Lab 17:
Gases

College Physics For AP® Courses

Advanced Placement® and AP® are trademarks registered and/or owned by the College Board, which was not involved in the production of, and does not endorse, this product.

In this lab you will learn

- how to determine the amount of work done on a system from the force and displacement values
- how to use the principle of conservation of energy qualitatively to predict changes in energy of the system due to heat transferred to the system or work done on the system
- how to create a plot of pressure versus volume using measured or given data

In this lab, you will experimentally obtain the relationship between the volume (*V*) of a sample of gas and its pressure (*P*). We need to know how volume changes with changing pressure in many real-life situations. Pumping air into a bicycle or car tire includes compression and expansion of the gas in accordance with increased and decreased pressure (for example, in the cylinder of the pump). A car engine compresses an air-gas mixture in its cylinders before igniting the mixture. A balloon can change its volume as the external pressure changes.

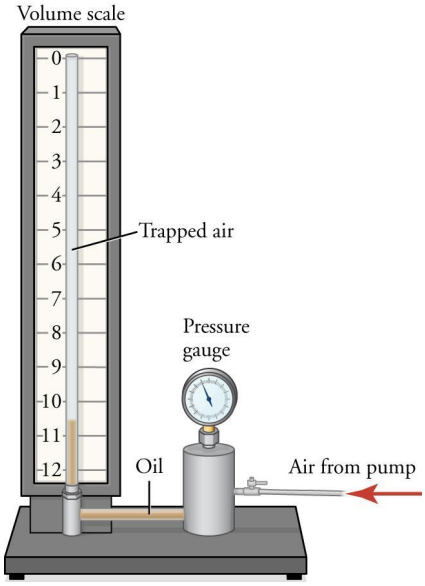


Figure 17.1: Boyle's law apparatus for measuring the pressure and volume of a gas.

It is convenient to measure the relationship between gas pressure and volume using a Boyle's law apparatus, such as the one shown schematically in Figure 17.1. Air is pumped to create pressure in the oil, which conveys this pressure to the trapped volume of gas. The gas volume can be measured with the volume scale. The pressure is measured with the pressure gauge. Therefore, by pumping the air at various pressures, we can measure different volumes of the trapped gas. We can then produce a pressure-volume table or graph from these data. Other versions of the apparatus can be used. In each of them, we can measure the value of equilibrium pressure of a trapped volume of gas.

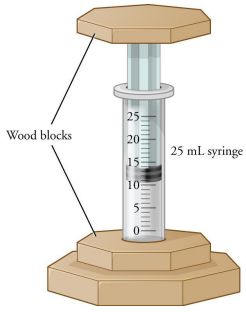


Figure 17.2: Another version of the Boyle's law apparatus. Pressure is applied by adding weight to the top wood block.

For example, Figure 17.2 shows a simple system in which objects of known mass (books, small bricks, etc.) can be placed on top of the upper wood block. The volume of the gas in the syringe is recorded, and then you can measure the total weight on top of the syringe. The pressure is the gravitational force *mg* divided by the area of the syringe piston $(A = \pi r^2)$, where *r* is the radius of the piston. Here *g* is the acceleration due to gravity, $g = 9.81\ \text{m/s}^2$.

You should always remember that if you use a system in which the pressure is varied by adding weights on top of a piston, the gravitational part of the pressure should be added to the atmospheric pressure that is already present. The atmospheric pressure value is approximately $1.01 \times 10^5\ \text{Pa}$, and the additional gravitational pressure should not be much less than this value. If the gravitational pressure is too small, you will not observe any appreciable change in the volume, and accurate measurements of the pressure-volume dependence will not be possible.

Finally, if it is completely impossible to obtain a Boyle's law apparatus, you can carry out this lab by using an online simulator at http://phet.colorado.edu/en/simulation/gas-properties .

Activity 1: Pre-Assessment

1. What do you predict is the relationship between the volume of a sample of gas and its pressure?
2. How could you experimentally determine the relationship between the temperature and pressure of a gas using the Boyle's law apparatus?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Determining the Relationship Between the Volume and the Pressure of a Gas Sample

You will use a Boyle's law apparatus to determine the relationship between the volume of a gas sample and its pressure. Assume that the atmospheric pressure is equal to $1.01 \times 10^5\ \text{Pa},$ unless your teacher provides a more accurate number for your location.

Safety Precautions

- Be careful when stacking objects on top of the upper wooden block of the Boyle's law apparatus, because they can fall.
- Excessive pressure buildup can lead to explosive breaking of the apparatus. You shouldn't have to use excessive force to compress the air.

For this activity you will need the following:

- Boyle's law apparatus
- Mass scales
- Solid objects
- Rulers
- Graph paper or graphing calculator
- Objects that are heavy enough to compress gas in the cylinder of the Boyle's law apparatus (books, small bricks, etc.)

For this activity you will work *in pairs.*

Structured Inquiry

Step 1: Hypothesize/Predict: How do you think the volume of a sample of gas changes as the pressure changes? Does the volume increase or decrease with increasing pressure? What is the mathematical relationship between the pressure and volume of a gas? Write a hypothetical equation in your notebook.

Step 2: Student-led Planning: You will now measure the physical quantities necessary to determine how the volume of the gas and its pressure are related. Determine what values (length, mass, area, etc.) have to be measured to find the relationship between a gas's volume and its pressure. Also discuss with your partner how best to set up the Boyle's law apparatus, what values have to be recorded, and how many series of measurements are needed.

The general procedure for using the apparatus is as follows.

1. Insert the piston into the cylinder.
2. Make sure the top and bottom wooden blocks are firmly attached.
3. Read the volume of gas inside the cylinder on the apparatus scale.
4. Calculate the pressure as the sum of the atmospheric pressure (use the value provided by the teacher or 1.01×10^5 Pa) and the total weight of the upper part of the apparatus (the mass of the upper part plus any additional weights times the free-fall acceleration *g*) divided by the area of the cylinder cross-section.

Step 3: Critical Analysis: Create a data table and record the necessary physical values and the resulting pressure and volume values. Are the predictions you made in Step 2 supported by your data? Why or why not? What methods could you have used that would improve your results? Discuss with your partner, and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How does the volume of a gas sample depend on the pressure of the gas? What is the dependence of the pressure on the mass of the additional objects placed on the upper part of the Boyle's apparatus? What shape of gas container would facilitate measuring the volume accurately and efficiently? Write your ideas in your notebook.

Step 2: Student-led Planning: Pick several objects that can be used to create pressure in the Boyle's law apparatus. Submit your chosen objects to your teacher. After your teacher approves, measure the volume of the gas in the apparatus as you place various combinations of the objects on top of the upper wooden block. Measure the mass of each combination of the objects that you use this way. Write your results in your science notebook. Create a table of weights and the corresponding positions of the piston.

Step 3: Critical Analysis: What is the dependence of the gas volume on the mass of the objects used to create pressure? Calculate the pressure and the gas volume for each of the measurements, and find the mathematical relationship between them. Draw a graph of the pressure versus volume to assist yourself in this task. Discuss your answers with your partner, and write them in your notebook.

Assessments

1. A student uses the Boyle's law apparatus with books. The masses of the books are 520 g, 785 g, and 423 g. Does this scenario describe precise measurements? Why or why not?
    a. Was this set of weights well chosen for the task of determining the volume-pressure relationship for the gas sample? Why or why not? Assume that the additional pressure due to the gravitational force is comparable with the atmospheric pressure.
2. A student uses the Boyle's law apparatus and takes several measurements of the resulting volume for each set of weights.
    a. Does this procedure increase the accuracy of the measurements?
    b. What other ways can you suggest for increasing the accuracy of determining the relationship between the volume and pressure?
3. A student is using the Boyle's law apparatus. The radius of the syringe is $r = 1.0 \text{ cm}.$ The mass of the weights is *m*= 1.25 kg. The height of the gas sample in the cylinder of the syringe is $h = 10.5 \text{ cm}.$
    a. What is the volume of the gas (in SI units)?
    b. What is the pressure of the gas (in SI units)?

Activity 2: Finding the Work Done on a Gas Sample

Activity 2: Pre-Assessment

1. A student is using a constant pressure to pump air into a bicycle tire. How would you calculate the amount of work done on the air if you know the force the student is applying to the pump and the dimensions of the pump chamber?
2. How can you measure the volume-pressure relationship required in the question above using the Boyle's law apparatus?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Finding the Work Done on a Gas Sample

In the previous part of the lab, we determined the dependence of gas volume on pressure, or Boyle's law. **Boyle's law** is an experimentally determined relation between the volume and the equilibrium pressure of a gas at constant temperature. It states that if a certain constant amount of gas is kept at a constant temperature, then the product of the gas volume by its pressure is a constant: $PV = \text{const.}$ Or, if we compare pressure and volume values at two different moments, 1 and 2, then $P_1V_1 = P_2V_2$. The units of *P* and *V* are not important as long as they are kept the same. If the temperature is not constant, then the behavior of gas can be approximately described by the **ideal gas law**

$$PV = nRT$$

.

Here *n* is the number of moles of the gas sample (the mass of the gas sample divided by the molar mass of the gas), *R* is the universal gas constant, and *T* is the temperature in degrees Kelvin. In SI units, the pressure is measured in pascal, the volume is determined in cubic meters, and the value of the gas constant is $R = 8.314\ \text{J/(mol}\cdot\text{K)}.$

You will use a Boyle's law apparatus to determine the work done on a sample of gas by changing external force (and thus changing pressure). Assume that the atmospheric pressure is equal to $1.01 \times 10^5\ \text{Pa},$ unless your teacher provides a more accurate number for your location.

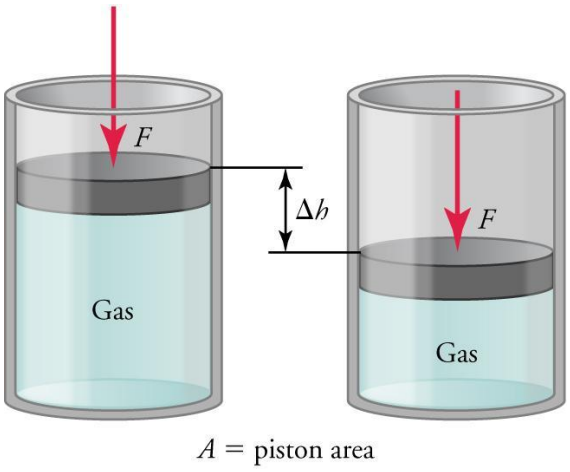


Figure 17.3: The work done on a sample of gas as a result of compression is based on the force (*F*) and displacement (*h*).

Let us consider the process shown in Figure 17.3. A sample of gas is compressed by an external force, *F*, and the piston moves a distance, □*h*. We can calculate the work done as the product of force and displacement, so the amount of work done in this compression is

$$\Delta W = F\Delta h.$$

In the case of a gas sample, this equation can be rewritten as

$$\Delta W = P\Delta V.$$

If the pressure is created by the gravitational force, it can be found as this force divided by the area of the piston, or

$$P = \frac{mg}{A}.$$

The atmospheric pressure has to be added to this value to find the total pressure on the gas.

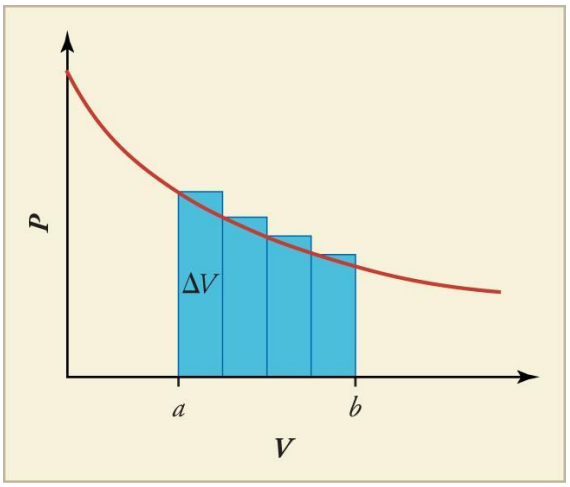


Figure 17.4: The work done on the gas while it is compressed from point *b* to point *a* can be calculated as the area under the *PV* curve between the vertical lines passing through points *a* and *b*.

Suppose that we need to obtain the amount of work done on the gas, and we know the pressure of the gas as a function of volume. Then the work done in each of these small parts of the path is equal to the product of the pressure at that part and the change of volume □*V*. Overall, the work done is equal to the area under the *PV* curve between the vertical lines passing through points *a* and *b* (Figure 17.4).

However, the pressure that is included in the equation for the work done on the gas is the external pressure. It can be approximated by the pressure of the gas itself only if the external pressure and the pressure of the gas are equal. This happens when the compression of the gas occurs very slowly. In this case, the width of the elements □*V* in Figure 17.4 becomes very small, and the amount of work done on the gas becomes very close to the area under the *PV* graph. Such a process is said to be reversible.

We must remember that the total pressure on the gas is the sum of the pressure of any weights on top of the Boyle's law apparatus and the atmospheric pressure.

Safety Precautions

- Be careful when stacking objects on top of the upper wooden block of the Boyle's law apparatus, because they can fall.
- Also, excessive pressure buildup can lead to explosive breaking of the apparatus. You shouldn't have to provide excessive force to compress the air.

For this activity you will need the following:

- Boyle's law apparatus
- Mass scales
- Solid objects
- Rulers
- Graph paper or graphing calculator
- Objects that are heavy enough to compress gas in the cylinder of the Boyle's law apparatus (books, small bricks, etc.)

For this activity you will work *in pairs*.

Structured Inquiry

Step 1: Determine what physical quantities (length, mass, area, etc.) you need to measure to find the amount of work done on a sample of gas by compression.

Step: Hypothesize/Predict: Relate the physical quantities determined in Step 1 to the work done on the gas. What other influences affect the amount of work done on the gas in the process of compression?

Step 3: Student-led Planning: You will now measure the physical quantities necessary to determine the compression work done on the gas. Discuss with your partner how best to set up the Boyle's law apparatus, what values have to be recorded, how many series of measurements are needed, and how to minimize experimental error. Discuss ways to find the area under the *PV* graph.

Step 4: Critical Analysis: Create a data table, and record the necessary physical values and the resulting pressure and volume. Are the predictions you made in Step 2 supported by your data? Why or why not? What methods could you have used that would improve your results? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Since the amount of work can be calculated from the *PV* graph, do you need to measure any more parameters than you did in the previous activity in this lab? What amount of work will be done when weights of various masses are used? What condition has to be observed in choosing the weights in order to obtain accurate readings for the work calculations? Write your ideas in your notebook.

Step 2: Student-led Planning: Pick several objects that can be used to create pressure in the Boyle's law apparatus. Make sure that the masses satisfy the conditions for the compression to be slow enough to permit accurate calculation of work. Submit your chosen objects to your teacher. After your teacher approves, measure the volume of the gas in the apparatus as you place various combinations of the objects on top of the upper wooden block. Measure the mass of each combination of objects that you use this way. Write your results in your science notebook. Create a table of weights and the corresponding positions of the piston. Carry out this part for both compression (increasing the amount of weight on top of the apparatus) and expansion (removing objects from the top block).

Step 3: Critical Analysis: How can the amount of work be calculated from the collected data? Calculate the pressure and the gas volume for each of the measurements. Draw the *PV* graph (the graph of pressure as a function of volume). Produce a separate graph for each measurement series. Find the area under the curve, the total amount of work on the gas during the process of compression, and the work done by the gas in the process of the following expansion. Are these amounts approximately equal? If not, which one is greater and why? Do the amounts of work you have calculated agree with your hypothesis in Step 1? Discuss your answers with your partner and write them in your notebook.

Assessments

1. A student uses the Boyle's law apparatus with small bricks. The masses of the bricks are 1,520 g, 3,785 g, and 5,423 g. The diameter of the piston is 2.0 cm.
   a. What is the additional pressure provided by the bricks and the total pressure for the smallest weight in the set?
   b. Was this set of bricks well chosen for the task of determining the amount of work done on the gas in the process of compression of the bricks are simply placed on top of the apparatus one by one? Why or why not?
   c. Is the range of the masses sufficient to obtain an accurate value of the compression work? Why or why not?
2. Give two factors that do not allow us to state that all the work done on the gas is transferred into the increase of the internal energy of the gas.
3. A student is using the Boyle's law apparatus to find the amount of the compression work done on the gas. The average pressure of the gas is 1.0×10^5 Pa as the volume decreases from 2.1×10^{-5} m^3 to 2.8×10^{-5} m^3. Find the work done on the gas by the external pressure (in SI units).
   a. Estimate the change in pressure in this process (in SI units)