Physics 216 Lab 10, Spring 2018
Ideal Gases and the First Law of Thermodynamics

OBJECTIVES

- To understand how a gas may be characterized by temperature, pressure, and volume.
- To understand and be able to use the ideal gas law.
- To investigate the relationship between heat, work, and thermal energy.

OVERVIEW

In introductory physics, we often talk about matter as if it were continuous. We don't need to think about individual aluminum atoms to understand how a ball rolls down a track. In recent years, scientists have been able to "see" individual molecules using scanning tunneling and atomic force microscopes. But long before atoms and molecules could be "seen," nineteenth-century scientists, such as James Clerk Maxwell and Ludwig Boltzmann in Europe and Josiah Willard Gibbs in the US, imagined these *microscopic* entities as the basis for models that account for the *macroscopic* properties of thermodynamic systems.

Even a small container filled with a gas contains a very large number of molecules, on the order of 10^{23}! Since it is impossible to use Newton's laws of motion to keep track of what each of these molecules is doing at any moment, we characterize the behavior of a gas by the macroscopic quantities: volume, *V*; pressure, *P*; and temperature, *T*. *Kinetic theory* is the area of physics that uses Newton's laws and <u>averages</u> of molecular behavior to explain the relationship between *P*, *V*, and *T*.

In thermodynamics we are also interested in heat and work, and in how the two are related. For example, if we transfer heat energy to a gas, can we get it to do work? One important system in our study of thermodynamics is a gas confined in a cylinder with a movable piston, such as in an automobile's internal combustion engine. The development of thermodynamics in the eighteenth and nineteenth centuries was closely tied to the development of the steam engine, which employed hot steam confined in just such a cylinder.

In this lab, we will first look at relationships between pressure, temperature, and volume described by the ideal gas law PV=nRT. Then we will examine the relationships between heat, work and thermal energy described by the First Law of Thermodynamics $\Delta E_{th} = Q + W$.

INVESTIGATION 1: PRESSURE MEASUREMENTS AND THE IDEAL GAS LAW

Activity 1-1: Measuring pressure

As an introduction to the use of the computer-based pressure sensor, we will measure the pressure in an ordinary balloon. Before beginning, familiarize yourself with the operation of the pressure sensor and flow-control valve by reading the following and examining the pressure sensor.

The heart of the pressure sensor is a membrane with vacuum on one side and the pressure to be measured on the other. The sensor produces a voltage that depends on the amount the membrane flexes under this difference in pressure. Over a pressure range of 0 to 100 psi (corresponding to 0 to 3.09 V), the voltage is proportional to the pressure.

There is a plastic tube on the pressure sensor running from a port inside the box to a three-way valve on the outside of the box. This three-way valve allows you to connect two different things to the pressure sensor and switch between them using the blue control handle. When the handle is aligned with one of the ports, that port is closed off. Note: don't force the plastic connectors – they can crack easily.

Prediction: What do you predict the pressure in a blown-up balloon to be, relative to atmospheric pressure?

To test your prediction, plug the pressure sensor into the interface and open the experiment file called **Measuring Pressure (L05A1-2)** to display the pressure in kPa digitally on the screen.

Record the pressure with the sensor open to the air:

Blow up the balloon and attach it to the pressure sensor. Record the pressure in the balloon:

Question 1-1: Was the pressure in the filled balloon significantly different from atmospheric pressure? If so, why is the pressure different? How good was your prediction?

Activity 1-2: Relationship between pressure and volume for a gas
Now that you are familiar with the pressure sensor, you will use it to measure the pressure of the air in a plastic syringe as the volume is changed.

Connect the syringe to one port of the three-way valve. Move the flow-control valve to connect the syringe to the port that's open to the atmosphere, and admit 5 cc of air at room pressure into the syringe. Then move the valve to close off the open port and connect the syringe to the pressure sensor. Record the volume and pressure readings in the table below, along with an estimate of the accuracy of each reading.

Vary the volume of the syringe in 1-cc increments from 1 to 10 cc. Record the pressure reading at each volume. Do this slowly enough that the air comes to thermal equilibrium with the room each time (and thus presumably remains at a constant temperature). Since you won't be watching temp, what can you watch to make sure you are in equilibrium? Hint: All state variables should be constant in equilibrium. Note that at low volumes (<3 cc) your reading may not stabilize due to small amounts of air leakage from the syringe; in this case you should refill your syringe at the 5-cc level after each reading.

Volume (cc)	Pressure (Pa)

Open a second copy of Logger Pro to Plot Volume vs. Pressure. Note that the pressure and volume are not related linearly. In light of the ideal gas law, do you expect a linear (straight-line) relationship between V and P for a constant-temperature process? What would you have to plot on the horizontal axis to see a straight line? Make it so.

Question 1-2: Record the values of the slope and intercept (and uncertainties) of this plot. What physical quantities do they represent? Hint: When the syringe indicates zero volume, is there really zero volume of gas in the system?

Repeat the experiment with a starting volume of 10 cc, measuring at 1-cc volume increments from 5 to 15 cc.

Volume (cc)	Pressure (Pa)

Question 1-3: What are the values of the slope and intercept (and uncertainties) in this case? Which parameter is statistically different than in the previous experiment, and why?

√ Checkpoint 1

Activity 1-3: Finding an unknown volume
In this experiment, you will use the ideal gas law to determine the volume of a container of unknown size: the extra length of plastic tubing found in the box with your pressure sensor.

Attach the extra tubing between the syringe and the flow-control valve and set the flow-control valve to connect the syringe+extra tube to the open port. Expel all the air from the syringe and fill the extra tube with room-pressure air. Set the flow-control valve to connect the syringe plus extra tube to the pressure sensor. Pull back on the plunger and record the measured pressure vs. the volume of the syringe at 1-cc increments from 0 to 10 cc.

Volume	Pressure

Since the total volume of air is now $V_{syringe} + V_{extra\ tube}$, we can write the ideal gas law as

$$P(V_{syringe} + V_{extra\ tube}) = nRT.$$

Solve this equation for $V_{syringe}$. Plot $V_{syringe}$ vs. $1/P$.

Question 1-4: Record the slope and intercept and their uncertainties. What does the value of the y-axis intercept tell you? Is it a reasonable number?

Using another technique (such as measuring the length and inner diameter of the extra tube), find the volume of the extra tube along with an estimate of uncertainty. Record your procedure, data, and calculations below.

Question 1-5: Compare the results of your two different determinations of the volume of the extra tubing.

√ Checkpoint 2

Activity 1-4: Pressure and Force
In this experiment, instead of using your hand to apply pressure to the plunger of a syringe, we will use calibrated masses to apply a known force to the plunger. We can then compare the applied force to the measured pressure of the air in the syringe. We will use glass syringes because of the lower friction of the plunger.

Warning: Please be very careful with the glass syringes. If they or their pistons fall, or if they're squeezed too tightly, they will break!

Use the supplied C-clamp and stand to hold the syringe high enough above the lab bench to allow several weights to be suspended from the plunger. I will demonstrate the setup for you. Once you have things set up, start with 3-4 cc of room pressure air in the syringe. Close off the syringe and sensor from the outside world.

Now hang a mass (200 g) on the plunger. Draw a free-body diagram of the plunger and use it to identify the force(s) that are supporting the weight of the plunger and the hanging mass.

Record in the table below the mass of the plunger plus the hanging mass, the weight of the plunger plus the hanging mass, and the pressure when the system is at equilibrium. Take several measurements of the pressure (move the plunger around between measurements to make sure any uncertainty in finding the equilibrium position is included). Find the mean and standard deviation of the mean of these measured pressure values and record them in the appropriate columns of the table below.

Calculate the net force on the plunger due to the difference in pressure and record these values in the last column of the table below.

Repeat for hanging masses of 400g and 600g.

Mass (kg)	Weight of mass (N)	Measured pressure values in syringe (kPa)	Mean pressure in syringe (kPa)	Standard deviation of mean pressure (kPa)	Force on plunger from pressure difference (N)

Question 1-6: Compare the weight of the plunger plus hanging mass to the force on the plunger due to the pressure difference. Is there agreement within the uncertainty (standard deviation of the mean) of the measurements? If you note any discrepancies, what might they be due to?

√ Checkpoint 3

INVESTIGATION II: THE FIRST LAW OF THERMODYNAMICS

By making some simple observations with your syringes, you can see experimentally how work and heat and thermal energy are related for a gas, and how a gas can be used to do work.

Activity 2-1: Work Done by a Gas in a Cylinder

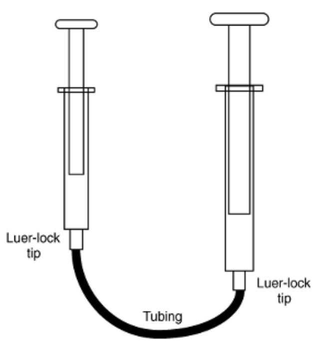
Admit some air to the plastic syringe and seal the end. Try compressing the air in the syringe by pushing the piston down against the foam pad on the table. Then let it go, and see what happens.

Question 2-1: Do you have to do work on the gas to compress it? What happens when you let go? Does the gas spring back?

In the next activity, you will explore why pressure is more useful than force in describing the behavior of gases. You will also extend the definition of work and combine it with the definition of pressure to calculate the work done by a gas on its surroundings as it expands out against the piston with a (possibly changing) pressure *P*. To do this, you will need

- Two different diameter low-friction glass syringes
- Nonexpanding plastic tubing to connect the syringes
- Vernier caliper
- Ring stand and two clamps to hold the syringes

Warning: Be very careful with the glass syringes. In the following activity, take special care that the pistons do not fly out of the syringes!



Activity 2-2: Pressure and Work

Mount the two syringes on the ring stand and connect using the tubing as shown, leaving an air space in the small syringe of about half its length. Be sure that the pistons in the syringes are free to move. If sticky, remove the pistons and dip them in *distilled* water.

Push down on the smaller diameter syringe and observe what happens to the larger diameter one. Then push down (carefully!) on the larger diameter syringe and see what happens to the smaller diameter one. Record your observations:

Place a 100-g (0.1-kg) mass on top of the handle of the larger diameter syringe. Then find what mass must be placed on the top of the handle of the smaller diameter syringe to just support the 100-g mass, and record it in Table 2-1 below.

Measure the diameters and masses of the pistons in the two syringes, and record the values in Table 2-1. Then do the necessary calculations to fill in the remainder of the table.

Table 2-1

	Supported mass (kg)	Mass of piston (kg)	Total mass (kg)	Total weight (force) (N)	Diameter of piston (m)	Area of piston (m^2)
Larger syringe	0.10					
Smaller syringe						

Calculate the pressure in each syringe using the definition of pressure as force per unit area:

Pressure in smaller syringe: ______

Pressure in larger syringe: ______

Question 2-2: Based on your observations, is it the force or the pressure applied to one syringe that gets transmitted to the other?

This two-syringe combination works on the same principle as a hydraulic lift used to multiply forces. One application is the car lift at your auto mechanic's shop.

√ Checkpoint 4

Activity 2-3: The Heated Syringe

In thermodynamics, the *thermal energy* E_{th} represents *any* way of storing energy inside a system. The thermal (or internal) energy of a system is the sum of all sorts of energies, including the helter-skelter translational kinetic energies of molecules in a gas, the vibrational energies of gas molecules or atoms in a crystal, and the rotational energies of spinning gas molecules. Transferring heat energy to a system could serve to increase its internal energy, but it might also result in the system doing work on its surroundings.

Prediction 2-1: What do you think would happen if you put a syringe with a sealed end in hot water? Would its piston experience a force? Could it do work on its surroundings?

To test your prediction you will use the larger plastic syringe and a 0.5-L container full of hot water (about 70°C). Admit 10-15 cc's of room temp air to the syringe. Seal the end with the extra Luer lock valve and, *while holding the piston fixed in place*, submerge most of the syringe in very hot water. Stir. After a minute or so, release the piston and let it move freely.

Question 2-3: What do you think might have happened to the gas while you heated it but prevented it from changing its volume by holding the piston fixed?

Question 2-4: What happened when you released the piston and let the gas expand? Did the gas do any work? Is this what you predicted would happen?

You should have concluded from the last activity that the transfer of heat energy to a system can cause it to do work on its surroundings and/or increase its internal energy, depending on the situation. The relationship between heat energy, work, and the change in internal energy is believed to hold for any system, not just a syringe filled with gas. It is known as the *first law of thermodynamics*. The first law of thermodynamics is a very general statement of conservation of energy for thermal systems.

There are many ways to achieve the same thermal energy change, ΔE_{th}. To achieve a small change in the thermal energy of gas in a syringe, you could transfer a large amount of heat energy to it and then allow the gas to do work on its surroundings. Alternatively, you could transfer a small amount of heat to the gas and not let it do any work at all. The change in thermal energy, ΔE_{th}, could be the same in both processes. ΔE_{th} depends only on $Q + W$ and not on Q or W alone.

Question 2-5: How can you arrange a situation where W is negligible and $\Delta E_{th}=Q$?

Question 2-6: How can you arrange a situation where Q is negligible and where $\Delta E_{th}=W$?

Activity 2-4: The Fire Syringe and Adiabatic Compression

Prediction 2-2: Suppose that you are told that the volume of a gas decreases. Can the ideal gas law by itself be used to calculate the change in temperature of the gas or do you need any additional information?

Prediction 2-3: If a gas is compressed <u>adiabatically</u>, what should happen to the temperature of the gas? (**Hint**: Consider the first law of thermodynamics, $\Delta E_{th} = Q + W$, and the relationship between thermal energy E_{th} and T.)

A device known as a *fire syringe* allows a rapid compression of air in a small tube that is inside a safety tube of Plexiglas. If this is done rapidly enough, there is no time for heat energy to be transferred and the compression can be nearly *adiabatic*.

What happens to an ideal gas if it is compressed adiabatically? Work is done on the gas, but no heat energy is transferred to the surroundings. Unlike an isothermal compression in which heat energy is transferred out and the internal energy and temperature remain constant, for an adiabatic compression, the internal energy increases and *the temperature increases*. It can be shown that the relationship between the final and initial temperatures (T_f and T_i) and the final and initial volumes (V_f and V_i) for a diatomic ideal gas (which approximates the behavior of air) undergoing an adiabatic process is given by

$$T_f V_f^{\gamma-1} = T_i V_i^{\gamma-1}$$

Note that the ideal gas law, $PV = (\text{constant})T$, is still correct, but the fact that the process is adiabatic has put an additional constraint on the system, described by the equation above.

Observe a movie of a fire syringe demonstration (follow the link given in lab). After observing what happens, estimate the approximate initial and final lengths of the air column and the inside diameter of the air column and record your estimates in the table below. Use your data to calculate the approximate final temperature of the air in the fire syringe and enter it in Table 2-2.

Table 2-2

Initial length of air column (cm)	
Final length of air column (cm)	
Inside diameter of the tube (cm)	
Initial volume V_i (calculated) (cm^3)	
Final volume V_f (calculated) (cm^3)	
Initial temperature T_i (room temperature) (K)	
Final temperature T_f (calculated) (K)	

Question 2-7: Compare your calculated final temperature to the "flash point" or burning point of paper–451°F. (The paper flash point of 451° is well known to readers of Ray Bradbury's famous science fiction novel, Fahrenheit 451, about book burning.) Can you now understand why the paper ignited? Why wouldn't the paper catch fire if you compressed the air slowly?

√ Checkpoint 5