Announcements

1. Schedule –
   Chapter 19 – macroscopic view of heat (today)
   Chapter 20 – microscopic view of heat (Tuesday – 11/18)
   Review Chapters 15-20 – (Thursday – 11/20)
   Exam 3 – (Tuesday – 11/25)

2. Physics colloquium today – Professor Gary Pielak from UNC will speak about “Protein Biophysics in Cells”.

3. Today’s lecture – Chapter 19
   Temperature
   Heat
   The first law of thermodynamics
Dictionary definition: temperature – a measure of the warmth or coldness of an object or substance with reference to some standard value. The temperature of two systems is the same when the systems are in thermal equilibrium.

“Zeroth” law of thermodynamics:

If objects A and B are separately in thermal equilibrium with a third object C, then objects A and B are in thermal equilibrium with each other.
Temperature scales

\[ T_F = \frac{9}{5} T_C + 32 \]

Kelvin scale:

\[ T = T_C + 273.15^\circ \]

\[ T \geq 0 \]
There is a lowest temperature:

\[ T_0 = -273.15^\circ C = 0 \text{ K} \]

Kelvin ("absolute temperature") scale

\[ T_C = -273.15 + T_K \]

Example –

Room temperature = 68\(^\circ\) F = 20\(^\circ\) C = 293.15 K
Temperature (K)

- $10^{39}$: Universe just after beginning
- $10^8$: Highest laboratory temperature
- $10^6$: Center of the Sun
- $10^4$: Surface of the Sun
- $10^2$: Tungsten melts, Water freezes
- $10^0$: Universe today
- $10^{-2}$: Boiling helium-3
- $10^{-9}$: Record low temperature
Effects of temperature on matter

Solids and liquids

Thermal expansion:

$$\Delta L = \alpha L_i \Delta T$$
Typical expansion coefficients at $T_C = 20^\circ C$:

Linear expansion: $\Delta L = \alpha L_i \Delta T$

Steel: $\alpha = 11 \times 10^{-6}/^\circ C$
Concrete: $\alpha = 12 \times 10^{-6}/^\circ C$

Volume expansion:

$V = L^3 \Rightarrow \Delta V = 3\alpha V_i \Delta T = \beta V_i \Delta T$

Alcohol: $\beta = 1.12 \times 10^{-4}/^\circ C$
Air: $\beta = 3.41 \times 10^{-3}/^\circ C$
Brass → Steel

Serway, Physics for Scientists and Engineers, 5/e
Figure 19.3c
Heat – $Q$ -- the energy that is transferred between a “system” and its “environment” because of a temperature difference that exists between them.

Sign convention:

$Q < 0$ if $T_1 < T_2$

$Q > 0$ if $T_1 > T_2$
Heat withdrawn from system

Thermal equilibrium – no heat transfer

Heat added to system
Units of heat: Joule

Other units: calorie = 4.186 J

Kilocalorie = 4186 J = Calorie

Heat capacity: \( C = \text{amount of heat which must be added to the “system” to raise its temperature by } 1\text{K (or } 1^\circ \text{C).} \)

More generally:

\[
Q = C \Delta T
\]

\[
Q_{i \rightarrow f} = \int_{T_i}^{T_f} C(T) \, dT
\]

Heat capacity per mass: \( C = mc \)

Heat capacity per mole (for ideal gas): \( C = nC_v \)

\[ C = nC_p \]
Some typical specific heats

<table>
<thead>
<tr>
<th>Material</th>
<th>J/(kg·°C)</th>
<th>cal/(g·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (15°C)</td>
<td>4186</td>
<td>1.00</td>
</tr>
<tr>
<td>Ice (-10°C)</td>
<td>2220</td>
<td>0.53</td>
</tr>
<tr>
<td>Steam (100°C)</td>
<td>2010</td>
<td>0.48</td>
</tr>
<tr>
<td>Wood</td>
<td>1700</td>
<td>0.41</td>
</tr>
<tr>
<td>Aluminum</td>
<td>900</td>
<td>0.22</td>
</tr>
<tr>
<td>Iron</td>
<td>448</td>
<td>0.11</td>
</tr>
<tr>
<td>Gold</td>
<td>129</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Heat and changes in phase of materials

Example: A plot of temperature versus Q added to 1g = 0.001 kg of ice (initially at T=-30°C)

Q=2260J

Serway, Physics for Scientists and Engineers, 5/e
Figure 20.2
Some typical latent heats

<table>
<thead>
<tr>
<th>Material</th>
<th>J/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice $\rightarrow$ Water (0°C)</td>
<td>333000</td>
</tr>
<tr>
<td>Water $\rightarrow$ Steam (100°C)</td>
<td>2260000</td>
</tr>
<tr>
<td>Solid N $\rightarrow$ Liquid N (63 K)</td>
<td>25500</td>
</tr>
<tr>
<td>Liquid N $\rightarrow$ Gaseous N$_2$ (77 K)</td>
<td>201000</td>
</tr>
<tr>
<td>Solid Al $\rightarrow$ Liquid Al (660°C)</td>
<td>397000</td>
</tr>
<tr>
<td>Liquid Al $\rightarrow$ Gaseous Al (2450°C)</td>
<td>11400000</td>
</tr>
</tbody>
</table>
Peer instruction question

Suppose you have a well-insulated cup of hot coffee (m=0.25kg, T=100°C). In order to get to class on time you add 0.25 kg of ice (at 0°C). When your cup comes to equilibrium, what will be the temperature of the coffee.

(A) 0°C     (B) 10°C     (C) 50°C     (D) 100°C
Review question

Suppose you have a well-insulated cup of hot coffee (m=0.25kg, T=100°C). In order to get to class on time you add 0.25 kg of ice (at 0°C). When your cup comes to equilibrium, what will be the temperature of the coffee.

\[ Q = m \cdot c_w (T_f - 100°C) + m \cdot L_{ice} + m \cdot c_w (T_f - 0°C) = 0 \]

\[ 2 \cdot c_w \cdot T_f = c_w \cdot 100 - L_{ice} \]

\[ T_f = \frac{c_w \cdot 100}{2 \cdot c_w} - \frac{L_{ice}}{2 \cdot c_w} \]

\[ T_f = \frac{50}{2 \cdot 4186} - \frac{333000}{2 \cdot 4186} = 10°C \]
Energy in the form of work:

Work done by the "system" due to volume change

\[ W = \int_{x_i}^{x_f} F \, dx = \int_{V_i}^{V_f} \frac{F}{A} \, dx = \int_{V_i}^{V_f} P \, dV \]

Sign convention:

- \( W > 0 \) if \( V_f > V_i \) (expansion)
- \( W < 0 \) if \( V_f < V_i \) (contraction)
Work done by a gas:

“Isobaric” (constant pressure process)

\[ W = P_o (V_f - V_i) \]
Work done by ideal gas:

“Isovolumetric” (constant volume process)

\[ W = 0 \]
Work done by a gas:

“Isothermal” (constant temperature process)

\[
W_{i \rightarrow f} = \int PdV = \int \frac{nRT}{V} dV = nRT \ln \left( \frac{V_f}{V_i} \right)
\]

For ideal gas:

\[
PV = nRT
\]

\[
P(1.013 \times 10^5) \text{ Pa}
\]

\[
\begin{array}{c}
V_i \\
Pi
\end{array}
\quad \quad \quad
\begin{array}{c}
V_f
\end{array}
\]
Work done by a gas:

“Adiabatic” (no heat flow in the process) \( Q_{i \to f} = 0 \)

For ideal gas:

\[ PV^\gamma = P_i V_i^\gamma \]

\[ W_{i \to f} = \int_{V_i}^{V_f} PdV = \int_{V_i}^{V_f} \frac{P V_i^\gamma}{V^\gamma} dV = \frac{P V_i}{\gamma - 1} \left[ \left( \frac{V_f}{V_i} \right)^{\gamma - 1} - 1 \right] \]
Thermodynamic statement of conservation of energy –

First Law of Thermodynamics

\[ \Delta E_{\text{int}} = Q - W \]

“Internal” energy of system

Heat added to system

Work done by system
“Internal energy” \( E_{\text{int}} = E_{\text{int}}(T,V,P) \) (for an ideal gas, \( E_{\text{int}} = E_{\text{int}}(T) \)) can be changed by interaction with the system

\[ \Delta E_{\text{int}} = Q - W \]

Note: Thermal equilibrium implies a uniform temperature. In this example, the system and the environment are presumed to be in thermal equilibrium within themselves but not in thermal equilibrium with each other.
Examples process:

\[
W_{\text{net}} = W_{\text{(ABCD)}} = W_{\text{BC}} + W_{\text{DA}} \\
= (P_f - P_i) (V_f - V_i)
\]

\[
\Delta E_{\text{int(ABCD)}} = \Delta E_{\text{int(AB)}} + \Delta E_{\text{int(BC)}} + \Delta E_{\text{int(CD)}} + \Delta E_{\text{int(DA)}} = 0
\]

\[
\Rightarrow Q_{\text{net}} = Q_{\text{(ABCD)}} = W_{\text{net}}
\]
3. HRW 19.P.049. [52190] A sample of gas expands from 1.0 m$^3$ to 6.0 m$^3$ while its pressure decreases from 30 Pa to 10 Pa. How much work is done by the gas if its pressure changes with volume via each of the three paths shown in the $p$-$V$ diagram in Fig. 19-34?

- J path A
- J path B
- J path C
4. HRW6 19.P.052. [52191] Gas within a chamber passes through the cycle shown in Fig. 19-37. Determine the net heat added to the system during process $CA$ if the heat $Q_{AB}$ added during process $AB$ is 25.0 J, no heat is transferred during process $BC$, and the net work done during the cycle is 12.0 J.

$0.133333$ J

Figure 19-37.
5. HW 6 19.P.053, [52192] When a system is taken from state $i$ to state $f$ along path $iaf$ in Fig. 19-40, $Q = 65$ cal and $W = 10$ cal. Along path $ibf$, $Q = 65$ cal.

![Diagram showing pressure and volume with points a, i, b, f, and j connected by paths iaf and ibf.]

Figure 19-40.

(a) What is $W$ along path $ibf$?
[0.133333] cal

(b) If $W = -18$ cal for the curved return path $fi$, what is $Q$ for this path?
[0.133333] cal

(c) Take $E_{\text{int},i} = 15$ cal. What is $E_{\text{int},f}$?
[0.133333] cal

Assume $E_{\text{int},b} = 11$ cal.

(d) What is the value of $Q$ for path $ib$?
[0.133333] cal

(e) What is the value of $Q$ for path $bf$?
[0.133333] cal
Mechanisms of heat transfer:

1. Thermal convection
   
   Heat transmitted by heated fluid flow. (Ex. -- home heating units, stove top cooking)

2. Radiation
   
   Heat transmitted by electromagnetic radiation. (Ex. – sun, microwave cooking)

3. Thermal conduction
   
   Heat transfer from one side of a material to another due to a temperature gradient.
Quantitative statement of thermal conduction:

$$\frac{\Delta Q}{\Delta t} = kA \frac{\Delta T}{\Delta x}$$

Units: 1 J/s = 1 Watt (W)

cross-sectional area
thermal conductivity coefficient

<table>
<thead>
<tr>
<th>Material</th>
<th>$k$ (W/(m(\cdot)°C))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>238</td>
</tr>
<tr>
<td>Glass</td>
<td>0.8</td>
</tr>
<tr>
<td>Water</td>
<td>0.6</td>
</tr>
<tr>
<td>Air</td>
<td>0.0234</td>
</tr>
</tbody>
</table>

Units: 1 J/s = 1 Watt (W)
Examples of thermal conduction

\[ \frac{dQ}{dt} = k_2 A \frac{T_2 - T_1}{L_2} \]

\[ \frac{dQ}{dt} = k_{\text{eff}} A \frac{T}{T_2 - T_1} \frac{L_2}{L_2 + L_1} \]

\[ k_{\text{eff}} = \frac{L_2 + L_1}{L_2 / k_2 + L_1 / k_1} \]
Example: \( T_1 = 20^\circ C, \ T_2 = 0^\circ C \)

Single pane glass window: \( A = 1 \text{m}^2, \ L_2 = 0.002 \text{m}, \ k_2 = 0.8 \text{ W/m} \cdot ^\circ \text{C} \)

\[
\frac{dQ}{dt} = k_2 A \frac{T_2 - T_1}{L_2} = 8000 \text{ W}
\]

Double pane glass window: \( L_1 = 0.01 \text{m}, \ k_1 = 0.0234 \text{ W/m} \cdot ^\circ \text{C} \) (air)

\[
\frac{dQ}{dt} = k_{\text{eff}} A \frac{T_2 - T_1}{L_2 + L_1 + L_0}
\]

\[
k_{\text{eff}} = \frac{L_2 + L_1 + L_0}{L_2 / k_2 + L_1 / k_1 + L_0 / k_0} = 46 \text{ W}
\]