Chapter 18

Temperature, Heat, and the First Law of Thermodynamics

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18-1 Temperature

Learning Objectives

18.01 Identify the lowest temperature as 0 on the Kelvin scale (absolute zero).

18.02 Explain the zeroth law of thermodynamics.

18.03 Explain the conditions for the triple-point temperature.

18.04 Explain the conditions for measuring a temperature with a constant-volume gas thermometer.

18.05 For a constant-volume gas thermometer, relate the pressure and temperature of the gas in some given state to the pressure and temperature at the triple point.

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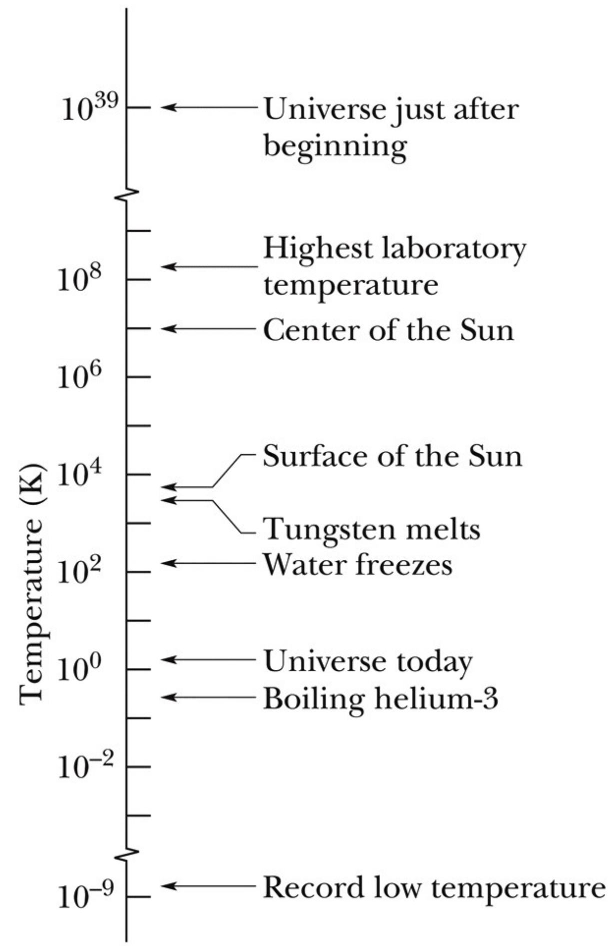
18-1 Temperature

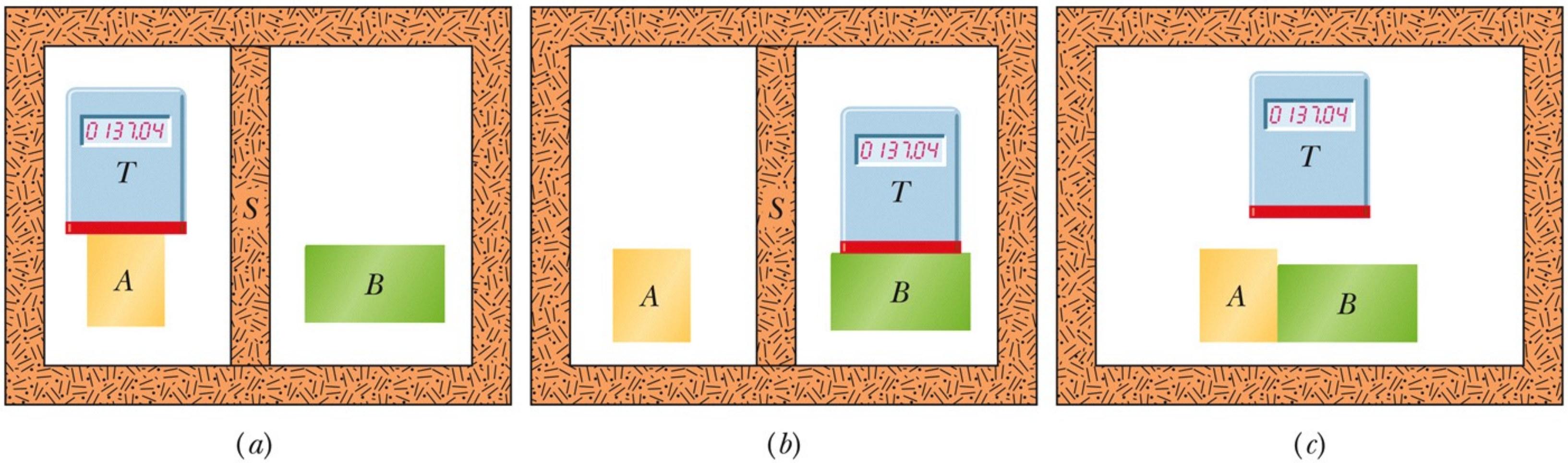
- **Thermodynamics** is the study and application of the thermal energy (often called the internal energy) of systems. One of the central concepts of thermodynamics is temperature.
- **Temperature** is an SI base quantity related to our sense of hot and cold. It is measured with a thermometer, which contains a working substance with a measurable property, such as length or pressure, that changes in a regular way as the substance becomes hotter or colder. Physicists measure temperature on the **Kelvin scale**, which is marked in units called kelvins.



18-1 Temperature

Two bodies are in thermal equilibrium if they are at the same temperature throughout and therefore no heat will flow from one body to the other.

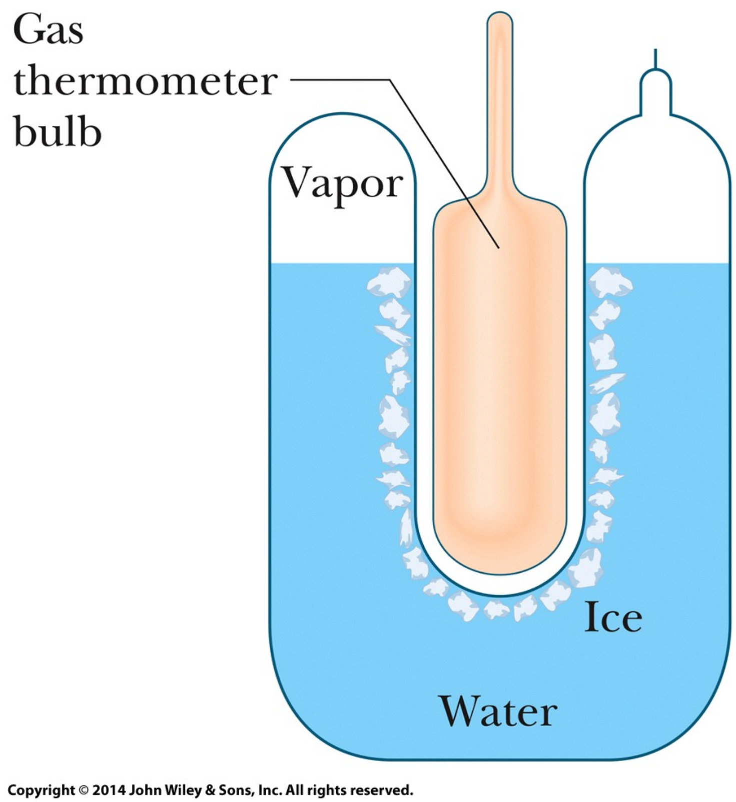
The Zeroth Law of Thermodynamics



If bodies A and B are each in thermal equilibrium with a third body T, then A and B are in thermal equilibrium with each other.

Triple Point of Water

- The Triple point of water is the point in which solid ice, liquid water, and water vapor coexist in thermal equilibrium. (This does not occur at normal atmospheric pressure.)
- By international agreement, the temperature of this mixture has been defined to be **273.16 K**. The bulb of a constant-volume gas thermometer is shown inserted into the well of the cell.



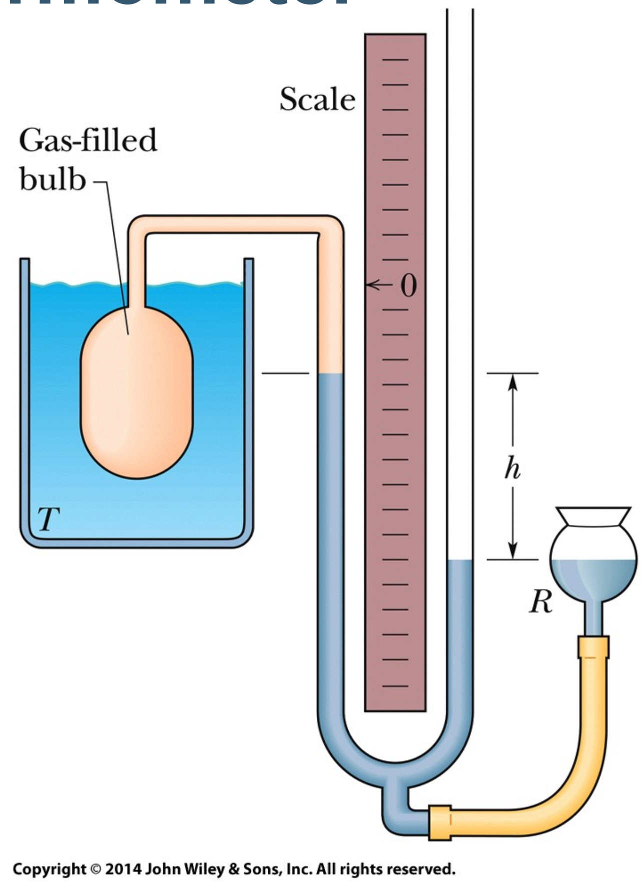
A triple-point cell

Constant-Volume Gas Thermometer

- It consists of a gas-filled bulb connected by a tube to a mercury manometer. By raising and lowering reservoir R, the mercury level in the left arm of the U-tube can always be brought to the zero of the scale to keep the gas volume constant.

- the recipe for measuring a temperature with a gas thermometer, where p is the observed pressure and p_3 is the pressure at the triple point of water, is

$$T = (273.16\ \mathrm{K})\left(\lim_{\text{gas}\to 0} \frac{p}{p_3}\right).$$



Constant-Volume Gas Thermometer

18-2 The Celsius and Fahrenheit Scales

Learning Objectives

18.06 Convert a temperature between any two (linear) temperature scales, including the Celsius, Fahrenheit, and Kelvin scales.

18.07 Identify that a change of one degree is the same on the Celsius and Kelvin scales.

18-2 The Celsius and Fahrenheit Scales

- The **Celsius temperature scale** is defined by

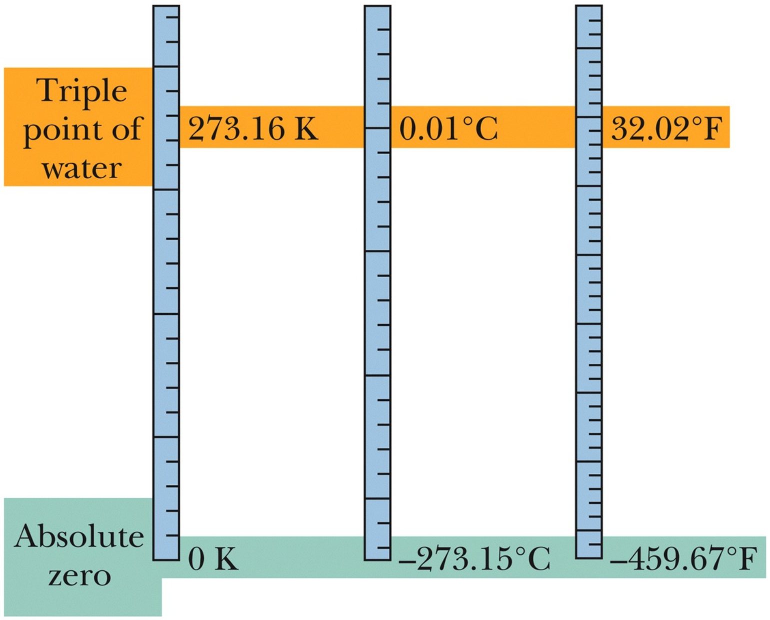
$$T_C = T - 273.15°,$$

with T in kelvins.

- The **Fahrenheit temperature scale** is defined by

$$T_F = \frac{9}{5}T_C + 32°.$$

Temperature	°C	°F
Boiling point of water[a]	100	212
Normal body temperature	37.0	98.6
Accepted comfort level	20	68
Freezing point of water[a]	0	32
Zero of Fahrenheit scale	≈ −18	0
Scales coincide	−40	−40



The Kelvin,Celsius,and Fahrenheit temperature scales compared.

18-3 Thermal Expansion

Learning Objectives

18.08 For one-dimensional thermal expansion, apply the relationship between the temperature change ΔT, the length change ΔL, the initial length L, and the coefficient of linear expansion α.

18.09 For two-dimensional thermal expansion, use one dimensional thermal expansion to find the change in area.

18.10 For three-dimensional thermal expansion, apply the relationship between the temperature change ΔT, the volume change ΔV, the initial volume V, and the coefficient of volume expansion β.

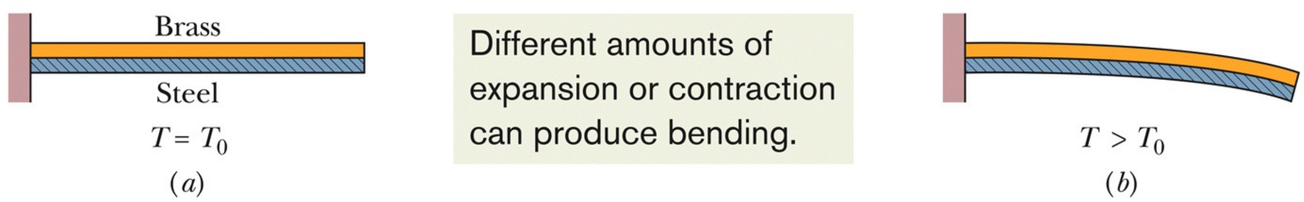
18-3 Thermal Expansion

Linear Expansion

- All objects change size with changes in temperature. For a temperature change ΔT, a change ΔL in any linear dimension L is given by

$$\Delta L = L\alpha\,\Delta T,$$

in which α is the **coefficient of linear expansion**.



The strip bends as shown at tempera tures above this reference temperature. Below the reference temperature the strip bends the other way. Many thermo-stats operate on this principle, making and breaking an electrical contact as the temperature rises and falls.

Volume Expansion

- If the temperature of a solid or liquid whose volume is V is increased by an amount ΔT, the increase in volume is found to be

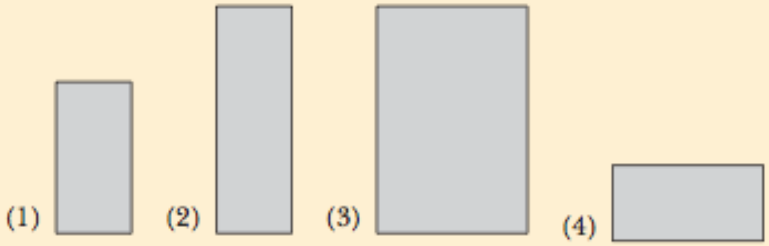
$$\Delta V = V\beta\Delta T,$$

in which β is the **coefficient of volume expansion** and is related to linear expansion in this way,

$$\beta = 3\alpha.$$

Checkpoint 2

The figure here shows four rectangular metal plates, with sides of L, $2L$, or $3L$. They are all made of the same material, and their temperature is to be increased by the same amount. Rank the plates according to the expected increase in (a) their vertical heights and (b) their areas, greatest first.



Answer: (a) – 2 and 3 (same increase in height), then 1, and then 4
(b) – 3, then 2, then 1 and 4 (identical increase in area)

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18-4 Absorption of Heat

Learning Objectives

18.11 Identify that *thermal energy* is associated with the random motions of the microscopic bodies in an object.

18.12 Identify that heat Q is the amount of transferred energy (either to or from an object's thermal energy) due to a temperature difference between the object and its environment.

18.13 Convert energy units between various measurement systems.

18.14 Convert between mechanical or electrical energy and thermal energy.

18.15 For a temperature change ΔT of a substance, relate the change to the heat transfer Q and the substance's heat capacity C.

18.16 For a temperature change ΔT of a substance, relate the change to the heat transfer Q and the substance's specific heat c and mass m.

18-4 Absorption of Heat

Learning Objectives (continued…)

18.17 Identify the three phases of matter.

18.18 For a phase change of a substance, relate the heat transfer Q, the heat of transformation L, and the amount of mass m transformed.

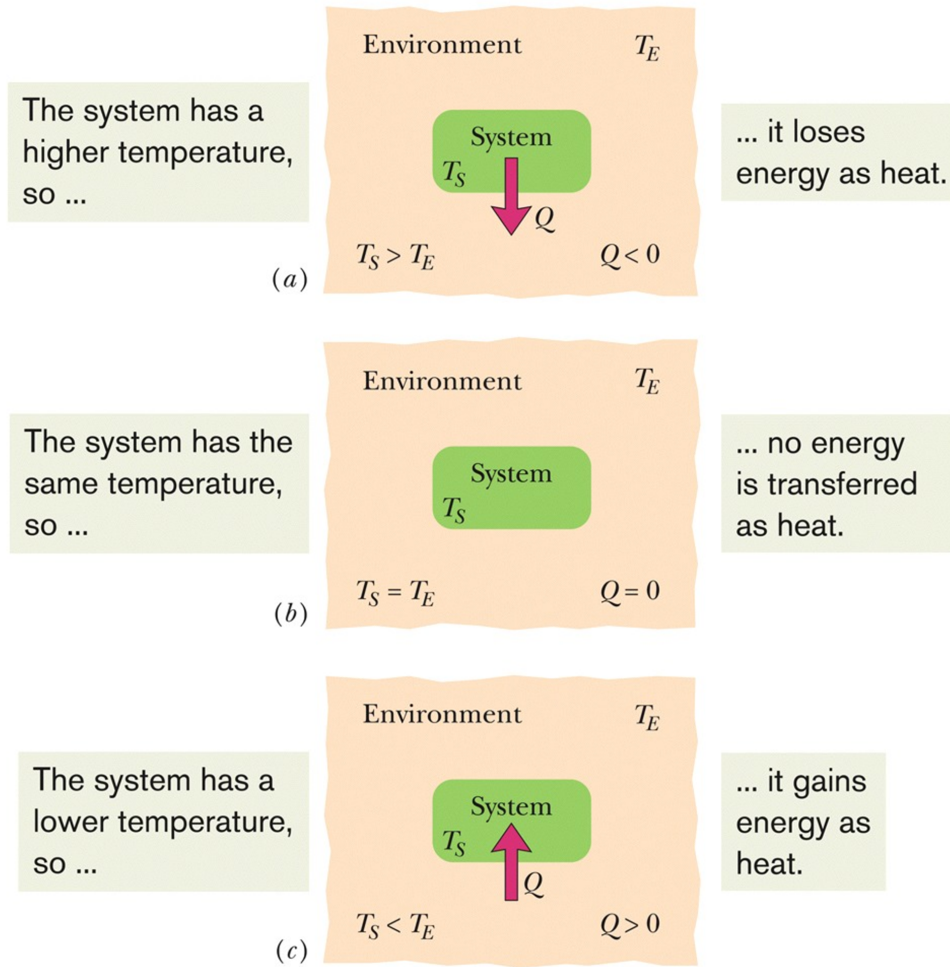
18.19 Identify that if a heat transfer Q takes a substance across a phase-change temperature, the transfer must be calculated in steps: (a) a temperature change to reach the phase-change temperature, (b) the phase change, and then (c) any temperature change that moves the substance away from the phase-change temperature.

Temperature and Heat

- Heat Q is energy that is transferred between a system and its environment because of a temperature difference between them.

- It can be measured in joules (J), calories (cal), kilocalories (Cal or kcal), or British thermal units (Btu), with

$$1 \text{ cal} = 3.968 \times 10^{-3} \text{ Btu} = 4.1868 \text{ J}.$$



Absorption of Heat by Solids and Liquids

- The **heat capacity** *C* of an object is the proportionality constant between the heat *Q* that the object absorbs or loses and the resulting temperature change ΔT of the object; that is,

$$Q = C\,\Delta T = C(T_f - T_i),$$

in which T_i and T_f are the initial and final temperatures of the object. If the object has mass m, then,

$$Q = cm\,\Delta T = cm(T_f - T_i).$$

where *c* is the **specific heat** of the material making up the object.

Checkpoint 3

A certain amount of heat Q will warm 1 g of material A by 3 C° and 1 g of material B by 4 C°. Which material has the greater specific heat?

Answer: Material A has the greater specific heat

18-4 Absorption of Heat

- When quantities are expressed in moles, specific heats must also involve moles (rather than a mass unit); they are then called **molar specific heats**. Table shows the values for some elemental solids (each consisting of a single element) at room temperature.

- The amount of energy per unit mass that must be transferred as heat when a sample completely undergoes a phase change is called the **heat of transformation** *L*. Thus, when a sample of mass *m* completely undergoes a phase change, the total energy transferred is

$$Q = Lm.$$

Substance	Specific Heat $\frac{\text{cal}}{\text{g}\cdot\text{K}}$	Specific Heat $\frac{\text{J}}{\text{kg}\cdot\text{K}}$	Molar Specific Heat $\frac{\text{J}}{\text{mol}\cdot\text{K}}$
Elemental Solids			
Lead	0.0305	128	26.5
Tungsten	0.0321	134	24.8
Silver	0.0564	236	25.5
Copper	0.0923	386	24.5
Aluminum	0.215	900	24.4
Other Solids			
Brass	0.092	380	
Granite	0.19	790	
Glass	0.20	840	
Ice (−10°C)	0.530	2220	
Liquids			
Mercury	0.033	140	
Ethyl alcohol	0.58	2430	
Seawater	0.93	3900	
Water	1.00	4187	

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18-5 The First Law of Thermodynamics

Learning Objectives

18.20 If an enclosed gas expands or contracts, calculate the work W done by the gas by integrating the gas pressure with respect to the volume of the enclosure.

18.21 Identify the algebraic sign of work W associated with expansion and contraction of a gas.

18.22 Given a *p-V* graph of pressure versus volume for a process, identify the starting point (the initial state) and the final point (the final state) and calculate the work by using graphical integration.

18.23 On a p-V graph of pressure versus volume for a gas, identify the algebraic sign of the work associated with a right-going process and a left-going process.

18.24 Apply the first law of thermodynamics to relate the change in the internal energy ΔE_{int} of a gas, the energy Q transferred as heat to or from the gas, and the work W done on or by the gas.

18-5 The First Law of Thermodynamics

Learning Objectives (Continued)

18.25 Identify the algebraic sign of a heat transfer *Q* that is associated with a transfer to a gas and a transfer from the gas.

18.26 Identify that the internal energy ΔE_{int} of a gas tends to increase if the heat transfer is to the gas, and it tends to decrease if the gas does work on its environment.

18.27 Identify that in an adiabatic process with a gas, there is no heat transfer *Q* with the environment.

18.28 Identify that in a constant-volume process with a gas, there is no work W done by the gas.

18.29 Identify that in a cyclical process with a gas, there is no net change in the internal energy ΔE_{int}.

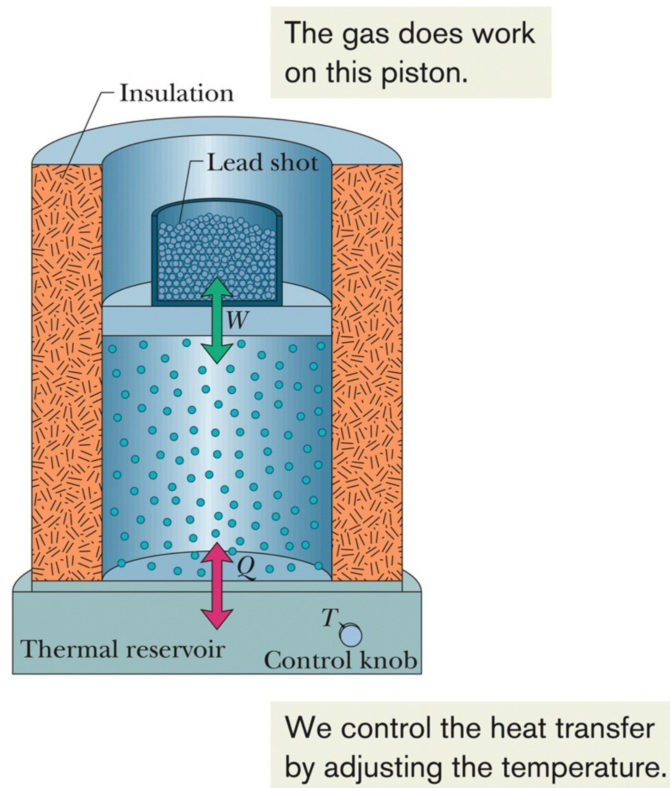
18.30 Identify that in a free expansion with a gas, the heat transfer *Q*, work done *W*, and change in internal energy ΔE_{int} are each zero.

Heat and Work

A gas may exchange energy with its surroundings through work. The amount of work W done by a gas as it expands or contracts from an initial volume V_i to a final volume V_f is given by

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

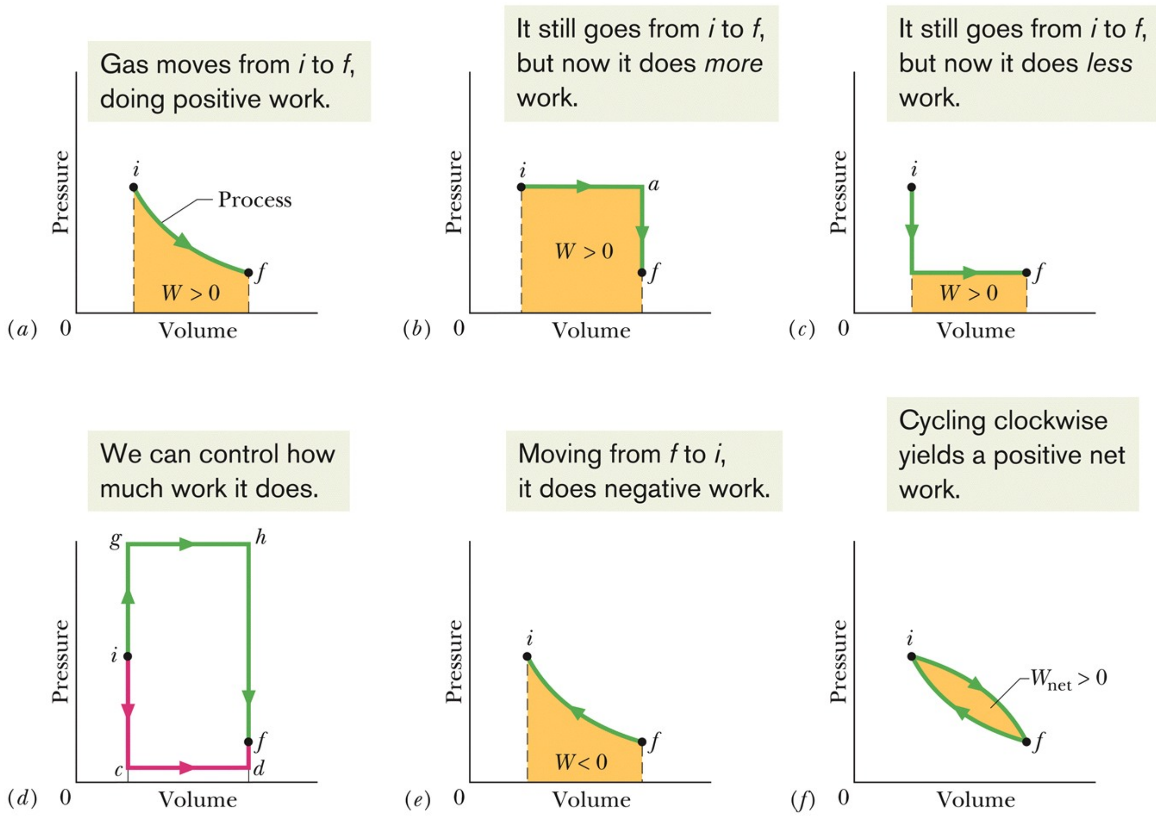
The integration is necessary because the pressure p may vary during the volume change.

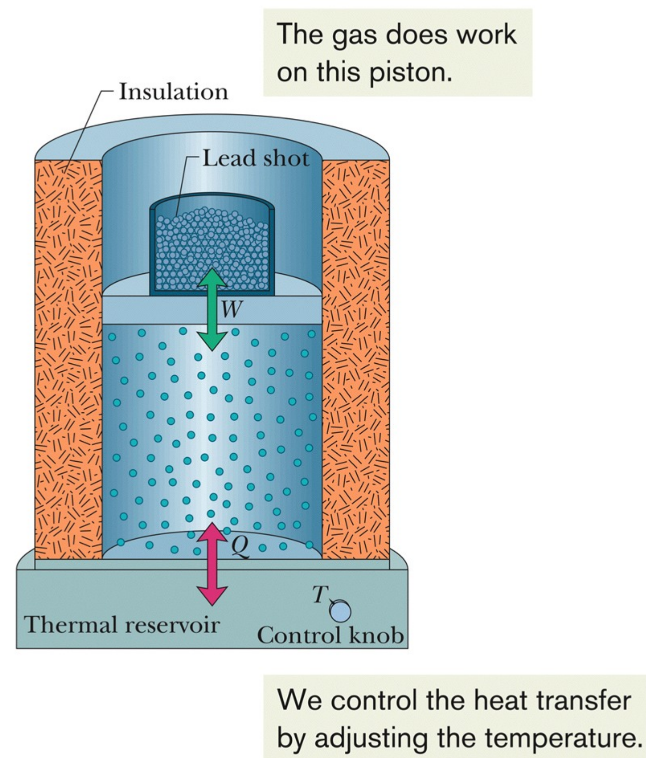


A gas confined to a cylinder with a movable piston.

18-5 The First Law of Thermodynamics

Heat and Work





A gas confined to a cylinder with a movable piston.

The First Law of Thermodynamics

The principle of conservation of energy for a thermodynamic process is expressed in the first law of thermodynamics, which may assume either of the forms:

$$\Delta E_{\text{int}} = E_{\text{int},f} - E_{\text{int},i} = Q - W \quad \text{(first law).}$$

Or, if the thermodynamic system undergoes only a differential change, we can write the first law as:

$$dE_{\text{int}} = dQ - dW \quad \text{(first law).}$$

The internal energy E_{int} of a system tends to increase if energy is added as heat Q and tends to decrease if energy is lost as work W done by the system.

18-5 The First Law of Thermodynamics

Table 18-5 The First Law of Thermodynamics: Four Special Cases

The Law: $\Delta E_{\text{int}} = Q - W$ (Eq. 18-26)

Process	Restriction	Consequence
Adiabatic	$Q = 0$	$\Delta E_{\text{int}} = -W$
Constant volume	$W = 0$	$\Delta E_{\text{int}} = Q$
Closed cycle	$\Delta E_{\text{int}} = 0$	$Q = W$
Free expansion	$Q = W = 0$	$\Delta E_{\text{int}} = 0$

18-6 Heat Transfer Mechanisms

Learning Objectives

18.31 For thermal conduction through a layer, apply the relationship between the energy-transfer rate P_{cond} and the layer's area A, thermal conductivity k, thickness L, and temperature difference ΔT (between its two sides).

18.32 For a composite slab (two or more layers) that has reached the steady state in which temperatures are no longer changing, identify that (by the conservation of energy) the rates of thermal conduction P_{cond} through the layers must be equal.

18.33 For thermal conduction through a layer, apply the relationship between thermal resistance R, thickness L, and thermal conductivity k.

18.34 Identify that thermal energy can be transferred by convection, in which a warmer fluid (gas or liquid) tends to rise in a cooler fluid.

18-6 Heat Transfer Mechanisms

Learning Objectives (Continued)

18.35 In the *emission* of thermal radiation by an object, apply the relationship between the energy-transfer rate P_{rad} and the object's surface area A, emissivity ε, and *surface* temperature T (in kelvins).

18.36 In the *absorption* of thermal radiation by an object, apply the relationship between the energy-transfer rate P_{abs} and the object's surface area A and emissivity ε, and the *environmental* temperature T (in kelvins).

18.37 Calculate the net energy transfer rate P_{net} of an object emitting radiation to its environment and absorbing radiation from that environment.

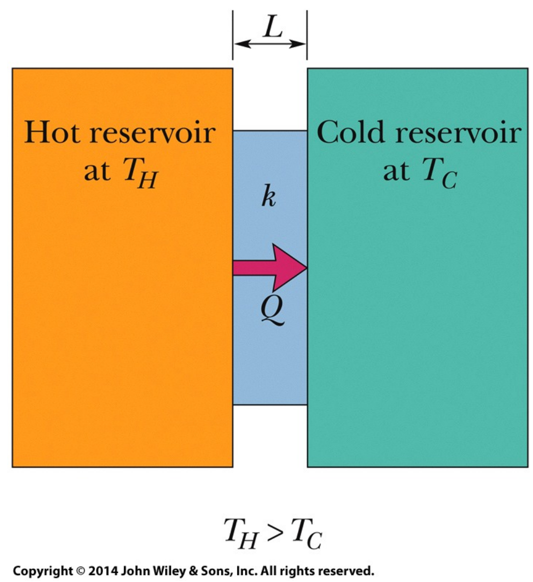
Thermal Conduction

The rate P_{cond} at which energy is conducted through a slab for which one face is maintained at the higher temperature T_H and the other face is maintained at the lower temperature T_C is

$$P_{\text{cond}} = \frac{Q}{t} = kA\,\frac{T_H - T_C}{L},$$

Here each face of the slab has area A, the length of the slab (the distance between the faces) is L, and k is the thermal conductivity of the material.

We assume a steady transfer of energy as heat.



Energy is transferred as heat from a reservoir at temperature T_H to a cooler reservoir at temperature T_C through a conducting slab of thickness L and thermal conductivity k.

Convection

- Convection occurs when temperature differences cause an energy transfer by motion within a fluid.

- When you look at the flame of a candle or a match, you are watching thermal energy being transported upward by convection.

- Convection is part of many natural processes. Atmospheric convection plays a fundamental role in determining global climate patterns and daily weather vari- ations. Glider pilots and birds alike seek rising thermals (convection currents of warm air) that keep them aloft. Huge energy transfers take place within the oceans by the same process.

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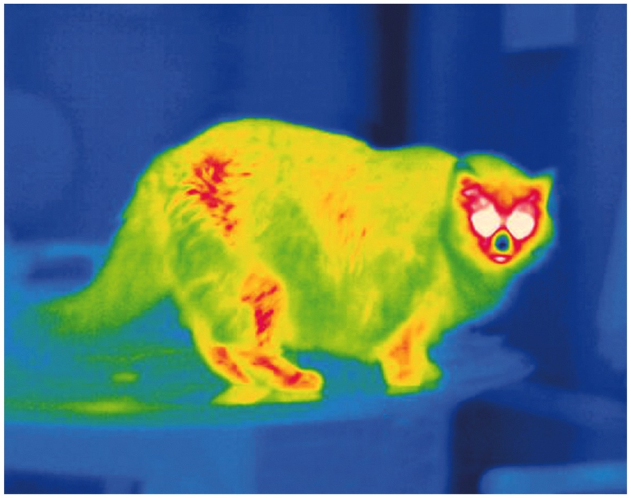
18-6 Heat Transfer Mechanisms

Thermal Radiation

Radiation is an energy transfer via the emission of electromagnetic energy. The rate P_{rad} at which an object emits energy via thermal radiation is

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



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Here σ (= 5.6704×10^{-8} W/m^2.K^4) is the Stefan– Boltzmann constant, ε is the emissivity of the object's surface, A is its surface area, and T is its surface temperature (in kelvins). The rate P_{abs} at which an object absorbs energy via thermal radiation from its environment, which is at the uniform temperature T_{env} (in kelvins), is

$$P_{\text{abs}} = \sigma\varepsilon A T_{\text{env}}^4.$$

18 Summary

Temperature and Thermometer
- SI base quantity related to our sense of hot and cold.
- It is measured using thermometer

Zeroth Law of Thermodynamics
- If bodies A and B are each in thermal equilibrium with a third body C (the thermometer), then A and B are in thermal equilibrium with each other.

The Kelvin Temperature Scale
- We define the temperature T as measured with a gas thermometer to be

$$T = (273.16\text{ K})\left(\lim_{\text{gas}\to 0} \frac{p}{p_3}\right). \quad \textbf{Eq. 18-6}$$

Celsius and Fahrenheit Scale
- The Celsius temperature scale is defined by

$$T_C = T - 273.15° \quad \textbf{Eq. 18-7}$$

- The Fahrenheit temperature scale is defined by

$$T_F = \tfrac{9}{5}T_C + 32°. \quad \textbf{Eq. 18-8}$$

Thermal Expansion
- Linear Expansion

$$\Delta L = L\alpha\,\Delta T, \quad \textbf{Eq. 18-9}$$

- Volume Expansion

$$\Delta V = V\beta\,\Delta T. \quad \textbf{Eq. 18-10}$$

18 Summary

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Heat Capacity and Specific Heat

- Heat Capacity:

$$Q = C(T_f - T_i).$$ **Eq. 18-13**

- Specific Heat

$$Q = cm(T_f - T_i),$$ **Eq. 18-14**

First Law of Thermodynamics

- The principle of conservation of energy for a thermodynamic process is expressed in:

$$\Delta E_{\text{int}} = E_{\text{int},f} - E_{\text{int},i} = Q - W$$ **Eq. 18-26**

$$dE_{\text{int}} = dQ - dW$$ **Eq. 18-27**

Application of First Law

adiabatic processes: $Q = 0, \quad \Delta E_{\text{int}} = -W$

constant-volume processes: $W = 0, \quad \Delta E_{\text{int}} = Q$

cyclical processes: $\Delta E_{\text{int}} = 0, \quad Q = W$

free expansions: $Q = W = \Delta E_{\text{int}} = 0$

Conduction, Convection, Radiation

- Conduction

$$P_{\text{cond}} = \frac{Q}{t} = kA\,\frac{T_H - T_C}{L}$$ **Eq. 18-32**

- Radiation:

$$P_{\text{rad}} = \sigma\varepsilon A T^4,$$ **Eq. 18-39**