within a reasonable time span, such as a human lifetime. U.S. oil production is following this pattern and is in the early stage of region C on the graph. World oil production is not as far along on this curve and might be in the early stages of region B. In any case, resource depletion is inevitably driving the world toward the end of the oil age, although other problems such as global warming or toxic pollution might end the oil age even sooner.

**Renewable resources** such as wood or solar energy can follow a different kind of history (Figure 7.26). In their early stages, renewable and nonrenewable resource use follow the same pattern. But for a renewable resource, consumption can be sustained indefinitely, provided that it proceeds at less than the replacement rate.

Finally, let’s consider world population growth. The number of humans in 6000 B.C. has been estimated at 30 million—less than the combined populations
of New York City and Tokyo today. By A.D. 200 the number had reached 200 million. Then it doubled during A.D. 200 to 1300, doubled again during 1300 to 1650, again during 1650 to 1800, and once more during 1800 to 1900. Because the doubling times decreased, the growth was faster than exponential.

Figure 7.27 charts this growth. It took about 4 million years for the human population to grow to its first billion in 1825. It reached its next billion in 1930, its third billion in 1960, its fourth in 1975, and its fifth in 1987. The sixth billion is expected in 2000. We can find the approximate current rate of growth from the population doubling during 1960 to 2000: \( P = 70/T = 70/40 = 1.75\% \), or a little under 2%. Although this might not sound like a large growth rate, you can see from the graph that the results over time can be explosive.

![Graph showing the population explosion](image)
When you ask the question of an ecologist, "What is the most important environmental issue," they will be unanimous in saying it is exponential population growth.

GAYLORD NELSON, FORMER U.S. SENATOR AND FOUNDER OF EARTH DAY IN 1970

- **Dialogue 10** Between 1870 and 1930, U.S. oil production had an 8% growth rate. What was its doubling time? It reached 1 billion barrels (1 barrel = 42 gallons) per year by 1930. What would the production be this year if it had maintained this growth rate?

- **Dialogue 11** During the 1980s, U.S. car and truck miles traveled increased by 4% per year, but the length of highway increased by only 0.1% per year. Find the doubling time for vehicle miles traveled and for miles of highway. Suppose that these rates are maintained in the future. While vehicle miles double (a 100% increase), by roughly what percentage will the amount of highway increase? Roughly, how much worse will traffic congestion be at that time?

10. $T = \frac{70}{P} = \frac{70}{8} = 9$ years. At this rate, production in 1995 alone (65 years after 1930—about seven doubling times) would be 128 billion barrels, nearly the entire amount of recoverable U.S. oil in the ground as of 1992.

11. For vehicle miles, $T = \frac{70}{P} = \frac{70}{4} = 18$-year doubling time. For miles of highway, $T = \frac{700}{0.1} = 7000$ yrs. During 18 years, the number of miles of highway will increase by about $(0.1\% \text{/yr}) \times (18 \text{ yrs}) = 1.8\%$. Congestion will be about twice as bad.
**SUMMARY OF IDEAS AND TERMS**

**Thermodynamics** The study of the general properties of energy. Thermal energy plays a central role in understanding these properties.

**Second law of thermodynamics** This law describes the general tendency of nonthermal forms of energy to end up as thermal energy. This law can be stated in three logically equivalent forms: The law of heating states that thermal energy flows spontaneously from higher to lower temperatures. The law of heat engines states that any cyclic process that uses thermal energy to do work must have a thermal energy exhaust. The law of increasing entropy states that the total entropy of all the participants in any physical process must either increase or remain unchanged.

**First law of thermodynamics** An alternative way (not stated or used in this book) of stating the law of conservation of energy.

**Heating** The spontaneous flow of thermal energy from a higher temperature object to a lower temperature object.

**Temperature** A quantitative measure of warmth. The units normally used to measure temperature are called degrees Celsius. Any device that measures temperature is called a thermometer.

**Heat engine** Any device that uses thermal energy to do work. Its energy efficiency, the fraction of its input thermal energy that is converted to work, will be higher if the input temperature is higher and the exhaust temperature is lower. The portion of the input energy that is not converted to work is called the exhaust.

**Cogeneration** The simultaneous production of both electricity and useful thermal energy.

**Energy quality** Thermal energy is considered to be of lower quality than other energy forms, because of the second law's restrictions on converting it to other forms of energy.

**Entropy** The amount of microscopic disorganization a system possesses.

**Irreversibility** The second law says that most processes are irreversible, i.e., that physical systems proceed spontaneously toward states of higher entropy, and will not proceed spontaneously in the reverse direction. This principle is responsible for the difference between forward and backward in time.

**Microscopic interpretation of the second law** Entropy increase results from the fact that microscopic disorganization is overwhelmingly likely to increase.

**Biology and the second law** The entropy of a growing plant decreases, at the expense of a far greater entropy increase in the absorbed and re-radiated solar energy that passes through the plant. A similar situation exists for all biological processes, including the evolution of species. Growth and biological evolution are organized by solar radiation and are in full accordance with the second law.

**Creationism** The belief that the various biological species, and especially humans, originated from specific acts of instantaneous creation rather than by the natural process of biological evolution.

**Internal combustion engine** A heat engine in which burning occurs within the hot gases that push directly on mechanical parts, such as a piston, to provide useful work. Typically, its energy efficiency is low, largely because of the second law.

**Transportation efficiency** Useful output (such as distance traveled, passengers moved, freight moved, or mass moved) per unit of fuel input.

**Steam-electric power plant** Uses thermal energy from an external source such as burning coal, to turn water into steam that pushes on a steam turbine that provides work to generate electricity. The device that converts the rotational motion of the turbine into electricity is called an electric generator. Since the steam is heated by fuel that burns outside of the boiler, the plant is an external combustion engine. Typically, its energy efficiency is less than 50%, mostly because of the second law.

**Exponential growth** Growth by a fixed percentage in each unit of time. It has a fixed doubling time, related to its fixed percentage growth rate by $T = \ln(2)/r$.

**Linear growth** Straight-line growth; it increases by the same amount (rather than the same percentage, as in exponential growth) in each unit of time.

**Nonrenewable resource** A natural resource that can be used up. Its use follows a curve that begins exponentially, levels off, and declines.

**Renewable resource** A natural resource that is continually replaced. Its use typically begins exponentially, then levels off at some sustainable level (provided that it is not overconsumed).

---

### REVIEW QUESTIONS

**HEATING**

1. What is heating?
2. In your own words, state the law of heating.
3. Give an example showing that thermal energy and temperature are really two different things.

**HEAT ENGINES AND ENERGY QUALITY**

4. Give an example of each of these energy transformations: kinetic to thermal, gravitational to thermal, thermal to kinetic.
5. In your own words, state the law of heat engines.
6. What properties of the input and the exhaust are the most important to determining a heat engine's efficiency? Describe the manner in which the efficiency depends on these properties.

7. Is the actual overall energy efficiency of an automobile closest to 98%, 90%, 40%, 10%, or 2%? What about a steam-electric power plant?

8. If a heat engine operated entirely without friction, would it then be 100% efficient? Explain.

9. In terms of energy, what happens when the motion of a rock swinging from a string "dies down"? In what sense is this behavior irreversible?

THE AUTOMOBILE AND TRANSPORTATION

10. Name two general types of heat engines of major social importance.

11. Why do we call it an internal combustion engine? Describe in your own words how it works.

12. Name two alternative fuels (not gasoline or diesel fuel) for the automobile.

13. What is the source of the largest inefficiency in an automobile's operation?

14. Describe two different ways of measuring a transportation mode's efficiency, and give an appropriate measurement unit for each.

15. Why are trains more efficient than other transportation vehicles?

THE STEAM-ELECTRIC POWER PLANT

16. In a steam-electric power plant, what is the purpose of the turbine? Generator? Condenser? Cooling tower? Stack?

17. What is thermal pollution?

18. What is the source of the most important inefficiency in a steam-electric power plant's operation?

19. What part of a steam-electric power plant is analogous to the piston in an automobile?

EXPONENTIAL GROWTH

20. What is the difference between exponential and linear growth?

21. Your savings account grows at 7% per year. What is its doubling time?

22. Draw a typical life-history graph for a nonrenewable resource. Is any part approximately exponential?

23. Repeat the previous question, but for a renewable resource.

THE LAW OF ENTROPY

24. What is entropy?

25. In your own words, state the entropy form of the second law.

26. Which law or laws of physics distinguish between forward and backward in time?

27. When a growing leaf increases its organization, does it violate the second law? Explain.

HOME PROJECTS

1. Line up three containers filled, respectively, with hot (not scalding) water, warm water, and ice water. For a few moments, put one finger into the hot water and one finger into the cold water. Now plunge both fingers into the warm water. Can you always trust your sense of hot and cold?

2. How much of your neighborhood is devoted to the automobile? Choose a single city block and measure the area devoted to the automobile, using a tape measure or pacing. Include garages, parking lots, gas stations, car dealers, and the like. Include only half the total area of streets bordering your block; the other half belongs to the adjoining block. Find the fractional area devoted to the car; it is nearly 50% in most U.S. cities. Your class could divide into groups and measure several blocks and then pool its results for an overall figure. Your local newspaper might be interested in your results.

3. Study your home electric bill. How many kWh of electric energy were used during the month? Use this figure to calculate your home's average power consumption in kilowatts. Use Table 6.1 to estimate the electric energy, in kWh, that your home appliances consume during one month, and compare your estimates with the total shown on the bill. Compare this with your classmates' results.

4. Is electricity a good buy? Look at your electric bill to see how much you pay for 1 kWh. Calculate the height to which 1 kWh of energy could lift you. Hint: Recall that \( \text{Gravitational Force} = \text{weight} \times \text{height} \); find your weight in newtons from the fact that 1 pound = 4.5 newtons and 1 kilogram weighs about 10 newtons.

5. Play the population explosion game. Put 100 pennies into a box. Bring a penny into "penny world" by taking one penny out of the box and putting it on a table. Flip it. Heads means it had a baby that year, so you should bring another penny into penny world, and tails means it didn't have a baby. Now penny world's population is 1 or 2. Flip all the pennies in penny world, getting 0 or 1 or 2 new babies during the second year. Continue in this fashion, and draw a graph showing the population of penny world versus the number of years beginning at 0 years with a population of 1. If 100 represents overpopulation, how many years does it take until overpopulation is reached? Play the game several times. Is it the same number of years each time? Is this growth approximately exponential? From your graph, measure the doubling time and yearly growth rate.
FOR DISCUSSION

1. Assess the transportation possibilities for your region:
   (a) List your region’s major transportation needs such as
campus to shopping, suburbs to downtown, campus to
evening entertainment, travel to nearest large city.
(b) List all the possible ways to fill each need, assuming
that the proper facilities (roads, bikeways, sidewalks, and
so on) exist. Include city-planning options such as reloca-
tion of workplaces and reduction in the distance to outlying
suburbs. (c) Underline the modes that actually do fill
each need. (d) Discuss the pros and cons of the different
modes listed for each need. Include energy consumption
as one consideration. Other considerations might include
convenience, pollution, safety, cost, traffic congestion,
community quality of life, and so forth.

2. List 10 globally significant inventions or technologies.
Which two or three of these have had the greatest impact
on our way of life?

3. List several quantities whose growth is exponential.
Which ones are likely to continue growing exponentially,
which are likely to follow a bell-shaped growth-and-decline
curve, and which are likely to level off at a sustain-
able level?

4. Should we seek alternatives to the car? If so, which alter-
 natives, and under what circumstances?

EXERCISES

HEATING

1. How would you describe the weather on a day when the
temperature was -3°C? +3°C? 22°C? 35°C?
2. Give the approximate temperature, in °C, of each of the
following: Your body; water boiling in an open pot; ice
water; a nice day.

3. Which is larger, a Celsius degree or a Fahrenheit de-
gree?
4. How does the flow of thermal energy through a closed
window illustrate the second law? Which direction is this
flow when it is cold outside? Hot outside?
5. Try to think of at least one technological device that
causes thermal energy to flow “uphill,” from colder to
hotter. Does this device violate the law of heating? Explain.

6. In the operation of a refrigerator, does thermal energy
flow from hot to cold, or is it from cold to hot? Does this
happen spontaneously, or is outside assistance required?

HEAT ENGINES

7. Is it possible to convert a given quantity of kinetic energy
entirely into thermal energy? Is it possible to convert a
given quantity of thermal energy entirely into kinetic en-
ergy? In each case, either give an example or explain
why it is impossible.
8. Is it possible to convert a given quantity of chemical en-
ergy entirely into thermal energy? Is it possible to con-
vert a given quantity of thermal energy entirely into
chemical energy? In each case, either give an example or
explain why it is impossible.
9. Which are not heat engines: natural gas-burning power
plant, hydroelectric power plant, ethanol-fueled automo-
tive, bicycle, solar-thermal electric power plant, steam
locomotive?
10. Which of the following are heat engines: nuclear power
plant, diesel locomotive, electric locomotive, geothermal
power plant, wind turbine (windmill for generating elec-
tricity), solar hot water heater?

11. What does the second law tell us about the efficiency of
heat engines?

12. Can you think of any way to drive a ship across the
ocean by using the ocean’s thermal energy, without violat-
ing the second law?

13. Farswell Slick (see Dialogue 10 of Chapter 6) approaches
you with plans for a revolutionary transportation system.
He has noticed that when he drives an automobile without
accelerating, all the input energy eventually shows up as
thermal energy. Slick proposes to use this thermal energy
to drive the car at a constant speed. The car will still need
fuel, but only for accelerating. It will be possible to travel
cross-country on only a few gallons of gasoline. He de-
scribes his scheme as a “computerized advanced-technol-
yogy exhaust feedback afterburner.” Should you invest in
Slick’s scheme? Explain.

ENERGY QUALITY AND THE LAW OF ENTROPY

14. When your book falls to the floor is this a thermodynam-
ically irreversible process? Is energy conserved? Does
entropy increase?

15. When we say that the motion of a rock swinging on a
string is irreversible, do we really mean that it is impos-
sible to get the rock back to its starting condition?
Explain.

16. When a block of wood slides down a sliding board, is this
a thermodynamically irreversible process? Does this
mean that it is impossible to make a block of wood slide
up a sliding board? Explain.

17. As an egg develops into a chicken, its contents become
more ordered. Does this violate the law of increasing en-
tropy? Explain.

18. A pan of liquid water freezes when you place it outside
on a cold day. Liquid water has greater molecular disor-
19. When orange juice and grapefruit juice are mixed, does entropy increase?

THE AUTOMOBILE AND TRANSPORTATION
20. Describe the energy input for walking and bicycling. How do walking and bicycling illustrate the second law?
21. Suppose an automobile's fuel could be made to burn hotter without harming the engine's operation (for instance, without cracking the engine). Would you still get the same amount of useful work from each gallon of gasoline?
22. Suppose an automobile could run on hard wheels that were not squeezed by the weight of the car on the road. Would this alter the car's efficiency? How might this affect the gas mileage? What kind of wheels and road might you suggest?
23. According to Figures 7.9, 7.10, and 7.11, which of the three main sectors of the U.S. economy (industry, residential-commercial, transportation) consumes the most oil?
24. One car has twice the overall energy efficiency (in km/l) of a second car. Compare the amounts of pollution they produce when they both travel the same distance.

THE STEAM-ELECTRIC POWER PLANT
25. Which type of generating plant would you expect to be more energy efficient, steam-electric or hydroelectric? Defend your answer.
26. Would it be more energy efficient to heat your home electrically or to heat it directly using a natural gas heater, assuming that the electricity comes from a steam-electric plant?
27. Which method of fueling your car is likely to be more energy efficient, and why: gasoline used in a standard car engine or electricity taken from a coal-fueled generating plant and stored in lightweight car batteries? Assume that the batteries convert electricity to work at 100% efficiency.

EXponential Growth and Resource Use
28. A lily pond doubles its number of lilies every month. One day, you notice that 2% of the pond is covered by lilies. About how long will it be before the pond is entirely covered?
29. On June 1 there are a few water lilies in a pond, and they then double daily. By June 30 they cover the entire pond. On what day was the pond still 50% uncovered?
30. Company X increases its profits every year by $50 million. Is its growth in profits exponential? Company Y increases its profits by 1% every year. Is its growth in profits exponential?
32. Which of the following are renewable energy resources: coal, firewood, nuclear power, wind, water behind a dam?
33. What is the original source of energy in each of the following energy resources: oil, firewood, wind, water behind a dam, geothermal, ocean-thermal electricity? Which of these are renewable resources?
34. The most recent world population doubling, to a total population of about 6 billion, has occurred in about 40 years. Making the (unrealistic!) assumption that this rate of population will continue for two centuries, what would the world's population be two centuries from now? Such unrealistic assumptions are often useful in projecting future trends, because they give us a sense of what is likely or unlikely. For example, this exercise shows us that it is very unlikely that our present population growth will continue for two more centuries.
35. The most recent world population doubling has occurred in about 40 years. Suppose that the next doubling occurs also in 40 years, but that a new agricultural "green revolution" manages to also double food production. Then how many people will be starving 40 years from now, as compared to the number starving now?

Problems

Heat engines
1. In one cycle of its operation, a heat engine does 100 J of work while exhausting 400 J of thermal energy. What is its energy input? Its efficiency?
2. In one cycle of its operation, a heat engine consumes 1500 J of thermal energy while performing 300 J of work. What is its efficiency? How much energy is exhausted in each cycle?
3. The steam entering the turbine in a certain coal-burning power plant is heated to 500°C. The steam is cooled and condensed to water at 80°C. Calculate the ideal efficiency of the power plant. Remember that you must convert Celsius temperatures to degrees Kelvin before using the formula.
4. A solar-heated steam-electric generating plant heats steam to 250°C. After passing through the turbine, cool-
ing towers cool the steam to 30°C. Calculate the ideal efficiency of this power plant. Suppose that, for every 1000 J of thermal energy going into this plant, the cooling towers remove 750 J as exhaust. What is the actual efficiency of this power plant?

THE AUTOMOBILE AND TRANSPORTATION
5. Out of every 100 barrels of gasoline, about how many actually go into driving a typical car down the road?
7. You travel alone from New York to Los Angeles, about 2800 miles. Working from Tables 7.3 and 7.4, how many gallons of gasoline will you use if you travel by car (assuming your car gets average gasoline mileage for U.S. automobiles)? How many gallons if you travel by air? By bus? By train?
8. A 100-car freight train hauls 16,000 tons of freight from New York to Los Angeles, about 2800 miles. How many trucks would be needed for this load, assuming that each truck carries 32 tons of freight? Working from Table 7.4, how many gallons of gasoline are saved if this load is carried by train rather than by truck? How many 42-gallon barrels of gasoline is this?

THE STEAM-ELECTRIC POWER PLANT
9. Out of every 100 tons of coal fed into an electric generating plant, roughly how many tons produce the electricity you can use at your home, and how many go into waste energy? Use the energy flows given in Figure 7.20.
10. For every 100 kilograms of coal entering a generating plant (recall that this much enters every second), about 15 kilograms of sulfur oxides and ash are removed, producing a significant solid-waste disposal problem. For a typical 1000 MW plant, how much of this solid waste is produced every day? Express your answer in tonnes (1 tonne = 1000 kg).

11. How would the pollution from two coal plants compare, if the first plant is twice as energy efficient as the second? Assume that they both produce the same amount of electric power.
12. Making estimates. In the U.S., solar energy strikes a single square meter of ground at an average rate (averaged over day and night and over the different seasons) of 200 watts. At what average rate does solar energy strike a football field (about 100 m by 30 m)? A typical home in the U.S. consumes electricity at an average rate of 1 kW. How much surface area would be needed to provide this electric power, assuming a 10% conversion efficiency? What dimensions would a square-shaped photovoltaic collector need to cover this area?

EXPONENTIAL GROWTH
13. How much electric energy would have been produced in 1985, if the exponential growth of 1935–75 had continued for another 10 years beyond 1975? If this growth had continued, roughly how many power plants would have been needed in 1985, as compared with 1975?
14. During 1985–1990, annual U.S. population growth was 0.8% per year, for Mexico it was 2.2%, and for Kenya (the highest) it was 4.2%. At these rates, how long will it take for the populations of each of these countries to double?
15. World population is now about 6 billion. The growth rate has been roughly 2% per year since the end of World War II (1945). If a 2% per year growth rate continued, when would world population be 12 billion?
16. Centerville, with a growth rate of 7% annually, is using its only sewage treatment plant at maximum capacity. If it continues its present growth rate, how many sewage treatment plants will it need 40 years from now?