ChemMatters

October 2003 Teacher's Guide

Puzzle: Mole Mischief!

In addition to National Chemistry Week (October 19–25, 2003), there's another chemistry celebration planned for October. Every October 23rd, the National Mole Day Foundation kicks off its 12-hour festivities promptly at 6:02 A.M. http://www.moleday.org/. As you'll see below, the date and time reflect an important chemistry concept, the *mole*.

You'll be hearing more about the famous "mole" as you study chemistry. Let's start with its official S.I. abbreviation—*mol*. That triplet of letters is found in many words of a chemist's vocabulary, not just the science words.

In this puzzle there are 14 words, each containing that triplet, *mol*. The word's clue/definition is given at left. For help, we've placed the letters MOL correctly in each word. Your task is to complete the word by filling the remaining blanks. #1 is done as an example.

Getting 11 or more correct is excellent. Good luck in matching moles!

1. 6.02×10^{23} items of a kind — M O L E
2. Element # 42 — M O L _ _ _ _ _ _ _ _
3. The diprotic indicator ___ blue, — _ _ _ M O L
4. A viscous syrup made from sugar — M O L _ _ _ _ _ _
5. Smallest unit of a compound — M O L _ _ _ _ _ _
6. A favorite Tex-Mex appetizer dip — _ _ _ _ _ M O L _
7. # of moles of solute/ kg solvent — M O L _ _ _ _ _
8. Burn and smoke without flames — _ M O L _ _ _
9. Has units of g/ mol (two words) — M O L _ _ _ _ _ _ _
10. Raze, tear apart completely — _ _ M O L _ _ _
11. Aluminum metal is prepared in ____cryolite — M O L _ _ _
12. The science that studies the universe's origin — _ _ _ M O L _ _ _
13. A famous novel by Daniel Defoe (two words) — M O L _ _ _ _ _ _ _ _ _ _
14. A fungus growth, especially on damp surfaces — M O L _

Student Questions

Whose Air is it Anyway?

1. It is sometimes said that every time you breathe, you take in about one molecule that passed through the lungs of Julius Caesar as he expelled his last breath. How is this statement related to the first few paragraphs of the article?

2. Why is air pollution a national and international issue rather than a local concern?

3. Why might it be advisable for an athlete to do strenuous workouts during the summer months in the early morning rather than in the afternoon?

4. What causes atmospheric ozone concentrations in urban areas to be higher in the afternoon during summer?

5. What is one of the major contributions that might come from NASA's Aura spacecraft related to ozone in our troposphere?

Alien Atmospheres: There's No Place Like Home

1. Describe the atmosphere of Venus in terms of its composition and atmospheric pressure.

2. What is meant by the *greenhouse effect* and the *runaway greenhouse effect*? What does this effect do on Venus?

3. Describe the atmosphere of Mars in terms of its composition and atmospheric pressure.

4. Discuss some ways in which the atmospheres of Mars and Earth are similar. Why are climate changes on Mars more rapid and drastic than on Earth?

5. What evidence suggests that Mars once had a more substantial atmosphere than it does today?

Clouds

1. What are condensation nuclei and what role do they play in the formation of clouds?

2. What is meant by the *dew point*, and what might prevent a cloud from forming even if the temperature of the air is below the dew point?

3. What kinds of particles act as condensation nuclei in our atmosphere?

4. What are two common substances used to seed clouds? How effective are they at relieving droughts?

5. What are CFCs and how are they involved in the destruction of the Earth's protective stratospheric ozone layer?

6. What type of cloud is a *PSC*, and how is its formation related to the destruction of the stratospheric ozone layer over the Earth's poles?

Life in a Greenhouse

1. What is the greenhouse effect? Explain how it operates.

2. What structural features of N_2 and O_2 prevent them from absorbing infrared radiation while CO_2 and H_20 can?

3. Explain how a molecule goes about absorbing infrared radiation.

4. What two factors determine the overall effect that a given greenhouse gas will contribute to global warming? Contrast carbon dioxide to water vapor.
5. What is a *carbon sink*? What are some common sinks?

Chemistry in the Sunlight

1. How does UV radiation help produce ozone in the upper atmosphere?

2. Why is ozone in the stratosphere considered good, while ozone in the troposphere is undesirable?

3. What are the two main groups of chemical compounds that result in the production of tropospheric ozone? What are some common sources of these chemicals?

4. How does NO_2 in the atmosphere lead to the formation of ozone? Explain, and illustrate with chemical equations.

5. Why are concentrations of ozone high during a summer afternoon in the city?

Beefing Up Atmospheric Models

1. What are two factors that limit the strength and accuracy of any mathematical model of Earth's atmosphere? How have these factors changed over the past several years?

2. Name and describe three key environmental processes that are very important to scientists trying to develop atmospheric models.

3. How is the quality of an atmospheric model evaluated?

4. What are the most sophisticated types of atmospheric models currently being used? What do these models take into consideration?

5. What quantitative measurements will be made when NASA launches the Earth Observatory Aura satellite in early 2004? List one of the key questions it will try to answer and two of the instruments that will gather data.

Answers to Student Questions

Whose Air is it Anyway?

1. There is basically is no such thing as "new" air. When a living thing inhales, molecules are taken in, and when it exhales, molecules are released back into the atmosphere to be reused later by some other living organism. Thus, at least in principle, the molecules of "air" (nitrogen and oxygen, mostly) that Caesar exhaled from his last breath have since that time been redistributed throughout Earth's entire atmosphere. When you breathe, it is entirely possible that you will inhale one or more of these molecules.

2. Pollution travels. Pollutants emitted into the air at one location often travel great distances through the atmosphere to produce problems thousands of miles away. For example, dust from the Sahara has been found on coral reefs in Florida. Dust from the Asian Gobi Desert has traveled to the East Coast of North America. Pollution from the eastern part of the United States can reach Europe.

3. Tropospheric ozone concentrations tend to rise in the afternoon during the summer season, and breathing ozone can eventually result in decreased lung capacity.

4. Tropospheric ozone is produced when pollutants such as nitrogen oxides and hydrocarbons interact with sunlight. Much of these pollutants come from the exhaust of automobiles and other vehicles. During heavy morning traffic these pollutants are released into the air. As the sun becomes more intense later in the day, the interaction of sunlight with these pollutants causes elevated ozone levels by afternoon.

5. NASA's Aura spacecraft is expected to provide the first truly global view of tropospheric ozone. According to Reinhold Beer, the principle investigator for one of the four instruments that will be carried aboard Aura, it will be able to track ozone both regionally within continents as well as from one continent to another.

Alien Atmospheres: There's No Place Like Home

1. The atmosphere of Venus is comprised of about 96% carbon dioxide (CO_2), about 3.5% nitrogen (N_2), no oxygen, and trace amounts of argon (Ar) and water vapor. Atmospheric pressure is extremely high—about 90 times what it is on Earth.

2. Atmospheric carbon dioxide prevents some radiation that is emitted from the surface of a planet from escaping back into space. On Earth, this is called the greenhouse effect. Since this results in some energy remaining on Earth rather than escaping back to space, it warms Earth's atmosphere. Because the atmosphere of Venus is 96% CO_2 compared to only 0.036% on Earth, the greenhouse effect on Venus is so much more pronounced that it is referred to as being "runaway," and it raises the temperature of the planet's surface to about 467 ^{o}C (873 ^{o}F).

3. Mars has very little atmosphere. Atmospheric pressure on Mars is only about 1/100 of what it is on Earth. What little atmosphere exists is comprised of about 95% carbon dioxide (CO_2), 2.7% nitrogen (N_2), 1.6% argon (Ar), and small amount of oxygen (O_2-0.15%) and water vapor (0.03%).

4. Although the atmospheres of Mars and Earth are very different, they do share some similarities. Both are transparent to sunlight and are heated largely by infrared radiation that emanates from their surfaces. They both exchange energy in similar manners. But because the orbit of Mars is more elliptical than that of Earth, its distance from the Sun varies by about 20% as it orbits the Sun every 687 "Earth days." It receives 40% more sunlight at its closest approach to the Sun compared to when it is farthest away. This produces rapid and significant changes in global temperatures.

One result of this rapid change is the production of massive storms that encompass the entire planet.

5. The surface of Mars has erosional features that closely resemble similar features on Earth that have been caused by rivers. There are also valley networks that could perhaps have been created by old river drainage systems. If these features were produced by water, then at one point in its history Mars must have been warm enough to support water flowing on its surface. In order to be that warm, it probably had a more substantial atmosphere. In addition, older craters on its surface appear to be more heavily eroded than younger craters, something that is also consistent with the presence of a more substantial atmosphere in its past history. There are alternate explanations for this observation, however.

   Geochemical evidence centers on isotope ratios found in the Martian atmosphere. Gravity on Mars is less than on Earth. Because of this, we expect that more of its atmosphere escaped. Isotopes of a given element differ only in the number of neutrons in their nuclei, and the lighter isotopes would tend to escape somewhat more readily than the heavier isotopes. So if Mars at one point had more of an atmosphere but much of it has escaped, then the ratio of the heavier isotopes to the lighter isotopes would be expected to be somewhat higher than is found on Earth. Since this is the case, it provides evidence for the idea that Mars may have had a more significant atmosphere in the past, but perhaps 90% has now escaped.

Clouds

1. The term *condensation nuclei* refers to tiny suspended particles with diameters of around 0.0001 cm or less that help gaseous water molecules condense to form droplets of liquid water or solid ice crystals. Condensation nuclei are needed in order for enough molecules of water to condense to form the visible droplets of water that make up a cloud.

2. The dew point is the temperature at which air becomes saturated with water vapor. If the temperature falls below the dew point the air is referred to as being *supersaturated*. It actually contains more moisture than it should be able to hold at that temperature. But if there are no condensation nuclei present, the water molecules may not be able to condense together to actually form a cloud.

3. There are number of common sources of condensation nuclei. One of the major sources is sea salts. They attract water molecules so strongly that they can produce cloud formation at temperatures above the dew point. Other common sources include smoke, exhaust, soil and even meteoritic dust.

4. Two common substances used to seed clouds are dry ice (solid carbon dioxide) and silver iodide, AgI. While the use of these substances has not been highly successful at relieving droughts, they have proven useful in dissipating cold fogs that might otherwise shut down airports.

5. CFCs are chlorofluorocarbons. These are human-made chemicals that were once commonly used in spray-can propellants, refrigerants, solvents and blowing agents for plastic foams. When these chemicals rose into the stratosphere, solar ultraviolet radiation split these molecules and released ozone-destroying chlorine.

6. PSC stands for polar stratospheric cloud. Its name describes what it is—a stratospheric cloud that forms over the North or South Pole of the Earth. Because the air over the Earth’s poles is extremely cold, clouds do not typically form there. But during the polar winters atmospheric temperatures can become so cold that ice crystal clouds can form even though the atmosphere contains very little moisture. The surfaces of these ice crystals unfortunately provide sites for chemical reactions that produce free radicals—atoms or molecules that contain one unpaired electron. These free radicals

are extremely reactive chemically, and some of these reactions result in the destruction of the ozone layer.

Life in a Greenhouse

1. The term *greenhouse effect* refers to the process by which the temperature of Earth's atmosphere is raised due to the presence of atmospheric gases that absorb infrared radiation that is emitted from the Earth's surface and then reemit some of it back towards the Earth.

2. Bonds connect atoms in molecules. The nuclei of the atoms are positively charged while the negatively charged electrons form a charged cloud that surrounds the entire molecule. The bonds stretch and bend with a kind of vibration that is unique for every different molecule. When a molecule contains only two atoms, the only way it can vibrate is for the bond connecting the two atoms to expand or contract. If the two atoms are identical, like in N_2 or O_2, the charges in the molecule remain symmetrically distributed as the atoms move back and forth. But for molecules like CO_2 and H_2O, some types of vibrational motion will distort the charges. The electron cloud will first concentrate more negative charge in one direction and then in the other. This difference is what allows CO_2 and H_2O to absorb infrared radiation while N_2 and O_2 cannot.

3. When a molecule vibrates, the charges in the molecule oscillate back and forth with a certain frequency. If this frequency happens to match the frequency of the light passing over the molecule then that frequency of light will be absorbed, just like the energy of someone pushing on a swing will be absorbed if they push at the frequency at which the swing is swinging.

4. The contribution that a given greenhouse gas makes to global warming depends both on its effectiveness as an absorber of infrared radiation and its abundance in the troposphere. Carbon dioxide is about ten times more effective at absorbing infrared radiation compared to water vapor, but it is not nearly as abundant in our atmosphere.

5. A carbon sink is a location at which the net effect is in favor of removing more carbon from the atmosphere than is being released. Some common carbon sinks include tropical rain forests and boreal forests.

Chemistry in the Sunlight

1. Ultraviolet radiation with wavelengths shorter than 242 nanometers can split O_2 molecules into two separate oxygen atoms. When some of these individual oxygen atoms come in contact with molecular oxygen (O_2), they can bond to the oxygen molecule to form an ozone molecule, O_3.

2. Ozone in the upper atmosphere, or stratosphere, protects us from ultraviolet light coming to Earth from the Sun. But in the lower atmosphere, or troposphere, it is considered a pollutant. It is one of the active ingredients in smog. It can react with biological tissue, donating oxygen atoms and oxidizing the tissue, which is undesirable. Breathing air containing ozone over a long period of time lowers human lung capacity and can cause illness, even death. Forests and crops are less productive if exposed to atmospheric ozone.

3. The two main groups of chemical compounds that result in the production of tropospheric ozone are nitrogen oxides, NO_x, and volatile organic compounds, or VOCs. Sources of NO_x include lightning, chemical processes in soils, forest fires, and the intentional burning of vegetation to make way for new crops (biomass burning) as well as smokestacks and by-products of the combustion of fossil fuels (coal, oil and natural gas). Coal-fired power plants are a significant source of NO_x in the United States.

4. The N-O bond in NO_2 is weaker than the O-O bond in O_2. Therefore it can be broken by less energetic, longer-wavelength ultraviolet light. This produces NO and O, as shown by the following equation:

   NO_2 + longer-wavelength UV light ----> NO + O

   The oxygen atoms produced can then combine with O_2 molecules in the air to produce ozone.

   $O + O_2$ -----> O_3

5. Concentrations tend to be highest in the summer because the formation of tropospheric ozone requires sunlight, which is most intense during the summer months. Formation also depends on the presence of NO_x and VOCs, both of which are released from the exhausts of automobiles and other vehicles. Vehicular traffic is high during the morning rush hour, so this is when the NO_x and VOCs are released. Several hours later, in the afternoon, they have had time to react and produce ozone.

Beefing Up Atmospheric Models

1. Two factors that limit the power of any atmospheric model to make accurate predictions are the quality of the data that is inputted into the model and the computing power available to run the complex mathematics upon which the model is based. Over the past several years, satellite observations have provided far more extensive and accurate data on the current state of the atmosphere and much more powerful computers have allowed far more complex models to be run.

2. Three key factors are emissions, deposition, and transport. Emissions refers to all processes that add substances to the atmosphere. Deposition refers to processes that remove substances from the atmosphere, and transport deals with how different substances move from one place to another through the atmosphere.

3. Data about the current state of the atmosphere is inputted into the model. The model is run, and it makes predictions about the state of the atmosphere at some other place or time. Then actual data from either laboratories or satellites is compared to the predictions made by the model. If there is close agreement, the model is considered to be a good one. If there is disagreement, the model is modified. The goal of any good model is to improve the agreement of its predictions with observations.

4. Currently the most sophisticated atmospheric models are called coupled atmosphere-ocean general circulation models, or AOGCMs. These are three-dimensional models that include equations that take into consideration the role of oceans, land vegetation, weather and many other factors as well.

5. Aura will make quantitative measurements of atmospheric ozone, water vapor and several other chemical species. One important question it will attempt to answer is, “What is happening to the stratospheric ozone?” Two instruments that will independently gather data from the same scene at the same time are the Ozone Monitoring Instrument, OMI, and the Tropospheric Emission Spectrometer, TES. Comparing the results from two different instruments will provide a “check” on the accuracy of each separate instrument.

Content Reading Materials Guide
October 2003 *ChemMatters*

Welcome! Here you will find correlations to the **National Science Education Standards**, **anticipation guides** for each article, and **graphic note-taking guides** to help your students understand the reading.

Encourage your students to develop effective content reading strategies for chemistry. Susan Cooper, an experienced chemistry teacher and content reading consultant from La Belle, Florida, created these reproducible pages.

Connections to the National Science Education Standards

Find out how the articles in this October issue relate to the content standards of the National Science Education Standards.

Anticipation guide

These guides help engage students by activating prior knowledge and stimulating student interest. If you have time, discuss their responses to each statement before reading each article. Students should read each selection and look for evidence supporting or refuting their responses. Evaluate student learning by reviewing the anticipation guides after student reading.

Graphic Organizer Set Guides

These content frames 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. 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

Tools for organizing information allow students to find meaningful patterns in the articles. These reproducible pages are excellent pre-writing activity sheets.

For an interesting discussion about promoting reading skills in the content areas, we recommend this Web article from the American Society for Curriculum Development: http://www.ascd.org/readingroom/classlead/0212/thomas.html

Please note: In this issue, students may be confused by the difference between tropospheric ozone and stratospheric ozone. Before you assign any reading, alert your students to the differences in where ozone is found, and why it is desirable in the stratosphere, but undesirable in the troposphere. You may need to explain that we live in the troposphere, and the stratosphere is much higher. As students read the articles, they must first determine where the ozone they are reading about is found, or they will be confused.

National Science Education Content Standards Addressed As a result of activities in grades 9-12, all students should develop understanding	**Atmospheric Models**	**Whose Air?**	**Greenhouse Gases**	**Alien Atmospheres**	**Clouds**	**Chemistry in the Sunlight**
Science as Inquiry Standard A: of abilities necessary to do scientific inquiry					✔	
Science as Inquiry Standard A: about scientific inquiry.	✔	✔	✔	✔	✔	✔
Physical Science Standard B: of the structure and properties of matter.		✔	✔		✔	✔
Physical Science Standard B: of chemical reactions.	✔			✔		✔
Physical Science Standard B: of conservation of energy and increase in disorder.			✔			
Physical Science Standard B: of interactions of energy and matter.	✔	✔	✔	✔	✔	✔
Life Science Standard C: of matter, energy, and organization in living systems.	✔		✔			
Earth and Space Standard D: of energy in the Earth system	✔		✔		✔	✔
Earth and Space Standard D: of geochemical cycles	✔		✔		✔	
Science and Technology Standard E: about science and technology.	✔	✔	✔	✔	✔	✔
Science in Personal and Social Perspectives Standard F: of personal and community health.		✔	✔			✔

National Science Education Content Standards Addressed As a result of activities in grades 9-12, all students should develop understanding	**Atmospheric Models**	**Whose Air?**	**Greenhouse Gases**	**Alien Atmospheres**	**Clouds**	**Chemistry in the Sunlight**
Science in Personal and Social Perspectives Standard F: of natural resources.	✔	✔	✔	✔		✔
Science in Personal and Social Perspectives Standard F: of environmental quality.	✔	✔	✔	✔	✔	✔
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

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. Cite information from the article that supports or refutes your original ideas.

Life in a Greenhouse

Me	Text		Statement
		1.	The greenhouse effect is good for our planet.
		2.	Molecules of greenhouse gases consist of at least 3 atoms.
		3.	Greenhouse gases absorb and re-emit infrared radiation as the molecules stretch and bend.
		4.	CO_2 is the most effective and most abundant greenhouse gas.
		5.	High clouds trap less infrared radiation than low clouds.
		6.	Some carbon is sequestered by tropical forests and boreal forests, making that carbon unavailable for increasing the greenhouse effect .
		7.	With the exception of CO_2 and H_2O, we can control which greenhouse gases get into the atmosphere.

Beefing Up Atmospheric Models

Me	Text		Statement
		1.	Mathematical models are used to make predictions.
		2.	When predictions from the model agree with observations, the model needs major adjustments.
		3.	Modelers need good, reliable data to minimize errors.
		4.	Models are tested on powerful computers using simulations similar to some video games.
		5.	Until the last 25 years, no prominent scientist was investigating the relationships among burning fossil fuels, CO_2 production, and global warming.
		6.	Earth’s atmosphere constantly undergoes many chemical and physical transformations.

Whose Air Is It Anyway?

Me	Text		Statement
		1.	The atmosphere over each continent stays mostly over that continent.
		2.	Ozone levels in the troposphere are lower in the morning.
		3.	All tropospheric ozone comes from human activity.
		4.	The source of ozone precursors, such as nitrogen oxides, can be determined fairly accurately.
		5.	Satellites can help track ozone levels near the ground.

Chemistry in the Sunlight

Me	Text		Statement
		1.	Shorter wavelengths of light are less energetic than longer wavelengths.
		2.	Ozone in the troposphere can reduce lung capacity and damage crops.
		3.	Sunlight and by-products of fossil fuel combustion produce tropospheric ozone.
		4.	People who live in rural areas do not breathe much ozone.
		5.	Ozone concentrations increase at night.
		6.	The highest ozone levels occur during the summer months.

Alien Atmospheres: There's No Place Like Home

Me	Text		Statement
		1.	The most abundant atmospheric gases on Mars and Venus are CO_2 and N_2.
		2.	Mars' orbit is less elliptical than Earth's.
		3.	Mars' climate is easy to study because Mars has no oceans.
		4.	There is evidence that most of the Martian atmosphere has escaped.
		5.	If methane is found in Mars' atmosphere by the Mars Express, life may be there now.
		6.	The composition of Earth's atmosphere has remained the same for the past 5 billion years.

Clouds

Me	Text		Statement
		1.	Cloud seeding to produce rain is only used during drought conditions
		2.	Clouds cannot form unless microscopic airborne particles are present.
		3.	Condensation heats the air in some clouds, producing convection currents.
		4.	Lightning causes the only damage from thunderclouds.
		5.	Only nimbostratus and nimbocumulus clouds produce precipitation.
		6.	All clouds result from natural causes.
		7.	Ozone depletion is occurring over both the north and south poles.

Graphic Organizer Sets

Clouds

Type of Cloud	Height	Appearance	Interesting Information
Nimbostratus			
Nimbocumulus			
Cirrus			
Contrails			
Polar Stratospheric Clouds (PSC)			

Life in a Greenhouse

Cause

Effect

Greenhouse effect

Non-greenhouse gases

Greenhouse gases & their sources

Whose Air Is It Anyway?

Examples of air pollution crossing international boundaries	Describe how the pollution was detected <u>and</u> the problems in detecting the pollution.
Dust	
Sea salt	
Ozone	
Ozone precursors	
Mold	

Alien Atmospheres: There's No Place Like Home

➢ Compare the atmospheres of Venus, Earth, and Mars by completing the chart below.

	Venus	Earth	Mars
Air pressure			
% CO_2			
% N_2			
% O_2			
% Ar			
Average surface temperature			
Interesting information			

Chemistry in the Sunlight

Ozone chemistry is affected by each of the following. Explain how.

	How does this contribute to tropospheric ozone?
Sunlight	
NO_x	
VOCs	
Changing environmental conditions	
Location	

Beefing Up Atmospheric Models

Why use them?	How are they used?
Characteristics of good models	Role of satellite data

Atmospheric Models

Question from the Classroom

Preliminary Comments

Although the “correct answers” to whether or not the listed items would “work,” or perhaps even work better on the hypothetical Planet X are in most cases reasonably clear and unambiguous, it should be noted that there may actually be some room for disagreement and debate on a few of them. “A siphon,” “a bow and arrow,” and “the game of golf” proved to be especially interesting and challenging. This first led to an Internet search that produced differing “expert” opinions, the second was fodder for several somewhat divergent responses from a physics ListServe, and the third provided motivation for several hours of research by your TG editor. I tried to ascertain whether a golf ball would actually fly farther—or not as far—in the absence of an atmosphere. This was my criterion for a “game of golf” being easier. If you play golf, the answer may appear obvious—the game couldn’t possibly be harder than it is right now!

There are a few implicit but not formally stated assumptions. Although “temperature” doesn’t have the same meaning in the absence of an atmosphere, all answers assume that everything is occurring at around room temperature, about 25 ^{o}C. Besides the lack of an atmosphere, it should be assumed that no other factors would be involved. For example, we all know you couldn’t swing a golf club very well while dressed in a pressurized space suit, etc., but these weren’t intended to be “trick” questions, so no “trick” answers are acceptable.

If you disagree with any of the listed answers, please share your thinking by contacting the TG editor, Frank Cardulla at:

chemtchur@aol.com

We would be very interested in hearing your arguments.

Answers to Life in a Vacuum

1. a suction cup

   No. As discussed in the article, there is no outside atmospheric pressure to push on the top of the cup and hold it on the surface.

2. a vacuum cleaner

   No. Again, there is no outside pressure that can push the dirt into the vacuum cleaner.

3. a drinking straw

   No. No pressure, no pushing. Even here on Earth, there is a limit to how tall a drinking straw can be and still work. Atmospheric pressure can support a column of mercury, Hg, approximately 760 mm high (about 29.92 inches). Since mercury is about 13.56 times denser than water, atmospheric pressure can support a column of water approximately 13.56 x 29.92 in, or about 405.7 inches high. This is equivalent to about 34 feet. If you leaned over the edge of a 35 ft building and tried to drink water from a cup on the ground, you would be unsuccessful. Even if you could produce a perfect vacuum in the straw (and you couldn’t come close), the water would end up a tantalizing 1 ft from your thirsty mouth.

4. a siphon

   No, but explaining why gets pretty involved.

   First, let’s make some simplifying assumptions. Assume the siphon is filled with water, but there are no attractions between the molecules. This eliminates any possible forces produced because molecules pull on each other. These kinds of forces can complicate things. For example, if intermolecular forces were very strong, then the siphon could be compared to a chain stretched over a pulley. If the amount of vertically hanging chain were longer on one side of the pulley than the other, the entire chain would move until it was completely on the "heavier" side. So a siphon containing a liquid with very strong intermolecular forces might be expected to work in a vacuum.

But what about a liquid with no intermolecular forces?

For numerical simplicity, let's use tubes with surface areas of 1 in^2. Atmospheric pressure is about 14.7 lbs./in^2.

First imagine a long vertical tube that has been evacuated and placed into a container of water. If you wanted to keep water from entering the tube, you would have to place an object that weighed 14.7 lbs. on top of the water.

Now imagine allowing the water to rise to a height of 17 ft. Now you could "hold back" the water with a 7.35 lb. weight. If you allowed the water to rise to a height of 34 ft it wouldn't take any weight to stop the water from rising further. That's as high as it can go.

So as the water rises in the tube, the force required to keep it from rising further diminishes.

Now imagine a siphon arrangement with the lower container on the right side and the higher container on the left. For simplicity let's make the right-side container one foot lower than the left.

Atmospheric pressure is trying to push the water from the left-side container into the right side container (clockwise) and vice-versa. At the top of the siphon there are pushing forces both clockwise and counterclockwise.

But the clockwise force is greater. That's because atmospheric pressure on the left side hasn't had to raise the water as great a distance as on the right. Remember—the higher the water has to rise in a tube, the lower the "pushing force" that remains.

So the water flows clockwise. The siphon works.

But if the siphon were more than 34 ft high, it wouldn't work. Atmospheric pressure could only push the water to a height of 34 ft. on both sides. There would be an empty space on both sides of the siphon. For example, if the top of the siphon were 40 ft. above the left side container and 41 ft. above the left container there would be 6 ft. of empty space on the left and 7 ft. on the right.

Now if atmospheric pressure were only one-half of its normal value, a siphon would still work, but only up to a height of 17 ft.

At very low pressures a siphon could still work, but only if the difference in liquid heights in the two containers was very small.

In a vacuum a siphon wouldn't work at all. Even if the tube were originally filled with liquid, the liquid would just drain back into the two containers leaving a completely empty tube.

5. a light stick

   Yes. Air is not needed for this chemiluminescent reaction.

6. a flashlight

   Yes. No trouble with batteries working. No trouble with electricity flowing. But there might be a problem with the bulb burning out. With no outside air to dissipate the heat produced by the bulb, the bulb might get so hot that the filament would melt.

7. a magnet

   Yes. Magnetic fields do not require air to exist.

8. a broom

   It would work, kind of, but not quite the same way. The broom bristles could certainly move dusts particles—no problem. But you'd have to contact each and every particle with the bristles or other moving particles because there wouldn't be any "wind" created by the moving bristles to help move other particles along. Sweeping dust in the absence of an atmosphere might be somewhat like sweeping dense sand particles here on Earth. But since most dust is created by wind, dust probably wouldn't be as much of a problem anyway.

9. an aerosol spray can

   Yes, but the spray pattern wouldn't be quite the same. With no air, each spray particle would travel in a parabolic path, like a baseball thrown in a vacuum. And if you were thinking that a pressurized container would certainly explode if it were put into a perfect vacuum, you are still thinking of a vacuum as having some kind of power. Imagine a can pressurized with 5 atm. of pressure. With 1 atm. pushing inward, and 5 pushing outward, the can has to withstand a pressure difference of 4 atm. With outside pressure removed, now it has to withstand a pressure difference of 5 atm. It was probably manufactured to withstand a pressure difference of 10-15 atm. or more, so this wouldn't be a problem.

10. an alarm clock

    Well, it could certainly keep accurate time, be it wind up, electric, or solar powered. But could it wake you up? The transmission of sound requires the presence of air or some other gas, so while the alarm might be ringing, you wouldn't hear anything.

11. a match

    Yes—for a second or two. Matches have their own built in oxidizing agent in the head, and so it will light. But after the original flare up, it will go out pretty quickly. Combustion requires the presence of oxygen.

12. a candle

    No. No oxygen, no combustion.

13. a blow dryer

    No. No air to heat up and blow around, and the filament would again probably melt. But wet hair wouldn't be much of a problem on this planet. With no pressure, keeping any kind of liquid around would prove quite difficult. At 0 atm., just about every liquid would quickly boil away.

14. an electric stove

    Yes. But heat dissipation would again be an issue.

15. a gas stove

    No. Methane, the gas burned in gas stoves, also needs oxygen to burn.

16. a pressure cooker

    Yes. In fact, that's just about the only way you could get water hot enough to cook anything.

17. a microwave oven

    Yes. At least the microwave oven could certainly put out microwaves. However, in the absence of any atmosphere, it might be pretty difficult to keep most foods intact and moist long enough to cook them.

18. a convection oven

    No. Not even if it's electric. With no air to create convection currents, the heat can't get to the food. That's why a Dewar flask or Thermos bottle is such a good insulator. Both are double-walled containers with a vacuum between the walls. Without air in that space, no heat can be conducted across the space between the walls, so things placed in them can be kept hot or cold for long periods of time.

19. a smoke detector

    No. The Am-241 inside the detector would still decay, but there would be no air for the radiation to ionize. And how is it going to warn people anyway with no air to carry the sound? Besides, what could catch fire anyway?

20. a soap bubble maker

No. Any realistic amount of air you blew into the bubble would burst it in a vacuum. Theoretically you could put in a very small amount of air that would expand, but not burst the bubble. However, the bubble would drop to the ground like a rock.

21. a boomerang

Not if you want it to come back. No air…no turns!

22. a yo-yo

Yes.

23. a Frisbee

It certainly wouldn't fly like we expect Frisbees to fly. It would fly more like a discus.

24. a kite

Not a chance! Kites require air to fly.

25. a swing

Should be even better! No air resistance to slow the swinger down. Once they start, they should be able to swing effortlessly for longer periods of time, with the only friction being where the rope is tied to the tree limb. And "pumping" would still work fine to get one going. It depends on shifting one's center of mass, not on pushing against the air as some might think.

26. a pogo stick

Yes. No problem here.

27. a bow and arrow

Yes—and No.

Posting this question to a physics ListServe prompted several responses offering differing opinions.

The arrow could certainly be propelled through the air by the bow, but with no air resistance, there would be no drag on the fletchings (feathers), and the arrow would likely go end over end and not hit the target point first.

But a more challenging question is whether the arrow would fly farther in a vacuum and whether the flight path of the center of mass would be approximately the same or very different.

Utilizing both his knowledge of physics and experience as an archer, the most comprehensive and authoritive answer was provided by Dr. Michael D. Edmiston of Bluffton College in Bluffton, Ohio.

"*When traveling through the atmosphere, and assuming no gyroscopic effect from spinning, a projectile can maintain a particular orientation with respect to its path if the center of drag is behind the center of gravity. If the projectile is launched with the center of drag ahead of the center of mass, the projectile will reverse its orientation after launch and thereafter "fly" with its center of drag behind its center of mass. If the center of drag is at the same location as the center of mass, the projectile can tumble. The tail feathers make sure the center of drag is well separated from the center of mass. The feathers would not be necessary if the arrowhead is massive enough and small enough that the center of mass is moved ahead of the center of drag even in the absence of feathers.*

Aside…I learned a lot of this from my younger days as an archer (making both the arrows and the bows) and as a rocket builder. In a propelled rocket, as opposed to a coasting arrow, getting the center of drag ahead of the center of mass is disastrous because the rocket goes berserk, whereas a coasting projectile simply reorients until the center of drag is behind the center of mass.

Other than this, the feathers do not provide any "lift." Their effect is simply making sure the center of drag is sufficiently behind the center of mass that the arrow is stable. Therefore, the presence of feathers reduces the range (because of air friction) compared to an arrow without feathers that is stable because of a dense tip.

In vacuum, the feathers do not affect the flight. Whether the arrow tumbles depends on whether it was launched with any torques around its center of mass. If the accelerating force was applied in-line with the center of mass, then all the energy given to the arrow ends up as linear kinetic energy. This arrow will go the farthest. It will not stick in the ground because it will land with the same orientation as it was launched.

If the arrow is launched with a torque, then the arrow launched in the vacuum will "tumble." This means some of the energy ends up as rotational kinetic energy rather than linear. This means the velocity of the center of mass is less. This arrow will not go as far as a vacuum arrow that is given a greater center-of-mass velocity.

Finally, to answer the question…if the identical arrows are given identical launches such that their center-of-mass launch velocities are the same, then the arrow in atmosphere suffers drag and will fall short of the range predicted by the usual textbook projectile-motion equations. The center of mass of the arrow in vacuum will follow the textbook projectile-motion equations and will go farther. The launch angle changes the range, but does not change the fact that the vacuum arrow wins the range contest."

So if we assume that the purpose of a bow and arrow is to hit a target with the point of the arrow, then we can conclude that it really doesn't work as well in a vacuum even though it would actually fly farther.

28. the game of golf

This is a pretty general statement, so let's simplify it to the question of whether a struck golf ball will fly farther in a vacuum as opposed to flying in Earth's atmosphere.

One thing is certain. There would be no hooking or slicing. Hooks and slices are the result of the action of air on a spinning golf ball. A ball struck in a vacuum would simply follow a parabolic path that could be calculated from the equations for projectile motion.

The dimples on a golf ball help it remain aloft for a longer period of time, which might suggest that a struck ball would fly farther in the presence of an atmosphere. But the atmosphere also produces considerable drag, which suggests that the ball struck in a vacuum would fly farther.

The physics of struck golf balls is very complex. It is not possible to just apply simple first-year physics equations to determine what will happen when a golf club strikes a golf ball. And in the presence of an atmosphere, the flight path of a spinning golf ball and its eventual landing point are very difficult to calculate. Where a struck golf ball lands depends on kind of club used, clubhead speed, where it is struck on the face of the club, the COR (coefficient of restitution) of the clubhead, the type of golf ball used, and probably several other factors as well.

But let's do some hypothetical calculations just for fun.

"Typical" values for clubhead speed, ball speed, launch angle and carry distance can be obtained from numerous websites. Although there will be variations from different sources, the following can probably be taken as being reasonable values for a typical driver being swung by an amateur golfer using a "normal" golf ball in normal atmospheric conditions.

Swing speed----------85 mph

Initial ball speed----127 mph
Time aloft------------5.3 seconds
Distance of carry---191 yards

These numbers came from a computer simulation program, but they do appear to be consistent with what one sees when actually playing the game.

Now let's do some simple projectile-motion calculations for a golf ball moving in a vacuum with an initial velocity of 127 mph. We will assume a launch angle of 45 degrees, which would produce the maximum carry distance in a vacuum.

The initial velocity, in m/s is:

(127 miles/hr)(5280 ft/mile)(12 in./ft)(2.54 cm/in)(1 m/100 cm)(1 hr/3600 s) =

56.77 m/s

When fired at a 45 degree angle, the horizontal and vertical components of velocity will be equal to each other, and from the properties of a 45-45-90 degree triangle, both will be equal to 56.77 m/s divided by 1.414 (the square root of 2), or 40.15 m/s.

The ball will take (40.15 m/s)/(9.8 m/s^2), or about 4.10 seconds to reach to top of its trajectory and the same amount of time to return to the ground. So the ball will be in flight for 8.20 seconds.

Since its horizontal velocity is also 40.15 m/s, it will travel a distance of (40.15 m/s)(8.20 s) or about 329 m, which is equivalent to 360 yards.

So if these calculations are at all reasonable, one would expect a struck golf ball to travel farther in a vacuum than on Earth.

It actually would be rather difficult to do a truly honest comparison. A real golf bal struck with a real golf club would not likely start off at a 45 degree angle, so perhaps the question really is open to serious debate.

29. the game of baseball

One's opinion as to whether the game played better or worse without an atmosphere might depend on whether you were a pitcher or a hitter.

No one would have to worry about how to hit a curve ball! With no atmosphere, all pitches would follow a simple parabolic path, which would appear to make them easier to hit. Batting averages would probably be much higher, as would the number of home runs!

30. a flower garden

No. No air, no CO_2 or O_2, both necessary for plants to grow.

31. a bicycle (and tire pump)

The bicycle should work fine, and the air in the tires shouldn't be a problem. But you'd probably need a cylinder of compressed air to inflate the tires.

32. a hang glider

No. You'd fall like a rock.

33. a golf cart

Yes, if they are electric. If powdered by a gasoline engine, they would need their own oxygen supply.

34. a helicopter

No. Not even if it were electric. With no air to push down, the helicopter couldn't go up!

35. a parachute

Not a chance! Like the hang glider, you'd fall like a rock.

36. a hover craft

No, unless it were using compressed air tanks.

37. an automobile (and air bag)

An electric one, yes. A gasoline powdered one, no—no oxygen to allow combustion of the fuel. But the air bag should still work, since it fills with nitrogen produced by a chemical reaction.

38. a hot air balloon

No. No air to fill the balloon, no oxygen to burn the fuel to heat up the air that's not in there to begin with. And even if you managed to somehow fill the balloon with hot air, it would immediately escape out the bottom of the balloon. And even if you somehow could avoid that, you're not going anywhere. Hot air may be less dense than regular air, but it's not less dense than a vacuum! No outside air, no buoyant force.

39. the Goodyear blimp

No. Filling it with helium wouldn't be a problem: in fact, it would take very little helium to do the job. But again, no outside air, no buoyant force.

40. the space shuttle

No problem taking off and maneuvering in a vacuum. The launching rockets carry their own oxidizer and fuel. Landing would have to be very different, however, since there would be no air on which to glide downward.

41. a shot gun

Yes. Gunpowder, like a match head, has its own built-in oxidizing agent. And the shot would certainly travel farther, making it even more dangerous for all wildlife on this planet!

42. an emergency road flare

Yes. Again, they have their own built-in oxidizing agent. This enables them to stay lit even in a torrential downpour.

43. dynamite (and fuse)

Yes and yes. Again, they both contain everything they need to operate.

44. lightning (and thunder)

No. Interestingly enough, scientists are still not certain about the exact mechanism by which lightning is produced. Current thinking is that it is produced when charge separations develop in clouds. These separations are thought to be the result of extreme turbulence produced by wind and large temperatures differences. Friction between small light particles moving upwards and heavy particles of hail moving downward cause these charges to be developed, although the specifics of the process are not really understood. But these charges certainly could never develop in a vacuum, which by definition is the complete absence of matter.

And even if lightning could occur, there would be no thunder. Thunder is sound, and sound requires air or some other gas for its transmission.

45. a coal burning power plant

No. No oxygen, no combustion.

46. a nuclear power plant

Yes. Fission would still work fine, although some engineering modifications might have to be made.

47. a nuclear warhead

Yes, and no. The warhead would still explode, unfortunately. But without an atmosphere, the typical shock wave that you may have seen in movies would not occur. This question is actually very complex. Fallout couldn't be carried across the Earth by winds, since there wouldn't be any wind. It doesn't seem very likely that the typical mushroom cloud that is always associated with nuclear explosions would occur. Perhaps the damage caused by the bomb would actually be much less, since it is the tremendous shock wave and heat that causes much of the damage.

48. a shooting star

No. With no air, falling meteorites would not burn up as they approached this planet. Instead they would impact on the planet's surface, making craters, just like on the moon.

49. our sun

Yes. It operates in a vacuum right now.

50. a beautiful sunset

No. Without the air to scatter the sunlight there would be no beautiful sunsets. The sky would not have a characteristic color because there is no atmosphere. The sky would be similar to what you would see standing on the Moon.

Whose Air is It Anyway?

Background Information

More about SeaWIFS

The article contains a SeaWIFS satellite image of the West Coast of North America on April 25, 1998.

SeaWIFS stands for *Sea-viewing Wide Field-of-view Sensor*. The project is designed to provide quantitative data on global bio-optical properties to the Earth science community. Sea WIFS is part of NASA's Earth Science Enterprise, which is a much broader project designed to look at Earth from space with the goal of achieving a better understanding of Earth's behavior and evolution.

As its acronym suggests, SeaWIFS's main focus is on the oceans. Additional information about SeaWIFS can be found at: http://seawifs.gsfc.nasa.gov/SEAWIFS.html

The site includes links to many teachers' resources.

Ozone concentrations at different times of day

Tropospheric ozone concentrations vary, depending on the time of day. In urban areas, they tend to peak in early afternoon. As discussed in *Chemistry in the Sunlight*, urban traffic releases NO_x and VOCs during the morning rush hour, and as the sun becomes stronger later in the morning, production of photochemical smog increases. A graph of ozone concentration vs. time can be found at: http://www.eman-rese.ca/eman/reports/publications/Forest/page17-5.html

Another example of ozone travels

Ozone produced in the lower troposphere in North America contributes, on average, about 5 ppb to the ozone concentrations found in Ireland. On occasion this can rise to as much as 10-15 ppb.

More quotes from Daniel Jacob and Guy Brasseur

The article cites some quotations from these two atmospheric scientists. The longer article on which the *ChemMatters* article is based includes additional quotations. Included are:

"You can look at a cloud and say, 'How can I describe what it's doing quantitatively?' I can't! The system is far too complicated. But should I give up? No! I can simplify the system so that it's tractable mathematically. Then I can run the model and compare the results with what I see nature doing." —Daniel Jacob

"When we see differences between our models and data from actual observations in the field or from satellites, we're not happy. But we often learn about a process that's new to us that way. Models are a means of testing our understanding, so that we can make predictions. Now our understanding of the atmosphere is developed in a partnership between observations, work in the lab, and modeling. " —Guy Brasseur

"More and more, we've learned that we cannot look at the atmosphere in isolation from the rest of the Earth. We must see it in the context of its interactions with the oceans, the biosphere, and human activities--with the whole Earth as a system. We must be developing global, comprehensive, integrated Earth system science models." —Guy Brasseur

"Now we have global three-dimensional models. We're not yet ready to put together the biosphere and the atmosphere and economics, but there are people who are dreaming about this."—Daniel Jacob

A little more information about how total ozone is measured using the TOMS

The Total Ozone Mapping Spectrometer (TOMS) measures the total amount of ozone in a column of atmosphere from the satellite to the Earth. In areas over the tropics, where the amount of stratospheric ozone is uniform, researchers can then subtract this amount from the total amount to determine how much ozone is in the part of the column within the troposphere.

The National Air Quality Standards

The Environmental Protection Agency (EPA) sets standards for six common air pollutants.

The standards for each pollutant are as follows:

Carbon monoxide, CO

8-hour average	9 ppm
1-hour average	35 ppm

NO_x—Which they call nitrogen dioxide

Annual Arithmetic Mean	0.053 ppm

Ozone, O_3

1-hour average	0.12 ppm
8-hour average	0.08 ppm

Lead, Pb

Quarterly Average	1.5 μg/m^3

Particulate matter (PM)

Annual Arithmetic Mean	50 μg/m^3
24-hour Average	65 μg/m^3

Sulfur dioxide, SO_2

Annual Arithmetic Mean	0.030 ppm
24 hour Average	0.14 ppm
3-hour Average	0.50 ppm

Connections to Chemistry Concepts

There is an interesting problem that can be linked to the notion that there is not such thing as "new" air, but rather we have basically only been recycling the same air for eons. See *Demonstrations and Lessons* for a presentation of this problem.

You encounter a lot of units dealing with the concentration of atmospheric pollutants. Some of them are:

ppm = parts per million
ppb = parts per billion
1 ppm = 1000 ppb
μ means "micro," and indicates 10^{-6}. A μg is one-millionth, or 10^{-6} of a gram
m^3 = cubic meter

Since there are 100 cm in a meter, a m^3 represents a cube 100 cm on a side, so there are $(10^2\ cm)^3$, or $10^6\ cm^3$ in one m^3.
Since there are 1000 cm^3 in a liter, there are 1000 L in a m^3.

Possible Student Misconceptions

The article does a nice job of pointing out that there is no such thing as "new" air. Instead we have simply been recycling the same air for millions of years. The same is basically true, at a practical level, for water and many other molecules (and basically always true for atoms). Students, may, however, not fully internalize this notion. Or, they may incorrectly conclude that all materials are perpetually recycled. This, of course, is not true. Oil, for example, is a nonrenewable resource. We don't just "recycle" it. We destroy it when we use it.

Students may think that the EPA sets air standards for all substances that might enter the atmosphere. The actually only set standards for six common pollutants. See *Background Information*.

Demonstrations and Lessons

1. If one of your goals for your students is to have them become proficient at reading and preparing graphs from scientific data, a nice activity entitled "Graphing Ozone Levels" can be found at:

   http://www.so.wustl.edu/science_outreach/curriculum/ozone/activities/1D-Graphing.p

2. You may have heard or read a statement similar to this: "When you take your next breath, there is a 99% chance that you will inhale at least one of the very same molecules of air that passed through the lungs of Julius Caesar as he inhaled his last breath." (or something similar).

   Could this possibly be true, or is it just something that someone said many years ago and got passed along like an old wife's tale? Trying to determine the answer to that question could make for an interesting and profitable class session. Students could be challenged to calculate the number of molecules of air that would have been exhaled by Caesar and if distributed uniformly through the troposphere, how many would be inhaled as you took a typical breath.

   There are a number of approaches to this problem, some simple, some more complex, depending on what kind of data you decide to begin with. The following data demand a moderately sophisticated calculation (for high school students) and also require some knowledge of basic physics. It should be noted that some data values are only approximate, and this solution is simple in the sense that it does not include any allowance for interaction of the atmosphere with the biosphere or solid earth. It assumes that in the 2000 or so years since Caesar's death the molecules he exhaled have simply been distributed uniformly across Earth's atmosphere.

   Volume of an average human breath--0.40 L at 37 ^{o}C and 1 atm.
   Surface area of Earth--510 x $10^6\ km^2$
   Average molar mass of air--29 g/mol
   Pressure at surface of Earth--101,300 Pa

   If you would like to obtain a solution to this problem, just send a request to:

   chemtchur@aol.com

Please title your request “Solution to Caesar Problem” and use your school’s email address to avoid the solution being sent to students.

Connections to the Chemistry Curriculum

This article connects nicely to both “traditional” and “non-traditional” chemistry topics. It clearly has strong ties to many environmental issues that are increasingly a significant focus of many of our courses, especially air pollution. It also can connect to gas laws (see *Demonstrations and Lessons*). The chemistry of ozone production in the troposphere will quickly take one into a discussion of chemical equations, chemical kinetics, and reaction mechanisms. If you delve into how atmospheric ozone concentrations are measured, you will need to discuss the nature of light, how molecules absorb and emit light, and how the presence of a molecule is determined from its optical spectrum.

Suggestions for Student Projects

1. Some of the instruments that are currently monitoring or will be monitoring Earth’s atmosphere in the future are mentioned, but not treated in any detail. Students might prepare a more detailed report on one instrument, the scientific principles that underlie its operation, what it is designed to measure, and how the data it gathers will be utilized. Some possible instruments are:

   TOMS--Total Ozone Mapping Spectrometer
   OMI--Ozone Monitoring Instrument
   TES--Tropospheric Emission Spectrometer
   MOPITT--Measurements of Pollution in the Troposphere
   HIRDLS--High Resolution Dynamics Limb Sounder

2. While knowing the limits for various types of pollutants may be interesting (see *Background Information*), a more useful number for the average citizen is probably what is referred to as the *Air Quality Index*. The EPA monitors the AQI for five pollutants--ground level ozone, particulate matter, carbon monoxide, sulfur dioxide, and NO_x. Students could report on what this index is, how it is determined, how it is reported, and the hazards connected to various values for each of the five pollutants.

3. The article discusses the fact that tropospheric ozone often travels from its original source to other places, but only touches lightly on its health effects. Students could research known effects of ozone exposure, the kinds of health problems that it might create, and the groups of individuals that are most susceptible to its effects.

4. There is an interesting “Caesar’s Last Breath” problem that could be assigned to individual students or small groups of students to try and solve. See *Demonstrations and Lessons*.

Anticipating Student Questions

1. One of the sidebars mentions two instruments called an “ozonesonde” and a “radiosonde.” What do those terms mean?

   It’s sort of implied, but not directly stated in the sidebar. An ozonesonde refers to an ozone-measuring instrument that is typically carried aloft by being attached to a balloon, while a radiosonde is just a miniature radio transmitter that is launched the same way and contains instruments for broadcasting the humidity, temperature and pressure.

   You can find a report, with photographs of students launching an ozonesonde at: http://tea.rice.edu/bergholz/8.13.1998.html

2. The article mentions and “Optical Transient Detector, or OTD.” What is that?

It’s a scientific instrument consisting of a highly compact combination of optical and electronic elements. The name refers to the fact that it is capable of detecting the momentary changes in an optical scene that occur because of the presence of lightning. There’s a nice graph that shows the flash density in flashes/km^3/year for most of the Earth along with additional information about the OTD at: http://thunder.msfc.nasa.gov/otd

Websites for Additional Information and Ideas

One of the very best Websites for all kinds of information about our atmosphere is the Earth Observatory. The general URL is: http://earthobservatory.nasa.gov

From there you can link to “Atmosphere,” “Oceans,” “Land,” “Energy,” and “Life,” and from each of these there are an enormous number of additional links. It is a tremendously valuable site for all kinds of information about Earth’s environment. You can view data sets on ozone concentrations and UV radiation exposure from Nov. 1978 until virtually the present. There are links to dozens of articles dealing with a wide range of environmental issues.

Information about the health risks associated with tropospheric ozone and the EPA Air Quality Standards can be found at: http://www.epa.gov/airnow/aqibroch/aqi.html

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Alien Atmospheres: There’s No Place Like Home

Background Information

A quick primer on the solar system

There actually is some disagreement about how to classify the objects in the solar system. Perhaps the most common classification scheme holds that the solar system consists of:

Nine planets
More than 100 satellites of the planets (moons)
A large number of small bodies
- Asteroids
  - small dense objects orbiting the Sun, many but not all in the Asteroid Belt that lies between Mars and Jupiter
- Comets
  - small icy objects with highly eccentric orbits

The interplanetary medium
- stuff in the space between the planets and other objects—electromagnetic radiation, hot plasma consisting of electrons, protons and ions, cosmic rays, microscopic dust particles and magnetic fields

The terrestrial, or rocky planets are Mercury, Venus, Earth and Mars
The Jovian, or gas planets are Jupiter, Saturn, Uranus and Neptune
- Pluto is basically a rocky snowball

The small planets are Mercury, Venus, Earth, Mars and Pluto
The giant planets are Jupiter, Saturn, Uranus and Neptune
Mercury, Venus, Mars, Jupiter and Saturn have been known since prehistoric times. They can all be seen with the naked eye.
Uranus, Neptune and Pluto were discovered in modern times. They are only visible with telescopes.

The inner planets are Mercury, Venus, Earth and Mars

The outer planets are Jupiter, Saturn, Uranus, Neptune and Pluto

The orbits of all the planets lay close to the same plane, called the *ecliptic*, which is defined by the Earth's orbit. The orbit of Pluto shows the greatest deviation, about 17 degrees. All the planets orbit in the same direction—counter-clockwise as viewed looking down from the Sun's north pole.

Remembering the names of the nine planets

Those of us who teach Earth Science probably think that everyone knows the order of the planets as one moves away from the sun. But to save any possible embarrassment if a student asks, there are a number of mnemonic devices that can help one recall the order. Perhaps the most popular one is:

My Very Educated Mother Just Showed Us Nine Planets, for

Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto

or, My Very Eager Mother Just Served Us Nine Pizzas

Actually this mnemonic device wasn't valid from 1979-1999. During this time the orbits of Neptune and Pluto crossed, and Pluto was actually closer to the Sun than Neptune.

Some basic comparisons of Earth, Mars and Venus

Parameter	Earth	Mars	Venus
Equatorial radius (km)	6378.14	3397	6051.8
Mass (x 10^{23} kg)	59.74	6.48	48.69
Average density (g/cm^3)	5.52	3.94	5.25
Average distance from Sun (AU*) 1 AU = 1.471 x 10^{11}m*	1	1.52	0.723
Surface gravity (m/s^2)	9.8	3.71	8.87
Length of a year (Earth days)	365	687	225
Length of a day (Earth time)	23.9345 hours	24.6230 hours	243.02 days
Solar irradiance (W/m^2)	1367.6	589.2	2613.9

*1 Au or Astronomical Unit is typically taken to be the "average" distance from the Earth to the Sun. There actually is a much more technical definition, which can be found at http://neo.jpl.nasa.gov/glossary/au.html, but for our purposes, the normal meaning of the term, somewhat imprecise as it is, should be satisfactory.

How studying the atmosphere of Mars connected to something important to Earth

In 1971, a Mariner spacecraft reached Mars. Unfortunately, the entire surface of the planet was obscured by a huge dust storm that had begun months before. Disappointed but not undaunted, some scientists decided to study the dust storm itself. They discovered that the normal temperature structure of the atmosphere of Mars had been inverted. Instead of temperatures decreasing as you moved up from the surface, the dust clouds appeared to be relatively warm, while the surface was relatively cold. The dust in the atmosphere was preventing sunlight from reaching the surface. In a self-perpetuating cycle, this temperature inversion resulted in even higher winds that kicked up even more dust, which made the storm even worse.

Computer models were later developed that modeled the effects of these dust storms on the planet's energy budget.

Several years later one of the scientists involved in developing the models read about the theory which argued that the extinction of dinosaurs could have been the result of the collision of a comet or asteroid with Earth. The impact could have blasted so much dust into Earth's atmosphere that an effect occurred similar to what happens on Mars during a dust storm. Computer models indicated that such an effect could, in fact, have occurred.

The results were presented at a scientific meeting. After the presentation someone asked whether a nuclear war might produce similar results. Applying the knowledge and models that had first been obtained and developed from the Martian studies, it appeared that indeed, in the event of a nuclear war, there would be no "winners." The climate of Earth would be so altered by the amount of dust blasted into the atmosphere that all humanity would suffer cataclysmic effects.

More about the Venera 13 and 14 missions and other missions to Venus

The article mentions the Russian space probe, Venera 13, which landed on Venus in 1982. It was able to return the first X-ray spectra from the planet's surface before being crushed. There actually were two closely spaced probes. Venera 13 was launched on Oct. 30, 1981 and arrived on Venus on March 1, 1982. Venera 14 was launched five days later and arrived on March 5, 1982. Some of the wonderful photographs relayed back can be found at: http://pages.preferred.com/~tedstryk/venerab.html

There actually were several earlier Venera missions, which flew by, orbited and in some cases attempted to land on Venus. More information about all these missions can be found at: http://nssdc.gsfc.nasa.gov/planetary/venera.html

The number of Venus missions, both successful and unsuccessful may come as a surprise to those of us who do not follow these kinds of things faithfully. It appears that there have been as many as forty-five different attempted missions, starting as early as 1961. A complete list can be found at: http://nssdc.gsfc.nasa.gov/planetary/chronology_venus.html

A wonderful NASA Website about Mars

NASA has a tremendous Website devoted to Mars. It can be accessed at: http://mars.jpl.nasa.gov/

From there you can link to "Mars for Kids," "Mars for Students," and "Mars for Educators." The amount of information available is staggering. At the student link you will find things like the Athena Student Interns Program where teams of students and teachers can become part of the Mars Exploration Rover mission science team, or the Mars Exploration Student Data Team, where teachers and students can work from their schools to help study and characterize different aspects of Mars, from the surface to the atmosphere. Students can participate in "Create a Colony on Mars," where they are challenged to imagine and design a livable community on what now is a very inhospitable planet. They can chat with a scientist and get their questions answered. They can build and assemble their own models of the Mars Pathfinder, Mars Global Surveyor and 2001 Mars Odyssey.

The Mars for Educators link is equally if not more impressive. There is a list of available Educator Workshops. There is an amazing list of classroom resources. One, the Mars Activity Book, is a 131 page downloadable pdf file. You can sign up for a free poster with classroom activities on the reverse side. There are four major programs: *Imagine Mars*, which teaches students science through the arts, letters and humanities, the *Mars Student Imaging Project*, which allows students to use a camera on the Odyssey orbiter to take their own image of Mars and then analyze it, the *Mars Robotics Education*, a program that aligns technology-education standards, and the previously mentioned *Mars Educator Workshops* which offer professional development support for teachers.

Connections to Chemistry Concepts

The pressure on Venus

The article states that to reach a pressure equal to that on the surface of Venus, about 90 atmospheres, you would have to dive to an ocean depth of "over a half mile." One simple way to calculate this is to realize that one atmosphere of pressure is equivalent to a column of mercury, Hg, 760 mm high. Since mercury has a density of about 13.56 g/mL, while the density of sea water is 1.03 g/mL, it would take a column of sea water slightly less than 13.56 times as tall as a column of mercury to exert the same pressure. Consequently, a pressure of 90 atmospheres would support a column of sea water about:

(90 atm)(760 mmHg/atm)(13.56/1.03), or 900,489 mm high (ignoring significant figures)

This is equivalent to:

(900,489 mm)(1 cm/10 mm)(1 in/2.54 cm)(1 ft/12 in)(1 mile/5280 ft) = 0.56 miles

The amount of carbon dioxide in the atmosphere of Venus

The article also states that the concentration of carbon dioxide on Venus is about 260,000 times what it is on Earth. The following reasoning can derive this number.

Atmospheric pressure on Venus is 90 atmospheres—about 90 times what it is on Earth. This means that it contains 90 times as many gas molecules per cm^3. The percentage of carbon dioxide on Venus is about 96%, compared to only about 0.036% on Earth.

So compared to Earth, the concentration of carbon dioxide on Venus would be approximately:

(90)(96/0.036) or about 240,000 times that on Earth, close enough to the "260,000 times" figure cited in the article, given the significant figures used in this calculation.

Graham's Law and the ancient atmosphere of Mars

The article also explains that scientists think that Mars may have possessed much more of an atmosphere in its distant past because isotopic ratios of light/heavy isotopes are only about 90% of what is normal. The argument is that because of Mars' lower gravitational pull, most of the atmosphere has escaped, and lighter isotopes would escape faster than heavier isotopes.

Lighter isotopes move faster. Graham's Law gives the ratio of the speeds of two different isotopes:

$$v_1/v_2 = (m_2/m_1)^{1/2}$$

which essentially says that the ratio of molecular speeds is inversely proportional to the square root of the molecular or atomic masses of the two molecules. So an if atom 1 is half as massive as atom 2, it will be moving 1.414 times as fast.

Possible Student Misconceptions

Unless a student has taken a class that deals with the planets and/or done some reading of genuine science or viewed some valid science programs, it is rather likely that they will have misconceptions about what Venus and/or Mars is really like. The article certainly goes far to dispel some of these myths and misconceptions, but there are many others that the article does not address. See *Demonstrations and Lessons*.

Demonstrations and Lessons

1. If you are interested in devoting class time to activities connected to Mars, there are probably enough of them in the Mars Activity Book that can be found in the Mars for Educators link at http://mars.jpl.nasa.gov/ (see *Background Information*) to keep you and your students busy for the rest of the school year. Included are things like Rover Races, Earth, Moon and Mars Balloons, Mars Bingo, Mud Splat Craters, Alka-Seltzer Rockets, Soda Straw Rockets and many others.

2. Students without a strong science background are likely to have a number of misconceptions about both Mars and Venus, especially in light of the way these planets are often misrepresented in popular media. The article certainly goes far to dispel several myths about their atmospheres, climates and general environments. But it might be interesting to quiz students about some other misconceptions. You can probably think of many to ask your students. A few possibilities might include:

   What is the order of Earth, Mars and Venus as you move out from the Sun?
   How do the sizes of the planets compare?
   How do the masses of the planets compare?
   How long is a "day" on Mars and Venus?
   How long is a "year" on Mars and Venus?
   How does the force of gravity compare on Earth, Mars and Venus?
   How do the densities of the planets compare?
   Which planet receives the most sunlight? Which the least? Why?

3. Sometimes we can be in need of a "filler" lesson plan in the event of an unplanned absence. Having students read a ChemMatters article and answer the Student Questions can certainly serve this purpose. Another possible student activity would be to take the quiz found at: http://www.astro.umn.edu/intro/syll/test10.html

   But this would have to be printed out ahead of time, since the answers are given after the quiz is taken.

Connections to the Chemistry Curriculum

There is a large amount of both chemistry and physics connected to any discussion and comparison of different planets. A physics class could spend a significant amount of time dealing with Kepler's Third Law, the orbits of the planets, how the mass of a planet is determined, the gravitational field of different planets, the distance of the planets from the Sun and the amount of solar radiation reaching their surfaces.

There are a great number of chemistry course concepts tied in as well. The composition of the atmospheres will tie to the effect of global warming on atmospheric temperature. The relative densities of the planets can be related to conclusions about the nature of their cores. The difference in atmospheric pressures ties into the gas laws and how much atmosphere is actually present. There are also connections to acid-base chemistry, redox reactions, and Graham's Law (see *Connections to Chemistry Concepts*).

Suggestions for Student Projects

1. For teachers and students who have only had a basic introduction to astronomy in general and the solar system in particular, it may come as a bit of a surprise that the "classical" way the solar system is described in most textbooks is not the only classification scheme. There are others based, for example, on chemical composition and/or point of origin. Students might want to report on how these classification schemes work, the rationale behind them and the ways in which one might consider them to be "superior" and "inferior." Perhaps a

student debate could even be held with different groups of students arguing in favor of one classification scheme or another.

2. Provide students with this challenge: can you envision any possible way of altering the atmosphere and climate of Mars to the point where it might be capable of supporting human life? Assume that you have unlimited time and money. Different student groups could design plans to achieve this transformation and present them to the class, perhaps even holding a debate over the merits of each plan.

3. If some of your chemistry students have already taken physics, an interesting project would be to prepare a report on how Kepler's Third Law can be used to determine the mass of a planet.

Anticipating Student Questions

1. What, exactly, makes something a "planet?" Aren't there a lot of things that orbit our Sun?

   Whether or not something should be called a "planet" can actually be debated. The most accepted criteria are probably that a planet is a large object that orbits the Sun, but unlike the Sun, doesn't emit any significant amount of energy. There actually are thousands of small objects in solar orbits beyond Neptune and Pluto, but they are quite small, the largest being only about half the size of Pluto. They are icy and disintegrate if interactions with other objects force them closer to the Sun. Pluto itself is basically a rocky snowball. Most astronomers agree that if Pluto were discovered today, it very likely would not be classified as a planet.

2. Have we sent spacecraft that either landed or orbited all of the planets?

   No. We haven't sent any spacecraft to Pluto. There was a project to do so, but it was put on hold. There are current plans for a new mission that would get a spacecraft to Pluto by the year 2020. Pluto is very far away. Its distance from Earth varies from about 4.3×10^9 km (2.7 billion miles) to about 7.5×10^9 km (4.7 billion miles).

3. How can we measure a planet's mass?

   Well, certainly not by placing it on a balance or scale! The basic idea is that the gravitational force exerted by a body depends on its mass, whether it is a planet or a grain of sand. That's essentially how we have determined the mass of the Earth.

   For other planets, the general method is to observe a body that is orbiting the planet (like a moon) and see how its path is affected by the planet's gravity. The stronger the gravitational field around the planet, the faster its moon would be orbiting.

   Determining the mass of Mercury and Venus was difficult because they have no moons. Before the development of space flight, the only way to estimate their masses was to measure the small effects these planets had on the motions of other planets—not a highly accurate technique. But after spacecraft were able to fly close to these planets, the effect of the planet on the spacecraft could be determined and much more accurate determinations of mass could be obtained.

Websites for Additional Information and Ideas

There is obviously an incredible amount of information available from both books and the internet on each of the nine planets. One very good source is:
http://seds.lpl.arizona.edu/nineplanets/nineplanets/nineplanets.html

There is an abbreviated and simplified version of the above, for kids, at:
http://mercury.nineplanets.org:8011/tnp4kids/

If you want far more detailed statistical comparisons of Venus and Earth, go to:
http://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html

For Mars: http://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

The article mentions the huge dust storms that take place on Mars and can encompass the entire planet. A description of one that occurred in 2001 can be found at:
http://www.space.com/scienceastronomy/solarsystem/mars_storm_update_011011.html

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Clouds

Background Information

More about Dr. Vincent J. Schaefer

Dr. Schaefer is credited with being the first scientist to experiment and develop the technique of cloud seeding. In 1946 he performed the first cloud seeding experiments at the General Electric laboratory in Schenectady, New York. He was attempting to produce artificial clouds in a chilled chamber. Thinking that one chamber was too warm, he decided to cool it quickly by inserting a piece of dry ice (solid carbon dioxide). A cloud immediately formed around the piece of dry ice because its surface had provided nucleation sites for the formation of water droplets. By November of that year Schaefer had conducted a successful field test, using an airplane to seed a natural cloud to get it to produce rain.

A 1946 photograph of Dr. Schaefer conducting one of his laboratory experiments can be found at:
http://snrs.unl.edu/amet351/rentschler/weathermodbegin.html

Schaefer and Bernard Vonnegut, another scientist at the General Electric Laboratory were dual pioneers in cloud seeding research. One interesting sidelight is that Bernard Vonnegut is the brother of the famous novelist Kurt Vonnegut Jr., author of several famous books, including *Slaughterhouse Five*. Although Kurt Vonnegut is still living, Bernard passed away in 1985.

More on the history of cloud classification

While people have probably looked at the sky and seen innumerable different cloud shapes, the first formal classification of clouds is generally credited to the French naturalist Jean Baptiste Lamarck in 1801. He proposed five main types of clouds.

Hazy clouds (en forme de voile)
Massed clouds (attroupes)
Dappled Clouds (pommeles)
Broom-like clouds (en balayeurs)
Grouped clouds (groupes)

Three years later he developed an even more complex and detailed scheme comprised of twelve different forms.

But his scheme never caught on. It may have been due to the odd French names he used, which didn't translate well into other languages or the fact that he published his scheme in a journal that also published astrological predictions.

Two years later, an English scientist, Luke Howard (1772-1864) published a different scheme that created the foundation for the scheme we use today. Howard designated three basic cloud shapes, cirrus, cumulus, and stratus. Howard was not a scientist by vocation. He was a London businessman and amateur scientist who kept detailed records of meteorological observations for over thirty years.

Howard's scheme divided clouds into three major groups:

Cumulus (Latin for *heap*):	"Convex or conical heaps, increasing upward from a horizontal base—Wool bag clouds"
Stratus (Latin for *layer*):	"A widely extended horizontal sheet, increasing from below"
Cirrus (Latin for *curl of hair*):	"Parallel, flexuous fibres extensible by increase in any or all directions"

Later he added a fourth category used to describe a "cloud in the act of condensation into rain, hail or snow"

Nimbus (Latin for *rain*):	"A rain cloud—a cloud or systems of clouds from which rain is falling"

Howard then combined these terms to describe other types of cloud formations. For example, Cumulo-stratus, "The cirro-stratus blended with the cumulus, and either appearing intermixed with the heaps of the latter or super-adding a widespread structure to its base."

Howard's scheme was not actually adopted by the International Meteorological Commission until 1929, almost three-quarters of a century after his death. In April of 2002, the British Meteorological Office honored Howard's memory by installing a plaque at 7 Bruce Grove, Tottenham, where Howard spent the last years of his life.

Modern cloud classification

Howard's general classification scheme was expanded in 1887 by Abercromby and Hildbrandsson. They identified clouds by the height of the cloud's base above the Earth's surface.

Your own personal observations have probably suggested that there are a large number of different looking clouds and trying to place them in clear classifications might become rather complicated. This is certainly the case. There now are ten basic cloud types. Their names are based on combinations of words like *cirrus* (tuft or filament), *cumulus* (a heap or pile), *stratus* (a layer) and *nimbus* (rain bearing). There are, however, other types of clouds that can be identified. The following should be considered only an introduction to the ten basic types. There are actually about 50-60 scientific names for different types of clouds.

There are four main groups.

High Clouds:	These rise above 20,000 ft. There are three types:
	Cirrus, Cirrostratus and Cirrocumulus
Middle Clouds:	From about 6,500-20,000 ft.
	Altocumulus, Altostratus and Nimbostratus
Low Clouds:	From the Earth's surface to about 6,500 ft.

Stratus, Cumulus, Stratocumulus and Cumulonimbus

It should be noted that cloud heights in each category actually vary with latitude. Near the equator clouds of a given type will occur at higher levels than near the poles.

Another common group is referred to as *Clouds with Vertical Development*. Categories can overlap. For example, cumulonimbus clouds can be contained in this category.

Becoming expert on identifying types of clouds can be a great challenge. There are a great number of Websites containing cloud photographs. See *Websites for Additional Information and Ideas.*

More about cloud seeding

For some general information about the mechanism by which cloud seeding takes place, see *Connections to Chemistry Concepts.*

Two of the most commonly used materials for cloud seeding are solid carbon dioxide (dry ice) and silver iodide, AgI.

The mechanism by which dry ice works may seem obvious. Since dry ice is much colder than the surrounding air, it will cool the air. This increases the amount of supersaturation and makes the deposition of additional ice on the surface of the existing crystals more likely.
The use of AgI may appear strange. Why AgI? It turns out that silver iodide has a hexagonal crystal structure that is very similar to the structure of ice. Most textbooks contain diagrams of the crystal structure of "normal" ice, but if you need to see one, you can go to: http://www.its.caltech.edu/~atomic/snowcrystals/ice/ice.htm

The oxygen atoms in an ice crystal are separated by a distance of 0.459 nm. In a silver iodide crystal the separation between the silver and iodide ions is also 0.459 nm. While the two structures do not match exactly, they are close enough to allow AgI to be effective as a cloud seeding material.

Of course there is more to it than just dumping some AgI into a cloud. In order to function as effective nucleation sites, the particles of AgI must be very small and a large quantity must be available. This can be achieved in various ways. Although grinding it or spraying solutions might appear to be best, it turns out that burning the AgI with acetone and then spraying the gaseous mixture into the air in generally the preferred method. This results in minute particles being formed when it cools. There are a number of different ways of introducing it into a cloud, but the most common is via an airplane. The AgI can either be dumped into the top of a cloud or put in the bottom, relying on strong updrafts to raise it to higher levels.

Connections to Chemistry Concepts

More on the general topic of classification

The topic of cloud classification can allow us to teach a "life lesson" to our students. In order to make "sense" out of things, we often attempt to organize our observations and then assemble them into a limited number of categories that we can classify and label. Concepts like "metals," "nonmetals," and "metalloids," or "acids" and "bases" are common chemical examples.

But after we set up our schemes of classification and learn them, there is a strong psychological tendency to begin to look at these labels as being "real" in the sense that these things exist, and we merely "discovered" them rather than creating them. For example, there really are no such things as "acids" and "bases" in the absolute sense. There are just chemical substances. We created these categories because by doing so, we were able to describe, predict and understand a whole lot of chemical reactions based on just a few simple principles and our classification scheme. When an Arrhenius acid reacts with an Arrhenius base, we anticipate the products being a salt and water. When a Bronsted-Lowry acid reacts with a Bronsted-Lowry base, the products are a conjugate acid and a conjugate base. The fact that there are several different definitions of acids and bases in common use indicates that these classifications are arbitrary, not absolute. Indeed, one could define an acid as being any substance whose English name begins with the letter "A," and a base any substance whose name begins with "B." This is a perfectly valid definition, but it isn't used because it doesn't lead to anything that is useful from a chemical sense.

Likewise for cloud classifications. There are no "cumulous" or "cirrus" clouds. There are just clouds. We created these classifications. That doesn't make them any less useful or any less valuable to learn. They are very useful. Now, with one word, we can communicate the type of cloud we are talking about. Haven't you at one time or another wished that the English language contained more words to describe different kinds of snow?

Vapor pressure, relative humidity, supersaturation and cloud seeding

Air can hold moisture, and the warmer the air, the more moisture it can hold. Most chemistry courses will include a discussion of the vapor pressure exerted by water, often in connection with a laboratory experiment involving the collection of a gas such as hydrogen via water displacement. Subsequent calculations of the actual amount of gas collected require "corrections" for the fact that water vapor was collected in addition to the desired gas. These corrections are normally made by subtracting the vapor pressure of water at the temperature of the experiment from the total pressure to obtain the pressure of the collected gas itself.

Air typically does not hold as much moisture as it is capable of holding. One popular way of expressing the relative amount of moisture in the air is called the *relative humidity*. If air at a given temperature is holding only half as much moisture as it is capable of holding, then the relative humidity is stated as being 50%.

If warm air is saturated or close to saturated with water vapor and it is cooled, the relative humidity may actually rise above 100%. In principle, this is impossible, since at 100% relative humidity air is saturated with water vapor and the "excess" should condense in the form of suspended or falling water droplets.

But as the article points out, water molecules need to have a place to start forming droplets. These are called nucleation sites, and without these, droplets cannot form. These nucleation sites consist of microscopic particles of dust, smoke, salt crystals, soil, or other materials that are always present in the atmosphere.

Precipitation forms in clouds via two basic mechanisms, called *warm rain* and *cold rain*. These terms do not relate to the temperature of the rain as it strikes the ground, but rather how it is formed. Warm rain forms from clouds in which the temperature never falls below 0 ^{o}C, which may, for example, occur in tropical regions. Very small droplets collide and combine with other small droplets in a process referred to as condensation, producing rain.

Cold rain is more typical. It forms in clouds that are below the freezing point of water. These kinds of clouds typically contain both ice crystals and water droplets. The ice crystals can grow and absorb moisture from surrounding droplets. Basically the liquid water is supercooled. It should turn into ice, but without nucleation sites it may remain as a supercooled liquid. Since this liquid is supersaturated with respect to the ice crystals, contact between the water and the crystals can result in this water being transformed to the solid state and deposited on a crystal. Eventually their mass becomes too large for them to remain aloft, and they begin to fall. As they fall, these ice crystals melt and reach the ground as rain. If temperatures are too cold for them to melt, the result is snow.

Possible Student Misconceptions

1. Students with little background in Earth Science may not even realize that clouds can be classified into ten basic types. Or, alternately, they may have been exposed to a very simplified version of cloud classification and may not be aware of how detailed and complex the scheme actually has become. While the purpose of the article and this Teacher's Guide is hardly to have them develop into cloud identification experts, both should help them become more knowledgeable about the general types of clouds as well as some of the more specific examples.

2. Because the word *nucleation* involves the word nucleus, some students may incorrectly assume that nucleation particles are actual atomic nuclei. It might be nice to point out that even though nucleation particles are very small, they are gigantic when compared to individual atomic nuclei.

3. Students may incorrectly think that relative humidity and temperature are related in a simple way. For example, they may assume that if the relative humidity is 50% at 80 ^{o}F, then if you were to lower the temperature to 40 ^{o}F the relative humidity would be 100%. This, of course, is not true, not even if you express temperature on the Kelvin scale. The vapor pressure of water vs. it temperature is not a linear function.

Demonstrations and Lessons

1. While cloud seeding to produce rain might appear to be a wonderful application of basic science, it can be fraught with difficulties from a legal and ethical standpoint. Rain that falls in one place cannot fall in another. Is it ethical to "steal" rain by coaxing it to fall in one place when it otherwise would have fallen somewhere else? If seeded clouds were to produce too much rain, resulting in flood damage, who is responsible for the financial hardships such flooding might produce?

   Students could conduct a debate about such issues. Should drought areas be allowed to "steal" rain from somewhere else simply because they need it more? Is it ever OK to "fool" Mother Nature, and if it is, what limitations should be imposed on the practice?

2. It is generally accepted that typical raindrops will have a diameter of approximately 2.5 mm. Students could be challenged to try and develop an experimental technique that could measure or at least estimate raindrop sizes. Students with higher mathematical and theoretical interests and abilities might want to learn how maximum droplet sizes can be estimated from measurements of a liquid's surface tension and the resisting force as it falls through the air.

   One simple experimental technique for estimating raindrop sizes can be found at: http://web2.iadfw.net/kboyle/Raindrop.htm

3. Clouds form when water droplets condense on nucleation sites. The cloud activity contained in this issue provides a nice classroom activity to illustrate this. A more memorable demonstration of nucleation may be the classic one involving a supersaturated solution of sodium acetate tri hydrate, $NaC_2H_3O_2{\cdot}3H_2O$, which undergoes dramatic crystallization when seeded with one of its own crystals. A Google search using words and phrases like "sodium acetate" + supersaturation should produce several Websites providing directions. In addition, the first volume of Bassam Shakhashiri's *Chemical Demonstrations* contains excellent directions for preparing the necessary solutions.

4. The topic of cloud classification can allow you to teach your students an important “life lesson”—that labels are often arbitrary and do not represent reality. See *Background Information* for additional discussion of this notion.

Connections to the Chemistry Curriculum

There is a tremendous amount of chemistry connected to the general topic of clouds, much of which is typically included in an introductory high school chemistry course. Just a few of the topics include:

the structure of ice
H-bonding
heat of vaporization of water
supersaturation
vapor pressure
electrical discharges
nucleation
surface tension
dew point

Suggestions for Student Projects

1. The history of cloud classification is interesting (see *Background Information*). Students might want to prepare a report or make a class presentation about the work of Jean Lamarck and Luke Howard. They are interesting individuals, and such a report can show the arbitrariness of classification schemes and why one might be selected over another.

2. Students can be challenged to try and develop a reasonably accurate experimental technique to measure the size of raindrops. One good project would be to develop more than one technique and then compare the results obtained by each. See *Demonstrations and Lessons*.

3. Students could prepare a report on cloud seeding, its history, the scientific principles that underlie its use, the extent of its current applications, and objective measures of its effectiveness.

4. Students with an interest or knowledge of Earth Science might want to prepare a class report on the classification of clouds, including photographs of several types. Alternately, after presenting their report, they could divide the class into teams and hold a contest to see which team was best at identifying different types of clouds from photographs.

Anticipating Student Questions

1. Can cloud seeding really produce rain?

   Yes. For example, one of the oldest programs was started in 1971, in Texas. It was designed to increase rainfall in a 3,600 square mile area in the upper Colorado River basin. Long-term results have indicated that this effort has succeeded in producing a 34% increase above the normal precipitation levels for that area. More information on this project can be found at: http://www.edwardsaquifer.net/cloudseeding.html

2. How large is a typical raindrop, and how does its size compare to a typical cloud droplet or a condensation nucleus?

   A typical raindrop has a diameter of about 2.5 mm. A typical cloud droplet is about 0.02 mm in diameter, while a typical condensation nucleus has a diameter of only about 0.0002 mm.

3. What is the shape of a raindrop as it is falling?

   Contrary to popular opinion, falling raindrops are not shaped like a teardrop, nor are they spherical. This is a common misconception, and probably due to the fact that when we observe hanging droplets of water from a faucet, they do assume a teardrop shape and probably retain close to that shape as they fall into the sink. Raindrops also are typically drawn this way in pictures that we have all seen.

   But a raindrop falling from a distance encounters significant resistance from the air as it falls, causing it to assume a somewhat irregular flattened shape.

4. When did scientists first classify clouds?

   Surprisingly, this answer is not until relatively recently. Because cloud names have Latin roots and because people have been looking at clouds for as long as there have been people, it seems reasonable to assume that clouds must have been classified from ancient times. This is not really the case, at least in the sense of a useful type of classification. Clouds were thought to be too changeable, transient and variable to make meaningful classification possible. See *Background Information.*

5. I keep hearing the term *dew point* used by the TV weatherperson. What does this mean?

   Dew point refers to the temperature to which the air would have to be cooled in order for the air to be saturated with water vapor. If the relative humidity were 100%, then the dew point would be the actual temperature of the outside air. Since relative humidity is typically less than 100%, the dew point is normally several degrees below the air temperature.

Websites for Additional Information and Ideas

The best source for a description of the different types of clouds and how to identify them is probably the International Cloud Atlas at: http://www.mid-c.com/manmar/The_Inte.htm

There are a great number of Websites containing beautiful photographs of clouds. You can easily locate several by doing a simple Google search. A couple you might enjoy looking at are:

http://geekphilosopher.com/MainPage/bkgSky.htm

http://www.pix-elitegraphics.ca/photos/clouds.shtml

"Funny" Story

When your Teacher's Guide editor was a young boy listening to the radio one humid summer afternoon, he heard the announcer state that the relative humidity was something like 95%. Knowing the basics of percents, but not knowing anything about relative humidity, he asked his mother, "What happens if the relative humidity reaches 100%," to which she replied, "I'm not sure, but I think the air turns into water."

I spent the next several hours in abject terror, looking out the window and listening to the radio for the next announcement of relative humidity, convinced that if it reached 100%, the world would end, we all would drown, and wondering how people could be so calm and just be going about their business like normal when we were all so close to death!

Living in a Greenhouse

Background Information

More about the Greenhouse Effect

Earth receives a given amount of solar radiation each day. The amount of energy being emitted from the Sun is not completely constant. It varies in cycles that range from a few days to millions of years. For example, the output is affected by the eleven-year sunspot cycle.

This entire topic can become quite technical and mathematical. If you are interested in learning more (a lot more) about this, a few good websites can be found at:

http://langley.atmos.colostate.edu/at622/lectures/lecture5.pdf

http://www.ou.nl/open/dja/Klimaat/System/solar_radiation_and_milank.htm

http://rredc.nrel.gov/solar/pubs/shining/chap3.html

Skipping the fine points of the technical definition and the complexities that explain how and why the energy output of the Sun varies, it can be stated that the amount of energy reaching the outer atmosphere of Earth is about 1370 W/m^2, which is 1370 $(J/s)/m^2$, or about 2 $(cal/minute)/cm^2$ (see *Connections to Chemistry Concepts* for a detailed discussion of the unit conversions). This value is referred to as the *solar constant*.

So what happens to all this energy? As the article points out, about 70% of this energy makes its way to the Earth's surface and about 30% is either reflected back or absorbed.

A much more detailed accounting of Earth's Energy Budget can be found at:
http://eosweb.larc.nasa.gov/EDDOCS/images/Erb/components2.gif

At first this illustration may look confusing. If you decide to discuss it with your class, the following elaboration may prove useful.

First Key Idea—The total energy in must equal the total energy out.

The total energy "in" is labeled, "Incoming solar energy 100%," and is colored yellow.

The total energy out consists of:

Reflected by atmosphere----------------------------------6%—in yellow
Reflected by clouds--------------------------------------20%—in yellow
Reflected from earth's surface---------------------------4%—in yellow
Radiated to space from clouds and atmosphere--64%—in red
Radiated directly to space from earth------------------6%—in red

Note that the total energy out is also 100%—the energy balance

Of the 70% that makes it to Earth:

Absorbed by atmosphere--------16%—in light orange
Absorbed by clouds-----------------3%—in light orange
Absorbed by land and oceans--51%—in light orange

Note that this adds to the 70% of incoming energy that wasn't reflected

Of the 64% that is radiated to space from clouds and atmosphere:

16% comes from the energy that was absorbed by the atmosphere
3% comes from the energy that was absorbed by clouds
7% comes from conduction and rising air
23% is carried to clouds and atmosphere by latent heat in water vapor
15% is radiation absorbed by atmosphere from the earth's surface

And the last 6% of energy returning to space is radiated directly to space from earth.

More about the release of CO_2 into the atmosphere from human activities

The technical term that is applied to materials released into the atmosphere because of human activities is *anthropogenic*. For example, there is a "natural" greenhouse effect that is the result of the normal concentration of carbon dioxide, water vapor and other gases that would be in Earth's atmosphere even if humans did not exist. Then there are the additional gases, especially carbon dioxide, that enter the atmosphere as a result of human activities, particularly the burning of fossil fuels. This results in what is called the *enhanced greenhouse effect.*

The amount of carbon dioxide released into the atmosphere is astounding. A table containing a vast amount of data from a large number of countries can be found at: http://www.emep.int/emis_tables/tab7.html

If you access any of this data, one thing should probably be kept in mind. Anthropogenic emissions are typically expressed in terms of metric tons of carbon. This means that if you are looking at anthropogenic emissions of carbon dioxide, for example, you need to convert the values to an equivalent amount of carbon. This is accomplished simply by using the relative molecular weight of the molecule in question compared to the atomic weight of carbon. For example, an anthropogenic emission of 5500 million metric tons of carbon dioxide is equivalent to:

$$(5550)(12/44) = 1514 \text{ million metric tons of carbon}$$

Because the molar mass of carbon dioxide is 44, while the atomic weight of carbon is 12.

An interesting table of conversion factors relating to different carbon containing compounds can be found at: http://www.eia.doe.gov/oiaf/1605/gg00rpt/appendixf.htm

Some interesting statistics

Population and energy consumption statistics will vary, depending upon the source of the information, so the data below should not be taken to represent definitive values, but rather as reasonable estimates.

The total population of the World is about 6,400,000,000, and is growing at about 150 people per minute.

The population of the United States is about 277,000,000, and is growing at the rate of about 5-6 people per minute.

So the U.S. represents about 4.5% of the total population of the world.

We account for about 35% of the world's energy consumption.

Less than 8% of our energy consumption is comes from renewable resources.

About 85% of our energy consumption comes from fossil fuels, almost half of which is imported.

Carbon sequestering

Research into carbon sequestering is in a relatively early stage, and there is much debate and uncertainty surrounding the entire area. We know for certain that the Earth does sequester carbon dioxide, removing it from our atmosphere. When one compares what life on Earth was perhaps 400-500 years ago to today, it can appear amazing that we haven't all suffocated long ago, given the amount of forest that has been removed and the amount of carbon dioxide that is now released into the air from industries and the internal combustion engine.

Much of this CO_2 is sequestered, or absorbed by the oceans and vegetation. But we are still in the early stages of measuring exactly how much is sequestered by these different “carbon sinks.” For example, two different methods have been used to measure how much carbon is “stored” by a given area of vegetation. One method involves measuring the amount of CO_2 in the air as it moves across a given land area, while a second method involves recording the amount of carbon in a given area of ground and then comparing it over a given period of time.

Drawing conclusions about how much carbon is sequestered and where is fraught with uncertainty, but it does appear that the Earth cannot naturally sequester all the carbon dioxide that is being emitted. Much dissolves into the oceans. Much is sequestered by vegetation. Some remains in the atmosphere. This is an area of intense research.

Connections to Chemistry Concepts

Converting the value of the solar constant

The solar constant of 1370 W/m^2 is equal to 1370 $(J/s)/m^2$ simply because the Watt is a unit of power and is equal to one Joule of energy arriving every second.

To convert 1370 $(J/s)/m^2$ to cal/min:

$$(1370\ J/s)(1\ cal/4.187\ J)(60\ s/min)(1m/100cm)^2 = 1.96\ cal/min$$

Why molecules like N_2, O_2, and Ar are “transparent” to light

Light consists of an electric and magnetic field that is transmitted through space. The electric field increases and decreases in magnitude (as does the magnetic field)—that’s what’s “waving” when we say light is a wave. When light passes over a molecule, the electric field can interact with the molecule if there is a separation of positive and negative charge in the molecule. Let’s take a simple example. In a molecule like HF, the fluorine atom will be slightly negatively charged and the hydrogen atom slightly positively charged, because fluorine exerts stronger attraction on the bonding electrons. When a given wavelength of light passes over this molecule, its electric field will interact with the charges on the atoms. The “waving” electric field will push the atoms in one direction (positive and negative in opposite directions) and then the other.

The atoms in the molecule of HF are bonded together, and the bond can be thought of as if it were a spring connecting the two atoms. This “spring” will have a natural frequency of vibration, just like a real spring. A strong bond, like a strong spring, will tend to vibrate quickly—we say it has a high frequency of vibration. A weak bond will tend to vibrate slowly.

If by chance the frequency of the light passing over the molecule happens to match its frequency of vibration, the molecule will absorb the light, and its energy will be converted into energy of vibration. The analogy of pushing on a swing is a good one. To have the energy of your “push” absorbed by the swing, you must push at the same frequency as the swing is swinging.

Molecules can often vibrate in several different ways. If you imagine a central ball connected by springs to several others, you can probably imagine many different ways that this conglomeration could vibrate. Frequencies of light that do not match one of the natural frequencies of vibration of a molecule are not absorbed to any extent. Frequencies that do match are absorbed.

It turns out that the natural frequencies of vibration of most molecules are about the same as the frequencies of some wavelengths of infrared light.

If a molecule is polar, it will absorb infrared light at some frequencies specific to that particular molecule. That's how molecules can be identified by their IR spectrum

If a molecule is nonpolar, it may still have an IR spectrum because some "modes of vibration" will produce atomic arrangements that are not symmetrical and therefore will have a dipole moment—the charges will not be arranged symmetrically in the molecule as it vibrates in that manner. For example, the arrangement of atoms in carbon dioxide is:

O=C=O

Consider the type of vibrational motion where the two oxygen atoms both move away from the central carbon and then back towards it. There is no way that the waving electric field of light could move one oxygen atom in one direction while at the same time moving the other oxygen atom in the opposite direction, since they both carry the same negative charge. Although this frequency of vibration will match some frequency of IR light, it will not be able to absorb that frequency.

But if the two oxygen atoms were to vibrate by both moving toward the top of the page and then toward the bottom, this would produce structures that were not symmetrical, the charges would not be distributed evenly as it vibrated, and it would absorb IR light that had the same frequency as this particular frequency of vibration.

But the charge in molecules like N_2, O_2 is always arranged symmetrically no matter how they vibrate, and a monatomic gas like Ar doesn't vibrate at all, so these kinds of molecules are basically "transparent" to infrared light.

Possible Student Misconceptions

Because the article states that all but 30% of the energy reaching our planet gets through the atmosphere while 30% is either reflected or absorbed, it is possible that some students may misinterpret this to mean that most of the energy reaching our planet is absorbed and therefore "stays" on our planet while only about 30% is returned to space.

This is not true. Essentially the amount of energy reaching our planet and the amount being returned to space must be equal. If it weren't, then the Earth would be constantly getting warmer or cooler. This notion that energy in must equal energy out is referred to as Earth's energy balance. All planets have an energy balance. Planets like Venus, whose atmosphere contains a high concentration of carbon dioxide, a greenhouse gas, have a "problem." These gases prevent a lot of energy from making it back into space, so in order for the amount of energy returning to space to equal the amount coming in, the temperature of the planet must be high. Objects at higher temperatures will radiate more energy. If a planet has little atmosphere, it will tend to be colder, all other factors being equal.

It also is very reasonable for students to think that carbon dioxide is the only, or certainly the most significant greenhouse gas in the atmosphere. It actually is water, by virtue of the fact that it has a much more significant abundance. But this should not be taken to mean that carbon dioxide is an unimportant greenhouse gas. As mentioned in *Background Information*, what is of concern is not the greenhouse effect itself—it's necessary for life to exist on Earth—but rather the *enhanced* greenhouse effect, which is attributed by many scientists to increasing concentrations of carbon dioxide in our atmosphere brought about by human activities.

A nice illustration of the fact that water vapor exerts the most significant greenhouse effect can be found at: http://zebu.uoregon.edu/1998/es202/l13.html

It shows an infrared map of the Earth. Areas of high heat retention in the atmosphere are shown in red. The fact that there is a red band around the equator is due to the fact that it is this area where the atmosphere contains the most water vapor.

Demonstrations and Lessons

1. The entire topic of the enhanced greenhouse effect, its connection to global warming, the possible consequences of global warming and what actions should or shouldn't be taken is immensely complex, and for many people, often charged with emotion. A wonderful classroom project would be for groups of students to study this issue and then discuss or debate whether (1) global warming is actually occurring, (2) it is caused by human activities, (3) it will have serious negative consequences, and (4) what actions, if any, need to be taken to address this issue. There is so much information and conflicting opinion on this topic that it could easily be a semester project, with a significant grade attached to the quality of one's research and argument. An "A+" could easily be given to two papers with completely opposing views.

2. There is a lot of misunderstanding about what the "greenhouse effect" really is. Perhaps one of the most common is that the only reason a greenhouse becomes warm is that light energy enters, but cannot escape. While that may basically be true, the major reason the greenhouse becomes hot is due to the fact that it is more or less sealed up and cannot exchange its inside air with outside air. There is an interesting discussion of this at: http://www.ems.psu.edu/~fraser/Bad/BadGreenhouse.html

   It would probably be a good classroom lesson to explain why the term "greenhouse effect," despite its widespread use, is probably not a very appropriate phrase. It really doesn't describe how gases such as water vapor and carbon dioxide function to keep the Earth warmer than it would be in their absence.

   In fact, the entire "Bad Science" site is something most of us who teach science could stand to read. http://www.ems.psu.edu/~fraser/BadScience.html

Connections to the Chemistry Curriculum

Whether you teach a "traditional" course or a course such as ChemCom, where much focus is placed on societal and "real world" chemistry, the topic of greenhouse gases and global warming should connect strongly.

Besides the major topics of the greenhouse effect and its connection to global warming, the article also connects to:

Light and the electromagnetic spectrum
Infrared light and molecular spectra
How and why molecules absorb (or don't absorb) different frequencies of light
The Earth's energy balance
Greenhouse gases, their structures, abundances and effectiveness
Anthropogenic emissions
Carbon sequestering
The carbon cycle
Burning of fossil fuels, combustion, oxidation-reduction

Suggestions for Student Projects

1. The article mentions studies aimed at determining whether it might be practical to sequester carbon dioxide in rock formations with underlying briny water. Students could report on the status of these efforts.

2. The Lake Nyos tragedy (see “The Lake Nyos Disaster,” *ChemMatters*, Feb. 1996) relates an account of a scientifically interesting but human disaster that occurred because of the sudden release of carbon dioxide from a lake where it had been “sequestered” to the point where it had built up to dangerous concentration levels. There is a lot of simple chemistry involved in this disaster, and a class report would probably prove both interesting and informative to and for most students.

3. There is a lot of speculation about possible large-scale effects of global warming, such as rising ocean levels, more severe storms, and dramatic changes in the agricultural state of different areas of the world. But there is also evidence of specific effects on specific animals, and a report on one or more of these very real and current effects might be more meaningful to some students rather than a discussion of broad possible effects that might or might not occur sometime in the future.

4. While the entire topic of global warming is the subject of much scientific and political debate, there are some “arguments” that one often hears that are basically either clearly false and based on unsound science and/or a misunderstanding of what global warming is and isn’t. For example:

   Global warming is a myth. It’s been cold around here for the past two weeks.

   We’d better do something about global warming right away or we’re all going to develop skin cancer from too much UV light.

   It would be fun to have students try to list all of the “silly” things and arguments they’ve heard or read about global warming.

Anticipating Student Questions

1. I keep reading the term *albedo*. What does that mean?

   Albedo refers to the reflectivity of something. For example, if you place a piece of white paper and a piece of black paper in the sun, the piece of black paper will become hotter while the piece of white paper will be brighter. That’s because the white paper reflects a higher percentage of the light striking it. Scientists would say it has a higher albedo. It is cooler (in the temperature sense) to wear light colored clothing in hot sunny climates for the same reason. The numerical values for albedos range from 0-1. The average albedo of the Earth is about 0.33. Oceans have an albedo of about 0.26, rain forests about 0.15, and deserts about 0.40.

2. How do we know that the temperature of the Earth would be –18 ^{o}C if the atmosphere didn’t contain any greenhouse gases?

   The complete answer is somewhat complicated mathematically, but basically we know how much energy reaches the Earth from the Sun. We know how much of this energy is absorbed by the Earth and how much is reflected. The energy that is absorbed warms the Earth. The Earth, like all objects, emits energy, and if it became warmer, it would emit even more energy. Of course the energy arriving on the Earth and the energy leaving the Earth must be equal. Otherwise the Earth would either be getting hotter or colder. So from this “energy balance,” scientists can calculate how warm the Earth would be in order to emit the same amount of energy it receives every day. That comes out to be –18 ^{o}C.

Websites for Additional Information and Ideas

More information about Earth’s Energy Balance can be found at:
http://eosweb.larc.nasa.gov/EDDOCS/radiation_facts.html

Two fairly comprehensive discussions of the Greenhouse Effect and the Enhanced Greenhouse Effect can be found at:

http://www.science.gmu.edu/~zli/ghe.html

http://zebu.uoregon.edu/1998/es202/l13.html

A nice photograph along with a story about Deborah and David Clark, two scientists mentioned in the article can be found at: http://geog-www.sbs.ohio-state.edu/courses/H294/clark-science.pdf

If you are interested in a derivation of how equations can be used to calculate the temperature of the Earth in the absence of any greenhouse gases, go to: http://www.ldeo.columbia.edu/~peter/Resources/Energy.Balance.html

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Chemistry in the Sunlight

Background Information

More general information about smog

The word "smog" is basically a combination of the words "smoke" and "fog."

While we may tend to think of smog as being a relatively recent type of pollution, this really is not the case. Although the term "smog" wasn't formally coined until 1911 by Dr. Harold deVoeux, it clearly existed during the 19th century, often at serious levels that resulted in many cases of illness and death. Prior to around 1950, the term "smog" was often used rather loosely to refer to any kind of polluted atmosphere.

Indeed, during the 17th century John Evelyn wrote:

It is horrid Smoake which obscures our Church and makes our palaces look old, which fouls our Cloth and corrupts the Waters, so as the very Rain, and refreshing Dews which fall in the several Seasons, precipitate to impure vapour, which, with its black and tenacious quality, spots, contaminates whatever is exposed to it.

Around the early 1950s, the unique kind of smog described in the article was recognized and given the specific name of photochemical smog, although the simpler term "smog" is often used to describe it.

There are two distinct types of smog, *industrial smog* and *photochemical smog.*

Industrial smog contains unburned carbon soot or smoke along with sulfur dioxide and forms in the presence of fog. It is sometimes called "London smog" because London during the 19th century was especially vulnerable to its formation and Londoners to its consequences. Its presence was linked to the burning of coal and oil, both from industries and homes.

Photochemical smog, on the other hand, is formed when NO_x and VOCs are acted upon by sunlight, as described in the article. Automobiles are the main culprit. Combustion products along with evaporation of the fuel itself provide many of the necessary ingredients for the formation of photochemical smog.

As the article so clearly states, the chemistry of smog formation is exceedingly complex. There is no way that this chemistry can be presented in anything resembling complete accuracy in a high school chemistry class. In one sense this is of course unfortunate. As teachers we want to provide our students with "the truth, the whole truth, and nothing but the truth" whenever possible.

But in another sense, the complexity can be considered a pedagogical blessing. We can focus our attention on general kinds of chemical processes and the general chemical principles that underlie smog formation and not be required to add so many details that the major focus gets obscured or our student's eyes begin to glaze over as they are inundated with an overwhelming amount of detail.

More about the chemical processes that produce photochemical smog

One point that might be mentioned is that there is a wide variation in the reactivity of different hydrocarbons molecules. This means that some are of greater significance in the production of photochemical smog. While knowing the specific rates of various hydrocarbons is probably not important for our students, a nice graph comparing the rates of several different molecules can be found at: http://naftp.nrcce.wvu.edu/techinfo/smog/smog.html

The article also mentions that hydroxyl radicals, OH, can play a role in the formation of tropospheric ozone. A brief discussion of some typical reaction sequences that illustrate this mechanism can be found at: http://www.edcenter.sdsu.edu/repository/pse/PSEXassignment.htm

Some biological effects produced by photochemical smog

While all people are affected by photochemical smog, children, the elderly, asthmatics, and individuals with heart and lung problems are especially susceptible. If a person's respiratory system is compromised in any way, either permanently or temporarily, the condition will be exacerbated by smog. Breathing passages may become inflamed; one may experience shortness of breath, wheezing and/or coughing, and even pain when breathing. Additional symptoms may include eye or nose irritation.

Slide photographs of microscopic views of human lung tissue showing the damage that can result from exposure to low levels of ozone can be found at:
http://earthobservatory.nasa.gov/Library/OzoneWeBreathe/ozone_we_breathe2.html

Photochemical smog can also compromise the body's immune system, increasing one's vulnerability to infection.

Photochemical smog and thermal inversions

The formation of photochemical smog is often associated with what are called thermal inversions.

As one move up through the atmosphere, temperature normally decreases with increasing altitude. While the change with altitude is variable, there is an accepted normal rate of decrease of about 6.5 ^{o}C/1000 m, (3.6 F^{o}/1000 ft) which is referred to as the normal "lapse rate."

The cooling of the atmosphere with increasing altitude serves to reduce ground-level pollution. Warmer air is less dense than cooler air. This means that warmer air tends to rise, and as it rises, it removes polluted air from the surface of the Earth where we live and breathe.

There are a number of ways in which a temperature inversion, or *thermal inversion* can be produced.

On a clear night the Earth can rapidly radiate heat away from its surface. This can cause the air near the surface to actually become cooler than the air at higher altitudes.

Another mechanism for producing a thermal inversion occurs when air blows onto land after passing over cool water. The air reaching land is cooler than the air at higher altitudes. Since cool air is denser than warm air, this cooler air tends to stay at ground level, again producing a thermal inversion. The technical term for this particular mechanism is *advectional* inversion.

Another mechanism occurs can occur at night in areas that contain valleys. Cold dense air will flow down the hills surrounding the valley and into the bottom of the valley, where its density will tend to keep it there, once again producing an inversion.

There are other mechanisms by which temperature inversions can be produced. Any kind of mechanism that moves cool air below warmer air is capable of causing this phenomenon.

Connections to Chemistry Concepts

In the early part of the article a general statement is made that different wavelengths of light carry different amounts of energy and that the shorter wavelengths carry more energy.

While this statement is accurate, it may be slightly misread by some students.

A more accurate statement would be that shorter wavelengths of light carry more energy *per photon*, not simply “more energy.” A distinction should be made between the energy carried by one photon of light and the total amount of energy that a given beam of light will deliver to a certain area per second. The latter is equal to the number of photons arriving at a given amount of surface area per second times the energy carried by each photon.

The energy carried by a photon of light depends upon, and is directly proportional to the frequency of the light, as expressed by the equation:

$E = h\nu$

Where h = Planck’s constant = 6.625×10^{-34} J·s and ν = frequency of the light in s^{-1} (Hz)

Since

$c = \lambda\nu$

Where λ = wavelength of the light in m and *c* is the speed of light in m/s

So the energy carried by a single photon of light, $E = hc/\lambda$

If you do much reading of the literature surrounding the mechanisms by which photochemical smog is produced, you will almost certainly encounter the term “free radical.” A free radical is typically a fragment of a molecule that contains an unpaired electron. For example, the neutral molecule OH, called the hydroxyl radical, has an odd number of electrons, one of which is unpaired. This is typically represented by a “dot” in the structure, e.g., $HO^{\bullet}$. Another commonly encountered representation is any hydrocarbon fragment with an unpaired electron, typically represented by $R^{\bullet}$.

Possible Student Misconceptions

When students first learn that light with a shorter wavelength consists of photons of higher energy, there is often a natural tendency to think that shorter wavelength light travels faster. This misconception is quite understandable because photons are often thought of as being “particles” in some sense of the word, and when a particle travels faster, it is more energetic. It often takes a lot of effort and some demonstrations to get students to rid their minds of the notion that more energetic means faster moving. All light (in a vacuum, at least), travels at the same velocity. This means that longer wavelength light has to have a lower frequency while light with a shorter wavelength must have a higher frequency to “keep up.” See *Demonstrations and Lessons*.

Demonstrations and Lessons

1. One fairly common and understandable misconception that students can have is that light with a shorter wavelength travels faster (see *Possible Student Misconceptions*).

   Of course all light travels at the same speed (in a vacuum, at least). One way of illustrating this is to have two students link arms and walk across the classroom at the same speed, only one takes small steps while the other takes large steps. Clearly the student taking smaller steps has to step at a higher "frequency" in order to have the same speed.

2. Several years ago your Teacher's Guide editor dumped some ice left over from a student laboratory into a deep sink that was part of the demonstration table and went home for the evening. The next morning I was initially surprise to find that not all of the ice had melted. This certainly appears to be an unplanned demonstration of a "mini-thermal inversion" (see *Background Information*). Students might enjoy comparing the melting time of ice placed in the bottom of a deep container with an equivalent amount of ice simply placed on a flat surface.

Connections to the Chemistry Curriculum

Atmospheric chemistry is very complex, and ties into a number of the most advanced concepts covered in most introductory high school chemistry courses. Foremost among them are chemical kinetics (the study of the rates of chemical reactions and the mechanisms by which they occur) and chemical equilibrium. In addition, looking at some of the reactions involved will lead to a discussion of bonding in molecules and the formation of free radicals. Discussing the effect of ultraviolet light on the chemical process that lead to ozone formation will require some knowledge of the electromagnetic spectrum and how the energy carried by a photon of light is related to its frequency (see *Connections to Chemistry Concepts*). A discussion of VOCs can quickly provide an opportunity to introduce or review many basic organic structures.

Suggestions for Student Projects

1. It's one thing to learn about photochemical smog and its dangers, it's another to do something about it. Students could prepare a report on how modern automobiles are equipped with thing such as catalytic converters to help reduce the emission of NO_x and VOCs into the atmosphere.

2. Many students probably think of smog as being a relatively recent phenomenon. But smog has been a problem, especially in highly industrialized urban areas, since the 19^{th} century and probably even earlier. One of the most deadly incidents began on Dec. 5, 1950 in London. It led to the deaths of over 4,000 people, perhaps even 2-3 times that total. Students could report on the meteorological events that precipitated this deadly occurrence as well as the human and social consequences that it produced.

3. If you have advanced classes with a strong background in equilibrium, chemical kinetics,and a basic knowledge of organic structures, they might be interested and capable of presenting a more comprehensive report on the kinds of reactions, equilibria and kinetics of some of the reactions involved in the formation of photochemical smog. A good starting point for information can be found at:

   http://naftp.nrcce.wvu.edu/techinfo/smog/smog.html

   http://www.mtsu.edu/~nchong/Smog-Atm1.htm

Anticipating Student Questions

1. I heard about serious cases of smog occurring in places like London during the 19th century. How is this possible if smog is largely a byproduct of the widespread use of automobiles and other internal combustion engines?

   The type of smog that is connected to the proliferation of automobile traffic is called *photochemical smog*. It requires the presence of sunlight along with things like NO_x and VOCs, as discussed in the article.

   There is another type of smog called *industrial smog*, which can be caused by the burning of coal, for example. This is the kind of smog that often reached serious levels before the growth of the automobile.

   See *Background Information*.

2. If automobiles are the major cause of photochemical smog, is there anything that can be done short of not using our cars?

   Definitely, and much has been done already. One of the major technological advances has been the installation of catalytic converters on automobiles. The name suggests what they do. The modern "three way" catalytic converter reduces emissions of unburned hydrocarbons, carbon monoxide, and NO_x by using catalysts made from transition metals such as palladium, platinum, and rhodium.
   http://auto.howstuffworks.com/catalytic-converter.html

3. Ozone concentrations are often expressed in something called a *Dobson Unit*. What is that?

   It is one of the most basic units connected to ozone research. It is named after G. M. B. Dobson, one of the earliest investigators of atmospheric ozone. To understand what a Dobson unit is, imagine a vertical column extending from the Earth's surface into the highest reaches of the atmosphere. This column will contain some ozone. Now imagine everything removed from this column except the ozone. Now imagine this ozone being at a temperature of 0 ^{o}C and compressed to 1 atm. of pressure, which means it is at STP. The atmosphere doesn't really contain a great deal of ozone, so even though the column of air was many miles high, this compressed column of ozone would only be a few mm thick. Take the thickness of this compressed ozone in mm, and multiply it by 100. That number represents the concentration of ozone in Dobson units. For example, if the compressed ozone formed a layer at STP that was 3 mm thick, then the concentration of ozone in that section of the atmosphere would be 300 Dobson units.

4. I've heard that lightning can produce ozone. Is this true, and can it produce significant quantities of ozone?

   Yes, lightning strikes do produce ozone. The tremendous voltages and high temperatures generated during a lightning strike can result in production of ozone. Recent research suggests that the amount of ozone produced by lightning strikes may be quite significant. It is estimated that lightning strikes occur on Earth perhaps as many as 100 times every second.

Websites for Additional Information and Ideas

There is an interesting series of quizzes relating to the science behind smog formation as well as the health effects produced by tropospheric smog at:
http://app.city.toronto.on.ca/im/taf/questionnaire3.jsp

A very nice Powerpoint presentation that includes numerous photographs of smoggy areas from around the world can be found at:
http://course1.winona.edu/jschneider/chem1002003/group%2017%20smog%20chemistry.ppt

You can find Total Ozone maps that will tell you the concentration of ozone in Dobson Units (see *Anticipating Student Questions*) at:
http://woudc.ec.gc.ca/e/ozone/Curr_allmap.htm

A series of quizzes about smog and its health effects can be found at:
http://www.city.toronto.on.ca/cleanairpartnership/quizindex.htm

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Beefing Up Atmospheric Models

Background Information

More about climate models

Atmospheric chemistry is immensely complex. Trying to develop climate models that can accurately predict future climate changes represents a great challenge along many fronts. Predictions require vast amounts of accurate climate data—the EOS-Aura project represents one of the most ambitious and sophisticated attempts to obtain this data. One needs highly complex, sophisticated computer programs that can model something as complex as the atmosphere. And finally one needs the most powerful computers that can be built to crunch all the data and run the complex programs. That requires tremendous computing resources.

There is a tradeoff between the complexity of the program and the computer power needed to run it. By reducing the former one can reduce the need for the latter.

There are five key components that climate modelers must take into account, and these components both change over time and interact with each other.

1. The **atmosphere** can change over a period of only hours. The behavior of the atmosphere cannot be predicted over a period of more than a few days. That's what weather forecasting does and why weather forecasts more than five days in advance or so are prone to a large degree of error, especially in areas that have changeable weather.
2. The **oceans**
3. The **biosphere** is comprised of all animals and vegetation.
4. The **cryosphere** includes all areas of the Earth covered by frozen water in any form.
5. The **geosphere** is the solid Earth.

There are actually several different general types of programs. Included are:

Atmosphere general circulation models, AGCMs

These models are basically three-dimensional representations of the atmosphere that are coupled to the land surface and the cryosphere (the frozen areas of the Earth covered in snow or ice). They are actually similar to the kind of computer models used to produce weather forecasts, but because they are designed to make climate projects decades into the future, they cannot operate at as detailed a level when applied for that purpose. They also need to be provided with data about sea surface temperature and sea-ice coverage.

AGCMs coupled to a "slab" ocean

This model utilizes a highly simplifying assumption—the ocean is treated as if it consisted only of a slab of water with a constant depth, usually about 50 meters. It has value in making predictions about what the Earth's climate would be like if levels of carbon dioxide in the atmosphere remained constant, but has limited utility to make predictions regarding the rate of change of climate. These kinds of predictions are highly influenced by processes that occur at much deeper ocean depths.

Ocean general circulation models, OGCM

This is basically a counterpart of an AGCM. It is also a three-dimensional representation, but now of the ocean and sea-ice. OGCMs are very useful for studying ocean circulation and processes that occur in ocean interiors, but to make climate predictions they need to be provided with data about surface air temperature and other atmospheric properties. It should be noted that the terrestrial carbon cycle is modeled in the AGCM, while the ocean carbon cycle is modeled within the OGCM.

Coupled atmosphere-ocean general circulation models, AOGCMs

These are the kinds of models referred to in the article. They represent the most complex models currently being used, and their name in indicative of their nature. They basically couple an AGCM with an OGCM. They can be used to predict future climates and the rate of change in the climate. They typically have a resolution of only a few hundred meters. They can make predictions about changes in atmospheric carbon dioxide given the amount of CO_2 being emitted into the atmosphere. They can also make predictions about how the concentrations of other atmospheric components will change in response to the emission of still other gases as well as climate changes.

Regional climate models, RCMs

While climate models, by their very nature, are designed to produce wide-spread predictions of climate, there is also a need to make predictions about how the climate might change in a more local area. Local areas can often be highly affected by things like the presence of mountains, and these kinds of features are often not well represented in global models. To include them requires too high a degree of resolution. RCMs are developed to include more detailed local features. They operate at a higher resolution, perhaps 50 meters, but only make predictions for shorter periods of times, perhaps a couple of decades.

If you'd like to see some animations of climate projections made from one climate prediction program, go to: http://www.met-office.gov.uk/research/hadleycentre/models/modeldata.html

How accurate are climate predictions made by computer models?

That, of course, is the proverbial $64,000 question. There certainly are wide variations in strongly held and passionately expressed opinions from individuals and groups on both sides of the global warming debate. As teachers, these kinds of issues can challenge us in the most significant of ways. We often argue that one of the most important reasons for students to take our course is to become informed citizens who can reach informed conclusions when faced with significant questions that have a significant scientific component. Global warming is certainly one of them, as is the destruction of the stratospheric ozone layer. Yet the complexity of many of these topics and the highly charged emotions that often surround them can place us in an uncomfortable position. We want to present "both sides (as if there were only two!)" of issues. We went to educate, not indoctrinate. We want our students to think for themselves, but it can be difficult to keep our personal views hidden when students ask us questions like, "Do you personally think that global warming represents a serious threat to the quality of life on planet Earth?" We can tap dance around questions like this or we can try to answer them as honestly and objectively as possible. There are arguments for both approaches. Perhaps what we do is not as important as how we do it.

Of course the focus of the article was not on the validity of climate models. The far more general purpose was simply to acquaint students with models in general and mathematical models in particular. But it's difficult for an article on atmospheric modeling to avoid this kind of question. After all, what's the point of developing atmospheric models if you cannot assess, to some degree, the confidence you have in the predictions they make? That's the whole point of developing the model in the first place.

You can find numerous Websites vociferously arguing on every possible side of this issue. Although somewhat dated, perhaps one of the most clearly written and objective can be found at: http://www.gcrio.org/CONSEQUENCES/fall95/mod.html

One critique of the accuracy of models that simulate global climate is at: http://www.nature.com/nsu/020624/020624-11.html

The GOME ozone monitoring instrument

One of the sidebars in the article mentions the Global Ozone Monitoring Experiment. It is an instrument on board the ERS-2 (European Remote Sensing) satellite. Launched in 1995, it measures the sunlight that is returned back to space by both the surface of the Earth and molecules in the atmosphere. By determining the ratio between the sunshine coming to Earth and the "Earthshine" coming back, it can determine the reflectivity of the Earth's atmosphere and surface. By studying wavelengths absorbed by a specific molecule like ozone, it can measure the total ozone concentration in a column of air between the Earth's surface and the top of the atmosphere.

More about Svante Arrhenius

Many chemistry courses mention and discuss the work of Svante Arrhenius (1859-1927), most likely in connection with a discussion of acids and bases or, in the case of advanced classes, chemical kinetics, namely the Arrhenius equation, which relates the effect of temperature on the rate of a chemical reaction. But rarely is his name connected with the topic of global warming, even though he anticipated this phenomenon almost a hundred years before it became a prominent scientific issue. Early in his life much of his work appears to have been under appreciated. For example, when he presented his Ph.D. thesis of ionic dissociation, he only received a fourth class (approved without praise) for the dissertation itself and a third class (approved with praise) for its defense, basically grades of "D" and "C." He later received the Nobel Prize for his work on electrolytic dissociation.

Connections to Chemistry Concepts

The article talks about, "Some of the simplest and least chaotic models…" The word "chaotic," as it is used here, does not have exactly the same meaning as the word as it may be used in everyday conversation, and a discussion of the difference may be worthwhile.

Any serious discussion of the atmosphere, weather and climate will almost certainly and fairly quickly lead one to what is called *Chaos Theory*. The topic of Chaos Theory is both too broad and too complex to deal with in any meaningful manner here. But if you have never encountered this term, it is an area of study that is truly fascinating and beautiful. It will rapidly bring you to the world of fractals, those incredibly complex and stunning images that we have all seen, perhaps the most famous being the Mandelbrot Set.

Although Chaos Theory can quickly become quite complex mathematically, the basic notion is quite simple. It involves what is often referred to as "sensitivity to initial conditions."

Most of the systems we learned about and studied in our science classes were nonchaotic. There's a good reason for that. We can easily do calculations and make predictions about nonchaotic systems. For example, if you throw a spherical object in a certain direction with a certain speed in a uniform gravitational field in a vacuum, Newton's Laws allow you to predict, with great accuracy, where and when it will land. The presence of an atmosphere complicates things a bit, but if it is a dense spherical object, we can basically ignore these complications and still make excellent predictions. We like to call these "simplifying assumptions."

But suppose you take an 8.5" x 11" piece of printer paper and hold it vertically about 10 ft. above the ground. When you release it, it won't fall straight down. It will encounter air resistance and will "flop around" as it falls. No matter how hard you try, you can never get it to fall the same way twice. The first few inches of its flight may be similar, but it quickly appears to fly in what is a virtually unpredictable pattern. It's motion is chaotic. The slightest change in the initial conditions makes predictions after a short period of time virtually useless.

Perhaps the most cited example of the discovery of chaos occurred in 1963, when Edward Lorenz developed a simple mathematical model of a weather system that showed rates of change in temperature and wind speed. The system only involved three mathematical equations. On one occasion he wanted to rerun something, so he reentered the "same" initial conditions as in a previous trial. However, in an effort to save time, he rounded off the initial numerical values of some data—but only after several decimal places. Such small changes, he assumed, would make little difference in the final answers.

Instead, the final answers were completely different. Although the system initially produced similar answers for temperature, etc., as time progressed the answers became increasingly divergent until they bore no relationship to each other. The system was chaotic. No matter how small the differences in the initial input, eventually the predictions made by the mathematics were completely unrelated. Lorenz dubbed this the "butterfly effect"—the notion that future weather is so dependent upon initial conditions that a if a butterfly in China decides to flap its wings, this small disturbance might conceivably result in a tornado in Texas a few months later.

Today there are hundreds of books about chaos theory and fractals, ranging from the relatively straightforward to highly technical and mathematical treatises.

If you are interested in learning more about this incredibly amazing and fascinating area, perhaps the best place to begin is with one of the older yet perhaps one of the best introductions, *Chaos: The Making of a New Science*, by James Gleick.

Possible Student Misconceptions

Although there is a great deal of difference between "climate" and "weather," there may still be a tendency for some students to confuse the two. See *Anticipating Student Questions*.

The word "chaotic," is used in the article. In everyday conversation this word normally means that something is completely without pattern and completely unpredictable. But the word, as used in the article, is connected to what is called Chaos Theory. Many of our students, perhaps most, will have little if any knowledge of what chaos theory is about. For some general information about this area of science and research, see *Connection to Chemistry Concepts.*

Demonstrations and Lessons

1. One "oldie but goodie" exercise on modeling dates back to the 1960's and the ChemStudy curriculum. It is often referred to as the "black box" experiment, but is really an exercise, not an experiment. It involves placing objects inside boxes (cigar boxes work especially well if you can obtain them), sealing the boxes, and then having students try to develop a model of the object without opening the box. For example, if the object rolls when the box is tiled up and down in the "north-south" direction but slides when tiled in the "east-west" direction, the student may conclude that it could be cylindrical in shape. If it rolls in all directions, it might be a sphere. Pieces of common laboratory equipment like test tubes, small

Erlenmeyer flasks, funnels, etc. can be placed in the boxes. The boxes can be numbered and inventoried if you desire to grade the students on whether their model reasonably estimates the shape of the actual object inside.

2. A class could be challenged not to actually develop the mathematical model, but just to think about all the factors that would have to be taken into consideration in order to create an accurate model to make a given prediction. For example, you might ask how many people will be in a given movie theatre at a certain time. Some factors that would have to be considered might be:

   What movie is playing? How popular will it probably be? What time does it start? Are people still working? Is it a weekday or a weekend? What's the weather forecast? Would some people rather be outside, or might bad weather keep them home? How many theatres are playing the film? What else is playing? How many theatres are in the area, and how many people? What age group would might like to see the movie, and how many people in that age group live in the area? How were the reviews? How long has the movie been playing?

   And can all this be quantified into a mathematical program?

   Some other possible topics might be:

   How many students will be in the school library or cafeteria at a given time?
   How many hot dogs will be sold at the local supermarket this weekend?
   How many points (or runs, or hits, etc.) will a certain athlete score next month?
   What will be the average score on the next chemistry exam?

3. Our chemistry courses are filled with various kinds of "models" (see *Connections to the Chemistry Curriculum).* An interesting classroom exercise might be to have students try and list the different kinds of "models" that they have encountered in the course, although this might be better done much later in the academic year, when students are closer to the end of the course rather than the beginning.

Connections to the Chemistry Curriculum

The topic of modeling lies at the very heart of science. Our chemistry courses are filled with what we often loosely refer to as "models," although the term is often used in different contexts and perhaps not everyone would agree that the use of the term "models" is appropriate. These can range from conceptual definitions of things such as ideal gases to mathematical equations we can use to describe them ($PV = nRT$), to visual models of atoms and molecules and various solid structures, to acid-base theory, to models such as VSEPR theory that allow us make predictions about some properties of different substances. The list seems almost endless, especially if one is willing to accept the word "model" as being somewhat analogous to "theory."

Suggestions for Student Projects

1. Climate modeling depends on and demands tremendous computing power. We often hear that climate modeling requires the use of "supercomputers." Of course what constitutes a "supercomputer" has changed dramatically over the past few decades. The world's most powerful supercomputer of the 1970's couldn't match the power of the computer you are currently using to access this Teacher's Guide. For example, the first Cray-1, which was installed at Los Alamos in 1976, cost 8.8 million dollars (1976 dollars, as well). It had 8 megabytes of memory.

   We all have students who love and are very knowledgeable about computers. They might enjoy preparing a report on the history of "supercomputers"—how fast they ran, how much memory they had, and how much they cost. They could also report on the current state of supercomputers, how they are used in climate modeling, and what might be expected in the next several years.

2. Students could try and develop the basic features of a model that might be used to predict something that is quite complex and not easily approximated with simple mathematical equations. See *Demonstrations and Lessons*.

3. Students could report on both Arrhenius's life and his work, which include some interesting sidelights. See *Background Information.*

Anticipating Student Questions

1. What's the difference between climate and weather?

   Weather refers to what atmospheric conditions are at a particular place at a particular time. Look outside your window, and you will see the weather. It is sunny, or raining, or windy, or snowing, or warm, or cold, or whatever.

   Climate refers to the average weather conditions in an area measured over a long period of time. Knowing the climate allows us to make educated guesses about what the weather might be like at a place. For example, we know that it will probably be hot in Phoenix, Arizona in August and we are essentially 100% certain that it won't be snowing. We also can predict that it will be cold in Buffalo, NY in January. We can't be certain it will snow, but it's a reasonable probability.

2. What's the best climate model we have today?

   There's no real answer to that question. A natural assumption is that the "best" climate model is probably the most sophisticated and complex one that takes into account the greatest number of different environmental factors and cycles.

   That's certainly a defendable position, and one would hope that newer climate models would build on the strengths of previous climate models while at the same time reducing or eliminating some of their weaknesses.

   But the "best" model is not always the most sophisticated. Increasing sophistication and complexity in turn demand increasing computer power and time, which increases computational cost. In addition, if more local predictions are of interest, then broader climate models may not be the most appropriate to use. See *Background Information*.

3. How does climate modeling differ from weather forecasting?

   While both utilize computer programs and do have common features, there are basic fundamental differences between the two. Weather forecasting is referred to as an "initial value" problem. The goal of a weather forecasting program is to be able to input the present state of the weather and then predict its future state, but only over a relatively brief period of time, such as a few days. Factors that might change over time, such as the atmospheric concentration of carbon dioxide or the energy output of the Sun are assumed to be constant. But in climate modeling, no attempt is made to predict the specific conditions at a particular point at a particular time. Climate models attempt to predict the average value of different parameters, such as temperature over a longer period of time. No climate model attempts to predict what the weather will be in your town on Oct. 22, 2175.

4. Do all climate models produce the same predictions?

No. If they did, we wouldn't need more than one climate model. As an example, you can compare temperature and precipitation predictions made by two different climate models at: http://metroeast_climate.ciesin.columbia.edu/climodels.html

Websites for Additional Information and Ideas

Two Websites that have high value to anyone interested in atmospheric research are those of the University Corporation for Atmospheric Research which operates the National Center for Atmospheric Research. The UCAR Website, with links to NCAR is: http://www.ucar.edu/

The Website for the National Oceanic and Atmospheric Administration, NOAA is at: http://www.noaa.gov/

There are a large number of different climate modeling groups throughout the world. Links to different models and groups can be found at:
http://stommel.tamu.edu/~baum/climate_modeling.html

The Harvard Atmospheric Chemistry Modeling Group referred to in the article can be accessed at: http://www-as.harvard.edu/chemistry/trop/index.html

Answers to Mole Madness Puzzle

1. mole
2. molybdenum
3. thymol
4. molasses
5. molecule
6. guacamole
7. molality
8. smolder
9. molar mass
10. demolish
11. molten
12. Cosmology
13. Moll Flanders
14. mold