Lab: Deriving the Gas Laws
FOR THE TEACHER

Summary
In this lab, students will investigate the relationships of the variables related to gases. They will draw particle diagrams and derive equations to express these relationships. They will then combine these relationships to derive the combined gas law and the ideal gas law. Finally, they will use the molar volume of a gas at STP to derive the ideal gas constant, R.

Grade Level
High school

NGSS Alignment
This lab will help prepare your students to meet the performance expectations in the following standards:

- Scientific and Engineering Practices:
  - Using Mathematics and Computational Thinking
  - Developing and Using Models
  - Analyzing and Interpreting Data

Objectives
By the end of this lab, students should be able to

- Understand how to represent direct and inverse relationships using multi-variable equations.
- Understand and model the relationships between
  - Temperature and volume of a gas at constant pressure.
  - Moles and volume of a gas at constant volume.
  - Pressure and volume of a gas at constant temperature.

Chemistry Topics
This lab supports students’ understanding of

- Gases
- Gas Laws
- Properties of Gases (temperature, volume, pressure and moles of particles)

Time
- Teacher Preparation: 20 minutes
- Lesson: one or two class periods, depending on student familiarity with using equations to model direct and inverse relationships, and with drawing particle models

Materials
Station 1:
- Balloons (standard 12 inch latex balloon)
- Trash Can

Station 2:
- Sealed Luer-lok syringe (with plunger and screw-on cap)
- Room thermometer
- 2 Thermometers
- Two 400-mL or 600 mL beakers for ice and warm water baths
- Hot plate
- Ice

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Station 3:
- Mini marshmallows
- Sharpie or other marker
- Unsealed Luer-lok Syringe with plunger and cap
- Trash can

Safety
- Always wear safety goggles when handling glassware and chemicals in the lab.
- Students should wash their hands thoroughly before leaving the lab.
- Food in the lab should be considered a chemical not for consumption.
- Exercise caution when using a heat source. Hot plates should be turned off and unplugged as soon as they are no longer needed.

Teacher Notes
- Many teachers find that gas behavior and the gas laws are some of the easier topics to teach. Students enjoy the many demos and labs available, and the equations they use to “plug and chug” are relatively straight-forward. However, students can memorize the relationships between the variables affecting gases (pressure, volume, temperature, and moles) without knowing what causes them on a particulate level. Likewise, students can successfully solve gas law problems without a conceptual understanding of what the equations represent. This activity was designed to help students connect macroscopic observations of gases with the equations which model the behaviors and with what is happening at the particulate level. First, students learn how to model direct and inverse relationships using multi-variable equations. They then make observations at three lab stations. At each station they come up with an equation modeling the behavior they observe, and draw diagrams depicting what the gas particles are doing. After the lab, students use the equations they generated to derive the Combined Gas Law and the Ideal Gas Law. Finally, using the value of molar volume at STP, then derive the ideal gas constant, R.
- My students have found this activity very helpful in understanding how the equations are connected with the particle behavior. Some of them have even derived the ideal gas constant on tests in extra credit questions!
- This lab is similar to the Three Station Gas Lab, but adds connecting the macroscopic observations with the gas law equations. It can be used for day one of a seven day gas law unit. See the full article in Chemistry Solutions for the other parts of the unit.
- Before the lab, guide students through the Prelab. Show them that direct relationships do not always have multiplication in them, nor are inverse relationships always shown with a division.
- At each station, student observe gas properties, write equations, and draw particle diagrams. If students have not drawn particle diagrams before, spend some time showing them how to model particles, their collisions, and how to represent temperature (with longer/shorter arrows for velocity).
- Example particle diagrams for Station 2:
  - Notice that there are the number of particles (arrows) in both syringes, but the hotter ones have longer arrows to show that they are moving faster.
• Station 1: Students simply blow up a balloon.
  o It seems simplistic, but it is helpful to start with a straight-forward direct relationship of # of moles to volume. More particles, more collisions.
  o Point out that this is a constant-pressure situation.
  o Watch that they throw the used balloons away so that the used balloons are not re-used.

• Station 2: Students cool, then heat a syringe.
  o Set up an ice water bath in one beaker.
  o Set up a second beaker of water on a hot plate. Turn on the hot plate before class to give it time to warm up (but don’t let it boil).
  o Double-check that the plungers of the syringes can slide easily (you may need to give them a little surreptitious help after cooling or heating).
  o Guide students to understand that pressure and moles are both constant at this station.

• Station 3: Students modify the volume of a sealed syringe.
  o Note that the volume of the marshmallow changes as the volume of the syringe changes.
  o When the volume of the syringe is decreased, the air molecules in the syringe collide with the marshmallow more often, while the air molecules inside the molecules are still hitting at the same rate, increasing the pressure on the outside of marshmallow and making it look “smushed”.
  o When the volume of the syringe is increased, the air molecules in the syringe collide with the marshmallow less often (less pressure), but the air particles inside the marshmallow are still colliding as often as before, so the marshmallow expands.
  o The instructor must point out that there are air molecules trapped inside the marshmallow, and that the # of particles in the syringe is constant (as well as temperature).
  o This is the station where it is most tempting for students to just say “pressure went up (or down)” without give a particle-level explanation.

• Parts II and III may be completed on a second day. Students may need some guidance on how to combine multiple equations into one. They may also require reminders about the values of molar volume and STP. It is recommended that students do all parts with their lab partners and not as homework.
FOR THE STUDENT
Lesson

Deriving the Gas Laws

You are a scientist!
Discover the laws that gases follow with a few simple experiments.

Materials
- Luer-lok Syringes and caps
- Mini-marshmallows
- Sharpies
- Balloons
- Beakers
- Hot plates
- Ice
- Thermometers

Safety
- Always wear safety goggles when handling chemicals in the lab.
- Wash your hands thoroughly before leaving the lab.
- Follow the teacher’s instructions for cleanup of materials and disposal of chemicals.

Prelab Questions
Discuss with your partners.
1. What does it mean when we say that two variables vary directly?

2. What does it mean when we say that two variables vary inversely?

3. Using the variables x and y and the constant k, show how to represent using a formula:
   a. A direct relationship: k =
   b. An inverse relationship: k =

Part I
Find the relationships between the variables that affect gases:
- Volume (V)
- Pressure (P)
- Temperature (T)
- # of particles (n)

For each station:
- Discover whether the two variables vary directly or inversely.
- The stations can be done in any order.
- Check your equations with your teacher before moving on.
• Drawings:
  o **show relative numbers** of particles
  o **show them moving with arrows**; larger arrows = moving faster
  o **for pressure**, show them **colliding with sides of container** (**bent arrows**)

**Station 1**
How are **volume** (**V**) and **# of particles** (**n, moles**) related?

1. Blow up a balloon (only one balloon per lab group). Do not tie it off.
2. Determine a general equation relating **# of particles** (**n**) and **volume** (**V**), using a constant ("k"):

3. Derive an equation using **n₁, n₂, V₁** and **V₂**. This is **Avogadro’s Law**:

4. **Draw** the balloon **before** and **after** you blew it up. Show the gas **particles** inside each. Show the motion of the particles with arrows. Throw the balloon away.

<table>
<thead>
<tr>
<th>Before</th>
<th>After</th>
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**Station 2**
How are **volume** and **temperature** related?

1. Choose a small syringe that is at room temperature (or close). Gently move the plunger in and out slightly to make sure it is not stuck. Seal the syringe with some air in it (about 5-7 mL). Record the starting volume of air and the ambient room temperature below.
2. Put the sealed syringe in the ice water bath. Leave the syringe in for 2-3 minutes.
   o Record the temperature of the ice bath.
   o Record the new volume of air in the syringe in mL. If it has not changed, push slightly on the plunger to see if it will move.
3. Put the syringe into a warm water bath. Leave the syringe in for 2-3 minutes.
   o Record the temperature of the warm water bath.
   o Record the volume of air in the syringe in mL. If it has not changed, pull slightly on the plunger to see if it will move.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Volume, mL</th>
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</thead>
<tbody>
<tr>
<td>Room temp.</td>
<td></td>
</tr>
<tr>
<td>Ice bath</td>
<td></td>
</tr>
<tr>
<td>Warm water bath</td>
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4. Remove the syringe from the warm water bath and dry it off.
   a. Come up with a general **equation** relating **temperature** (**T**) and **volume** (**V**), using a constant ("k"): 
b. Derive an equation using \( V_1, V_2, T_1, \) and \( T_2 \). This is **Charles’ Law**:

c. Draw the syringe and how the air particles look in the syringe. **Show the entire area containing the gas particles.** Use arrows to represent movement – larger arrows = moving faster.

<table>
<thead>
<tr>
<th>Ice bath</th>
<th>Warm Water Bath</th>
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*Clean-up:* If you are the last group to use the warm water bath, turn the hot plate off.

**Station 3**

How are **pressure** and **volume** related?

1. Use a Sharpie to draw a smiley face on a mini-marshmallow and place it in the syringe.
2. Place the plunger in to the 50mL mark.
3. Screw the cap onto the syringe.
4. Observe what happens to the marshmallow when you depress the plunger, and when you pull it out.
5. Record each volume below the boxes. (Do not press so hard that the syringe leaks.)
   a. Come up with a general **equation** relating pressure \( P \) and volume \( V \), using a constant (“k”):

   b. Derive an equation using \( P_1, P_2, V_1, \) and \( V_2 \). This is **Boyles’ Law**:

   c. Draw pictures of the marshmallow and syringe with the plunger at the 50mL mark, with the plunger depressed, and with it pulled out past 50 mL. **Show the air particles as well! Remember there are air particle inside the marshmallow!**

| Volume: 50 mL | Volume: _____mL | Volume: _____mL |
*Clean-up:* Remove the cap and remove the marshmallow. **Throw away** the marshmallow. (Do not eat it!)

**Part II**
- Determine an equation relating **pressure**, **volume** and **temperature**, using $P_1$, $P_2$, $V_1$, $V_2$, $T_1$, and $T_2$.
- This is the **Combined Gas Law**:

**Part III**
One equation, combining all of these variables.
- Determine a **single equation** that relates all **four variables and a constant**. All of the relationships you discovered in Part I must still be valid. Arrange so that there no variables in a denominator (nothing looks like a fraction. (for example, instead of $k = x/y$, use $ky = x$) Put the constant on the same side of the equation as temperature. This is the **ideal gas law**:

**Part IV**
Finding the ideal gas constant, $R$
- The **constant** in the equation you found in Part III is called the “ideal gas constant”. We use the variable “$R$” for this constant.
- Find the value and units of the ideal gas constant, $R$.
- Some hints:
  - What do you know about molar volume? At what **conditions** is this value valid?
  - You may use either atm or kPa as the pressure unit.
  - Do you think the temperature unit should be in °C or K?
  - Use three significant figures.

- The **ideal gas constant**, $R =$