Physics 216 Lab 11, Spring 2018
Heat Engines

OBJECTIVES

- To be able to describe a heat engine in terms of an energy flow diagram and to calculate the work done in a cycle.
- To investigate theoretically and experimentally the relationship between work done by a heat engine and changes in the pressure and volume of the engine's working medium.
- To examine the efficiency of a heat engine in converting heat energy input to useful work output.

OVERVIEW

In general, engines convert various forms of energy into mechanical work. For example, an athlete uses chemical energy released during the oxidation of molecules obtained from food to do mechanical work. The efficiency of an athlete's muscles in transforming chemical energy into work is at best only about 20%. The other 80% of the chemical energy released during physical activity is ultimately converted into waste heat energy that must be transferred to her surroundings.

The nineteenth-century industrial revolution was based on the invention of heat engines. The basic goal of any heat engine is to convert heat energy into work as efficiently as possible. This is done by taking a *working medium*–a substance that can expand and thus do work when heat energy is transferred to it–and placing it in a system designed to produce work in continuous, repeated cycles.

An engine that is 100% efficient would have a working medium that transforms all of the heat energy transferred to it to useful work. Such a process would not violate the first law of thermodynamics, since energy would still be conserved. However, no heat engine has ever been capable of transforming *all* of the heat energy transferred to it into useful work. Some of the heat energy transferred in is always transferred back to the engine's surroundings at a lower temperature as waste heat energy. The universal existence of waste heat energy has led scientists to formulate the *second law of thermodynamics*. A common statement of the second law is simply that *it is impossible to transform* ***all*** *of the heat energy transferred to a system into useful work*.

In this lab you will explore the actual behavior of several simple heat engines. We can use any substance that changes its volume when heat energy is transferred to it as the working medium for a heat engine.

INVESTIGATION 1: HEAT ENGINES AND CYCLES
Activity 1-1: The Rubber Band as a Heat Engine Medium

Let's examine what happens when a large rubber band with a weight at one end is heated with a heat gun or hair dryer. The equipment for this demonstration is as follows:

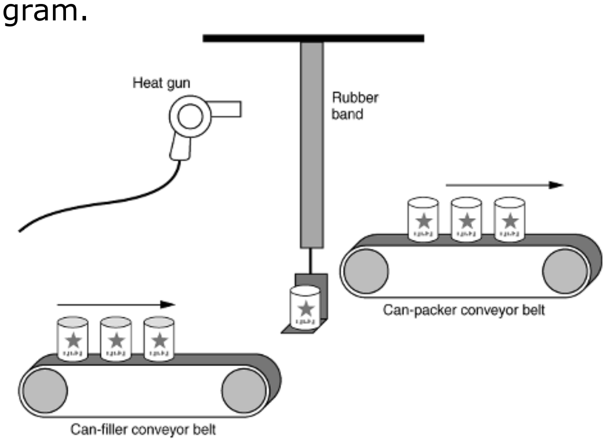
- large rubber band
- 500 g mass
- table clamp with long rod, short support rod, and right-angle clamp
- heat gun

Prediction 1-1: What do you predict will happen when the rubber band that is stretched by a hanging weight is heated? Explain.

The rubber band engine will be demonstrated to you.

Question 1-1: Describe what actually happened when the rubber band was heated. Compare this to your prediction.

This behavior of a heated rubber band is helpful if all we want to do is to lift a weight once, but it hardly fits our intuitive notion of an engine. Let's say you own a factory that produces a canned beverage. (We will let you choose the beverage!) You wish to design a machine that lifts cans from the conveyor belt leaving the filling machine up to the conveyor belt entering the packing machine. You have at your disposal a large rubber band and a hair dryer. Can you design a mass lifter? It might look like the one in the following diagram.



Question 1-2: Can you describe a complete *cycle* that would repeatedly lift cans to the packer conveyor? Describe the steps in your cycle.

Question 1-3: Carefully point out where heat energy is transferred in your cycle, the direction of heat energy transfer, where work is done, and by which part of the engine that work is done.

Question 1-4: Would the engine work on a very hot day when the temperature inside the factory was as hot as the heated air coming from the hair dryer or heat gun? Why or why not?

Question 1-5: Does it appear likely that our rubber band lifter converts *all* of the heat energy transferred to it from the hair dryer into useful mechanical work (i.e., work done lifting cans)? Does any of that transferred heat energy have to go elsewhere? (**Hint**: What has to happen to the rubber band after the lifted can is taken away but before it can pick up a new can from the lower belt?)

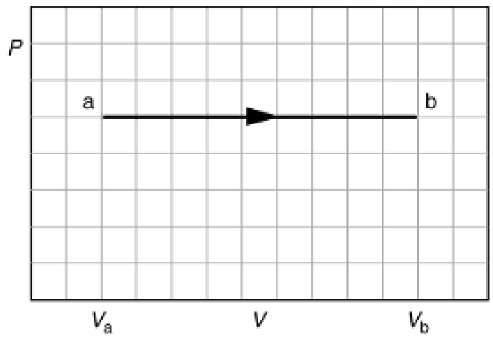
√ Checkpoint 1

Investigation 2: Volume change of gases
It is important to understand what happens to gases when they undergo volume changes, since many practical devices, from automobile engines to refrigerators, use expanding gases to operate.

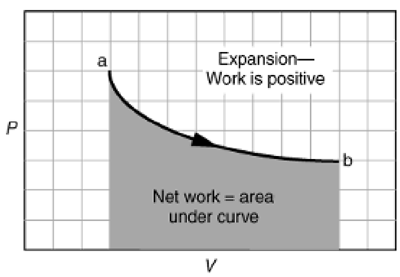
Activity 2-1: Work Done by an Expanding Gas
A system we have already met often in our study of thermodynamics is a mass of gas confined in a syringe with a movable piston. The behavior of a gas compressed and expanding in a syringe is a simulation of what goes on in the cylinders in a real engine like the internal combustion engine in your car, or like a steam engine.

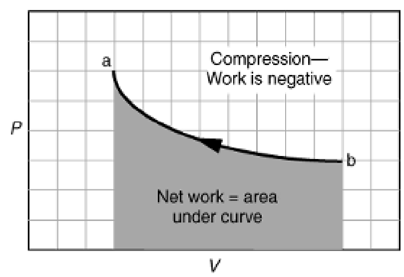
Question 2-1: If a gas expands inside a cylinder with a movable piston so that the volume changes by an amount ΔV while the pressure is kept constant at a value P (isobaric process), what is the mathematical expression to calculate the amount of work done by the gas? (Remember that work done by the gas is the opposite of the work done on the gas. In other words, we're asking for $W_s = -W$: W is by external forces, W_s is by the gas—our system)

The graph that follows shows an isobaric expansion from a volume V_a to a volume V_b represented on a *P-V* diagram. You can find the work done by the gas in the expansion from a to b *from the graph* by calculating the area under the P vs V curve.



You can always calculate the work done by finding the area under the curve, even if the pressure does not remain constant during the process. Work by the gas, W_s, is *positive* if the gas *expands* in the process. If the gas is compressed during the process, then work is done on the gas by the surroundings, and the work done by the gas is *negative*. Examples are shown below.





According to the first law of thermodynamics, the conservation of energy is

$$\Delta E_{th} = Q + W$$

where Q is the net heat energy transferred to the system (a positive number if heat energy is transferred *into* the system) and W is the work done on the system. That is, *transfer of heat energy into the system or work done on the system increases* the internal energy. Note that the work done by the system is the opposite of the work done on the system, so we can also write the first law as $\Delta E_{th} = Q + W_s$.

One of the key features of our rubber band engine is that it must cool, by transferring heat energy to its surroundings, to be ready to lift the next can. To do so, the surroundings must be cooler than the hot air from the hair dryer. After the rubber band has cooled to its original temperature, and stretched back to its original length, it is in the same *thermodynamic state* that it was in at the start. In other words, all its properties, including its internal energy, are the same. *For one complete cycle of our rubber band engine $\Delta E_{th} = 0$*.

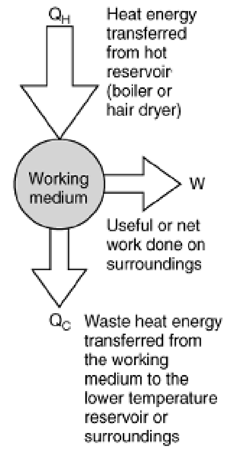
If Q_H is the heat energy transferred to the rubber band from the air heated by the hair dryer and Q_C is the heat energy transferred from the rubber band to the cooler room air, the net heat energy transferred to the rubber band in the cycle is $Q = Q_H - Q_C$ and the first law of thermodynamics becomes

$$\Delta E_{th} = Q - W = (Q_H - Q_C) - W_s.$$

Since $\Delta E_{th} = 0$ for our *complete* cycle, we can simplify this by writing

$$W_s = Q_H - Q_C.$$

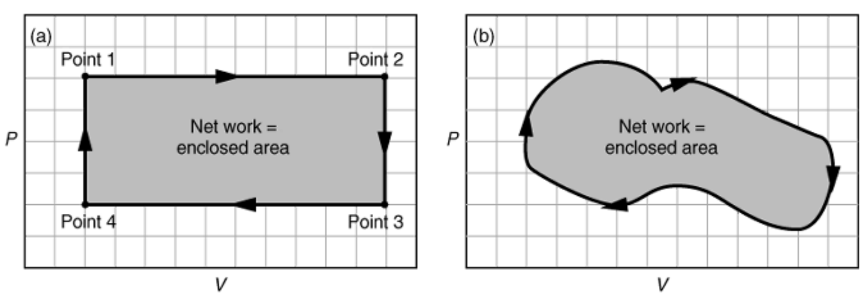
This basic fact about heat engines is often discussed in terms of an energy flow diagram such as the one shown on the right. This diagram would work equally well for an old - fashioned steam engine or our rubber band can lifter. The engine has heat energy Q_H transferred to it, does work W_s, and transfers some of the original heat energy Q_C to the lower temperature surroundings.



Finding Net Work Done in a Complete *P-V* Cycle
As we have seen, during parts of a cycle when a gas is expanding it is doing *positive* work *on the surroundings*. When it is being compressed, work is being *done on the gas by the surroundings*, so the work done by the gas W_s comes out *negative*.

At the completion of a heat engine cycle, the gas has the same internal energy, temperature, pressure, and volume that it started with. It is then ready to start another cycle. During various phases of the cycle, (1) heat energy transferred to the gas from the hot reservoir (e.g., a boiler) causes the gas to do work on its surroundings as it expands, (2) the surroundings do work on the gas to compress it, and (3) the gas transfers waste heat energy to the surroundings or cold reservoir. The total useful or net work done in an engine cycle is the difference between the work done during expansion and the work done on the gas during compression.

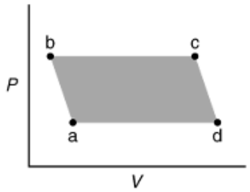
Because the work done going from one state to another in one direction is positive and the work done in the other direction is negative, it can be shown mathematically that the work done by the gas around a closed loop on a *P-V* diagram, representing a complete cycle of the engine, is the same as the area enclosed by the trace of the process on the diagram. This is illustrated below for two different imaginary cycles.



In the next investigation, you will investigate this relationship between useful work and the area on a *P-V* diagram for a real engine.

INVESTIGATION 3: THE INCREDIBLE MASS-LIFTING HEAT ENGINE
Your working group has been approached by the Newton Apple Company about testing a model heat engine that lifts apples from a processing conveyor belt to the packing conveyor belt, which is several cm higher. The engine you are to experiment with is a real heat engine that can be taken through a four-stage expansion and compression cycle and that can do useful mechanical work by lifting small masses from one height to another.

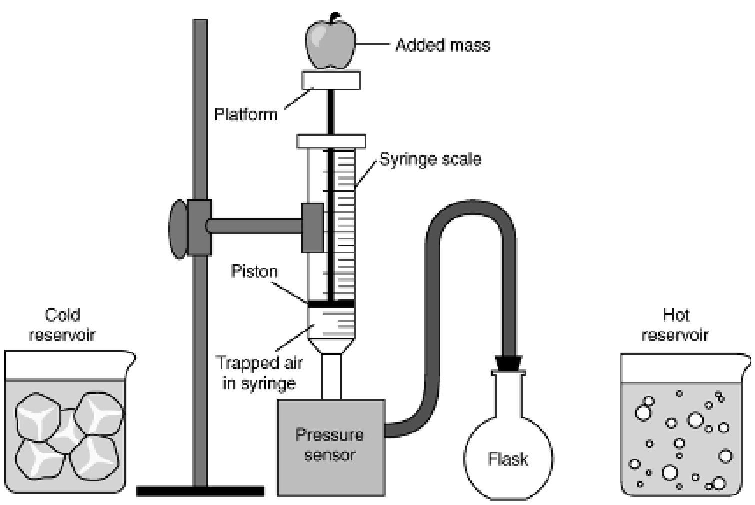
First, you will experimentally compare the useful mechanical work done in lifting the mass (work=force acting over a distance, *mgy,* which we hope you believe in and understand already) with the accounting of work in an engine cycle *given by the area enclosed by the cycle*.



To carry out this experiment you will need

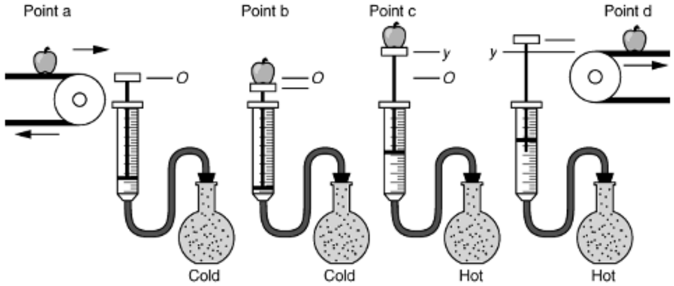
- 10-cm^3 low-friction glass syringe with ring stand support
- several lengths of Tygon tubing
- 35-mL flask with one-hole rubber stopper
- 2 insulated (e.g., Styrofoam) containers (to use as reservoirs)
- ruler
- 50-g mass
- hot water (about 80 °C)
- ice water
- pressure sensor and temperature sensor

The cylinder of the incredible mass-lifter engine is a low-friction glass syringe. The flat top of the handle of the piston serves as a platform for lifting masses. The flask and pressure sensor can be connected to the syringe with short lengths of flexible Tygon tubing, and the flask can be placed alternately in a cold reservoir and a hot reservoir. A schematic diagram of this mass lifter follows.



If the temperature of the air trapped inside the cylinder, hose, and flask is increased, then its pressure will increase, causing the platform to rise. Thus, you can increase the volume of the trapped air by moving the flask from the cold to the hot reservoir. Then when the mass has been raised through a distance *y*, it can be removed from the platform. The platform should then rise a bit more as the pressure on the cylinder of gas decreases a bit. Finally, the volume of the gas will decrease when the flask is returned to the cold reservoir. This causes the piston to descend to its original position once again. The various stages of the mass lifter cycle are shown in the diagrams that follow.

The lifting and lowering parts of the cycle should be approximately *isobaric*, since the pressure in the air trapped in the syringe is determined by the weight of the piston (and the mass on top of the handle) pushing down on the gas. The other two parts of the cycle, when the mass is added and removed from the piston handle, should be approximately *adiabatic*, since they occur quickly.



Before taking data on the pressure, air volume, and height of lift with the heat engine, you should set it up and run it through a few cycles to get used to its operation.

The engine cycle is much easier to describe if you begin with the piston resting above the bottom of the syringe. Thus, we suggest you raise the piston so that the volume of air trapped in the syringe is about 3 cc before inserting the rubber stopper firmly in the flask. Also, air does leak out of the syringe slowly. If a large mass is being lifted, the leakage rate increases, so we suggest that you limit the added mass to 50 g.

IMPORTANT: As you take the engine through its cycle, observe whether the piston is moving freely in the syringe. If it is sticking, it should be removed and dipped into *distilled* water, then dried with a Kimwipe, to free it up. If it continues to get stuck, ask your instructor for help.

After observing a few engine cycles, you should be able to describe each of the points **a**, **b**, **c**, and **d** of a cycle, carefully indicating which of the transitions between points are approximately adiabatic and which are isobaric.

You should reflect on your observations by answering the questions in the next activity. You can observe changes in the volume of the gas directly and you can predict how the pressure exerted on the gas by its surroundings ought to change from point to point by using the definition of pressure as force per unit area.

Activity 3-1: Description of the Engine Cycle

Prediction 3-1: With the system closed to the outside air and the flask at thermal equilibrium in the cold reservoir, what should happen to the height of the platform during transition **a** → **b**, as you add the mass to the platform? Explain the basis of your prediction.

Make sure the rubber stopper is firmly in place in the flask. Add the mass to the platform.

Question 3-1: Describe what happened. Is this what you predicted? Why might this process be approximately adiabatic?

Prediction 3-2: What do you expect to happen during transition **b**$\rightarrow$**c**, when you place the flask in the hot reservoir?

Now place the flask in the hot reservoir and let it come to equilibrium. (This is the engine power stroke!)

Question 3-2: Describe what happens. Is this what you predicted? Why should this process be isobaric?

Prediction 3-3: If you continue to hold the flask in the hot reservoir, what will happen when the added mass is now lifted and removed from the platform during transition **c**$\rightarrow$**d** (and moved onto an upper conveyor belt)? Explain the reasons for your prediction.

Remove the added mass.

Question 3-3: Describe what actually happens. Is this what you predicted? Why might this process be approximately adiabatic?

Prediction 3-4: What do you predict will happen during transition **d**$\rightarrow$**a**, when you now place the flask back in the cold reservoir? Explain the reasons for your prediction.

Complete the cycle by cooling the system down to its original temperature by placing the flask in the cold reservoir.

Question 3-4: Describe what actually happens to the volume of the trapped air during this transition. Why should this process be isobaric?

Question 3-5: How does the volume of the gas at the end of the cycle (when the gas has cooled to its initial temperature) actually compare to the original volume of the trapped air at point **a** at the beginning of the cycle? Is it the same or has some of the air leaked out?

Question 3-6: Once you cool the system back to its original temperature, the pressure of the gas should be the same as its initial pressure. Why?

√ Checkpoint 2

Activity 3-2: Running the Heat Engine
To find the thermodynamic work done during a cycle of this engine you will take the data needed to plot a *P-V* diagram for the engine based on determinations of the volumes and pressures of the trapped air in the cylinder, Tygon tubing, and flask at the points **a**, **b**, **c**, and **d** in the cycle.

Estimate the total volume of the tubing between the flask and syringe and the pressure sensor using the inside diameter and length. Show your calculation.

Inside diameter:______cm   Total length:______cm

Estimated volume of tubing:______

Enter this value in the fourth column of Table 3-2a.

Also enter the volume of the pressure sensor (which will be given to you by your instructor) and the volume of the flask in the appropriate columns of Table 3-2a.

Table 3-2a

State of system	Volume of air in syringe (cm^3)	Volume of flask (cm^3)	Volume of tubing (cm^3)	Volume of sensor (cm^3)	Total volume of air (cm^3)
a					
b					
c					
d					
a'					

Connect the pressure sensor and temperature sensor to the interface and open the experiment file called **Press. & Temp. (L06A3-2)** to display axes for pressure vs. volume. This will also set up the software in **prompted event mode** so that you can continuously measure pressure and decide when you want to **keep** a value. Then you can enter the measured volume.

Now you should be able to take your engine through a cycle and make the measurements of volume and pressure of the air needed to determine the *P-V* diagram for your heat engine. You should take your data *rapidly* to avoid air leakage around the piston.

Begin with the flask and temperature sensor in the ice water, and without the mass on the handle of the syringe (state **a**). (There should be about 2 cc in the syringe once the air in the flask cools.) Stir the ice water and begin collecting data. When the temperature and pressure seem to be fairly stable, **keep** those data values. Read the volume of air in the syringe, enter it in Table 3-2a, calculate the total volume of air, and **enter this value** into the computer.

Quickly place the mass on top of the handle of the syringe (state **b**). When the temperature and pressure seem to be fairly stable, **keep** those data values. Again, record the volume of air in the syringe in the table, calculate the total volume of air, and enter this value into the computer.

Quickly move the flask and temperature sensor to the hot water reservoir (state **c**). When the temperature and pressure seem to be fairly stable, **keep** those data values. Again, record the volume of air in the syringe in the table, calculate the total volume of air, and enter this value into the computer.

Quickly remove the mass (state **d**). When the temperature and pressure seem to be fairly stable, **keep** those data values. Again, record the volume of air in the syringe in the table, calculate the total volume of air, and enter this value into the computer.

Finally, move the flask and temperature sensor back to the ice-water reservoir (state **a'**). Stir the ice water. When the temperature and pressure seem to be fairly stable, **keep** those data values. Again, record the volume of air in the syringe in the table, calculate the total volume of air, and enter this value into the computer.

Print the graph and the data table.

Record the value of the mass to be lifted in Table 3-2b.

Measure the height that the mass was raised. This can easily be done after all measurements by going back, looking at your volume data, and measuring the difference in positions of the piston from state **b** to state **c**. Record in Table 3-2b. Also read the temperatures of the two water reservoirs (states **a** and **c**) from the data table and record them in Table 3-2b.

Table 3-2b

Mass lifted *(g)*	
Height mass was raised *y* (*m*)	
Hot reservoir temperature (K)	
Cold reservoir temperature (K)	

Question 3-7: You expected that the transitions from **b**→**c** and from **d**→**a** were isobaric. According to your data, were they? Explain.

√ Checkpoint 3

Activity 3-3: Calculating the Work Done by the Heat Engine
We'll use two different ways to find the area of the pV cycle that gives the work done by the heat engine:

Method I: Since the pressure doesn't change (much) from point **b** to point **c,** you can take the average pressure of those two points as a constant pressure. The same holds for the transition from **d** to **a**. This gives you a figure that is approximately a parallelogram with two sets of parallel sides. You can look up and properly apply the appropriate equation to determine the area and net thermodynamic work performed.

Method II: Display your graph with a grid (right click on graph area, choose Graph Options and near the bottom pull down the "Minor Tick Style an set it to dashed line) and count the boxes in the area enclosed by the lines connecting points **a**, **b**, **c**, and **d**. Then multiply by the number of joules each box represents. You will need to make **careful** estimates of fractions of a box when a cycle cuts through a box.

Find the work done in one cycle by the heat engine by both of these methods. Show all work below. Be sure that your units are correct to produce an answer in joules (J) — please ask if you have questions. Do your results agree, at least roughly? If they don't, let me know. If they do, probably averaging the two would be best.

Use the equation $W = mgy$ to calculate the useful mechanical work done in lifting the mass from one level to the other in joules (J).

Question 3-8: How does the thermodynamic work compare to the useful mechanical work? Use the correct number of significant figures in your comparison.

√ Checkpoint 4

Activity 3-4: Efficiency of the Mass-Lifting Heat Engine
The efficiency of a heat engine is defined in the following way:

$$e = \frac{W_{out}}{Q_{in}} \times 100\%$$

You have just found W_{out}. The heat energy input from the hot reservoir takes place in the process **b**$\rightarrow$**c**. (Remember that **c**$\rightarrow$**d** is an *adiabatic process with no heat energy transfer*.)

The heat energy transferred into a gas during an isobaric process in which the temperature changes by ΔT is given by

$$Q = nC_P \Delta T$$

where n is the number of moles of gas and C_P is the molar heat capacity at constant pressure, which is 29.1 J/mol·K for air.

The most efficient possible heat engine operating with a hot reservoir at T_H and a cold reservoir at T_C is called a Carnot engine, after Sadi Carnot, the French engineer who studied engine efficiencies in the early nineteenth century. According to his theoretical calculations, the maximum possible, or Carnot, efficiency is given by

$$e_c = 100\% \left(1 - \frac{T_C}{T_H}\right)$$

where both T_C and T_H are in K.

In the following activity you will determine the efficiency of your engine and of a Carnot engine operating between the same two thermal reservoirs.

Calculate the number of moles of gas in your system.

Calculate the heat energy transferred into the gas during the process **b**$\rightarrow$**c**. (**Hint**: Use the equation above for Q, and the temperatures of the two reservoirs.)

Now calculate the efficiency of the mass-lifting heat engine.

Calculate the efficiency of a Carnot engine operating with the same hot and cold reservoirs.

Question 3-9: Is the mass-lifting heat engine very efficient? What percentage of the input heat energy is converted to useful work? What percentage is lost as waste heat energy?

Question 3-10: How does the efficiency of the mass-lifting heat engine compare to the maximum possible efficiency (the Carnot efficiency)? Are you surprised by the answer?

Comment: Note that a careful analysis of the incredible mass-lifting engine is actually not so simple. There are several reasons for this. First, air is not an ideal gas. Second, the mass-lifting engine is not well insulated, and so the air that is warmed in the hot reservoir transfers heat energy through the cylinder walls. Thus, the air in the flask and the air in the cylinder are probably not at the same temperature. Third, air does leak out around the piston, especially when larger masses are added to the platform. This means that the number of moles of air decreases over time. (You can observe this by noting that in the transition from point **d** to point **a** the piston can actually end up in a lower position than it had at the beginning of the previous cycle.) However, the incredible mass-lifting engine does help us understand typical stages of operation of a real heat engine.

√ Checkpoint 5