Chapters 17

- Temperature and heat

Michael Wong – PHY 1122 Spring 2023

Learning Goals

- **Thermal equilibrium** and thermometers.
- **Kelvin** temperature scale.
- **Thermal expansion**.
- Calculations for **heat flow**, temperature change, and phase change.
- **Heat transfer** mechanisms.

Introduction

- Does molten iron at a temperature of $1500°C$ contain heat? Energy?

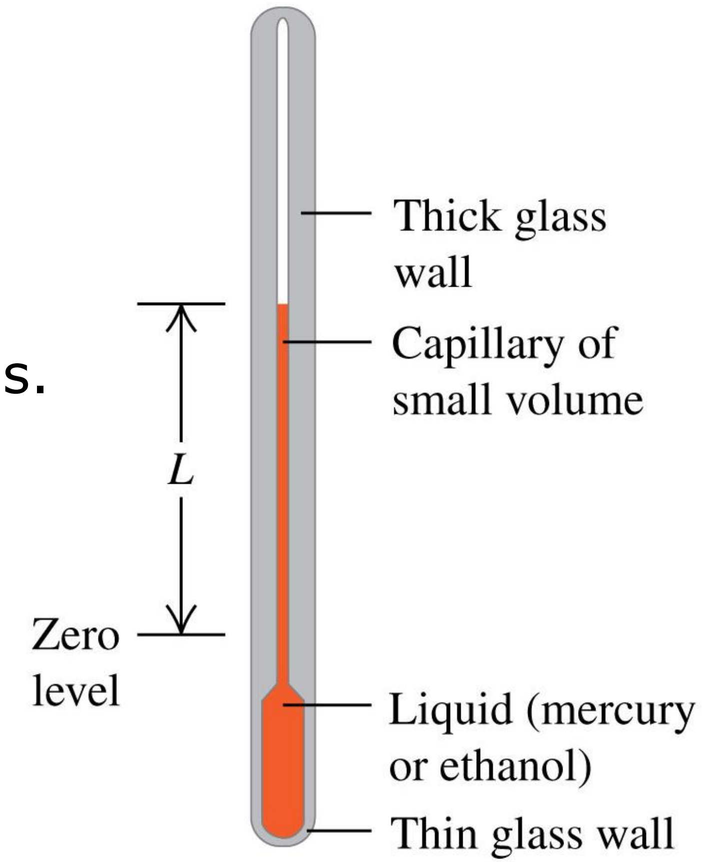
- Most people use heat and temperature interchangeable, we'll learn why we shouldn't.

- Ch. 17: Properties of matter on *macroscopic* scale
  - Ie. think about the thermodynamics of your body…

- Ch. 18 will introduce *microscopic* scale.

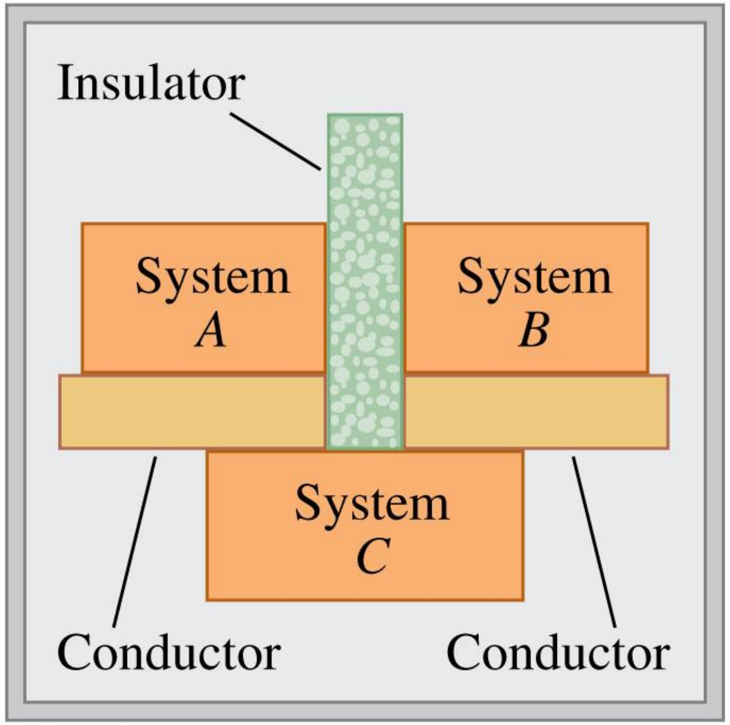
Temperature and thermal equilibrium

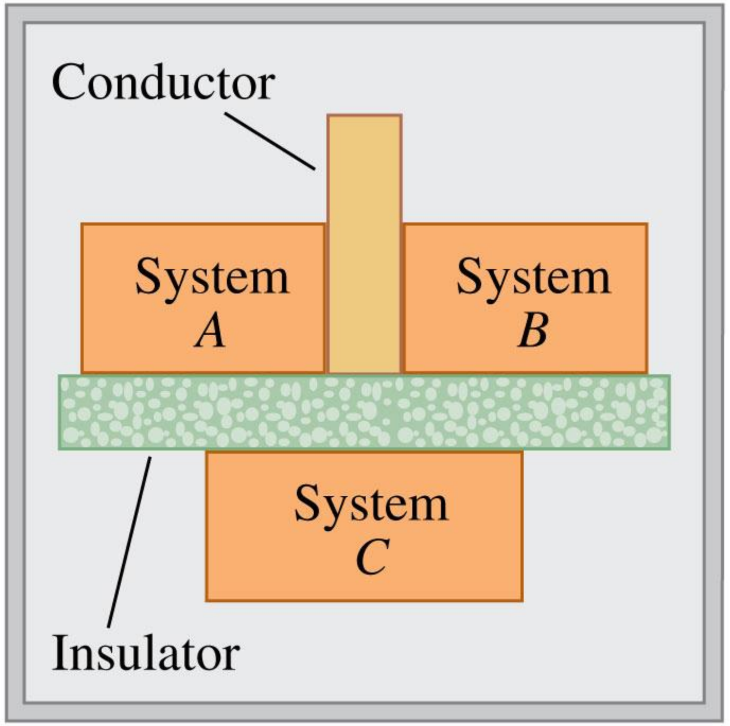
- A **thermometer** measures **temperature**. (yes it does!)
- Put thermometer in cup of coffee, eventually the temperature stabilizes. Thermometer in **thermal equilibrium** with the coffee.
- An **insulator** restricts the interaction between two systems.
- A **conductor** enables interaction.



Zeroth law of thermodynamics

- If system C is in thermal equilibrium with both A and B, then A and B are in thermal equilibrium with each other.





Zeroth law of thermodynamics

- If system C is in thermal equilibrium with both A and B, then A and B are in thermal equilibrium with each other.

- This also means: Two systems are in thermal equilibrium if (and only if) they have the same temperature.

- A standard thermometer measures it's *own* temperature which is the *same* temperature as the coffee.
  - Not true for all thermometers (ie. infrared)…

Temperature scales

- On the **Celsius** (centigrade) temperature scale, $0°\mathrm{C}$ is the freezing point and $100°\mathrm{C}$ is the boiling point of water.
  - Colder than freezing is a negative number.

- On the **Fahrenheit** scale, $32°\mathrm{F}$ is freezing point and $212°\mathrm{F}$ is boiling point of water (used in USA, Bahamas, Belize…).

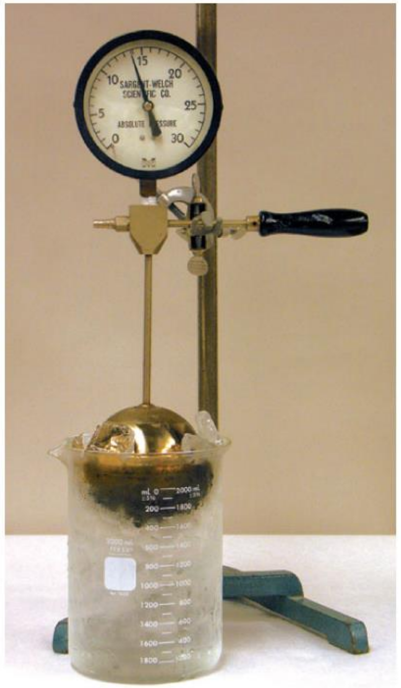
- To convert from $°\mathrm{C}$ to $°\mathrm{F}$ and back:

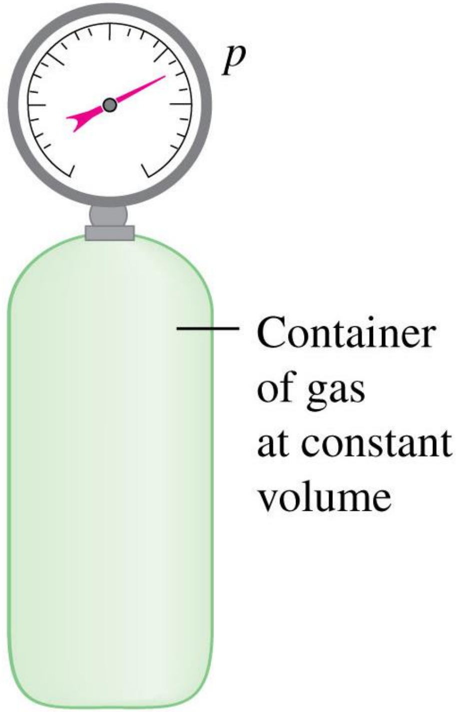
$$\boxed{T_\mathrm{F} = \frac{9}{5} T_\mathrm{C} + 32°}$$

$$\boxed{T_\mathrm{C} = \frac{5}{9} (T_\mathrm{F} - 32°)}$$

Gas-pressure thermometer

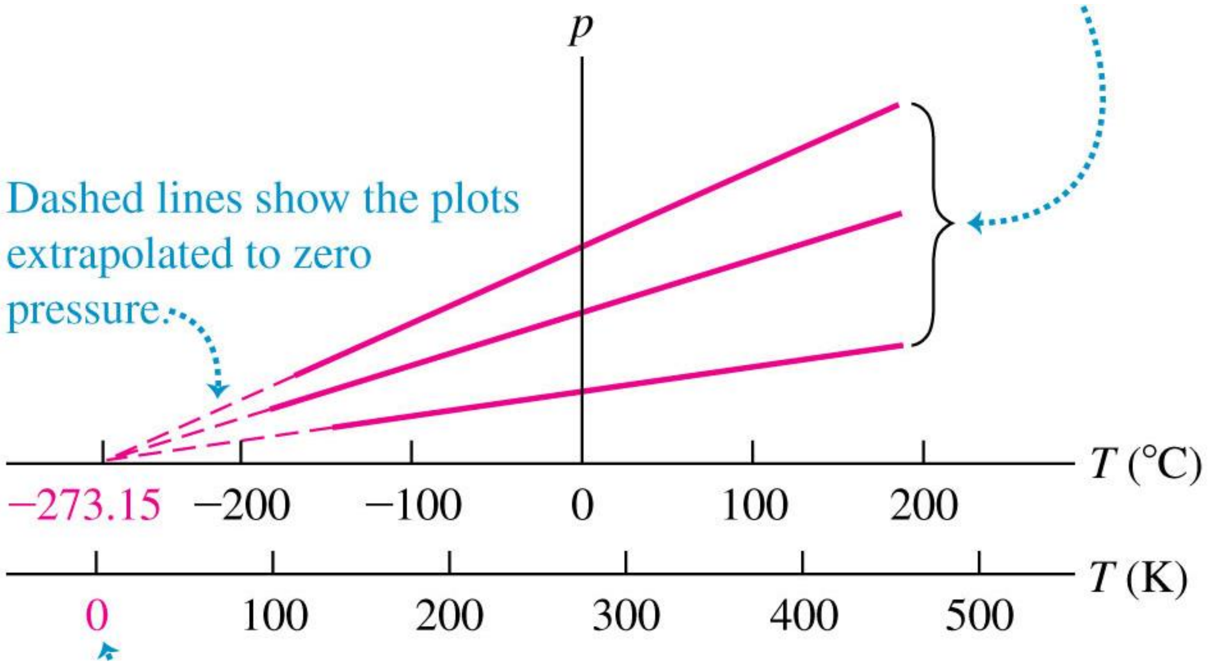
- The "constant volume gas-pressure thermometer" is close to ideal (we'll define ideal in Ch. 20).
- The pressure of a gas at constant volume increases linearly with temperature.
- To calibrate, measure P at $0°\text{C}$ and $100°\text{C}$ and draw a straight line between the points.





Absolute zero

- Different gases have different calibration "slopes".
- There exists a hypothetical temperature, $-273.15°\mathrm{C}$, where the pressure of most gases would be zero – **absolute zero**.

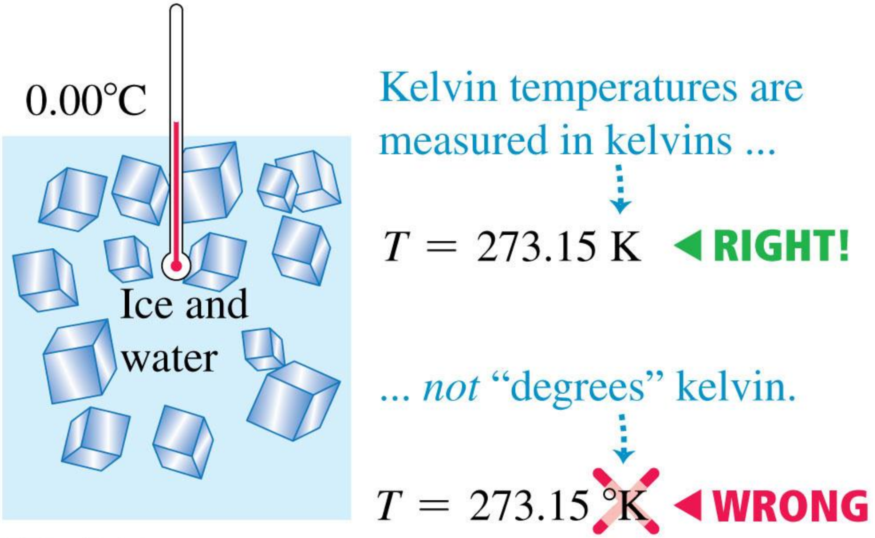


Kelvin temperature scale

- On the **Kelvin** temperature scale, the extrapolated zero-pressure temperature is $0\ \mathrm{K}$.

- "Size" of units if the same as ℃:

$$\boxed{T_{\mathrm{K}} = T_{\mathrm{C}} + 273.15}$$



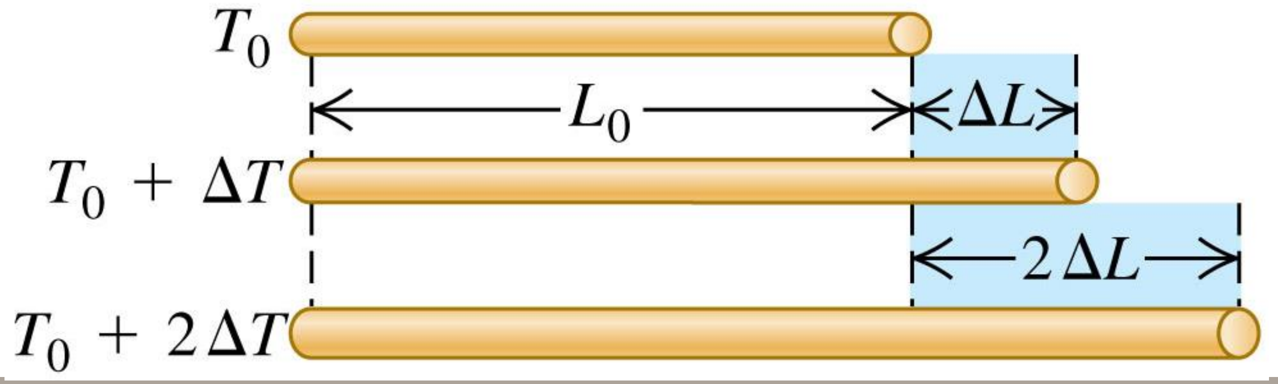
Linear thermal expansion

- Most materials **expand** when their **temperature increases**.
  - Eg. It's how a liquid-in-tube thermometer works.

- Consider expansion in one dimension for a solid rod.
  - For "moderate" temp. changes ($\sim 100℃$), $\Delta L \propto \Delta T$

$$\boxed{\Delta L = \alpha L_0 \Delta T}$$

  - α is the **coefficient of linear expansion** (units $1/℃$ or 1/K)



Linear thermal expansion

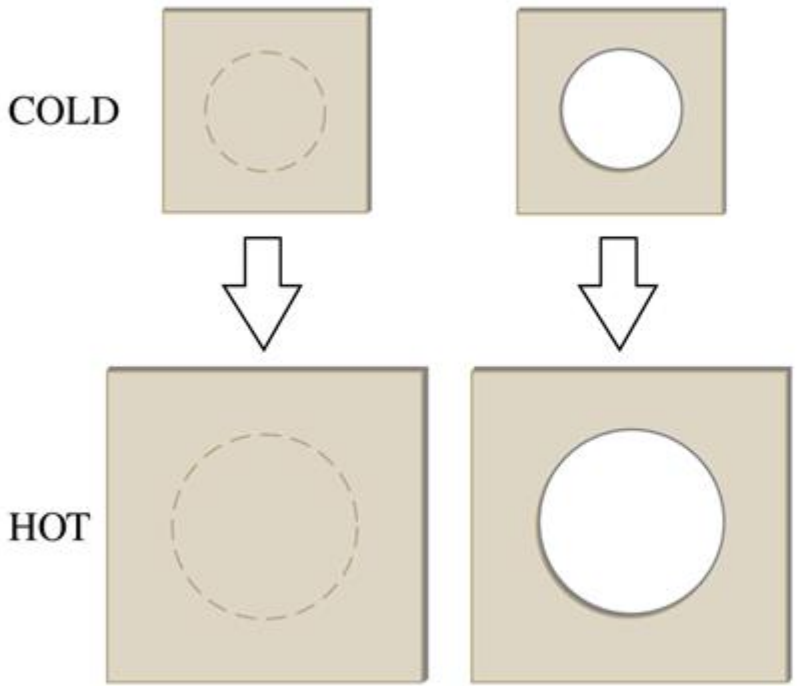
- From $\Delta L = \alpha L_0 \Delta T$ we get equation for new length:

$$L - L_0 = \alpha L_0 \Delta T$$
$$\boxed{L = L_0(1 + \alpha \Delta T)}$$

- Can be used to describe thermal expansion in any linear dimension.
  - Length of rod
  - thickness of rod
  - side length of a sheet
  - Even size of a hole →

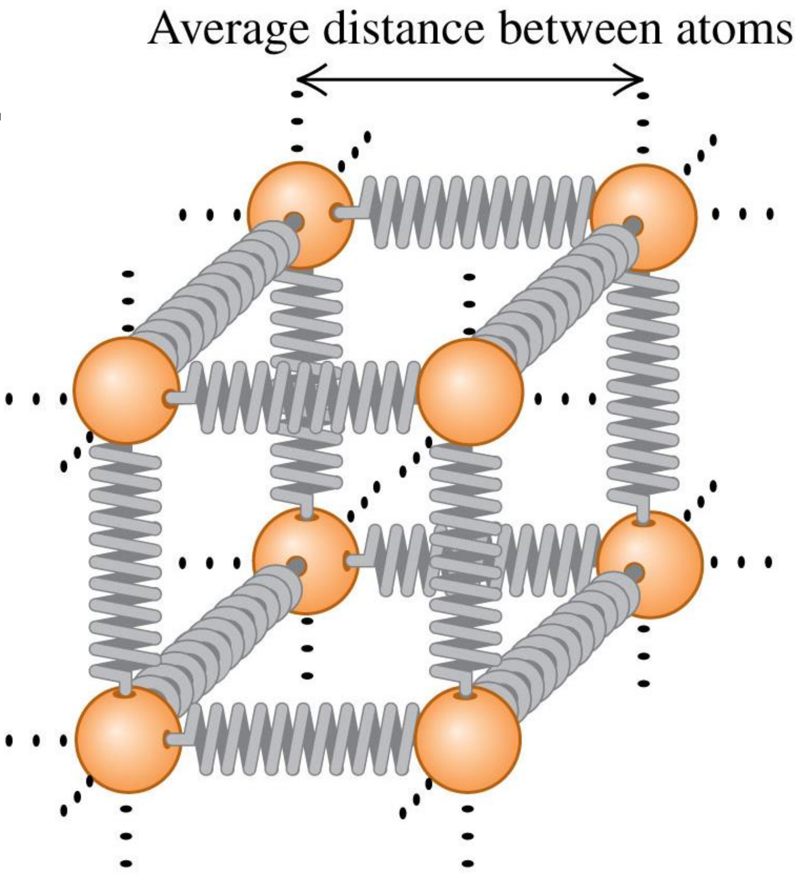
- Typical α only $\sim$1-2 $\times 10^{-5}$ $(°\mathrm{C})^{-1}$

Recall:
$$R = R_0(1 + \alpha \Delta T)$$



Molecular basis for expansion

- We model atoms in a solid to be held together by springs.
- As T increases, energy and vibration of atoms increase.
  - Average distance between atoms increases
- Atoms are farther apart, every dimension increases.



Volume expansion

- For solids, extend linear expansion to volume expansion. Works for liquids too.

$$\boxed{\Delta V = \beta V_0 \Delta T}$$

where β is **coefficient of volume expansion**.

- Same units: $1/°\mathrm{C}$ or $1/\mathrm{K}$
- Relationship:

$$\boxed{\beta = 3\alpha}$$

- Example: train tracks

Derivation of volume expansion coeff.

- Consider 3D object with volume $V_i = LWH$.
  - For a temperature change of ΔT, we get:

$$V_i + \Delta V = (L + \Delta L)(W + \Delta W)(H + \Delta H)$$
$$= (L + \alpha L \Delta T)(W + \alpha \mathrm{W} \Delta T)(H + \alpha \mathrm{H} \Delta T)$$
$$= LWH(1 + \alpha \Delta T)^3$$
$$= V_i(1 + 3\alpha\Delta T + 3\cancel{(\alpha\Delta T)^2} + \cancel{(\alpha\Delta T)^3})$$

  - Terms are cancelled because they are $\ll 1$.

$$V_i + \Delta V = V_i + 3\alpha V_i \Delta T$$
$$\Delta V = 3\alpha V_i \Delta T = \beta V_i \Delta T$$
$$\boxed{\beta = 3\alpha}$$

Ex. 17.3 – Volume change

- A glass flask with volume $V = 200\ \mathrm{cm}^3$ is filled to the brim with mercury at $20.0°\mathrm{C}$. How much mercury overflows when the temperature of the system is raised to $100.0°\mathrm{C}$?

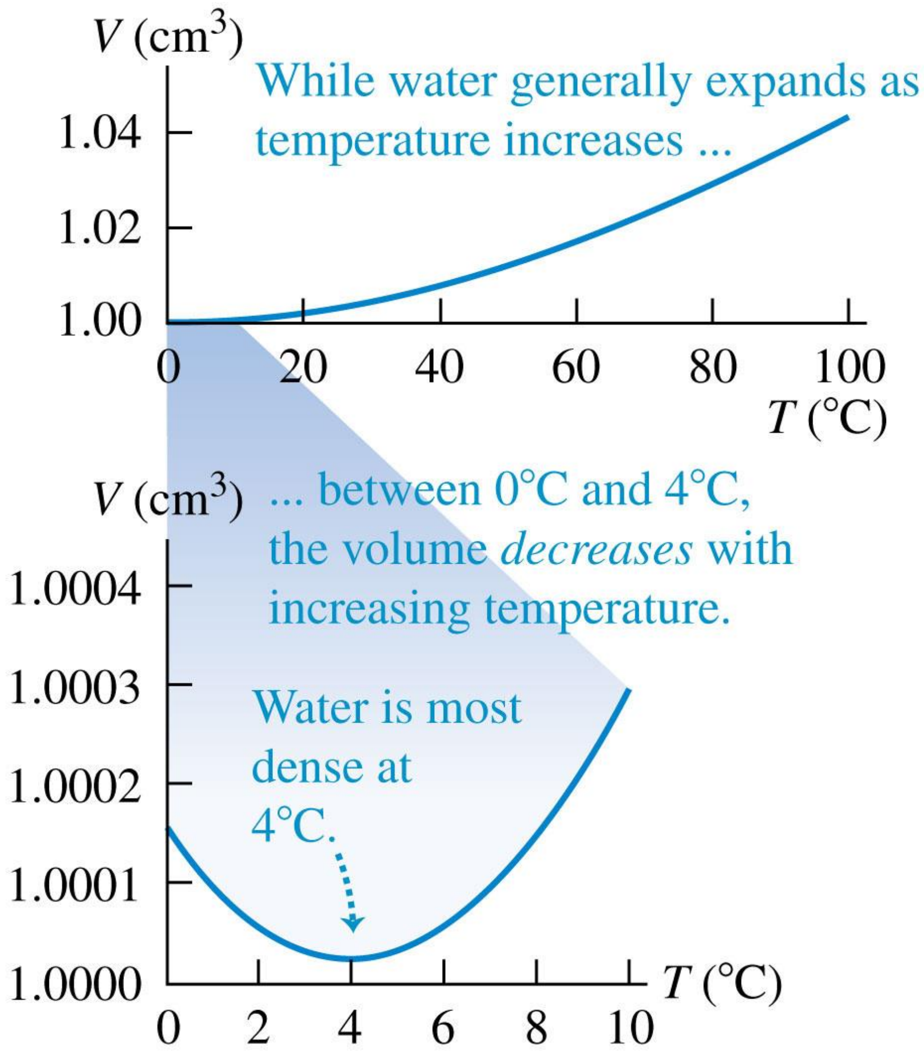
Simple conversion: $1\ \mathrm{cm}^3 = 1\ \mathrm{mL}$

- $\alpha_{glass} = 0.40 \times 10^{-5}\ \mathrm{K}^{-1}$
- $\beta_{Hg} = 18 \times 10^{-5}\ \mathrm{K}^{-1}$
  - Mercury will expand more since $\beta_{Hg} > 3\alpha_{glass}$

Thermal expansion of water

- Between $0°\text{C}$ to $4°\text{C}$, water decreases in volume.
  - β_{H2O} is negative
- Above $4°\text{C}$ volume increases.

- This is why lakes freeze from top-down instead of bottom-up.

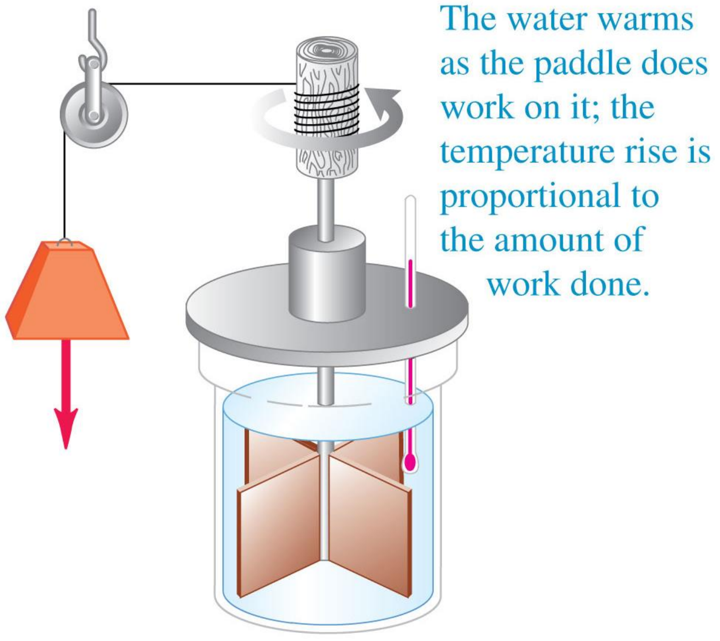


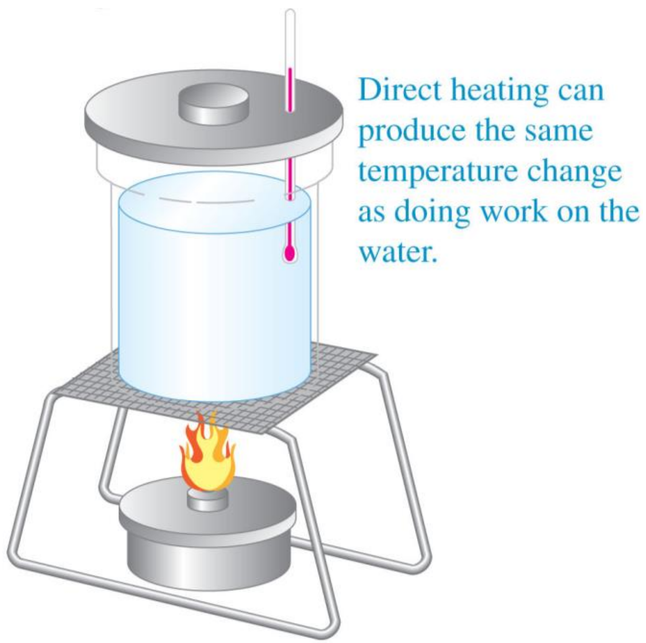
Temperature vs. heat

- **Temperature** depends on state of a material and measures *hotness* or *coolness*.
- **Heat** refers to movement of energy from one body to another because of a temperature difference.
- We change the temperature of a body by “adding heat” or “taking away heat”.

Quantity of heat

- We can increase temperature of a system by:
  - (a) doing work on it (paddle wheel stirring water).
  - (b) adding heat to it (flame in contact with container).





Quantity of heat

- We define a *unit* of quantity of heat: amount of heat needed to change temperature of a material.

- The **calorie** (cal) is amount of heat required to raise the temp of 1 g of water from $14.5°\mathrm{C}$ to $15.5°\mathrm{C}$.
  – (food "calorie" or "Calorie" is actually 1 kcal = 1000 cal)

- The **British thermal unit** (Btu) is amount of heat to raise the temp of 1 pound of water from $63°\mathrm{F}$ to $64°\mathrm{F}$.

- In terms of **joules** (SI unit)
  1 cal = 4.186 J
  1 Btu = 1055 J

Specific heat or heat capacity

- The quantity of heat (Q) needed to increase the temperature of a mass m of a certain material by ΔT is given by:

$$\boxed{Q = mc\,\Delta T}$$

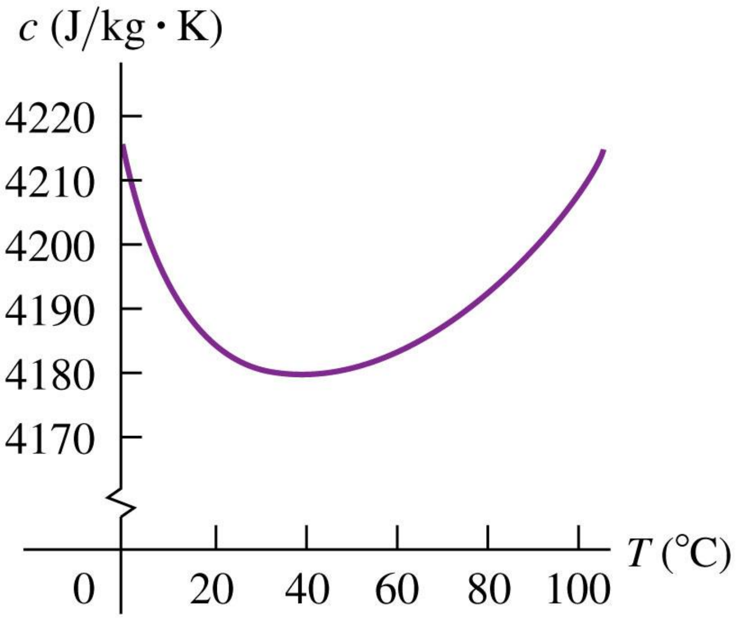
  where c is the **specific heat** (or **heat capacity**) of the material:

$$\boxed{c = \frac{1}{m}\frac{dQ}{dT}}$$

- For water (approximately),

$$c_{H2O} = 4190\,\frac{\mathrm{J}}{\mathrm{kg{\cdot}K}}$$

  (or $c_{H2O} = 1\,\frac{\mathrm{cal}}{\mathrm{g{\cdot}°C}}$ or $c_{H2O} = 1\,\frac{\mathrm{Btu}}{\mathrm{lb{\cdot}°F}}$)



Ex. 17.5 – "Feed a cold, starve a fever" ??

- A man with mass $80\ \mathrm{kg}$ has the flu and has a fever of $39.0°\mathrm{C}$ (instead of normal body temperature $37.0°\mathrm{C}$).

  Assuming the human body is mostly water, how much heat is required to raise his temperature by that amount
  $(\Delta T = 2°\mathrm{C} = 2\ \mathrm{K})$?

- Use $Q = mc\,\Delta T \quad \rightarrow \quad \boxed{Q} = (80\ \mathrm{kg})\left(4190\,\frac{\mathrm{J}}{\mathrm{kg{\cdot}K}}\right)(2\ \mathrm{K}) = \boxed{6.7 \times 10^5\ \mathrm{J}}$

- (about 160 Calories = 4 chicken nuggets)

Molar heat capacity

- We can also describe heat quantity in terms of # of moles (instead of mass).
- M is the molar mass of a substance, n is number of moles:

$$m = nM$$

- Heat can now be expressed as:

$$\boxed{Q} = nMc\,\Delta T = \boxed{nC\,\Delta T}$$

where C (uppercase) is the **molar heat capacity** (or **molar specific heat**).

$$C = \frac{1}{n}\frac{dQ}{dT} = Mc$$

For water: $C = 75.4\,\frac{\mathrm{J}}{\mathrm{mol\cdot K}}$

Table 17.3 and "Rule of Dulong and Petit"

Substance	Specific Heat, c (J/kg · K)	Molar Mass, M (kg/mol)	Molar Heat Capacity, C (J/mol · K)
Aluminum	910	0.0270	24.6
Beryllium	1970	0.00901	17.7
Copper	390	0.0635	24.8
Ethanol	2428	0.0461	111.9
Ethylene glycol	2386	0.0620	148.0
Ice (near 0°C)	2100	0.0180	37.8
Iron	470	0.0559	26.3
Lead	130	0.207	26.9
Marble ($CaCO_3$)	879	0.100	87.9
Mercury	138	0.201	27.7
Salt (NaCl)	879	0.0585	51.4
Silver	234	0.108	25.3
Water (liquid)	4190	0.0180	75.4

Phase changes

- The **phases** (or states) of matter that exist: solid, liquid, and gas.
- A **phase change** is a transition from one phase to another.
- Temperature is constant during a phase change (see ice/water).
- The **latent heat** L (in $\mathrm{J/kg}$) is the heat per unit mass that is transferred in a phase change (note the $\pm$).

$$\boxed{Q = \pm mL}$$

Phase change for water

- To melt a mass m of ice at $0℃$ to liquid water at normal atmospheric pressure (101.3 kPa):
  - Equation for the **heat *added*** is: $\boxed{Q = +mL_f}$ where L_f is the **heat of fusion** L_f (for water).

- It refers to fusion (freezing) even though we are *melting*.

- This process is reversible. To freeze water into ice at $0℃$ we ***remove* heat**:

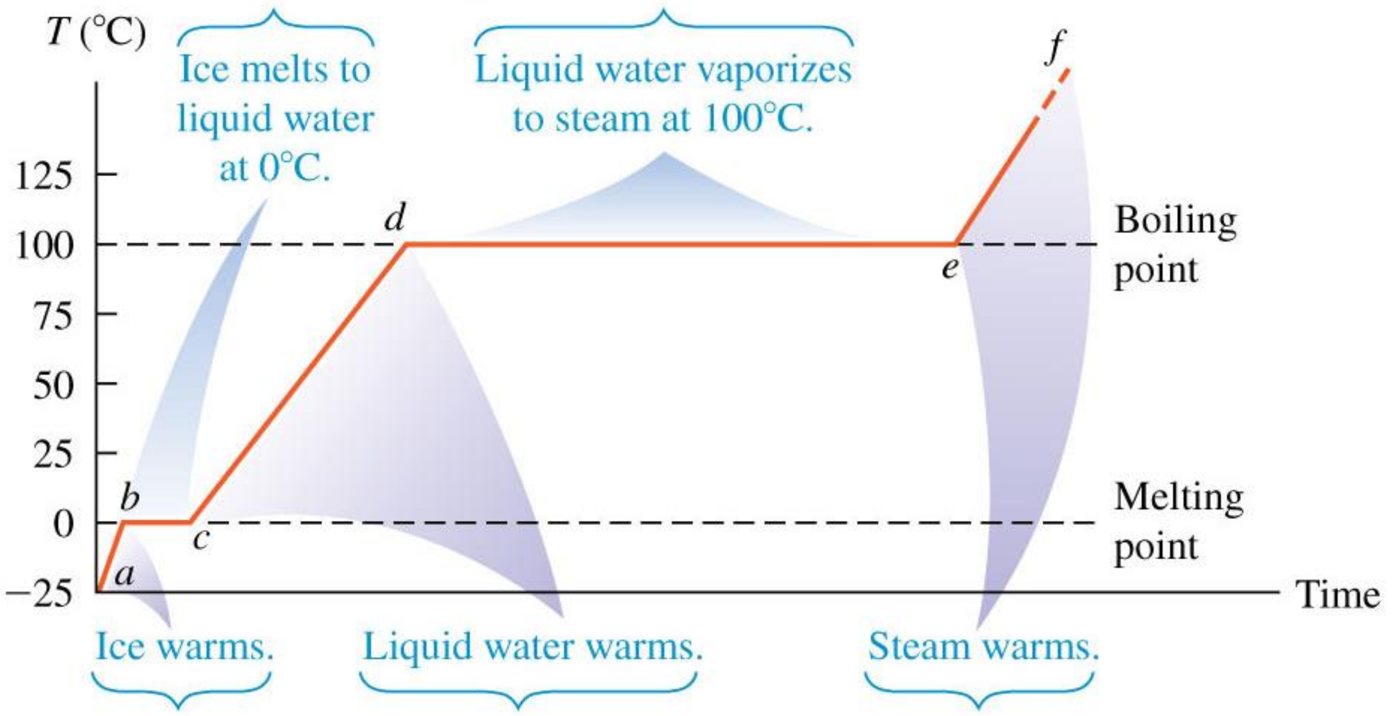
$$\boxed{Q = -mL_f}$$

- For 1 kg of ice it requires 3.34×10^5 J of heat to melt.

Phase change (cont.)

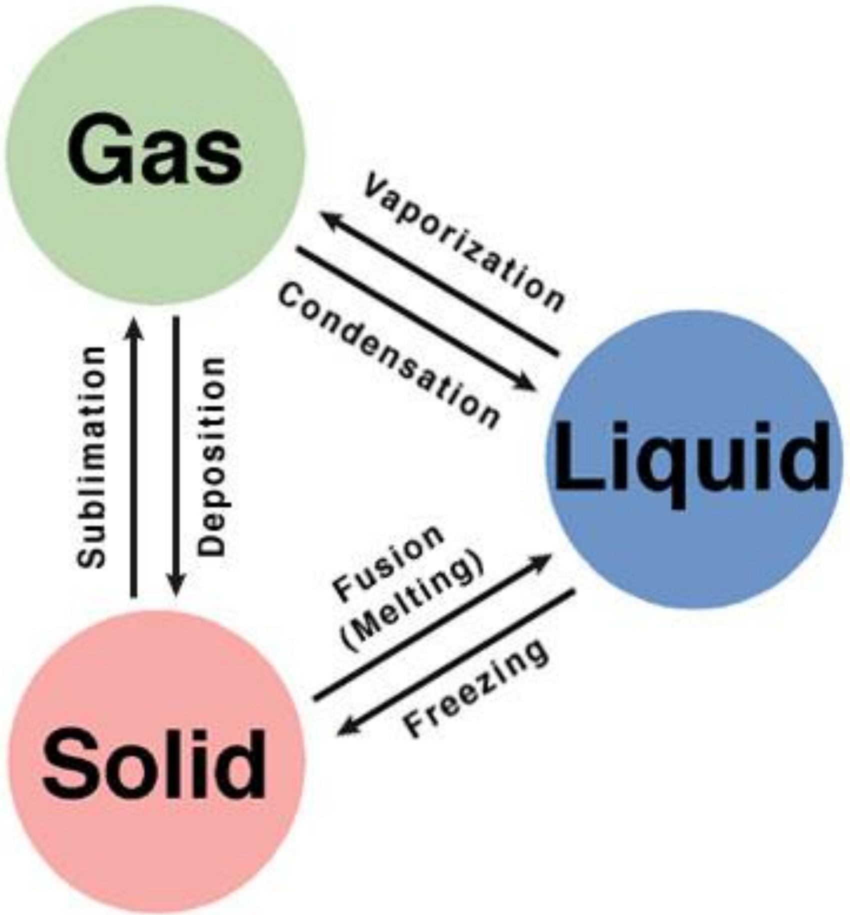
- For solid → liquid → solid (heat of fusion)
- For liquid → gas → liquid, **heat of vaporisation** L_v.

- For water:
  $L_v = 2.256 \times 10^6$ J/kg.



Sublimation

- Sometimes a substance can change state directly from solid to gas (no liquid state needed). This is called **sublimation**.
- The corresponding heat is called **heat of sublimation** L_s.
- Example, solid CO_2 (dry ice) at atmospheric pressure sublimes (not sublimates!). ($T \sim -80°\text{C}$).



Other definite quantities of latent heat

- When a compound undergoes combustion (burning) under standard conditions.
  - Eg. gasoline reacts with O_2 to form CO_2, H_2O, and heat.
  - The **heat of combustion** for gasoline is:

$$L_c = 4.6 \times 10^7 \text{ J/kg}$$

- *Also exists **heat of formation** which is the energy needed to form one mole of a substance from its elements but this is not covered in this course.

Heat calculations (Calorimetry)

- **Calorimetry** means to measure heat.

- Basic principle:
  When heat flow occurs between two bodies that are isolated from their surroundings, the amount of heat lost by one body must equal the amount of heat gained by the other. (basically just conservation of energy)

- 1) Identify 2) ΔT and/or phase change 3) Consult 4) List

  5) Execute: use your equations (with $\Sigma Q = 0$) and solve for the variables you want. Note: $\Delta T = t_{final} - t_{initial}$.

Ex. 17.8 – Changes in both T and phase

- A glass contains 0.25 kg of Omni-Cola (mostly water) initially at $25°\mathrm{C}$. How much ice, initially at $-20°\mathrm{C}$ must you add to obtain a final temperature of $0°\mathrm{C}$ with all ice melted? Ignore the heat capacity of the glass.

$$c_w = 4.19 \times 10^3\ \mathrm{J/kg \cdot K}$$
$$c_i = 2.1 \times 10^3\ \mathrm{J/kg \cdot K}$$
$$L_f = 3.34 \times 10^5\ \mathrm{J/kg}$$

Ex. 17.10 – Combustion, ΔT, and phase

- In a particular camp stove, only 30% of the energy released in burning gasoline goes to heating the water in a pot on the stove. How much gasoline must we burn to heat 1.00 L (1 kg) of water from $20°\mathrm{C}$ to $100°\mathrm{C}$ and boil away 0.25 kg of it?

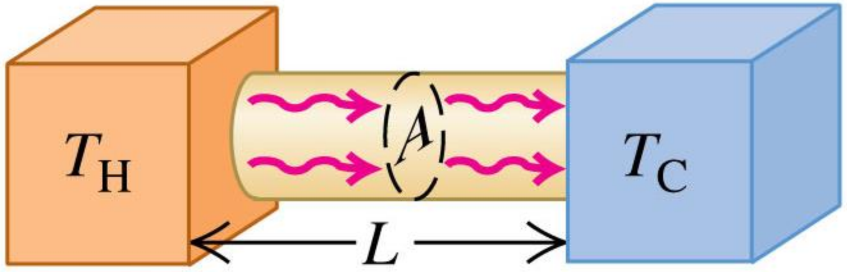
$$L_v = 2.256 \times 10^6\ \mathrm{J/kg}$$
$$L_c = 4.6 \times 10^7\ \mathrm{J/kg}$$

Mechanisms of heat transfer

- **Heat transfer** is the flow of energy from higher T objects to lower T objects.
  - Three mechanisms: **conduction, convection, radiation**
- Conduction: contact between two bodies
- Convection: motion of mass from a region in space to another
- Radiation: heat transfer by electromagnetic radiation

Conduction of heat

- Heat flows from a high T to low T through contact.
  - Eg. metal handles of a metal pot.



- Consider solid rod, length L, cross-sectional area A.

- Left end touching temperature T_H and right end touching T_C.

- The rate of heat transfer (**heat current** in W) is:

$$\boxed{H} = \frac{dQ}{dt} = \boxed{kA\frac{T_H - T_C}{L}}$$

k is **thermal conductivity**, $\frac{T_H - T_C}{L}$ is **temperature gradient**.

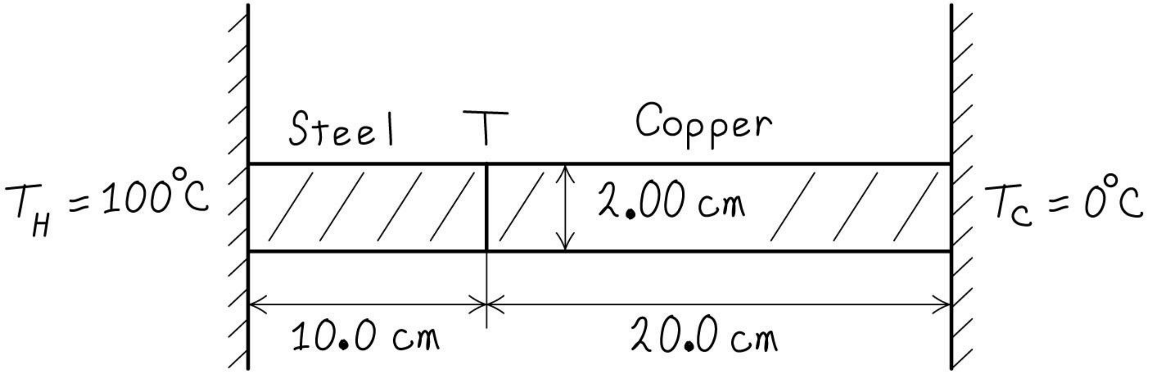
Heat conduction problem solving

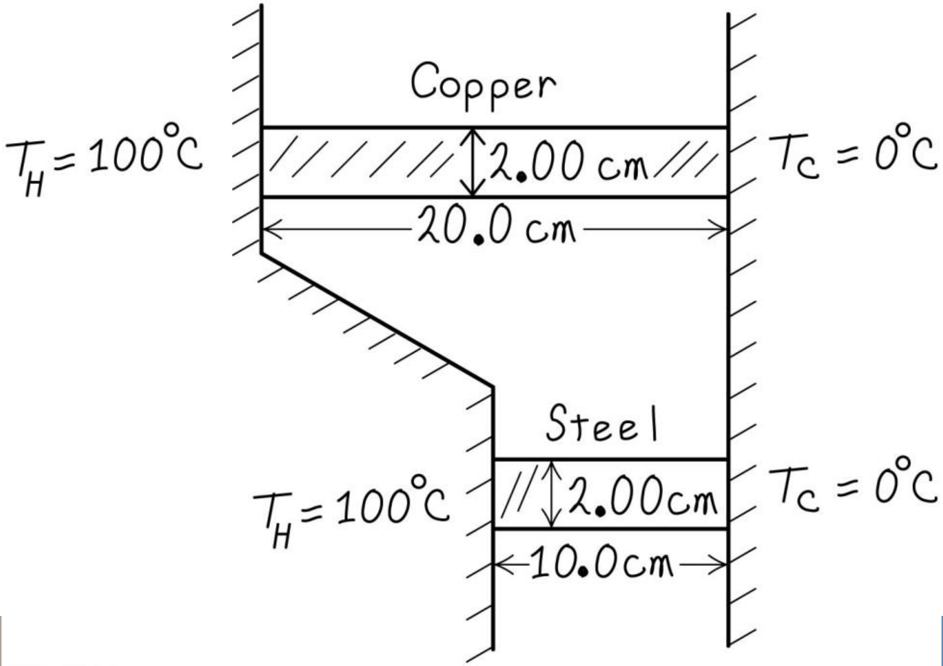
- Identify direction of heat flow (hot to cold) and list known quantities and variables.
- Does heat flow through a single object? $H = kA\frac{T_H - T_C}{L}$, as long as T doesn't change.
- If heat flows through two different *connected* materials (in *series*):
  - The temperature at the interface is T and ΔT for the materials is $(T_H - T)$ and $(T - T_C)$.
  - The same heat passes through both materials (H is the same in both materials).
- If heat flows through two or more *parallel* paths:
  - Total heat current is sum of currents $H = H_1 + H_2 + \cdots$, etc…

Ex. 17.12 and 17.13

- One steel bar and one copper bar are used for heat conduction (either end to end or separately). Bars have square cross-sectional areas. Bars are perfectly insulated on their sides.

- 17.12 – Find steady-state T at junction and rate of heat flow.
- 17.13 – Find **total** heat current in the two bars.

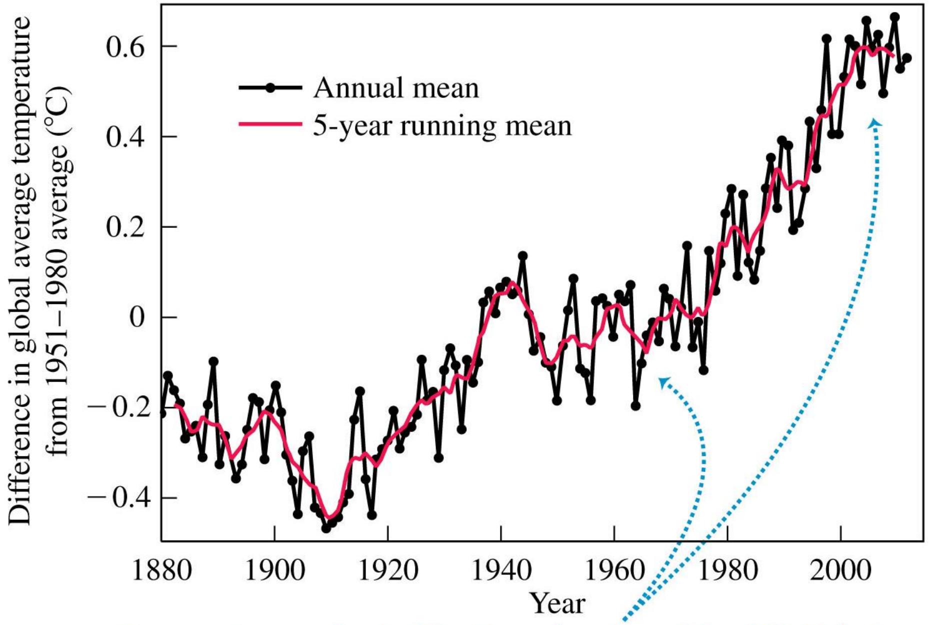




Convection and radiation*

- Convection: heat is transferred by mass motion of fluid from one region of space to another region.
  - Eg. hot-air or hot-water heating in homes/apartments.
  - No simple equation to describe convection.

- Radiation: transfer of heat by light (electromagnetic radiation)
  - Warm rays from sun, intense heat from fire.
  - *Everything* radiates, even cold things.
  - Applications include baby incubator, Thermos bottles, greenhouse effects (global warming).



Increased atmospheric CO_2 due to burning of fossil fuels is the cause of this continuing increase in global average temperatures.