Physics 201

Professor P. Q. Hung

311B, Physics Building

Thermodynamics

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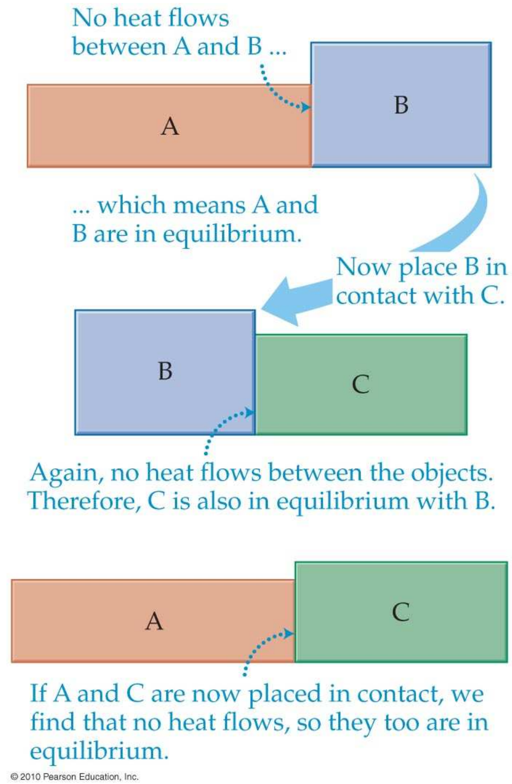
- Heat: Energy transferred between objects because of temperature difference.
- Temperature: Property of a body to be made more precise below.
- Thermal contact: Objects are in thermal contact when heat flows between them.
- Thermal equilibrium: Objects are in thermal equilibrium with each other when they reach the same temperature.

Thermodynamics

Zeroth Law of Thermodynamics



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

Thermodynamics

The measurement of temperature and Temperature scales

- Kelvin scale:
  International agreement for standard fixed point: point where liquid water, solid ice and water vapor can coexist. This point is defined as having a temperature
  $T_3 = 273.16K$
  Triple fixed point.
  The size of the Kelvin is $\frac{1}{273.16}$ of the difference between absolute zero and the triple-point temperature of water.

Thermodynamics

The measurement of temperature and Temperature scales

- Thermometer:
  Standard Thermometer: Constant Volume Gas Thermometer.
  Measure the pressure of the gas at the triple point. Call it P_3. The pressure changes as the gas is heated up. Call that P. The temperature at that point will be proportional to the ratio P/P_3.

Thermodynamics

The measurement of temperature and Temperature scales

- Different gases give slightly different results at the boiling point unless we put smaller and smaller amount of gas until they converge to a single temperature. This gives $T = (273.16\,K)(lim_{gas\rightarrow 0}\frac{P}{P_3})$

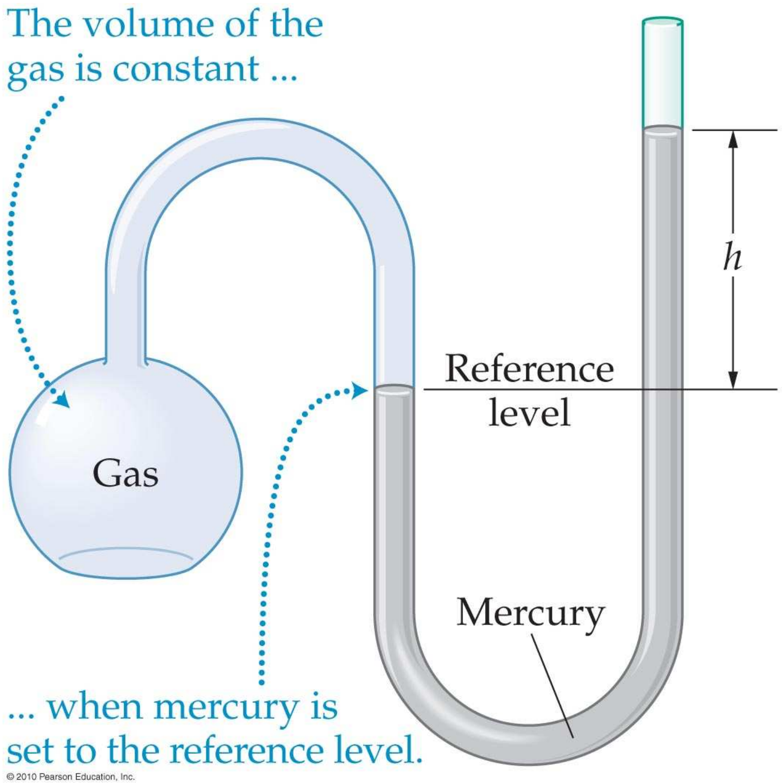
Thermodynamics

The measurement of temperature and Temperature scales

- Different gases give slightly different results at the boiling point unless we put smaller and smaller amount of gas until they converge to a single temperature. This gives $T = (273.16\,K)(lim_{gas\to 0}\frac{P}{P_3})$
- Using this thermometer, the boiling point is measured to be at $T = 373.15\,K$.

Thermodynamics

The measurement of temperature and Temperature scales



Constant Volume Gas Thermometer

Thermodynamics

The measurement of temperature and Temperature scales

- Celsius scale: Defined to be $0\,^0C$ at the freezing point and $100\,^0C$ at the boiling point. It is related to the scientific Kelvin scale by $T_C = T - 273.15\,K$
  So the triple point in the Celsius scale is $T_C = 0.01\,^0C$.

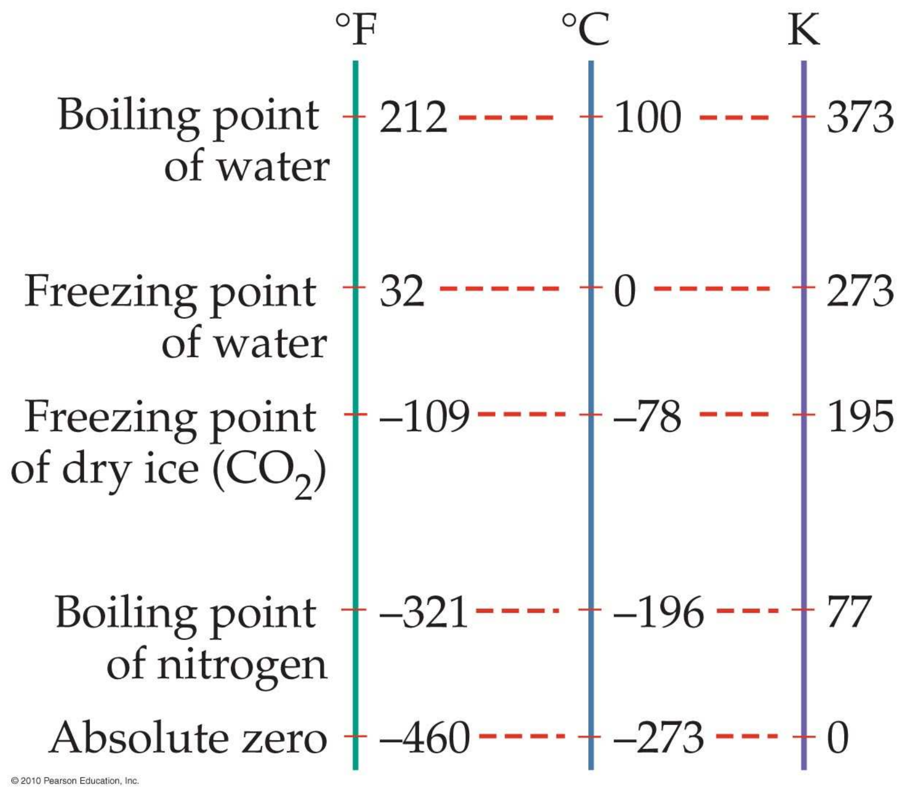
Thermodynamics

The measurement of temperature and Temperature scales

- **Fahrenheit scale**: The Fahrenheit scale is related to the Celsius scale by
  $T_F = \frac{9}{5}T_C + 32^0$
  At the freezing point, $T_C = 0\,^0C$ giving $T_F = 32\,^0F$. At the boiling point, $T_C = 100\,^0C$ giving $T_F = 212\,^0F$

Thermodynamics

The measurement of temperature and Temperature scales



Thermodynamics

Thermal expansion

- Linear expansion:
  $\Delta L = L\,\alpha\,\Delta T$
  α is the linear coefficient of expansion given in Table 16-1 for various material. It has the unit of K^{-1}.

Thermal expansion

TABLE 16–1 Coefficients of Thermal Expansion near 20 °C

Substance	Coefficient of linear expansion, α (K^{-1})
Lead	29×10^{-6}
Aluminum	24×10^{-6}
Brass	19×10^{-6}
Copper	17×10^{-6}
Iron (steel)	12×10^{-6}
Concrete	12×10^{-6}
Window glass	11×10^{-6}
Pyrex glass	3.3×10^{-6}
Quartz	0.50×10^{-6}
Substance	**Coefficient of volume expansion, β (K^{-1})**
Ether	1.51×10^{-3}
Carbon tetrachloride	1.18×10^{-3}
Alcohol	1.01×10^{-3}
Gasoline	0.95×10^{-3}
Olive oil	0.68×10^{-3}
Water	0.21×10^{-3}
Mercury	0.18×10^{-3}

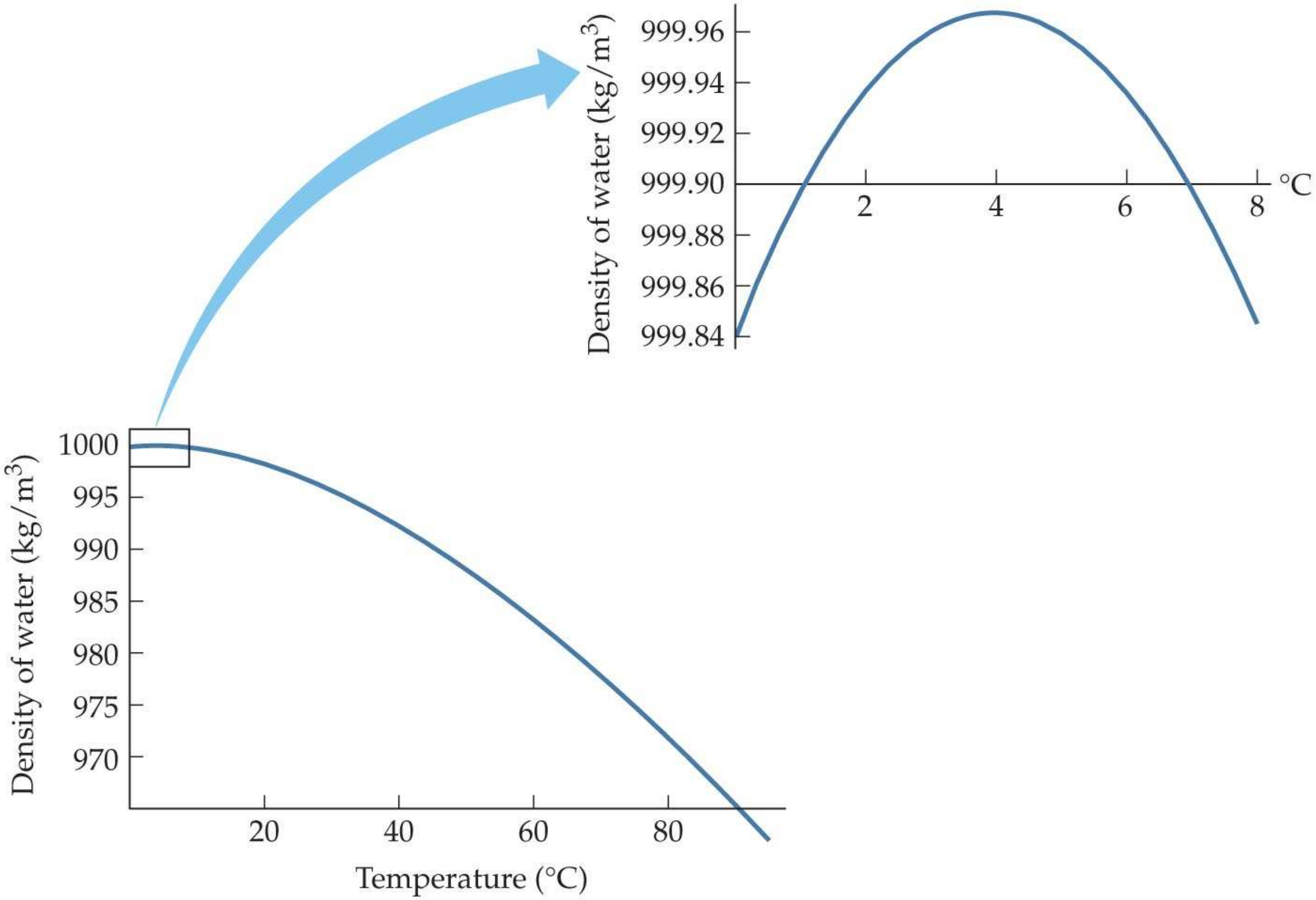
Thermodynamics

Thermal expansion

Peculiar property of water (unlike other fluids): Above $4\,^0C$, water expands as the temperature rises so the density decreases. Between $0\,^0C$ and $4\,^0C$, water shrinks as the temperature rises so the density increases. This fact explains the behavior of a frozen lake for example. See the explanation on p. 550.

Thermodynamics

Thermal expansion



Thermodynamics

Thermal expansion

On a hot day in Las Vegas, an oil trucker loaded 9785 gal of diesel fuel. He encountered cold weather on the way to Payso, Utah, where the temperature was $41\,^0F$ lower than in Las Vegas, and where he delivered his load. How many gallons did he delivered? The coefficient of volume expansion for diesel fuel is $9.5 \times 10^{-4}/\,^0C$ and the coefficient of linear expansion for his steel truck tank is $11 \times 10^{-6}/\,^0C$.

Thermodynamics

Thermal expansion

- $\Delta V = \beta V \Delta T = (9785 gal)(9.5 \times 10^{-4}/\,^0C)(-41\,^0F)(\frac{5}{9}) = -212 gal.$

Thermodynamics

Thermal expansion

- $\Delta V = \beta V \Delta T = (9785 gal)(9.5 \times 10^{-4}/\,^0C)(-41\,^0F)(\frac{5}{9}) = -212 gal$.
- Amount delivered: $V_{del} = V + \Delta V = 9600\, gal$. The steel tank is irrelevant for this problem.

Thermodynamics

Heat and mechanical work:

- One kilocalorie (kcal) is defined as the amount of heat needed to raise 1 kg of water from $14.5\,^0C$ to $15.5\,^0C$.

Thermodynamics

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- Joule's experiment showed that $1\,cal = 4.186\,J$

Thermodynamics

Heat and mechanical work:

- One kilocalorie (kcal) is defined as the amount of heat needed to raise 1 kg of water from $14.5\,^0C$ to $15.5\,^0C$.
- Joule's experiment showed that
  $1\,cal = 4.186\,J$
- Heat is denoted by
  Q = energy transferred due to temperature differences. Unit:J

Thermodynamics

Heat Capacity and Specific Heat

The amount of heat energy Q needed to raise the temperature of a substance is proportional to the temperature change and to the mass of the substance

$$Q = C\,\Delta T = c\,m\,\Delta T$$

- C: Heat capacity. Unit: J/K.

Thermodynamics

Heat Capacity and Specific Heat

The amount of heat energy Q needed to raise the temperature of a substance is proportional to the temperature change and to the mass of the substance

$$Q = C\,\Delta T = c\,m\,\Delta T$$

- C: Heat capacity. Unit: J/K.
- c: Specific Heat. It depends only on the substance. Unit: $J/kg.K$.

Thermodynamics

Heat Capacity and Specific Heat

- $Q > 0 \Rightarrow \Delta T > 0$: Heat added.

Thermodynamics

Heat Capacity and Specific Heat

- $Q > 0 \Rightarrow \Delta T > 0$: Heat added.
- $Q < 0 \Rightarrow \Delta T < 0$: Heat removed.
  $c_W = 4186\, J/kg.K$ for water and
  $c_L = 128\, J/kg.K$ for lead. More examples are given in Table 16-2.

Specific Heat

TABLE 16–2 Specific Heats at Atmospheric Pressure

Substance	Specific heat, c [J/(kg · K)]
Water	4186
Ice	2090
Steam	2010
Beryllium	1820
Air	1004
Aluminum	900
Glass	837
Silicon	703
Iron (steel)	448
Copper	387
Silver	234
Gold	129
Lead	128

Thermodynamics

Heat Capacity and Specific Heat

A 2 kg Aluminum block is originally at $10\,^0C$. If $36\,kJ$ of heat energy are added to the block, what is its final temperature?

- For aluminum, $c = 900\,J/kg.K$.

Thermodynamics

Heat Capacity and Specific Heat

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- For aluminum, $c = 900\,J/kg.K$.
- $Q = c\,m\,\Delta T = c\,m\,(T_f - T_i)$

Thermodynamics

Heat Capacity and Specific Heat

A 2 kg Aluminum block is originally at $10\,^0C$. If $36\,kJ$ of heat energy are added to the block, what is its final temperature?

- For aluminum, $c = 900\,J/kg.K$.
- $Q = c\,m\,\Delta T = c\,m\,(T_f - T_i)$
- $T_f = T_i + \frac{Q}{mc} = 10\,^0C + \frac{36kJ}{2kg \times 0.9kJ/kg.^0C} = 30\,^0C$.

Thermodynamics

Calorimetry

Lead shot of mass $600g$ is heated to $100\,^0C$ and placed in an aluminum can of mass $200\,g$ which contains $500\,g$ of water initially at $17.3\,^0C$. The specific heat of aluminum is $0.9kJ/kg.^0C$. The final equilibrium temperature of the mixture is $20.0\,^0C$. What is the specific heat of lead?

Thermodynamics

Calorimetry

We have assumed above that the aluminum can containing water is insulated, in the sense that heat transfer only occurs between the container and objects which are in thermal contact with it. The procedure is called calorimetry and the container is called calorimeter. Since there is no heat transfer to the surroundings, the sum of heat transfer between indidual components should sum up to zero.

$$\sum Q_i = 0$$

Thermodynamics

Calorimetry

- From the above, one concludes:
  $Q_{lead} + Q_{aluminum} + Q_{water} = 0$.

Thermodynamics

Calorimetry

- From the above, one concludes: $Q_{lead} + Q_{aluminum} + Q_{water} = 0$.
- $Q_{lead} = (0.6\,kg)c_{lead}(20.0\,^0C - 100\,^0C) = -(0.6\,kg)c_{lead}\,80.0\,^0C$.

Thermodynamics

Calorimetry

- From the above, one concludes:
$Q_{lead} + Q_{aluminum} + Q_{water} = 0$.
- $Q_{lead} = (0.6\,kg)c_{lead}(20.0\,^0C - 100\,^0C) = -(0.6\,kg)c_{lead}\,80.0\,^0C$.
- $Q_{aluminum} = (0.2\,kg)(0.900\,kJ/kg.^0C)(20.0\,^0C - 17.3\,^0C) = (0.2\,kg)(0.900\,kJ/kg.^0C)(2.7\,^0C) = 0.486\,kJ$.

Thermodynamics

Calorimetry

- $Q_{water} = (0.5\,kg)(4.18\,kJ/kg.^0C)(20.0\,^0C - 17.3\,^0C) = (0.5\,kg)(4.18\,kJ/kg.^0C)(2.7\,^0C) = 5.64\,kJ$.

Thermodynamics

Calorimetry

- $Q_{water} = (0.5\,kg)(4.18\,kJ/kg.^{0}C)(20.0\,^{0}C - 17.3\,^{0}C) = (0.5\,kg)(4.18\,kJ/kg.^{0}C)(2.7\,^{0}C) = 5.64\,kJ$.
- Using the equation in (1), one obtains $c_{lead} = \frac{6.13\,kJ}{48.0 kg.K} = 0.128\,kJ/kg.K$.

Thermodynamics

Conduction, Convection, Radiation

Conduction:

Heat energy can be transferred from one point to another point in a given material. This is called **thermal conduction**. Experimentally, the **rate of conduction** is found to be

- $$P_{cond} = \frac{Q}{t} = k\,A\,\frac{\Delta T}{L}$$

Thermodynamics

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Conduction:

Heat energy can be transferred from one point to another point in a given material. This is called thermal conduction. Experimentally, the rate of conduction is found to be

- $P_{cond} = \frac{Q}{t} = k\,A\,\frac{\Delta T}{L}$
- A= area; L = length.

Thermodynamics

Conduction, Convection, Radiation

- k = thermal conductivity. A constant which depends on the material. A good thermal conductor has high k, such as silver for example. Air is a poor thermal conductor. Also woods, etc..

Thermodynamics

Conduction, Convection, Radiation

- k = thermal conductivity. A constant which depends on the material. A good thermal conductor has high k, such as silver for example. Air is a poor thermal conductor. Also woods, etc..
- In building construction, one needs a poor thermal conductor i.e. a good thermal insulator. Define a heat resistance $R = \frac{L}{k}$. This is also called the R-value. Low $k \Rightarrow$ High R. For buildings in cold climates, usually an R-value of around 30 is desirable.

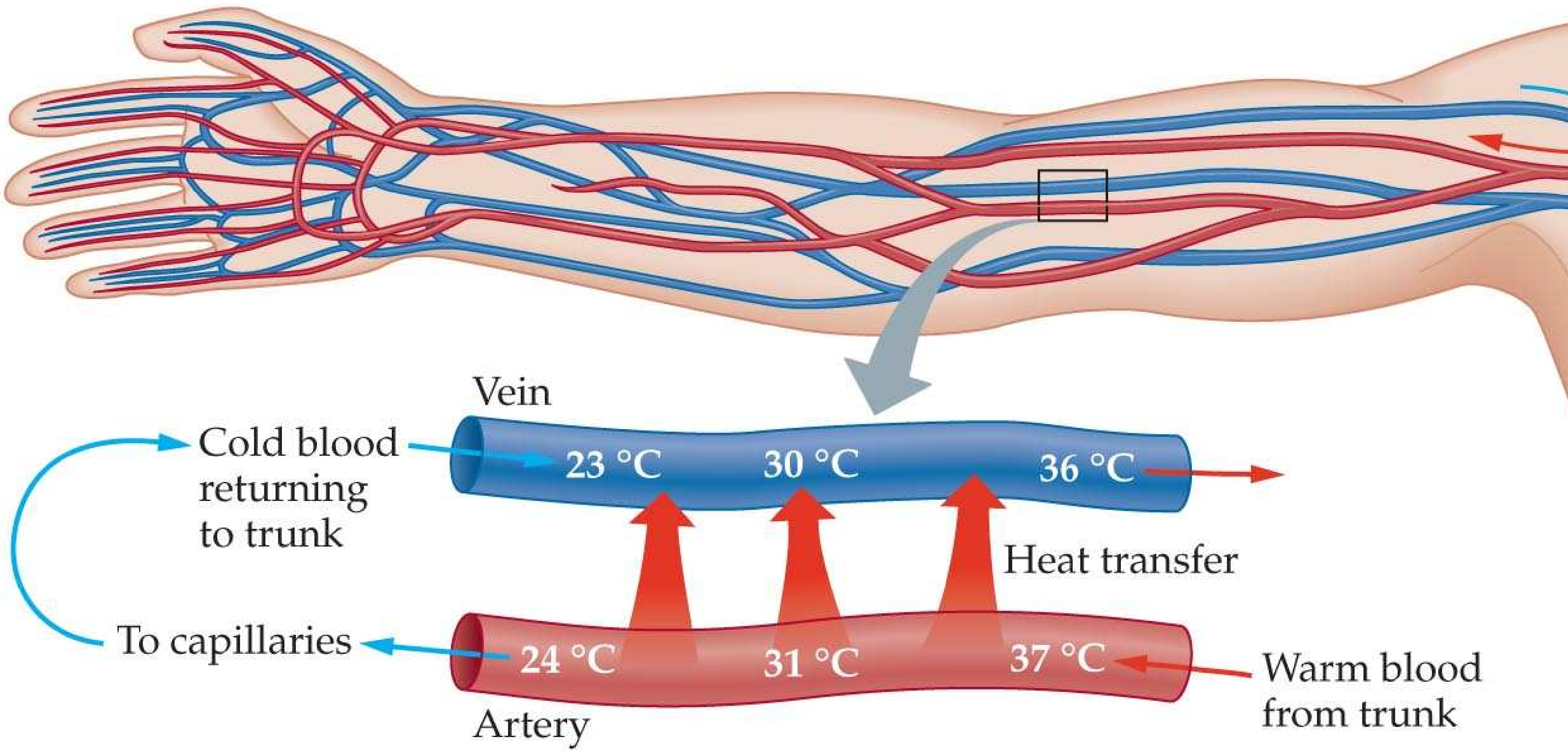
Conduction

TABLE 16–3 Thermal Conductivities

Substance	Thermal conductivity, k[W/(m · K)]
Silver	417
Copper	395
Gold	291
Aluminum	217
Steel, low carbon	66.9
Lead	34.3
Stainless steel—alloy 302	16.3
Ice	1.6
Concrete	1.3
Glass	0.84
Water	0.60
Asbestos	0.25
Wood	0.10
Wool	0.040
Air	0.0234

Thermodynamics

Conduction



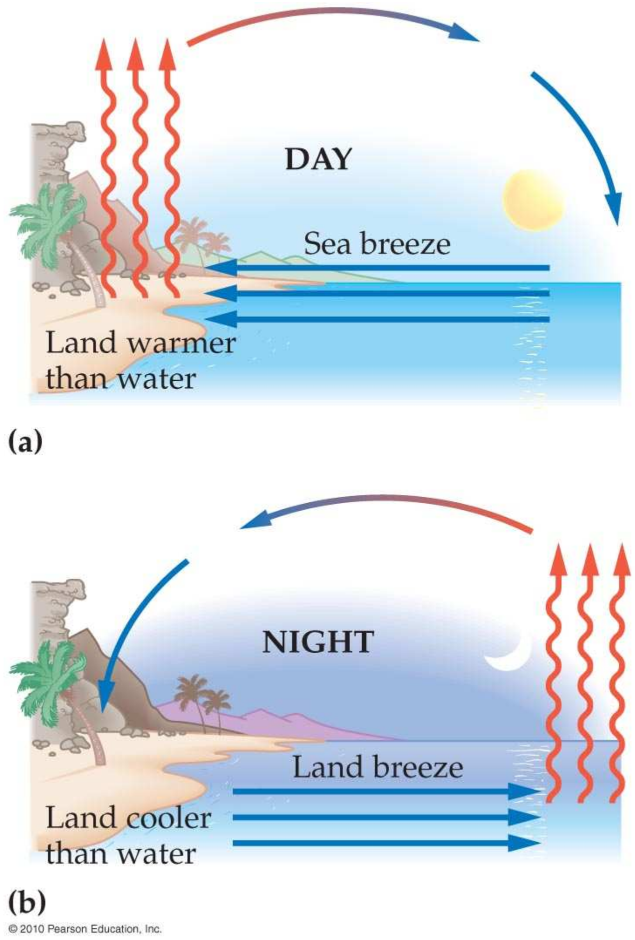
Thermodynamics

Conduction, Convection, Radiation

- Convection:
  Take a heat source such as a candle. As air around it heats up, it expands and its density decreases. Buoyant force makes it rise. Cooler air flows down to take its place. All of this creates a phenomenon called convection current.

Thermodynamics

Conduction



Thermodynamics

Conduction, Convection, Radiation

- Radiation:
  Another form of heat transfer is by radiating electromagnetic waves. This form of energy transfer is called thermal radiation. No medium is required for heat transfer by thermal radiation because electromagnetic waves can propagate even in vacuum.

Thermodynamics

Conduction, Convection, Radiation

You feel hot standing in front of a fire is because you absorb thermal radiation coming from the fire.

The rate at which an object emits energy via electromagnetic radiation is given by the Stefan-Boltzman law

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Conduction, Convection, Radiation

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Thermodynamics

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- $P_{rad} = e\sigma A T^4$
- e: emissivity
- $\sigma = 5.6703 \times 10^{-8} W/m^2.K^4$: Stefan-Boltzman constant

Thermodynamics

Conduction

Ideal Reflector