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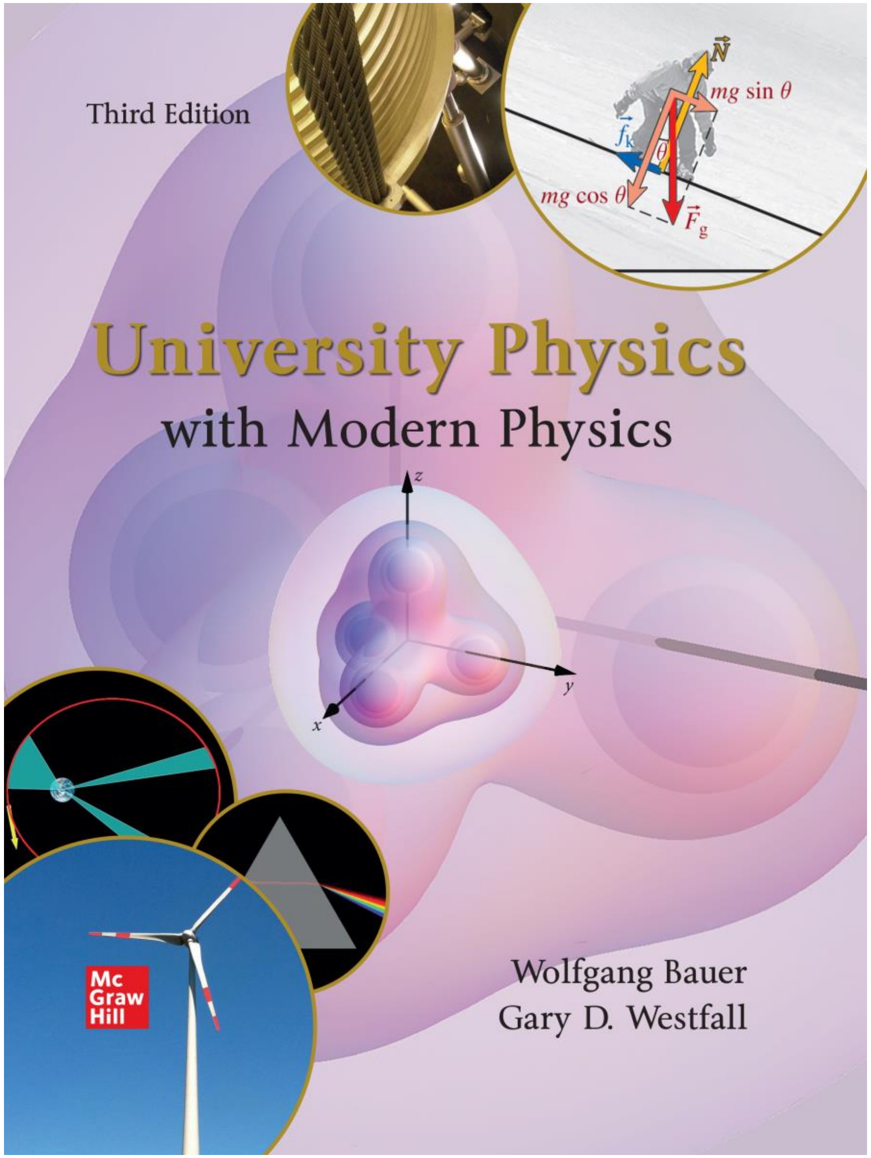
Chapter 18

Heat and the First Law of Thermodynamics

University Physics with Modern Physics
Third Edition

Wolfgang Bauer Gary D. Westfall



Heat and the First Law of Thermodynamics

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The First Law of Thermodynamics

- This chapter examines the nature of heat and the mechanisms of thermal energy transfer.
- Heat is a form of energy that is transferred into or out of a system.
- Thus, heat is governed by a more general form of the law of conservation of energy, known as the First Law of Thermodynamics.
- We'll focus on this law in this chapter, along with some of its applications to thermodynamic processes and to changes in heat and temperature.
- Heat is essential to life processes; no life could exist on Earth without heat from the Sun or from the Earth's interior.

Definition of Heat 1

- Heat is one of the most common forms of energy in the universe, and we all experience it every day.
- If you pour cold water into a glass and then put the glass on the kitchen table, the water will slowly warm until it reaches the temperature of the air in the room.
- Similarly, if you pour hot water into a glass and place it on the kitchen table, the water will slowly cool until it reaches the temperature of the air in the room.
- The warming or cooling takes place rapidly at first and then more slowly as the water comes into thermal equilibrium with the air in the kitchen.
- At thermal equilibrium, the water, the glass, and the air in the room are all at the same temperature.

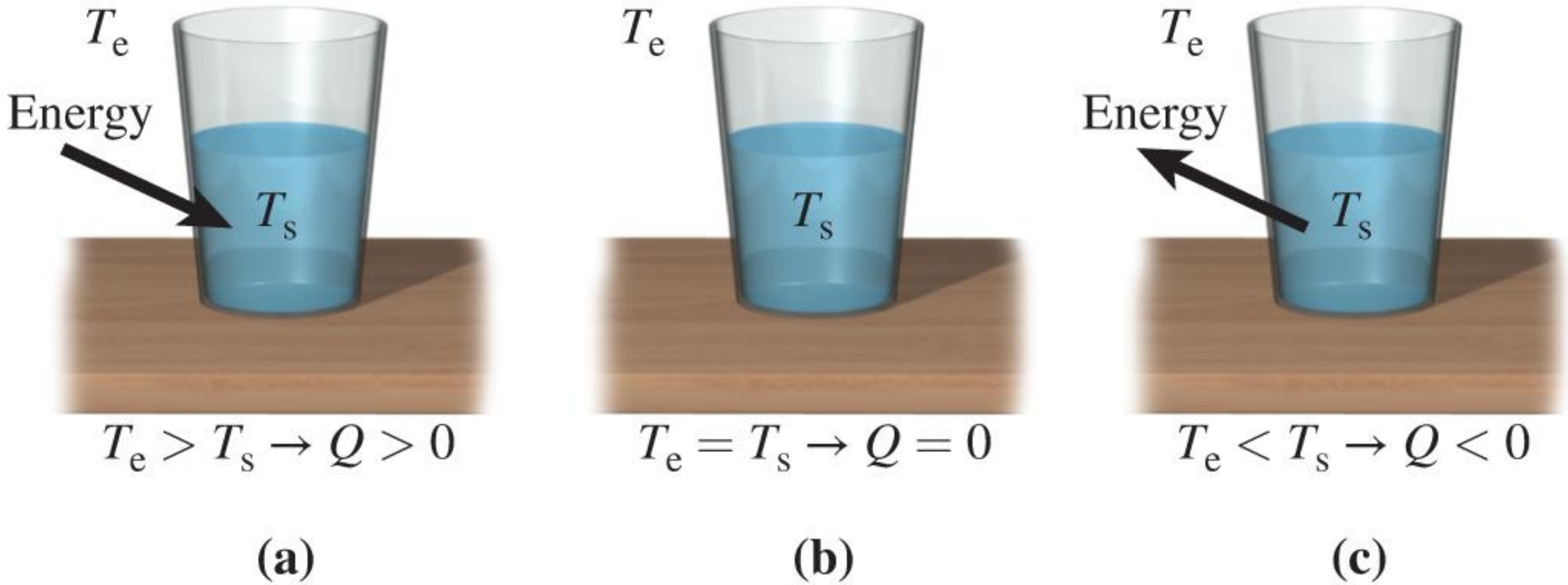
Definition of Heat 2

- The water in the glass is a **system** with temperature T_s, and the air in the kitchen is an **environment** with temperature T_e.
- If $T_s \neq T_e$, then the temperature of the system changes until it is equal to the temperature of the environment.
- A system can be simple or complicated; it is just any object or collection of objects we wish to examine.
- The difference between the environment and the system is that the environment is large compared to the system.
- The temperature of the system affects the environment, but we will assume that the environment is so large that any changes in its temperature are imperceptible.

Definition of Heat 3

- The change in temperature of the system is due to a transfer of energy between the system and its environment.
- This type of energy is **thermal energy**, an internal energy related to the motion of the atoms, molecules, and electrons that make up the system or the environment.
- Thermal energy in the process of being transferred from one body to another is called **heat** and is symbolized by Q.
- If thermal energy is transferred into a system, then $Q > 0$.
- If thermal energy is transferred from the system to its environment, then $Q < 0$.
- If the system and its environment have the same temperature, then $Q = 0$.

Definition of Heat 4



A system embedded in an environment that has a higher temperature.

A system embedded in an environment having the same temperature.

A system embedded in an environment that has a lower temperature.

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Mechanical Equivalent of Heat 1

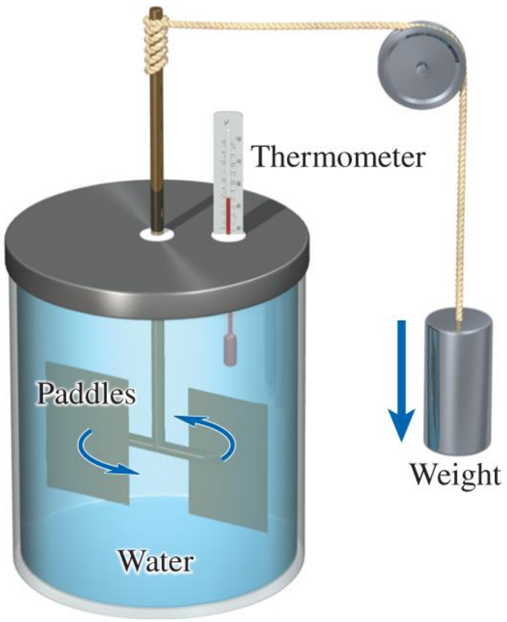
- Energy can be transferred between a system and its environment as work done by a force acting on a system or by a system.
- The concepts of heat and work can be defined in terms of the transfer of energy to or from a system.
- We can refer to the internal energy of a system, but not to the heat contained in a system.
- If we observe hot water in a glass, we do not know whether thermal energy was transferred to the water or work was done on the water.
- Heat is transferred energy and can be quantified using the SI unit of energy, the joule.

Mechanical Equivalent of Heat 2

- Originally, heat was measured in terms of its ability to raise the temperature of water.
- The calorie (cal) was defined as the amount of heat required to raise the temperature of 1 gram of water by 1 °C.
- Another common measure of heat, still used in the United States, is the British thermal unit (BTU), defined as the amount of heat required to raise the temperature of 1 pound of water by 1 °F.
- However, the change in temperature of water as a function of the amount of thermal energy transferred to it depends on the original temperature of the water.
- Reproducible definitions of the calorie and the British thermal unit required that the measurements be made at a specified starting temperature.

Mechanical Equivalent of Heat [3]

- In 1843, the English physicist James Prescott Joule showed that the mechanical energy of an object could be converted into thermal energy.
- The apparatus consisted of a large mass supported by a rope that was run over a pulley and wound around an axle.
- As the mass descended, the rope turned a pair of large paddles in a container of water.
- The rise in temperature of the water was related to the mechanical work done by the falling object.
- Mechanical work could be turned into thermal energy.



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Mechanical Equivalent of Heat 4

- The modern definition of the calorie is based on the joule.
- The calorie is defined to be exactly 4.186 J, with no reference to the change in temperature of water.
- The following are some conversion factors for energy units:
  - 1 cal = 4.186 J,
  - 1 BTU = 1055 J,
  - 1 kWh = $3.60 \cdot 10^6$ J
  - 1 kWh = 3412 BTU.
- A food calorie, often called a *Calorie* or a *kilocalorie*, is not equal to the calorie just defined.
- A food calorie is equivalent to 1000 cal.
- The cost of electrical energy is usually stated in cents per kilowatt-hour (kWh).

Candy Bar

PROBLEM:

- The label of a candy bar states that it has 295 Calories.
- What is the energy content of this candy bar in joules?

SOLUTION:

- Food calories are kilocalories and 1 kcal = 4186 J.
- The candy bar has 275 kcal, or:

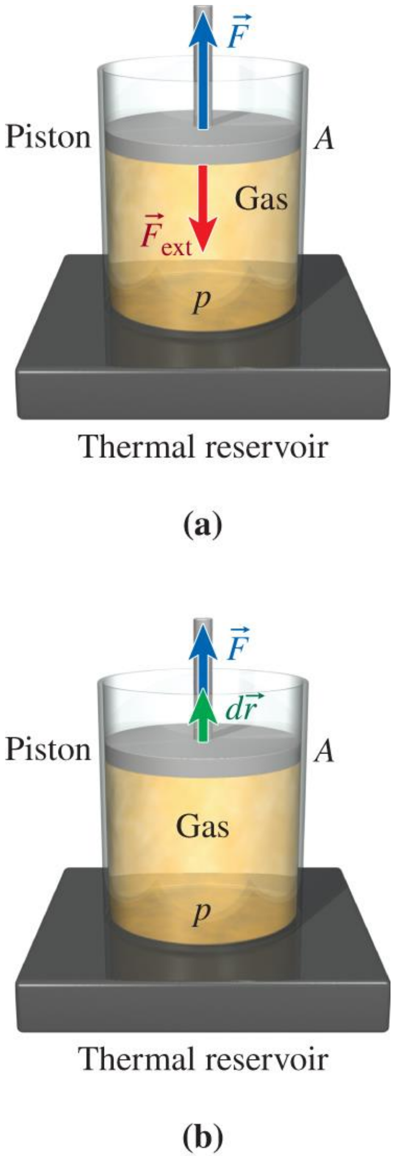
$$275 \text{ kcal} \left(\frac{4186 \text{ J}}{1 \text{ kcal}} \right) = 1.15 \cdot 10^{6} \text{ J}$$

DISCUSSION:

- Note that this energy is enough to raise a small truck with a weight of 22.2 kN (5000 lb) 52 m.

Heat and Work 1

- Let's look at how energy can be transferred as heat or work between a system and its environment.
- We consider a system consisting of a gas-filled cylinder with a piston.
- The gas in the cylinder is described by a temperature T, a pressure p, and a volume V.
- We assume that the side wall of the cylinder does not allow heat to penetrate it.
- The gas is in thermal contact with an infinite thermal reservoir, which is an object so large that its temperature does not change even though it experiences thermal energy flow into it or out of it.



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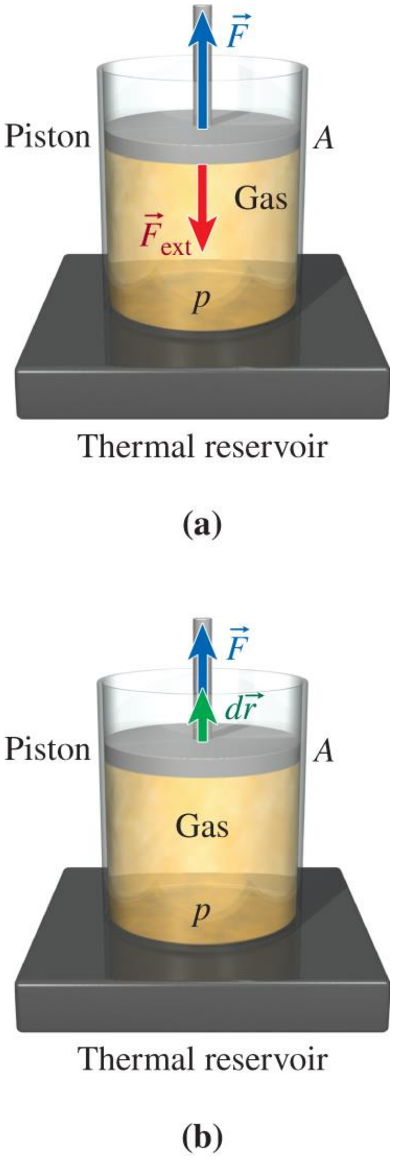
Heat and Work 2

- This reservoir also has temperature *T*.
- An external force pushes on the piston.
- The gas then pushes back with a force, *F*, given by the pressure of the gas, *p*, times the area, *A*, of the piston: $F = pA$.
- We consider the change from an initial state specified by p_i, V_i, and T_i to a final state specified by p_f, V_f, and T_f.
- Changes are made slowly so that the gas remains close to equilibrium, allowing measurements of *p*, *V*, and *T*.
- The progression from the initial state to the final state is a **thermodynamic process**.



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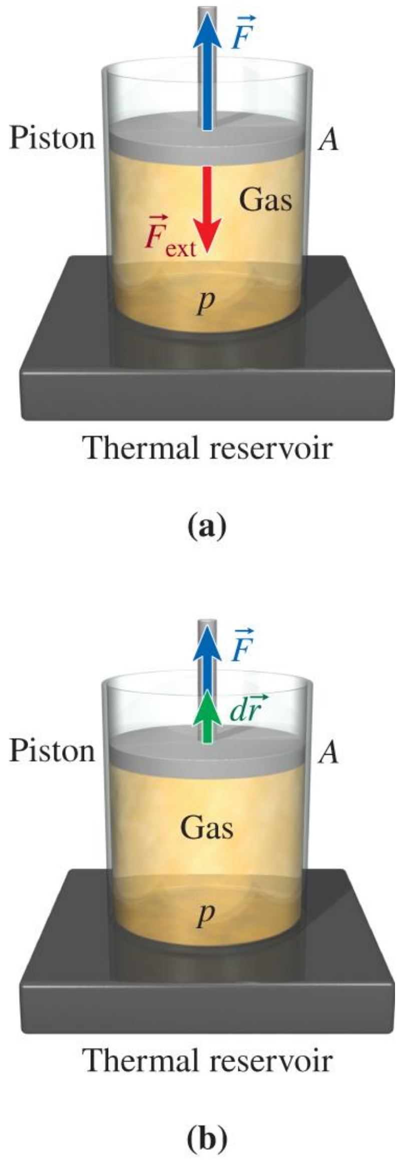
Heat and Work 3

- During this process, thermal energy may be transferred into the system (positive heat), or it may be transferred out of the system (negative heat).
- When the external force is reduced, the gas in the cylinder pushes the piston out a distance *dr*.
- The work done by the system is:

$$dW = \vec{F} \cdot d\vec{r} = (pA)(dr) = p(Adr) = p\Delta V$$

- The work done by the system going from the initial to the final configuration is:

$$W = \int dW = \int_{V_i}^{V_f} p dV$$



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Heat and Work 4

- Note that during this change in volume, the pressure may also change.
- To evaluate this integral, we need to know the relationship between pressure and volume for the process.
- For example, if the pressure remains constant, we obtain:

$$W = \int_{V_\mathrm{i}}^{V_\mathrm{f}} p dV = p \int_{V_\mathrm{i}}^{V_\mathrm{f}} dV = p(V_\mathrm{f} - V_\mathrm{i})$$

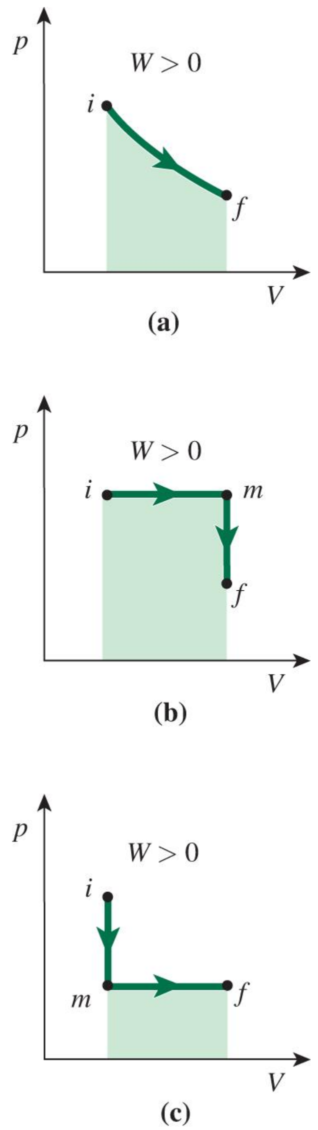
- We can see that for a constant pressure, a negative change in the volume corresponds to negative work done by the system.
- We can illustrate these processes with graphs of pressure versus volume, called ***pV*-diagrams**.

Heat and Work 5

- Here are three different paths, or ways to change the pressure and volume of a system from an initial to a final condition.
- In part (a), the process proceeds such that the pressure decreases as the volume increases.
- The work done by the system is given by:

$$W = \int_{V_i}^{V_f} p dV$$

- The work done by the system can be represented by the area under the curve.
- In this case, the work done by the system is positive because the volume of the system increases.



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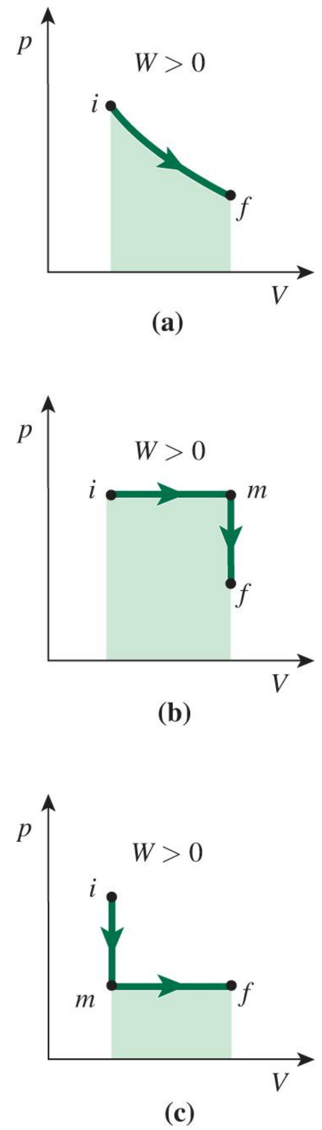
Heat and Work 6

- In part (b), the process starts at an initial point *i* and proceeds to a final point *f* through an intermediate point *m*.
- The first step involves increasing the volume while holding the pressure constant.
- One way to complete this step is to increase the temperature of the system as the volume increases, maintaining a constant pressure.
- The second step consists of decreasing the pressure while holding the volume constant.
- One way to accomplish this task is to lower the temperature by taking thermal energy away from the system.



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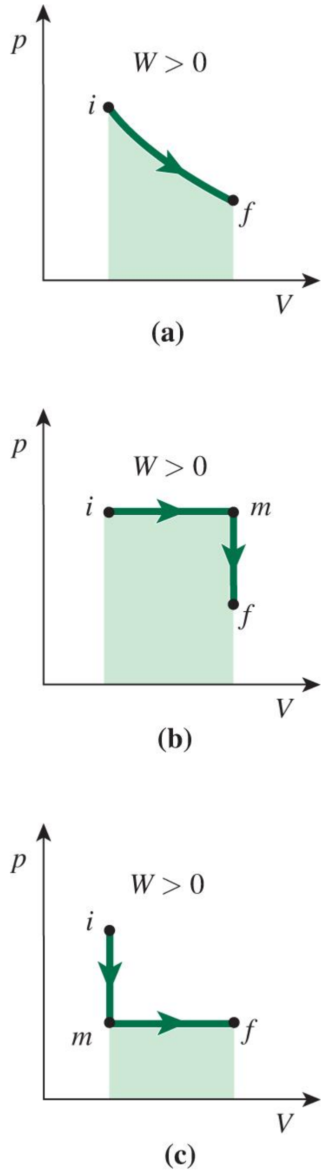
Heat and Work 7

- In part (b), the work done by the system can be represented by the area under the curve, shown by the green shading.
- The work done by the system is positive because the volume of the system increases.
- However, the work done by the system originates only in the first step.
- In the second step, the system does no work because the volume does not change.
- Part (c) shows another process starts at an initial point *i* and proceeds to a final point *f* through an intermediate point *m*.



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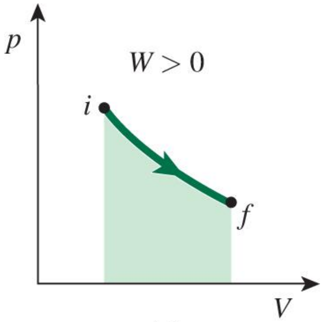
Heat and Work 8

- In part (c), the first step involves decreasing the pressure of the system while holding the volume constant.
- The second step consists of increasing the volume while holding the pressure constant.
- The work done by the system can be represented by the area under the curve.
- The work done by the system is positive because the volume of the system increases.
- However, the work done by the system originates only in the second step.
- In the first step, the system does no work because the volume does not change.



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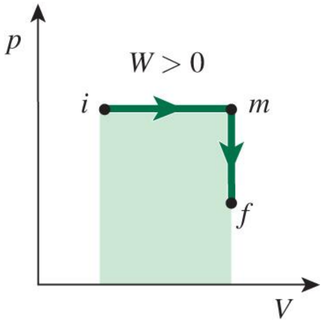

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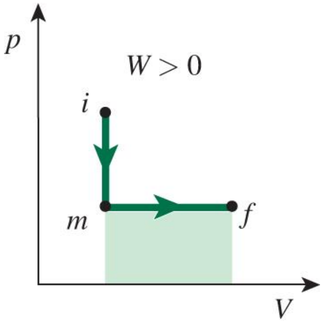

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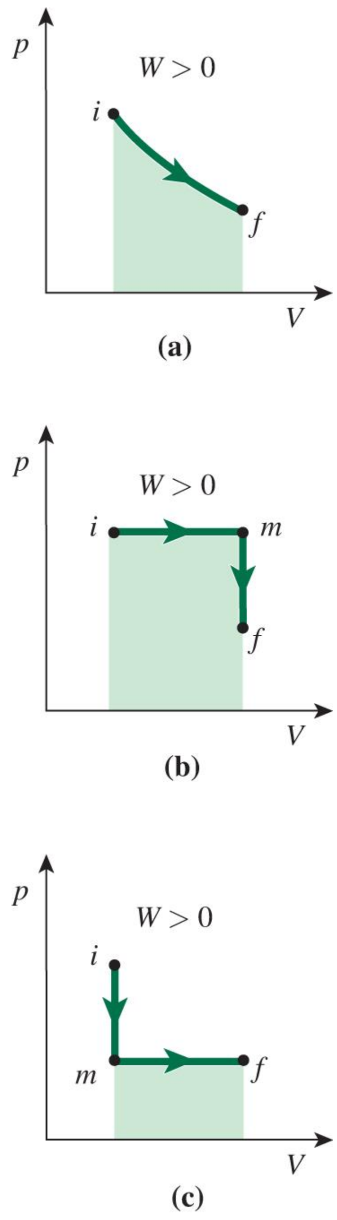
Heat and Work 9

- The work done in part (c) is less than the work done by the process in part (b).
- The thermal energy absorbed must also be less because the initial and final states are the same in these two processes, so the change in internal energy is the same.
- The work done by a system and the thermal energy transferred to the system depend on how the system moves from an initial point to a final point in a pV-diagram.
- This type of process is thus referred to as a **path-dependent process**.



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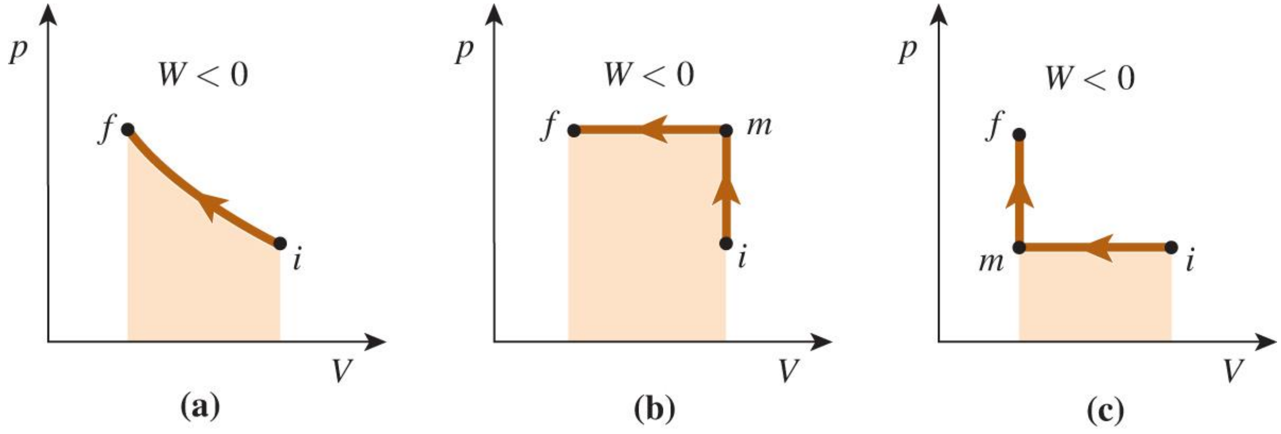
Heat and Work 10

- We can reverse these three processes.



- In each of these cases, the area under the curve represents the negative of the work done by the system in moving from an initial point *i* to a final point *f*.
- In all three cases, the work done by the system is negative because the volume of the system decreases.

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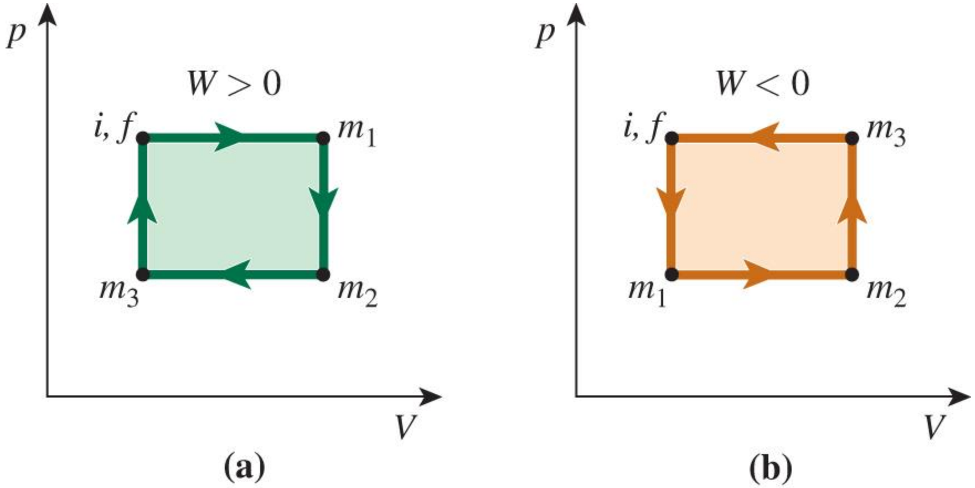
Heat and Work 11

- A process that starts at some initial point on a pV-diagram, follows some path, and returns to the original point is called a **closed path**.
- Two examples of closed paths are illustrated below:



- The amount of work done by the system and the thermal energy absorbed by the system depend on the path taken on a pV-diagram, as well as on the direction in which the path is taken.

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Concept Check 1

- In the isothermal compression of a gas, the volume occupied by the gas is decreasing, but the temperature of the gas remains constant.
- In order for this to happen,

A. heat must enter the gas.

B. heat must exit the gas.

C. no heat exchange should take place between the gas and the surroundings.

Solution Concept Check [1]

- In the isothermal compression of a gas, the volume occupied by the gas is decreasing, but the temperature of the gas remains constant.
- In order for this to happen,

A. heat must enter the gas.

B. heat must exit the gas.

C. no heat exchange should take place between the gas and the surroundings.

Concept Check 2

- Which of the following statements is true?

  A. When a system does work, its internal energy always decreases.

  B. Work done on a system always decreases its internal energy.

  C. When a system does work on its surroundings, the sign of the work is always positive.

  D. Positive work done on a system is always equal to the system's gain in internal energy.

  E. If you push on the piston of a gas-filled cylinder, the energy of the gas in the cylinder will increase.

Solution Concept Check 2

- Which of the following statements is true?
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  B. Work done on a system always decreases its internal energy.
  C. When a system does work on its surroundings, the sign of the work is always positive.
  D. Positive work done on a system is always equal to the system's gain in internal energy.
  E. If you push on the piston of a gas-filled cylinder, the energy of the gas in the cylinder will increase.

First Law of Thermodynamics 1

- **Thermodynamic systems** are classified according to how they interact with their environment.
- An **open system** can exchange heat, energy, and mass with its surroundings.
- A **closed system** is a system into or out of which thermal energy can be transferred but from which no constituents can escape and to which no additional constituents are added.
- An **isolated system** is a system that has no interactions or exchanges of constituents with its environment.

First Law of Thermodynamics 2

- Combining several of the concepts we covered in this chapter allows us to express the change in internal energy of a closed system in terms of heat and work as:

$$\Delta E_{\text{int}} = \Delta E_{\text{int,f}} - \Delta E_{\text{int.i}} = Q - W$$

- This equation known as the **First Law of Thermodynamics**.
- It can be stated as:

The change in the internal energy of a closed system is equal to the heat acquired by the system minus the work done by the system.

- In other words, energy is conserved.

First Law of Thermodynamics 3

- Heat and work can be transformed into internal energy, but no energy is lost.
- Note that here the work is done by the system, not done on the system.
- The First Law of Thermodynamics extends the conservation of energy beyond mechanical energy to include heat as well as work.
- Note also that the change in internal energy is path-independent, while changes in heat and work are path-dependent.

Weightlifter 1

PROBLEM:

- A weightlifter snatches a barbell with mass m = 180.0 kg and moves it a distance h = 1.25 m vertically.
- If we consider the weightlifter to be a thermodynamic system, how much heat must he give off if his internal energy decreases by 4000. J?

SOLUTION:

- We start with the First Law of Thermodynamics:

$$\Delta E_{\text{int}} = Q - W$$

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Weightlifter 2

- The work is the mechanical work done by the weightlifter:

$$W = mgh$$

- The heat is then given by:

$$Q = \Delta E_{\text{int}} + W = \Delta E_{\text{int}} + mgh$$

$$Q = -4000.\text{ J} + (180.0\text{ kg})(9.81\text{ m/m}^2)(1.25\text{ m})$$

$$Q = -1790\text{ J} = -0.428\text{ kcal}$$

- The weightlifter cannot turn internal energy into useful work without giving off heat.
- Note that the decrease in internal energy of the weightlifter is less than 1 food calorie: (4000 J)/(4186 J/kcal) = 0.956 kcal.
- The heat output is only 0.428 kcal.
- Thus, rather small amounts of internal energy and heat are associated with the large effort required to lift the weight.

Truck Sliding to a Stop 1

PROBLEM:

- The brakes of a moving truck with a mass m = 3000. kg lock up.
- The truck skids to a stop on a horizontal road surface in a distance L = 83.2 m.
- The coefficient of kinetic friction between the truck tires and the surface of the road is μ_k = 0.600.
- What happens to the internal energy of the truck?

SOLUTION:

- The First Law of Thermodynamics relates the internal energy, the heat, and the work done on the system:

$$\Delta E_{\text{int}} = Q - W$$

Truck Sliding to a Stop 2

- No thermal energy is transferred to or from the truck because the process of sliding to a stop is sufficiently fast that there is no time to transfer thermal energy.
- Thus, $Q = 0$.
- The dissipation of energy from the friction force, W_{f}, is always negative.
- The energy dissipated is equal to original kinetic energy of the truck.
- The energy dissipated by the friction force is:

$$W_{\mathrm{f}} = -\mu_{\mathrm{k}} m g L$$

- The work-kinetic energy theorem tells us that:

$$\Delta K = W = W_{\mathrm{f}}$$

Truck Sliding to a Stop 3

- Applying the First Law gives us:

$$\Delta E_{\text{int}} = 0 - (-\mu_{\text{k}} mgL) = \mu_{\text{k}} mgL$$

- Putting in our numerical values:

$$\Delta E_{\text{int}} = (0.600)(3000.\,\text{kg})(9.81\ \text{m/s}^2)(83.2\ \text{m}) = 1.47\ \text{MJ}$$

- This increase in internal energy can warm the truck's tires.

DISCUSSSION:

- When the truck begins to skid, the tires may leave skid marks on the road, removing matter and energy from the system.
- The assumption that no thermal energy is transferred to or from the truck in this process is also not exactly valid.
- In addition, the internal energy of the road surface will also increase because of the friction between the tires and the road, taking some of the total energy available.

First Law for Special Processes

- The First Law of Thermodynamics holds for all kinds of processes involving a closed system, but energy can be transformed, and thermal energy transported in some special ways in which only a single or a few of the variables that characterize the state of the system change.
- Some special processes, which occur often in physical situations, can be described using the First Law of Thermodynamics.
- These special processes are also usually the only ones for which we can compute numerical values for heat and work.
- These processes are simplifications or idealizations, but they often approximate real-world situations closely.

Adiabatic Processes

- An **adiabatic process** is one in which no heat flows when the state of a system changes.
- This can happen, for example, if a process occurs quickly and there is not enough time for heat to be exchanged.
- Adiabatic processes are common because many physical processes do occur quickly enough that no thermal energy transfer takes place.
- For adiabatic processes, $Q = 0$, so:

  $$\Delta E_{\text{int}} = -W$$

- Another situation in which an adiabatic process can occur is if the system is thermally insulated from its environment while pressure and volume changes occur.

Constant Volume Processes

- Processes that occur at constant volume are called **isochoric processes**.
- For a process in which the volume is held constant, the system can do no work, so $W = 0$, giving:

  $$\Delta E_{\text{int}} = Q$$

- An example of a constant-volume process is warming a gas in a rigid, closed container that is in contact with other bodies.
- No work can be done because the volume of the gas cannot change.
- The change in the internal energy of the gas occurs because of heat flowing into or out of the gas because of contact between the container and the other bodies.
- Cooking food in a pressure cooker is an isochoric process.

Closed-Path Processes

- In a closed-path process, the system returns to the same state at which it started.
- Regardless of how the system reached that point, the internal energy must be the same, so $\Delta E_{\text{int}} = 0$.
- This gives:

  $$Q = W$$

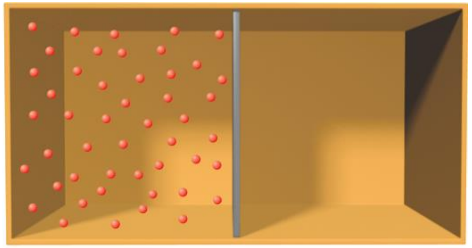
- Thus, the net work done by a system during a closed-path process is equal to the thermal energy transferred into the system.
- Such cyclical processes form the basis of many kinds of heat engines.

Free Expansion 1

- If the thermally insulated container for a gas suddenly increases in size, the gas will expand to fill the new volume.
- During this free expansion, the system does no work, and no heat is absorbed.
- W = 0 and Q = 0 and the First Law gives us:

$$\Delta E_{\text{int}} = 0$$

- To illustrate this situation, consider a box with a barrier in the center.
- A gas is confined in the left half of the box.
- When the barrier between the two halves is removed, the gas fills the total volume.



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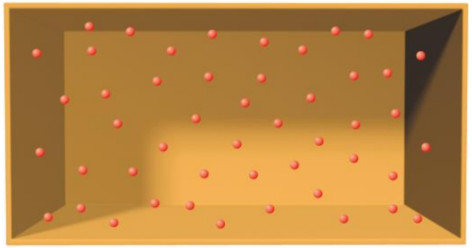

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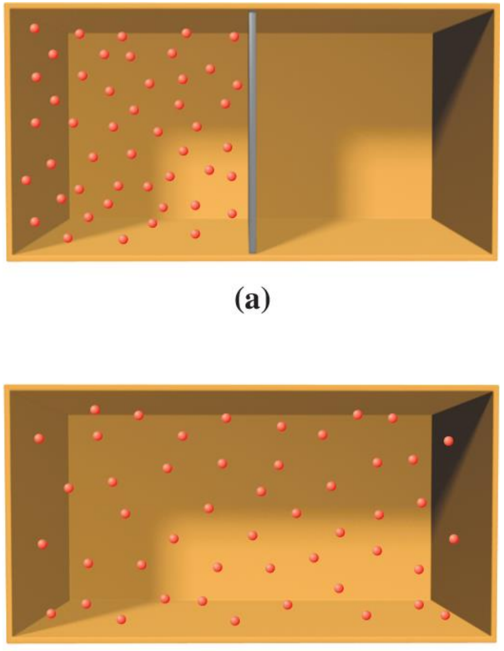
Free Expansion 2

- However, the gas performs no work.
- This last statement requires a bit of explanation.
- In its free expansion, the gas does not move a piston or any other material device.
- Thus, it does no work on anything.
- During the expansion, the gas particles move freely until they encounter the walls of the expanded container.
- The gas is not in equilibrium while it is expanding.
- For this system, we can plot the initial state and the final state on a *pV*-diagram, but not the intermediate state.



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Constant-Pressure Processes

- Constant-pressure processes are called **isobaric processes**.
- Such processes occur in the study of the specific heat of gases.
- In an isobaric process, the volume can change, allowing the system to do work.
- Since the pressure is kept constant:
  $W = p(V_\mathrm{f} - V_\mathrm{i}) = p\Delta V$
- Thus, equation 18.4 can be written as follows:
  $\Delta E_\mathrm{int} = Q - p\Delta V$
- An example of an isobaric process is the slow warming of a gas in a cylinder fitted with a frictionless piston, which can move to keep the pressure constant.
- The path of an isobaric process on a pV-diagram is a horizontal straight line.
- Cooking food in an open saucepan is another example of an isobaric process.

Constant-Temperature Processes

- Constant-temperature processes are **isothermal processes**.
- The temperature of the system is held constant through contact with an external thermal reservoir.
- Isothermal processes take place slowly enough that heat can be exchanged with the external reservoir to maintain a constant temperature.
- For example, heat can flow from a warm reservoir to the system, allowing the system to do work.
- The path of an isothermal process in a pV–diagram is called an **isotherm**.
- The product of the pressure and the volume is constant for an ideal gas undergoing an isothermal process, giving the isotherm the form of a hyperbola.
- Isothermal processes play an important part in the analysis of devices that produce useful work from sources of heat.

Concept Check 3

- In which type of process is no work done on a gas?
  - A. isothermal
  - B. isochoric
  - C. isobaric
  - D. None of the above.

Solution Concept Check 3

- In which type of process is no work done on a gas?

  A. isothermal

  B. isochoric

  C. isobaric

  D. None of the above.

Specific Heats of Solids and Fluids 1

- Suppose a block of aluminum is at room temperature.
- If heat, Q, is then transferred to the block, the temperature of the block goes up proportionally to the amount of heat.
- The proportionality constant between the temperature difference and the heat is the **heat capacity**, C, of the block:

  $$Q = C\Delta T$$

- The term *heat capacity* does not imply that an object contains a certain amount of heat.
- Rather, it tells how much heat is required to raise the temperature of the object by a given amount.
- The SI units for heat capacity are joules per kelvin (J/K).

Specific Heats of Solids and Fluids 2

- The temperature change of an object due to heat can be described by the specific heat, *c*, which is defined as the heat capacity per unit mass, *m*:

  $c = C/m$
- With this definition, the relationship between temperature change and heat can be written as:

  $Q = cm\Delta T$
- The SI units for the specific heat are J/(kg K).
- The specific heats of various materials are given in the table.

Table 18.1 Specific Heats for Selected Materials

	Specific Heat, *c*	
Material	**kJ/(kg K)**	**cal/(g K)**
Aluminum	0.900	0.215
Asphalt	0.92	0.22
Basalt	0.84	0.20
Copper	0.386	0.0922
Glass	0.840	0.20
Granite	0.790	0.189
Ice	2.06	0.500
Iron	0.450	0.107
Lead	0.129	0.0308
Limestone	0.217	0.908
Nickel	0.461	0.110
Sandstone	0.92	0.22
Steam	2.01	0.48
Steel	0.448	0.107
Water	4.19	1.00

Specific Heats of Solids and Fluids 3

- Note that specific heat and heat capacity are usually measured in two ways.
- For most substances, they are measured under constant pressure and denoted by c_p and C_p.
- For fluids, the specific heat and heat capacity can also be measured at constant volume and denoted by c_V and C_V.
- Measurements under constant pressure produce larger values, because mechanical work must be performed in the process, and the difference is particularly large for gases.
- The specific heat of a substance can also be defined in terms of the number of moles of the substance rather than its mass.
- This type of specific heat is called the *molar specific heat*.

Specific Heats of Solids and Fluids 4

- The effect of differences in specific heats of substances can be observed readily at the seashore, where the sunlight transfers energy to the land and to the water roughly equally during the day.
- The specific heat of the land is about five times lower than the specific heat of the water.
- The land warms up more quickly than the water, and it warms the air above it more than the water warms the air above it.
- This temperature difference creates an onshore breeze during the day.
- The high specific heat of water helps to moderate climates around oceans and large lakes.

Warming Water

PROBLEM:

- You have 2.00 L of water at a temperature of 20.0 °C.
- How much energy is required to raise the temperature of that water to 95.0 °C?
- If you use electricity to warm the water, how much will it cost at 10.0 cents per kilowatt-hour?

SOLUTION:

- The mass of 1.00 L of water is 1.00 kg.
- The energy required to warm 2.00 kg of water from 20.0 °C to 95.0 °C is:

$$Q = c_{\text{water}} m_{\text{water}} \Delta T = \big(4.19 \text{ kJ/(kg K)}\big)(2.00 \text{ kg})(95.0 \text{ °C} - 20.0 \text{ °C})$$

$$Q = 629{,}000 \text{ J}$$

Calorimetry [1]

- A **calorimeter** is a device used to study internal energy changes by measuring thermal energy transfers.
- The thermal energy transfer and internal energy change may result from a chemical reaction, a physical change, or differences in temperature and specific heat.
- A simple calorimeter consists of an insulated container and a thermometer.
- For simple measurements, a Styrofoam cup and an ordinary alcohol thermometer will do.
- We'll assume that no heat is lost or gained in the calorimeter or the thermometer.

Calorimetry 2

- When two materials with different temperatures are placed in a calorimeter, heat will flow from the warmer substance to the cooler substance until the temperatures of the two substances are the same.
- No heat will flow into or out of the calorimeter.
- The heat lost by the warmer substance will be equal to the heat gained by the cooler substance.
- A substance such as water with a high specific heat requires more heat to raise its temperature by the same amount than does a substance with a low specific heat, like steel.
- The following solved problem illustrates the concepts of calorimetry:

Water and Lead 1

PROBLEM:

- A metalsmith pours 3.00 kg of lead shot at a temperature of 94.7 °C into 1.00 kg of water at 27.5 °C in an insulated container, which acts as a calorimeter.
- What is the final temperature of the mixture?

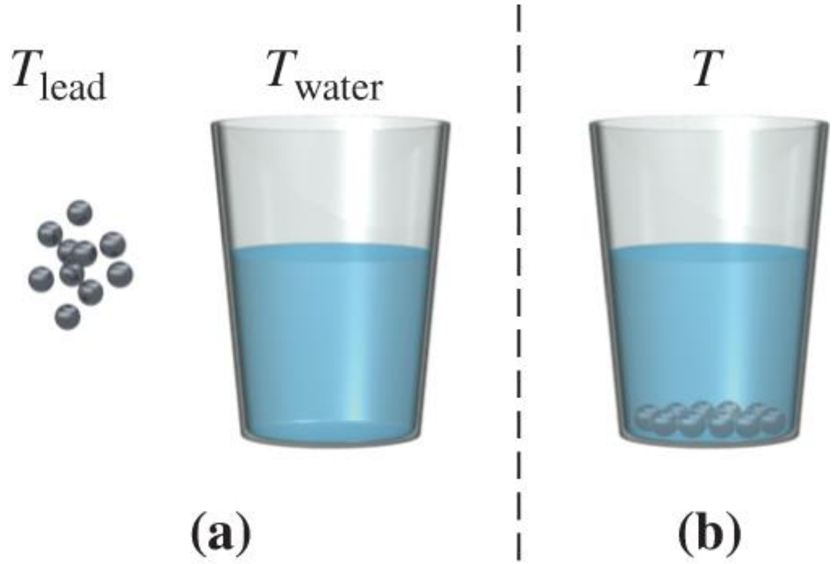
SOLUTION:

Think

- The lead shot will give up heat and the water will absorb heat until both are at the same temperature.
- In this case, there will be no phase transitions.

Water and Lead 2

Sketch



Research

- The heat lost by the lead shot, Q_{lead}, to its environment is given by $Q_{lead} = m_{lead}c_{lead}(T - T_{lead})$, where c_{lead} is the specific heat of lead, m_{lead} is the mass of the lead shot, T_{lead} is the original temperature of the lead shot, and T is the final equilibrium temperature.

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Water and Lead 3

- The sum of the heat lost by the lead shot and the heat gained by the water is zero, because the process took place in an insulated container and because the total energy is conserved.
- So, we can write:

$$Q_{\text{lead}} + Q_{\text{water}} = 0 = m_{\text{lead}} c_{\text{lead}} (T - T_{\text{lead}}) + m_{\text{water}} c_{\text{water}} (T - T_{\text{water}})$$

Simplify

- We multiply through on both sides and reorder so that all the terms containing the unknown temperature, T, are on the right side of the equation:

$$m_{\text{lead}} c_{\text{lead}} T_{\text{lead}} + m_{\text{water}} c_{\text{water}} T_{\text{water}} = m_{\text{lead}} c_{\text{lead}} T + m_{\text{water}} c_{\text{water}} T$$

Water and Lead 4

- We solve for T:

$$T = \frac{m_{\text{lead}} c_{\text{lead}} T_{\text{lead}} + m_{\text{water}} c_{\text{water}} T_{\text{water}}}{m_{\text{lead}} c_{\text{lead}} + m_{\text{water}} c_{\text{water}}}$$

Calculate

- Putting in our numerical values gives:

$$T = \frac{(3.00\text{ kg})\big(0.129\text{ kJ/(kg K)}\big)(94.7\text{ °C}) + (1.00\text{ kg})\big(4.19\text{ kJ/(kg K)}\big)(27.5\text{ °C})}{(3.00\text{ kg})\big(0.129\text{ kJ/(kg K)}\big) + (1.00\text{ kg})\big(4.19\text{ kJ/(kg K)}\big)}$$

$$T = 33.182\text{°C}$$

Round

- We report our results to three significant figures:

$$T = 33.2\text{ °C}$$

Water and Lead 5

Double-check

- The final temperature of the mixture of lead shot and water is only 5.7 °C higher than the original temperature of the water.
- The masses of the lead shot and water differ by a factor of 3, but the specific heat of lead is much lower than the specific heat of water.
- It is reasonable that the lead has a large change in temperature and the water has a small change in temperature.
- To double-check, we calculate the heat lost by the lead and the heat gained by the water.

Water and Lead 6

- For the lead we have:

$$Q_{\text{lead}} = m_{\text{lead}} c_{\text{lead}} (T - T_{\text{lead}})$$

$$Q_{\text{lead}} = (3.00\ \text{kg})\big(0.129\ \text{kJ}/(\text{kg K})\big)(33.2\ ℃ - 97.4\ ℃)$$

$$Q_{\text{lead}} = -23.8\ \text{kJ}$$

- For the water we have:

$$Q_{\text{water}} = m_{\text{water}} c_{\text{water}} (T - T_{\text{water}})$$

$$Q_{\text{water}} = (1.00\ \text{kg})\big(4.19\ \text{kJ}/(\text{kg K})\big)(33.2\ ℃ - 27.5\ ℃)$$

$$Q_{\text{water}} = 23.8\ \text{kJ}$$

- Our results are reasonable.

Concept Check 4

- Suppose you raise the temperature of copper block 1 from −10 °C to +10 °C, of copper block 2 from +20 °C to +40 °C, and of copper block 3 from +90 °C to +110 °C.
- If the blocks have the same mass, to which one did you add the most heat?

A. block 1

B. block 2

C. block 3

D. All the blocks received the same amount of heat.

Solution Concept Check 4

- Suppose you raise the temperature of copper block 1 from −10 °C to +10 °C, of copper block 2 from +20 °C to +40 °C, and of copper block 3 from +90 °C to +110 °C.
- If the blocks have the same mass, to which one did you add the most heat?

A. block 1

B. block 2

C. block 3

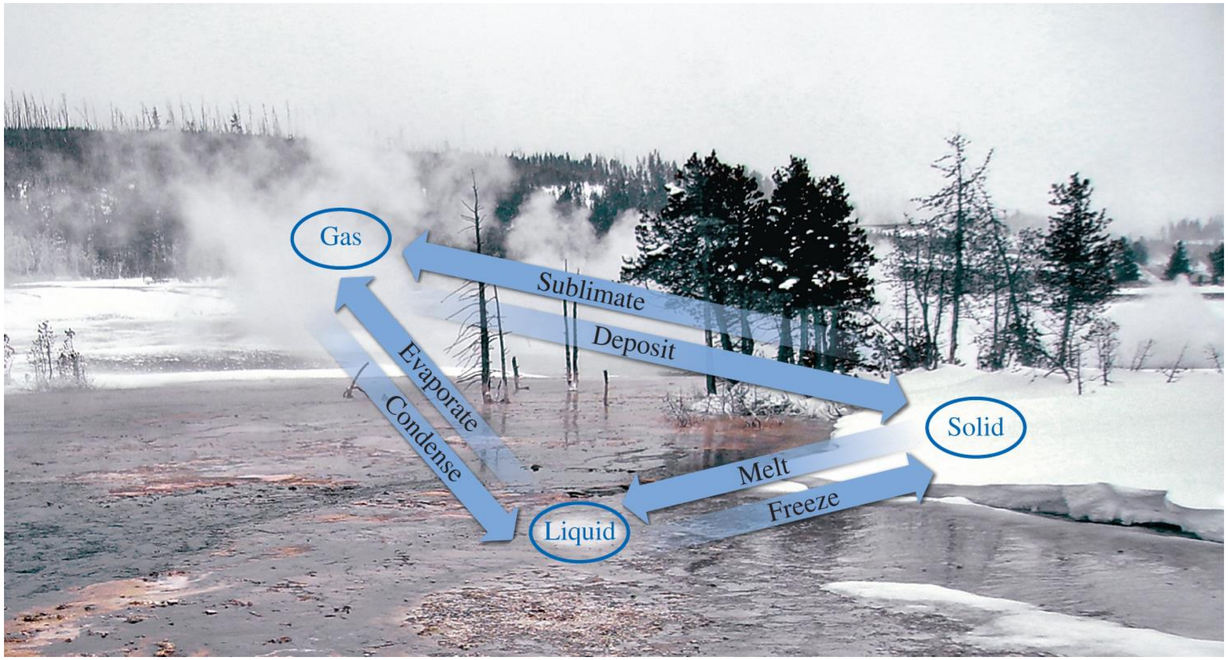
D. All the blocks received the same amount of heat.

Latent Heat and Phase Transitions 1

- The three common states of matter are solid, liquid, and gas.
- We have been considering objects for which the change in temperature is proportional to the amount of heat that is added.
- This linear relationship between heat and temperature is, strictly speaking, an approximation, but it has high accuracy for solids and liquids.
- For a gas, adding heat will raise the temperature but may also change the pressure or volume, depending on whether and how the gas is contained.
- Substances can have different specific heats depending on whether they are in a solid, liquid, or gaseous state.

Latent Heat and Phase Transitions 2

- If enough heat is added to a solid, it melts into a liquid.
- If enough heat is added to a liquid, it vaporizes into a gas.
- These are **phase changes**, or **phase transitions**.



W. Bauer and G. D. Westfall

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Latent Heat and Phase Transitions 3

- During a phase change, the temperature of an object remains constant.
- The heat that is required to melt a solid, divided by its mass, is called the **latent heat of fusion**, L_{fusion}.
- Melting changes a substance from a solid to a liquid.
- The heat that is required to vaporize a liquid, divided by its mass, is called the **latent heat of vaporization**, $L_{\text{vaporization}}$.
- Vaporizing changes a substance from a liquid to a gas.
- The temperature at which a solid melts to a liquid is the melting point, T_{melting}.
- The temperature at which a liquid vaporizes to a gas is the boiling point, T_{boiling}.

Latent Heat and Phase Transitions 4

- The relationship between the mass of an object at its melting point and the heat needed to change the object from a solid to a liquid is given by:

$$Q = mL_{\text{fusion}} \quad (\text{for } T = T_{\text{melting}})$$

- The relationship between the mass of an object at its boiling point and the heat needed to change the object from a liquid to a gas is given by:

$$Q = mL_{\text{vaporization}} \quad (\text{for } T = T_{\text{boiling}})$$

- The SI units for latent heats of fusion and vaporization are joules per kilogram (J/kg).
- The latent heat of fusion for a given substance is different from the latent heat of vaporization for that substance.

Latent Heat and Phase Transitions 5

- A substance can change directly from a solid to a gas.
- This process is called **sublimation**.
- For example, sublimation occurs when dry ice, which is solid (frozen) carbon dioxide, changes directly to gaseous carbon dioxide without passing through the liquid state.
- When a comet approaches the Sun, some of its frozen carbon dioxide sublimates, helping to produce the comet's visible tail.
- If we continue to heat a gas, it will become ionized, which means that some or all the electrons in the atoms of the gas are removed.
- An ionized gas and its free electrons form a state of matter called a **plasma**.

Latent Heat and Phase Transitions 6

- Cooling an object means reducing the internal energy of the object.
- As thermal energy is removed from a substance in the gaseous state, the temperature of the gas decreases, in relation to the specific heat of the gas, until the gas begins to condense into a liquid.
- This change takes place at a temperature called the *condensation point*, which is the same temperature as the boiling point of the substance.
- To convert all the gas to liquid requires the removal of an amount of heat corresponding to the latent heat of vaporization times the mass of the gas.

Latent Heat and Phase Transitions 7

- If thermal energy continues to be removed, the temperature of the liquid will go down, as determined by the specific heat of the liquid, until the temperature reaches the freezing point, which is the same temperature as the melting point of the substance.
- To convert all of the liquid to a solid requires removing an amount of heat corresponding to the latent heat of fusion times the mass.
- If heat then continues to be removed from the solid, its temperature will decrease in relation to its specific heat.
- Let’s do an example of warming ice to water and water to steam.

Warming Ice to Water and Water to Steam 1

PROBLEM:

- How much heat, Q, is required to convert 0.500 kg of ice at a temperature of −30.0 °C to steam at 140. °C?

SOLUTION:

- We solve this problem in steps, with each step corresponding to either a rise in temperature or a phase change.
- We first calculate how much heat is required to raise the temperature of the ice from −30.0 °C to 0 °C.
- The specific heat of ice is 2.06 kJ/(kg K), so the heat required is:

$$Q_1 = cm\Delta T = \left(2.06\ \text{kJ}/(\text{kg K})\right)(0.500\ \text{kg})(30.0\ \text{K}) = 30.9\ \text{kJ}$$

Warming Ice to Water and Water to Steam 2

- We continue to add heat to the ice until it melts.
- The temperature remains at 0 °C until all the ice is melted.
- The latent heat of fusion for ice is 334 kJ/kg, so the heat required to melt all the ice is:

$$Q_2 = mL_{\text{fusion}} = (0.500 \text{ kg})(334 \text{ kJ/kg}) = 167 \text{ J}$$

- Once all the ice has melted to water, we continue to add heat until the water reaches the boiling point, at 100 °C.
- The required heat for this step is:

$$Q_3 = cm\Delta T = \left(4.19 \text{ kJ/(kg K)}\right)(0.500 \text{ kg})(100.\ \text{K}) = 209.5 \text{ kJ}$$

- We continue to add heat to the water until it vaporizes. The heat required for vaporization is:

$$Q_4 = mL_{\text{vaporization}} = (0.500 \text{ kg})(2260 \text{ kJ/kg}) = 1130 \text{ J}$$

Warming Ice to Water and Water to Steam 3

- We now warm the steam and raise its temperature from 100 °C to 140. °C.
- The heat necessary for this step is:

$$Q_5 = cm\Delta T = \left(2.01\ \text{kJ}/(\text{kg K})\right)(0.500\ \text{kg})(40.0\ \text{K}) = 40.2\ \text{kJ}$$

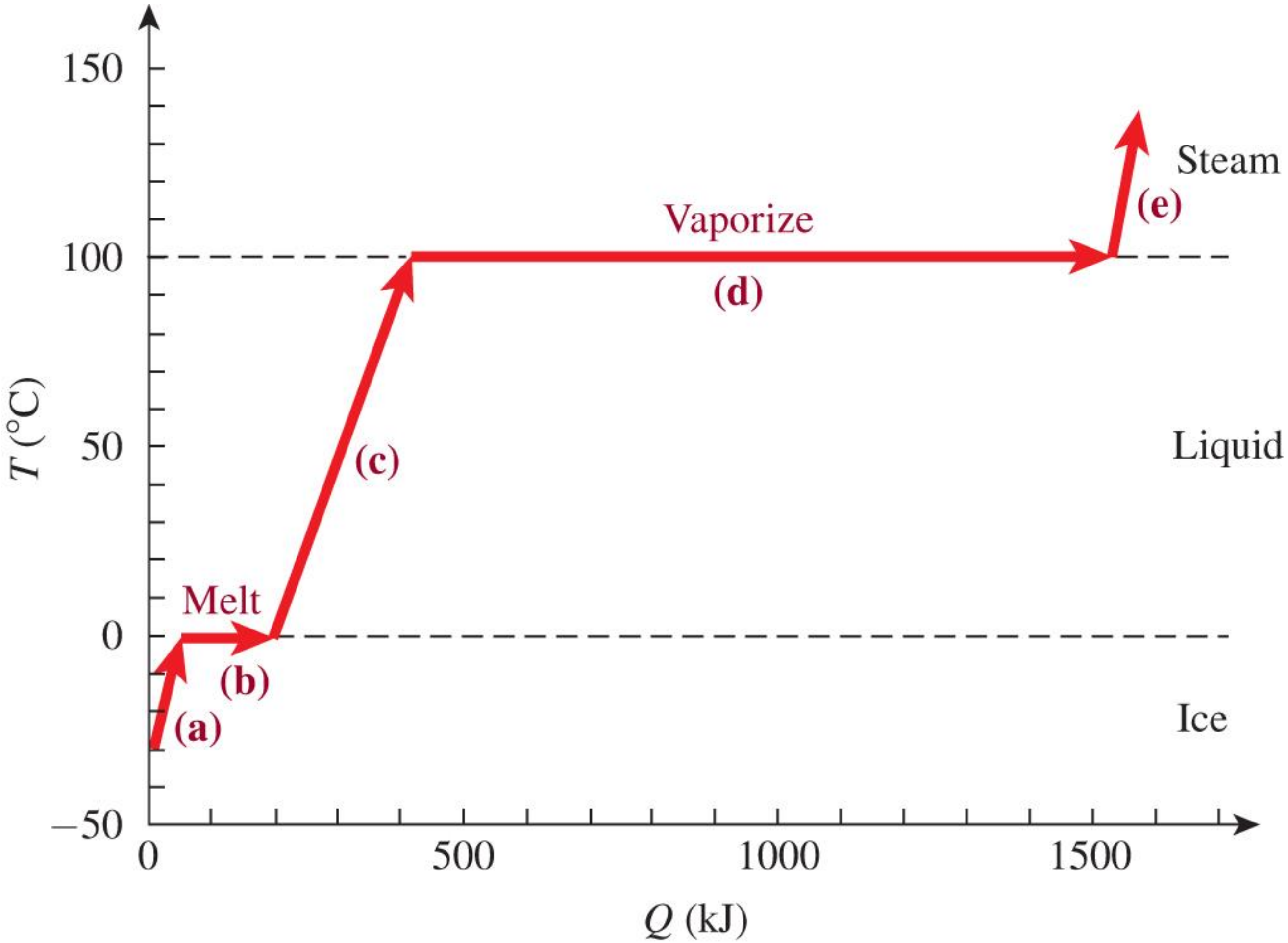
- The total heat required is:

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$$

$$Q = 30.9\ \text{kJ} + 167\ \text{kJ} + 209.5\ \text{kJ} + 1130\ \text{kJ} + 40.2\ \text{kJ} = 1580\ \text{kJ}$$

- Note that almost three quarters of the total heat in this entire process of warming the sample must be spent to convert the liquid water to steam in the process of vaporization.
- We can look at a plot of the warming process.

Warming Ice to Water and Water to Steam 4



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Concept Check 5

- You have a block of ice of mass m at a temperature of $-3\ °C$ in a thermally insulated container and you add the same mass m of liquid water at a temperature of $6\ °C$ and let the mixture come to equilibrium.
- What is the final temperature of the mixture?

A. $-3\ °C$

B. $0\ °C$

C. $+3\ °C$

D. $+4.5\ °C$

E. $+6\ °C$

Solution Concept Check 5

- You have a block of ice of mass *m* at a temperature of −3 °C in a thermally insulated container and you add the same mass *m* of liquid water at a temperature of 6 °C and let the mixture come to equilibrium.
- What is the final temperature of the mixture?

A. −3 °C

B. 0 °C

C. +3 °C

D. +4.5 °C

E. +6 °C

For the water, the Q that must be removed to bring it to 0 °C is

$$Q = (4.19)m(6 - 0) = 25.14m$$

For the ice, the Q that must be added to bring it to 0 °C is

$$Q = (2.08)m\big(0 - (-3)\big) = 6.1m$$

To melt all the ice requres

$$Q = (334)m = 334m$$

There will be an ice/water mixture at 0 °C at equilibrium

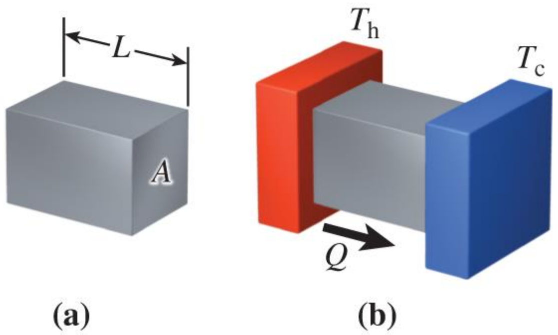
Modes of Thermal Energy Transfer

- The three main modes of thermal energy transfer are conduction, convection, and radiation.
- All three are illustrated by the campfire in this photo.
- **Radiation** is the transfer of thermal energy via electromagnetic waves.
- You can feel heat radiating from a campfire when you sit near it.
- **Convection** involves the physical movement of a substance (such as water or air) from thermal contact with one system to thermal contact with another system.

Dmitry Naumov/iStock-360/Getty Images

Conduction 1

- **Conduction** involves the transfer of thermal energy within an object (such as thermal energy transfer along a fire poker whose tip is hot) or the transfer of heat between two (or more) objects in thermal contact.
- Heat is conducted through a substance by the vibration of atoms and molecules and by motion of electrons.
- Consider a bar with cross-sectional area A and length L.
- This bar is put in physical contact with a thermal reservoir at a hotter temperature, T_h, and a thermal reservoir at a colder temperature, T_c, which means $T_h > T_c$.



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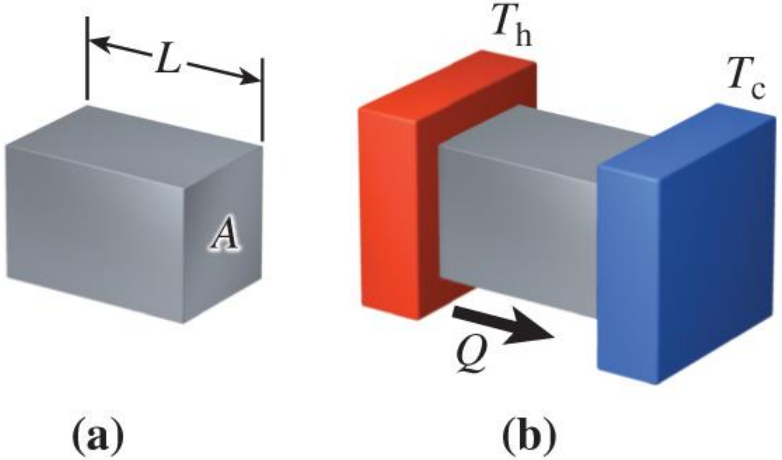
Conduction 2

- Heat then flows from the reservoir at the higher temperature to the reservoir at the lower temperature.
- The thermal energy transferred per unit time, P_{cond}, by the bar connecting the two heat reservoirs is given by:

$$P_{\mathrm{cond}} = \frac{Q}{t} = kA\frac{T_{\mathrm{h}} - T_{\mathrm{c}}}{L}$$

- Here k is the **thermal conductivity** of the material of the bar.
- The SI units of thermal conductivity are W/(m K).



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Conduction 3

- Here are some typical values of thermal conductivity.
- Note the huge range of conductivities!
- The highest values are those for forms of pure carbon.
- The coinage metals have very high thermal conductivities, but they are an order of magnitude lower than those of the forms of pure carbon.
- The materials at the bottom of the table are used for thermal insulation.

Table 18.3 Some Representative Thermal Conductivities

Material	*k* [W/(m K)]
Graphene	5000
Carbon nanotube	3500
Diamond	2000
Silver	420
Copper	390
Gold	320
Aluminum	220
Nickel	91
Iron	80
Lead	35
Stainless steel	20
Granite	3
Ice	2
Limestone	1.3
Concrete	0.8
Glass	0.8
Water	0.5
Rubber	0.16
Wood	0.16
Paper	0.05
Air	0.025
Polyurethane foam	0.02

Conduction 4

- We can rearrange our expression for the thermal energy transferred per unit time to get:

$$P_{\text{cond}} = \frac{Q}{t} = kA\frac{T_{\text{h}} - T_{\text{c}}}{L} = A\frac{T_{\text{h}} - T_{\text{c}}}{R}$$

- The **thermal resistance**, *R*, is defined to be:

$$R = L/k$$

- The SI units of *R* are $\text{m}^2\ \text{K/W}$
- A higher *R* value means a lower rate of thermal energy transfer.
- A good insulator has a high *R* value.
- In the United States, thermal resistance is often specified by an *R* factor, which has the units $\text{ft}^2\ {}^\circ\text{F h/BTU}$.

Conduction 5

- Here is a common insulating material an *R* factor of R-30:

a: Diane39/iStock/Getty Images

b: Kuchina/Shutterstock

- To convert an *R* factor from ft^2 °F h/BTU to m^2 K/W, divide the *R* factor by 5.678.

Roof Insulation [1]

- Suppose you insulate above the ceiling of a room with an insulation material having an *R* factor of R-30.
- The ceiling measures 5.00 m by 5.00 m.
- The temperature inside the room is 21.0 °C, and the temperature above the insulation is 40.0 °C.

PROBLEM:

- How much heat enters the room through the ceiling in a day if the room is maintained at a temperature of 21.0 °C?

SOLUTION:

- We solve for the heat:

$$\frac{Q}{t} = A\frac{T_\mathrm{h} - T_\mathrm{c}}{R} \quad \Rightarrow \quad Q = At\frac{T_\mathrm{h} - T_\mathrm{c}}{R}$$

Roof Insulation 2

- One day has 86,400 s.
- Converting the R factor to SI units:

$$R = \frac{30}{5.678}\ \text{m}^2\ \text{K/W} = 5.283\ \text{m}^2\ \text{K/W}$$

- The heat entering the room through the roof in one day is:

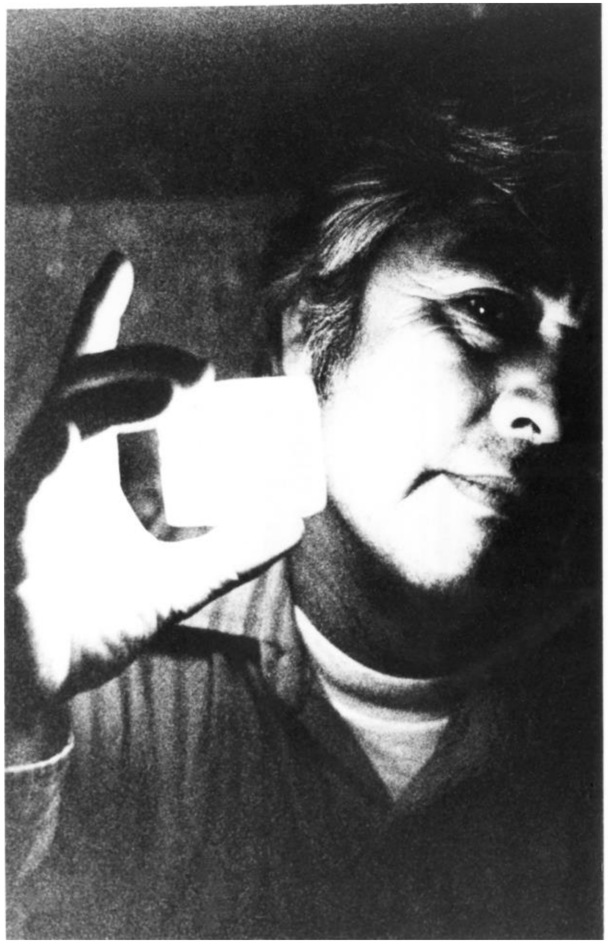
$$Q = (5.00\ \text{m} \cdot 5.00\ \text{m})(86{,}400\ \text{s})\frac{313\ \text{K} - 294\ \text{K}}{5.283\ \text{m}^2\ \text{K/W}} = 7.77 \cdot 10^6\ \text{J}$$

Thermal Insulation 1

- Thermal insulation is a key component of spacecraft that must reenter the Earth's atmosphere.
- The reentry process creates thermal energy from friction with air molecules.
- As a result of the high speed, a shock wave forms in front of the spacecraft, which deflects most of the thermal energy created in the process.
- However, excellent thermal insulation is still required to prevent this heat from being conducted to the frame of the spacecraft, which is basically made of aluminum and cannot stand temperatures significantly higher than 180 °C.

Thermal Insulation 2

- The underside of the Space Shuttle was covered with passive heat protection, consisting of over 20,000 ceramic tiles made of 10% silica fibers and 90% empty space.
- They were such good thermal insulators that after being warmed to a temperature of 1260 °C (which is the maximum temperature the underside of the Space Shuttle encountered during reentry); they can be held by unprotected hands.



NASA

Concept Check 6

- If you double the temperature (measured in kelvins) of an object, the thermal energy transferred away from it per unit time will

  A. decrease by a factor of 2.

  B. stay the same.

  C. increase by a factor of 2.

  D. increase by a factor of 4.

  E. change by an amount that cannot be determined without knowing the temperature of the object's surroundings.

Solution Concept Check 6

- If you double the temperature (measured in kelvins) of an object, the thermal energy transferred away from it per unit time will

  A. decrease by a factor of 2.

  B. stay the same.

  C. increase by a factor of 2.

  D. increase by a factor of 4.

  E. change by an amount that cannot be determined without knowing the temperature of the object's surroundings.

Cost of Warming a House in Winter 1

- You build a small house with four rooms.
- Each room is 10.0 ft ×10.0 ft, and the ceiling is 8.00 ft high.
- The exterior walls are insulated with a material with an *R* factor of R-19, and the floor and ceiling are insulated with a material with an *R* factor of R-30.
- During the winter, the average temperature inside is 20.0 °C, and the average temperature outside is 0.00 °C.
- You warm the house for 6 months in winter using electricity that costs 9.5 cents per kilowatt-hour.

PROBLEM:

- How much do you pay to warm your house for the winter?

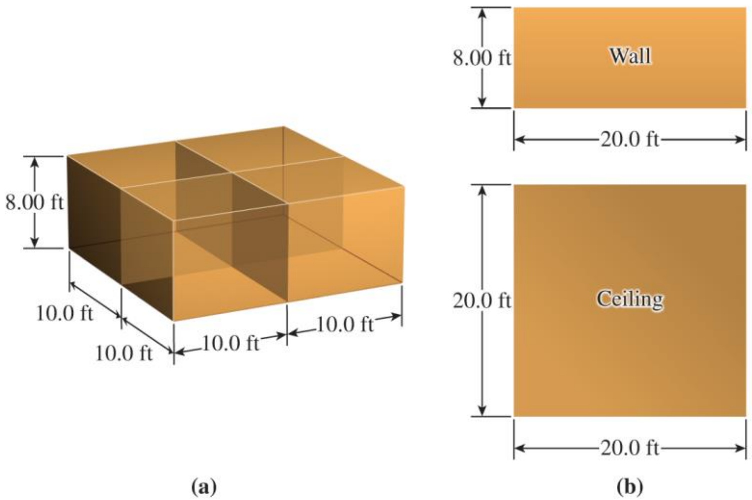
Cost of Warming a House in Winter 2

SOLUTION:

Think

- We can calculate the total heat lost over 6 months through the walls (R-19) and through the floor and ceiling (R-30).
- We can then calculate how much it will cost to add this amount of heat to the house.

Sketch



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Cost of Warming a House in Winter 3

Research

- Each of the four exterior walls has an area of A_{wall}.
- The ceiling has an area of A_{ceiling}.
- The floor and ceiling have the same area.
- The thermal resistance of the walls is R-19.
- The thermal resistance of the floor and ceiling is R-30.
- The thermal resistance of the walls in SI units is:

$$R_{\text{wall}} = \frac{19}{5.678}\ \text{m}^2\ \text{K/W} = 3.346\ \text{m}^2\ \text{K/W}$$

- The thermal resistance of the floor and ceiling is:

$$R_{\text{ceiling}} = \frac{30}{5.678}\ \text{m}^2\ \text{K/W} = 5.284\ \text{m}^2\ \text{K/W}$$

Cost of Warming a House in Winter 4

Simplify

- Taking the total area of the walls to be four times the area of one wall and the total area of the floor and ceiling as twice the area of the ceiling:

$$\frac{Q}{t} = 4A_{\text{wall}}\left(\frac{T_{\text{h}} - T_{\text{c}}}{R_{\text{wall}}}\right) + 2A_{\text{ceiling}}\left(\frac{T_{\text{h}} - T_{\text{c}}}{R_{\text{ceiling}}}\right) = 2(T_{\text{h}} - T_{\text{c}})\left(\frac{2A_{\text{wall}}}{R_{\text{wall}}} + \frac{A_{\text{ceiling}}}{R_{\text{ceiling}}}\right)$$

Calculate

- The area of each exterior wall is:

$$A_{\text{wall}} = (8.00\text{ ft})(20.0\text{ ft}) = 160.0\text{ ft}^2 = 14.864\text{ m}^2$$

- The area of the ceiling is:

$$A_{\text{ceiling}} = (20.0\text{ ft})(20.0\text{ ft}) = 400.0\text{ ft}^2 = 37.161\text{ m}^2$$

Cost of Warming a House in Winter 5

- The number of seconds in 6 months is:

$$t = (6\text{ months})(30\text{ days/month})(24\text{ h/day})(3600\text{ s/h}) = 1.5552 \cdot 10^7\text{ s}$$

- The amount of heat lost in 6 months is:

$$Q = 2t(T_\text{h} - T_\text{c})\left(\frac{2A_\text{wall}}{R_\text{wall}} + \frac{A_\text{ceiling}}{R_\text{ceiling}}\right)$$

$$Q = 2(1.5552 \cdot 10^7\text{ s})(293\text{ K} - 273\text{ K})\left(\frac{2(14.864\text{ m}^2)}{3.346\text{ m}^2\text{ K/W}} + \frac{37.161\text{ m}^2}{5.284\text{ m}^2\text{ K/W}}\right)$$

$$Q = 9.902 \cdot 10^9\text{ J}$$

- The cost of electricity is:

$$\text{Cost} = \left(\frac{\$0.095}{1\text{ kWh}}\right)\left(\frac{1\text{ kWh}}{3.60 \cdot 10^6\text{ J}}\right)(9.902 \cdot 10^9\text{ J}) = \$261.3041$$

Cost of Warming a House in Winter 6

Round

- We round to two significant figures:

$$\text{Cost} = \$260$$

Double-check

- To double-check, let's use the R values the way a contractor would.
- The total area of the walls is $4(160\ \text{ft}^2)$, and the total area of the floor and ceiling is $2(400\ \text{ft}^2)$.
- The heat lost per hour through the walls is:

$$\frac{Q}{t} = 4(160\ \text{ft}^2)\frac{20\left(\frac{9}{5}\right)\ °\text{F}}{19\ \text{ft}^2\ °\text{F h/BTU}} = 1213\ \text{BTU/h}$$

Cost of Warming a House in Winter 7

- The heat lost per hour through the ceiling and floor is:

$$\frac{Q}{t} = 2(400\ \text{ft}^2)\frac{20\left(\frac{9}{5}\right)\ °\text{F}}{30\ \text{ft}^2\ °\text{F h/BTU}} = 960\ \text{BTU/h}$$

- The total heat lost in 6 months is:

$$Q = (4320\ \text{h})(1213\ \text{BTU/h} + 960\ \text{BTU/h}) = 9.387 \cdot 10^6\ \text{BTU}$$

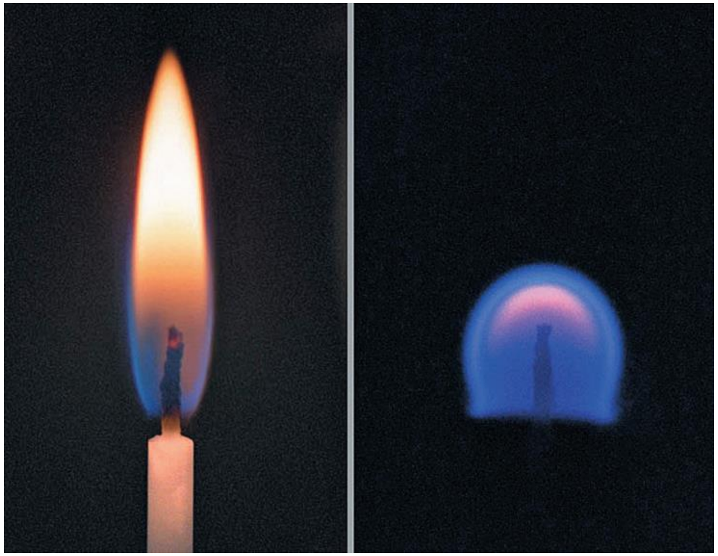
- The cost is:

$$\text{Cost} = \left(\frac{\$0.095}{1\ \text{kWh}}\right)\left(\frac{1\ \text{kWh}}{3412\ \text{BTU}}\right)\left(9.387 \cdot 10^6\ \text{BTU}\right) = \$261.37$$

- Our answer is reasonable.
- Note that our house is small and well insulated, so the cost to heat the house for the winter is relatively small.

Convection [1]

- If you hold your hand above a burning candle, you can feel the thermal energy transferred from the flame.
- The warmed air is less dense than the surrounding air and rises.
- The rising air carries thermal energy upward from the candle flame.
- This type of thermal energy transfer is called **convection**.
- Here is a candle flame on Earth (a)
- and (b) on the orbiting Space Shuttle.
- The thermal energy travels upward on Earth and expands spherically on the Shuttle.

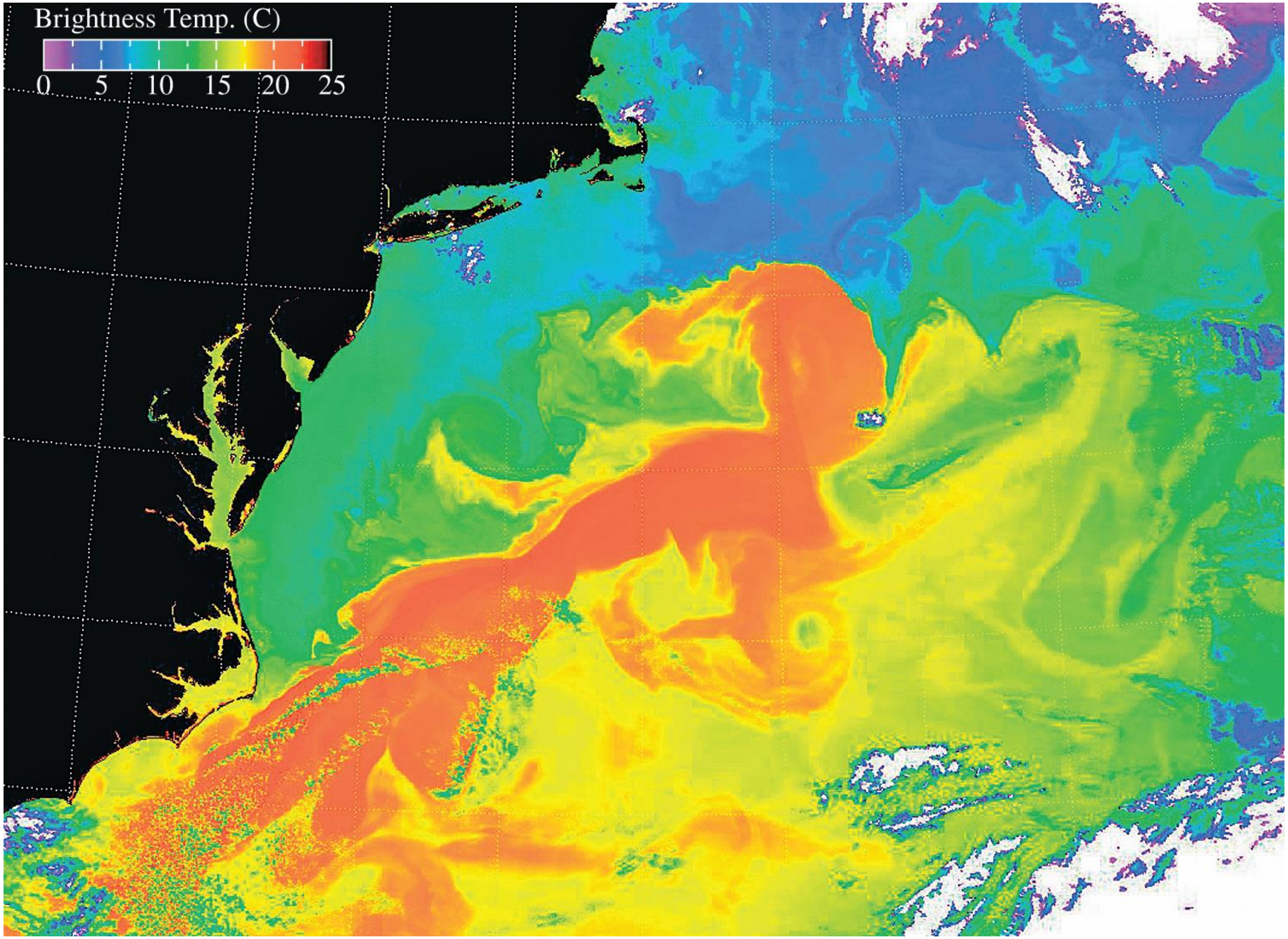


NASA Glenn Research Center

Convection 2

- Most houses and office buildings in the United States have forced-air heating; that is, warm air is blown through heating ducts into rooms.
- This is an excellent example of thermal energy transfer via convection.
- Large amounts of energy are transferred by convection in the Earth’s atmosphere and in the oceans.
- For example, the Gulf Stream carries warm water from the Gulf of Mexico northward through the Straits of Florida and up the east coast of the United States.
- The temperature of the water in the Gulf Stream can be measured using satellites.

Convection 3



NASA Goddard Space Flight Center, Visible Earth

Convection 4

- The Gulf Stream has a temperature around 20 °C as it flows with a speed of approximately 2 m/s up the east coast of the United States into the North Atlantic.
- The Gulf Stream then splits.
- One part continues to flow toward Britain and Western Europe, while the other part turns south along the African coast.
- The average temperature of Britain and Western Europe is approximately 5 °C higher than it would be without the thermal energy carried by the warmer waters of the Gulf Stream.
- Some climate models predict that global warming may possibly threaten the Gulf Stream because of the melting of ice at the North Pole.

Gulf Stream 1

- Assume that a rectangular pipe of water 100 km wide and 500 m deep can approximate the Gulf Stream.
- The water in this pipe is moving with a speed of 2.0 m/s.
- The temperature of the water is 5.0 °C warmer than the surrounding water.

PROBLEM:

- Estimate how much power the Gulf Stream is carrying to the North Atlantic Ocean.

SOLUTION:

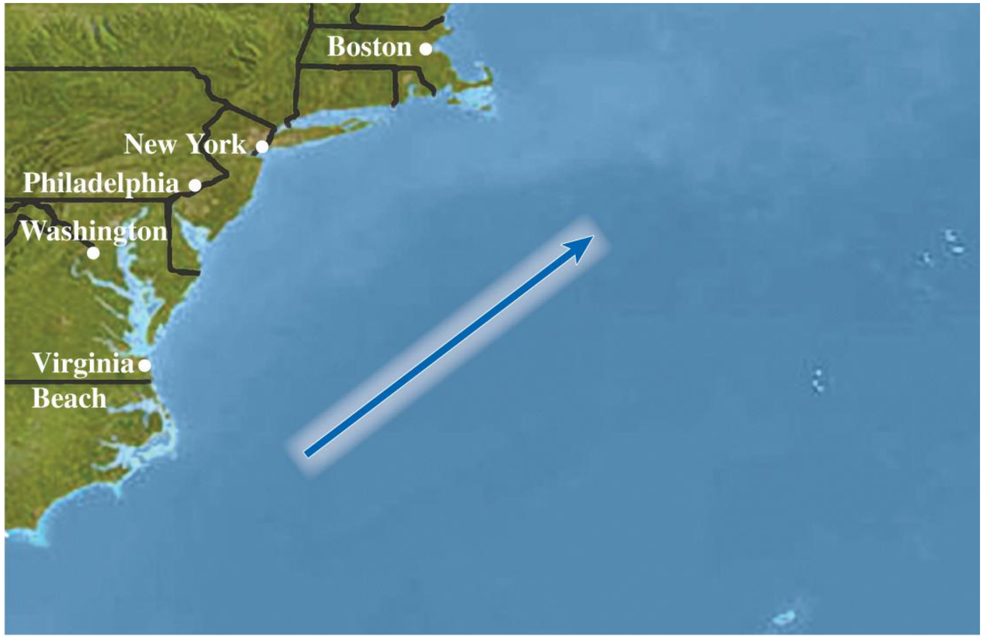
Think

- We can calculate the volume flow rate by taking the product of the speed of the flow and the cross-sectional area of the pipe.

Gulf Stream 2

- Using the density of water, we can calculate the mass flow rate.
- Using the specific heat of water and the temperature difference between the Gulf Stream water and the surrounding water, we can calculate the power carried by the Gulf Stream to the North Atlantic.

Sketch



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Gulf Stream 3

Research

- We assume that the Gulf Stream has a rectangular cross section of width w =100 km and depth d = 500 m.
- The area of the Gulf Stream flow is then:

  $A = wd$

- The speed of the flow of the Gulf Stream is assumed to be: v = 2.0 m/s.
- The volume flow rate is given by:

  $R_V = vA$

- The density of seawater is $\rho = 1025\ \text{kg/m}^3$.
- We can express the mass flow rate as:

  $R_m = \rho R_V$

Gulf Stream 4

- The specific heat of water is 4186 J/(kg K).
- The heat required to raise the temperature of a mass m by ΔT is given by:

$$Q = cm\Delta T$$

- The power carried by the Gulf Stream is equal to the heat per unit time:

$$\frac{Q}{t} = P = \frac{cm\Delta T}{t} = cR_m\Delta T$$

Simplify

- The power carried by the Gulf Stream is:

$$P = cR_m\Delta T = c\rho R_V\Delta T = c\rho vwd\Delta T$$

Gulf Stream 5

Calculate

- The temperature difference is $\Delta T = 5\ °C = 5\ K$.
- Putting in our numerical values gives us:

$$P = \left(4186\ \text{J/(kg K)}\right)(1025\ \text{kg/m}^2)(2.0\ \text{m/s})(100 \cdot 10^3\ \text{m})(500\ \text{m})(5\ \text{K})$$

$$P = 2.1453 \cdot 10^{15}\ \text{W}$$

Round

- We round to two significant figures:

$$P = 2.1 \cdot 10^{15}\ \text{W} = 2.1\ \text{PW}$$

Double-check

- To double-check, let's calculate how much power is incident on the Earth from the Sun.

Gulf Stream 6

- This total power is given by the cross-sectional area of Earth times the power incident on Earth per unit area:

$$P_{\text{total}} = \pi(6.4 \cdot 10^6 \text{ m})^2(1400 \text{ W/m}^2) = 180 \text{ PW}$$

- Now calculate how much of this power could be absorbed by the Gulf of Mexico.
- The area of the Gulf Stream is $1.0 \cdot 10^6 \text{ km}^2 = 1.0 \cdot 10^{12} \text{ m}^2$
- If the Gulf Stream absorbed all the energy from the Sun for half of each day, then:

$$P = \frac{(1.0 \cdot 10^{12} \text{ m}^2)(1400 \text{ W/m}^2)}{2} = 0.7 \text{ PW}$$

- This is less than our calculated power of 2.1 PW.

Gulf Stream 7

- Thus, more of the Atlantic Ocean must be involved in providing energy for the Gulf Stream than just the Gulf of Mexico.
- In fact, the Gulf Stream gets its energy from a large fraction of the Atlantic Ocean.
- The Gulf Stream is part of a network of currents flowing in the Earth's oceans, induced by prevailing winds, temperature differences, and the Earth's topology and rotation.

Concept Check 7

- The power carried by the Gulf Stream could be doubled by
  A. decreasing its speed by a factor of 2.
  B. decreasing its temperature difference by a factor of 2.
  C. increasing its temperature by a factor of 2.
  D. increasing its speed by a factor of 4.
  E. none of the above.

Solution Concept Check 7

- The power carried by the Gulf Stream could be doubled by
  A. decreasing its speed by a factor of 2.
  B. decreasing its temperature difference by a factor of 2.
  C. increasing its temperature by a factor of 2.
  D. increasing its speed by a factor of 4.
  E. none of the above.

Radiation 1

- Radiation occurs via the transmission of electromagnetic waves.
- Electromagnetic waves can carry energy from one site to another without any matter having to be present between the two sites.
- All objects emit electromagnetic radiation in the form of thermal radiation.
- The temperature of the object determines the radiated power of the object, P_{radiated}, which is given by the **Stefan-Boltzmann equation**:

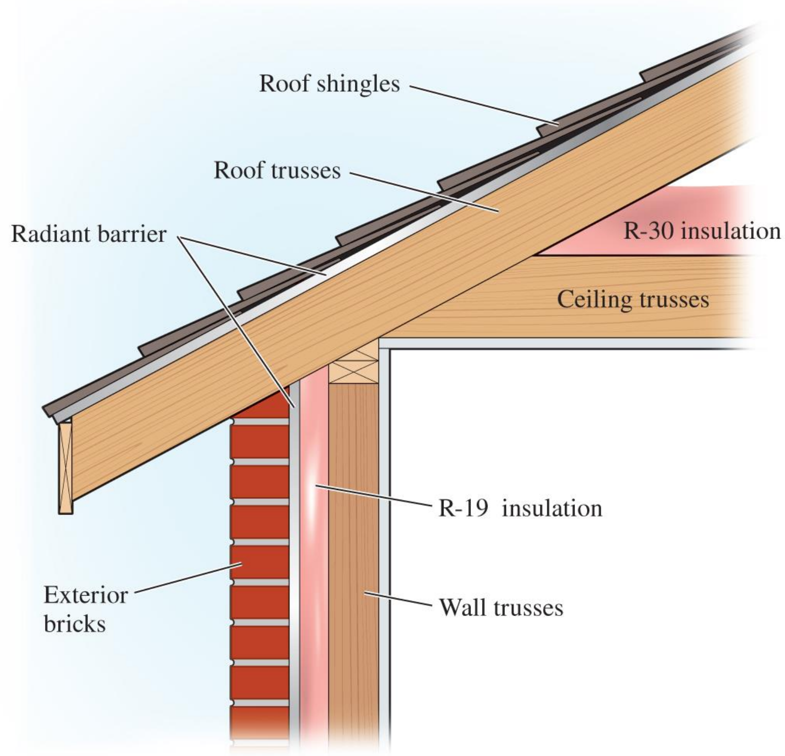
  $$P_{\text{radiated}} = \sigma \varepsilon A T^4$$

Radiation 2

- In this equation, $\sigma = 5.67 \cdot 10^{-8}$ W/(K^4 m^2) is the **Stefan-Boltzmann constant**, ε is the **emissivity**, which has no units, and A is the surface area.
- The temperature must be expressed in kelvins.
- The emissivity varies between 0 and 1, with 1 being the emissivity of an idealized object called a **blackbody**.
- A blackbody radiates 100% of its power and absorbs 100% of any radiation incident on it.
- Although some real-world objects are close to being a blackbody, no perfect blackbodies exist; thus, the emissivity is always less than 1.

Radiation 3

- The heat loss of a house in winter or the heat gain in summer depends not only on conduction but also on radiation.
- New building techniques have aimed at increasing the efficiency of house insulation by using radiant barriers.
- A radiant barrier is a layer of material that effectively reflects electromagnetic waves, especially infrared radiation (which is the radiation we feel as warmth).



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Radiation 4

- A radiant barrier is constructed of a reflective substance, usually aluminum.
- A typical commercial radiant barrier is made of aluminum-coated polyolefin, which reflects 97% of infrared radiation.
- Tests by Oak Ridge National Laboratory of houses in Florida with and without radiant barriers have shown that summer heat gains of ceilings with R-19 insulation can be reduced by 16% to 42%, resulting in the reduction of air-conditioning costs by as much as 17%.

Courtesy of www.EnergyEfficientSolutions.com

Radiation 5

- It is relatively straightforward to find out where a house is losing heat due to radiation by taking its picture with an infrared camera.
- Such images are called *thermograms*, and here is an example.
- The red areas in the image show that this particular house loses the most heat through its roof, and thus an investment in better roof insulation might be called for.

Ivan Smuk/Shutterstock

Earth as a Blackbody 1

- Suppose that the Earth absorbed 100% of the incident energy from the Sun and then radiated all the energy back into space, just as a blackbody would.

PROBLEM:

- What would the temperature of the surface of Earth be?

SOLUTION:

- The intensity of sunlight arriving at the Earth is approximately $S = 1400\ \text{W/m}^2$.
- The Earth absorbs energy as a disk with the radius of the Earth, R, whereas it radiates energy from its entire surface area of $4\pi R^2$.

Earth as a Blackbody 2

- At equilibrium, the energy absorbed equals the energy emitted:

  $S(\pi R^2) = (\sigma)(1)(4\pi R^2)T^4$

- Solving for the temperature, we get:

$$T = \sqrt[4]{\frac{S}{4\sigma}} = \sqrt[4]{\frac{1400\ \mathrm{W/m^2}}{4\left(5.67 \cdot 10^{-8}\ \mathrm{W/(K^4 m^2)}\right)}} = 280\ \mathrm{K}$$

- This simple calculation gives a result close to the actual value of the average temperature of the surface of the Earth, which is about 288 K.

Concept Check 8

- If the temperature (measured in kelvins) of an object is doubled, the heat it radiates per unit time will

  A. decrease by a factor of 2.

  B. stay the same.

  C. increase by a factor of 2.

  D. increase by a factor of 4.

  E. increase by a factor of 16.

Solution Concept Check 8

- If the temperature (measured in kelvins) of an object is doubled, the heat it radiates per unit time will

  A. decrease by a factor of 2.

  B. stay the same.

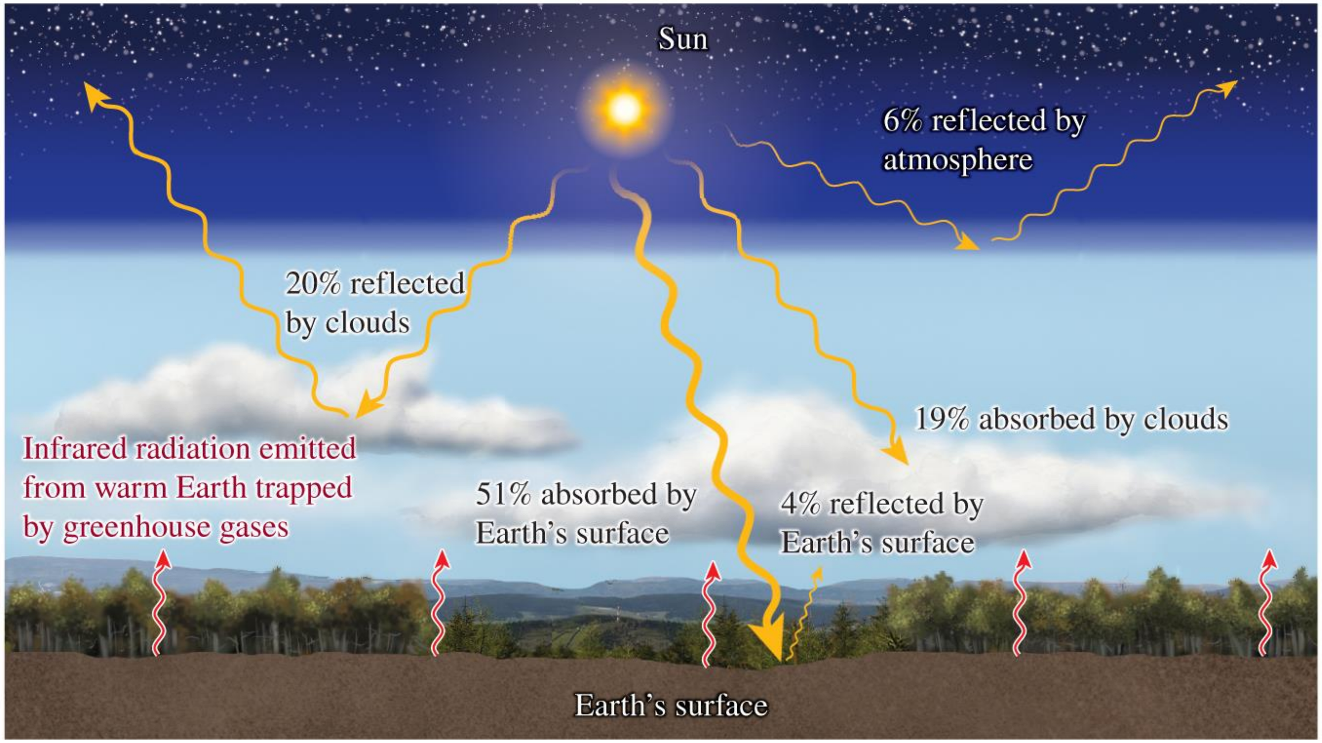
  C. increase by a factor of 2.

  D. increase by a factor of 4.

  E. increase by a factor of 16.

Global Warming 1

The difference between the temperature calculated for Earth as a blackbody and the actual temperature of the Earth's surface is partly due to the Earth's atmosphere.



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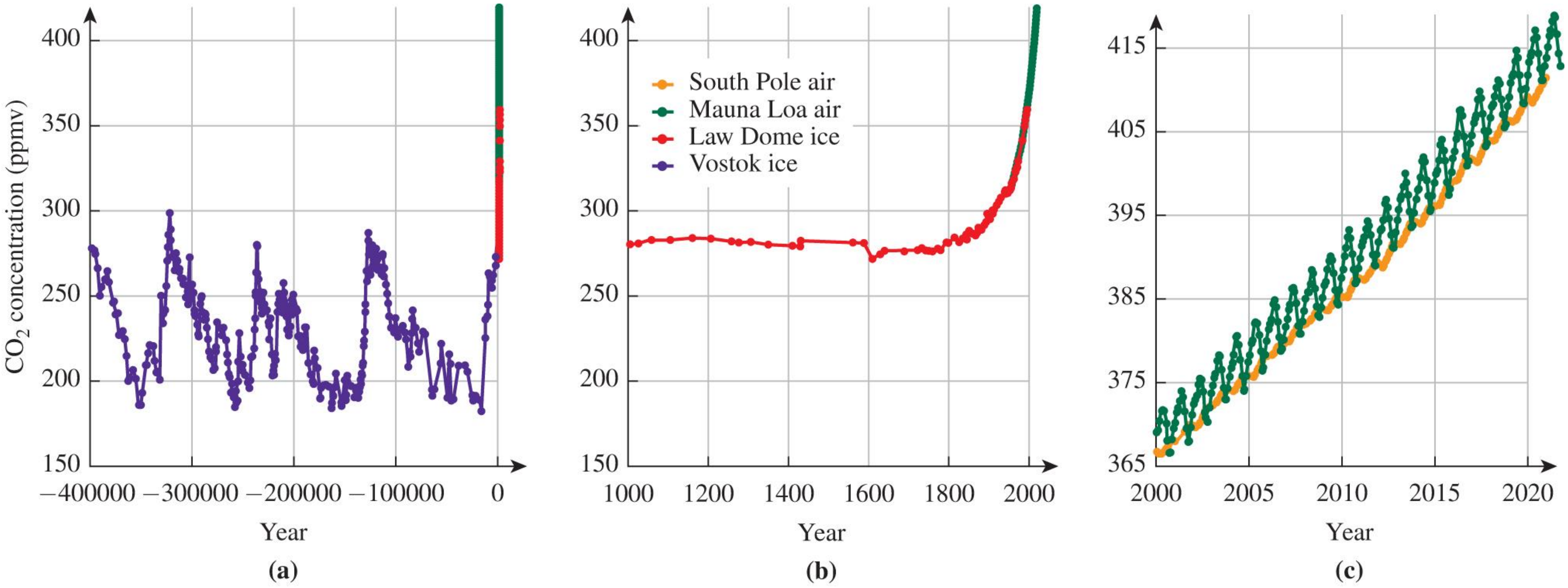
Global Warming 2

- Solar energy is absorbed by the surface of the Earth and warms it, causing the surface to give off infrared radiation.
- Certain gases in the atmosphere such as water vapor and carbon dioxide, absorb some of this infrared radiation, trapping a fraction of the energy.
- This is called the **greenhouse effect**.
- The greenhouse effect keeps the Earth warmer than it would otherwise be and minimizes day-to-night temperature variations.
- The burning of fossil fuels and other human activities have increased the amount of carbon dioxide in the atmosphere and increased the surface temperature by trapping infrared radiation that would otherwise be emitted into space.

Global Warming 3

- Here are measurements of the carbon dioxide in Earth's atmosphere.



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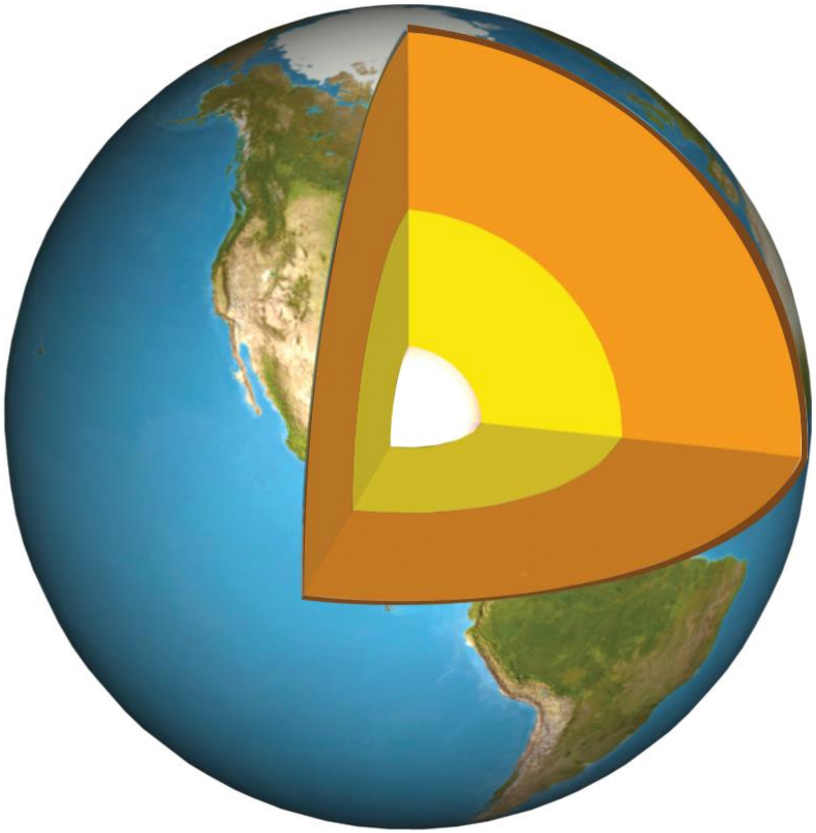
Global Warming 4

- Some researchers estimate that the current concentration of carbon dioxide is at its highest level in the past 20 million years.
- Models of the composition of the Earth's atmosphere based on current trends predict that the concentration of carbon dioxide will continue to increase in the next 100 years.
- This increase in the atmospheric concentration of carbon dioxide contributes to the observed global warming described in Chapter 17.
- Worldwide governments are reacting to these observation in many ways.

Geothermal Power Resources 1

- Earth has a solid inner core with a radius of approximately 1200 km, predominantly composed of iron (80%) and nickel.
- The inner core is encased by a liquid outer core with a radius of about 3400 km.
- Around the outer core is the mantle, which is mainly composed of oxygen, silicon, and magnesium and has a thickness of about 2800–2900 km.
- Earth's outermost layer is the crust, composed of solid tectonic plates with a thickness between 5 km and 70 km.

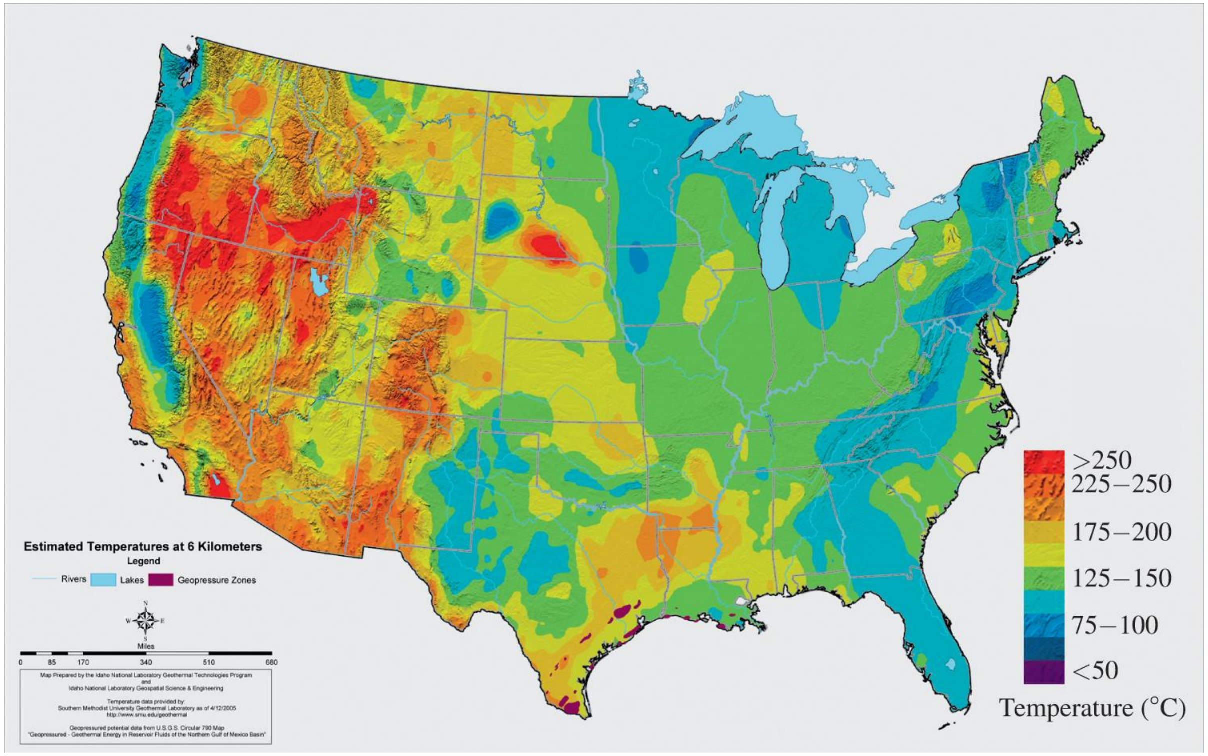


Geothermal Power Resources 2

- Currently, the best estimate of the temperature at Earth's center is approximately 6000 K.
- This temperature is mainly due to the radioactive decay of long-lived isotopes of uranium, potassium, and thorium.
- The average surface temperature of Earth is approximately 290 K, so a very important question is how Earth's temperature varies with depth.
- Near the edges of the tectonic plates, relatively high temperatures can be found fairly close to the surface; these are the source of volcanic events.
- Away from the plate edges, however, a simple rule of thumb is that the temperature in the crust increases by 25 to 30 K per kilometer of depth.
- This number is called the *geothermal gradien*t.

Geothermal Power Resources 3

- Here are the expected temperatures at a depth of 6 km below ground level in the continental United States.



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Geothermal Power Resources 4

- Tremendously large thermal resources are available in Earth's interior, and there is a huge flow of heat through the Earth's surface.
- The question is how to utilize these resources.
- In some countries, utilization of geothermal power is quite actively pursued; foremost among them is Iceland.
- Iceland has the advantage of being located where the Earth's crust is very thin; thus, the thermal resources of the Earth's interior can be tapped into comparatively easily.
- Five large geothermal power plants supply 25% of Iceland's electrical power and almost 90% of its hot water and home heating.

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