Answer to Chapter Opening Question

Yes. That’s what a refrigerator does: it makes heat flow from the cold interior of the refrigerator to the warm outside. The second law of thermodynamics says that heat cannot spontaneously flow from a cold body to a hot one. A refrigerator has a motor that does work on the system to force the heat to flow in that way.

Answers to Test Your Understanding Questions

Section 20.1 This process is irreversible. Like sliding a book across a table, rubbing your hands together uses friction to convert mechanical energy into heat. The (impossible) reverse process would involve your hands spontaneously getting colder, with the released energy forcing your hands to move rhythmically back and forth!

Section 20.2 Each truck’s engine rejects 8000 J of heat per cycle and goes through 25 cycles per second. The total heat released in 24 hours is therefore

\[
|Q_c - \text{total}| = (1000 \text{ trucks}) \left( \frac{8000 \text{ J}}{\text{truck \cdot cycle}} \right) \left( \frac{25 \text{ cycles}}{\text{s}} \right) \\
\times \left( \frac{60 \text{ s}}{\text{min}} \right) \left( \frac{60 \text{ min}}{\text{h}} \right) \left( \frac{24 \text{ h}}{1} \right) \\
= 1.7 \times 10^{13} \text{ J}
\]

This is equivalent to 4.8 \times 10^6 kilowatt-hours (a kilowatt-hour is a unit of energy used in electric power systems, equal to 10^7 watts of power delivered for one hour). A kilowatt-hour of electric energy costs a few cents, so this discarded heat is equivalent to approximately $100,000 of lost energy.

Section 20.3 Let \(Q_H\), the heat input at volume \(V\), be constant. Then a greater compression ratio \(r\) means a greater maximum volume \(rV\), so the points \(d\) and \(a\) are farther to the right in the \(pV\)-diagram of Fig. 20.5 and the area enclosed by the loop \(abcd\) is greater. The area within this loop is \(W\), the work done by the engine, so a greater compression ratio means more work for the same input of heat and hence a greater efficiency \(\epsilon = W/Q_H\).

Section 20.4 A refrigerator uses an input of work to transfer heat from one system (the refrigerator’s interior) to another system (its exterior, which includes the house in which the refrigerator is installed). If the door is open, these two systems are really the same system and will eventually come to the same temperature. By the first law of thermodynamics, all of the work input to the refrigerator motor will be converted into heat and the temperature in your house will actually increase. To cool the house you need a system that will transfer heat from it to the outside world, such as an air conditioner or heat pump.

Section 20.5 The expanding steam does work to push the cork upward and pop it into the air. This process is not 100% efficient because only part of the heat absorbed from the burner goes into doing work; the remainder goes into raising the temperature of the water and the test tube.

Section 20.6 The efficiency can be no better than that of a Carnot engine running between the same two temperature limits, \(\epsilon_{\text{Carnot}} = 1 - (T_c/T_H)\) [Eq. (20.14)]. The temperature \(T_c\) of the cold reservoir for this air-cooled engine is about 300 K (ambient temperature) and the temperature \(T_H\) of the hot reservoir cannot exceed the melting point of copper, 1356 K (see Table 17.4). Hence the maximum possible Carnot efficiency is \(\epsilon = 1 - (300 \text{ K})/(1356 \text{ K}) = 0.78\), or 78%. The temperature of any real engine would be less than this, so it would be impossible for the inventor’s engine to attain 85% efficiency. You should invest your money elsewhere.

Section 20.7 The process described is exactly the opposite of the process used in Example 20.10, so the net entropy change would be \(-102 \text{ J/K}\). This result violates the second law of thermodynamics, which states that the entropy of an isolated system cannot decrease. This remarkable process is quite impossible.

Section 20.8 (a) We saw in Example 20.8 (Section 20.7) that for an ideal gas, the entropy change in a free expansion is the same as in an isothermal expansion. From Eq. (20.23), this implies that the ratio of the number of microscopic states after and before the expansion, \(w_2/w_1\), is also the same for these two cases. From Example 20.11, \(w_2/w_1 = 2^n\), so the number of microscopic states increases by a factor \(2^n\). (b) In a reversible expansion the entropy change is \(\Delta S = \int dQ/T = 0\); if the expansion is adiabatic there is no heat flow, so \(\Delta S = 0\). From Eq. (20.23), \(w_2/w_1 = 1\) and there is no change in the number of microscopic states. The difference is that in an adiabatic expansion the temperature drops and the molecules move more slowly, so they have fewer microscopic states available to them than in an isothermal expansion.

Discussion Questions

Q20.1 A pot is half-filled with water, and a lid is placed on the pot, forming a tight seal so that no water vapor can escape. The pot is heated on a stove, forming water vapor inside the pot. The heat is then turned off and the water vapor condenses back to liquid. Is this cycle reversible or irreversible? Why?
Q20.2 Give two examples of reversible processes and two examples of irreversible processes in purely mechanical systems, such as blocks sliding on planes, springs, pulleys, and strings. Explain what makes each process reversible or irreversible.
Q20.3 What irreversible processes occur in a gasoline engine? Why are they irreversible?
Q20.4 Suppose you try to cool the kitchen of your house by leaving the refrigerator door open. What happens? Why? Would the result be the same if you left open a picnic cooler full of ice? Explain the reason for any differences.
Q20.5 A member of the U.S. Congress proposed a scheme to produce energy as follows. Water molecules (H₂O) are to be broken apart to produce hydrogen and oxygen. The hydrogen is then burned (that is, combined with oxygen), releasing energy in the process. The only product of this combustion is water, so there is no pollution. In light of the second law of thermodynamics, what do you think of this energy-producing scheme?
Q20.6 Some critics of biological evolution claim that it violates the second law of thermodynamics, since evolution involves simple life forms developing into more complex and more highly ordered organisms. Explain why this is not a valid argument against evolution.

Q20.7 Is it a violation of the second law of thermodynamics to convert mechanical energy completely into heat? To convert heat completely into work? Explain your answers.

Q20.8 A growing plant creates a highly complex and organized structure out of simple materials such as air, water, and trace minerals. Does this violate the second law of thermodynamics? Why or why not? What is the plant’s ultimate source of energy? Explain your reasoning.

Q20.9 Imagine a special air filter placed in a window of a house. The tiny holes in the filter only allow air molecules moving faster than a certain speed to exit the house, and only allows air molecules moving slower than that speed to enter the house from outside. Explain why an air filter would cool the house, and why the second law of thermodynamics makes building such a filter an impossible task.

Q20.10 An electric motor has its shaft coupled to that of an electric generator. The motor drives the generator, and some current from the generator is used to run the motor. The excess current is used to light a home. What is wrong with this scheme?

Q20.11 When a wet cloth is hung up in a hot wind in the desert, it is cooled by evaporation to a temperature that may be 20°C or so below that of the air. Discuss this process in light of the second law of thermodynamics.

Q20.12 If no real engine can be as efficient as a Carnot engine operating between the same two temperatures, what is the point of developing and using Eq. (20.14)?

Q20.13 Suppose you want to increase the efficiency of a heat engine. Would it be better to increase $T_H$ or to decrease $T_C$ by an equal amount? Why?

Q20.14 What would be the efficiency of a Carnot engine operating with $T_H = T_C$? What would be the efficiency if $T_C = 0$ K and $T_H$ were any temperature above 0 K? Interpret your answers.

Q20.15 Real heat engines, like the gasoline engine in a car, always have some friction between their moving parts, although lubricants keep the friction to a minimum. Would a heat engine with completely frictionless parts be 100% efficient? Why or why not? Does the answer depend on whether or not the engine runs on the Carnot cycle? Again, why or why not?

Q20.16 Does a refrigerator full of food consume more power if the room temperature is 20°C than if it is 15°C? Or is the power consumption the same? Explain your reasoning.

Q20.17 Explain why each of the following processes are examples of increasing disorder or randomness: mixing hot and cold water; free expansion of a gas; irreversible heat flow; and developing heat by mechanical friction. Are entropy increases involved in all of these? Why or why not?

Q20.18 Are the earth and sun in thermal equilibrium? Are there entropy changes associated with the transmission of energy from the sun to the earth? Does radiation differ from other modes of heat transfer with respect to entropy changes? Explain your reasoning.

Q20.19 Discuss the entropy changes involved in the preparation and consumption of a hot fudge sundae.

Q20.20 If you run a movie film backwards, it is as if the direction of time is reversed. In the time-reversed movie, would you see processes that violate conservation of energy? Conservation of linear momentum? Would you see processes that violate the second law of thermodynamics? In each case, if law-breaking processes could occur, give some examples.

**Exercises**

**Section 20.2 Heat Engines**

**20.1** A diesel engine performs 2200 J of mechanical work and discards 4300 J of heat each cycle. a) How much heat must be supplied to the engine in each cycle? b) What is the thermal efficiency of the engine?

**20.2** An aircraft engine takes in 9000 J of heat and discards 6400 J each cycle. a) What is the mechanical work output of the engine during one cycle? b) What is the thermal efficiency of the engine?

**20.3** A Gasoline Engine. A gasoline engine takes in $1.61 \times 10^4$ J of heat and delivers 3700 J of work per cycle. The heat is obtained by burning gasoline with a heat of combustion of $4.60 \times 10^4$ J/g. a) What is the thermal efficiency? b) How much heat is discarded in each cycle? c) What mass of fuel is burned in each cycle? d) If the engine goes through 60.0 cycles per second, what is its power output in kilowatts? In horsepower?

**20.4** A gasoline engine has a power output of 180 kW (about 241 hp). Its thermal efficiency is 28.0%. a) How much heat must be supplied to the engine per second? b) How much heat is discarded by the engine per second?

**20.5** A certain nuclear-power plant has a mechanical-power output (used to drive an electric generator) of 330 MW. Its rate of heat input from the nuclear reactor is 1300 MW. a) What is the thermal efficiency of the system? b) At what rate is heat discarded by the system?

**Section 20.3 Internal-Combustion Engines**

**20.6** What compression ratio $r$ must an Otto cycle have to achieve an ideal efficiency of 65.0% if $\gamma = 1.40$?

**20.7** For an Otto cycle with $\gamma = 1.40$ and $r = 9.50$, the temperature of the gasoline-air mixture when it enters the cylinder is 22.0°C (point $a$ of Fig. 20.5). a) What is the temperature at the end of the compression stroke (point $b$)? b) The initial pressure of the gasoline-air mixture (point $a$) is $8.50 \times 10^5$ Pa, slightly below atmospheric pressure. What is the pressure at the end of the compression stroke?

**20.8** The Otto-cycle engine in a Mercedes-Benz SLK230 has a compression ratio of 8.8. a) What is the ideal efficiency of the engine? Use $\gamma = 1.40$. b) The engine in a Dodge Viper GT2 has a slightly higher compression ratio of 9.6. How much increase in the ideal efficiency results from this increase in the compression ratio?

**Section 20.4 Refrigerators**

**20.9** A refrigerator has a coefficient of performance of 2.10. Each cycle it absorbs $3.40 \times 10^4$ J of heat from the cold reservoir. a) How much mechanical energy is required each cycle to operate the refrigerator? b) During each cycle, how much heat is discarded to the high-temperature reservoir?
20.10 Liquid refrigerant at a pressure of $1.34 \times 10^5$ Pa leaves the expansion valve of a refrigerator at $-23.0^\circ$C. It then flows through the evaporation coils inside the refrigerator and leaves as vapor at the same pressure and at $-20.5^\circ$C, the same temperature as the inside of the refrigerator. The boiling point of the refrigerant at this pressure is $-23.0^\circ$C, the heat of vaporization is $1.60 \times 10^4$ J/kg, and the specific heat capacity of the vapor at constant pressure is 485 J/kg·K. The coefficient of performance of the refrigerator is $K = 2.8$. If 8.00 kg of refrigerant flows through the refrigerator each hour, find the electric power that must be supplied to the refrigerator.

20.11 A window air-conditioner unit absorbs $9.80 \times 10^4$ J of heat per minute from the room being cooled and in the same time period deposits $1.44 \times 10^5$ J of heat into the outside air. a) What is the power consumption of the unit in watts? b) What is the energy efficiency rating of the unit?

20.12 A freezer has a coefficient of performance of 2.40. The freezer is to convert 1.80 kg of water at $25.0^\circ$C to 1.80 kg of ice at $-5.0^\circ$C in one hour. a) What amount of heat must be removed from the water at $25.0^\circ$C to convert it to ice at $-5.0^\circ$C? b) How much electrical energy is consumed by the freezer during this hour? c) How much wasted heat is rejected to the room in which the freezer sits?

Section 20.6 The Carnot Cycle

20.13 A Carnot engine whose high-temperature reservoir is at 620 K takes in 550 J of heat at this temperature in each cycle and gives up 335 J to the low-temperature reservoir. a) How much mechanical work does the engine perform during each cycle? b) What is the temperature of the low-temperature reservoir? c) What is the thermal efficiency of the cycle?

20.14 A Carnot engine is operated between two heat reservoirs at temperatures of 620 K and 300 K. a) If the engine receives 6.45 kJ of heat energy from the reservoir at 620 K in each cycle, how many joules per cycle does it reject to the reservoir at 300 K? b) How much mechanical work is performed by the engine during each cycle? c) What is the thermal efficiency of the engine?

20.15 An ice-making machine operates in a Carnot cycle. It takes heat from water at 0.0°C and rejects heat to a room at 24.0°C. Suppose that 85.0 kg of water at 0.0°C are converted to ice at 0.0°C. a) How much heat is rejected to the room? b) How much energy must be supplied to the device?

20.16 A Carnot refrigerator is operated between two heat reservoirs at temperatures of 320 K and 270 K. a) If in each cycle the refrigerator receives 41.5 J of heat energy from the reservoir at 270 K, how many joules of heat energy does it deliver to the reservoir at 320 K? b) If the refrigerator goes through 165 cycles each minute, what power input is required to operate the refrigerator? c) What is the coefficient of performance of the refrigerator?

20.17 A Carnot device extracts 5.00 kJ of heat from a body at $-10.0^\circ$C. How much work is done if the device exhausts heat into the environment at a) 25.0°C? b) 0.0°C? c) $-25.0^\circ$C? In each case, is the device acting as an engine or as a refrigerator?

20.18 The Kwik-Freeze Appliance Co. wants you to design a food freezer that will keep the freezing compartment at $-5.0^\circ$C and will operate in a room at $20.0^\circ$C. This freezer is to make 5.00 kg of ice at 0.0°C, starting with water at 20.0°C. Find the least possible amount of electrical energy needed to make this ice and the smallest possible amount of heat expelled into the room.

20.19 An ideal Carnot engine operates between 500°C and 100°C with a heat input of 250 J per cycle. What minimum number of cycles are necessary for the engine to lift a 500-kg rock through a height of 100 m?

20.20 A Carnot heat engine has a thermal efficiency of 0.600 and the temperature of its hot reservoir is 800 K. If 3000 J of heat is rejected to the cold reservoir in one cycle, what is the work output of the engine during one cycle?

20.21 A Carnot heat engine uses a hot reservoir consisting of a large amount of boiling water and a cold reservoir consisting of a large tub of ice and water. In five minutes of operation of the engine, the heat rejected by the engine melts 0.0400 kg of ice. During this time, how much work W is performed by the engine?

20.22 An inventor claims to have developed an engine that in each cycle takes 2.60 $\times 10^4$ J of heat at a temperature of 400 K, does 42.0 kWh of mechanical work, and rejects heat at a temperature of 250 K. Would you advise investing money to put this engine on the market? Why or why not?

20.23 a) Show that the efficiency $e$ of a Carnot engine and the coefficient of performance $K$ of a Carnot refrigerator are related by $K = (1 - e)/e$. The engine and refrigerator operate between the same hot and cold reservoirs. b) What is $K$ for the limiting values $e \rightarrow 1$ and $e \rightarrow 0$? Explain.

Section 20.7 Entropy

20.24 A sophomore with nothing better to do adds heat to 0.350 kg of ice at 0.0°C until it is all melted. a) What is the change in entropy of the water? b) The source of heat is a very massive body at a temperature of 25.0°C. What is the change in entropy of this body? c) What is the total change in entropy of the water and the heat source?

20.25 You pour 100 g of water at 80.0°C into the ocean, which is at 20.0°C, and wait about ten minutes. Treat the water you pour and the ocean as an isolated system. a) Is this process reversible or irreversible? Explain your reasoning using simple physical reasoning without resorting to any equations. b) Calculate the net entropy change of the system during this process. Explain whether or not this result is consistent with your answer to part (a).

20.26 A 15.0-kg block of ice at 0.0°C melts inside a large room that has a temperature of 20.0°C. Treat the ice and the room as an isolated system and assume that the room is large enough for its temperature change to be ignored. a) Is this process reversible or irreversible? Explain your reasoning using simple physical reasoning without resorting to any equations. b) Calculate the net entropy change of the system during this process. Explain whether or not this result is consistent with your answer to part (a).

20.27 Calculate the entropy change that occurs when 1.00 kg of water at 20.0°C is mixed with 2.00 kg of water at 80.0°C.

20.28 Three moles of an ideal gas undergo a reversible isothermal compression at 20.0°C. During this compression, 1850 J of work is done on the gas. What is the change of entropy of the gas?
20.29 What is the change in entropy of 0.130 kg of helium gas at the normal boiling point of helium when it all condenses isothermally to 1.00 L of liquid helium? (Hint: See Table 17.4 in Section 17.6.)

20.30 a) Calculate the change in entropy when 1.00 kg of water at 100°C is vaporized and converted to steam at 100°C (see Table 17.4). b) Compare your answer to the change in entropy when 1.00 kg of ice is melted at 0°C, calculated in Example 20.5 (Section 20.7). Is the change in entropy greater for melting or for vaporization? Interpret your answer, using the idea that entropy is a measure of the randomness of a system.

20.31 a) Calculate the change in entropy when 1.00 mol of water (molecular mass 18.0 g/mol) at 100°C evaporates to form water vapor at 100°C. b) Repeat the calculation of part (a) for 1.00 mol of liquid nitrogen, 1.00 mol of silver, and 1.00 mol of mercury when each is vaporized at its normal boiling point. (See Table 17.4 for the heats of vaporization, and Appendix D for the molar masses. Note that the nitrogen molecule is N₂.) c) Your results in parts (a) and (b) should be in relatively close agreement. (This is called the rule of Dulong and Petit.) Explain why this should be so, using the idea that entropy is a measure of the randomness of a system.

20.32 A block of copper with a mass of 3.50 kg, initially at 100.0°C, is dropped into 0.800 kg of water initially at 0.0°C. a) What is the final temperature of the system? b) What is the total change in entropy of the system?

20.33 Two moles of an ideal gas undergo a reversible isothermal expansion from 0.0280 m³ to 0.0420 m³ at a temperature of 25.0°C. What is the change in entropy of the gas?

*Section 20.8 Microscopic Interpretation of Entropy

*20.34 A box is separated by a partition into two parts of equal volume. The left side of the box contains 500 molecules of nitrogen gas; the right side contains 100 molecules of oxygen gas. The two gases are at the same temperature. The partition is punctured, and equilibrium is eventually attained. Assume that the volume of the box is large enough for each gas to undergo a free expansion and not change temperature. a) On average, how many molecules of each type will there be in either half of the box? b) What is the change in entropy of the system when the partition is punctured? c) What is the probability that the molecules will be found in the same distribution as they were before the partition was punctured, that is, 500 nitrogen molecules in the left half and 100 oxygen molecules in the right half?

*20.35 Two moles of an ideal gas occupy a volume $V$. The gas expands isothermally and reversibly to a volume $3V$. a) Is the velocity distribution changed by the isothermal expansion? Explain. b) Use Eq. (20.23) to calculate the change in entropy of the gas. c) Use Eq. (20.18) to calculate the change in entropy of the gas. Compare this result to that obtained in (b).

*20.36 You toss four identical coins on the floor. Each coin has an equal probability of showing heads or tails. a) What is the probability of all four coins showing heads? Of all four showing tails? b) What is the probability of three coins showing heads and one tails? What is the probability of three coins showing tails and one heads? c) What is the probability of two coins showing heads and two showing tails? d) What is the sum of the five probabilities calculated in parts (a) through (c)? Explain.

**Problems**

20.37 You are designing a Carnot engine that has two moles of CO₂ as its working substance; the gas may be treated as ideal. The gas is to have a maximum temperature of 527°C and a maximum pressure of 5.00 atm. With a heat input of 400 J per cycle, you want 300 J of useful work. a) Find the temperature of the cold reservoir. b) For how many cycles must this engine run to melt completely a 10.0-kg block of ice originally at 0.0°C, using only the heat rejected by the engine?

20.38 A Carnot engine whose low-temperature reservoir is at 80.0°C has an efficiency of 40.0%. An engineer is assigned the problem of increasing this to 45.0%. a) By how many Celsius degrees must the temperature of the high-temperature reservoir be increased if the temperature of the low-temperature reservoir remains constant? b) By how many Celsius degrees must the temperature of the low-temperature reservoir be decreased if that of the high-temperature reservoir remains constant?

20.39 A heat engine takes 0.350 mol of a diatomic ideal gas around the cycle shown in the pV-diagram of Fig. 20.20. Process 1 → 2 is at constant volume, process 2 → 3 is adiabatic, and process 3 → 1 is at a constant pressure of 1.00 atm. The value of $γ$ for this gas is 1.40. a) Find the pressure and volume at points 1, 2, and 3. b) Calculate $Q$, $W$, and $ΔU$ for each of the three processes. c) Find the net work done by the gas in the cycle. d) Find the net heat flow into the engine in each cycle. e) What is the thermal efficiency of the engine? How does this compare to the efficiency of a Carnot-cycle engine operating between the same minimum and maximum temperatures $T_1$ and $T_2$?

20.40 A heat engine operates with cycle abed. The working substance of the engine is CO₂ gas; the gas can be treated as ideal. The maximum temperature of the gas during the cycle is 1000 K. The pressure and volume of the gas in each state is $p_a = p_c = 2.00 \times 10^5 \text{ Pa}$; $p_b = p_d = 6.00 \times 10^5 \text{ Pa}$; $V_a = V_c = 0.0100 \text{ m}^3$; $V_b = V_d = 0.0300 \text{ m}^3$. Calculate a) the number of moles of CO₂; b) the heat input in each cycle; c) the waste heat per cycle; d) the work performed by the engine in each cycle; e) the thermal efficiency of the engine.

20.41 Heat Pump. A heat pump is a heat engine run in reverse. In winter it pumps heat from the cold air outside into the warmer air inside the building, maintaining the building at a comfortable temperature. In summer, it pumps heat from the cooler air inside the building to the warmer air outside, acting as an air conditioner. a) If the outside temperature in winter is −5.0°C and the inside temperature is 17.0°C, how many joules of heat will the heat pump deliver to the inside for each joule of electrical energy used to run the unit, assuming an ideal Carnot cycle? b) Suppose you have the option of using electrical resistance heating rather than a heat pump. How much electrical energy would you need in order to deliver the
same amount of heat to the inside of the house as in part (a)? Consider a Carnot heat pump delivering heat to the inside of a house to maintain it at 68°F. Show that the heat pump delivers less heat for each joule of electrical energy used to operate the unit as the outside temperature decreases. Notice that this behavior is opposite to the dependence of the efficiency of a Carnot heat engine on the difference in the reservoir temperatures. Explain why this is so.

20.42 A heat engine operates using the cycle shown in Fig. 20.21. The working substance is 2.00 moles of helium gas, which reaches a maximum temperature of 327°C. Assume the helium can be treated as an ideal gas. Process $bc$ is isothermal. The pressure in states $a$ and $c$ is $1.00 \times 10^5$ Pa and the pressure in state $b$ is $3.00 \times 10^5$ Pa. a) How much heat enters the gas and how much leaves the gas each cycle? b) How much work does the engine do each cycle and what is its efficiency? c) Compare this engine’s efficiency with the maximum possible efficiency attainable with the hot and cold reservoirs used by this cycle.

20.43 As a budding mechanical engineer, you are called upon to design a Carnot engine that has 2.00 moles of a monatomic ideal gas as its working substance and that operates from a high-temperature reservoir at 500°C. The engine is to lift a 15.0-kg weight 2.00 m per cycle, using 500 J of heat input. The gas in the engine chamber can have a minimum volume of 5.00 L during the cycle. a) Draw a $pV$-diagram for this cycle. Show in your diagram where heat enters and leaves the gas. b) What must be the temperature of the cold reservoir? c) What is the thermal efficiency of the engine? d) How much heat energy does this engine waste per cycle? e) What is the maximum pressure that the gas chamber will have to withstand?

20.44 An experimental power plant at the Natural Energy Laboratory of Hawaii generates electricity from the temperature gradient of the ocean. The surface and deep-water temperatures are 27°C and 6°C, respectively. a) What is the maximum theoretical efficiency of this power plant? b) If the power plant is to produce 210 kW of power, at what rate must heat be extracted from the warm water? What rate must heat be absorbed by the cold water? Assume the maximum theoretical efficiency. c) The cold water that enters the plant leaves it at a temperature of 10°C. What must be the flow rate of cold water through the system? Give your answer in kg/h and L/h.

20.45 What is the thermal efficiency of an engine that operates by taking $n$ moles of diatomic ideal gas through the cycle $1 \to 2 \to 3 \to 4 \to 1$ shown in Fig. 20.22?

20.46 A cylinder contains oxygen at a pressure of 2.00 atm. The volume is 4.00 L, and the temperature is 300 K. Assume that the oxygen may be treated as an ideal gas. The oxygen is carried through the following processes:

i) Heated at constant pressure from the initial state (state 1) to state 2, which has $T = 450$ K.

ii) Cooled at constant volume to 250 K (state 3).

iii) Compressed at constant temperature to a volume of 4.00 L (state 4).

iv) Heated at constant volume to 300 K, which takes the system back to state 1.

a) Show these four processes in a $pV$-diagram, giving the numerical values of $p$ and $V$ in each of the four states. b) Calculate $Q$ and $W$ for each of the four processes. c) Calculate the net work done by the oxygen. d) What is the efficiency of this device as a heat engine? How does this compare to the efficiency of a Carnot-cycle engine operating between the same minimum and maximum temperatures of 250 K and 450 K?

20.47 Thermodynamic Processes for a Refrigerator. A refrigerator operates on the cycle shown in Fig. 20.23. The compression ($d \to a$) and expansion ($b \to c$) steps are adiabatic. The temperature, pressure, and volume of the coolant in each of the four states $a$, $b$, $c$, and $d$ are given in the table below.

<table>
<thead>
<tr>
<th>State</th>
<th>$T$ (°C)</th>
<th>$P$ (kPa)</th>
<th>$V$ (m$^3$)</th>
<th>$U$ (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>80</td>
<td>2305</td>
<td>0.0682</td>
<td>1969</td>
</tr>
<tr>
<td>$b$</td>
<td>80</td>
<td>2305</td>
<td>0.00946</td>
<td>1171</td>
</tr>
<tr>
<td>$c$</td>
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<td>363</td>
<td>0.2202</td>
<td>1005</td>
</tr>
<tr>
<td>$d$</td>
<td>5</td>
<td>363</td>
<td>0.4513</td>
<td>1575</td>
</tr>
</tbody>
</table>

Percentage That Is Liquid

a) In each cycle, how much heat is taken from inside the refrigerator into the coolant while the coolant is in the evaporator? b) In each cycle, how much heat is exhausted from the coolant into the air outside the refrigerator while the coolant is in the condenser? c) In each cycle, how much work is done by the motor that operates the compressor? d) Calculate the coefficient of performance of the refrigerator.

20.48 A monatomic ideal gas is taken around the cycle shown in Fig. 20.24 in the direction

![Figure 20.23 Problem 20.47.](image1)

![Figure 20.24 Problem 20.48.](image2)
shown in the figure. The path for process \( c \rightarrow a \) is a straight line in the \( pV \)-diagram. a) Calculate \( Q \), \( W \), and \( \Delta U \) for each process \( a \rightarrow b \), \( b \rightarrow c \), and \( c \rightarrow a \). b) What are \( Q \), \( W \), and \( \Delta U \) for one complete cycle? c) What is the efficiency of the cycle? 20.49 A Stirling-cycle Engine. The Stirling cycle is similar to the Otto cycle, except that the compression and expansion of the gas is done at constant temperature, not adiabatically as in the Otto cycle. The Stirling cycle is used in external combustion engines, which means that the gas inside the cylinder is not used in the combustion process. Heat is supplied by burning fuel steadily outside the cylinder, instead of explosively inside the cylinder as in the Otto cycle. For this reason Stirling-cycle engines are quieter than Otto-cycle engines, since there are no intake and exhaust valves (a major source of engine noise). While small Stirling engines are used for a variety of purposes, Stirling engines for automobiles have not been successful because they are larger, heavier, and more expensive than conventional automobile engines. In the cycle, the working fluid goes through the following sequence of steps (Fig. 20.25):

i) Compressed isothermally at temperature \( T_1 \) from the initial state \( a \) to state \( b \), with a compression ratio \( r \).
ii) Heated at constant volume to state \( c \) at temperature \( T_2 \).
iii) Expanded isothermally at \( T_2 \) to state \( d \).
iv) Cooled at constant volume back to the initial state \( a \).

Assume that the working fluid is \( n \) moles of an ideal gas (for which \( C_v \) is independent of temperature). a) Calculate \( Q \), \( W \), and \( \Delta U \) for each of the processes \( a \rightarrow b \), \( b \rightarrow c \), \( c \rightarrow d \), and \( d \rightarrow a \). b) In the Stirling cycle, the heat transfers in the processes \( b \rightarrow c \) and \( d \rightarrow a \) do not involve external heat sources, but rather use regeneration: the same substance that transfers heat to the gas inside the cylinder in the process \( b \rightarrow c \) also absorbs heat back from the gas in the process \( d \rightarrow a \). Hence the heat transfers \( Q_{b \rightarrow c} \) and \( Q_{d \rightarrow a} \) do not play a role in determining the efficiency of the engine. Explain this last statement by comparing the expressions for \( Q_{b \rightarrow c} \) and \( Q_{d \rightarrow a} \) calculated in part (a). c) Calculate the efficiency of a Stirling-cycle engine in terms of the temperatures \( T_1 \) and \( T_2 \). How does this compare to the efficiency of a Carnot-cycle engine operating between these same two temperatures? (Historically, the Stirling cycle was devised before the Carnot cycle.) Does this result violate the second law of thermodynamics? Explain. Unfortunately, actual Stirling-cycle engines cannot achieve this efficiency, due to problems with the heat-transfer processes and pressure losses in the engine.

20.50 A Carnot engine operates between two heat reservoirs at temperatures \( T_H \) and \( T_C \). An inventor proposes to increase the efficiency by running one engine between \( T_H \) and an intermediate temperature \( T' \) and a second engine between \( T' \) and \( T_C \) using as input the heat expelled by the first engine. Compute the efficiency of this composite system and compare it to that of the original engine.

20.51 The maximum power that can be extracted by a wind turbine from an air stream is approximately

\[
P = \frac{k d^3 v^3}{m}
\]

where \( d \) is the blade diameter, \( v \) is the wind speed, and the constant \( k = 0.5 \text{ W \cdot m}^3 / \text{s}^2 \). a) Explain the dependence of \( P \) on \( d \) and on \( v \) by considering a cylinder of air that passes over the turbine blades in time \( t \) (Fig. 20.26). This cylinder has diameter \( d \), length \( L = vt \), and density \( \rho \). b) The Mod-5B wind turbine at Kahuku on the Hawaiian island of Oahu has a blade diameter of 97 m (slightly longer than a football field) and sits atop a 58-m tower. It can produce 3.2 MW of electric power. Assuming 25% efficiency, what wind speed is required to produce this amount of power? Give your answer in m/s and in km/h. c) Commercial wind turbines are commonly located in or downwind of mountain passes. Why?

20.52 Fuel Economy and Automobile Performance. The Otto-cycle engine of a Volvo V70 has a compression ratio \( r = 8.5 \). The U.S. Environmental Protection Agency (EPA) fuel economy rating of this car is 25 miles per gallon on the highway (105 km/h, or 65 m/h). Gasoline has a heat of combustion of \( 4.60 \times 10^7 \text{ J/kg} \), and its density is 740 kg/m^3. a) At 105 km/h, what is the rate of gasoline consumption in L/h? b) What is the theoretical efficiency of the engine? Use \( \gamma = 1.4 \). c) How much power is the engine producing at 105 km/h? Assume that the engine is operating at its theoretical efficiency, and give your answer in watts and in horsepower. By comparison, the engine of the Volvo V70 has a maximum power of 236 hp. d) Due to heat losses and friction in the drive train, the actual efficiency is approximately 15%. Repeat part (c) using this information. What fraction of the maximum possible power is used for highway driving?

20.53 Automotive Thermodynamics. A Volkswagen Passat has a six-cylinder Otto-cycle engine with compression ratio \( r = 10.6 \). The diameter of each cylinder, called the bore of the engine, is 82.5 mm. The distance that the piston moves during the compression in Fig. 20.4, called the stroke of the engine, is 86.4 mm. The initial pressure of the air-fuel mixture (at point \( a \) in Fig. 20.5) is \( 8.50 \times 10^5 \text{ Pa} \), and the initial temperature is 300 K (the same as the outside air). Assume that 200 J of heat is added to each cylinder in each cycle by the burning gasoline, and that the gas has \( C_v = 20.5 \text{ J/mol \cdot K} \) and \( \gamma = 1.4 \). a) Calculate the total work done in one cycle in each cylinder of the engine, and the heat released when the gas is cooled to the temperature of the outside air. b) Calculate the volume of the air-fuel mixture at point \( a \) in the cycle. c) Calculate the pressure, volume, and temperature of the gas at points \( b \), \( c \), and \( d \) in the cycle. In a \( pV \)-diagram, show the numerical values of \( p \), \( V \), and \( T \) for each of the four states. d) Compare the effi-
ciency of this engine with the efficiency of a Carnot-cycle engine operating between the same maximum and minimum temperatures.

20.54 In a factory, an insulated iron bar 65.0 cm long having thermal conductivity 79.5 W/m-K and cross-sectional area 15.0 cm$^2$ conducts heat from a furnace at 250.0°C to a cool water reservoir at 40.0°C. a) By how much does the entropy of the factory change each second due to this process? b) Interpret your answer in terms of the reversibility or irreversibility of this process.

20.55 Unavailable Energy. The discussion of entropy and the second law that follows Example 20.10 (Section 20.7) says that the increase in entropy in an irreversible process is associated with energy becoming less available. Consider a Carnot cycle that uses a low temperature reservoir with Kelvin temperature $T_L$. This is a true reservoir, that is large enough not to change temperature when it accepts heat from the engine. Let the engine accept heat from an object of temperature $T'$, where $T' > T_L$. The object is of finite size, so cools as heat is extracted from it. The engine continues to operate until $T' = T_L$. a) Show that the heat rejected to the low temperature reservoir is $T_L |\Delta S_L|$, where $\Delta S_L$ is the change in entropy of the high-temperature reservoir. b) Apply the result of part (a) to 1.00 kg of water initially at a temperature of 373 K as the heat source for the engine and $T_L = 273$ K. How much total mechanical work can be performed by the engine until it stops? c) Repeat part (b) for 2.00 kg of water at 323 K. d) Compare the amount of work that can be obtained from the energy in the water of Example 20.10 before and after it is mixed. Discuss whether your result shows that energy has become less available.

20.56 Recalculate the change in entropy between points $a$ and $b$ of Fig. 20.15c if the reversible path is a) an isobaric expansion to 2$V$ followed by an isochoric process; b) an isochoric cooling to $p_{cr}/2$ followed by an isobaric expansion.

20.57 A 0.0500-kg cube of ice at an initial temperature of $-15.0°C$ is placed in 0.600 kg of water at $T = 45.0°C$ in an insulated container of negligible mass. Calculate the change in entropy of the system.

20.58 a) For the Otto cycle shown in Fig. 20.5, calculate the changes in entropy of the gas in each of the constant-volume processes $b \rightarrow c$ and $d \rightarrow a$ in terms of the temperatures $T_c$, $T_d$, $T_c$, and $T_d$ and the number of moles $n$ and the heat capacity $C_v$ of the gas. b) What is the total entropy change in the engine during one cycle? (Hint: Use the relation between $T_c$ and $T_d$ and between $T_d$ and $T_a$.) c) The processes $b \rightarrow c$ and $d \rightarrow a$ occur irreversibly in a real Otto engine. Explain how this can be reconciled with your result in part (b).

20.59 A $TS$-Diagram. a) Graph a Carnot cycle, plotting Kelvin temperature vertically and entropy horizontally. This is called a temperature-entropy diagram, or $TS$-diagram. b) Show that the area under any curve representing a reversible path in a temperature-entropy diagram represents the heat absorbed by the system.

c) Derive from your diagram the expression for the thermal efficiency of a Carnot cycle. d) Draw a temperature-entropy diagram for the Stirling cycle, described in Problem 20.49. Use this diagram to relate the efficiency of the Carnot and Stirling cycles.

20.60 A physics student immerses one end of a copper rod in boiling water at 100°C and the other end in an ice-water mixture at 0°C. The sides of the rod are insulated. After steady-state conditions have been achieved in the rod, 0.160 kg of ice melts in a certain time interval. For this time interval find a) the entropy change of the boiling water; b) the entropy change of the ice water mixture; c) the entropy change of the copper rod; d) the total entropy change of the entire system.

20.61 To heat one cup of water (250 cm$^3$) to make coffee, you place an electric heating element in the cup. As the water temperature increases from 20°C to 65°C, the temperature of the heating element remains at a constant 120°C. Calculate the change in entropy of a) the water; b) the heating element; c) the system of water and heating element. (Make the same assumption about the specific heat of water as in Example 20.10 (Section 20.7), and ignore the heat that flows into the ceramic coffee cup itself.) d) Is this process reversible or irreversible? Explain.

20.62 An object of mass $m_1$, specific heat capacity $c_1$, and temperature $T_1$ is placed in contact with a second object of mass $m_2$, specific heat capacity $c_2$, and temperature $T_2 > T_1$. As a result, the temperature of the first object increases to $T$ and the temperature of the second object decreases to $T'$. a) Show that the entropy increase of the system is

$$\Delta S = m_1c_1 \ln \frac{T}{T_1} + m_2c_2 \ln \frac{T'}{T_2}$$

and show that energy conservation requires that

$$m_1c_1(T - T_1) = m_2c_2(T_2 - T')$$

b) Show that the entropy change $\Delta S$, considered as a function of $T$, is a maximum if $T = T'$, which is just the condition of thermodynamic equilibrium. c) Discuss the result of part (b) in terms of the idea of entropy as a measure of disorder.

**Challenge Problem**

20.63 Consider a Diesel cycle that starts (at point $a$ in Fig. 20.6) with air at temperature $T_a$. The air may be treated as an ideal gas. a) If the temperature at point $c$ is $T_c$, derive an expression for the efficiency of the cycle in terms of the compression ratio $r$. b) What is the efficiency if $T_a = 300$ K, $T_c = 950$ K, $\gamma = 1.40$, and $r = 21.0$?