

Activity 7 Solutions: Applications of the Laws of Thermodynamics

7.1 Conservation of Energy

Your instructor will discuss how changes in internal energy ΔU relate to energy conservation.

1) Internal Energy

Your instructor will demonstrate two rolling carts colliding with a barrier. Both carts have the same mass and the same frictional force with the table top.

- a) Which cart has more kinetic energy after it hits the barrier – the cart that rolls back a shorter distance or a longer distance? **_longer distance_** How do you know?

The cart that rolls back a longer distance must have bounced off of the barrier with a faster velocity. This cart has more kinetic energy because kinetic energy is proportional to the velocity squared.

$$E_{kin} = \frac{1}{2} M v^2$$

- b) Now watch the carts, without their outer covers, collide with the barrier. How can you explain the difference in the kinetic energy of the carts after they hit the barrier?

During the collision, some of the initial kinetic energy of motion of the elastic band cart is used to vibrate the washers. This kinetic energy goes into increasing the internal energy of the cart. The cart with rigid rods rolls farther away from the wall because none of its initial kinetic energy went into vibrating its washers. Since the elastic band cart has less kinetic energy after the collision, it does not move as far away from the wall.

- c) Explain how energy was conserved when each cart collided with the barrier.

If each cart is pushed with the same force, both carts start with the same amount of kinetic energy. Their kinetic energy goes into moving against the force of friction with the table top and into colliding with the wall. Since after the collision the elastic band cart uses energy not only to rebound, but to vibrate the washers as well, it does not roll as far after the collision.

- d) How does this demonstration illustrate an increase in the internal energy ΔU of an object?

The carts demonstrate what happens inside of a solid when kinetic energy is converted into the thermal energy of vibrating atoms and molecules. The faster the atoms and molecules of an object vibrate, the greater the internal energy of the object.

7.2 Pressure, Temperature, Volume and the Ideal Gas Law

2) Crushing Cans

Your instructor will illustrate the relationship between pressure and volume by changing the internal energy and the phase of water molecules inside cans.

- a) What happens to the internal energy and the motion of the water molecules in the can as the water is heated into steam?

As their temperature increases, the water molecules have more internal energy. As the water molecules change phase from liquid to steam, they move freely throughout the can with substantial kinetic energy.

- b) Pressure in the can is caused by the collisions of molecules of steam with the can walls. When the water is heated, what happens to the pressure inside the can?

Now that the steam molecules move freely throughout the can, they contribute substantially to the pressure inside the can, balancing the air pressure on the outside of the can. The higher the temperature of the steam, the faster the steam molecules move, and the more often they collide with the walls of the can.

- c) What happens to the motion of the water molecules and the pressure inside the can when the steam is quickly cooled and condenses into liquid water?

Some of the steam molecules condense into water droplets. The cooled water molecules no longer move freely throughout the can. This results in fewer molecular collisions with the can walls. The pressure inside the can decreases.

- d) Why do the walls of the can collapse?

The atmospheric pressure in the room is greater than the pressure inside the can, and the can collapses.

3) The Ideal Gas Law

Next we consider the relationship among pressure, temperature, volume, and number of molecules of a gas and discuss the Ideal Gas Law. We will find that ratio reasoning is useful and can be based on proportionalities.

- a) The previous demonstration discussed the relationship between the temperature of a gas and the pressure the gas exerts on the walls of a container. At a fixed volume of gas, pressure and temperature are directly proportional. Write a proportionality to show this relationship. **$P \propto T$**

Write a ratio of the initial pressure of a gas P_{initial} (or P_i) to the final pressure P_{final} (or P_f) and a second ratio of the initial gas temperature T_i to the final temperature T_f . Based on your proportionality above, relate these two ratios by an equation.

$$\frac{P_i}{P_f} = \frac{T_i}{T_f}$$

- b) We showed that the pressure inside the can resulted from steam molecules hitting the can walls. Suppose that you could change the volume of a container of gas without changing the temperature of the gas. As you decrease the gas volume, what happens to the number of times that gas molecules hit the can walls?

there are more collisions with the can walls

At a fixed temperature and number of molecules, write a proportionality to show how the pressure of a gas is related to its volume.

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

Write a ratio of the initial pressure of a gas P_i to the final pressure P_f and a second ratio of the initial volume V_i to the final volume V_f . Based on your proportionality above, relate these two ratios by an equation.

$$\frac{P_i}{P_f} = \frac{V_f}{V_i} \quad \text{or} \quad \frac{P_i}{P_f} \frac{V_i}{V_f} = 1$$

- c) Combine your equations from parts a) and b) into an equation that relates the pressure, the volume, and the temperature of a gas.

$$\frac{P_i V_i}{P_f V_f} = \frac{T_i}{T_f}$$

- d) Your instructor will demonstrate the relationships between pressure, temperature, volume, and the number of gas molecules.

If the volume and temperature of a gas are held constant and the number of gas molecules is increased, how will the gas pressure change? pressure increases

At a fixed volume and temperature, write a proportionality to show how the pressure of a gas is related to the number N of molecules of gas. $P \propto N$

Write a ratio of the initial pressure of a gas P_i to the final pressure P_f and a second ratio of the initial number of gas molecules N_i to the final number of gas molecules N_f . Based on your proportionality above, relate these two ratios by an equation.

$$\frac{P_i}{P_f} = \frac{N_i}{N_f}$$

- e) Now combine all four variables – pressure, volume, temperature, and number of molecules – into a single equation.

$$\frac{P_i V_i}{P_f V_f} = \frac{N_i T_i}{N_f T_f}$$

- f) Write this equation as a proportionality between P , V , N , and T . $PV \propto NT$

- g) You can illustrate this relationship with a pump and a liter bottle. Note the temperature on the thermometer inside the bottle. Then pump air into the bottle.

Which of the four variables **P**, **V**, **N**, and **T** changed as you pumped air into the bottle? Indicate below the change in variables.

Pressure: Pressure increased as air is pumped in.

Volume: The volume of the liter bottle is fixed.

Temperature: The thermometer indicates an increase in temperature.

Number of molecules: Adding more air increases the number of air molecules.

- h) Introducing the constant **k** into the proportionality obtained in part f) gives the equation for the Ideal Gas Law:

$$P V = N k T$$

A car tire has a pressure of 30 pounds/in² or 2.07×10^5 newtons/m². The volume of air in the tire is 0.05 meters³. The tire temperature is 27 °C or 300 K. The constant **k** = 1.38×10^{-23} J/K degree. How many molecules of air does the tire contain?

$$N = \frac{P V}{k T} = \frac{(2.07 \times 10^5 \text{ N/m}^2) \times (0.05 \text{ m}^3)}{(1.38 \times 10^{-23} \text{ J/K degree}) \times (300 \text{ K})} = 2.5 \times 10^{24} \text{ molecules}$$

- i) The owner's manual of your new car indicates two tire pressures: a maximum pressure of 36 pounds/in² and a recommended pressure of 28 pounds/in². To which pressure should you inflate your tires? Why?

Inflate the tires to the recommended pressure. As you drive, friction between the tires and the road heats up the air in the tires. The heated air will increase the tire pressure. If the tire pressure is already at the maximum allowed, the pressure could reach a dangerous level and affect the car's handling and braking, or even cause a blowout.

7.3 Work from Thermodynamic Systems

Your instructor will discuss how changes in internal energy ΔU relate to energy conservation and the first law of thermodynamics.

4) The Dippy Duck Does Work

The dippy duck contains liquid freon, which changes phase easily at room temperature. Wet the head of the duck and place the cup of water in front of the duck's head. How does evaporation from the duck's head do work on the freon in the duck?

Water evaporates from the duck's head, cooling it. Cooling the freon gas inside the duck's head causes the gas molecules to condense. This reduces the volume of the gas and, thus, the gas pressure in the head. As a result, liquid freon flows up the tube from the region of higher pressure in the duck's tail to the region of lower pressure in the head. Each time the duck's head fills with liquid freon, work has been done on the freon to lift it to a higher level. As the freon moves up, the center of mass is raised until the duck topples over into the cup of water. While the duck's head is in the water, freon flows from the head into the tail, and the duck stands up again. The process repeats.

5) The Electric Drill Popper

The electric drill activity illustrates work done by an electric motor (the drill) and a thermodynamic system (the steam in the tube). Your instructor will explain the electric drill activity. Be sure to hold the cardboard tube over the end of the drill while you perform this activity.

- a) How was heat Q added to the system of the drill and the stopper?
Friction between the moving drill tube and the wooden clamp produced thermal energy.
- b) What evidence do you have that the internal energy of this system increased?
The water in the tube became steam.
- c) How was work done by this system?
As the stopper flew up, work was done against the force of gravity and the force of friction holding the stopper into the tube.
- d) How much work was done on the stopper by the drill if 505 joules of heat transferred to the water resulted in a 500 joule increase in the internal energy of the system?

$$W = Q - \Delta U = 505 \text{ J} - 500 \text{ J} = 5 \text{ J}$$

6) Thermodynamic Systems Doing Work

- a) How is work related to equilibrium?
Work or energy is required to change a system from an equilibrium state. As the system is moving back toward equilibrium, the stored energy can be given off as wasted energy or can be used to do work. For example, the electric motor runs only if there is difference in voltage, and a steam engine runs only if there is a difference in temperature. These devices will only run as long as a nonequilibrium situation exists.
- b) Can a system ever return to a non-equilibrium state?
Yes, but it will not do so by itself. A system can return to a non-equilibrium state only if work is done on that system or energy is put into the system.
- c) In the next section, you will see how different types of engines work. What is the one necessary condition for any engine or machine to do work?
The system of the engine and its environment must be not be at equilibrium. Work can be taken out as the system goes toward an equilibrium state.

7.4 Engines and Work

7) Electric Motors

Electric motors convert electrical energy into mechanical energy of motion. An example is the electric motor in a drill that turns the drill shaft. Electricity to run a motor can be generated by a thermodynamic system as shown below.

- a) Attach the thermocouple to the ammeter. Place the thermocouple on the table and warm one side with your hand. What happens?

The ammeter shows that the thermocouple generates a current.

- b) What is the energy source of this current?

heat flow from the warm to the cool side of the thermocouple generating an electric current

- c) Your instructor will demonstrate a fan that uses energy from thermocouples. How does this thermodynamic system do work?

Electricity generated by the thermocouples turns a fan blade.

8) Internal Combustion Engines

Internal combustion engines also use thermodynamics systems to do work. Your instructor will demonstrate models of internal combustion engines.

- a) What causes the pistons in an engine to move?

An explosion inside the piston chamber produces hot gases. The gas pressure forces the piston to move.

- b) What is the energy source for an internal combustion engine?

Chemical energy in droplets of gasoline or other fuel is ignited by a spark. The chemical energy is converted into kinetic energy when the fuel explodes.

9) External Combustion Engines

Your instructor will discuss and demonstrate external combustion engines.

- a) What causes the pistons in the steam engines engine to move?

Water is heated to boiling. The pressure from the steam forces the piston to move.

- b) What is the energy source for an external combustion engine?

Fuel, such as coal, oil, or wood, is burned to heat water in the steam boiler. The chemical energy in the fuel is converted into thermal energy of the steam.

- c) What happens to the temperature of the steam as the steam does work?

Energy is taken from the steam to do work, so the temperature of the steam decreases.

- d) You instructor will demonstrate an engine that runs on liquid nitrogen. What does this engine have in common with a steam engine?

In both cases, work is done as the steam or liquid nitrogen moves toward thermal equilibrium with the surrounding air.

- e) Why are internal and external combustion engines known as heat engines?

Combustion engine operation requires a transfer of heat.

10) Heat Engines using Nitinol Wire

- a) Place a piece of nitinol wire into a beaker of hot water. What happens to the wire?

The wire bends because nitinol wire contracts when heated.

- b) A mass is hung from a piece of nitinol wire. What happens when you close the switch?

The mass is raised because the heated nitinol wire contracts.

- c) Your instructor will help you make a heat engine that uses nitinol wire. What happens when the wire is dipped into beakers of hot and cold water?

The wheel turns.

- d) Why must the nitinol wire be dipped in different temperatures of water?

The wire alternately expands and contracts when it is exposed to hot and cold temperatures.

- e) Group Discussion Question: What is the difference between a heat engine and an electric motor?

11) Heat Engine Efficiency

- a) What is the maximum efficiency of a heat engine for which the high temperature is at 100 °C and the low temperature is at 20 °C?

(Hint: First, convert the temperatures from Celsius to Kelvin by adding 273 K.)

$$Eff = \frac{T_H - T_L}{T_H} = \frac{373 \text{ K} - 293 \text{ K}}{373 \text{ K}} = \frac{80 \text{ K}}{373 \text{ K}} = 0.21 = 21\%$$

7.5 Refrigerators, Air Conditioners, and Heat Pumps

12) Air Conditioners

- a) In Activity 3.f), you found that increasing the pressure on the gas in a liter bottle increased the temperature of the gas. What do you think happens to the temperature of a gas when it is allowed to expand? **_temperature decreases_**

- b) Hold the palm glass upright and warm one bulb with your palm. What happens to the freon in the glass tube? Why are liquids with low boiling points, such as freon, good coolants for air conditioners?

Freon has such a low boiling point that heating the glass bulb in your palm can cause some freon molecules to change phase from liquid to gas. The phase change increases the pressure in the palm glass. The fact that the phase change occurs just above room temperature makes it possible to operate an air conditioner with less energy wasted.

- c) What does an air conditioner do?

Air conditioners pump heat from inside a building to outside the building.

- d) What is the cooling mechanism in an air conditioner (or refrigerator)?

Cooling occurs in the air conditioner coils when the pressure on the freon (or other liquid) is quickly reduced as the freon is allowed to expand through a small opening. As the liquid freon expands, it becomes a gas. To change phase from a liquid to a gas, heat must have been added to the freon. That heat comes from the surroundings, and the surroundings are cooled.

13) Heat Pumps

- a) What is a heat pump?

A heat pump can pump heat from colder outdoor air inside to help warm a home.

- b) How is a heat pump similar to an air conditioner? How does a heat pump differ from an air conditioner?

Both devices operate on the same principles of expansive cooling. A heat pump brings heat from outside into a building and an air conditioner pumps heat out of a building.

- c) Group Discussion Question: Do you think heat pumps could be used as the only source of central heating for homes? What benefit could a heat pump produce?

14) Coefficient of Performance of Heat Pumps

You use a heat pump to warm your house. If the air temperature outside of the house is -10°C and the temperature inside is 23°C , what is the maximum coefficient of performance for this heat pump?

First, convert the Celsius temperatures to Kelvin by adding 273 degrees.

$$COP = \frac{Q_H}{W} = \frac{T_H}{T_H - T_C} = \frac{273 + 23}{(273 + 23) - (273 - 10)} = \frac{296}{296 - 263} = 9.0$$

15) Coefficient of Performance of Air Conditioners or Refrigerators

The temperature inside your refrigerator is 40 °F (4 °C) and the temperature in your kitchen is 78 °F (26 °C). What is the maximum coefficient of performance of your refrigerator?

$$\text{COP} = \frac{Q_L}{W} = \frac{T_C}{T_H - T_C} = \frac{273 + 4}{(273 + 26) - (273 + 4)} = \frac{277}{299 - 277} = 12.6$$