Chapter 17. Work, Heat, and the First Law of Thermodynamics

This false-color thermal image (an infrared photo) shows where heat energy is escaping from a house. In this chapter we investigate the connection between work and heat.

Chapter Goal: To expand our understanding of energy and to develop the first law of thermodynamics as a general statement of energy conservation.



Chapter 17. Work, Heat, and the First Law of Thermodynamics

Topics:

- It's All About Energy
- Work in Ideal-Gas Processes
- Heat
- The First Law of Thermodynamics
- Thermal Properties of Matter
- Calorimetry
- The Specific Heats of Gases
- Heat-Transfer Mechanisms

Chapter 17. Reading Quizzes

What quantities appear in the first law of thermodynamics?

- A. force, mass, acceleration
- B. inertia, torque, angular momentum
- C. work, heat, thermal energy
- D. work, heat, entropy
- E. enthalpy, entropy, heat

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What was the original unit for measuring heat?

- A. BTU
- B. Watt
- C. Joule
- D. Pascal
- E. Calorie

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What is the name of an ideal-gas process in which no heat is transferred?

- A. Isochoric
- B. Isentropic
- C. Isothermal
- D. Isobaric
- E. Adiabatic

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A. Isochoric

- B. Isentropic
- C. Isothermal
- D. Isobaric



Heat is

- A. the amount of thermal energy in an object.
- B. the energy that moves from a hotter object to a colder object.
- C. a fluid-like substance that flows from
 - a hotter object to a colder object.
- D. both A and B.
- E. both B and C.

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The thermal behavior of water is characterized by the value of its

A. heat density.

- B. heat constant.
- C. specific heat.
- D. thermal index.

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Chapter 17. Basic Content and Examples

Work in Ideal-Gas Processes

Consider a gas cylinder sealed at one end by a moveable piston. **FIGURE 17.4** The external force does work on the gas as the piston moves.



Work in Ideal-Gas Processes

If we let the piston move in a slow quasi-static process from initial volume V_i to final volume V_f , the total work done by the environment on the gas is

$$W = -\int_{V_i}^{V_f} p \, dV$$
 (work done on a gas)

or, graphically

W = the negative of the area under the pV curve between V_i and V_f

STRATEGY 17.1 Work in ideal-gas processes

MODEL Assume the gas is ideal and the process is quasi-static.

VISUALIZE Show the process on a pV diagram. Note whether it happens to be one of the basic gas processes: isochoric, isobaric, or isothermal.

SOLVE Calculate the work as the area under the pV curve either geometrically or by carrying out the integration:

Work done on the gas
$$W = -\int_{V_i}^{V_f} p \, dV = -(\text{area under } pV \text{ curve})$$

ASSESS Check your signs.

- W > 0 when the gas is compressed. Energy is transferred from the environment to the gas.
- W < 0 when the gas expands. Energy is transferred from the gas to the environment.
- No work is done if the volume doesn't change. W = 0.

Work in Ideal-Gas Processes

In an **isochoric process**, when the volume does not change, no work is done.

W = 0 (isochoric process)

In an **isobaric process**, when pressure is a constant and the volume changes by $\Delta V = V_f - V_i$, the work done during the process is

 $W = -p\Delta V$ (isobaric process)

In an **isothermal process**, when temperature is a constant, the work done during the process is

$$W = -nRT \ln\left(\frac{V_{\rm f}}{V_{\rm i}}\right) = -p_{\rm i}V_{\rm i} \ln\left(\frac{V_{\rm f}}{V_{\rm i}}\right) = -p_{\rm f}V_{\rm f} \ln\left(\frac{V_{\rm f}}{V_{\rm i}}\right)$$

(isothermal process)

QUESTION:

EXAMPLE 17.2 The work of an isothermal compression

A cylinder contains 7.0 g of nitrogen gas. How much work must be done to compress the gas at a constant temperature of 80°C until the volume is halved?

MODEL This is an isothermal ideal-gas process.

SOLVE Nitrogen gas is N₂, with molar mass $M_{mol} = 28$ g/mol, so 7.0 g is 0.25 mol of gas. The temperature is T = 353 K. Although we don't know the actual volume, we do know that $V_f = \frac{1}{2}V_i$. The volume ratio is all we need to calculate the work:

$$W = -nRT \ln\left(\frac{V_{\rm f}}{V_{\rm i}}\right)$$

= -(0.25 mol)(8.31 J/molK)(353 K)ln(1/2) = 508 J

ASSESS The work is positive because a force from the environment pushes the piston inward to compress the gas.

Heat, Temperature, and Thermal Energy

• Thermal energy $E_{\rm th}$ is an energy of the system due to the motion of its atoms and molecules. Any system has a thermal energy even if it is isolated and not interacting with its environment. The units of $E_{\rm th}$ are Joules.

• Heat Q is energy transferred between the system and the environment as they interact. The units of Q are Joules.

• **Temperature** *T* is a state variable that quantifies the "hotness" or "coldness" of a system. A temperature difference is required in order for heat to be transferred between the system and the environment. The units of *T* are degrees Celsius or Kelvin.

The First Law of Thermodynamics

Work and heat are two ways of transfering energy between a system and the environment, causing the system's energy to change. If the system as a whole is at rest, so that the bulk mechanical energy due to translational or rotational motion is zero, then the conservation of energy equation is

 $\Delta E_{\rm th} = W + Q$ (first law of thermodynamics)

Temperature Change and Specific Heat

The amount of energy that raises the temperature of 1 kg of a substance by 1 K is called the **specific heat** of that substance. The symbol for specific heat is *c*. If W = 0, so no work is done by or on the system, then the heat needed to bring about a temperature change ΔT is

 $Q = Mc\Delta T$ (temperature change)

Temperature Change and Specific Heat

TABLE 17.2	Specific heats	and molar
specific hea	its of solids an	d liquids

Substance	c (J/kg K)	C(J/molK)	
Solids			
Aluminum	900	24.3	
Copper	385	24.4	
Iron	449	25.1	
Gold	129	25.4	
Lead	128	26.5	
Ice	2090	37.6	
Liquids			
Ethyl alcohol	2400	110.4	
Mercury	140	28.1	
Water	4190	75.4	

QUESTION:

EXAMPLE 17.3 Quenching hot aluminum in ethyl alcohol

A 50.0 g aluminum disk at 300°C is placed in 200 cm³ of ethyl alcohol at 10.0°C, then quickly removed. The aluminum temperature is found to have dropped to 120°C. What is the new temperature of the ethyl alcohol?

MODEL Heat is the energy transferred due to a temperature difference. If we assume that the container holding the alcohol is well insulated, then the disk and the alcohol interact with each other but nothing else. Conservation of energy tells us that the heat energy transferred out of the disk is the heat energy transferred into the alcohol.

SOLVE The temperature change of the disk is $\Delta T_{Al} = (120^{\circ}C - 300^{\circ}C) = -180^{\circ}C = -180$ K. It is negative because the temperature decreases. The energy removed from the disk is

 $Q_{\rm Al} = Mc\Delta T = (0.0500 \text{ kg})(900 \text{ J/kgK})(-180 \text{ K}) = -8100 \text{ J}$

 $Q_{\rm Al}$ is negative because the energy is transferred out of the aluminum. The ethyl alcohol *gains* 8100 J of energy; thus $Q_{\rm ethyl} = +8100$ J. We need to know the mass of the ethyl alcohol. Its density was given in Table 16.1 as $\rho = 790$ kg/m³; hence its mass is

$$M = \rho V = (790 \text{ kg/m}^3)(200 \times 10^{-6} \text{ m}^3) = 0.158 \text{ kg}$$

The heat from the aluminum causes the alcohol's temperature to change by

$$\Delta T = \frac{Q_{\text{ethyl}}}{Mc} = \frac{8100 \text{ J}}{(0.158 \text{ kg})(2400 \text{ J/kg K})} = 21.4 \text{ K}$$
$$= 21.4^{\circ}\text{C}$$

The ethyl alcohol ends up at temperature

$$T_{\rm f} = T_{\rm i} + \Delta T = 10.0^{\circ} \text{C} + 21.4^{\circ} \text{C} = 31.4^{\circ} \text{C}$$

Phase Change and Heat of Transformation

A **phase change** is characterized by a change in thermal energy without a change in temperature.

The amount of heat energy that causes 1 kg of substance to undergo a phase change is called the **heat of transformation** of that substance.

The symbol for heat of transformation is *L*. The heat required for the entire system of mass *M* to undergo a phase change is

Q = ML (phase change)

Phase Change and Heat of Transformation

Two specific heats of transformation are the **heat of fusion** L_f , the heat of transformation between a solid and a liquid, and the **heat of vaporization** L_v , the heat of transformation between a liquid and a gas. The heat needed for these phase changes is

 $Q = \begin{cases} \pm ML_{\rm f} & \text{melt/freeze} \\ \pm ML_{\rm v} & \text{boil/condense} \end{cases}$

TABLE 17.3	Melting/boiling	temperatures	and heats	of transformation
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Substance	$T_{\mathrm{m}}(^{\mathrm{o}}\mathrm{C})$	$L_{\rm f}({\rm J/kg})$	$T_{\mathfrak{b}}(^{\circ}\mathbf{C})$	$L_{\rm v}({\rm J}/{\rm kg})$
Nitrogen (N ₂)	-210	0.26×10^{5}	-196	1.99×10^{5}
Ethyl alcohol	-114	$1.09 imes 10^5$	78	8.79×10^{5}
Mercury	-39	0.11×10^{5}	357	2.96×10^{5}
Water	0	3.33×10^{5}	100	22.6×10^{5}
Lead	328	0.25×10^{5}	1750	8.58×10^{5}

EXAMPLE 17.4 Turning ice into steam

QUESTION:

EXAMPLE 17.4 Turning ice into steam

How much heat is required to change 200 mL of ice at -20° C (a typical freezer temperature) into steam?
MODEL Changing ice to steam requires four steps: Raise the temperature of the ice to 0° C, melt the ice to liquid water at 0° C, raise the water temperature to 100° C, then boil the water to produce steam at 100° C.

SOLVE The mass is $M = \rho V$. The density of ice (from Table 16.1) is 920 kg/m³, and $V = 200 \text{ mL} = 200 \text{ cm}^3 = 2.00 \times 10^{-4} \text{ m}^3$. Thus

$$M = \rho V = (920 \text{ kg/m}^3)(2.00 \times 10^{-4} \text{ m}^3) = 0.184 \text{ kg}$$

The heat needed for each step is

$$Q_1 = Mc_{ice}\Delta T_{ice} = (0.184 \text{ kg})(2090 \text{ J/kgK})(20 \text{ K}) = 7,700 \text{ J}$$

$$Q_2 = ML_f = (0.184 \text{ kg})(3.33 \times 10^5 \text{ J/kg}) = 61,300 \text{ J}$$

$$Q_3 = Mc_{water}\Delta T_{water} = (0.184 \text{ kg})(4190 \text{ J/kgK})(100 \text{ K}) = 77,100 \text{ J}$$

$$Q_4 = ML_v = (0.184 \text{ kg})(22.6 \times 10^5 \text{ J/kg}) = 415,800 \text{ J}$$

NOTE ► We used the specific heat of ice while warming the system in its solid phase. Then we used the specific heat of *water* while warming the system in its liquid phase.

The total heat required is

$$Q = Q_1 + Q_2 + Q_3 + Q_4 = 562,000 \text{ J}$$

ASSESS Roughly 75% of the heat is used to change the water from a 100°C liquid to a 100°C gas. This is consistent with your experience that it takes much longer for a pan of water to boil away than it does to reach boiling.

Calorimetry

Suppose to systems start at different temperatures T_1 and T_2 . Heat energy will naturally be transferred from the hotter to the colder system until they reach a common final temperature T_f . **FIGURE 17.18** Two systems interact thermally.

Heat energy is transferred from system 1 to system 2. Energy conservation requires

 $|Q_1| = |Q_2|$

Opposite signs mean that



STRATEGY 17.2 Calorimetry problems



MODEL Identify the interacting systems. Assume that they are isolated from the larger environment.

VISUALIZE List known information and identify what you need to find. Convert all quantities to SI units.

SOLVE The mathematical representation, which is a statement of energy conservation, is

$$Q_{\rm net} = Q_1 + Q_2 + \dots = 0$$

- For systems that undergo a temperature change, $Q = Mc(T_f T_i)$. Be sure to have the temperatures T_i and T_f in the correct order.
- For systems that undergo a phase change, $Q = \pm ML$. Supply the correct sign by observing whether energy enters or leaves the system.
- Some systems may undergo a temperature change *and* a phase change. Treat the changes separately. The heat energy is $Q = Q_{\Delta T} + Q_{\text{phase}}$.

ASSESS Is the final temperature in the middle? T_f that is higher or lower than all initial temperatures is an indication that something is wrong, usually a sign error.

The Specific Heats of Gases

It is useful to define two different versions of the specific heat of gases, one for constant-volume (isochoric) processes and one for constant-pressure (isobaric) processes. We will define these as molar specific heats because we usually do gas calculations using moles instead of mass. The quantity of heat needed to change the temperature of *n* moles of gas by ΔT is

$Q = nC_{\rm V}\Delta T$	(temperature change at constant volume)
$Q = nC_{\rm P}\Delta T$	(temperature change at constant pressure)

where C_V is the molar specific heat at constant volume and C_P is the molar specific heat at constant pressure.

The Specific Heats of Gases

TABLE 17.4 Molar specific heats of gases(J/mol K)

Gas	C_{P}	$C_{ m V}$	$C_{\rm P} - C_{\rm V}$
Monat	omic Gases		
He	20.8	12.5	8.3
Ne	20.8	12.5	8.3
Ar	20.8	12.5	8.3
Diatom	ic Gases		
H_2	28.7	20.4	8.3
N_2	29.1	20.8	8.3
O_2	29.2	20.9	8.3

Conduction

FIGURE 17.25 Conduction of heat through a solid.



Conduction

For a material of cross-section area A and length L, spanning a temperature difference $\Delta T = T_H - T_C$, the rate of heat transfer is

$$\frac{Q}{\Delta t} = k \frac{A}{L} \Delta T$$

where *k* is the **thermal conductivity**, which characterizes whether the material is a good conductor of heat or a poor conductor.

Conduction

Material	k (W/m K)	
Diamond	2000	
Silver	430	
Copper	400	
Aluminum	240	
Iron	80	
Stainless steel	14	
Ice	1.7	
Concrete	0.8	
Glass	0.8	
Styrofoam	0.035	
Air (20°C, 1 atm)	0.023	

TABLE 17.5	Thermal	conductivities
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QUESTION:

EXAMPLE 17.10 Keeping a freezer cold

A 1.8-m-wide by 1.0-m-tall by 0.65-m-deep home freezer is insulated with 5.0-cm-thick Styrofoam insulation. At what rate must the compressor remove heat from the freezer to keep the inside at -20° C in a room where the air temperature is 25° C?

MODEL Heat is transferred through each of the six sides by conduction. The compressor must remove heat at the same rate it enters to maintain a steady temperature inside. The heat conduction is determined primarily by the thick insulation, so we'll neglect the thin inner and outer panels.

SOLVE Each of the six sides is a slab of Styrofoam with crosssection area A_i and thickness L = 5.0 cm. The total rate of heat transfer is

$$\frac{Q}{\Delta t} = \sum_{i=1}^{6} k \frac{A_i}{L} \Delta T = \frac{k \Delta T}{L} \sum_{i=1}^{6} A_i = \frac{k \Delta T}{L} A_{\text{tota}}$$

The total surface area is

$$A_{\text{total}} = 2 \times (1.8 \text{ m} \times 1.0 \text{ m} + 1.8 \text{ m} \times 0.65 \text{ m})$$

+ 1.0 m × 0.65 m) = 7.24 m²

Using k = 0.035 W/mK from Table 17.5, we find

$$\frac{Q}{\Delta t} = \frac{k\Delta t}{L} A_{\text{total}} = \frac{(0.035 \text{ W/mK})(45 \text{ K})(7.24 \text{ m}^2)}{0.050 \text{ m}} = 230 \text{ W}$$

Heat enters the freezer through the walls at the rate 230 J/s; thus the compressor must remove 230 J of heat energy every second to keep the temperature at -20° C.

ASSESS We'll learn in Chapter 19 how the compressor does this and how much work it must do. A typical freezer uses electric energy at a rate of about 150 W, so our result seems reasonable.

Convection

Air is a poor conductor of heat, but thermal energy is easily transferred through air, water, and other fluids because the air and water can flow. A pan of water on the stove is heated at the bottom. This heated water expands, becomes less dense than the water above it, and thus rises to the surface, while cooler, denser water sinks to take its place. The same thing happens to air. This transfer of thermal energy by the motion of a fluid—the well-known idea that "heat rises"—is called **convection**.



Warm water (colored) moves by convection.

Radiation

All objects emit energy in the form of **radiation**, electromagnetic waves generated by oscillating electric charges in the atoms that form the object. If heat energy Qis radiated in a time interval Δt by an object with surface area A and absolute temperature T, the rate of heat transfer is found to be

$$\frac{Q}{\Delta t} = e\sigma A T^4$$

The parameter *e* is the **emissivity** of the surface, a measure of how effectively it radiates. The value of *e* ranges from 0 to 1. σ is a constant, known as the Stefan-Boltzmann constant, with the value $\sigma = 5.67 \times 10^{-8}$ W/m²K⁴.

Chapter 17. Summary Slides

General Principles

First Law of Thermodynamics

 $\Delta E_{\rm th} = W + Q$

The first law is a general statement of energy conservation.

Work *W* and heat *Q* depend on the process by which the system is changed.



The change in the system depends only on the total energy exchanged W + Q, not on the process.

General Principles

Energy

Thermal energy E_{th} Microscopic energy of moving molecules and stretched molecular bonds. ΔE_{th} depends on the initial/final states but is independent of the process.

Work W Energy transferred to the system by forces in a mechanical interaction.

Heat *Q* **Energy transferred to the system via atomic-level collisions when there is a temperature difference. A thermal interaction.**

The work done on a gas is $W = -\int_{V_i}^{V_f} p \, dV$ = -(area under the pV curve)



An adiabatic process is one for which Q = 0. Gases move along an adiabat for which $pV^{\gamma} = \text{constant}$, where $\gamma = C_P/C_V$ is the **specific heat** ratio. An adiabatic process changes the temperature of the gas without heating it.



Calorimetry When two or more systems interact thermally, they come to a common final temperature determined by

$$Q_{\rm net} = Q_1 + Q_2 + \dots = 0$$

The heat of transformation *L* is the energy needed to cause 1 kg of substance to undergo a phase change

$$Q = \pm ML$$

The specific heat *c* of a substance is the energy needed to raise the temperature of 1 kg by 1 K:

$$Q = Mc\Delta T$$

The molar specific heat *C* is the energy needed to raise the temperature of 1 mol by 1 K:

$$Q = nC\Delta T$$

The molar specific heat of gases depends on the *process* by which the temperature is changed:

 $C_{\rm V}$ = molar specific heat at **constant volume**

 $C_{\rm P} = C_{\rm V} + R =$ molar specific heat at **constant pressure**

Heat is transferred by conduction, convection, radiation, and evaporation.

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Conduction: Q/\Delta t = (kA/L)\Delta T
Radiation: Q/\Delta t = e\sigma AT^4
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Summary of Basic Gas Processes

Process	Definition	Stays constant	Work	Heat
Isochoric	$\Delta V = 0$	V and p/T	W = 0	$Q = nC_{\rm V}\Delta T$
Isobaric	$\Delta p = 0$	p and V/T	$W = -p\Delta V$	$Q = nC_{\rm P}\Delta T$
Isothermal	$\Delta T = 0$	T and pV	$W = -nRT\ln\left(V_{\rm f}/V_{\rm i}\right)$	$\Delta E_{\rm th} = 0$
Adiabatic	Q = 0	pV^{γ}	$W = \Delta E_{\rm th}$	Q = 0
All gas processes	First law $\Delta E_{\text{th}} = W +$	$Q = nC_{\rm V}\Delta T$	Ideal-gas law $pV = nRT$	

Chapter 17. Questions

A gas cylinder and piston are covered with heavy insulation. The piston is pushed into the cylinder, compressing the gas. In this process, the gas temperature



A. decreases.B. increases.C. doesn't change.D. There's not sufficient information to tell.

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Two process are shown that take an ideal gas from state 1 to state 3. Compare the work done by process A to the work done by process B.



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Which of the following processes involve heat?

- A. The brakes in your car get hot when you stop.
- B. You push a rigid cylinder of gas across a frictionless surface.
- C. A steel block is placed under a candle.
- D. You push a piston into a cylinder of gas, increasing the temperature of the gas.

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Which first-law bar chart describes the process shown in the *pV* diagram?



p



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p

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Objects A and B are brought into close thermal contact with each other, but they are well isolated from their surroundings. Initially $T_A = 0^{\circ}$ C and $T_B = 100^{\circ}$ C. The specific heat of A is more than the specific heat of B. The two objects will soon reach a common final temperature T_f . The final temperature is



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For the two processes shown, which of the following is true:



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Suppose you are an astronaut in space, hard at work in your sealed spacesuit. The only way that you can transfer excess heat to the environment is by

- A. conduction
- B. radiation
- C. convection
- D. evaporation

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