# Ideal Gas Law

*Lab Activity by John Estes, SUNY Old Westbury*

The simplest model of a gas consists of many randomly moving point particles which do not interact with each other. Many real gases are well described as an ideal gas, such as nitrogen, oxygen, hydrogen, and the noble gases. Even mixtures of gases, such as air can be described as a mixture of ideal gases.

Gases are described in terms of their pressure and temperature and the volume the gas occupies.

- Pressure: Force per area. The air we breathe is a gas. One atmosphere ($1\ \mathrm{atm}$) of pressure is roughly the average air pressure at sea level. The SI unit of pressure is a Pascal which is one Newton per square meter.

$$1\ \mathrm{atm} = 101{,}325\ \mathrm{Pa}$$

- Temperature: The SI unit of temperature is kelvin. $0℃ = 273\mathrm{K} = 32℉$ . Room temperature is around $20℃$, which is $68℉$.
- Volume: The space the gas molecules are restricted to. The SI unit of volume is meters cubed.

The development of the ideal gas law occurred over a couple of centuries, starting in the mid-1600s and reaching its first full statement in 1834.

This experiment will make use of the "Gasses Intro" simulation provided by PhET, which is available at

https://phet.colorado.edu/en/simulation/gases-intro

Feel free to download the simulation for offline use. Load the simulation and select the "Laws" version.

**Part 1: Boyle's Law**

Boyle's law is named after chemist and physicist Robert Boyle, who published the original law in 1662. Boyle's law relates the pressure of an ideal gas to the volume it occupies. For a fixed temperature, the pressure varies inversely with the volume.

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

Start the simulation and select "Laws". Pump some particles into the box and heat up or cool the gas to a temperature of your choice. Set the temperature scale to Celsius and click the "Width" box to display the width of the box in nanometers. Record your starting temperature, pressure, and width in the table below. Assume the area of the box is $100\ \mathrm{nm}^2$ and compute the volume using $V = area \cdot width$.

| Temperature (℃) | Pressure (atm) | Width (nm) | Volume ($\mathrm{nm}^3$) |
|---|---|---|---|
| | | | |

Under the "Hold Constant" list, select temperature to hold the temperature constant. Move the handle of the box to resize the box and observe what happens to the pressure.

**Question 1:** Does the pressure increase or decrease as the box is made smaller?

To test Boyle's law, we will measure the pressure of the gas for various sizes of the box. Take five different width-pressure measurements to fill out the table below. Compute the volume of the box for each case.

| Pressure (atm) | Width (nm) | Volume ($\mathrm{nm}^3$) |
|---|---|---|
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| | | |
| | | |

Boyle's law states that pressure varies inversely with the volume.

**Graph 1:** To test Boyle's law, fill out the table below and make a graph with $1/V$ on the x-axis and pressure on the y-axis.

| 1/V ($\mathrm{nm}^{-3}$) | Pressure (atm) |
|---|---|
| | |
| | |
| | |
| | |
| | |

**Question 2:** Does your graph demonstrate Boyle's law? Explain how.

**Part 2: Gay-Lussac's Law (Amontons' law)**

Gay-Lussac's Law states that at a constant volume, the pressure of an ideal gas will vary linearly with its temperature.

$$P \propto T$$

Joseph Gay-Lussac discovered this relationship while building an "air thermometer" between 1800 and 1802.

Do not change the number of particles in your box from part 1. Resize your box to a volume of your choice. Set the "Hold Constant" selection to volume. Next heat or cool your gas to some temperature. Record your starting temperature, pressure, and width. As before, assume the area of the box is $100\ \mathrm{nm}^2$ and compute the volume using $V = area \cdot width$.

| Temperature (℃) | Pressure (atm) | Width (nm) | Volume ($\mathrm{nm}^3$) |
|---|---|---|---|
| | | | |

Turn on the heater and observe what happens to the pressure. Next, set the heater to "cool" and see what happens to the pressure.

**Question 3:** Does the pressure increase or decrease as the temperature is increased?

| Temperature (°C) | Pressure (atm) |
|---|---|
| | |
| | |
| | |
| | |
| | |

**Graph 2:** To test Gay-Lussac's Law, make a graph with pressure on the y-axis and temperature on the x-axis.

**Question 4:** Does your graph demonstrate Gay-Lussac's Law? Explain how.

Absolute zero: Absolute zero temperature is the smallest possible temperature a substance may reach. It was conjectured to exist as a universal value for all matter by William Kelvin, with a value of $T_{\text{zero}} = -273°\text{C}$. One motivation for its existence was found by studying the pressure versus temperature graphs for a variety of gasses. The smallest possible pressure of any substance is zero. Thus, the smallest possible temperature of a gas is given by the value of the x-intercept. It turned out that the x-intercept of every gas ended up taking the same value, even for different gasses.

**Question 5:** Extract the value of absolute zero from your graph. Does it agree with the known value?

**Part 3: Ideal Gas Law**

From our two experiments, we can deduce a general form for the equation describing the thermodynamic state of a gas.

$$P = k\,\frac{(T - T_0)}{V}$$

The quantity $T_0$ is the value of absolute zero. The quantity $k$ is a constant, which can be obtained from the slope of our graphs. In general, the constant $k$ depends on the gas being studied and will take different values for different gasses.

**Question 6:** Obtain a value of $k$ from each of your graphs. Do the two values agree?

It was later discovered that the constant depends only on the amount of gas. This final observation lead to the ideal gas law.

$$P\,V = n\,R\,T$$

The quantity $n$ is the amount of gas in moles and $R$ is the ideal gas constant, with a value $R = 8.3145\,\frac{\text{J}}{\text{K mol}}$. Note that in this equation, the temperature is measured in Kelvins, defined from the Celsius scale by setting the absolute zero of temperature to zero Kelvins, $T_K = T_C + 273.15$.

**Question 7:** How many moles of gas was used in your simulation?