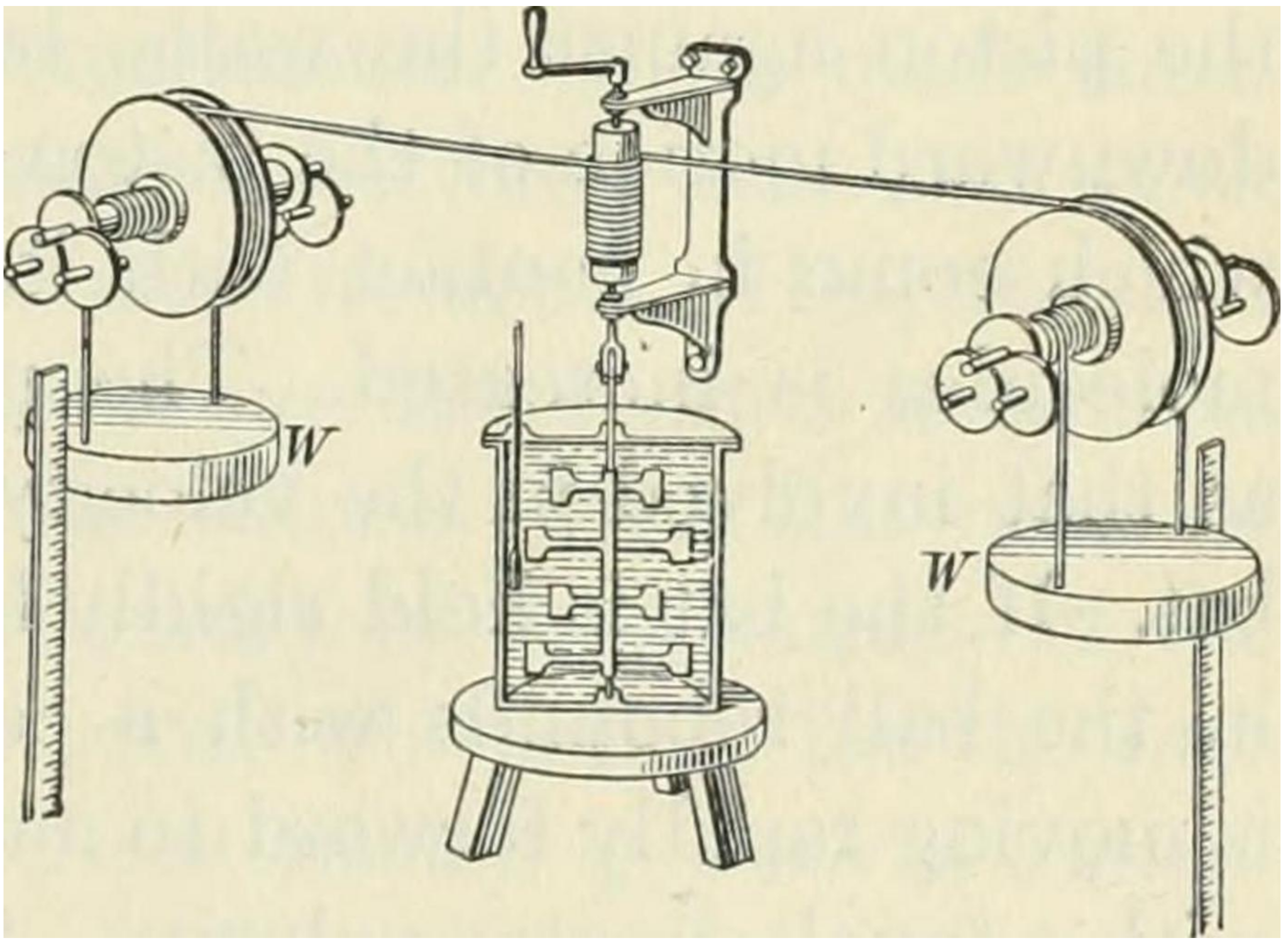
Lecture 31: Phase Change and Heat Transfer

Physics for Engineers & Scientists **(Giancoli): Chapter 19**
University Physics V2 **(Openstax): Chapter 1**

Calories and James Joule

- Initially it wasn't known that heat and mechanical energy were equivalent. Consequently, heat had its own units (calorie).
- A **calorie** is defined as the amount of heat needed to raise the temperature of one gram of water by 1°C.
- In 1847, James Joule performed a definitive experiment showing that heat and mechanical energy were equivalent.



- Falling masses were used to turn agitators inside an insulated fluid.
- The potential energy of the masses was converted into a rise in temperature of the fluid.

$$1\,cal = 4.186\,J$$

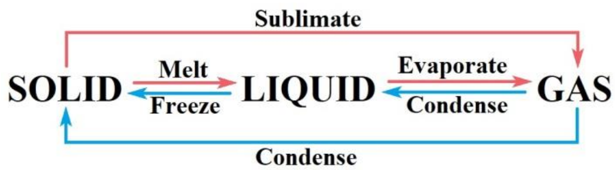
Nutritionist use "Calories" to measure the energy value of food, but these are actually kilo-calories.

"cal" = calorie. "Cal" = kcal = kilo-calorie.

Heat and Phase Change

- Traditionally there are 3 states ("phases") of matter: solids, liquids, and gases

  Today some would include plasmas, Bose-Einstein condensates, quark-gluon plasmas, etc.



- When a substance changes from one phase to another an amount of heat must be added (or removed) for the atoms/molecules rearrange themselves.

$$Q = mL$$

- 'Q' is the heat added to the substance, and 'm' is the mass of the substance.
- The Latent Heat (L) is a property of the material and depends upon which transition is occurring.
  - Solid/liquid transitions use the Latent Heat of Fusion (L_F)
  - Liquid/gas transitions use the Latent Heat of Vaporization (L_v)
  - Solid/gas transitions use the Latent Heat of Sublimation (L_s)

Example: 3.78 kg of water (a gallon) has been frozen into ice. How much heat is required to convert it from ice at -15.0°C into steam at 130°C? The latent heat of fusion for water/ice is 334 J/g. The latent heat of vaporization for water/steam is 2230 J/g. The specific heat of water is 4187 J/(kg·K). The specific heat for ice is 2108 J/(kg·K). The specific heat for steam is 1996 J/(kg·K).

Ice from -15°C to 0°C: $Q_1 = cm\Delta T = \left(2108 \frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right)(3.78\,kg)(15.0°\mathrm{C}) = 119{,}523.6\,J$

Ice to water at 0°C: $Q_2 = mL_F = \left(334 \frac{\mathrm{J}}{\mathrm{g}}\right)(3780\,g) = 1{,}262{,}520\,J$

Water from 0°C to 100°C: $Q_3 = cm\Delta T = \left(4187 \frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right)(3.78\,kg)(100°\mathrm{C}) = 1{,}582{,}686\,J$

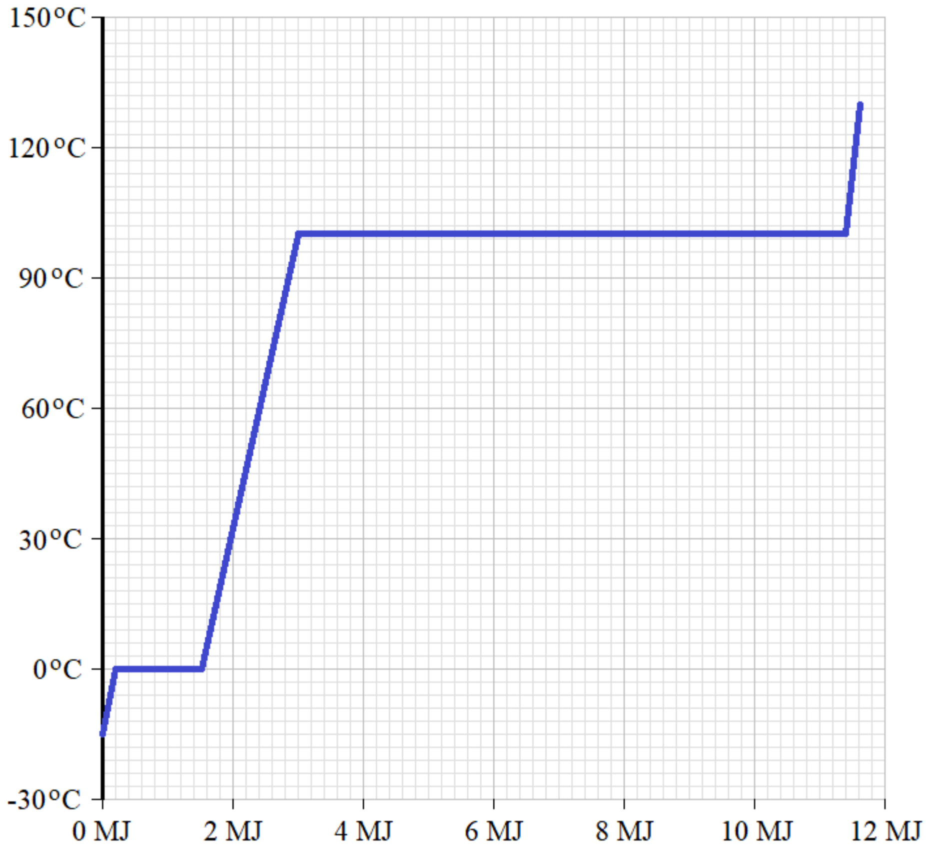
Water to steam at 100°C: $Q_4 = mL_V = \left(2230 \frac{\mathrm{J}}{\mathrm{g}}\right)(3780\,g) = 8{,}429{,}400\,J$

Steam from 100°C to 130°C: $Q_5 = cm\Delta T = \left(1996 \frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right)(3.78\,kg)(30°\mathrm{C}) = 226{,}346.4\,J$

$$Q_{Tot} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$$

$$Q_{Tot} = 119{,}523.6\,J + 1{,}262{,}520\,J + 1{,}582{,}686\,J + 8{,}429{,}400\,J + 226{,}346.4\,J$$

$$Q_{Tot} = 11.6\,MJ$$

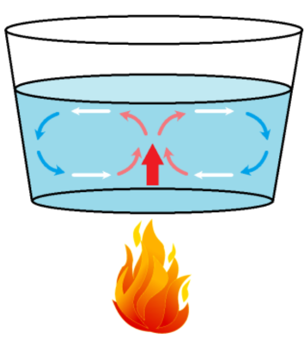


As heat is added the temperature of the ice rises until it hits 0°C.
Once the ice hits 0°C (the melting point of ice) additional energy only changes the state.
Once it has been converted to a liquid (water) the temperature rises with added heat.
At 100°C (the boiling point), additional energy changes the state into a gas (steam).
Once the water has all been vaporized, additional heat can once again raise the temperature.

Heat Transfer

- There are 3 methods in which heat is transferred: convection, conduction, and radiation.
- In **Convection**, heat is transferred by the bulk movement of a gas or liquid.

For example, the hot air coming out of a blow dryer carries heat with it.



Water expands as it is heated, becoming less dense. This causes it to rise to the surface.

The rising water pushes warmer water from the center to the outsides, cooling as it moves.

Cooler water on the outer edges falls replacing the water that has risen in the center.

The flow of liquid or gas responsible for transporting heat is called a **Convection Current**.

- In **Conduction**, heat is transferred directly through a material without bulk movement of that material.

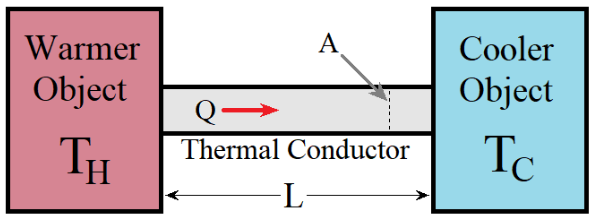
For example, if you were to grab the handle of a hot iron skillet, heat would flow through the metal and into your hand.

  - **Thermal Conductors** readily transport heat.

Iron skillets are thermal conductors.

  - **Thermal insulators** transport heat poorly.

Oven mitts are thermal insulators.



$$Q = \left(\frac{kA\Delta T}{L}\right)t \qquad P = \frac{Q}{t} = \frac{kA\Delta T}{L}$$

Q is the heat transferred.

k is the thermal conductivity of the conducting material.

A is the cross-sectional area of the conducting material (the area through which heat can flow).

ΔT is the temperature difference between the ends. $\Delta T = T_H - T_C$

L is the length of the thermal conductor (how far the heat must travel).

t is the time interval.

P is the conductive power.

Example: The temperature of an oven is 375°F when baking bread. The temperature of the kitchen outside the oven door is 78.0°F. The surface of the oven door is 0.300 m^2 and is coated with a 2.00 mm thick calcium silicate insulator with a thermal conductivity of 0.0500 J/(s·m·°C). (A) How much energy is used to operate the pre-heated oven for 5.00 hours if losses through the other surfaces are negligible compared to losses through the door, and (B) How much does this cost at 12¢ per kilo-Watt-hour for energy?

$$\Delta T = T_H - T_C = 375°\text{F} - 78.0°\text{F} = 297°\text{F} \qquad \Delta T(°\text{C}) = \frac{5}{9}\Delta T(°\text{F}) = \frac{5}{9}(297°\text{F}) = 165°\text{C}$$

$$5.00\ hours\left(\frac{3600\ s}{1\ hour}\right) = 18000\ s$$

$$Q = \left(\frac{kA\Delta T}{L}\right)t = \left(\frac{\left(0.0500\ \frac{J}{s\cdot m\cdot °\text{C}}\right)(0.300\ \text{m}^2)(165°\text{C})}{2.00\times 10^{-3}\ m}\right)(18000\ s) = 2.2275\times 10^7\ J$$

$$2.2275\times 10^7\ J\left(\frac{\$\ 0.12}{1\ kW\cdot hr}\right)\left(\frac{1\ kW\cdot hr}{3.60\times 10^6\ J}\right) = \$\ 0.7425$$

- In **Radiation**, heat is transferred by electromagnetic waves (typically in the infra-red range).
    - Objects appear black because they absorb most of the light and reflect little. Objects that readily absorb radiation are also good emitters.
    - A **Black Body** is an ideal emitter of radiation.
    - **Stefan-Boltzmann Law of Radiation** $Q = e\sigma T^4 A\mathrm{t}$ $P = \frac{Q}{t} = e\sigma T^4 A$
        - Q is the heat transferred.
        - e is the emissivity (0 to 1), a measure of how close the object is to an ideal black body (e = 1)
        - Stefan-Boltzmann constant (σ): $\sigma = 5.67 \times 10^{-8} \frac{J}{s \cdot m^2 \cdot K^4}$
        - T is the temperature in **Kelvin**.
        - A is the surface area of the object (the area emitting the EM waves).
        - t is the time interval.
        - P is the radiant power.

Example: Betelgeuse is a red supergiant star in the constellation Orion. It has a surface temperature of 3590 K and emits a radiant power of 4.64×10^{31} W. Determine the radius of Betelgeuse assuming it is approximately spherical and a perfect emitter (e = 1).

$$P = \frac{Q}{t} = e\sigma T^4 A = \sigma T^4 A = \sigma T^4 (4\pi r^2) = 4\pi\sigma T^4 r^2$$

$$r^2 = \frac{P}{4\pi\sigma T^4}$$

$$r = \sqrt{\frac{P}{4\pi\sigma T^4}} = \sqrt{\frac{4.64 \times 10^{31}\ \mathrm{W}}{4\pi \left(5.67 \times 10^{-8} \frac{J}{s \cdot m^2 \cdot K^4}\right) (3590\ \mathrm{K})^4}} = 6.26 \times 10^{11}\ m$$

For comparison, the average separation between the sun and Jupiter is 7.78×10^{11} m.