**Temperature** \( (T) \) is the quantity that determines the direction in which thermal energy will flow when two objects are brought into contact.

**Heat** \( (Q) \) is the energy exchanged between two bodies in thermal contact.

\[ T_A > T_B : \text{heat energy is transferred from A to B} \]
**0th Law of Thermodynamics**

Two objects in thermal contact, i.e., the objects that are able to transfer heat to one another, are said to be in **thermal equilibrium** if there is no net energy (heat) exchange between them. At thermal equilibrium, the objects have the same temperature.

Also, if object A is in thermal equilibrium with object B, and B is in thermal equilibrium with object C, A is in thermal equilibrium with C.

\[
T_A > T_B \quad \Rightarrow \quad T_A = T_B
\]
Kinetic theory

Molecular speed distribution of a given gas as a function of $T$

Molecular speed distribution of different gases at the same $T$
Kinetic theory and pressure

We will consider a gas of $N$ molecules, each of mass $m$, enclosed in a cubic container of volume $V = L^3$. Let’s consider a molecule traveling with a speed $v_x$ along the x-axis that collides perpendicularly and elastically with the wall (for definiteness, we consider the wall to the right). Then the momentum transfer from the particle to the wall is:

$$\Delta \pi_x = \pi_{xf} - \pi_{xi} = m(v_{xf} - v_{xi}) = m(v_x - (-v_x)) = 2mv_x$$

The time between collisions of this molecule with the righthand wall is:

$$\Delta t = \frac{2L}{v_x}$$

Thus, the force imparted to the righthand wall in the x-direction from the single molecule is:

$$F_x = \frac{\Delta \pi_x}{\Delta t} = \frac{(2mv_x)}{2L/v_x} = \frac{mv_x^2}{L}$$
Considering the effect of all \( N \) particles, the total force is:

\[
\overline{F_x} = \frac{Nm\overline{v}_x^2}{L}
\]

where \( \overline{v}_x \) denotes the mean speed of the molecules in the x-direction.

If the gas is **isotropic**, i.e., behaves the same way in all directions, and has a mean speed \( \overline{v} \), then

\[
\overline{v}_x^2 = \frac{1}{3} \overline{v}^2
\]

in which case

\[
\overline{F_x} = \frac{Nm\overline{v}^2}{3L}
\]

Since the force on the righthand wall acts over an area \( L^2 \), the pressure exerted by the gas on the wall is:

\[
p = \frac{\overline{F}_x}{L^2} = \frac{Nm\overline{v}^2}{3L^3} = \frac{Nm\overline{v}^2}{3V} = \frac{nm\overline{v}^2}{3}
\]

where \( n = \frac{N}{V} \) is the number density.
Kinetic theory and temperature

From the Ideal Gas Law [as you’ll see later in the semester]:

\[ pV = Nk_bT \Rightarrow p = nk_bT \]

where \( k_b = 1.38 \times 10^{-23} \text{ JK}^{-1} \) is the **Boltzmann constant**.

Comparing to the previous result for pressure acting along a wall of the container yields

\[ k_bT = \frac{m\bar{v}^2}{3} \]

Since the average molecular kinetic energy of the gas is given by

\[ KE = \frac{m\bar{v}^2}{2} \]

the above result shows that the gas’s temperature is proportional to the average molecular kinetic energy.
# Temperature scales

<table>
<thead>
<tr>
<th></th>
<th>Kelvin</th>
<th>Celsius</th>
<th>Rankine</th>
<th>Fahrenheit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>steam point</strong></td>
<td>373</td>
<td>+100 K</td>
<td>+672°</td>
<td>+212°</td>
</tr>
<tr>
<td><strong>ice point</strong></td>
<td>273</td>
<td>0°</td>
<td>492°</td>
<td>+32°</td>
</tr>
<tr>
<td><strong>solid CO₂</strong></td>
<td>195</td>
<td>-78°</td>
<td>351°</td>
<td>-109°</td>
</tr>
<tr>
<td><strong>oxygen point</strong></td>
<td>90</td>
<td>-183°</td>
<td>162°</td>
<td>-297°</td>
</tr>
<tr>
<td><strong>absolute zero</strong></td>
<td>0</td>
<td>-273°</td>
<td>0°</td>
<td>-460°</td>
</tr>
</tbody>
</table>

M.W. Zemansky, *Temperatures Very Low and Very High*
An **emagram** is a diagram used to represent vertical profiles of thermodynamic data.

**Lapse rate** \( (\Gamma) \) is the measure of temperature change in the vertical, i.e.,

\[
\Gamma = - \frac{\partial T}{\partial z}
\]
Inversions

Golden Gate Bridge, San Francisco, and marine layer

Smog in Salt Lake City, subsidence inversion
Liquid-in-glass Thermometers

Mercury-in-glass thermometer

Gallileo thermometer
Bi-metallic Thermometer

When heated
Stevenson screen

Interior showing instrumentation
Radiosondes
Integrated Global Radiosonde Archive

National Climatic Data Center, NOAA
Comparison of temperature profiles for Green Bay, WI (12Z 25 Aug 2005) plotted on an emagram (left) and skew-T (right)

Petty Figure 1.19
Skew-T Diagram (cont’d)