Energy and Particles in Motion

Learning Objectives

2.1. Temperature	I can explain and illustrate differences in particle motion and how they relate to temperature.
2.2. Thermal Expansion	I can describe thermal expansion at both macroscopic and particulate levels.
2.3 Pressure	I can explain and illustrate the differences in pressure in terms of particle interactions
2.4. Gases	I can explain and apply gas property relationships using math, graphs, drawings, and words.

Unit Overview

This unit begins with a demonstration of the diffusion of gases and liquids. The first demonstration is the diffusion of the scent of air freshener in the air. The students are asked to observe the movement of the scent through the classroom and infer some properties of matter at its most basic level that would be consistent with their observations. Primarily, 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

Unit 2

Outline

Week 1

Demo/Discussion: diffusion of gases

Demo/Discussion: diffusion of dye in hot and cold water

Observation/Discussion: Phases of matter

Demonstration: Thermal expansion of liquids, assign worksheet 1

Whiteboard/Review worksheet 1

Week 2

Introduce pressure & assign worksheet 2

PVTn Lab
- Part 1: P vs V
- Part 2: P vs n

Concept check

Week 3

- Part 3: P v T

Relate lab to KMT

Solving PVTn problems using IFE tables

Concept check

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. 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.	**Week 4** Whiteboard worksheet 3 Concept check Summative assessment objectives 2.1-2.3

Diffusion of Gas Demo

Students are asked to observe the movement of scent molecules from air freshener in the classroom. Ask students how we can 'observe' (detect) the scent we cannot see. When the use of the sense of smell is identified, it may be necessary to discuss (briefly!) how this sense operates. Likewise, the sensors in our nose require contact with the thing being smelled. With this one idea in mind, spray the air freshener in a central location in the classroom and ask them to indicate by raised hand when their 'scent sensors' detect the arrival of the buttery-flavor scent at their seat.

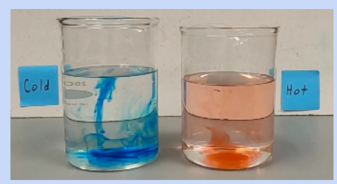
Once a pattern of spread has been observed, the students are asked to hypothesize what matter must be like at its simplest level to explain their observations. Most students come to the course with some idea of atoms or molecules and are likely to use these terms. It is important at this point to have them describe what they envision 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!). 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 particles of the flavoring could have left the bag (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 adequately represent what is happening. 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 changes over time from when the air freshener was sprayed to the time it had spread over the room.. They must include all matter particles involved in their system (the closed room) that were involved in producing the observed pattern of diffusion.

Since students often overlook the role of air particles in diffusion, it is beneficial to demonstrate a simulation to them. A simulation of diffusion can be found at the Concord Consortium site: https://concord.org/stem-resources/diffusion

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 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 which is cold during the 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 demonstration is followed up with the assignment to prepare two storyboard sequences, 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, prepare in groups on whiteboards.

Observations of phases of matter

Animations of matter at the particle level in the three states are helpful to show at this point. The 1st three episodes of the video *Eureka: Heat & Temperature*[1] (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.

The entire set of Eureka videos is available at https://www.youtube.com/playlist?list=PL4EE139D689C7CD27

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)
(See image in notes at right)

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 a 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 the water. Point out that the change in the 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. In 2016, Derek Muller at Veritasium released a YouTube video showing that Celsius never devised nor used the scale that now bears his name. Check out https://www.youtube.com/watch?v=rjht4oAByCI.

Assign Worksheet 1

Introduce Pressure

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 hesitance on their part as they try to provide an explanation in terms of the motion of particles. Suggest to students that when you suck on a straw, you are expanding your nasopharyngeal cavity. Particles of air in the straw can spread out, so there are fewer of them striking the surface of the liquid in the straw than there are particles of air striking the liquid in the cup. The greater push exerted by these particles effectively *pushes* the liquid up into your mouth; there are no "suck-ons" that pull the liquid up the straw. Students can test this by sucking on a straw in a cup of water while another, shorter straw is in their mouth. The air that enters their mouth through this shorter straw doesn't allow a reduction in pressure, so they will find it very difficult to get any liquid into their mouth.

It would be very helpful if you could provide a simulation that helps students visualize the behavior of particles in a box. A simulation from the PhET website 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 kilopascal. Show that each has a unit of force (pound or newton) exerted on a unit area (in^2 or 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 2nd-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.[2] 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 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 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 the fact that the Earth's atmosphere could support this much weight. To them, the 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 the soda 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. The YouTube video at https://bit.ly/oil_drum shows the demonstration using an oil drum.

Assign Worksheet 2

Paradigm Lab: PVTn

Part I: P vs V

Apparatus:

These instructional notes were originally based on the use of Vernier software and equipment. Other equally useful probe/interface systems are also available from PASCO.

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

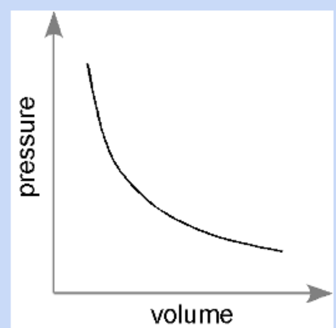
Pre-lab Discussion:

In preparation for this set of labs, show students different containers that can hold a gas (like a syringe or stoppered flask) and ask them to brainstorm ways to alter the pressure of the gas. 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 that the students suggest (volume, number of particles, and temperature should be brought out). Narrow the list to ones that can reasonably be carried out with the equipment and time available. Students should be guided to construct a guiding question or purpose statement for each independent-dependent variable pair.

The experiment question for this part of the lab would be worded in a manner similar to "What is the relationship between pressure and volume for a gas?" or "How does a change in volume affect the pressure of a gas in a sealed container?" Instruct the students to predict the shape of the graph they expect to obtain *before* they perform the experiment. Most are likely to suggest a straight line with a negative slope.

Apparatus

Graph



Lab Performance Notes:

Set up whatever device and software you use to collect and analyze the data.

The data from this experiment should show that the pressure is inversely proportional to the volume (P). 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 should express the *graphical* relationship they have found both *algebraically* ($P \propto 1/V$) and *verbally*.

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),and their mathematical and verbal descriptions of the relationship. The class results should be compared, and a consensus should be 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 still when the volume is small.

Students may be surprised that the graph is hyperbolic rather than linear. Suggest that a linear graph, with a negative slope, would yield a volume at which the pressure would drop to zero; larger volumes would then yield negative pressures! They can be guided to verbalize the inverse relationship between pressure and volume by predicting what will happen when the pressure is changed by simple ratios such as doubling volume (1/2*P), tripling volume (1/3*P), or cutting V in half (2*P).

Have students select two points from their data and use the first pressure in their data pairs and the ratio of the two volumes to predict their second pressure value: $P_1 * V/V = P_2$. They will need to decide how to place the two volumes in the ratio so it fits the pattern seen in their graph (if 2V, then 1/2P). They can also use their first volume value and the ratio of their two pressure values to see if they get close to their second volume: $V_1 * P/P = V_2$.

The use of ratios, in this case of like quantities that produce a pure number multiplier (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, such as stoichiometry, that utilize proportional reasoning.

Part 2: P vs n

Apparatus

These instructional notes were originally based on the use of Vernier software and equipment. Other equally useful probe/interface systems are also available from PASCO.

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

Pre-lab Discussion

The goal of this experiment is to investigate the effect of changing the number of particles (n) of gas in the system. 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 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.

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

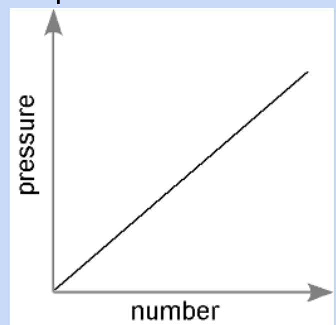
At this time, a way of reproducibly adjusting the number of particles while keeping the volume constant will have to be discussed. This is not a trivial concern because adding air to the syringe by pulling back on the plunger changes not only the number of gas particles but also the volume. To get around this problem, suggest that we could vary the number of particles in the syringe *while it is open to the air*; clearly, 6 mL contains twice as many particles as 3 mL.

Since we have no way of knowing how many particles are in, say, 3 mL, we can make up a unit name (call it a “puff”). Get students to agree that each 3 mL addition of air to the syringe contains another “puff” of air. By *connecting the syringe to the gas pressure sensor* and choosing a fixed volume at which they make all the pressure measurements, students can measure the pressure for each particle count at constant volume and temperature. But, before they perform the experiment, instruct the students to predict the shape of the P vs n graph.

Lab Performance Notes:

Apparatus

Graph



Set up the equipment as shown in the figure in Part 1, using the same procedure for attaching the probe and interface to the computer as described in Part 1 of the lab. The unit for amount of air can be “puffs” or something similar. The computer/Chromebook/tablet (or LabQuest 2) 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 when they read the pressure.

Students should express the relationship found in the graph *mathematically* as a proportional statement ($P \propto n$). An equation with slope and intercept has little utility. They should also express this relationship *verbally*. Stating how doubling n affects P is a useful way to express this relationship.

Post-lab Discussion:

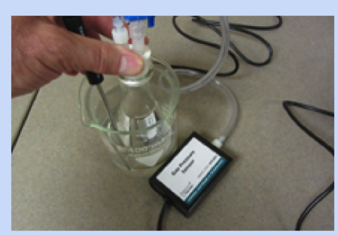
Following the lab, each lab team prepares a whiteboard to present their results to the class for discussion. The presentations should include a description of how they carried out the experiment (set up diagram), their graph (a data table is redundant), and their mathematical and verbal descriptions of the relationship.

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. Have the students inspect their data to verify this. They should find that $P_1 * n/n = P_2$. Again, we find a ratio using the number of “puffs” that lets us predict how the pressure of a gas will change. If the number of particles increases, n/n 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, it will be < 1, and the final pressure will be proportionately less than the initial pressure. It can also be helpful to verify that the pressure ratio can predict the data point for the resulting number of particles.

Part 3: P vs T

Apparatus

The data collection set-up is similar to the previous experiments except in this case a temperature probe is also required. 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.

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. As before, instruct the students to predict the shape of the graph they expect to obtain.

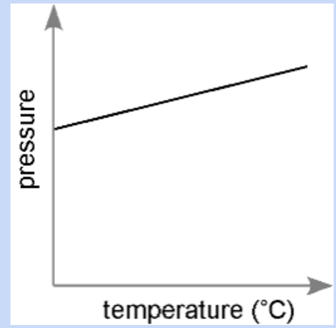
Lab Performance Notes

Set up the equipment as shown in the figure on the previous page. Use the same procedure for attaching the probes and interface to the computer/Chromebook/tablet as described earlier. Choose [Selected Events] as the mode of data collection and choose to display one graph with P on the vertical axis and T on the horizontal axis. Students may also open one of the versions of the P vs T experiment files found in the resources folder. This experiment file enables students to collect data so they can generate a P-T graph without additional set up.

Students can vary the temperature of the gas by changing the temperature of the water bath in which the flask is immersed. 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. Students should be careful to hold the neck of the flask and not the stopper while bobbing the flask.

In order to get a clear pattern of relationship, students should collect data for at least six 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 temperature readings that vary by 15 – 20°C; the final reading should be 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. An additional data point can be obtained 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.

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



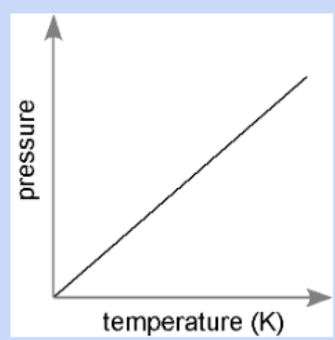
Post-lab Discussion

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 and verbal descriptions of the relationship.

Following the lab, ask how this graph is different from the previous two experiments (the graph is linear, but has a large, positive intercept). 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. Ask students what the value of the pressure intercept is telling us about the gaseous particles at 0°C. This point on the graph would, of course, be the pressure when the temperature was 0°C, and with a pressure around 80-90kPa, we can know the particles must still be in motion. Help the student recognize that we can't use the doubling reasoning for *pressure* and *temperature* like we did with *pressure* and *number of particles* by checking a couple of values in their data. What would the graph need to look like to use the simple proportional reasoning we saw previously? Students should recognize we would need to have the pressure intercept be 0 kPa when temperature is zero. Briefly discuss how the gas particles must behave to get the pressure to zero.

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 using Logger *Pro* or Graphical Analysis[1] by stretching the horizontal axis or by manually choosing the left end of the temperature axis so that the place where the best-fit line crosses the temperature axis, i.e. the temperature at which the pressure drops to 0. 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°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 at right.

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. Have the students inspect their data to verify this. They should find that

P_1 x T/T = P_2. Again we find a ratio using the temperature readings that lets us predict how the pressure of a gas will change. If the temperature increases, T/T needs to be >1 to cause the final pressure (P_2) to be higher than the pressure before the change. Conversely, if temperature for the system decreases, T/T needs to be <1, and the final pressure will be proportionately less than the initial pressure. Students can add 273 to the temperature readings in their data (if their temperature intercept was reasonably close to -250 to –300°C) and check to see if this approach allows reasonable predictions of their own pressure values. This experiment has more sources of error (typically leaks at higher temperatures) that significantly increases the uncertainty in the data, which should be taken into account.

Summarize the relationships observed in the three experiments. The pressure of a gas appears to be inversely proportional to the volume ($P \propto T$), 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.

KMT; how theories differ from laws

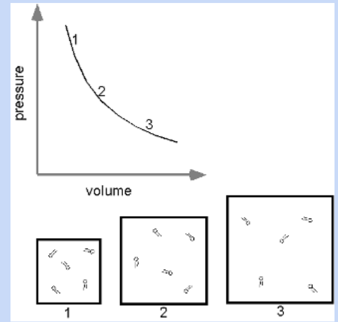
At this point elicit from the class what are the behaviors of the particles of a gas that would account for the regularities they have observed. This can be done by having students observe the behavior of the particles in the PhET simulation. Make sure that they recognize that our *theory* of gaseous matter must include the following features:

Particles of a gas:

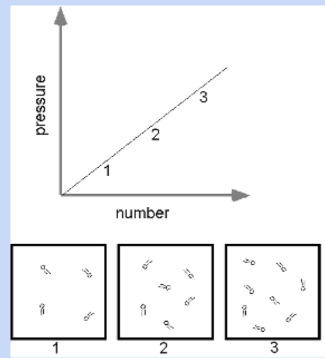
a. are in constant motion, moving in straight lines until they collide with another particle or a wall of the container in which they are enclosed.
b. experience elastic collisions; i.e., they do not eventually "run down".
c. do not stick to other particles.
d. The speed of the particles is related to their temperature.
e. 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

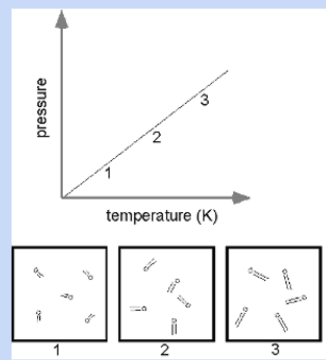
performed the experiment and account for the graphical relationship they observed. Conduct a board meeting in which groups can compare and contrast the differences in their representations.
For example, in the P vs. V experiment, their diagrams should look like the ones at right. Both the number of particles 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 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.

Solving PVTn problems, worksheet 3

This worksheet asks students to use the relationships 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.

In the 'Effect' row, students can predict how the unknown target variable will change because of changes in the other variables (e.g., if pressure is reduced the temperature will also decrease, P↓T↓ would be recorded in the effect cell in the pressure column). In the ratio row, students will indicate whether the ratio should be greater or less than 1. Students then construct their ratios for each variable to produce the predicted outcome (see equation below). The effect and ratio rows are especially useful when more than one state variable is changing.

Sample set up for Ws 3 #7:

	P	**T (K)**	**V**	**n**
Initial	1.20 atm	303 K	350 mL	const
Final	1.00 atm	T_f = ?	450 mL	const
Effect	P↓T↓	—	V↑T↑	—
Ratio	P/P< 1	—	V/V>1	—

$$T_f = 303\text{K} \times \frac{1.00\,atm}{1.20\,atm} \times \frac{450\,mL}{350\,mL}$$

Whiteboard ws 3, Unit 2 review