\[ \Delta Q = \ell \Delta (\text{quant.}) \]  
\[ \Delta Q = (\text{quant.}) C \Delta T \]

Phase change
Temperature change
Temperature

How do we keep track of energy when it is distributed over many, many \[\sim 10^{23}\] objects that are constantly exchanging energy?

Temperature is a measure of the average energy per molecule.

Measure: \(\text{°K} : \text{°C} : \text{°F}\)

- High average speed
- High energy per molecule
- High \(T\)
- Low average speed
- Low energy per molecule
- Low \(T\)

http://phet.colorado.edu/en/simulation/gas-properties
http://www.falstad.com/gas/
In the 18th century, some erroneously believed that an object certain amount of “heat fluid” or caloric that could flow from one place to another.

Benjamin Thomas (1753-1814) A.K.A Count Rumford observed the heat generated from the boring of cannon barrels by large drills.

James Prescott Joule (1818-1889) quantitatively measured the increased temperature done by mechanical energy.

=> Energy is Conserved
**Establishing Thermal Equilibrium**

Definition: Heat is the energy transferred between objects due to a temperature difference.

Separated, but in thermal contact

\[ T_c \quad \text{"colder"} \quad \quad \Delta Q \quad \quad \rightarrow \quad \quad \quad \quad \quad \text{"hotter"} \quad T_h \]

In Thermal Contact after a long period

\[ A \quad B \]

\[ T \]

\[ T_c < T < T_h \]

Equilibrium established by heat flow, \( \Delta Q \), from hotter to colder system

**Zero’th Law of Thermo**

If A is in thermal equilibrium with B, and C is also in thermal equilibrium with B, then A and C will be in thermal equilibrium if brought into thermal contact.

**temperature is a universal function**
Energy Transfer Processes

Convection: hot fluid/gas moves hot & cold material change places (most efficient transport mechanism)

Physics of
- Storm formation
- Heating buildings
- Heat transport in Earth’s mantle
- Source of volcanoes
- Primary cooling of electronics
Conduction: no material motion
Heat is transferred via atoms and electrons exchanging kinetic energy via collisions with adjacent atoms/electrons.

Electrons most efficient. Conduction is strong in metals (e.g. copper, Pt, Au, Fe) and least effective in insulators. [actually wrought iron is not so good- pokers for fires]

Energy moves but individual atoms/electrons move only short dist.

Copper (metal) - rod – free electrons enable excellent heat flow
How is Heat transferred (cont.)

**Radiation** - energy transfer by electromagnetic waves (or photons) e.g., light

![Diagram](image)

Energy radiated/surface area $\propto T^4$

**Stefan-Boltzmann law**

Power radiated (energy/time) $P = \varepsilon A \sigma T^4$

- Emissivity (let $=1$ often)
- $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^2$
Retarding Energy Transfer

Which feature of the thermos bottle or cryogenic container is responsible for “insulating” against each of the heat-transfer processes?

Vacuum – cuts conduction and convection
Silvered faces reflect radiation – cuts radiation
### Temperature Benchmarks

<table>
<thead>
<tr>
<th></th>
<th>Kelvin (k)</th>
<th>°C</th>
<th>°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun (center)</td>
<td>$10^6$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sun (surface)</td>
<td>6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>light bulb</td>
<td>4000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hot stove</td>
<td>2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$O boils</td>
<td>373</td>
<td>100</td>
<td>212</td>
</tr>
<tr>
<td>H$_2$O freezes</td>
<td>273</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>CO$_2$ sublimes</td>
<td>195</td>
<td>-78</td>
<td>-109</td>
</tr>
<tr>
<td>N$_2$ boils</td>
<td>77</td>
<td>-196</td>
<td>-320</td>
</tr>
<tr>
<td>N$_2$ freezes</td>
<td>44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>He boils</td>
<td>4.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute Zero</td>
<td>0</td>
<td>-273</td>
<td>-460</td>
</tr>
</tbody>
</table>

**K scale**

0= temperature where all motion stops (KE=0)

14-8
Constant Volume Gas Thermometer (variation)

Move up or down to keep V constant as T varies.

\[ P = \frac{mgh}{A} \]

We know.

\[ \rho = \frac{mgh}{A} \]

Pressure

\[ T = 273.15 \text{ K} \]

where gas KE and speed is smallest.

\[ \rho = \frac{mgh}{A} \]

Absolute O°

O° for Kelvin Scale

(\text{can't get there})

where gas P extrapolates to 0

O = KE classically.
The most grown-up (i.e. physicist’s) temperature scale

The Kelvin Scale

The pressure in a gas is proportional to its temperature.

While each gas has a different proportionality (slope), all reach zero pressure at the exact same temperature. This value is called Absolute Zero and the Kelvin Scale is identical to the Celsius scale minus 273.15 degrees.
Heat & Internal Energy

Heat \( (\Delta Q) \) = \text{energy that is transferred from} \( T_{th} \to T_L \)

Where does \( \Delta Q \) energy come from?

- Move some molecules with their energy
- Slow down some molecules in one system + speed up some in the other

Internal energy of \( T_{th} \)

\[ \text{Internal Energy} = KE_{\text{molecules}} + PE_{\text{molecules}} \]
Thermal Expansion (how to view)

$\Delta l \sim 10 \text{ model solid}$

- 
  - Atoms
  - mass
  - Atoms oscillate
  - low $T$
  - high $T$
  - springs (to simulate atomic attraction)
  - what holds solid together
  - heat up by $\Delta T$  

- need
  - strong/rigid springs
  - hard material
  - low $\alpha$
  - fused quartz
    $\alpha = 0.5 \times 10^{-6}$
  - soft material
  - soft springs
  - large $\alpha$
  - $\Delta l / l_0 = \alpha \Delta T$

$Al \quad \alpha = 2.3 \times 10^{-6}$

$Fe \quad \alpha = 2.9 \times 10^{-6}$

$\Delta l = l - l_0$

$\frac{\Delta l}{l_0} = \alpha \Delta T$

$l - l_0 = \alpha \Delta T$

$l_0 - l_0 = l_0 \alpha \Delta T$

$l = l_0 + l_0 \alpha \Delta T$
Thermal expansion cause
- Atomic vibrations
- + Interatomic potential asymmetric (lopsided)
  \{can’t push atoms into each other\}

\[ r(T) = r_0 + \alpha T \]

Extra background

Atoms \( r_0 \) apart \( T=0 \) K

Vibrations \( T>0 \) K
Most substances expand when heated in proportion to the change in temperature.

**Definition of Coefficient of Linear Expansion, \( \alpha \)**

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

SI unit for \( \alpha \): \( K^{-1} = (C^\circ)^{-1} \)
**Ex: Thermal Expansion**

From our definition: \( \Delta L = L_0 \alpha \Delta t \)

where \( \alpha \) - thermal expansion coefficient

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

\[
L = L_0 [1 + \alpha (T - T_0)]
\]

**Ex: Verrazano-Narrows Bridge (Center Span)**

\( L_0 = 1300 \text{ m} \)

\( \Delta T \sim 100 \text{ °C} \)

\( \alpha_{\text{stress}} = 12 \times 10^{-6} \text{ m/°C} \)

\[
\Delta L = (1300 \text{ m})(12 \times 10^{-6})(100) = 1.56 \text{ m}
\]
The Thermostat

Bimetals with different thermal expansions. e.g. brass - steel

When Hot

When Cold

Glass vial with mercury

Dial

Bimetal Coil

The glass vial containing mercury acts as the switch. When the vial gets tipped horizontally, the mercury makes electrical contact, starting the home heating system.
\[ \Delta Q \Rightarrow \text{system} \quad \text{observe} \quad \Delta T \]

**Define heat capacity** (property of system)

Heat input in = + direction

\[ \Delta Q = C \Delta T \]

The larger the system the larger the \( C \) (heat capacity).

\[ C = \frac{\Delta Q}{\Delta T} \quad [\text{J/K} = \text{J}/^\circ\text{C}] \]

\[ \Delta Q = C \Delta T \]

\[ c = \frac{C}{m} \quad [\text{J/kg} \cdot \text{K} = \text{J/kg} \cdot ^\circ\text{C}] \]

\[ \Delta Q = m \cdot c \cdot \Delta T \]
\[ \Delta Q \Rightarrow \text{calorics} \quad 1 \text{g water} \quad \Delta T = 1^\circ C \]

\[ \text{kilo-calorics} - 1 \text{kg H}_2\text{O} \quad 14.5^\circ C \rightarrow 15.5^\circ C \]

\[ 1 \text{BTU} = 1 \text{lb water} \quad 63^\circ F \rightarrow 64^\circ F \]

\[ 1 \text{kcal} = 1000 \text{cal} = 3.968 \text{BTU} \]

\[ 15 = 9.48 \times 10^{-4} \text{BTU} \]

\[ 1 \text{cal} = 4.187 \text{J} \]

\[ 1 \text{kcal} = 4187 \text{J} \]

\[ \frac{\text{kcal}}{\text{kg} \cdot ^\circ C} = \frac{10^3 \text{cal}}{\text{kg} \cdot ^\circ C} \cdot 4.187 \text{J} = 4187 \text{J} \]

\[ c(\text{H}_2\text{O}) = 1 \frac{\text{cal}}{\text{g} \cdot ^\circ C} \]

Molar Specific Heat Capacity better!!

\[ \frac{\Delta Q}{\Delta T} = C \quad \rightarrow \quad \#	ext{ mole} \]

Per-molecule Specific Heat Capacity best!!!
Suppose 69.4 J is added to 0.121 kg of a metal M. By how much does the temperature rise?

\[
\Delta Q = m \cdot c \cdot \Delta T
\]

\[
\Delta T = \frac{\Delta Q}{m \cdot c} = \frac{69.4 \text{ J}}{(0.121 \text{ kg})(900 \text{ J/kg} \cdot \text{K})} = 0.637 \text{ °K}
\]

\[
\Delta T = \frac{\Delta Q}{m \cdot c}
\]

M = Al

\[
\Delta T = \frac{\Delta Q}{m \cdot c} = \frac{69.4 \text{ J}}{(0.121 \text{ kg})(128 \text{ J/kg} \cdot \text{K})} = 4.48 \text{ °K}
\]

M = Pb

Same mass – fewer atoms (greater mass per atom)

Example
A Pb ball is dropped from $h=5.43$ m. Once the ball has come to rest on the floor by how much has the temperature increased?

Just before impact

- $PE = mgh$

Later after impact (at rest – energy trans. to heat)

- $KE = \frac{m}{2} v^2$
- $\Delta Q$
- $\Delta T$

$PE \Rightarrow KE \Rightarrow \Delta Q = mc \Delta T$

$mgh = mc \Delta T$

$$\Delta T = \frac{gh}{c} = \frac{9.8 \times (5.43) \text{ m/s}^2 \text{ (m)}}{128 \text{ J/kg} \text{ °K}} = 0.416 \frac{\text{kg} \text{ m}^2/\text{s}^2}{\text{°K}} = 0.416 \text{ °K}$$
From Chemistry 3 Later Chapter

\[ N_A = \text{Avogadro's } \# = \frac{\# \text{ molecules}}{\text{mole}} = 6.02 \times 10^{23} \]

mole \rightarrow g \text{-molecular weight}

carbon: \( ^{12} \) \[ 12 \text{ g of C} = 1 \text{ mole of C} \]

\( \frac{g \text{-mw}}{1000 \text{ g}} \)

1 kg = \# of kg for 1 mole

\[ C \left( \frac{5}{kg \cdot K} \right) \cdot \frac{1 \text{ kg}}{1000 \text{ g}} \cdot g \text{-mw} = C \uparrow \]

specific heat capacity / kg

\[ \text{specific heat capacity} / \text{mole} \]

more fundamental!!
### Table 13.3

**Specific Heat Capacity for Some Materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific heat capacity $\text{kJ/kg-K}$</th>
<th>Specific heat capacity $\text{kcal/kg-K}$</th>
<th>$\text{g-Mol/W}^\circ 1000$</th>
<th>Molar Heat Capacity $\text{J/mole-K}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solids</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.90 (J/kg-K)</td>
<td>0.21 (kcal/kg-K)</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td>Clay (dry)</td>
<td>0.92</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>0.39 (J/kg-K)</td>
<td>0.093 (kcal/kg-K)</td>
<td>0.0655</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>0.84</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>0.13</td>
<td>0.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human body (average)</td>
<td>3.47</td>
<td>0.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice (water, $-5^\circ\text{C}$, $\text{H}_2\text{O}$)</td>
<td>2.1 (J/kg-K)</td>
<td>0.50 (kcal/kg-K)</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>0.47</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyamides (e.g., Nylon)</td>
<td>1.7</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylenes</td>
<td>2.3</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polytetrafluoroethylene (e.g., Teflon)</td>
<td>1.0</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>0.13 (J/kg-K)</td>
<td>0.031 (kcal/kg-K)</td>
<td>0.2072</td>
<td></td>
</tr>
<tr>
<td>Marble</td>
<td>0.86</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platinum</td>
<td>0.14</td>
<td>0.032</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protein</td>
<td>1.7</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>0.23 (J/kg-K)</td>
<td>0.056 (kcal/kg-K)</td>
<td>0.108</td>
<td></td>
</tr>
<tr>
<td>Stainless steel (type 304)</td>
<td>0.50</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>1.8</td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gases</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air ($100^\circ\text{C}$)</td>
<td>1.0</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argon</td>
<td>0.52 (J/kg-K)</td>
<td>0.13 (kcal/kg-K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>1.0</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>14.2 (J/kg-K)</td>
<td>3.39 (kcal/kg-K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>2.2</td>
<td>0.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam ($110^\circ\text{C}$)</td>
<td>2.01</td>
<td>0.481</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*At <20°C.

### Table 14-2

**Specific Heats of Gases**

<table>
<thead>
<tr>
<th>Gas</th>
<th>$c_p$ (constant pressure)</th>
<th>$c_v$ (constant volume)</th>
<th>$\text{g-Mol/W}^\circ 1000$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam ($100^\circ\text{C}$)</td>
<td>0.482</td>
<td>0.350</td>
<td></td>
</tr>
<tr>
<td>$\text{O}_2$ Oxygen ($2$)</td>
<td>0.218 [11]</td>
<td>0.155</td>
<td>0.032</td>
</tr>
<tr>
<td>$\text{He}$ Helium ($4$)</td>
<td>1.15 [11]</td>
<td>0.75</td>
<td>0.047</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.199</td>
<td>0.139</td>
<td>0.25</td>
</tr>
<tr>
<td>$\text{N}_2$ Nitrogen ($28$)</td>
<td>0.248 [11]</td>
<td>0.15</td>
<td>0.028</td>
</tr>
</tbody>
</table>

*5/s/kg°C*
Solid Phase

Solid looks like

(! ! ! !)

\[ C \sim 25 \pm 1 \text{ J mole}^{-1} \text{ K}^{-1} \]

monatomic

H\text{_}2O ice

\[ C \sim 37.8 \text{ J mole}^{-1} \text{ K}^{-1} \]

polyatomic

Gas Phase

Gas looks like

(! ! !)

He, Ar, ...

\[ C_\text{p} \sim 20 \text{ J mole}^{-1} \text{ K}^{-1} \]
Phase Changes

Solid

Liquid

Gas

Low T

High T

PE dominates (molecular-attraction)

Low: v, KE

Intermediate: v, E

High: v, KE

PE important

PE un-important

Solid

Liquid

Gas

Phase change

Water boils

Water vapor warms up

Temperature, °C

0

-30

100

Ice melts

Water warms up

Ice warms up

Q = Heat input

L_{se} = Latent heat

Solid → Liquid

L_{se} = Latent heat

Solid → Liquid
The diagram illustrates the phase change of water. Here is the description:

- **Solid**: The phase where water is in the solid state (ice).
- **Liquid**: The phase where water is in the liquid state.
- **Gas**: The phase where water is in the gaseous state (water vapor).

**Temperature, °C**

- **Ice melts**: When ice melts, the temperature increases until it reaches 0°C. The equation for this is $\frac{\Delta T}{\Delta Q} = \frac{1}{C_{\text{solid}}}$.
- **Water warms up**: When water warms up, the temperature remains constant until it reaches 100°C.
- **Water boils**: When water boils, it changes to the gaseous state.
- **Water vapor warms up**: The temperature increases for water vapor.

**Equation**: $\frac{\Delta T}{\Delta Q} = \frac{1}{C_{\text{water}}}$

**Heat input (Q)**: The total heat input is the sum of all heat changes.
Phase change

Observation 1:
\[ \Delta Q = C_i m_i \Delta T \]

Observation 2:
\[ \Delta Q = C_w m_w \Delta T \]

- Same \( \Delta Q \) in but \( \Delta T = 0 \)
- What happens is some of the ice melts to water

\[ \Delta Q = \int (\Delta m) \text{ latent heat} \]

80 kcal/kg