Last week:
temperature and thermal expansion
Pressure, Temperature, and Speed of molecules

\[ v_{rms} = \sqrt{\frac{3RT}{m}} \]

\( mN_A \) is the molar mass \( M \)

Root-mean-square speed

\[ K_{avg} = \frac{1}{2} m v_{avg}^2 \sim T \]

\[ K_{avg} = \frac{1}{2} m v_{avg}^2 = \frac{3}{2} k_B T \]

\( k_B \) – Boltzmann Constant

Boltzmann constant = \( 1.3806503 \times 10^{-23} \) m² kg s² K⁻¹

Linear thermal expansion

\[ \Delta L = L_0 \alpha \Delta T \]

Some Coefficients of Linear Expansion

<table>
<thead>
<tr>
<th>Substance</th>
<th>( \alpha ) (10⁻⁶/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice (at 0°C)</td>
<td>31</td>
</tr>
<tr>
<td>Lead</td>
<td>29</td>
</tr>
<tr>
<td>Aluminum</td>
<td>23</td>
</tr>
<tr>
<td>Brass</td>
<td>19</td>
</tr>
<tr>
<td>Copper</td>
<td>18</td>
</tr>
<tr>
<td>Concrete</td>
<td>12</td>
</tr>
<tr>
<td>Steel (ordinary)</td>
<td>9</td>
</tr>
<tr>
<td>Glass (Pyrex)</td>
<td>3.2</td>
</tr>
<tr>
<td>Diamond</td>
<td>1.2</td>
</tr>
<tr>
<td>Fused quartz</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\( \alpha \) – linear expansion coefficient

\( \Delta T \) – change in temperature

\( L_0 \) – original length

\( \Delta L \) – change in length

Room temperature values except for the listing for ice.

This alloy was designed to have a lower coefficient of expansion. The word is a shortened form of “invar.”
Properties of Water (H$_2$O)

- Negative thermal expansion of water between 0 and 4 °C
- Freezes at 0 °C, boils at 100 °C

Negative thermal expansion in ZrW$_2$O$_8$

The Triple Point of Water

A triple-point cell, in which solid ice, liquid water, and water vapor coexist in thermal equilibrium. 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.
Thermal expansion QZ

The coefficient of expansion of a certain steel is $0.000012$ per C°. The coefficient of volume expansion, in $(C°)^{-1}$, is:

- **A.** $(0.000012)^3$
- **B.** $(\pi/3)(0.000012)^3$
- **C.** $3 \times 0.000012$
- **D.** $0.000012$
- **E.** depends on the shape of the volume to which it will be applied

What is the ocean level increase due to $+1$ C° global warming?
Water linear expansion coefficient is $\sim 69e-6/C°$ at 20 C°.
Average ocean depth is 4 km

Heat:
Temperature difference determines the Heat transfer process

What is the direction for the heat transfer Between a,b,c,d?

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Heat and Heat Transfer

(a) Heat is the energy that is transferred between a system and its environment because of a temperature difference that exists between them.

Units of Heat are Joules [J], same as for Work

(b) If the temperature of a system exceeds that of its environment as in (a), heat $Q$ is lost by the system to the environment until thermal equilibrium (b) is established.

(c) If the temperature of the system is below that of the environment, heat is absorbed by the system until thermal equilibrium is established.

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Properties of Water (H₂O)

Heat absorbed by a material may change the material's physical state or phase—for example, from solid to liquid or from liquid to gas. The amount of energy required per unit mass to change the phase (but not the temperature) of a particular material is its **heat of transformation** $L$. Thus,

$$Q = Lm$$

The **heat of vaporization** $L_v$ is the amount of energy per unit mass that must be added to vaporize a liquid or that must be removed to condense a gas. The **heat of fusion** $L_f$ is the amount of energy per unit mass that must be added to melt a solid or that must be removed to freeze a liquid.

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**Heat Transfer Mechanisms**

- **Convection**
- **Radiation**
- **Conduction**

Buoyant forces cause the warm air to rise.
Heat Transfer Mechanisms

- Convection
- Radiation
- Conduction

\[ P = \frac{Q}{\Delta t} \]

\[ P_{\text{net}} = P_{\text{abs}} - P_{\text{rad}} = \sigma \varepsilon A (T_{\text{env}}^4 - T^4) \]

\[ \sigma = 5.6703 \times 10^{-8} \text{ W/m}^2\text{K}^4 \]

\( \sigma \) is called the Stefan–Boltzmann constant

\( \varepsilon \) represents the emissivity of the object's surface, which has a value between 0 and 1, depending on the composition of the surface. A surface with the maximum emissivity of 1.0 is said to be a blackbody radiator; but such a surface is an ideal limit and does not occur in nature.

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Heat Transfer Mechanisms

- Convection
- Radiation
- Conduction

Some Thermal Conductivities:

<table>
<thead>
<tr>
<th>Substance</th>
<th>( k ) (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td></td>
</tr>
<tr>
<td>Stainless steel</td>
<td>14</td>
</tr>
<tr>
<td>Lead</td>
<td>35</td>
</tr>
<tr>
<td>Aluminum</td>
<td>235</td>
</tr>
<tr>
<td>Copper</td>
<td>401</td>
</tr>
<tr>
<td>Silver</td>
<td>428</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
</tr>
<tr>
<td>Air (dry)</td>
<td>0.0025</td>
</tr>
<tr>
<td>Helium</td>
<td>0.15</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.18</td>
</tr>
<tr>
<td>Building Materials</td>
<td></td>
</tr>
<tr>
<td>Polyurethane foam</td>
<td>0.034</td>
</tr>
<tr>
<td>Rock wool</td>
<td>0.043</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>0.048</td>
</tr>
<tr>
<td>White pane</td>
<td>0.11</td>
</tr>
<tr>
<td>Window glass</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\[ Q = k A (\Delta T / L) t, \]

Where \( k \) is the thermal conductivity.
Heat and Work

A gas is confined to a cylinder with a movable piston. Heat $Q$ can be added to, or withdrawn from, the gas by regulating the temperature $T$ of the adjustable thermal reservoir. Work $W$ can be done by the gas by raising or lowering the piston.

The internal energy $E_{\text{int}}$ 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.

2. **Constant-volume processes.** If the volume of a system (such as a gas) is held constant, then system can do no work. Putting $W = 0$ in the first law (Eq. 19-26) yields

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

(constant-volume process) \hspace{1cm} (19-29)

Thus, if heat is absorbed by a system (that is, if $Q$ is positive), the internal energy of the system increases. Conversely, if heat is lost during the process (that is, if $Q$ is negative), the internal energy of the system must decrease.

3. **Cyclical processes.** These are processes in which, after certain interchanges of heat and work, the system is restored to its initial state. In that case, no intrinsic property of the system—including its internal energy—can possibly change. Putting $\Delta E_{\text{int}} = 0$ in the first law (Eq. 19-26) yields

$$Q = W$$

(cyclical process) \hspace{1cm} (19-30)

Thus, the net work done during the process must exactly equal the net amount of energy transferred as heat; the store of internal energy of the system remains unchanged. Cyclical processes form a closed loop on a $p-V$ plot, as shown in Fig. 19-14f. We shall discuss such processes in some detail in Chapter 21.

4. **Free expansions.** These are adiabatic processes in which no transfer of heat occurs between the system and its environment and no work is done on or by the system. Thus, $Q = W = 0$ and the first law requires that

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

(free expansion) \hspace{1cm} (19-21)

Figure 19-16 shows how such an expansion can be carried out. A gas, which is in thermal equilibrium within itself, is initially confined by a closed stopcock to one half of an isolated double chamber; the other half is evacuated. The stopcock is opened, and the gas expands freely to fill both halves of the chamber. No heat is transferred to or from the gas because of the insulation. No work is done by the gas because it rushes into a vacuum and thus does not meet any pressure.
Review & Summary

Temperature; Thermometers

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.

Zeroth Law of Thermodynamics

When a thermometer and some other object are placed in contact with each other, they eventually reach thermal equilibrium. The reading of the thermometer is then taken to be the temperature of the other object. The zeroth law provides consistent and useful temperature measurements because of the zeroth law of thermodynamics: If bodies A and B are 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

In the SI system, temperature is measured on the Kelvin scale, which is based on the triple point of water (273.16 K). Other temperatures are then defined by use of a constant-volume gas thermometer, in which a sample of gas is maintained at constant volume so its pressure is proportional to its temperature. We define the temperature $T$ as measured with a gas thermometer.

Celsius and Fahrenheit Scales

The Celsius temperature scale is defined by
\[ T_C = T - 273.15^\circ, \]
with $T$ in Kelvin. The Fahrenheit temperature scale is defined by
\[ T_F = \frac{9}{5} T + 32^\circ. \]

Thermal Expansion

All objects change size with changes in temperature. For a temperature change $\Delta T$, a change $\Delta L$ in any linear dimension $L$ is given by
\[ \Delta L = \alpha L \Delta T, \]
in which $\alpha$ is the coefficient of linear expansion. The change $\Delta V$ in the volume $V$ of a solid or liquid is
\[ \Delta V = V\beta \Delta T. \]
Here $\beta = 3\alpha$ is the material's coefficient of volume expansion.

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
\[ 1 \text{ cal} = 3.969 \times 10^4 \text{ Btu} = 4.1868 \text{ J}. \]

Heat Capacity and Specific Heat

If heat $Q$ is absorbed by an object, the object's temperature change $T_f - T_i$ is related to $Q$ by
\[ Q = C(T_f - T_i), \]
in which $C$ is the heat capacity of the object. If the object has mass $m$, then
\[ Q = cm(T_f - T_i), \]
where $c$ is the specific heat of the material making up the object. The molar specific heat of a material is the heat capacity per mole, or per $6.02 \times 10^{23}$ elementary units of the material.
Conduction, Convection, and Radiation

The rate $P_{\text{cond}}$ at which energy is conducted through a slab whose faces are maintained at temperatures $T_L$ and $T_W$ is

$$P_{\text{cond}} = \frac{Q}{L} = kA \frac{T_L - T_W}{L},$$

in which $A$ and $L$ are the face area and length of the slab, and $k$ is the thermal conductivity of the material.

Convection occurs when temperature differences cause an energy transfer by motion within a fluid. Radiation is an energy transfer via the emission of electromagnetic energy. The rate $P_{\text{rad}}$ at which an object emits energy via thermal radiation is

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

where $\sigma (= 5.67 \times 10^{-8} \text{ Wm}^2\text{K}^{-4})$ is the Stefan-Boltzmann constant, $A$ is the emissivity of the object's surface, $T$ is its surface temperature (in kelvins), and $T$ is its surface temperature. The rate $P_{\text{abs}}$ at which an object absorbs energy via thermal radiation from its environment, which is at the uniform temperature $T_{\text{env}}$ (in kelvins), is

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

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Prepare for the First Common QZ

1. A cylindrical window of 18 cm radius in a submarine can withstand a maximum force of $5.0 \times 10^5$ N. What is the maximum depth in a lake to which the submarine can go without damaging the window? ($\rho_w = 1000 \text{ kg/m}^3$)
   A) 501 m
   B) 722 m
   C) 1200 m
   D) 1327 m
   E) 1520 m

2. A solid object floats in water (density = 1000 kg/m$^3$) with three-fourth of its volume beneath the surface. What is the density of the object?
   A) 1333 kg/m$^3$
   B) 1000 kg/m$^3$
   C) 750 kg/m$^3$
   D) 250 kg/m$^3$
   E) 120 kg/m$^3$

3. A weight of a solid object is 2.06 N when weighed in air and 1.76 N when weighed in a liquid of density 1200 kg/m$^3$. The density of the object is
   A) 7000 kg/m$^3$
   B) 3500 kg/m$^3$
   C) 8240 kg/m$^3$
   D) 14000 kg/m$^3$
   E) 6500 kg/m$^3$

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