24

THERMODYNAMICS

Objectives

- Describe what happens to the temperature of a substance when the thermal motion of the atoms approaches zero. (24.1)
- State the first law of thermodynamics. (24.2)
- Describe the effect of adiabatic compression on a gas. (24.3)
- State the second law of thermodynamics. (24.4)
- Explain how the second law of thermodynamics applies to heat engines. (24.5)
- Describe what happens to the orderly state of any natural system. (24.6)
- Describe what happens to the entropy of any system. (24.7)

This chapter focuses on the environment and the atmosphere, and provides some physics insights into processes that underlie weather. This chapter is not a prerequisite to the chapters that follow. It may be skipped if a brief discussion of heat is sufficient.

PAUL

discover!

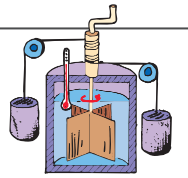
MATERIALS rubber band

EXPECTED OUTCOME When stretched, the rubber band felt slightly warmer; when contracted, it felt slightly cooler.

ANALYZE AND CONCLUDE

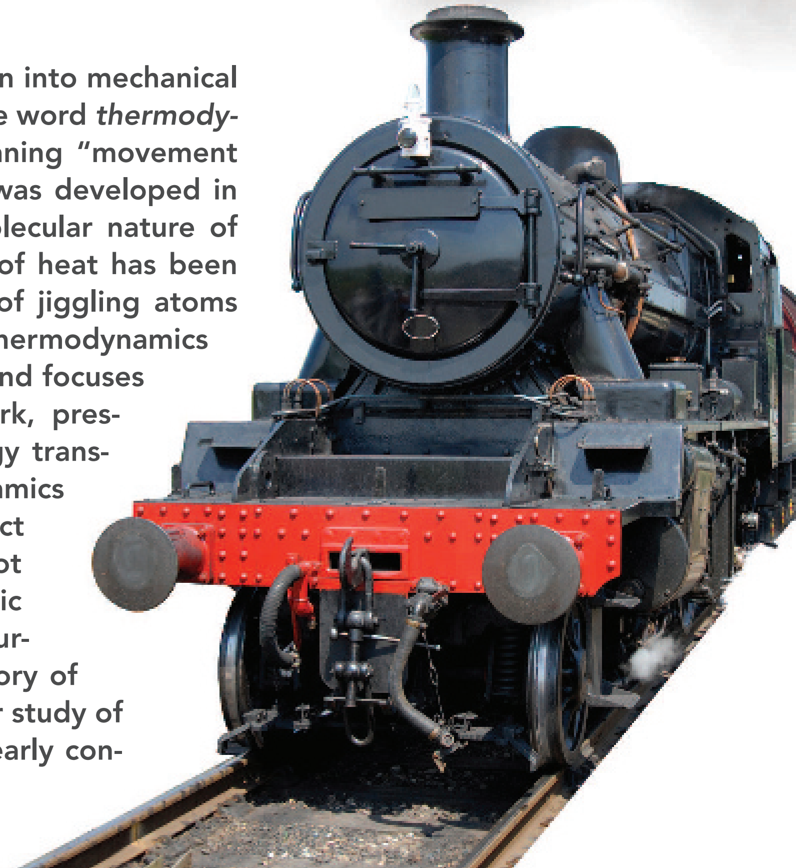
1. See Expected Outcome.
2. No temperature change
3. The faster a process, the less time for other changes to occur.

24 THERMODYNAMICS



THE BIG IDEA Heat normally flows from hot to cold.

The study of heat and its transformation into mechanical energy is called **thermodynamics.** The word *thermodynamics* stems from Greek words meaning "movement of heat." The science of thermodynamics was developed in the mid-1800s, before the atomic and molecular nature of matter was understood. So far, our study of heat has been concerned with the microscopic behavior of jiggling atoms and molecules. Now we will see that thermodynamics bypasses the molecular details of systems and focuses on the macroscopic level—mechanical work, pressure, temperature, and their roles in energy transformation. The foundation of thermodynamics is the conservation of energy and the fact that heat flows from hot to cold, and not the other way around. It provides the basic theory of heat engines, from steam turbines to fusion reactors, and the basic theory of refrigerators and heat pumps. We begin our study of thermodynamics with a look at one of its early concepts—a lowest limit of temperature.



discover!

Can Temperature Change Without Heat Transfer?

1. Place a rubber band, loosely looped over your index fingers, in contact with your upper lip.
2. Quickly stretch the rubber band.
3. Now let the rubber band contract quickly. Do not snap the rubber band.

Analyze and Conclude

1. **Observing** Describe what you felt when the rubber band was stretched and then allowed to contract rapidly.
2. **Predicting** What do you think you would feel if the rubber band were stretched and allowed to contract more slowly?
3. **Making Generalizations** Why do you think the rate of performing a process may affect the outcome of the process?

24.1 Absolute Zero

As thermal motion of atoms increases, temperature increases. There seems to be no upper limit of temperature. In contrast, there is a definite limit at the other end of the temperature scale. If we continually decrease the thermal motion of atoms in a substance, the temperature will drop. **As the thermal motion of atoms in a substance approaches zero, the kinetic energy of the atoms approaches zero, and the temperature of the substance approaches a lower limit.** This limit is the *absolute zero* of temperature. **Absolute zero** is the temperature at which no more energy can be extracted from a substance and no further lowering of its temperature is possible. This limiting temperature is 273 degrees below zero on the Celsius scale. This value was found in the 1800s by experimenters who discovered that all gases contract by the same proportion when temperature is decreased.[24.1]

Absolute zero corresponds to zero degrees on the Kelvin, or thermodynamic, scale and is written 0 K (short for "zero kelvin"). Unlike the Celsius scale, there are no negative numbers on the thermodynamic scale. Degrees on the Kelvin scale are the same size as those on the Celsius scale. Thus, ice melts at 0°C, or 273 K, and water boils at 100°C, or 373 K. The Kelvin scale was named after the British physicist Lord Kelvin, who coined the word *thermodynamics* and first suggested such a scale.

Figure 24.1 shows the temperature of various objects and phenomena with respect to absolute zero. At very high temperatures, the measurements of temperature on the Kelvin and Celsius scales are close to identical.

CONCEPT CHECK What happens to a substance's temperature as the motion of its atoms approaches zero?

think!

A sample of hydrogen gas has a temperature of 0°C. If the gas is heated until its molecules have doubled their average kinetic energy (the gas has twice the absolute temperature), what will be its temperature in degrees Celsius? *Answer: 24.1*

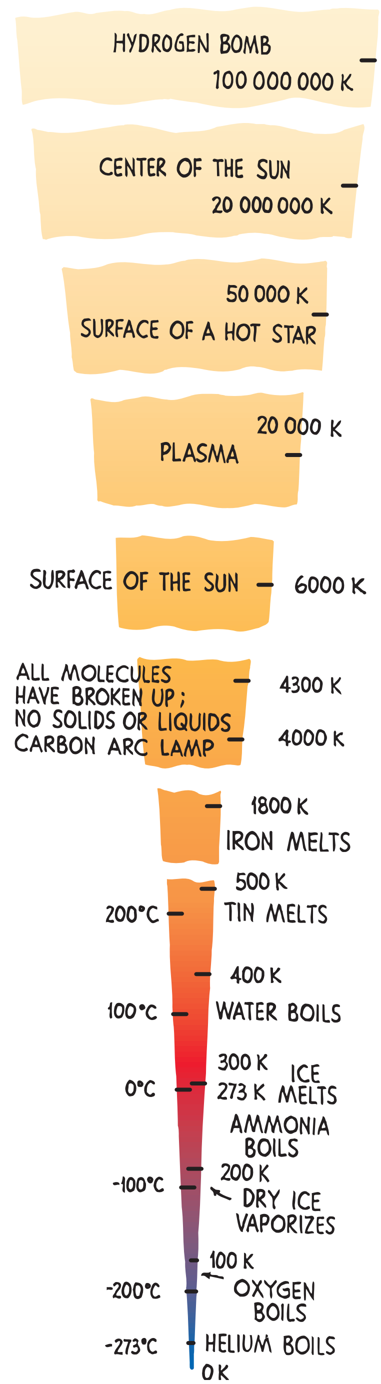


FIGURE 24.1 ▶
The figure shows the absolute temperatures of various objects and phenomena.

24.1 Absolute Zero

Key Terms
thermodynamics, absolute zero

▶ **Teaching Tip** Use the following analogy: Electrons still move in the lowest energy state of an atom, just as atoms still vibrate in the lowest temperature state of a solid.

▶ **Teaching Tip** Review the Celsius and Fahrenheit temperature scales. Discuss the idea of a lowest temperature—absolute zero and the Kelvin (K) scale. State that the Kelvin scale is "nature's scale" and its zero point is the coldest possible value. (Note the degree symbol (°) is not used with K. This should reinforce the concept that the Kelvin scale's zero point was not chosen by human convention.)

When William Thompson was made a Baron, he took the title Lord Kelvin from the Kelvin River that ran through his estate.
PAUL

CONCEPT CHECK As the thermal motion of atoms in a substance approaches zero, the kinetic energy of the atoms approaches zero, and the temperature of the substance approaches a lower limit.

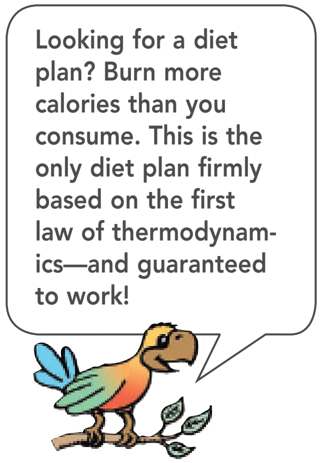
Teaching Resources
- **Reading and Study Workbook**
- **Laboratory Manual** *67*
- **Transparency** *47*
- **Presentation*EXPRESS***
- **Interactive Textbook**

24.2 First Law of Thermodynamics

Key Term
first law of thermodynamics

▶ **Teaching Tip** Introduce the first law of thermodynamics by citing the findings of Count Rumford: that when cannon barrels were being drilled and became very hot, it was the friction of the drills that produced the heating. Recall the definition of work, *force* × *distance*, and explain that the metal is heated by the frictional force × distance that the various parts of the drill bit move. Have your students rub their hands together and feel them warm up.

▶ **Teaching Tip** Discuss the account of James Joule with his paddle-wheel apparatus for measuring the mechanical equivalent of heat. Joule attempted to extend this experiment to a larger scale while on his honeymoon in Switzerland. Joule and his bride honeymooned near the Chamonix waterfall. According to Joule's conception of heat, the gravitational PE of the water at the top should go into increasing the internal energy of the water at the bottom. Joule made a rough estimate of the increase in water temperature at the bottom of the waterfall. His measurements did not substantiate his predictions, however, because considerable cooling occurred due to evaporation as the water fell through the air. Without this added complication his predictions would have been supported. What happens to the temperature of a penny, after all, when you slam it with a hammer? The effect is the same with water. Emphasize that the first law is simply the law of energy conservation for thermal systems.



24.2 First Law of Thermodynamics

In the eighteenth century, heat was thought to be an invisible fluid called *caloric,* which flowed like water from hot objects to cold objects. Caloric was conserved in its interactions, a discovery that led to the law of conservation of energy. In the 1840s, using the apparatus shown in Figure 24.2, scientist James Joule demonstrated that the flow of heat was nothing more than the flow of energy itself. The caloric theory of heat was gradually abandoned.[24.2.1] Today we view heat as a form of energy. Energy can neither be created nor destroyed.

The **first law of thermodynamics** is the law of conservation of energy applied to thermal systems. **The first law of thermodynamics states that whenever heat is added to a system, it transforms to an equal amount of some other form of energy.**

Heat By *system,* we mean any group of atoms, molecules, particles, or objects we wish to deal with. The system may be the steam in a steam engine, the whole Earth's atmosphere, or even the body of a living creature. It is important to define what is contained within the system as well as what is outside of it. If we add heat energy to the steam in a steam engine, to Earth's atmosphere, or to the body of a living creature, these systems will be able to do work on external things. This added energy does one or both of two things: (1) increases the internal energy of the system if it remains in the system and (2) does external work if it leaves the system. So, the first law of thermodynamics states

$$\text{Heat added} = \begin{array}{c}\text{increase in}\\ \text{internal energy}\end{array} + \begin{array}{c}\text{external work done}\\ \text{by the system}\end{array}$$

Let's say you put an air-filled, rigid, airtight can on a hotplate and add a certain amount of energy to the can. **Caution:** *Do not actually do this.* Since the can has a fixed volume, the walls of the can don't move, so no work is done. All of the heat going into the can increases the internal energy of the enclosed air, so its temperature rises.

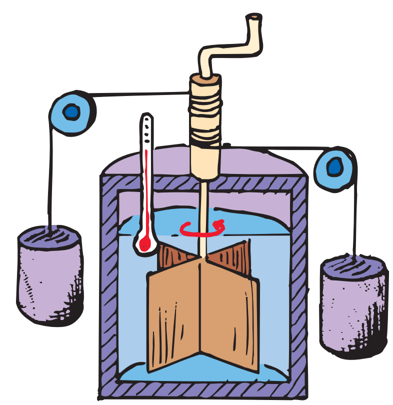


FIGURE 24.2 ▶
Paddle-wheel apparatus first used to compare heat energy with mechanical energy. As the weights fall, they give up potential energy and warm the water accordingly. This was first demonstrated by James Joule, for whom the unit of energy is named.

470

discover!

Can You Feel the Heat?

1. Briskly rub your palms together. What happens to the temperature of your palms?
2. **Think** You see that work can easily be converted into thermal energy. Can thermal energy be as easily converted into work?

Now suppose instead that we replace the can with a balloon. This time, as the air is heated it expands, exerting a force for some distance on the surrounding atmosphere. Since some of the heat added to the air goes into doing work, less of the added heat goes into increasing the enclosed air's internal energy. Can you see that in this second situation the temperature of the enclosed air will be lower because some of the energy added to the system goes to work outside the system? The first law of thermodynamics makes good sense.

When a given quantity of heat is supplied to a steam engine, some of this heat increases the internal energy of the steam and the rest is transformed into mechanical work as the steam pushes a piston outward. That is, heat input equals the increase in internal energy plus the work output. The first law of thermodynamics is simply the thermal version of the law of conservation of energy.

Work Adding heat is not the only way to increase the internal energy of a system. If we set the "heat added" part of the first law to zero, we will see that changes in internal energy are equal to the work done on or by the system.[24.2.2] If work is done on a system—compressing it, for example—the internal energy will increase. The temperature of the system rises without any heat input. On the other hand, if work is done *by* the system—expanding against its surroundings, for example—the system's internal energy will decrease. With no heat extracted, the system cools.

Consider a bicycle pump. When we pump on the handle, the pump becomes hot. Why? Because we are putting mechanical work into the system and raising its internal energy. If the process happens quickly enough, so that very little heat is conducted from the system during compression, then nearly all of the work input will go into increasing internal energy, significantly raising the air's temperature.

CONCEPT CHECK What does the first law of thermodynamics state?

think!

If 10 J of energy is added to a system that does no external work, by how much will the internal energy of that system be raised?
Answer: 24.2

discover!

EXPECTED OUTCOME The work done by rubbing the hands together is converted into thermal energy as evidenced by the increased temperature of the hands.

THINK No

CONCEPT CHECK The first law of thermodynamics states that whenever heat is added to a system, it transforms to an equal amount of some other form of energy.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book *24–1***
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question *24–1***

24.3 Adiabatic Processes

Key Term
adiabatic

Demonstration

Bring water to a boil in a regular pressure cooker. Then remove the weighted cap so that steam expands violently from the nozzle. For drama, put your gloved hand in the path of the "steam" about 20 cm above the nozzle. Ask if you would dare do the same with a bare hand. Then remove the glove and hold your hand in the stream. **Caution** *Do not put your hand any closer to the nozzle.* Amazing! Actually the "steam" is quite cool. Acknowledge that your hand is not in the steam, which is invisible and is in the first 1 cm to 3 cm above the nozzle. Your hand is in condensed vapor, considerably cooled by expansion (and mixing with air).

▶ **Teaching Tip** Point out that constant-temperature processes are not adiabatic.

▶ **Teaching Tip** If you have a model of an internal combustion engine, such as is shown in Figure 24.4, consider showing and explaining it in class. Many of your students likely have little idea of the process.

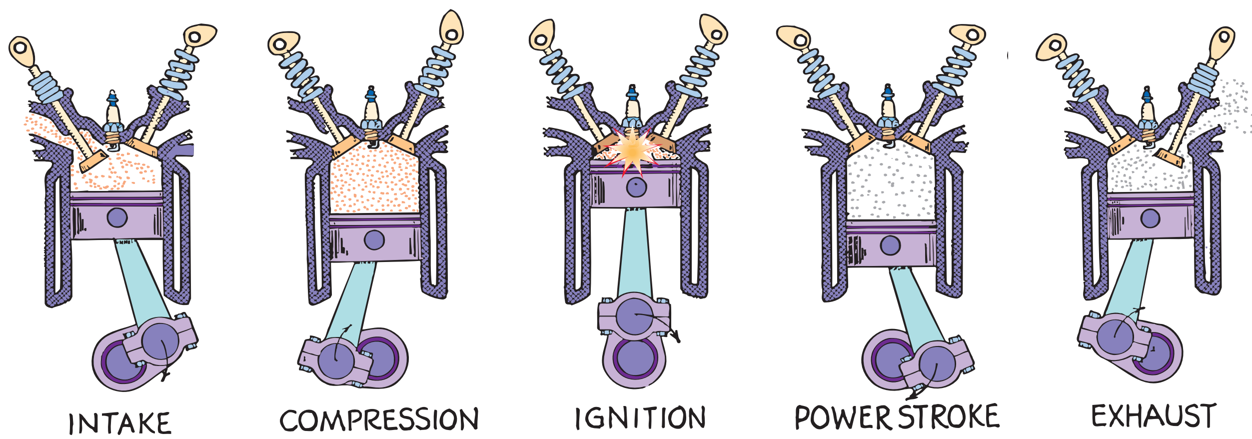
▶ **Teaching Tip** Explain that the processes of compression and expansion of air are opposite and describe how each affects the temperature of the air. It's easy to see that compressing air into a tire warms the air; and also that when the same air expands through the nozzle in escaping, it cools.

FIGURE 24.3 ▲
Do work on a pump by pressing down on the piston and the air is warmed.

24.3 Adiabatic Processes

When a gas is compressed or expanded so that no heat enters or leaves a system, the process is said to be **adiabatic** (Greek for "impassible"). Adiabatic changes of volume can be achieved by performing the process rapidly so that heat has little time to enter or leave (as with the bicycle pump in Figure 24.3), or by thermally insulating a system from its surroundings (with polystyrene foam, for example).

A common example of a near adiabatic process is the compression and expansion of gases in the cylinders of an automobile engine, shown in Figure 24.4. Compression and expansion occur in only a few hundredths of a second, too short a time for appreciable heat energy to leave the combustion chamber. For very high compressions, like those in a diesel engine, the temperatures achieved are high enough to ignite a fuel mixture without the use of a spark plug. Diesel engines have no spark plugs.



a. A fuel–air mixture fills the cylinder as the piston moves down.

b. The piston moves up and compresses the mixture—adiabatically, since no heat transfer occurs.

c. The spark plug fires, ignites the mixture, and raises its temperature.

d. Adiabatic expansion pushes the piston downward—the power stroke.

e. The burned gases are pushed out the exhaust valve, and the cycle repeats.

FIGURE 24.4 ▲
One cycle of a four-stroke internal combustion engine is shown above.

✓ **When work is done on a gas by adiabatically compressing it, the gas gains internal energy and becomes warmer.** When a gas adiabatically expands, it does work on its surroundings and gives up internal energy, and thus becomes cooler. Recall the activity in Chapter 22 of blowing on your hand with puckered lips so your breath expands as it leaves your mouth, repeated here in Figure 24.5. Your breath is considerably cooler than when blown without expanding from your wide-open mouth.

Heat and Temperature Air temperature may be changed by adding or subtracting heat, by changing the pressure of the air, or by both. Heat may be added by solar radiation, by long-wave Earth radiation, by moisture condensation, or by contact with the warm ground. Heat may be subtracted by radiation to space, by evaporation of rain falling through dry air, or by contact with cold surfaces.

There are many atmospheric processes, usually involving time scales of a day or less, in which the amount of heat added or subtracted is very small—small enough that the process is nearly adiabatic. In this case, an increase in pressure will cause an increase in temperature, and vice versa. We then have the adiabatic form of the first law:

$$\text{Change in air temperature} \sim \text{pressure change}$$

Pressure and Temperature Adiabatic processes in the atmosphere occur in large masses of air that have dimensions on the order of kilometers. We'll call these large masses of air *blobs.* Due to their large size, mixing of different temperatures or pressures of air occurs only at their edges and doesn't appreciably alter the overall composition of the blobs. A blob behaves as if it were enclosed in a giant, tissue-light garment bag. As a blob of air flows up the side of a mountain, its pressure lessens, allowing it to expand and cool. The reduced pressure results in reduced temperature, as shown in Figure 24.6. Measurements show that the temperature of a blob of dry air drops by 10°C for each 1-kilometer increase in altitude (or for a decrease in pressure due to a 1-kilometer increase in altitude). Air flowing over tall mountains or rising in thunderstorms or cyclones may change elevation by several kilometers. So if a blob of dry air at ground level with a comfortable temperature of 25°C rose to 6 kilometers, its temperature would be a frigid –35°C. On the other hand, if air at a typical temperature of –20°C at an altitude of 6 kilometers descended to the ground, its temperature would be a roasting 40°C.

think!

If a blob of air initially at 0°C expands adiabatically while flowing upward alongside a mountain a vertical distance of 1 km, what will its temperature be? When it has risen 5 km?
Answer: 24.3.1

Imagine a giant dry-cleaner's garment bag full of air at a temperature of –10°C floating like a balloon with a string hanging from it 6 km above the ground. If you were able to yank it suddenly to the ground, what would its approximate temperature be?
Answer: 24.3.2

FIGURE 24.5 ▲
Blow warm air onto your hand from your wide-open mouth. Now reduce the opening between your lips so the air expands as you blow. Adiabatic expansion—the air is cooled.

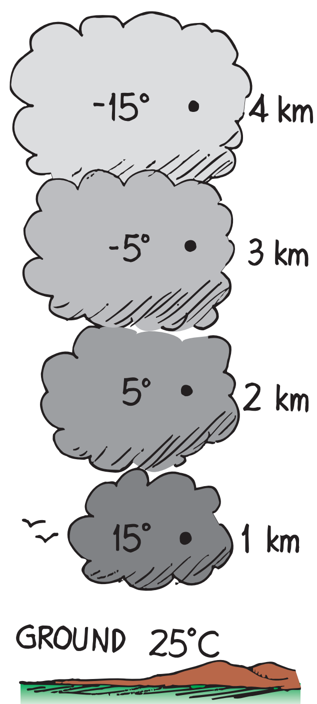


FIGURE 24.6 ▲
The temperature of a blob of dry air that expands adiabatically changes by about 10°C for each kilometer of elevation.

▶ **Teaching Tip** Review the concept of cloud formation as moist air rises, expands, and cools.

▶ **Teaching Tip** Discuss the adiabatic expansion of rising air in our atmosphere. Ask if it would be a good idea to wear only a T-shirt on a hot day when going for a balloon ride. Or would it be a good idea to bring warm clothing? A glance at Figure 24.6 will answer that one.

▶ **Teaching Tip** Discuss the Think! question about yanking down a giant dry-cleaner's garment bag from a high altitude and the changes in temperature it undergoes.

On the matter of pollution, we find now that even rain is polluted. Acid rain has wreaked havoc on the environment in many parts of the world. Interestingly enough, it isn't the destruction of vast forests or poisoning of wildlife that has evoked the loudest public outcry—acid rain dulls the high-tech finishes on automobiles, and for many people that is going too far!

PAUL

▶ **Teaching Tip** Revisit the Discover! activity on p. 468. The rapid expansion and contraction of the rubber band is an example of an adiabatic process. An adiabatic process is one in which no heat is added to or removed from a system. This does not mean that the temperature of the system necessarily remains constant, for even in the absence of external interactions with the surroundings, the system is free to exchange energy between thermal (internal energy) and mechanical forms. Adiabatic conditions are closely approximated when the process happens so quickly that there is no time to transfer heat, or if the system is very well insulated from its surroundings.

▶ **Teaching Tip** Discuss temperature inversion and the role it plays in air pollution, or at least in confining air pollution.

▶ **Teaching Tip** Warm moist air rising over a mountain cools as it expands, and then precipitation forms as vapor changes state to liquid (rain) or solid (snow). As precipitation forms, the vapor releases latent heat to the air. The energetic dry air is compressed as it descends on the other side of the mountain and it is appreciably warmer than if precipitation hadn't formed. Without the heat given to the air by precipitation, it would cool a certain amount in adiabatically expanding and warm the same amount in adiabatically compressing, with no net increase in temperature.

CONCEPT CHECK When work is done on a gas by adiabatically compressing it, the gas gains internal energy and becomes warmer.

Teaching Resources

- **Reading and Study Workbook**
- **Transparency** *48*

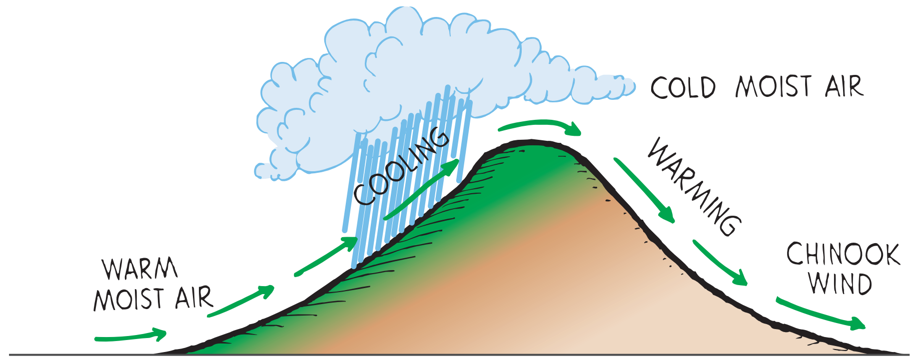
24.4 Second and Third Laws of Thermodynamics

Key Term
second law of thermodynamics

Common Misconception
The vast internal energy of bodies like the ocean can be converted to useful energy.

FACT It is not possible to convert a given amount of heat into mechanical energy without external effort.

FIGURE 24.7 ▶
Chinooks, warm dry winds, occur when high-altitude air descends and is adiabatically warmed.



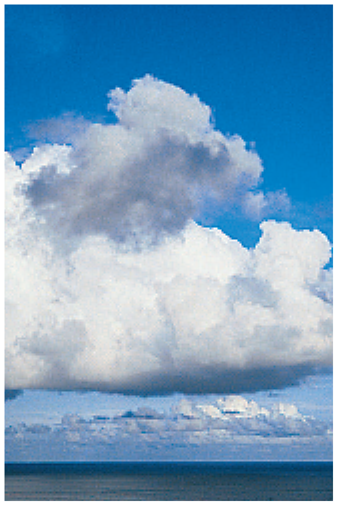


FIGURE 24.8 ▲
A thunderhead is the result of the rapid adiabatic cooling of a rising mass of moist air. Its energy comes from condensation and freezing of water vapor.

A dramatic example of this adiabatic warming is the *chinook*—a wind that blows down from the Rocky Mountains across the Great Plains. Cold air moving down the slopes of the mountains is compressed by the atmosphere into a smaller volume and is appreciably warmed, as shown in Figure 24.7. In this way communities in the paths of chinooks experience relatively warm weather in midwinter. The effect of expansion or compression on gases is quite impressive.[24.3] It can even create thunderheads like the one in Figure 24.8.

CONCEPT CHECK **What is the effect of adiabatic compression on a gas?**

24.4 Second and Third Laws of Thermodynamics

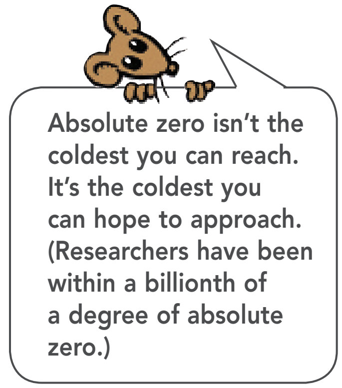
If we place a hot brick next to a cold brick, heat flows from the hot brick to the cold brick until both bricks arrive at a common temperature: thermal equilibrium. No energy will be destroyed, in accord with the first law of thermodynamics. But pretend the hot brick takes heat from the cold brick and becomes hotter. Would this violate the first law of thermodynamics? No, because energy is still conserved in the process. But it would violate the *second law of thermodynamics*. The **second law of thermodynamics** describes the direction of heat flow in natural processes. **The second law of thermodynamics states that heat will never of itself flow from a cold object to a hot object.**

Heat flows one way, from hot to cold. In winter, heat flows from inside a warm heated home to the cold air outside. In summer, heat flows from the hot air outside into the home's cooler interior. Heat can be made to flow the other way, but only by imposing external effort—as occurs with heat pumps that move heat from cooler outside air into a home's warmer interior, or air conditioners that remove heat from a cool interior to warmer air outside. Without external effort, the direction of heat flow is from hot to cold.

There is a huge amount of internal energy in the ocean, but all this energy cannot be used to light a single flashlight lamp without external effort. Energy will not of itself flow from the lower-temperature ocean to the higher-temperature lamp filament.

There is also a *third law of thermodynamics,* which restates what we've learned about the lowest limit of temperature: *no system can reach absolute zero*.

As investigators attempt to reach this lowest temperature, it becomes more difficult to get closer to it. Physicists have been able to record temperatures that are less than a millionth of 1 kelvin—but never as low as 0 K.



CONCEPT CHECK What does the second law of thermodynamics state about heat flow?

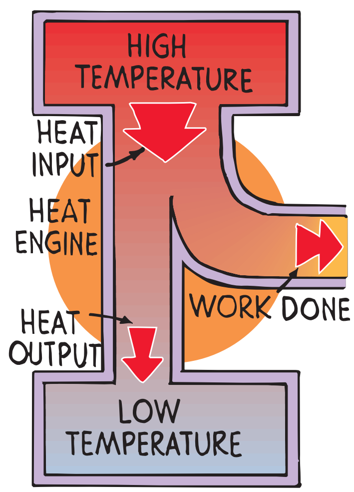
24.5 Heat Engines and the Second Law

It is easy to change work completely into heat—simply rub your hands together briskly. Or push a crate at constant speed along a floor. All the work you do in overcoming friction is completely converted to heat. But the reverse process, changing heat completely into work, can never occur. The best that can be done is the conversion of some heat to mechanical work. The first heat engine to do this was the steam engine, invented in about 1700.

Heat Engine Mechanics A **heat engine** is any device that changes internal energy into mechanical work. The basic idea behind a heat engine, whether a steam engine, internal combustion engine, or jet engine, is that mechanical work can be obtained only when heat flows from a high temperature to a low temperature. In every heat engine only some of the heat can be transformed into work.

In considering heat engines, we talk about *reservoirs.* We picture a "high-temperature reservoir" as vast, something from which we can extract heat without cooling it down. Likewise we picture a "low-temperature reservoir" as something that can absorb heat without itself warming up. Heat flows out of a high-temperature reservoir, into the heat engine, and then into a low-temperature reservoir, as shown in Figure 24.9. Every heat engine will (1) increase its internal energy by absorbing heat from a reservoir of higher temperature, (2) convert some of this energy into mechanical work, and (3) expel the remaining energy as heat to some lower-temperature reservoir. In a gasoline engine, for example, (1) the burning fuel in the combustion chamber is the high-temperature reservoir, (2) mechanical work is done on the piston, and (3) the expelled energy goes out as exhaust.

FIGURE 24.9 ▼
When heat energy flows in any heat engine from a high-temperature place to a low-temperature place, part of this energy is transformed into work output.



CONCEPT CHECK The second law of thermodynamics states that heat will never of itself flow from a cold object to a hot object.

Teaching Resources
- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook

24.5 Heat Engines and the Second Law

Key Terms
heat engine, Carnot efficiency

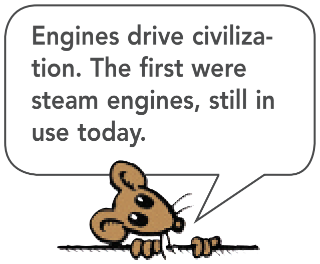
Common Misconception
A friction-free heat engine would be a 100%-efficient engine.

FACT Even without friction, a heat engine can only convert some of the heat input to work.

▶ **Teaching Tip** Stress that for ratios, temperature must be expressed in kelvins. For differences, kelvins and Celsius degrees are the same.

Ask Temperatures must be expressed in kelvins when using the formula for ideal efficiency, but may be expressed in either Celsius or kelvins for Newton's law of cooling. Why? *In Carnot's equation, ratios are used; in Newton's law of cooling, only differences are used.*

▶ **Teaching Tip** Tell the story of the engineer who is explaining the operation of a steam engine to a peasant back in the 1800s. The engineer explains in detail the engine's steam cycle, whereupon the peasant asks, "Yes, I understand all that, but where's the horse?" It's difficult to abandon our ways of looking at the world when a newer method comes along to replace established ways.



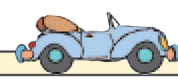
According to the second law of thermodynamics, no heat engine can convert all heat input to mechanical energy output. Only some of the heat can be transformed into work, with the remainder expelled in the process. Applied to heat engines, the second law states that when work is done by a heat engine running between two temperatures, T_{hot} and T_{cold}, only some of the input heat at T_{hot} can be converted to work, and the rest is expelled as heat at T_{cold}.

There is always heat exhaust, which may be desirable or undesirable. Hot steam expelled in a laundry on a cold winter day may be quite desirable, while the same steam on a hot summer day is something else. When expelled heat is undesirable, we call it *thermal pollution.*

Heat Engine Efficiency Before the second law was understood, it was thought that a very-low-friction heat engine could convert nearly all the input energy to useful work. But not so. In 1824 the French engineer Sadi Carnot carefully analyzed the cycles of compression and expansion in a heat engine and made a fundamental discovery. He showed that the upper fraction of heat that can be converted to useful work, even under ideal conditions, depends on the temperature difference between the hot reservoir and the cold sink. The **Carnot efficiency,** or ideal efficiency, of a heat engine is the ideal maximum percentage of input energy that the engine can convert to work. The equation for the ideal efficiency is given as follows:

$$\text{Ideal efficiency} = \frac{T_{hot} - T_{cold}}{T_{hot}}$$

T_{hot} is the temperature of the hot reservoir and T_{cold} is the temperature of the cold. Ideal efficiency depends only on the temperature difference between input and exhaust. Whenever ratios of temperatures are involved, the absolute temperature scale must be used.



Link to TECHNOLOGY

Fuel Cells and Electric Vehicles One of the attractions of fuel cells, and of electric vehicles in general, is that they are *not* heat engines—their efficiencies are not limited by the Carnot cycle constraints of the second law. While the efficiency of an engine that burns (combusts) fuel will always be limited by the temperature difference between the cylinder and the exhaust, fuel cells and batteries have no such thermal constraints. Fuel cells running on pure hydrogen can be as much as 80% efficient in converting chemical energy to electrical energy. Watch the growth of fuel-cell technology and electric automobiles.

476

So T_{hot} and T_{cold} are expressed in kelvins. For example, when the hot reservoir in a steam turbine is 400 K (127°C) and the sink is 300 K (27°C), the ideal efficiency is

$$\frac{(400\text{ K} - 300\text{ K})}{400\text{ K}} = \frac{1}{4}$$

This means that even under *ideal* conditions, only 25% of the internal energy of the steam can be converted into work, while the remaining 75% is expelled as waste. This is why steam is superheated to high temperatures in steam engines and power plants. The higher the steam temperature driving a motor or turbogenerator, the higher the efficiency of power production. (Increasing operating temperature in the example to 600 K yields an efficiency of (600 K − 300 K)/600 K = 1/2, twice the efficiency at 400 K.)

think!

What is the ideal efficiency of an engine if both its hot reservoir and exhaust are the same temperature—say 400 K?
Answer: 24.5

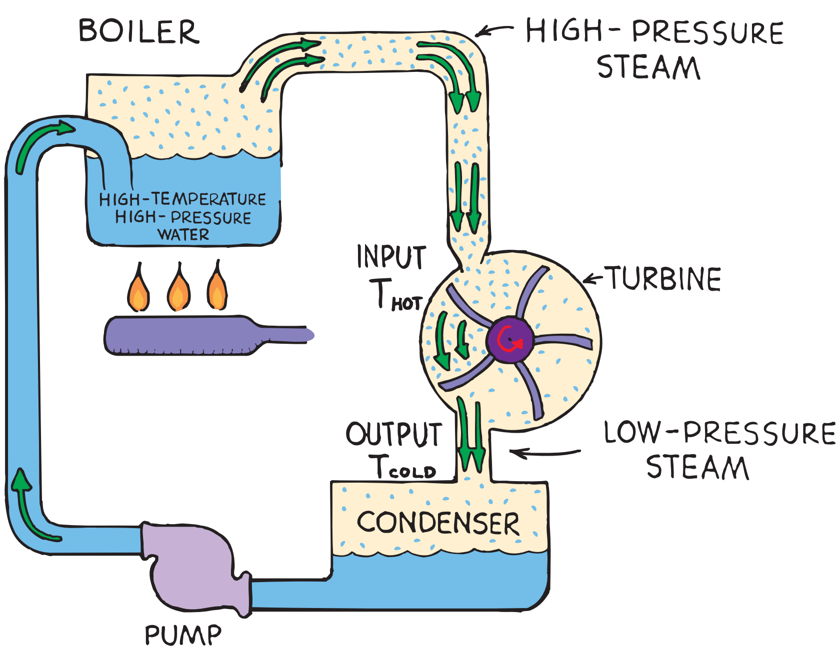


FIGURE 24.10
A steam turbine turns because high-temperature steam from the boiler exerts more pressure on the front side of the turbine blades than the low-temperature steam exerts on the back side of the blades. Without a pressure difference, the turbine would not turn.

Heat Engine Physics We can see the role of temperature difference between heat reservoir and sink in the operation of the steam-turbine engine in Figure 24.10. Steam from the boiler is the hot reservoir while the sink is the exhaust region after the steam passes through the turbine. The hot steam exerts pressure and does work on the turbine blades when it pushes on their front sides. This is nice. But steam pressure is not confined to the front sides of the blades; steam pressure is also exerted on the *back sides* of the blades—countereffective and not so nice. A pressure *difference* across the blades is vital, for it causes the turbine to keep spinning, allowing it to do work. (If pressures were the same on both the front and the back of the blades, no work would be done.)

Teaching Tip Distinguish between ideal efficiency of a heat engine and the efficiency of other devices. For example, an electric lamp may be only 15% efficient at converting electrical energy to light, but when the light is absorbed it is 100% efficient at converting electrical energy to thermal energy. Electric heaters are 100% efficient at converting electrical energy to thermal energy. Emphasize that when we speak of efficiency, we usually refer to the energy that doesn't become thermal energy.

Ask **Incandescent lamps are typically rated only 5% efficient, and fluorescent lamps are only 20% efficient. Now we say they are 100% efficient. Isn't this contradictory?** *The lamps are 5% and 20% efficient as light sources, but 100% efficient as heat sources. All the energy input, even what becomes light, very quickly becomes heat.*

discover!

MATERIALS can, water, stove

EXPECTED OUTCOME The can is crushed.

THINK The condensation of the steam reduces the pressure in the can.

▶ **Teaching Tip** Ask your class if there is a connection between the Discover! activity and Figure 24.10 on the previous page. There's a remarkable connection. The remarkable decrease in air pressure when condensation occurs accounts for the condensation cycle of a steam turbine. Without reduction of pressure on the backside of the turbine blades, there would be no net force and no work would be done on the blades! No work done; no electricity!

CONCEPT CHECK According to the second law of thermodynamics, no heat engine can convert all heat input to mechanical energy output.

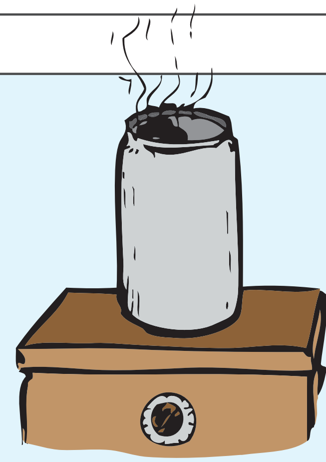
Teaching Resources

- **Reading and Study Workbook**
- **Transparency *49***
- **Presentation*EXPRESS***
- **Interactive Textbook**

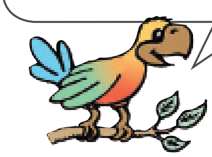
discover!

What Can Air Do to a Can?

1. Put a small amount of water in an aluminum soft drink can and heat it on the stove until steam issues from the opening.
2. With a pair of tongs, invert the can into a pan of water. Observe what happens to the can.
3. **Think** What role did condensation play in what happened to the can?



Biological systems are enormously complex, and while living, never reach thermal equilibrium.

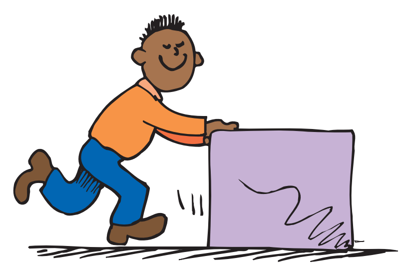


How do you get a pressure difference? By condensing the steam, the pressure on the back sides is greatly reduced. We know that with confined steam, temperature and pressure go hand in hand—increase temperature and you increase pressure; decrease temperature and you decrease pressure. So the pressure difference necessary for the operation of a heat engine is directly related to the temperature difference between the heat source and the exhaust. The greater the temperature difference, the greater the efficiency.[24.5.1]

Carnot's equation states the upper limit of efficiency for all heat engines. The higher the operating temperature (compared with exhaust temperature) of any heat engine, whether in an ordinary automobile, a nuclear-powered ship, or a jet aircraft, the higher the efficiency of that engine. In practice, friction is always present in all engines, and efficiency is always less than ideal.[24.5.2] So whereas friction is solely responsible for the inefficiencies of many devices, in the case of heat engines, the overriding concept is the second law of thermodynamics; only some of the heat input can be converted to work—even without friction.

CONCEPT CHECK **How does the second law of thermodynamics apply to heat engines?**

FIGURE 24.11 ▶
Try to push a heavy crate across a rough floor and all your work will go into heating the floor and crate. Work against friction turns into disorganized energy.



24.6 Order Tends to Disorder

The first law of thermodynamics states that energy can be neither created nor destroyed. The second law adds that whenever energy transforms, some of it degenerates into waste heat, unavailable to do work. Another way to say this is that organized, usable energy degenerates into disorganized, nonusable energy. The energy of gasoline is in an organized and usable form. When gasoline burns in an automobile engine, part of its energy does useful work such as moving the pistons, part of the energy heats the engine and surroundings, and part of the energy goes out the exhaust. Useful energy degenerates to nonuseful forms and is unavailable for doing the same work again.

Organized energy in the form of electricity that goes into electric lights in homes and office buildings degenerates to heat energy. This is a principal source of heating in many office buildings in moderate climates, such as the Transamerica Pyramid in San Francisco. All of the electrical energy in the lamps, even the part that briefly exists in the form of light, turns into heat energy, which is used to warm the buildings (that explains why the lights are on most of the time). This energy is degenerated and has no further use.

We see that the quality of energy is lowered with each transformation. Organized energy tends to disorganized forms. In this broader regard, the second law can be stated another way: **Natural systems tend to proceed toward a state of greater disorder.**

Imagine that in a corner of a room sits a closed jar filled with argon gas atoms. When the lid is removed, the argon atoms move in haphazard directions, eventually mixing with the air molecules in the room. This is what we would expect—the system moves from a more ordered state (argon atoms concentrated in the jar) to a more disordered state (argon atoms spread evenly throughout the room).

You would not expect the argon atoms to spontaneously order themselves back into the jar to return to the more ordered containment. This is because compared with the immense number of ways the argon atoms can randomly move, the chance of them returning to such an ordered state is practically zero.

Disordered energy can be changed to ordered energy only at the expense of work input. For example, plants can assemble sugar molecules from less organized carbon dioxide and water molecules only by using energy input from sunlight. But without some imposed work input, no increase in order occurs.

In the broadest sense, the message of the second law is that the tendency of the universe, and all that is in it, tends to disorder.

CONCEPT CHECK What happens to the orderly state of any natural system?

FIGURE 24.12 ▲
The Transamerica® Pyramid and some other buildings are heated by electric lighting, which is why the lights are on most of the time.

FIGURE 24.13 ▲
Argon gas goes from the jar to the air and not the other way around.

24.6 Order Tends to Disorder

▶ **Teaching Tip** Explain that the first law of thermodynamics speaks of the *quantity* of energy and the second law speaks of the *quality* of energy. For example, once water flows over a waterfall, it loses its potential for useful work. As energy is transformed, the quality of the energy is lowered with each transformation.

▶ **Teaching Tip** Ask students to consider a system consisting of a stack of pennies on a table, all heads up. Suppose somebody walks by, bumps against the table, and the pennies topple to the floor. The pennies will certainly not land all heads up. Order becomes disorder!

CONCEPT CHECK Natural systems tend to proceed toward a state of greater disorder.

Teaching Resources

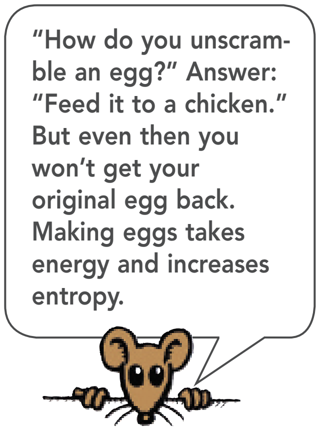
- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook

24.7 Entropy

Key Term
entropy

▶ **Teaching Tip** Explain that entropy depends on the number of possibilities. A flipped coin can come up only as heads or tails. Flip a coin and the probability of it landing heads up is 0.5. Flip two coins and they can land four ways (both heads, both tails, head and tail, tail and head). The probability of both landing heads up is 0.25. Three flipped coins can land eight ways; the chances of all three landing heads up diminishes to 0.125. The greater the number of coins, the less the probability of their landing in an ordered arrangement. Dump a barrel of coins on the floor and the chances of them all landing heads up is vanishingly small. Landing all heads up is possible, but enormously improbable.

▶ **Teaching Tip** Explain that entropy can be expressed as a mathematical equation, stating that the increase in entropy ΔS in an ideal thermodynamic system is equal to the amount of heat added to a system ΔQ divided by the temperature T of the system: $\Delta S = \Delta Q/T$. If the probability P of the state is high, then the entropy is high, as expressed in Boltzman's famous equation, $S = k \log P$.



24.7 Entropy

The idea of ordered energy tending to disordered energy is embodied in the concept of *entropy*.[24.7.1] **Entropy** is the measure of the amount of disorder in a system. Disorder increases; entropy increases. **According to the second law of thermodynamics, in the long run, the entropy of a system always increases for natural processes.** Gas molecules escaping from a bottle move from a relatively orderly state to a disorderly state. Organized structures in time become disorganized messes. Things left to themselves run down, such as the house in Figure 24.14. Whenever a physical system is allowed to distribute its energy freely, it always does so such that entropy increases while the available energy of the system for doing work decreases.

Entropy normally increases in physical systems. However, when there is work input, as in living organisms, entropy decreases. All living things, from bacteria to trees to human beings, extract energy from their surroundings and use it to increase their own organization. This order in life forms is maintained by increasing entropy elsewhere, so for the system "life forms plus their waste products" there is still a net increase in entropy.[24.7.2] Energy must be transformed into the living system to support life. When it is not, the organism soon dies and tends toward disorder.

FIGURE 24.14 ▶ This run-down house demonstrates entropy. Without continual maintenance, the house will eventually fall apart.

The first law of thermodynamics is a universal law of nature for which no exceptions have been observed. The second law, however, is a probability statement. Disordered states are much more probable than ordered states. Given enough time, even the most improbable states may occur; entropy may sometimes spontaneously decrease. Although theoretically the haphazard motions of air molecules could momentarily become harmonious in a corner of the room, or a barrelful of pennies dumped on the floor could all come up heads, or a breeze might come into a messy room and make it organized, the odds of these things actually occurring are infinitesimally small.

Go Online SCILINKS NSTA
For: Links on entropy
Visit: www.SciLinks.org
Web Code: csn – 2407

480

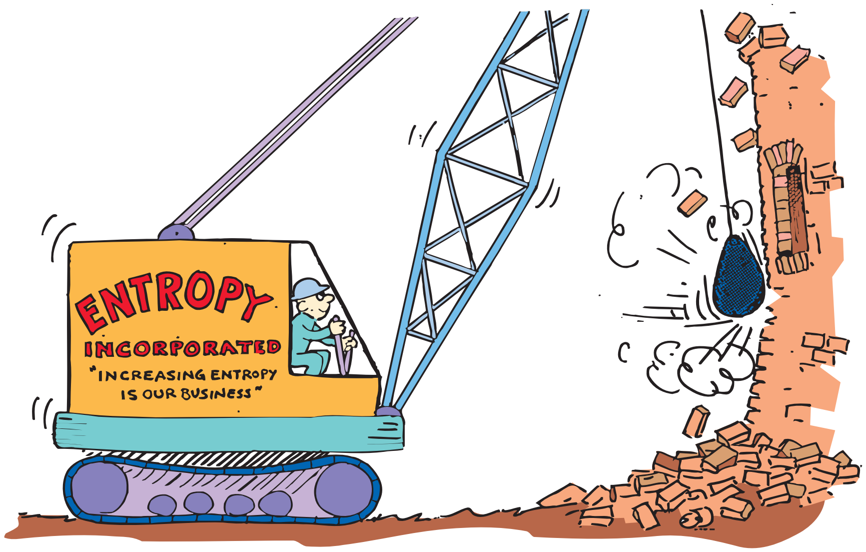


FIGURE 24.15
The motto of this contractor—"Increasing entropy is our business"—is appropriate because by knocking down the building, the contractor increases the disorder of the structure.

These situations are possible—but so highly improbable that they are never observed. The second law tells us the most probable course of events—not the only possible one.

The laws of thermodynamics are sometimes put this way: You can't win (because you can't get any more energy out of a system than you put in), you can't break even (because you can't even get as much energy out as you put in), and you can't get out of the game (entropy in the universe is always increasing).

CONCEPT CHECK What always happens to the entropy of systems?

Science, Technology, and Society

Thermodynamics and Thermal Pollution

A modern electric power plant, though large and complex, can be approximated as a simple heat engine. The power plant uses heat from the burning of coal, oil, gas, or heat from nuclear fission to do work turning electric generators. In this process, it also produces waste heat as an inevitable consequence of the second law of thermodynamics. This waste heat is sometimes called *thermal pollution* because, like chemical wastes, it pollutes the environment.

Waste heat discharged into waterways can raise temperatures of aquatic environments enough to kill organisms and disrupt ecosystems. Waste heat discharged into the air can contribute to weather changes. Thermal pollution is unlike chemical pollution, since chemical pollution can be reduced by various methods. The only way to manage thermal pollution is to spread waste heat over areas large enough to absorb it without significantly increasing temperatures. Conservation and efficient technology are absolutely crucial to the health of our planet.

Critical Thinking Explain how the second law of thermodynamics tells us that it is impossible to produce usable energy with zero environmental impact.

▶ **Teaching Tip** Compare entropy to playing cards. A new deck of cards comes out of its box in ordered suits. Shuffle the deck once and you have disorder. Shuffle it again and you have more disorder. Think of the probability of shuffling the deck enough times to get some degree of order from the disorder.

Consider the old riddle, "How do you unscramble an egg?" The answer is simple: "Feed it to a chicken." But even then, you won't get all your original egg back—egg making has its inefficiencies, too!
PAUL

CONCEPT CHECK According to the second law of thermodynamics, in the long run, the entropy of a system always increases for natural processes.

Science, Technology, and Society

CRITICAL THINKING All energy transformations produce waste heat, and waste heat pollutes the environment.

Teaching Resources
- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook

Teaching Resources

- Teacher*EXPRESS*

24 REVIEW

Go Online PHSchool.com
For: Self-Assessment
Visit: PHSchool.com
Web Code: csa – 2400

Concept Summary

- As the thermal motion of atoms in a substance approaches zero, the kinetic energy of the atoms approaches zero, and the temperature of the substance approaches a lower limit.
- The first law of thermodynamics states that whenever heat is added to a system, it transforms to an equal amount of some other form of energy.
- When work is done on a gas by adiabatically compressing it, the gas gains internal energy and becomes warmer.
- The second law of thermodynamics states that heat will never of itself flow from a cold object to a hot object.
- According to the second law of thermodynamics, no heat engine can convert all heat input to mechanical energy output.
- Natural systems tend to proceed toward a state of greater disorder.
- According to the second law of thermodynamics, in the long run, entropy always increases for natural processes.

Key Terms

thermodynamics *(p. 468)*
absolute zero *(p. 469)*
first law of thermodynamics *(p. 470)*
adiabatic *(p. 472)*
second law of thermodynamics *(p. 474)*
heat engine *(p. 475)*
Carnot efficiency *(p. 476)*
entropy *(p. 480)*

think! Answers

24.1 At 0°C the gas has an absolute temperature of 273 K. Twice as much average kinetic energy means it has twice the absolute temperature, or two times 273 K. This would be 546 K, or 273°C. Do you and your classmates agree?

24.2 10 J.

24.3.1 At 1 km elevation, its temperature will be –10°C; at 5 km, –50°C.

24.3.2 If it were pulled down so quickly that heat conduction was negligible, it would be adiabatically compressed by the atmosphere and its temperature would rise to a piping hot 50°C (122°F), just as compressed air gets hot in a bicycle pump.

24.5 Zero efficiency; (400 K – 400 K)/400 K = 0. This means no work output is possible for any heat engine unless a temperature difference exists between the reservoir and the sink.

482

24 ASSESS

Check Concepts

Section 24.1

1. What is the meaning of the Greek words from which we get the word *thermodynamics?*

2. Is the study of thermodynamics concerned primarily with microscopic or macroscopic processes?

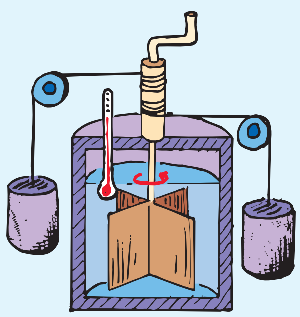
3. What is the lowest possible temperature on the Celsius scale? On the Kelvin scale?

4. What is the temperature of melting ice in kelvins? Of boiling water?

Section 24.2

5. How does the law of the conservation of energy relate to the first law of thermodynamics?

6. What happens to the internal energy of a system when work is done on it? What happens to its temperature?



7. What is the relationship between heat added to a system and the internal energy and external work done by the system?

8. If work is done adiabatically on a system, will the internal energy of the system increase or decrease? If work is done by a system, will the internal energy of the system increase or decrease?

Section 24.3

9. What condition is necessary for a process to be adiabatic?

10. What happens to the temperature of air when it is adiabatically compressed? When it adiabatically expands?

11. What generally happens to the temperature of rising air?

12. What generally happens to the temperature of sinking air?

Section 24.4

13. How does the second law of thermodynamics relate to the direction of heat flow?

Section 24.5

14. What three processes occur in every heat engine?

15. What is thermal pollution?

16. If all friction could be removed from a heat engine, would it be 100% efficient? Explain.

17. What is the ideal efficiency of a heat engine that operates with its hot reservoir at 500 K and its sink at 300 K?

18. Why are heat engines intentionally run at high operating temperatures?

24 ASSESS

Check Concepts

1. Heat and movement
2. Macroscopic
3. −273.15°C; 0 K
4. 273 K; 373 K
5. The first law of thermodynamics *is* the law of conservation of energy applied to thermal systems.
6. Increases; increases
7. Amount of heat added = increase in internal energy + work done
8. Increase; decrease
9. No heat enters or leaves while the process occurs.
10. Increases; decreases
11. Decreases, if adiabatic
12. Increases, if adiabatic
13. It defines the direction of heat flow from hot to cold.
14. Energy absorption, conversion of some energy to work, expulsion of the rest
15. Unwanted exhausted energy
16. No; efficiency depends on input and output temperatures.
17. 0.4 or 40%
18. To increase efficiency

19. Electricity converting to heat, car braking to a stop
20. 100%
21. Become disordered; yes, but only with work input
22. Entropy
23. Only with work or other organized energy input
24. Entropy increases in natural systems.
25. The first law has no exceptions; the second law may have some exceptions; the third law has none.

Plug and Chug

26. IE = $(T_{hot} - T_{cold})/T_{hot}$ = (800 K − 300 K)/(800 K) = 0.63
27. IE = $(T_{hot} - T_{cold})/T_{hot}$ = (530 K − 290 K)/(530 K) = 0.45
28. IE = $(T_{hot} - T_{cold})/T_{hot}$ = [(273 + 112) K − (273 + 27) K] ÷ (273 + 112) K = 0.22
29. IE = $(T_{hot} - T_{cold})/T_{hot}$ = (293 K − 283 K)/(293 K) = 0.034

Think and Explain

30. Kelvin scale
31. Half its absolute temperature, or (1/2)(10 + 273) K = 141.5 K = −131.5°C

24 ASSESS *(continued)*

Section 24.6

19. Give at least two examples to distinguish between organized energy and disorganized energy.
20. How much of the electrical energy transformed by a common lightbulb becomes heat energy?
21. With respect to orderly and disorderly states, what do natural systems tend to do? Can a disorderly state ever transform to an orderly state? Explain.

Section 24.7

22. What is the physicist's term for a measure of messiness?
23. Under what condition can entropy decrease in a system?
24. What is the relationship between the second law of thermodynamics and entropy?
25. Distinguish between the first, second, and third laws of thermodynamics in terms of whether or not exceptions occur.

Plug and Chug

Use the following equation to help you answer Questions 26–29.

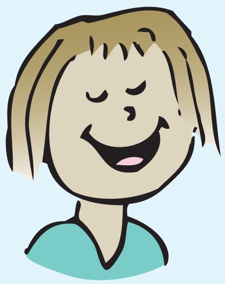
$$\text{Ideal efficiency} = \frac{T_{hot} - T_{cold}}{T_{hot}}$$

26. Calculate the *ideal* efficiency of a heat engine that takes in energy at 800 K and expels heat to a reservoir at 300 K.
27. Calculate the ideal efficiency of a ship's boiler when steam comes out at 530 K, pushes through a steam turbine, and exits into a condenser that is kept at 290 K by circulating seawater.
28. Calculate the ideal efficiency of a steam turbine that has a hot reservoir of 112°C high-pressure steam and a sink at 27°C.
29. In a heat engine driven by ocean temperature differences, the heat source (water near the surface) is at 293 K and the heat sink (deeper water) is at 283 K. Calculate the ideal efficiency of the engine.

Think and Explain

30. On which temperature scale does the average kinetic energy of molecules double when the temperature doubles?
31. On a 10°C day, your friend who likes cold weather says she wishes it were twice as cold. Taking this to mean she wishes the air had half the internal energy, what temperature would this be?

32. A friend said the temperature inside a certain oven is 600 and the temperature inside a certain star is 60,000. You're unsure about whether your friend meant kelvins or degrees Celsius. How much difference does it make in each case?

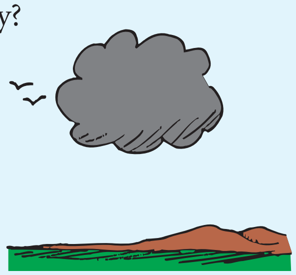


33. Maria vigorously shakes a can of liquid back and forth for more than a minute. Does the temperature of the liquid increase? Why or why not? (Try it and see.)

34. When you pump a tire with a bicycle pump, the cylinder of the pump becomes hot. Give two reasons why this is so.

35. What happens to the gas pressure within a sealed gallon can when it is heated? When it is cooled?

36. We know that warm air rises. So it might seem that the air temperature should be higher at the top of mountains than down below. But the opposite is most often the case. Why?



37. The combined molecular kinetic energies of molecules in a very large container of cold water are greater than the combined molecular kinetic energies in a cup of hot tea. Pretend you partially immerse the teacup in the cold water and that the tea absorbs 10 joules of energy from the water and becomes hotter, while the water that gives up 10 joules of energy becomes cooler. Would this energy transfer violate the first law of thermodynamics? The second law of thermodynamics? Explain.

38. Is it possible to entirely convert a given amount of heat into mechanical energy? Is it possible to entirely convert a given amount of mechanical energy into heat? Cite examples to illustrate your answers.

39. Suppose one wishes to cool a kitchen by leaving the refrigerator door open and closing the kitchen door and windows. What will happen to the room temperature? Why?

40. Will the efficiency of a car engine increase, decrease, or remain the same if the muffler is removed? If the car is driven on a very cold day? Defend your answers.

32. An oven at 600°C (873 K) is hotter than an oven at 600 K by 45% in absolute temperature, whereas a star at 60,273 K is hotter than a star at 60,000 K by only 0.45%.

33. Yes, work is done on liquid and increases internal energy.

34. Compression of air and friction of the piston on the inner wall of the chamber

35. Pressure increases when heated; decreases when cooled.

36. Rising air undergoes adiabatic expansion and cools.

37. No, energy is conserved; yes, internal energy will not freely transfer from a cooler to a warmer object.

38. No; yes; if you drag a block across a floor, you produce heat but heat cannot drag the block back.

39. After a very brief momentary decrease due to the mixing of warm and cold air, the room temperature will increase, because the room itself is the effective heat sink.

40. Increase; back pressure is reduced. Efficiency also increases on a cold day due to the increase in the temperature difference between the hot reservoir in the engine and its surroundings (the sink).

41. Greater crushing in cold water, but also in hot water. Not in boiling water; any vapor that condenses offset by vapor from boiling.

42. Jet engine; it saves a step, so is more efficient.

43. No, the lights assist the heating process. Leaving them on in a building that is being air conditioned is wasteful, because the air conditioner must extract the extra energy given off by the lights.

44. It refers to an undesirable by-product of some process, and desirability is relative.

45. Yes; if the exhausted heat is desirable then no thermal pollution is produced.

46. Increases (substitution of a smaller value of T_{cold} into the Carnot efficiency equation will confirm this.)

47. No, work has been put into the refrigeration system.

48. Agree with both, without contradiction.

Think and Solve

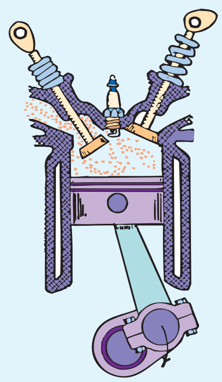
49. 10°C is 283 K; 2×283 K = 566 K, or 293°C.

50. Adiabatic compression would heat the confined air by about 10°C/km descent.
$\Delta T = 10 \text{ km} \times 10°\text{C/km} = 100°\text{C}$; $(-35°\text{C} + 100°\text{C}) = 65°\text{C}$, or 149°F

24 ASSESS *(continued)*

41. Consider the inverted soft drink can placed in a pan of water, as featured in the Discover! box in Section 24.5. The can is crushed by atmospheric pressure. Would crushing occur if the water were hot but not boiling? Would it be crushed in boiling water? (Try it and see!)

42. A mixture of fuel and air is burned rapidly in a combustion engine to push a piston in the engine that in turn propels the vehicle. In a jet engine, a mixture of fuel and air is burned rapidly and, instead of pushing pistons, pushes the aircraft itself. Which do you suppose is more efficient?



43. In buildings that are being heated electrically, is it wasteful to turn on all the lights? Is turning on all the lights wasteful if the building is being cooled by air conditioning? Defend your answers.

44. Why is "thermal pollution" a relative term?

45. Is it possible to construct a heat engine that produces no thermal pollution? Defend your answer.

46. What happens to the efficiency of a heat engine when the temperature of the reservoir into which heat energy is ejected is lowered?

47. Water put into a freezer compartment in your refrigerator goes to a state of less molecular disorder when it freezes. Is this an exception to the entropy principle? Explain.

48. Carlos says that perpetual motion machines are impossible to construct. John says that perpetual motion is common in nature—the motion of molecules, for example. Do you agree with Carlos, John, or both?

Think and Solve

49. Helium has the special property that its internal energy is directly proportional to its absolute temperature. Consider a flask of helium with a temperature of 10°C. If it is heated until it has twice the internal energy, what will its temperature be?

50. Imagine a giant dry-cleaner's bag full of air at a temperature of –35°C floating like a balloon with a string hanging from it 10 km above the ground. Estimate its temperature if you were able to yank it suddenly to Earth's surface.

486

51. What is the ideal efficiency of an automobile engine wherein fuel is heated to 2700 K and the outdoor air is 300 K?

52. Dr. Knute C. Cuckoo claims to have invented a heat engine that will revolutionize life as we know it. It runs between a hot source at 300°C and cold heat "sink" at 25°C. Dr. C. claims that his engine is 92% efficient.

   a. What is the actual maximum efficiency of his heat engine?
   b. What error did he make in his choice of temperature scales?

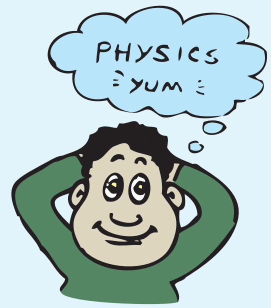
53. Which heat engine has greater ideal efficiency, one that operates between the temperatures 600 K and 400 K or one that operates between 500 K and 400 K? Explain how your answer conforms to the idea that a higher operating temperature yields higher efficiency.

54. To increase the efficiency of a heat engine, would it be better to increase the temperature of the reservoir while holding the temperature of the sink constant, or to decrease the temperature of the sink while holding the temperature of the reservoir constant? Show your work.

55. A heat engine takes in 100 kJ of energy from a source at 800 K and expels 50 kJ to a reservoir at 300 K. Calculate the ideal efficiency and the actual efficiency of the engine.

56. A certain heat engine takes in 25 kJ of heat and exhausts 17 kJ. Chris says that the efficiency of the engine is 0.32. Confirm his findings.

57. During one cycle, an ideal heat engine exhausts 3800 J of heat while performing 1200 J of useful work. Anthony says the efficiency of the engine is 0.24. Show that he is correct.



58. A heat engine operates between $T_{hot} = 750°C$ and $T_{cold} = 35°C$. Michael says that the theoretical maximum efficiency is about 70%. Do you agree? If so, show why. If not, show why not.

59. A college physics exam states that a power plant generating 420 MW of electricity runs between 540°C and 30°C, and asks for the minimum amount power input required for such a plant. The answer key reveals that the answer is 670,000 kJ each second, or 670 MW. Show how this figure comes about.

More Problem-Solving Practice
Appendix F

51. IE = (2700 K − 300 K) ÷ 2700 K = 88.9%

52. **a.** IE = $(T_{hot} - T_{cold}) \div T_{hot}$ = [(273 K + 300 K) − (273 K + 25 K)]/(273 K + 300 K) = 0.48
b. Dr. Cuckoo used Celsius temperatures instead of Kelvin: IE = $(T_{hot} - T_{cold})/T_{hot}$ = (300°C − 25°C)/(300°C) = 0.92

53. (600 K − 400 K)/600 K = 1/3, which is greater than (500 K − 400 K)/500 K = 1/5; greater efficiency is obtained for the higher operating temperature.

54. Decreasing T_{cold} will contribute to a greater increase in efficiency than increasing T_{hot} by the same amount.

55. IE = (800 K − 300 K)/(800 K) = 0.63; AE = 50 kJ/100 kJ = 0.5

56. Eff = $W/Q_{in} = (Q_{in} - Q_{out})/Q_{in}$ = (25 kJ − 17 kJ)/25 kJ = 0.32

57. Eff = W_{out}/Q_{in}. Since $W = Q_{in} - Q_{out}$, $Q_{in} = Q_{out} + W$. So Eff = $W/(Q_{out} + W)$ = (1200 J)/(3800 J + 1200 J) = 0.24.

58. Agree; IE = $(T_{hot} - T_{cold})/T_{hot}$ = [(273 + 750) K − (273 + 35) K]/(273 + 750) K = 0.70, or 70%

59. Since Ideal Efficiency IE = W/Q_{in}, Q_{in} = W/IE. Since IE = $(T_{hot} - T_{cold})/T_{hot}$ = [(273 + 540) K − (273 + 30)K]/(273 + 540) K = 0.627, then Q_{in} = 420 MJ/0.627 = 670 MJ each second.

Teaching Resources
- Computer Test Bank
- Chapter and Unit Tests