially dangerous, why do cavers use rebreathers, rather than SCUBA gear?"** *The article doesn't specifically state why cavers use rebreathers, but it seems obvious that rebreathers can be used for a significantly longer period of time than scuba gear, since the same volume/mass of air can be used and reused many times with a rebreather, whereas with scuba gear, the air is used only once, then expelled completely.* At the very least, a diver using a rebreather could dive with a smaller tank of air/oxygen/Nitrox than could a scuba diver for the same duration of dive.
3. **"Why are rebreathers so hazardous? If the oxygen in a rebreather is getting close to being used up, won't the diver notice this and be able to do something to remedy the situation?"** *Our breathing is actually triggered more by the buildup of carbon dioxide in our blood than the lack of oxygen present. So as long as the carbon dioxide is being removed by the scrubber and the gas (nitrogen, helium or other inert gases, minus the used up oxygen) is flowing at normal pressure, the diver breathes normally and he probably won't even (consciously) notice the hazardous decrease in oxygen content. By the time the diver recognizes there is a problem, he will probably be on the verge of unconsciousness. Even if he realizes the problem in a timely fashion, he may be so far underwater that he would not be able to surface in time to get his next breath (rising too fast would make him subject to "the bends").*
4. **"Could other substances be used in rebreathers that would be less toxic?"**

   Industries that produce carbon dioxide in large quantities frequently use CO_2 scrubbers to minimize the amount of CO_2 that escapes into the atmosphere. The chemicals they use are usually monoethanolamine and Ascarite II. The first is corrosive and toxic, even in small amounts, and the second is simply asbestos (although the non-fibrous variety) coated with sodium hydroxide.

   Potassium superoxide, KO_2, is being researched for use in submarines and space vehicles. The advantage of KO2 is that in its reaction with CO2, it also produces oxygen, according to this equation:

   $4\ KO_2 + 2\ CO_2 \rightarrow 2\ K_2CO_3 + 3\ O_2$

   (Information taken from http://antoine.frostburg.edu/chem/senese/101/environmental/faq/co2-recycling.shtml) This last reaction looks like it would be a win-win situation, but potassium superoxide is expensive and very reactive—and is also toxic.

   Other hydroxides could also be used instead of the alkali metal or alkaline earth element compounds alluded to in the article. Unfortunately, many of the other hydroxides are a) not water soluble, meaning that when water is produced in the reaction, it could react with them and produce a sticky mass that would coat the particles of the dry hydroxide, rendering it useless as a CO2 adsorbent, and b) many of the other hydroxides, such as barium hydroxide and mercury hydroxide are themselves toxic to the diver.

From all these alternatives, you can see that our options are somewhat limited.

5. **"Could the chemical reaction going on in rebreathers be used more globally to remove carbon dioxide from the atmosphere?"** [Ed. Note: From the ridiculous (#1, above) to the sublime (this question)] *The astute student might notice that the goal in both processes is the same – to eliminate carbon dioxide from our environment. Indeed, calcium hydroxide has been used for decades to remove carbon dioxide from industrial processes. The problem is one of scale and economics, however. What we are willing to pay on a small scale for our enjoyment (diving) we seem not to be so willing to pay on a global scale to ensure our survival as a species. Of course, willingness to pay is not the only factor in this great debate. It would be impractical to expect that this inorganic method of eliminating CO_2 would be sufficient by itself to accomplish so large a goal—or that we have enough calcium hydroxide on the planet to accomplish the task.*

Web Sites for Additional Information

The references below all can be found on the *ChemMatters* 20-year CD, obtainable from ACS for $25 (or a site/school license for $99) at this site: http://www.chemistry.org/portal/a/c/s/1/acsdisplay.html?DOC=education%5Ccurriculum%5Ccmprods.html#CDsite.

A basic article on scuba diving that relates the behaviors of gases to the sport can be found in "Gas Laws & Scuba Diving", Kathleen Dombrink and David Tanis, *ChemMatters*, February, 1983, pp. 4-6. Boyle's law involving pressure (at various depths) and volume, and Henry's law involving the concentration of gases and pressure (at various depths) are featured. The relationship between temperature and solubility of gases is also discussed briefly.

A second article dealing with scuba diving appeared in the February, 2001 issue of *ChemMatters*: "SCUBA—The Chemistry of an Adventure", Melissa Belleman, *ChemMatters*, February, 2001, pp. 7-9. This article repeats some of the information relating to gas laws, but it also describes the effect of water's heat capacity on divers, the refraction of light by water and its effect on a diver's ability to see colors under water, and the density of fresh water vs. that of ocean water.

You can find a timeline of the development of underwater diving and breathing in the February, 2001 *ChemMatters* Teachers Guide. Unfortunately the timeline does not include rebreathers in its coverage.

The December, 2000 issue of *ChemMatters* contains an article on Henry's law, which includes a brief discussion of scuba diving and the bends, along with a more detailed discussion of cracking knuckles and the trapped gases contained in the synovial fluid of the finger joints. The article can be found here: "Henry's Law", Doris Kimbrough, *ChemMatters*, December 2000, pp. 12-13.

In "Mystery Matters: Poisoned Milk", from the *ChemMatters* December 1992 issue, pages 10-13, C.M. Plummer includes a sidebar to the article on page 13 that deals with the topic of acidosis, caused by toxins in cow's milk.

Lest you think that pH balance is important only for humans, you might want to access the *ChemMatters* article, "Aquarium Chemistry: Life in the Balance" in the February, 2002 issue on pages 6-7. Author Laura Ruth explores the chemical factors involved in maintaining an aquarium, including the question of pH balance. The Teachers Guide for this issue also gives more insights into the complexity of maintaining a pH balance in your aquarium, and why it is necessary to do so. The equilibrium in question for aquarium water is the bicarbonate / carbonate system, which is really just a slight extension of the carbon dioxide / carbonic acid / bicarbonate system in the blood.

For yet another look at the carbon dioxide / carbonic acid / bicarbonate ion / carbonate ion equilibrium, see "Chickens lose equilibrium…Prefer Perrier water to panting" on page 15 of the February, 1985 issue of *ChemMatters*. Authors David Brown and John MacKay show how chickens' inability to perspire and Perrier water relate to the carbon dioxide / carbonic acid equilibrium system.

More sites on the history of rebreathers

The International Association of Rebreather Trainers offers a brief history of rebreathers, along with several links to other sites offering more information: http://www.iart.de/history.html.

Halcyon also provides some history of rebreathers. Students should be aware that Halcyon produces rebreathers, so the site advertises its wares throughout the text. Find the information at http://www.halcyon.net/rebreather/rebreather_types.shtml.

More sites on acidosis and alkalosis

This site gives a good introduction to these two conditions, using a faucets and drains analogy: http://www.labtestsonline.org/understanding/conditions/acidosis.html

Virtual ChemBook by Charles Ophardt of Elmhurst College contains a concise discussion of the CO_2/H_2CO_3 blood buffer system. You can find this discussion at http://www.elmhurst.edu/~chm/vchembook/260acidbasebal.html. The site has specific pages on respiratory and metabolic acidosis, respiratory and metabolic alkalosis, the oxygen transport system, the carbon dioxide transport system, and blood and kidney buffers.

More sites on rebreathers

The Rebreather Web Site provides this first hand account of "A Learner's Guide to Closed-Circuit Rebreather Operations", by Richard Pyle. The article contains all a novice rebreathing device user could want to know about survival with a rebreather.
http://www.nwdesigns.com/rebreathers/RichPyleArticle_1.htm#Search%20Query%20Form

Here's another source, from the Bishop Museum, for the same Pyle article, above: http://www.bishopmuseum.org/research/treks/palautz97/lgrb.html.

The Bishop Museum provides this guide to how rebreathers work: http://www.bishopmuseum.org/research/treks/palautz97/rb.html. This site describes differences among oxygen rebreathers, semi-closed rebreathers and closed-circuit rebreathers.

More sites on global climate changes and carbon sequestration

The US Geological Survey offers information on carbon sequestration efforts in Africa. This particular site gives some background for students about how agricultural sequestration is working in semi-arid regions of the globe: http://edcintl.cr.usgs.gov/carbonseq/pampeng.pdf.

The US Department of Energy offers a wealth of data on the environment at http://www.eia.doe.gov/environment.html.

Three renowned scientists, Lackner, Grimes and Ziock, have proposed an economically-feasible global-scale carbon dioxide recovery system based on calcium hydroxide as the scrubber. You can view their paper at http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/7b1.pdf. And here is their paper to explain the rationale behind their proposal: http://www.americanenergyindependence.com/Reddy8.pdf.

More sites from NASA on the Apollo XIII mission

NASA provides a great deal of information about the mission on its web site.

The NASA Apollo XIII homepage, at http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo13info.html, has a wealth of information on the mission.

Pictures from the mission can be found at http://images.jsc.nasa.gov/luceneweb/browse.jsp. These photos include several showing the damages to the control module after the oxygen tank explosion (although you would need to know what an undamaged module looked like to note the difference).

Files, including short video clips and documents, from the mission can be found here: http://science.ksc.nasa.gov/history/apollo/apollo.html.

A brief account of the mission by NASA mission control people and the astronauts themselves can be found here: http://science.ksc.nasa.gov/history/apollo/apollo-13/apollo-13.html.

A much more detailed account of the accident, including a link to the official review board's extremely detailed report, can be found at http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo13info.html.

For a slightly more interesting account of the accident, try "Human Journey", "Apollo XIII, Successful Failure" at http://liftoff.msfc.nasa.gov/Academy/History/APOLLO-13/mission-report.html.

More sites on the Apollo XIII mission

The Smithsonian National Air and Space Museum also has a fairly detailed web site on the Apollo XIII mission at http://www.nasm.si.edu/collections/imagery/apollo/AS13/a13.htm.

For another viewpoint on the accident and the solutions devised by ground crews, see the IEEE *Spectrum* article at http://www.spectrum.ieee.org/apr05/2697. According to the author, Steve Cass, “Rather than hurried improvisation, saving the crew of Apollo 13 took years of preparation.” He contends that it is the knowledge and expertise of the engineers and other scientists at Houston control and across the US that enabled the crew of Apollo XIII to return home safely from that catastrophic accident. He offers an accounting by the engineers themselves of the incident.

The Not So Simple Life of Filters

Background Information

More on filters

Most high school chemistry students have used white circular filter paper to separate, for example, a precipitate from its supernatant liquid. Solid-liquid separations are probably the most common in a chemistry class. However, solid-gas separations might also be familiar to students, especially in an environmental chemistry course in which air quality is studied. The substance passing through the filter must be a fluid, either a liquid or a gas. This kind of filtration is a physical process, not chemical.

Properties that should be considered when discussing filters include thickness, porosity, loading capacity, flow rate, particle retention, chemical compatibility and ash content. Of these the most important are flow rate, loading capacity and particle retention rate.

Retention rate, which students will most closely associate with filters, is a measure of the smallest particles which the filter will retain at a rate of 98%. Flow rate for liquids is measured using the Hertzberg method. In this method pre-filtered water is passed through a 10 cm^2 filter with a constant height of liquid above the filter of 10 cm. The rate of flow is the time (in seconds) required for 100 mL to flow through the filter. The porosity of a filter is the size of the openings through which the liquid flows. This determines the size of the particles retained by the filter. Loading capacity measures the amount of retained solid that can be trapped in the filter itself while still allowing a reasonable flow rate. Ash content is important if the filtration is quantitative, requiring that the filter be incinerated after the filtration. It is important to be sure that the chemical that will pass through the filter will not alter the filter itself in any way.

Most filters should be thought of as a dense mass of entangled strands that provide pores of varying dimensions through which the liquid (usually water) and the particulate matter must try to pass. The route that the particles must take through the filter has many twists and turns, and along the way, particles become trapped, either individually or in clumps, at various spots in the filter.

The article emphasizes the types of filters in use and the ways in which they are made. The following sections of the Teachers Guide describe each of these filters.

More on paper filters

Filter paper is typically made from paper with high alpha-cellulose content. Such paper is considered high-grade paper. The raw material is cotton linters, which are small fibers of cotton which remain attached to cotton seeds after ginning. Cellulose has a formula of $(C_6H_{10}O_5)_n$. It is a natural polysaccharide. In paper filters the cellulose molecules are arranged so that the resulting paper is strong and absorbent and is capable of retaining particles as small as 2.5 μm.

The structure and quality of the paper depends on it use. For example, if the paper is made into a coffee filter, the paper must be able to maintain its structure when subjected to the water temperature of most coffee makers. Cellulose oil filters must be able to stand up to both temperature and the chemicals found in motor oil.

More on glass filters

Glass filters are typically made of borosilicate glass. Its composition is 70% silica (SiO_2), 10% boric oxide (B_2O_3), 8% sodium oxide (Na_2O), 8% potassium oxide (K_2O) and 1% lime (CaO). Typical pore sizes are as follows:

Porosity	Maximum Pore Size (μm)
Extra Coarse	170.-200
Coarse	40.-60
Medium	10.-15
Fine	4.-5
Ultra-Fine	0.9-1.4

These filters can be used at temperatures up to 500ºC. They have a fine capillary structure and can be made transparent, in case the results need to be examined under a microscope. The article mentions the term “frit.” This is the actual glass filter. They are often used in suction filtrations.

More on ceramic filters

The article describes the manufacture of ceramic filters from porcelain, which is formed by heating kaolinite clay ($Al_2Si_2O_5(OH)_4$) or diatomite to temperatures as high as 1400ºC. The resulting substance has low permeability but high strength and hardness and high resistance to chemical changes, all desirable filter properties.

The polymer sponges referred to in the article are often made of polyurethane, cellulose, polyvinyl chloride, polystyrene or latex. Slurry is made from the ground porcelain and the sponge is immersed in the slurry, which is absorbed by the sponge substrate, replacing the air pockets. The slurry-sponge combination is then dried and fired at high temperatures to burn off the polymer sponge, leaving the porous ceramic filter ready for use.

A variation of this ceramic filter is being used in developing countries for purifying scarce water supplies. The ceramic filters are impregnated with colloidal silver which acts as a disinfectant. Silver ions in solution disable the enzymes that microorganisms in the water need to “breathe.” Thus the silver acts as a bactericide, fungicide and algaecide. Potters in these regions are being taught to make the ceramic filters using low cost kilns which use biomass as fuels.

Another recent innovation that applies ceramic filters to kidney dialysis is described in the online journal “Medical News Today” (http://www.medicalnewstoday.com/articles/66651.php). According to this news service the new filter, designed by William Van Geertruyden, who holds three degrees in materials science and engineering from Lehigh, will increase both the number of toxins filtered and also the rate at which they are filtered. The news release says, “Specifically, the new filter promises to double the amount of toxins removed during dialysis and to double the glomulellar filtration rate (GFR), or rate of toxin removal. GFR is 100 percent in a normal person but only 15 percent at best for a dialysis patient, a rate that has changed little in the past 30 years.

“The ceramic filter's secret”, says Van Geertruyden, “lies in its pores, which are organized in orderly rows and columns and which measure mere nanometers in diameter." One nm is one one-billionth of a meter.

"These nanopores", says Van Geertruyden, "correspond more closely to the nano-sized toxins in the blood than do the larger pores of the standard dialysis filter. These polymeric pores vary in size and, when viewed with a microscope, appear in random arrangements of ovals, circles, slits and other shapes."

More on polymer filters (membranes)

Some, like polytetrafluoroethylene or mixed cellulose esters, are best used for air filtration systems. Polyether sulfone, nitrocellulose, PVDF, and cellulose acetate are often used in aqueous systems in microbiological settings. Nylon and polytetrafluoroethylene are used in non-aqueous filtrations. Pore sizes range from 0.02 to 5 μm).

A list of polymers that are often used in filtration membranes include:

- Polyethylene terephthalate
- Polycarbonate (derived from 4, 4'-dihydroxydiphenyl-2,2'-propane)
- Cellulose Nitrate
- Cellulose Acetate
- Polymer (Hexamethylenediamine;Nylon-66)
- Polytetrafluoroethylene
- Polypropylene
- Polyether Sulfone
- Polyamide
- Polyvinyl chloride (medical grade)
- Polyester

More on reverse osmosis

Osmosis is a spontaneous process that takes place through a semi-permeable membrane in which the concentration of solute (or water) is different on opposite sides of the membrane. In osmosis, water moves spontaneously across the membrane from the side with the higher water concentration (the "dilute" side) to the side with the lower water concentration (the "concentrated" side).

In fact, what happens is that water moves across the membrane in both directions, but the movement of water is faster from the "dilute" side than it is from the "concentrated" side. This movement of water will continue until the concentration is equal on both sides of the membrane. At this point there will be a dynamic equilibrium across the membrane. In this case the semi-permeable membrane is one that allows water molecules to pass through, but not larger solute molecules. It would be possible to stop the movement of molecules by osmosis by applying just enough pressure on the "concentrated" side to keep water molecules from crossing the membrane. This pressure is called osmotic pressure.

If we think about this in terms of water purification, we can easily imagine a sample of contaminated water separated from a sample of pure water by a semi-permeable membrane. If we do nothing, water will move from the pure side to the contaminated side. That is, osmosis will occur. We could apply pressure to the contaminated side sufficient to just stop the flow of pure water into the contaminated solution. But if we apply additional pressure to the contaminated side, water will flow out of the contaminated sample into the pure water. In this way we can purify the contaminated water in the process called reverse osmosis (RO). The required pressure depends on the concentration of contaminants, but is typically in excess of 200 psi.

The semi-permeable membranes most often used in RO are frequently made of either polyamide thin film composites (TFC), synthetic cellulose polymers or sulfonated polysulfone. The membrane is usually either wound up into a spiral or into tubes that are grouped together. This is done to provide greater surface area for the RO to take place. TFC membranes are stronger, will reject more dissolved solids, and resist attack by microbes, but they are deteriorated by chlorinated water.

RO removes up to 99% of all contaminants in water, including asbestos, heavy metals, bacteria and organic compounds. Because RO membranes remove such a high percentage of contaminants, the rate of flow in RO is low. A unique feature of RO is that it will remove dissolved ions from the solution. Dielectric interactions in the membrane attract ions dissolved in the water. Ions with higher charges are more easily retained than those with lower charges, like sodium ions.

More on particle size and SI units

The article notes the relative sizes of particles that can be retained by various kinds of filters. This is an opportunity for you to review (or introduce) SI units and prefixes, especially those smaller units that are not commonly used in a general chemistry class. Note that the article uses both *micrometers* and *microns* as units of size. They are the same unit of length, with the term “micron” being a shortened version of micrometer. Both terms were approved as SI units until 1968, when the General Conference on Weights and Measures recommended that the term “micrometer” be used exclusively. However, the term “micron” is still in common use.

NIST, the U.S. National Institute of Standards and Technology, gives the prefixes in a concise table:

Table 5. SI prefixes

Factor	Name	Symbol	Factor	Name	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	µ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

From: http://physics.nist.gov/cuu/Units/prefixes.html

It will be helpful for students to have some way of comparing SI units, especially those smaller than the human eye can see, to known sizes. Here are some possible comparisons *with all the sizes in micrometers* (or microns), the units most frequently used to measure filtering ability:

Object/Particle	**Size** (µm)
Radius of solar system	1×10^{19}
Radius of the earth	1×10^{13}
Radius of Earth's moon	1×10^{12}
Distance walked in 5 city blocks	1×10^{9}
Height of 6-10 year-old child	1×10^{6}
Grain of salt	1×10^{3}
Diameter of human hair	1×10^{2}
Metal hydroxide precipitates molecule	25-40
Ragweed pollen	20
Amoeba	12-30
Yeast cell	2.0–8.0
Blood platelet	2–3
Tobacco smoke	0.5
Bacteria, Cocci	0.5
Smallest bacterium	0.22
Virus	0.1
Radius of an atom	1×10^{-4}
Radius of a proton	1×10^{-9}

The article also uses the "dalton" as a unit. High school chemistry students may be more familiar with amu as the units of molecular mass. The dalton (Da) and amu are equivalent units.

More on uses of filters

Clean water systems

Throughout the world, clean water is a major issue that your students will be able to relate to. In addition to various filtration methods (including reverse osmosis), methods of purifying water include carbon treatment, ozonation, and ultraviolet light.

Filtering water with activated charcoal removes many organic compounds like benzene and trichloroethylene by adsorbing them on the carbon particles. This filtration also removes inorganics like arsenic, chromium and mercury complexes. Treating water with ozone removes gases and other volatiles by aeration. Ozone, an oxidizing agent, removes iron, manganese and sulfur by converting them into insoluble compounds that can be removed by filtration. Ultraviolet treatment kills bacteria in the water. Water is passed around UV lamps and the radiation acts as a germicide.

Car air filters

Automobile air filters treat air intake to remove undesirable particles. Most of these types of filters are made of paper, foam or cotton.

Car oil filters

Currently most oil filters use filters made of cellulose. Some filters use fine glass fibers like fiberglass backed with steel mesh. Early automobile oil filters were made of wire mesh, bulk cotton or other woven fabrics like linen.

Breathing apparatus filters

Gas masks operate on one or more of three types of filtration. Canisters in gas masks contain mechanical filters of the type described in the article. They may be made of various synthetics and are designed to filter out small particulate matter. The second layer of filtration is designed to remove dangerous gases. This layer is made up of activated charcoal, which is finely divided carbon particles that have been heated to high temperatures in the absence of oxygen, creating a very large surface area and low porosity. As gases pass over the charcoal, molecules of the gases are adsorbed by the carbon particles and, therefore, retained. Adsorption is the weak physical attraction of molecules to the surface of the carbon particles. Many organic molecules and other nonpolar molecules are easily adsorbed. A third filtration layer in gas masks contains chemicals designed to neutralize or counteract other dangerous chemicals in the air. The components of this part of the mask depend on the chemicals targeted for elimination.

Home indoor air filters

There is a variety of air filters for home heating and cooling systems. Inexpensive duct filters are made of familiar fiberglass. Others are made from polyester or other glass fibers. Some of these are combined with cloth fibers. Polypropylene is also used, and high efficiency particulate air (HEPA) filters use microfibers made of polyamide and polyester. Electrostatic filters can also remove particles by charge.

Cigarette filters

Since the mid 1950's most cigarettes sold in the U.S. have filters attached to reduce unwanted combustion products in the inhaled smoke. These are made from the synthetic material acetylated cellulose, which is made into long fibers (as many as 12,000 per filter) that are arranged into a bundle to form the filter and are wrapped in paper. Many filters are "ventilated." The filter is perforated to allow air to be drawn in as the smoker inhales. The effect of the perforation is to dilute, but not filter, amounts of tar or carbon monoxide.

Connections to Chemistry Concepts

1. **Separations—**You probably have a unit in your course on separating mixtures, and you probably teach students (or review with them) how to perform a filtration in the lab. Perhaps it is related to a lab in which a precipitate is produced and the mass is required. Perhaps it is in a more general context of mixtures. The article provides applications for you to discuss with students.
2. **Environmental chemistry—**The larger context for this article could be the environmental efforts to provide clean drinking water. In many parts of the world clean water is a major issue. You might apply the ideas in the article to the ways in which filtration is used as a means of producing clean water. You might consider

with your students the types of filtration systems and the kinds of contaminants each one is able to remove.

3. **Size and Scale**—Important in the discussion of filters in the article is the size of particles that each type of filter is able to remove. This is a chance for you to review and reinforce SI units with students and help them to develop a sense of scale using the SI units.
4. **Polymers**—Since many of the filters discussed in the article are polymers, the article provides you with an opportunity to introduce a topic that you might not otherwise be able to cover in your general chemistry course. You could supplement the discussion of polymers with material from your textbook or other sources.

Possible Student Misconceptions

1. **"Filters have holes."** *"Holes" is probably the wrong way to think about filter paper. "Passageways" is a better model for thinking about the route taken through filter paper by water or air. The fibers (or other materials) that make up the filter are assembled so that there are convoluted paths that molecules can follow through the paper. Nothing passes through in a straight line.*
2. **"All filters are made of paper."** *As the article describes, filters can be made of materials other than paper. The article includes filters made of glass, polymer membranes and ceramics*

Demonstrations and Lesson

1. You can assign students to participate in a filtration competition, using common materials. An outline of this assignment can be found here: http://www.esi.utexas.edu/outreach/groundwater/resources/lessons/waterFiltration.pdf.
2. The Geological Society of America has a wide range of lesson plans on water, including some on filtration. See http://www.geosociety.org/educate/LessonPlans/i_water.htm.
3. The National Science Teachers Association "Science NetLinks" has a lesson plan for showing students natural water purification and filtration at http://www.sciencenetlinks.com/lessons.cfm?DocID=275.
4. For an activity on particle size see http://www.quarked.org/parents/lesson1.html.
5. You might incorporate any chemistry lab that requires a filtration step.
6. A lesson plan for separating a mixture of salt and sand appears here: http://www.chemheritage.org/scialive/julian/teachers/7a4.html.
7. Other separation activities, including actual chemical separations, as well as models/simulations of separations and of filtering, can be found here: http://www.chemheritage.org/scialive/julian/teachers/7a.html.
8. A lab procedure for separating mixtures is here: http://www.ccmr.cornell.edu/education/modules/documents/PhysicalPropertiesofMatter.pdf.

Student Projects

1. Students can research regions and countries of the world where clean drinking water is an important problem. A good place to begin is the WHO site at http://www.who.int/water_sanitation_health/dwq/en/, or the Pacific Institute's site, "The World's Water", at http://www.worldwater.org/data.html.
2. Students could test the filtering ability of a variety of porous materials that they bring from home. Some of these might include various types of cloth, wire mesh, granular solids, etc.

Anticipating Student Questions

1. **"How can there be holes in a solid like glass?"** *The article suggests ways that openings or passageways can be created in a substance like glass or metal.*
   The article says, "To make a filter, glass pellets or fibers are packed into a mold and heated at increased pressure. As the glass softens it begins to stick together where it touches forming a mass called a 'frit'. Since it is not allowed to melt completely there are tortuous paths through the frit. The size of these paths can be controlled by the size of the particles/fibers and the amount of heat and pressure applied. The same process can be used with metal beads or fibers."
2. **"Some books give small sizes in microns. What are they?"** *The term "micron" is a shortened form of micrometer (μm) or 1 x 10^{-6} meter. Until 1968, it was officially recognized as an SI unit, but in 1968 its use was discouraged in favor of the term "micrometer." Microns are still used informally today.*
3. **"What's a Dalton?"** *The dalton (Da) and amu (sometimes abbreviated as u) are equivalent units.*

References

Stewart, Melissa. "Tapping Saltwater for a Thirsty World", *ChemMatters*, October, 2002, p. 4. The article contains information on filtering, especially reverse osmosis.

Brennan, M.B. "Waterworks", *Chemical and Engineering News.* April 9, 2001, pp. 32–38.

Martindale, D. "Sweating the Small Stuff: Extracting Freshwater from the Salty Oceans", *Scientific American.* February, 2001, pp. 52–55.

Web Sites for Additional Information

More on basic filtration

Whatman provides some filtration basics on their web site. Included here are definitions and descriptions of important concepts related to filtration: http://www.whatman.com/repository/documents/s7/Appendix%20A.pdf.

More on SI units

For the complete NIST web page on units, see http://physics.nist.gov/cuu/Units/.

More on fritted funnels

A guide to fritted funnels and their use can be found here: http://www.ilpi.com/inorganic/glassware/frittedfunnel.html.

More on ceramic filters

For water purification in developing areas of the world see http://www.potpaz.org/pfpfilters.htm.

More on World Health Organization

For a web site describing WHO's efforts to provide safe drinking water throughout the world, see http://www.who.int/household_water/en/.

More on filtration

For an online tutorial on filtration see http://www.chem.ubc.ca/courseware/154/tutorials/exp4A/crufilt/index.html#3.

More on powers of ten

The Molecular Expressions web site has an interactive page showing orders of magnitude at http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/.

More on water filtration

The web site Free Drinking Water provides a complete review of water filtration methods. http://www.freedrinkingwater.com/water-education/quality-water-filtration-method.htm#Anchor-Reverse-23240.

More on reverse osmosis

The extension service at the University of Nebraska-Lincoln has a complete review of reverse osmosis:
http://www.ianrpubs.unl.edu/epublic/live/g1490/build/g1490.pdf.

More on water treatment

For a history of water treatment see http://www.historyofwaterfilters.com/.

More on water quality

For data on the quality of U.S. water, see http://waterdata.usgs.gov/nwis/qw.

For data on the world's water see http://www.worldwater.org/data.html.

“Follow the Carbon.” Follow the *What*?

Background Information

More on the soil chemistry of Mars

In ancient times, Greeks named the planet after their war god Ares, and the Romans followed suit by calling it Mars, their name for Ares. They did this because the planet’s red color reminded them of the blood of battle. On the surface of Mars, the iron(III) ions come in the form of a dust rich in iron(III) oxide that covers most of the planet.

It is thought that this iron(III) oxide dust was formed by the weathering of basaltic rocks. Similar red soils are found in Hawaii, where volcanic basalt is common. Red soils are also common in Georgia, produced by the weathering of Appalachian granites, which are similar in chemical composition to basalts. On earth, this kind of weathering typically occurs in moist environments (like Hawaii and Georgia). This has led scientists to speculate that the red Martian soils may have formed under conditions much wetter than those found on Mars today.

Experiments carried out on simulated Mars rocks in a series of simulated atmospheres showed no production of iron(III) oxide in an atmosphere like that which Mars currently possesses. However, a wetter atmosphere did result in the formation of iron(III) compounds. This suggests that Mars may have once been wetter. This is important for anyone hoping to find signs of past life on Mars, since water is necessary for any form of life as we know it. These results do not rule out other possibilities, however, such as the red dust arriving on Mars via meteorites.

It is in this iron-rich soil that scientists hope to find the carbon-rich materials that would suggest life may have once lived on the red planet, perhaps in a wetter past where iron(III) oxides easily formed.

Spirit, a NASA rover currently active on the surface of Mars, recently made another soil chemistry discovery with implications for the search for past life on the planet. In December of 2007, NASA reported that the rover had discovered a patch of soil uncharacteristically light-colored against the ubiquitous red of the surrounding terrain. This patch turned out to be rich in silica, crystalline silicon dioxide. Two hypotheses have been proposed to explain this oddity. In one hypothesis, an ancient geyser dissolved silica beneath the surface, and deposited it at its mouth when the hot water boiled into steam. In the other hypothesis, the silica is the result of an ancient fumarole, a volcanic steam vent. Acidic steam from the fumarole would have dissolved other minerals, leaving silica behind. Either way scientists are encouraged, because both geysers and fumaroles are places where bacteria thrive on earth. Sites like this new discovery are the kinds of locations where scientists would like to look for signs of ancient life.

More on the Antarctic Mars meteorite ALH 84001

One of the more infamous incidents in the search for signs of ancient Martian life took place in 1996, when a meteorite of Martian origin was discovered in Antarctica. Named ALH 84001 by scientists, this rock contained two features that some took as signs of ancient microorganisms from the red planet. First, the meteorite contained organic material atypical of meteorites. Specifically, it contained polycyclic aromatic compounds, which are almost always of biotic origin. Second, it contained pieces of magnetite very similar in shape to those produced by certain species of terrestrial bacteria. A NASA press conference announced these discoveries, prematurely in the opinion of many in the scientific community. Today, the meteorite is not generally considered to be conclusive evidence of Martian life. An excellent case study classroom activity on this subject is available from the Center for Case Studies in Science Teaching at the University at Buffalo, and is referenced below.

More on abiotic organic chemistry

An alternate explanation for the organics in ALH 84001 has been proposed. Scientists have recently found evidence that organic molecules could have formed from carbonate rocks on Mars billions of years ago. Earth rocks from the Norwegian island of Svalbard have been found to contain organic material. It is thought that the rock was born when lava from a volcano cooled. The rock would have cooled very rapidly in the cold climate of the Arctic, and this rapid cooling may have converted the molten carbonate rock into organic molecules. The Svalbard rocks are very similar in composition to ALH 84001, being rich in carbonates and magnetite. The scientists who studied the Svalbard rocks have proposed that the same abiotic process that formed the organics in the Svalbard rocks may have formed the organics in the Martian meteorite.

Volcanoes aren't the only non-living systems that can produce hydrocarbons. For example, hydrothermal systems, such as hot springs, are thought to produce hydrocarbons. It has been proposed that the hydrocarbons are produced in a set of reactions similar to an industrial process known as the Fischer-Tropsch process. In this series of reactions CO or CO_2 is reduced to form methylene molecular fragments. These fragments can then assemble into larger organic molecules. There is controversy over whether this is actually taking place in hydrothermal systems in the Earth, however. Experiments that simulated the conditions of hydrothermal systems have not met with a good deal of success in synthesizing hydrocarbons other than methane from CO and CO_2. Larger hydrocarbons have been produced in simulations in which native iron metal is present. However, scientists are not certain if iron is present in the real geologic hydrothermal systems where we find abiotic synthesis of hydrocarbons taking place. In short, there is still much to learn about how organic compounds are produced in non-living systems in the Earth.

Organic compounds have also been observed in interstellar space. Spectroscopic studies of starlight passing through interstellar dust clouds have detected the presence of molecules such as polyacetylenes and fullerenes. At the same time, complex organic molecules such as amino acids have been found in meteorites. These amino acids are generally though to be abiotic in origin because they tend to be mixtures of L- and D-isomers, rather than the pure L-isomers found in terrestrial organisms.

In searching for signs of former life on Mars, it must be kept in mind that any organic compounds found on Mars may have resulted from abiotic processes like those described above. Meteorites could have brought organic material to Mars, even as some have speculated the seeds of life may have arrived on Earth via meteorites. It is not known whether Mars ever had the kinds of hydrothermal systems that produce hydrocarbons on Earth. At the same time, life almost certainly developed from organic molecules of abiotic origin. The presence of even abiotic organics could be a sign that conditions may have been right for life to develop on Mars at some time in the remote past.

More about exobiology

Exobiology has been derided as a “science without anything to study.” This comes from the mistaken notion that exobiology is mainly the study of life on other worlds. In fact, exobiology is very much concerned with life on this planet and explores the biological prospects of other worlds to help us better understand how life arose on Earth. To this end, exobiology is often involved with the study of prebiotic chemistry, or the chemistry of organic compounds that existed before life arose, their origins (discussed above), and how they may have ultimately given rise to living things. In the famous Miller/Urey experiment, Stanley Miller prepared a mixture of methane, hydrogen, and ammonia, and in the presence of liquid water, exposed the gases to electric sparks. After a few days, amino acids were found in the mixture. Although scientists no longer think the earth’s early atmosphere consisted of methane, ammonia, and hydrogen, this experiment marks the beginning of chemical studies into the origins of life. There are many questions left to be answered in this field, and links to websites below provide more information on the study of the pre-biotic origins of life.

More on mass spectrometry

Mass Spectrometry is a technique for measuring the molecular mass of a substance. In this technique, a sample of the analyte is ionized, either by a beam of electrons, heat, light, or bombardment with molecular or ionic species. When the analyte is ionized, its molecules break apart into fragments, which are usually cationic.

There are several ways that mass spectrometers measure the masses of the cationic fragment. In the simplest approach, called time-of-flight spectrometry, an electric field is applied to the ionized sample, and the time it takes for the cationic fragments to reach the negative electrode of the electric field is measured. The time of flight can be used to calculate the rate at which the cationic fragments accelerated as they traveled toward the negative electrode. Since the force of the electric field is known, the masses of the samples can be calculated from the basic equation from high school physics, $F = ma$, force equals mass times acceleration, which rearranges to give $m = F/a$. Strictly speaking, mass spectrometry doesn’t measure the molecular masses of the fragments, but their mass-to-charge ratios. However, instruments are designed so that most of the ionic fragments produced have the same charge, of +1, so that the mass-to-charge ratio of a fragment easily yields its mass. Since mass spectrometry gives the masses of fragments rather than intact molecules of the analyte, some reasoning must be applied to determine the molecular mass of the analyte. Logic must be used to determine the likely nature of the fragments based on their masses, and then the masses used to determine the mass of the whole molecule.

The mass spectrometer to be used on the Mars Science Laboratory mission is of a type known as a quadrupole mass spectrometer. Such instruments are much more complicated than the time-of-flight spectrometers described above, using multiple perpendicular electric fields to achieve separation. Even so, they too measure the mass-to-charge ratio of molecular fragments rather than directly measuring mass. Quadrupole mass spectrometers are the most common type used on earth because of their ruggedness and speed, qualities which make them ideal for use in a space mission.

More on gas chromatography

At its core, gas chromatography is a technique for measuring how many different components are present in a mixture of substances. In most gas chromatographs, a very small (microliter range) sample is vaporized by heating, and a stream of inert gas (such as helium or nitrogen) blows the sample through a column (really a thin coiled tube). This column is packed with a material called the *stationary phase,* in contrast to the gas, which is called the *mobile phase*. The stationary phase might be a solid material such as a silicone polymer or, more commonly, it is a high-boiling-temperature liquid, coated onto the surface of a support material like diatomaceous earth. The job of the stationary phase is to slow certain molecules more than others as they pass through the column. Different molecules will have different affinities for the material of the stationary phase. Molecules with low affinity for the stationary phase will pass through the column relatively quickly. Meanwhile, molecules with a high affinity for the stationary phase will adhere to it somewhat, slowing passage through the column. In this way, each separate component of the mixture will take a different amount of time to pass through the column.

A detector at the end of the column measures the amount of each substance in the mixture, and produces a readout as a series of peaks. Each peak corresponds to a different substance in the mixture, while the position of the peak corresponds to the length of time it took that substance to pass through the column, or the *retention time*. The area under a peak is indicative of the relative abundance of that substance in the mixture. Most GC instruments calculate the percentage each component constitutes of the whole.

More on Gas Chromatography/ Mass Spectrometry

Gas chromatography is coupled with mass spectrometry to analyze mixtures of materials. Since Martian soil is a mixture, mass spectrometry alone would be of little use in analyzing it. Mass spectrometry tells you the masses of ionic fragments of analyte molecules, and if the components of a mixture aren't separated before carrying out mass spectrometry, there would be no way to know which component of the mixture produced which ionic fragment in a mass spectrometry readout. For this reason, gas chromatography is used to separate the components of a mixture, such as Martian soil, before mass spectrometry is carried out on them.

More on Tunable Laser Spectrometry

The tunable laser spectrometer that will be part of the Mars Science Laboratory is a cousin of the conventional infrared spectrometers found in most chemistry labs. Like the name suggests, this spectrometer uses an infrared laser as its light source, and that laser can be tuned to produce different frequencies of IR radiation. Organic molecules absorb infrared light as it interacts with covalent bonds between the various carbon, hydrogen, and other atoms in the molecules. Different bonds absorb different wavelengths of IR radiation. Therefore, a spectrum of the wavelengths of IR radiation absorbed by a particular molecule can tell you what kinds of bonds the molecule contains, and can help you determine the structure of the molecule. The IR absorption spectrum of a particular compound is a sort of fingerprint that can be used to identify that compound.

On Mars, the tunable laser spectrometer will be used to look for methane in the Martian atmosphere, by carrying out IR spectrometry on the Martian air, and looking for the characteristic peaks in the spectrum that correspond to the wavelengths of light absorbed by C-H bonds. In addition, the spectrometer will be used to study the isotopic content of water and carbon dioxide on Mars. This is possible because the way a bond absorbs IR radiation is affected by the masses of the atoms joined by the bond. A heavier or a lighter atom changes the wavelength of light that is absorbed. Therefore, carbon dioxide containing carbon-12 absorbs IR light at a slightly different wavelength than carbon dioxide containing carbon-13 or carbon-14.

Connections to Chemistry Concepts

1. **Organic chemistry**—The Mars Science Laboratory will be searching for signs of organic compounds in the Martian soil.
2. **Isotopes**—Since biological systems fractionate carbon-12 from carbon-13, the isotopic ratios can be used to distinguish biotic from abiotic organics.
3. **Chemical Reactions**—The article describes the chemical reactions involved in abiotic methanogenesis.
4. **Separations**—The gas chromatograph in the SAM will perform the essential work of separating the various substances in Martian soil samples prior to further study.
5. **Atomic and molecular mass**—The mass spectrometer in the SAM will characterize compounds by their molecular masses.
6. **Elements and compounds**—It isn't necessarily elemental carbon the Mars Science Laboratory mission hopes to find, but compounds containing carbon, hydrogen, and possibly other elements like oxygen and nitrogen.

Possible Student Misconceptions

1. **"The Mars Science Laboratory mission aims to find living organisms on Mars ."** *It is generally thought that conditions on Mars are too hostile for life today. Rather, most efforts are focused on finding signs of life that may have lived long ago when conditions on Mars may have been much friendlier to life.*
2. **"Organic compounds on Mars are proof that life once lived there."** *Organic compounds can be formed by a variety of abiotic processes. The presence of organics on Mars does not necessarily mean that life once lived there. However, even abiotic organics are a good sign, because they are almost certainly necessary for life to arise.*
3. **"Humans will be traveling to Mars on the Mars Science Laboratory mission."** *This will be a robotic mission, like Spirit and Pathfinder. People are not likely to visit Mars for several decades.*
4. **"All organic compounds come from living things."** *Originally, the phrase "organic chemistry" did mean the chemistry of living things. However, the term has broadened to mean any carbon-based compound (with the exceptions of CO, CO_2, carbonate minerals, graphite, and diamond). This is appropriate, not only because we now know that several abiotic processes can make complex carbon-based molecules, but also because humans can produce them synthetically as well.*
5. **"'Organic' means 'natural'."** *In common parlance, the word "organic" often refers to things that are all-natural, but in chemistry, the word refers to carbon-based materials, natural or not.*

Demonstrations and Lessons

1. "Life on Mars: A Dilemma Case Study in Planetary Geology", was created by Bruce C. Allen and Clyde Freeman Herreid, University at Buffalo, State University of New York. This case study explores the dilemmas faced by NASA scientists when they suspected they might have found evidence of life in a Martian meteorite unearthed in Antarctica,

and also explores the scientific evidence behind the controversy: http://www.sciencecases.org/mars_life/mars_life.asp.

2. You could use a lesson that focuses on pure substances, mixtures, and separations. The separation (by gas chromatography) of the components of Martian soil is an important part of the work the Mars Science Laboratory mission hopes to accomplish. This set of inquiry-based activities, part of *Science Alive!* from the Chemical Heritage Foundation, allows students to carry out both model separations of coins, marbles, and other objects, as well as actual chemical separations: http://www.chemheritage.org/scialive/julian/teachers/7a.html.
3. Dramatizing isotopes: deuterated ice cubes sink. The MSL mission will include isotopic analysis, and this demonstration makes isotopic differences plainly visible. This demonstration was published by Ellis, Arthur B.; Adler, Edward A.; Juergens, Frederick H., *Journal of Chemical Education*, 1990, *67*, 159. The J Chem Ed CD-ROM, “Chemistry Comes Alive!”, videodisc 2, contains the video of this demonstration. The video can also be viewed free on the University of Wisconsin general chemistry web site at http://genchem.chem.wisc.edu/demonstrations/Gen_Chem_Pages/02atomsmolpage/dramatizing_isotopes__deut.htm.
4. NASA provides an entire 1-week curriculum on the topic of mass spectrometry. (The actual mass spec activity only requires 1 day.) The lessons are based on Genesis, a probe that measured solar wind. The mass spec is used to analyze the data from the probe. Both student and teacher versions are provided. Find it at: http://genesismission.jpl.nasa.gov/educate/scimodule/sims_mini-mod.pdf.
5. You could use a mass spectrometry simulation. Mass spectrometry will be an important part of the MSL mission. A simulation activity which shows students how molecular masses are determined from mass spec data is found in “Mass Spectra,” *Journal of Chemical Education*, 2003, *80,* 176A.
6. Several science supply companies also
7. Life on Mars: Science Fact or Science Fiction? In this activity, students explore the requisite conditions for life, and weigh the actual conditions on Mars against those requisites. From the New York Times Learning Network: http://www.paragonspace.org/downloads/life_v2.pdf.

Student Projects

1. You could have your students join in the hunt for life elsewhere in the solar system. Assign students working alone or in groups to investigate different planets and moons in the solar system, to find out whether there is any possibility of life on those bodies. Students can present their findings as presentations or as written papers.
2. Students can explore the history of Mars exploration. Assign students working alone or in groups to investigate different Mars missions, from the early Mariner probes, to Viking 1 and 2, to modern missions like Pathfinder and Spirit. You may choose to tell you students to focus on what was learned about the chemistry of Mars on each mission, and how this affected the search for Martian life. Students can present their findings as presentations or as written papers.
3. You could have students explore the chemistry of other NASA missions. Mars isn’t the only planet where interesting chemistry takes place. Many unmanned NASA missions to the planets and their moons have explored the chemistry of these bodies. Assign students or groups of students different planets or moons, and have them research the chemical discoveries of NASA missions to their assigned worlds. Students can present their findings as presentations or as written papers.

4. Students can investigate extremophiles and extraterrestrial life. Extremophiles are life forms, usually microorganisms, that live in environments that are too harsh for most living things. They might be found at very high temperatures in deep sea thermal vents, highly acidic waters near volcanic fumaroles, or in the cold and dry conditions of the Gobi desert. Students working alone or in groups could investigate different types of terrestrial extremophiles, and discuss the ramifications for the possibility of life in seemingly less-than-ideal environments in the solar system. Students can present their findings as presentations or as written papers.

Anticipating Student Questions

1. **"Why can't we just send people to Mars to look for life?"** *It will probably be a few decades before people set foot on Mars so, in the meantime, the next best thing is sending robots to Mars. Sending robots is easier and cheaper because they don't need food, water, or oxygen, and they can withstand the cosmic radiation that could be very dangerous to human astronauts on a long mission.*
2. **"If there was once life on Mars, what happened to it?"** *It is thought that Mars was once a much warmer and wetter planet, maybe with a thicker atmosphere than it has today. Conditions on Mars billions of years ago may have been favorable for life to develop. Today, Mars is far too cold and dry for most terrestrial species to survive.*
3. **"If Mars was once wetter than it is today, what happened to all the water?"** *Mars is about half the size of Earth. This means its gravity is much weaker. On Earth, when water evaporates, it eventually falls back to earth as rain. On Mars, if it had lakes and oceans, water would have evaporated just like on Earth. With less gravity to hold it back, some of that water might have escaped into space rather than falling back to the surface as rain. Over time, most of its water probably departed in this way. However, it is thought that some water remains frozen in the ground as permafrost. If Mars once had a thicker atmosphere, much of it was probably lost to space as well.*
4. **"Why is Mars colder now than it was billions of years ago?"** *Water vapor is a potent greenhouse gas, even more potent than carbon dioxide. Without water vapor, Earth would probably be too cold for life. If Mars had surface water, it probably had water vapor in its atmosphere as well, which would have kept the planet warmer than it is today. If Mars ever had water vapor in its atmosphere, it has long since escaped into space. In addition, a thicker atmosphere of carbon dioxide would have helped warm Mars as well. Today all but the thinnest blanket of* CO_2 *has left the red planet.*
5. **"Could there be life on Mars that isn't based on carbon?"** *If there were life based on elements other than carbon, it would be very different than anything we know on Earth. Only carbon atoms can form the complicated molecules that make up living things. Even silicon, the element most analogous to carbon, can't form analogs to all the carbon molecules that make life possible. For example, amino acids made from silicon rather than carbon have never been observed.*
6. **"Could there be life on other planets in the solar system besides Earth and Mars?"** *Currently, scientists consider Europa, a moon of Jupiter, as the most likely place to find life beyond Earth. The surface of this moon is thought to be a crust of water ice, and it is also thought that there is an ocean of liquid water beneath the ice. Tidal forces from Jupiter's immense gravity keep this moon warm enough for liquid water to exist despite being very far from the sun. Scientists would like to send a probe to land on Europa, and drill through the ice into the liquid water beneath to search for signs of life. Scientists are skeptical that life could exist elsewhere in the solar system.*

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Web Sites for Additional Information

More on Mars

Mars Exploration Home—official Mars page of NASA, with information on the planet as well as NASA missions to Mars past, present, and future: http://mars.jpl.nasa.gov/

The Mars Society—a private, non-profit group promoting Mars science and exploration, with lots of information on how humans might explore and live on Mars in the future: http://www.marssociety.org/portal

Mars (the planet)—page from *The New York Times*, with links to their news stories relating to the planet: http://topics.nytimes.com/top/news/science/topics/mars_planet/index.html

More on scientific instrumentation

Gas chromatography—a tutorial from Sheffield Hallam University: http://teaching.shu.ac.uk/hwb/chemistry/tutorials/chrom/gaschrm.htm

What is mass spectrometry? —a tutorial from the American Society for Mass Spectrometry: http://www.asms.org/whatisms/index.html

Teacher tools for mass spectrometry—contains several tools: a complete list of all isotopes of all elements, an interactive periodic table that shows all isotopes of each element, and a simulated spectrogram ("mass spec plotter") of any compound you input: http://www.sisweb.com/mstools.htm

A history of mass spectrometry—NASA and the Genesis mission to measure elemental composition of solar wind: http://genesismission.jpl.nasa.gov/educate/scimodule/sims_mini-mod.pdf

A mass spectrometry model/simulation—Irwin Talesnick's science supply company S17 from Canada offers for sale a model of a mass spectrometer. The kit uses steel spheres of various sizes (and therefore various masses) and a strong magnet to show how the path of heavier objects in a magnetic field differs from those of lighter objects. The basic model is available for $66.00 Canadian and the deluxe model costs $150.00 Canadian. See both at http://www.s17science.com/. Click on "Kits and Supplies" at the top of the home page, and then find pages 6 and 7.

Mars science instrument development—contains descriptions of instrumentation that will be used on various Mars missions, from NASA's Jet Propulsion Laboratory. http://marstech.jpl.nasa.gov/content/category.cfm?Sect=IG&Cat=base&subCat =MIDP&subSubCat=MIDPII

More on Organic Chemistry

What is Organic Chemistry?—a reading which introduces students to the subject of organic chemistry, part of *Science Alive!* from the Chemical Heritage Foundation: http://www.chemheritage.org/scialive/julian/teachers/2b.html

More on Exobiology

Ames Exobiology through Space and Time—official site of NASA's exobiology program: http://exobiology.nasa.gov/

From Primordial Soup to the Prebiotic Beach—interview with Stanley Miller, who carried out early experiments studying how abiotic organic compounds may have given rise to life: http://www.accessexcellence.org/WN/NM/miller.html

Introduction to Exobiology—site discussing studies into prebiotic chemistry and their ramifications for life on Earth and for the possibilities of life elsewhere, from Duke University: http://www.chem.duke.edu/~jds/cruise_chem/Exobiology/