

# MODELING INSTRUCTION

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## SAMPLES OF CHEMISTRY UNIT 2: ENERGY & STATES OF MATTER – PART 1

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### CONTENTS

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1. Teacher notes with laboratory activities
2. Objectives
3. Worksheet 1
4. Unit Review

This sample is designed to provide prospective users with enough material to evaluate the content and flow of the unit, but omits many worksheets/readings/etc, as well as the quizzes and tests. The Teacher Notes contain a complete list of all activities and documents for the unit.

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# Unit 2 – Energy & States of Matter – Part 1

## Instructional goals

1. Recognize that the model of matter that we use during this unit is essentially that proposed by Democritus.
2. Relate observations of diffusion to particle motion and collision in both liquid and gas phases.
3. Relate observations regarding the addition of energy by warming to increased particle motion.
4. Explain, at the particle level, how a thermometer measures the temperature of the system.
5. Explain the basis for the Celsius temperature scale.
6. State the basic tenets of Kinetic Molecular Theory (KMT) as they relate to gases:  
Particles of a gas:
  - a. are in constant motion, moving in straight lines until they collide with another particle or a wall of the container in which they are enclosed.
  - b. experience elastic collisions; i.e., they do not eventually “run down”.
  - c. do not stick to other particles.The speed of the particles is related to their temperature.  
The pressure of a gas is related to the frequency and impact of the collisions of the gas particles with the sides of the container in which they are enclosed.
7. The 3 variables P, V and T are interrelated. Any factor that affects the number of collisions has an effect on the pressure. You should be able to:
  - Predict the effect of changing P, V or T on any of the other variables.
  - $P \propto \frac{1}{V}$     $P \propto T$     $V \propto T$
  - Explain (in terms of the collisions of particles) *why* the change has the effect you predicted.
8. Explain the basis for the Kelvin scale. Keep in mind that one must use the absolute temperature scale to solve gas problems.
9. Use factors to calculate the new P, V or T. Make a decision as to how the change affects the variable you are looking for.

## Sequence

1. Demonstration/discussion: diffusion of gases. Prepare a storyboard of the arrangement and behavior of particles during gas diffusion. [Optional: first part of Video: *The Earliest Models*]
2. Demonstration/discussion: diffusion of liquids in hot and cold liquids. Prepare a storyboard contrasting the arrangement and behavior of the particles in hot and cold water diffusion.
3. Observe the three states of matter and relate observations of rigidity vs. fluidity and density differences to the arrangement and behavior of matter particles. Eureka videos 1 – 3

4. Define temperature, Eureka videos 4 – 5, demo on thermal expansion of liquids, explanation of how a thermometer works, worksheet 1 – temperature and motion of molecules
5. Notes on pressure and how devices can measure pressure
6. Worksheet 2 – measuring pressure
7. PVT lab – part 1: P vs V, PVT lab – part 2: P vs n
8. PVT lab – part 3: P vs T, discussion on laws
9. KMT; how theories differ from laws
10. Solving PVTn problems, ws 3
11. Whiteboard ws 3, Unit 2 review
12. Unit 2 test

## Overview

Observing how students describe matter and its changes, it became evident that beginning chemistry students do not have, and often do not fully develop, a consistent mental model of matter as discrete particles. Instead they tend to view matter, at least in part, as a continuous material with no substructure even in the face of explicit instruction in atomic theory and its applications. This becomes particularly clear when students are asked to describe phase changes at the microscopic level. Through informal observation over the duration of the class, we have noted that those who had robust mental models at this stage tended to be more successful in dealing with the more demanding reasoning involved in characterizing reactions and solving problems in stoichiometry. Those with weaker microscopic models, or who utilized particulate reasoning inconsistently tended to struggle more through the course, usually resorting to algorithmic approaches rather than conceptual understanding.

Vanessa Barker (University of London, in a report “*Beyond Appearances: Students’ misconceptions about basic chemical ideas*”) cites research that points directly to evidence for the poor development of a particle model of matter in most students.

“...only a small portion of students age 16 are likely to use a developed particle model to explain chemical and physical phenomena. The continuous model of matter is powerful, such that despite teaching most students use a primitive particle model, retaining aspects of this naïve view...A small portion of students do not use taught particle ideas at all, offering only low-level macroscopic responses to questions involving particle behavior retaining their naïve view of matter in a more complete form...[E]vidence suggests that students apply different ideas to the three states of matter without seeing this as contradictory...These ideas may contribute to difficulties for students in understanding chemical bonding.” (Barker, pg 12)

This difficulty exists in spite of our sincere efforts to communicate the particle nature of matter to our students. They may use the right language in assignments, but it falls apart for many when pushed to give explanations of the observed behavior of matter. This lack of clarity often causes more difficulty in later topics that require particle-based reasoning such as balancing equations.

To address this difficulty, the opening units of this curriculum are very deliberate in requiring students to connect observed macroscopic phenomena to the microscopic characteristics of matter particles. After developing the need for a particle model of matter in Unit 1 to account for mass conservation and density differences, the students are asked to explain phenomena regarding the states of matter using their model. The students are led to realize that they must modify their model of matter to account for the existence of different states for the same substance.

This unit begins with a demonstration of the diffusion of gases and liquids. The first demonstration is the diffusion of perfume in air. The students are asked to observe the movement of perfume through the classroom and infer some properties of matter at its most basic level that would be consistent with their observations: primarily that matter behaves like tiny particles in motion that move randomly through collisions.

In the second demonstration students are asked to observe the effect of temperature on particle motion. By restricting this to observing particle movement via diffusion, the relationship between temperature (macroscopic observation), diffusion rate (macroscopic observation) and thermal energy (microscopic inference) is introduced.

Once students recognize the relationship between particle motion and temperature, a third demonstration on the thermal expansion of liquids sets the stage for understanding how we measure temperature. Again, the macroscopic observations of temperature and volume are used to infer the microscopic behavior of the particles of the liquid. This activity provides another opportunity for students to recognize that particle collisions provide the mechanism for transferring energy from one particle to another.

After we have established that matter is particulate, we focus on the behavior of gases, beginning the development of kinetic molecular theory.

1. Matter is made of microscopic particles that are in motion. Particles of different substances that are in the gas and liquid phase slowly mix because of the collisions of moving particles that produce random motion.
2. Changing the temperature of a gas changes the speed of the particles. As energy is added, particles move faster. The temperature is a measure of the energy due to the motion of particles. We use thermal energy ( $E_{th}$ ) as the account in which the system stores this energy.
3. In the gas phase, the attractions between the particles are negligible, so the particles experience elastic collisions with one another.
4. The pressure of a gas is due to the collisions of the particles with the sides of the container in which it is enclosed.
5. Ideally, nearly all substances exhibit similar behavior in the gas phase due to the large relative distances between the particles. This results in predictable relationships between the state variables pressure, volume, temperature and quantity of gas.

As students perform experiments to determine the relationships between pressure and volume, pressure and temperature, and pressure and the number of particles, they use particle diagrams to account for the functional relationships between these pairs of variables.

This emphasis allows students to solve quantitative problems involving changes in  $P$ ,  $V$ ,  $T$  and  $n$  using proportional reasoning rather than by using an algorithmic approach.

# Instructional Notes

## 1. Demo/discussion: diffusion of gases

Students are asked to observe the movement of perfume in the classroom. Ask students how we can ‘observe’ (detect) perfume we cannot see. When the use of the sense of smell is identified, it may be necessary to discuss (briefly!) how this sense operates. Students often do not understand that the sense of smell behaves in a similar manner as the sense of taste. Food cannot be tasted at a distance; contact must be made first. Likewise the sensors in our nose require contact with the thing being smelled. With this one idea in mind, open the bottle in a central location in the classroom and ask them to indicate by raised hand when their ‘perfume sensors’ detect the arrival of the perfume at their seat.

Once a pattern of spread has been observed, the students are asked to hypothesize what matter must be like at its simplest level to explain their observations. Most students come to the course with some idea of atoms or molecules, and are likely to use these terms. It is important at this point to have them describe what they are envisioning is happening at this microscopic level in everyday language with sufficient detail to elicit a mental picture. It is helpful to ban the terms *atom* and *molecule* until these ideas are actually developed so students cannot hide behind language they may not understand adequately. Instead, encourage them to use words that are common to everyday speech (though, hopefully used more carefully than everyday speech!). We are, at this stage, essentially using the idea of simple particles first proposed by Democritus in the 4<sup>th</sup> century B.C.<sup>1</sup> You should wait until Unit 4 to show the rest of the video. It is also important to encourage the students to view the entire system of particles involved. If they do not readily include the air particles in their discussion, ask them to explain how the perfume particles could have left the bottle (upward) and then moved in so many directions (outward).

The mental images they are ‘seeing’ can be communicated through drawings on whiteboards. It should become evident that a static picture cannot represent what is happening adequately. The model of matter that fits the observations should include microscopic particles (commonly seen as spheres) that are in constant motion and collide with one another randomly.

Following the discussion in class, students are asked to prepare a **storyboard** of the diffusion process by drawing a sequence of 5-7 particle diagrams that show how the arrangement of particles change over the time from when the bottle was just opened until the perfume had well-permeated the room. They must include all matter particles involved in their system (the closed room) that were involved in producing the pattern of diffusion they observed.

Since students frequently forget about the role of the particles of air in the room in diffusion, it might be useful to have the students visit the Davidson web site to view an [applet on diffusion](http://www.chm.davidson.edu/ChemistryApplets/KineticMolecularTheory/Diffusion.html).<sup>2</sup>

## 2. Demo/discussion: diffusion of dye in hot and cold water

In this demonstration, obtain two large beakers or flasks. Fill one with cool to cold water and the other with very warm water (not boiling). Allow the water to become still on a demo table

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<sup>1</sup> <http://en.wikipedia.org/wiki/Democritus>

<sup>2</sup> <http://www.chm.davidson.edu/ChemistryApplets/KineticMolecularTheory/Diffusion.html>

before beginning the demonstration. Add 1-2 drops of a dark food dye to the water in each flask and observe the diffusion of the dye in the water. Using two different colors, such as red and blue, makes it easier to keep track of which beaker is hot and cold during discussion.

Students are asked to describe what they saw macroscopically, and then explain their observations in terms of the particle model we have developed so far (small, separate particles in motion that move randomly by collision). The discussion should draw students to explain the observed behavior in terms of the effect that adding energy to the system of particles has on temperature and the speed of the particles.

An important aspect of our model of matter that is being developed in this unit is that particles interact via collision to change motion and transfer energy from particle to particle. This feature of our model provides a mechanism for understanding energy transfer by both heating and working (introduced in Unit 3) and for understanding reactions beginning in Unit 7. It is helpful to students to explicitly identify these features of our model following these activities.

This demonstration is followed up with the assignment to prepare two storyboard sequences<sup>3</sup>, one each for the hot water and cold water diffusion observations. To contrast the difference in rate, each storyboard sequence should contain the same number of frames at the same time intervals. These can be prepared individually as a homework assignment or, if preferred and class time allows, prepared in groups on whiteboards.

### 3. Observations of phases of matter

Students observe the three phases of water to compare characteristics such as density, fluidity, and rigidity. After describing the three phases in class discussion, students should offer explanations of these differences by preparing particle diagrams on whiteboards that would support their observations. Students can compare their drawings and come to consensus and the best explanation of their observations. Animations of matter at the particle level in these three states are helpful to show at this point. The 1<sup>st</sup> three episodes of the video *Eureka: Heat & Temperature*<sup>4</sup> (Molecules in Solids, Molecules in Liquids, and Evaporation and Condensation) do an excellent job of showing the behavior of particles in the solid and liquid phases and what happens during phase changes. While phase changes are introduced in the third video, the intent is not to develop a full discussion of changes in phase at this time but to develop a clear mental picture of how the three phases of matter would differ at the particle level in order to explain differences in properties of each phase (*microscopic explanations for macroscopic observations*). Changes between phases will be discussed more thoroughly in Unit 3, Energy and States, part 2.

## 4. Demonstration: Thermal expansion of liquids, worksheet 1

### Apparatus

600 - 1000 mL beaker  
hot plate or burner and stand      alcohol thermometer  
two 18 x 150 mm test tubes fitted with 1-hole stoppers and glass tubes  
water and alcohol (ethanol or methanol)

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<sup>3</sup> Sample story boards can be found in the miscellaneous folder for this unit.

<sup>4</sup> Films for the Humanities and Sciences, Item BVL4057, \$130 - <http://www.films.com/>

## Demo performance notes

Assemble the apparatus while you begin the discussion. Fill one tube with water with a drop of blue food coloring, and the other with alcohol (red food coloring). Insert the stoppers into the test tubes and adjust the fit until the fluid level is the same in both tubes. Clamp the test tubes in a room temperature water bath and make marks on the glass tubes at the liquid levels. Then heat with burner or hot plate. From previous discussions students should have a sense that when a substance is heated, its molecules are moving around more rapidly. Ask them what property of the substance might change as a result. Hopefully, they might suggest that the substance would expand when heated. See if you can get students to suggest why you put thinner tubing in the stoppers in the larger test tubes (This is necessary to amplify the expansion of the liquids.) At 10°C intervals, mark the level of the liquids in each of the tubes. Continue until the water bath has reached 60-70°C.

## Discussion

Students should note that both liquids rose in the thinner glass tubing when they were heated, and the alcohol expanded more than did the water. Point out that the change in height of the liquid level was relatively constant for each 10° C temperature change. Then, pass around thermometers and ask students to explain how they work. You may need to explain that the red tip is really a reservoir of colored alcohol with really thin glass walls (why you should never use a thermometer as a stirring rod). When particles surrounding the thermometer strike the bulb, they transfer some of their energy to the alcohol inside, causing it to expand. Since the thermal expansion of water or alcohol is reasonably linear, the height of the liquid in the thin capillary tube can be used as a measure of the "hotness" of the surroundings. What happens when the thermometer is placed in surroundings that are "colder" than the alcohol in the reservoir? Then energy flows from the hotter alcohol to the surroundings; the particles in the bulb slow down and contract and the level of alcohol in the capillary tube falls. The word "thermometer" comes from the words for hotness (thermos) and measure (meter). If you have access to the video series *Eureka: Heat & Temperature*, this would be an ideal time to show episodes 4 (Expansion and contraction) and 5 (Measuring temperature). If not, you will have to explain how a thermometer is calibrated and how the Fahrenheit and Celsius scales were developed. At this point have the students work on worksheet 1.

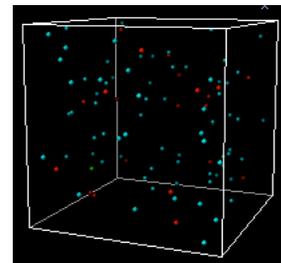
## 5. Notes on gas pressure

Most high school texts describe pressure as force per unit area as well as provide an explanation of atmospheric pressure. These usually include particle diagrams that show "snapshots" of particles in a box moving around in random thermal motion. While this approach does touch the basic concept, we recommend starting by probing students' ideas about "suction"; i.e., by asking students how they draw a liquid through a straw from a cup into their mouth. There is likely to be some hesitation on their part as they try to provide an explanation in terms of the motion of particles. It's not difficult to convey the idea that when you suck on a straw, you are removing some of the particles of air in the straw. Since there are more particles of air striking the liquid in the cup than are striking the liquid in the straw, the effect of these extra collisions is to push the liquid up into your mouth; there are no "suck-ons" that pull the liquid up the straw.

The concept of gas pressure can be further illustrated using the "Blow up a student" demo. A student lies across a heavy gauge garbage bag that has been sealed with packing tape except for four straws inserted in the four corners of the bag. Four students then blow up the bag under the student, lifting him/her off the table supported on a bed of air. Discuss what must be happening at the particle level for air to lift the student off the table (collisions of the air molecules with the

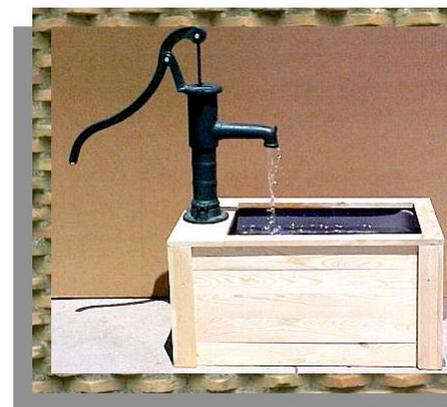
sides of the bag provide many individual interactions with the bag, providing enough collective force to balance the gravitational force on the student). By having students develop particle representations of how the student is kept suspended above the table, the idea of gas pressure as the force of the collisions on each unit area can be developed.

It is very helpful if you can show some simulation that helps students picture the behavior of particles in a box. A simulation from the [PhET website](http://phet.colorado.edu)<sup>5</sup> at U of Colorado helps to illustrate the features of the kinetic molecular theory of gases. You can run the simulation from the website, or download it to your computer and run it locally. You can find it in the miscellaneous folder for this unit. This applet can be used at this point to simply illustrate particle motion in a container. It can also be useful as a follow up to the gas behavior lab to assist students in visualizing the effects of changes in system variables at the particle level.



There are a variety of ways to express the pressure of a gas, ranging from the familiar “psi” to the less familiar pascal. Show that each has a unit of force (pound or newton) exerted on a unit area ( $\text{in}^2$  or  $\text{m}^2$ ). Another way to express pressure is to measure the height of a column of liquid that is supported by the pressure. You should remind students that the force exerted by the earth on the liquid has to be balanced by the force of the molecules colliding with the surface in contact with the column in order for the column to remain above the level of the liquid in the dish (or some reservoir). Now, ask your students to imagine that they were on a 2<sup>nd</sup> floor balcony and a friend had a cup of soft drink 8 feet below them. Ask them if they think they could use a really long straw to “suck” the beverage into their mouth. Most will say no; see if you can induce them to provide an explanation in terms of the weight of the column of liquid and the force of the collisions of air molecules on the surface of the liquid in the cup. Students begin to see a limit to the height of a column of liquid that can be supported by the difference in pressure.

Next, ask them if they can explain how a pump (such as one in the figure at the right) can pump water out of a well. You may have to inform them that each stroke of the handle removes some air from the pipe above the water. Students should be able to see the parallel between this mechanical device and their ability to suck a liquid up a straw. If you like, you can tell the account of what Torricelli (1606-1647) learned when he tried to figure out why he could not pump liquid up to the top floor of his villa with such a device. He reasoned that even if the pump could remove all the air above the column of liquid, the pressure exerted by the atmosphere could only support a column of liquid so high (~34 ft). As the story goes, he replaced the top portion of the pipe with a glass tube and noted that the water level fluctuated depending on the weather. It occurred to him that he could more conveniently study this behavior if he used a liquid with a greater density. He filled the tube with mercury ( $d = 13.6 \text{ g/mL}$ ) and found that atmospheric pressure could support a column of mercury varying from 28-31 inches. Such a device is called a barometer. The pressure unit, mm Hg, is often referred to as the “torr” in his honor. Standard pressure is given as 760 mm Hg, or 101.3 kPa.



It's not easy for students to grasp that the fact that the Earth's atmosphere could support this much weight. To them, air seems totally insubstantial. A tool teachers use to help illustrate the pressure exerted is the “crush-the-can” demo. This is effective *if* students recognize that when

<sup>5</sup> <http://phet.colorado.edu/en/simulation/gas-properties>

the pop can filled with steam is inverted in the bucket of water, the steam condenses to liquid water, thus greatly reducing the pressure inside the can. A larger scale version of this effect is shown in the image “Tankerview1.jpg” found in the unit folder.

## 6. Worksheet 2: Measuring Pressure

While most schools no longer have mercury to use in manometers (or even barometers), you can use colored water in a manometer to help illustrate the effect of adding or withdrawing air (using a syringe) from a flask. The problems on the first page help students see that a manometer can be used to measure the pressure in a vessel by comparing it to the pressure in a room. This worksheet also familiarizes students with various units of pressure along with defining Standard Pressure (SP).

## 7. PVT lab – part 1: P vs. V

### Apparatus:

These instructional notes are based on the use of Vernier software, interface and sensors (Logger *Pro*, LabPro, LabQuest or Go!Link interface and gas pressure sensor). Other equally useful probe/interface systems are also available from PASCO. Some of these activities may be done using low-tech methods for schools that do not have access to the computer interface equipment.

The equipment set up is shown in the figure at the right.

- Vernier Gas Pressure Sensor
- Interface and computer with Logger *Pro* software
- 25 mL syringe with Luer-lock tip (to attach to pressure probe)
- The experiment files: PV.cmbl, Pn.cmbl and PT.cmbl can be found in the miscellaneous folder.



### Pre-lab Discussion:

In preparation for this set of labs, students are asked to brainstorm ways to alter the pressure of the gas in a sealed syringe (such as the one provided with Vernier’s gas pressure sensor). The use of a syringe for this discussion helps students more readily recognize the possibility of volume changes, which they typically won’t think of with a rigid container such as a sealed flask. List the independent variables the students suggest (volume and temperature should be brought out). Narrow the list to ones that can reasonably be carried out with equipment and time available. Numbers of particles in the container often comes up, so an optional part for P vs. n is discussed for use at teacher discretion. Students should be guided to construct a guiding question or purpose statement for each independent-dependent variable pair.

Equipment needed for each experiment should be introduced. If students have not worked with Luer-lock connectors, they should be instructed in how to connect them without over-tightening them (and thereby stripping the connector and losing the seal). Lightly finger tight should be adequate. Also, it may be wise to remind them not to make a contest out of getting the highest pressure possible – at least one syringe has been split open from exuberant competition (you know whom to watch!).

The experiment question for this part of the lab would be worded in a manner similar to “What is the relationship between volume and pressure for a gas in a sealed container?” or “How does a change in volume affect the pressure of a gas in a sealed container?”

### Lab Performance Notes:

Set the plunger to a position of 10-15 mL and attach the pressure sensor to the stopcock. Attach the pressure sensor to the interface. The interface is then attached to the computer via the USB port and the power cord plugged in. With the sensor/interface set up and powered, open the Logger Pro file: P-V.cmbl. This experiment file uses the “Events With Entry” mode of data collection, allowing students to set a volume on the syringe and press the [Keep] button, so that they may enter the volume via an input window. The pressure is recorded for the volume entered and the data point is plotted on the graph as the students enter the data.

By setting the syringe at a mid-point in the volume range, the pressure data range will be both above and below the ambient pressure. This increases the volume range that can be attained without damaging the syringe or luer-lock connection. Generally the viable range on a 25 mL plastic syringe using this initial volume setting is approximately 5 mL to 25 mL. This procedure also more readily opens the discussion to include circumstances where volume is increased or decreased.

The data from this experiment should show that the pressure is inversely proportional to the volume ( $P \propto \frac{1}{V}$ ). Students may not have encountered this relationship before, so you might have to ask them to articulate how the pressure changes as the volume either increases or decreases. Students then can use the “Inverse” function (Curve Fit tool) or, if you prefer, they can create a new calculated column (inverse pressure) to linearize the graph. In either case, it is not recommended to use the tube (provided in the Vernier gas pressure kit) to connect the syringe to the sensor. Doing so will result in points that do not fall on the curve or a best-fit line with a significant y-intercept.

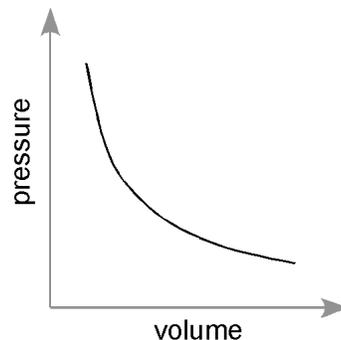
Students should develop a *mathematical description* of the relationship found in the graph (either as an equation via linearization or as a proportional statement) and a *verbal description* of the relationship they have found.

### Post-lab Discussion:

Following the lab, each lab team prepares a whiteboard to present their results to the class for discussion. The presentations should include a description of how they carried out the experiment (set up diagram), their graph (a data table is redundant), their mathematical relationship, and their verbal description. The class results should be compared and consensus reached on the best description of how volume affects the pressure of a gas. If students get poor results from this lab (especially at the lowest and highest volumes), it is usually the result of not reading the volume carefully enough as they attempt to hold the plunger steady when the volume is small. Once it gets difficult to hold the plunger steady, it is a good sign they should stop so they don't damage the syringe.

Students can be guided to verbalize the inverse relationship between pressure and volume by predicting what will happen to the pressure when is changed by simple ratios such as doubling volume ( $1/2*P$ ), tripling volume ( $1/3*P$ ), or cutting V in half ( $2*P$ ) or to a tenth ( $10*P$ ).

The inverse relationship of pressure and volume can be expressed mathematically as  $P = k(1/V)$ , which can be rearranged to produce  $P*V = k$ . Students should inspect their data to find that the product of



P and V do, in fact, give a reasonably constant value. From this we can infer that the product  $P \cdot V$  for any (P,V) pair for that system will be equal:  $P_1 V_1 = P_2 V_2$ , which can also be written as  $P_1 \times \frac{V_1}{V_2} = P_2$ . During a particular volume change, the original pressure of the gas ( $P_1$ ) will be changed by the conversion factor  $\frac{V_1}{V_2}$  to give the new gas pressure ( $P_2$ ). If the volume increases in the process, the  $\frac{V_1}{V_2}$  factor will be  $< 1$  and the pressure will decrease proportionately. If the volume decreases, the  $\frac{V_1}{V_2}$  factor will be  $> 1$  and the pressure will increase proportionately.

The use of conversion ratios (rather than plug and chug equations) strengthens proportional reasoning skills and helps students verbalize the reason for the change in pressure. This will better prepare the student for other areas of chemistry that utilize proportional reasoning such as stoichiometry (as well as other sciences and problem solving in general!).

## PVT lab – part 2: P vs. n

### Apparatus

These instructional notes are based on the use of the Vernier gas pressure sensor linked to an interface<sup>6</sup> connected to a computer running Logger *Pro* software. Other equally useful probe/interface systems are also available from PASCO. It would be difficult to perform this experiment without the use of such technology.

The equipment set up is the same as that used in part 1.

- Vernier Gas Pressure Sensor
- interface and computer with Logger *Pro* software
- 25 mL syringe with Luer-lock tip

### Pre-lab Discussion

This experiment can be used if a general discussion about the effect of changing the number of particles (n) of gas in the system is desired. It would not be appropriate at this point to introduce a formal discussion of moles. Reasoning in terms of counts of particles in conceptual terms comes fairly easily here and can provide a foundation for that discussion at the appropriate time. Since this is being done without a defined unit of count (particularly, the mole), the students can have the fun of defining and naming their own unit of gas particle counts.

If you prefer to wait until you have developed the mole concept to examine this relationship, you should note that Unit 9 (Stoichiometry II) will use the P vs. n relationship for gases to help develop concepts of partial pressure, molar volume, and the ideal gas law. It is recommended that this activity be carried out as a lab or a demo to set up the portion of Unit 9 addressing moles and gases. Two versions of Unit 2 worksheet 3 are provided; the version containing questions addressing PVT relationships only is available in the miscellaneous folder for Unit 2.

The pre-lab discussion is outlined in Part 1 above. Focusing on the P vs. n relationship, students should be guided to construct a question or purpose statement such as “What is the relationship between pressure and number of particles for a gas in a sealed container?” or “How does changing the number of gas particles affect the pressure in a sealed container?” Equipment

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<sup>6</sup> LabPro, LabQuest or even a Go!Link will work.

needed to carry out this experiment and their use should be discussed, including reviewing the correct care of Luer-lock connectors and the need to carry out measurements at a constant volume.

At this time, a way of reproducibly adjusting the number of particles while keeping the volume constant will have to be discussed. Ask how the density of the gas in the syringe compares to the density of the room air if the syringe is left open to the air (the same – usually pretty quickly seen). Then ask how the number of particles in the syringe would compare for the same volume of air if the density hasn't changed. Then we can choose a particular *volume* of gas in our syringe and know it has a particular *count* of particles if it is open to the same room air. This will be one unit of gas particles, which we can give a convenient name (such as 2 mL of air contains 1 “puff” of particles). Once the syringe contains a given number of “puffs” of air, students can connect it to the sensor and then adjust the closed syringe to a predetermined volume (such as 10 mL). This allows them to measure the pressure for each particle count at constant volume and temperature.

### Lab Performance Notes:

Set up the equipment as shown in the figure in Part 1. Use the same procedure for attaching the probes and interface to the computer as described in Part 1 of the lab. Open the Logger Pro file: P-n.cmbl. This experiment file also allows students to collect data in “Events With Entry” mode so they can generate a P-n graph.

Students can vary the number of particles of the gas by adjusting the syringe to various volumes while open to the air. The syringe is then attached to the pressure sensor and adjusted to a predetermined volume (say, 10 mL). When the adjustment is done, click the KEEP button, enter the number of particles in the syringe (in “puff” units), and hit enter. The computer will record the count and pressure in the data table and automatically graph the data.

This experiment should produce a very linear relationship between P and n. Possible sources of error are:

- (1) The syringe is not securely reattached to the pressure sensor before changing the volume to the predetermined value.
- (2) Students fail to keep a consistent final volume for the syringe.

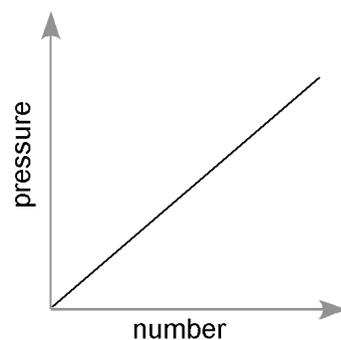
Students should develop a *mathematical description* of the relationship found in the graph (either as an equation with slope and intercept or as a proportional statement) as well as a *verbal description* of the relationship found between pressure and particle counts.

### Post-lab Discussion:

Following the lab, each lab team prepares a whiteboard to present their results to the class for discussion. The presentations should include a description of how they carried out the experiment (set up diagram), their graph (a data table is redundant), their mathematical relationship, and their verbal description. The class results should be compared and consensus reached on the best description of how the number of particles affects the pressure of a gas.

Students should be able to state that the pressure is directly proportional to the number of particles. Doubling the number of particles would double the pressure. This means the **ratio** of P/n should be constant for their data. Have the students inspect their data

to verify this. They should find  $\frac{P_1}{n_1} = \frac{P_2}{n_2}$ , which can be rewritten as



$P_1 \times \frac{n_2}{n_1} = P_2$ . Again we find a conversion factor using the number of “puffs” that lets us predict how pressure of a gas will change. If the number of particles increases,  $\frac{n_2}{n_1}$  will be  $>1$ . This will cause the final pressure ( $P_2$ ) to be higher than the pressure before the change. Conversely, if the number of particles in the system decreases,  $\frac{n_2}{n_1}$  will be  $<1$ , and the final pressure will be proportionately less than the initial pressure.

## 8. PVT lab – part 3: P vs. T

### Apparatus

These instructional notes (as with part 1) will be based on the use of computer-based lab equipment. Other probe/interface systems and low-tech methods are also available for schools that have access to alternative equipment. Equipment set up for this experiment is shown in the figure at the right. The beaker should be large enough to allow the water to cover the flask up to the neck near the stopper.



- Vernier Gas Pressure Sensor
- Vernier Temperature Probe
- Interface and computer with Logger *Pro* software
- One 125 mL Erlenmeyer flask
- One-hole stopper fitted with a luer-lock stopcock.
- Two to three 400 mL beakers to use as water baths at various temperatures
- Ice
- Large beaker of water on a hot plate kept at a simmer (may be shared between lab groups)
- Saturated brine-ice mixture (may be shared between lab groups)

### Pre-lab Discussion

The pre-lab discussion is outlined in part 1 above. Focusing on the P vs. T relationship, students should be guided to construct a question or purpose statement such as “What is the relationship between pressure and temperature for a gas in a sealed container?” or “How does temperature affect the pressure of a gas in a sealed container?” Equipment needed to carry out this experiment and their use should be discussed, including reviewing the correct care of luer lock connectors and the need to keep the flask sealed during the experiment to keep all other variables (especially number of gas particles) constant during the experiment.

### Lab Performance Notes

Set up the equipment as shown in the figure above. Use the same procedure for attaching the probes and interface to the computer as described in Part 1. Open the Logger Pro file: P-T.cmbl.

This experiment file enables students to collect data in “Events With Entry” mode so they can generate a P-T graph.

Students can vary the temperature of the gas by changing the temperature of the water bath the flask is immersed in. The water bath should be gently agitated by stirring or by gently ‘bobbing’ the flask in the water while keeping the flask well submerged. This will bring the system to equilibrium faster.

In order to get a clear pattern of relationship, students should collect data for at least five temperatures in as wide a temperature range as is practical. We recommend starting with very hot water (80-85°C) first and cooling the water in the beaker by pouring out some of the water in the beaker and replacing it with cooler water to obtain readings of around 50 - 55°C, then 25 - 30°C, then 10 - 15°C and finally near 0°C. The exact temperature used for each reading is less critical than having a wide range of data collected with each reading taken at thermal equilibrium. Advise the students to hold the stopper in the flask firmly for the hottest temperature reading so that the pressure does not pop the stopper out of the flask. As the flask is cooled and the pressure decreases, the outside pressure will help keep a good seal between the stopper and flask. A sixth data point can be achieved by including a saturated brine-ice bath, or even a dry ice-alcohol bath. This last option should be well-supervised by the teacher. One suggestion is to have a cart with the dry ice bath on it that can be taken between stations by the teacher or a designated TA.

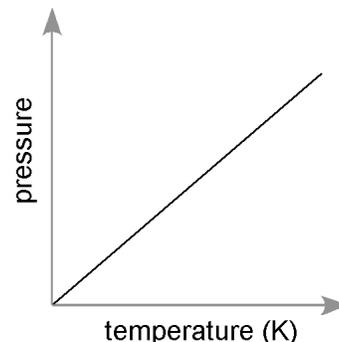
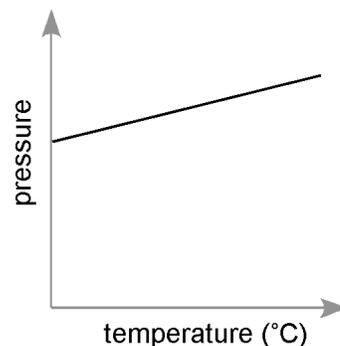
In this experiment both the temperature and pressure are read real-time by the computer and saved to the data table using the KEEP function. The temperature probe is placed in the water bath rather than directly in the gas itself, which means the system must be allowed to equilibrate for several seconds before recording the pressure and temperature. Thermal equilibrium will be evident when both the pressure and temperature readings become stable. When equilibrium is achieved, clicking the KEEP button will save the data pair to the computer. Each data point is displayed in the data table and plotted on the graph as the students enter the data.

The data from this experiment should produce a linear relationship, but one that is not proportional. Make sure that the students save their file before they return for the post-lab discussion.

## Post-lab Discussion

Following the lab, either sketch a graph of pressure vs. temperature (°C) or display sample data from the class. Point out that while the graph is linear, the pressure is NOT proportional to the Celsius temperature; i.e. a doubling of the Celsius temperature does not produce a doubling of the pressure.

It is important for students to address the physical meaning of the pressure intercept. This point on the graph would, of course, be the pressure when the temperature was 0°C. Students should describe the conditions they used to achieve 0°C (ice-water mixture) and be asked if 0°C is the lowest temperature possible. If a brine-ice bath was used, the answer will be obvious from their data. Ask them to predict what would happen to the pressure if we continued to cool the gas. Have the students predict the temperature that would be needed to reach a pressure of zero using their data. They can do this by using *Logger Pro* and manually choosing the left extreme of the temperature axis to be some value below -350°C, or by entering the data into a graphing calculator and finding the horizontal intercept.



Select a method that is consistent with the skills of your students and the tools available to them. If their data and graphing techniques are good, they should get class values that center in the neighborhood of  $-250$  to  $-300^{\circ}\text{C}$ .

The Kelvin scale can now be defined as the temperature scale where each degree is the same size as a degree on the Celsius scale, but with the zero point set where the pressure of the gas is zero. If they were to slide the vertical axis of their graph to this point, the graph would look like the one above.

Have the students print this extrapolated graph for their lab report.

Adjusting their data to the Kelvin scale, the relationship is now a simple proportion where doubling temperature would double the pressure. Both temperature and pressure must increase by the same ratio. This means the **ratio** of  $P/T$  should be constant for their data. Have the

students inspect their data to verify this. They should find  $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ , which can be rewritten as

$P_1 \times \frac{T_2}{T_1} = P_2$ . Again we find a conversion factor using the temperature readings that lets us

predict how the pressure of a gas will change. If the temperature increases,  $\frac{T_2}{T_1}$  will be  $>1$ . This will cause the final pressure ( $P_2$ ) to be higher than the pressure before the change. Conversely, if temperature for the system decreases,  $\frac{T_2}{T_1}$  will be  $<1$ , and the final pressure will be proportionately less than the initial pressure.

Summarize the relationships observed in the three experiments. The pressure of a gas appears to be inversely proportional to the volume ( $P \propto \frac{1}{V}$ ), and directly proportional to the number of particles ( $P \propto n$ ) and the absolute temperature ( $P \propto T$ ). Statements such as these are examples of *laws* – statements of observed regularities that have value because of their predictive power. The relationship between pressure and volume is known as Boyle’s law, the relationship between pressure and the number of particles is known as Avogadro’s law, and the relationship between pressure and temperature is known as Gay-Lussac’s law. We need to dig deeper to determine how our particle model of a gas can account for these regularities.

## 9. KMT; how theories differ from laws

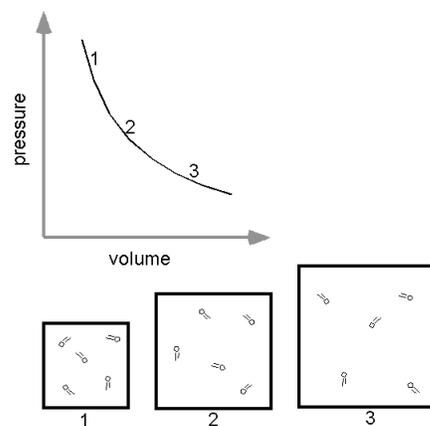
At this point elicit from the class what are the behaviors of the particles of a gas that would account for the regularities they have observed. Make sure that they recognize that our *theory* of gaseous matter must include the following features:

Particles of a gas:

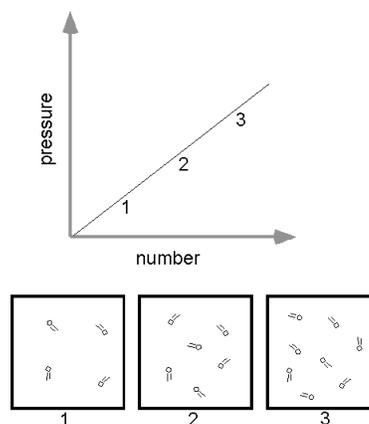
- are in constant motion, moving in straight lines until they collide with another particle or a wall of the container in which they are enclosed.
- experience elastic collisions; i.e., they do not eventually “run down”.
- do not stick to other particles.
- The speed of the particles is related to their temperature.
- The pressure of a gas is related to the frequency and impact of the collisions of the gas particles with the sides of the container in which they are enclosed.

Divide the class into three groups and have each group draw on their whiteboards particle diagrams representing the gas at three points along the graph that are both consistent with both the way they performed the experiment and account for the graphical relationship they observed. Conduct a board meeting in which groups can compare and contrast the differences in their representations.

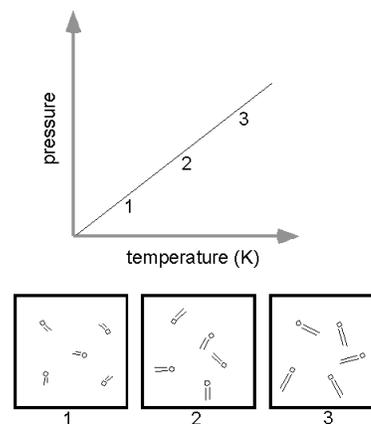
For example in the P vs. V experiment, their diagrams should look like the ones at right. Both the number of particles and the length of the “whooshies” on the particles remain the same since both the amount of gas and the temperature remained unchanged. However, as the volume increased, the frequency of collisions of the particles with the sides of the container decreased, so the pressure also decreased. The boxes are drawn larger to represent the increase in volume.



In part 2, both the volume and the temperature were held constant, as shown by the equal size boxes and the length of the whooshies. Adding more particles would increase the frequency of collisions on the side of the container, which would result in a higher average force on each  $1 \text{ cm}^2$  of the container. By definition, this means the pressure is higher.



In part 3, both the volume and the number of particles were kept constant, so the size of the boxes and the number of particles should remain unchanged. However, an increase in the temperature speeds up the particles. This would cause an increase in both the frequency of collisions and the impact of each of the collisions. Both changes would result in an increase in pressure. It may be helpful to students to experience the effect of speed on collision force by rolling or tossing tennis balls at their stationary hands at different speeds. This will let them get a feel (literally!) for the effect speed has on the force experienced during a collision.



To summarize, point out that we had to make some assumptions about the behavior of the particles of a gas that we had no way of directly proving. But if the particles of gas behaved as we proposed, we could very neatly account for the laws we observed. Kinetic Molecular Theory, then, has *explanatory* power, whereas the laws of Boyle, Avogadro and Gay-Lussac had only *predictive* power. The theory helps us to explain the regularities we observed.

## 10. Solving PVTn problems, worksheet 3

This worksheet asks students to use the conversion factors they have discovered and predict how changes in the conditions of a gas system will affect one of the variables. An analysis table is included on worksheet 3 that asks students to record the initial and final states for each variable and identify its direction of change by placing an up or down arrow on the variable symbol at the head of the column (ex:  $T \uparrow$ ). In the 'Effect' row, students can predict how the unknown target variable will change because of changes in the other variables (ex: if pressure is being predicted for a temperature increase,  $P \uparrow$  would be recorded in the temperature column). Students then construct their conversion ratios for each variable to produce the predicted outcome. Two versions of unit 2 worksheet 3 are provided; the version containing questions addressing PVT relationships only is available in the miscellaneous folder for Unit 2.

## 11. Whiteboard ws 3, Unit 2 review

Students with literary inclinations might enjoy reading an excerpt from Lucretius' lengthy poem "On the Nature of Things" written in the 1<sup>st</sup> century B.C. (provided in the miscellaneous folder). They might be surprised to see how much of the behavior of matter they have been observing was explained so nicely so long ago.

## 12. Unit 2 test

## Unit 2 Worksheet 1

1. You decide to boil water to cook noodles. You place the pan of water on the stove and turn on the burner.
  - a. How does the behavior of the water molecules change as the pan of water is heated?
  
  
  
  
  
  
  
  
  
  
  - b. What about your answer to (a) would change if there were more water in the pan?
  
  
  
  
  
  
  
  
  
  
2. What property of matter best describes the way a typical alcohol thermometer works? Explain (in terms of energy transfer) why the alcohol level in the thermometer rises (or falls) when you place the thermometer in contact with both warmer (or colder) objects.
  
  
  
  
  
  
  
  
  
  
3. If you feel feverish, why can't you take your own temperature with your hand?



## Unit 2 –Energy & States of Matter – Part 1 - Objectives

<p>1. Relate observations of diffusion to particle motion and collision in the gas and liquid phases.</p>	
<p>2. Relate observations regarding the addition of energy by warming to increased particle motion.</p>	
<p>3. Describe the characteristics of solids, liquids and gases in terms of particles and their arrangement: use particle diagrams to account for motion and density differences; describe the process of how the arrangement of particles changes during phase changes.</p>	
<p>4. Relate temperature to the thermal energy (<math>E_{th}</math>) of particles in motion.</p>	
<p>5. Explain, at the particle level, how a thermometer measures the temperature of the system.</p>	

<p>6. Explain the basis for the Celsius temperature scale.</p>	
<p>7. State the basic tenets of the Kinetic Molecular Theory (KMT).</p>	
<p>8. The 3 variables P, V and T are interrelated. Any factor that affects the number of collisions has an effect on the pressure. You should be able to:</p> <ul style="list-style-type: none"> <li>• Predict the effect of changing P, V or T on any of the other variables.</li> </ul> $P \propto \frac{1}{V} \quad P \propto T \quad V \propto T$ <ul style="list-style-type: none"> <li>• Explain (in terms of the collisions of particles) <i>why</i> the change has the effect you predicted.</li> <li>• Explain the basis for the Kelvin scale. Use the absolute temperature scale to solve gas problems.</li> <li>• Use factors to calculate the new P, V or T. Make a decision as to how the change affects the variable you are looking for.</li> </ul>	

# Chemistry – Unit 2 Review

To prepare to do well on the Unit 2 test, you should assemble your notes, the 3 worksheets and the quiz and review them, preferably in a small group where you can draw from each other's understanding. Here are the key points you should know.

## Energy

Think of energy as a quantity that is always involved when there is a *change* in the state of matter. When a substance gets hotter or colder or changes phase, energy is either transferred into or out of the system. One way energy is stored in a system is **thermal energy** (due to the motion of the particles). As particles move faster, their thermal energy increases. As the particles move faster, they tend to move farther apart from one another. Temperature is a measure of the thermal energy of the system.

1. Explain why the alcohol level in a thermometer rises when it is placed in a warmer fluid. (3-step process)
2. Explain why the alcohol level in a thermometer falls when it is placed in a cooler fluid. (3-step process)
3. Explain how the Celsius scale was devised and why it is not appropriate to use it when describing the behavior of gases. (review ws 1, PVTn lab)

## Kinetic Molecular Theory

This theory describes all matter as being composed of tiny particles in endless random motion. In a solid, the particles vibrate, but are locked into an orderly array. In a liquid, the particles are still touching but are free to move around past one another. In a gas, the particles are moving very rapidly and are widely separated. Using particle diagrams represent samples of a cold gas and a hot gas.

## Gas behavior

Gas pressure is a measure of the collisions of the molecules with the sides of the container. A barometer is used to measure atmospheric pressure; a manometer is used to measure the pressure in a container. (review ws 2)

The 3 variables P, V and T are interrelated. Any factor that affects the number of collisions has an effect on the pressure. You should be able to:

- Predict the effect of changing P, V or T on any of the other variables.

$$P \propto \frac{1}{V} \quad P \propto T \quad V \propto T$$

- Explain (in terms of the collisions of particles) why the change has the effect you predicted.
- Explain why one must use the absolute temperature scale to solve gas problems.
- Use factors to calculate the new P, V or T (review ws 3). Make a decision as to how the change affects the variable you are looking for.
- Suppose that you lowered the temperature of a gas from 100°C to 50 °C. By what factor do you change the volume of the gas?
- Suppose that 25.0 mL of a gas at 725 mm Hg and 20°C is converted to standard pressure and temperature. What would be the new volume?
- Find your copy of The Model so Far and note what modifications in our particle model of matter we have made in this unit.