This week in the physics course

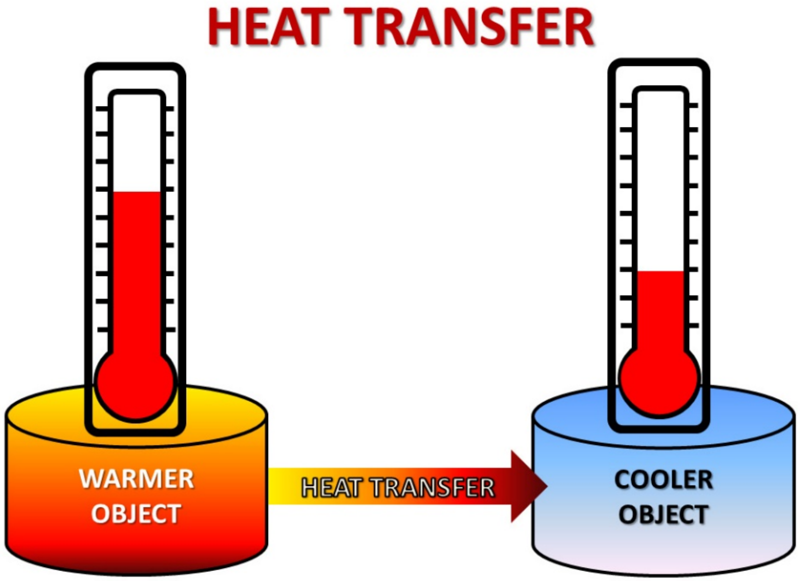
- **Lectures** will cover *Chapter 16 (Temperature and Heat)* and start *Chapter 17 (Thermal Behaviour of Matter)*
- **Tutorial class** will practise problems from last week's lectures on *Chapter 15 (Fluid Motion)*
- **Laboratory class** will perform buoyancy experiments
- Physics help available in **MASH centre** (Wayne Rowlands, Tuesday 10.30-12.30 and Thursday 2.30-4.30)
- Don't hesitate to get in touch with any questions – cblake@swin.edu.au

Chapter 16 : Temperature and Heat

- Difference in **temperature** causes **heat energy** to flow
- Measuring temperature with **thermometers**
- **Heat capacity** of a material determines temperature rise
- Heat transfer by **conduction**, **convection** and **radiation**

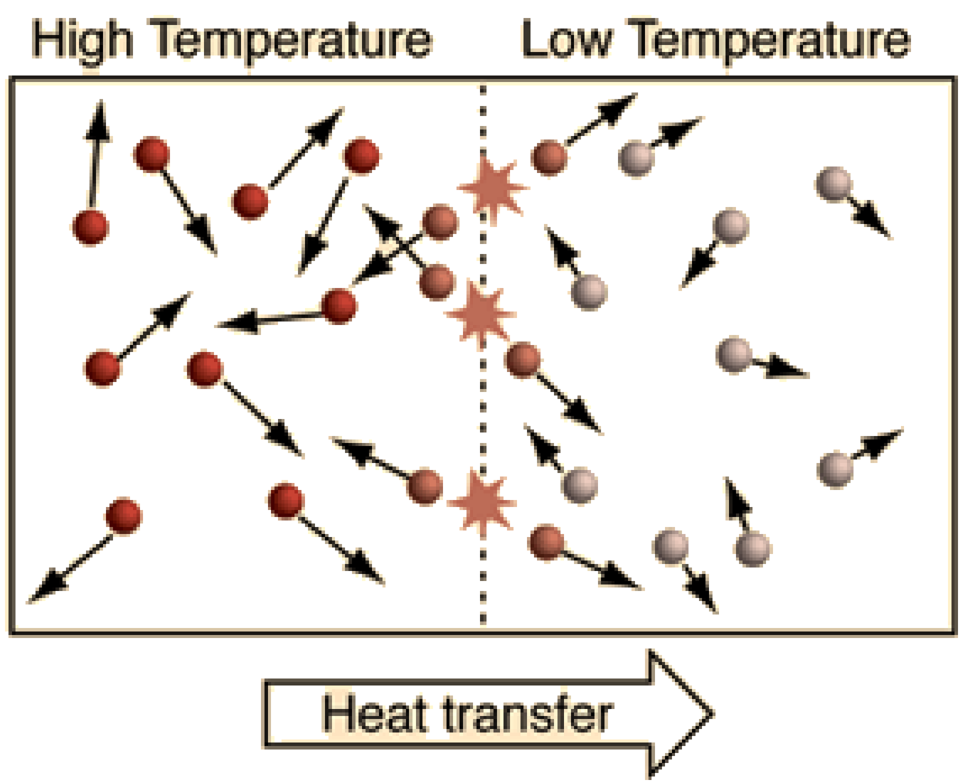
Temperature and Heat Energy

- A temperature difference causes heat energy to flow to bring systems into equilibrium



Temperature and Heat Energy

- Temperature is associated with the internal molecular energy of a substance

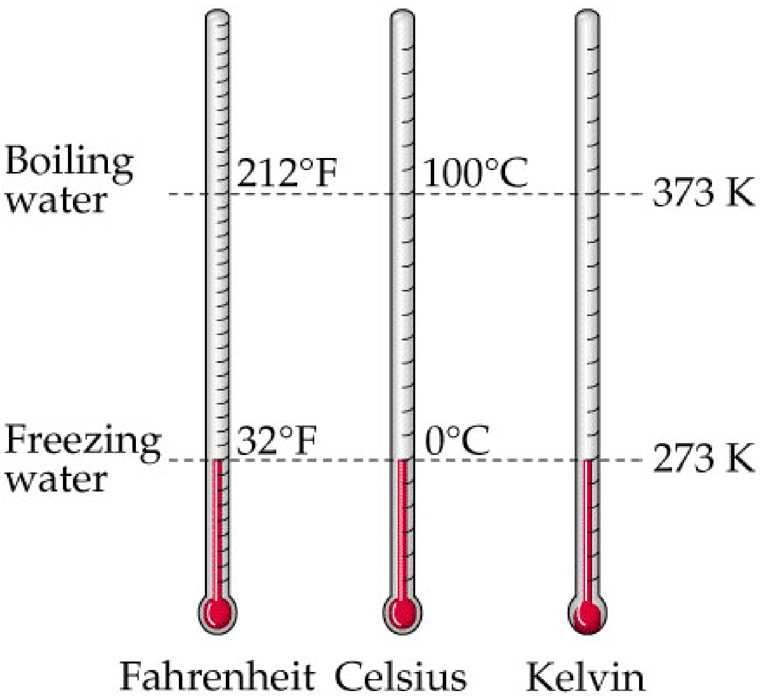


Units of temperature

- Absolute temperature is measured in units of **Kelvin** (K) where 0 K is **absolute zero** (at which a gas has zero pressure)

Units of temperature

- Absolute temperature is measured in units of **Kelvin** (K) where 0 K is **absolute zero** (at which a gas has zero pressure)
- The **Celsius** temperature scale is offset such that the **melting point of ice** at standard atmospheric pressure is 0 ^oC



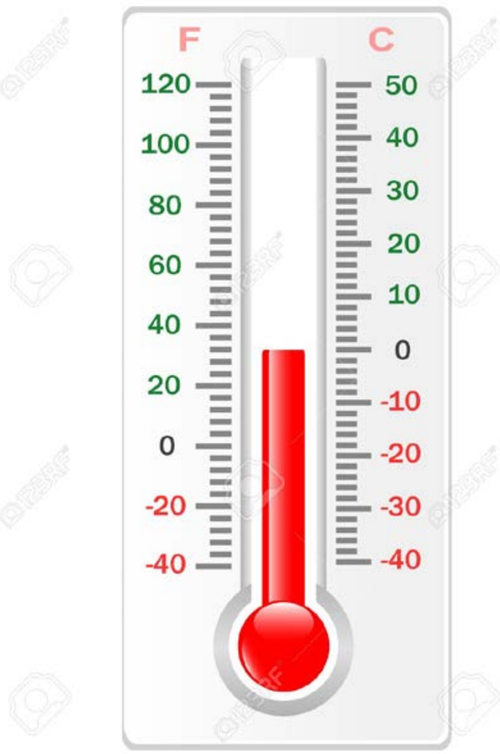
$$T_{Celsius} = T_{Kelvin} - 273.15$$

1 degree change in Celsius =
1 degree change in Kelvin

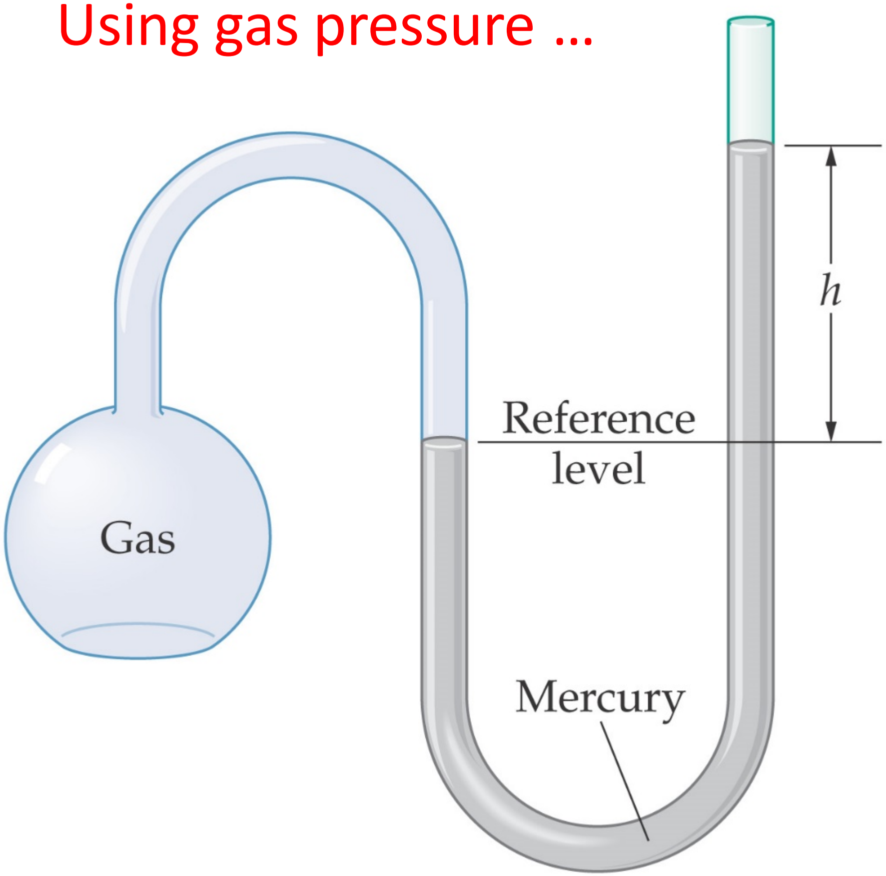
Units of temperature

- Temperature is measured by **thermometers** which are brought into thermal equilibrium with the system

Using expansion …



Using gas pressure …



Heat Capacity and Specific Heat

- When heat energy flows into a substance, its temperature will increase

- The **specific heat capacity** is the heat energy (in J) needed to raise the temperature of 1 kg of the substance by 1 K

$$Q = m\,c\,\Delta T$$

- Q: Heat energy in J
- m: Mass in kg
- c: Specific heat capacity in J/K/kg
- ΔT: Temperature change in K

Heat Capacity and Specific Heat

- Values given in Table 16.1 of the textbook (page 306 of 3rd ed.)

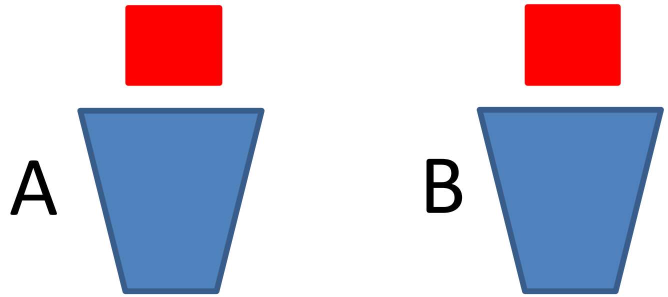
Substance	Specific Heat, c: SI Units: J/kg•K	Specific Heat, c: cal/g•°C, kcal/kg•°C, or Btu/lb•°F
Aluminum	900	0.215
Concrete	880	0.24
Copper	386	0.0923
Iron	447	0.107
Glass	753	0.18
Mercury	140	0.033
Steel	502	0.12
Stone (granite)	840	0.20
Water:		
Liquid	4184	1.00
Ice, −10°C	2050	0.49
Wood	1400	0.33

*Temperature range 0°C to 100°C except as noted.

Specific heat capacity determines the heat energy needed to raise the temperature:

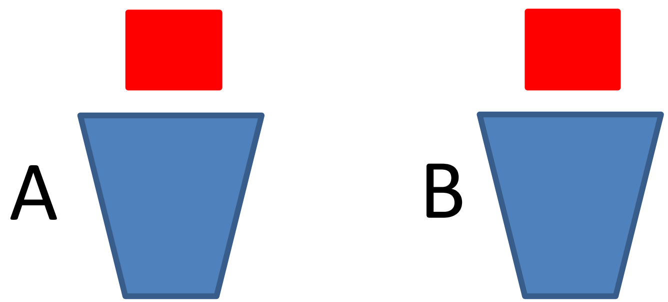
$$Q = mc\Delta T$$

Two identical mass metals at 95°C are placed in separate identical beakers of water at 25°C. You measure the temperature of the water after each metal has cooled by 10°C and find that the water in A is hotter than the water in B. Which metal has the higher specific heat ?



1. Metal A
2. Metal B
3. They are the same
4. Can't tell since not in equilibrium

Two identical mass metals at 95°C are placed in separate identical beakers of water at 25°C. You measure the temperature of the water after each metal has cooled by 10°C and find that the water in A is hotter than the water in B. Which metal has the higher specific heat ?



Heat energy lost by metal = heat energy gained by water

$$Metal\ A: m_{metal}\, c_A\, \Delta T_{metal} = m_{water}\, c_{water}\, \Delta T_A$$

$$Metal\ B: m_{metal}\, c_B\, \Delta T_{metal} = m_{water}\, c_{water}\, \Delta T_B$$

$$\Delta T_A > \Delta T_B \rightarrow c_A > c_B$$

Heat Capacity and Specific Heat

(a) How much heat does it take to bring a 3.5 kg iron frypan from 20℃ to 120℃ ? (b) If a $2kW$ stovetop heats the pan, how long will this take? ($c_{iron} = 447\ J\ kg^{-1}K^{-1}$)

(a) $Q = m\ c\ \Delta T$

$m = 3.5\ kg$

$c = 447\ J\ kg^{-1}K^{-1}$

$\Delta T = 100\ K$

$Q = 3.5 \times 447 \times 100 = 0.16\ MJ$

(b) $Power = Energy/Time$

$Time = Energy/Power$

$Energy = 0.16\ MJ = 1.6 \times 10^5\ J$

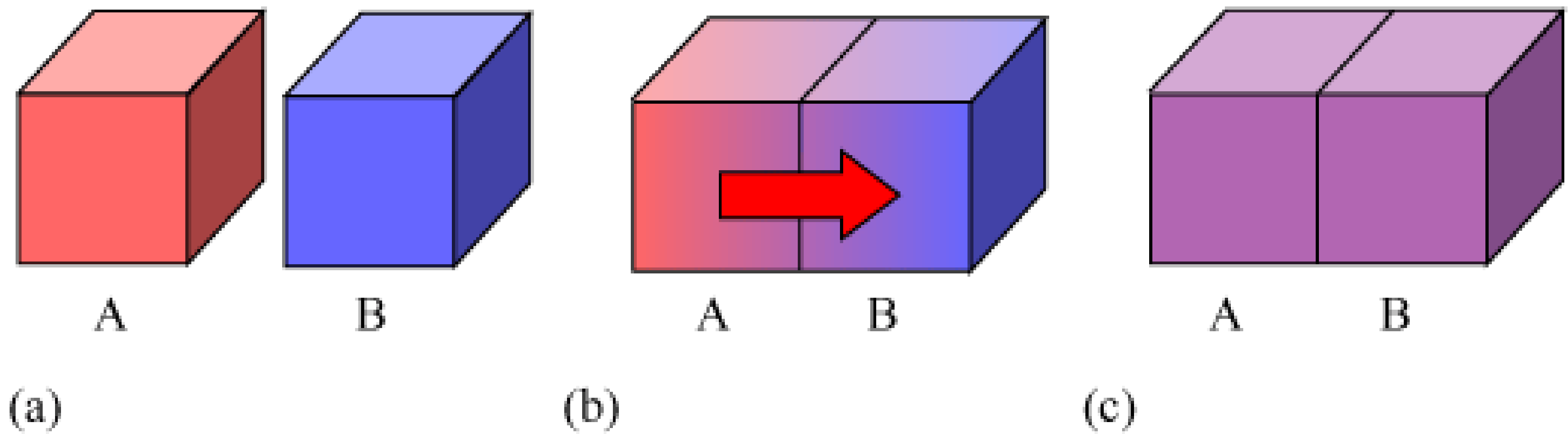
$Power = 2\ kW = 2 \times 10^3 W$

$$t = \frac{1.6 \times 10^5}{2 \times 10^3} = 78\ s$$

Specific heat capacity determines the heat energy needed to raise the temperature:

$$\boldsymbol{Q = mc\Delta T}$$

(c) The same $3.5\ kg$ iron frypan at 120°C is plunged into a sink filled with $2\ litres$ of water at 20°C. What is the equilibrium temperature? ($c_{iron} = 447\ J\ kg^{-1}K^{-1}$, $c_{water} = 4184\ J\ kg^{-1}K^{-1}$)



- Heat energy flows until equilibrium is reached
- Heat energy lost by frypan = Heat energy gained by water
- Total heat energy change = 0 **(conservation of energy)**

(c) The same 3.5 kg iron frypan at 120°C is plunged into a sink filled with 2 $litres$ of water at 20°C. What is the equilibrium temperature? ($c_{iron} = 447\ J\ kg^{-1}K^{-1}$, $c_{water} = 4184\ J\ kg^{-1}K^{-1}$)

$$Q = mc\Delta T = mc\left(T_f - T_i\right) \quad and \quad \sum Q = 0$$

$$m_1c_1\left(T_{eq} - T_1\right) + m_2c_2\left(T_{eq} - T_2\right) = 0$$

$$T_{eq}(m_1c_1 + m_2c_2) = m_1c_1T_1 + m_2c_2T_2$$

$$T_{eq} = \frac{m_1c_1T_1 + m_2c_2T_2}{m_1c_1 + m_2c_2}$$

$$T_{eq} = \frac{3.5 \times 447 \times 393 + 2 \times 4184 \times 293}{3.5 \times 447 + 2 \times 4184}$$

$$T_{eq} = 308.75°K = 36°\text{C}$$

Heat Transfer

- How is heat energy transferred from one place to another?

conduction

convection

radiation

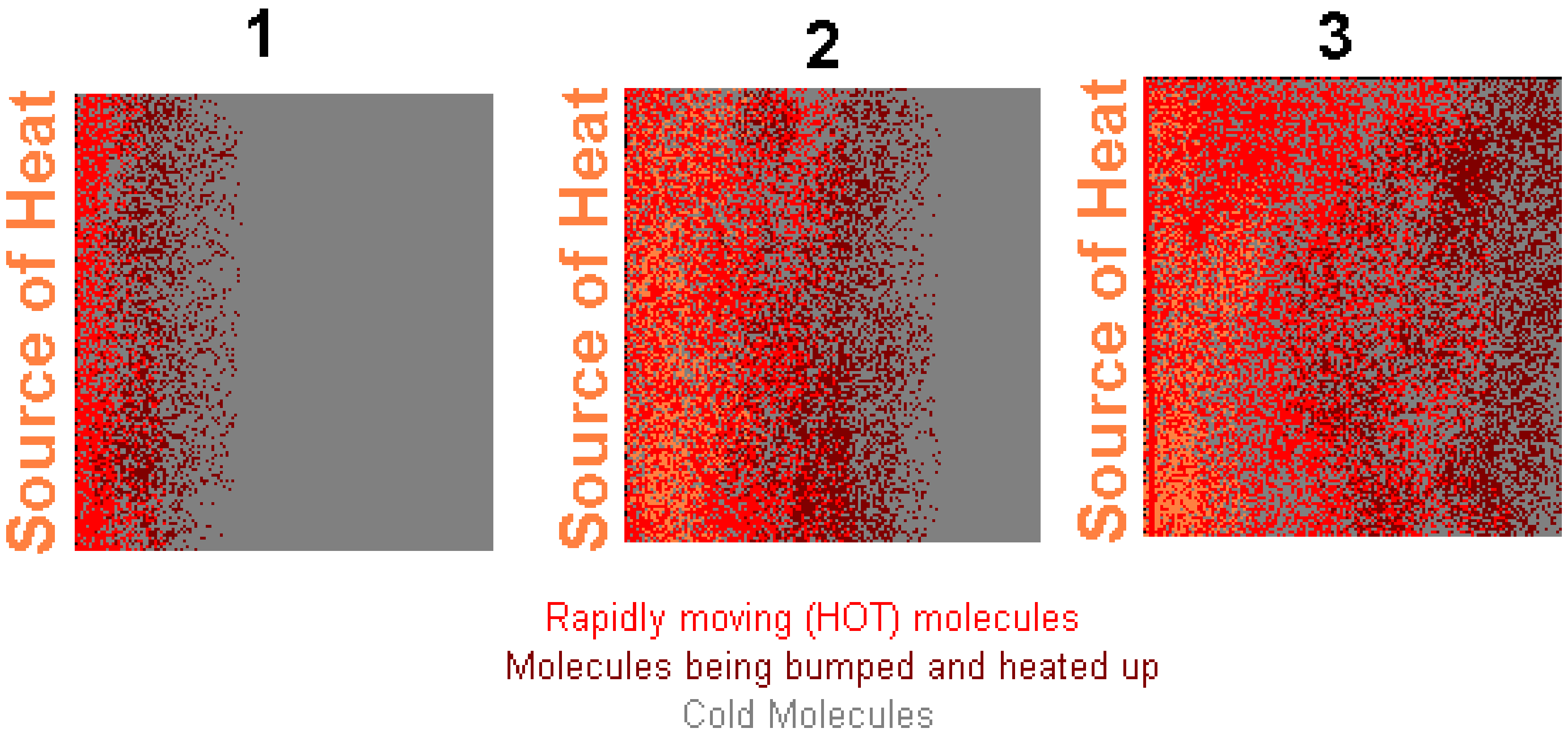
Usually for a given situation **one mechanism will dominate** however in some cases all three need to be considered simultaneously.

Conduction

- Heat transfer by **direct molecular contact**

Conduction

- Heat transfer by **direct molecular contact**



Conduction

- Heat flow rate (H) increases with **area** and **temperature drop**

$$H = \frac{\Delta Q}{\Delta t} \propto A\frac{\Delta T}{\Delta x}$$

heat flows from high T to low T

$$H = -kA\frac{dT}{dx}$$

temperature gradient

thermal conductivity (W/m ˚C)

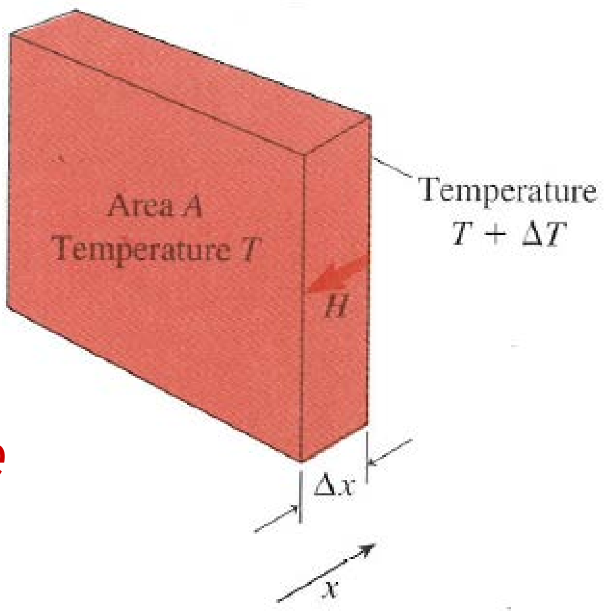


FIGURE 16.5 Heat flows from the hotter to the cooler face of the slab.

Heat flow is the rate of heat transfer by conduction. The larger the area the greater the heat flow. The higher the thermal conductivity the greater the heat flow. Heat flow is driven by a temperature gradient, so the larger the temperature difference the greater the heat flow.

Conduction

Conduction is heat transfer through **direct physical contact**. Materials are quantified by their **thermal conductivity** k $(W\ m^{-1}K^{-1})$.

- Values given in Table 16.2 of the textbook (page 308 of 3rd ed.)

Material	Thermal Conductivity, k SI Units: W/m• K	Thermal Conductivity, k British Units: Btu• in./h •ft^2• °F
Air	0.026	0.18
Aluminum	237	1644
Concrete (varies with mix)	1	7
Copper	401	2780
Fiberglass	0.042	0.29
Glass	0.7–0.9	5–6
Goose down	0.043	0.30
Helium	0.14	0.97
Iron	80.4	558
Steel	46	319
Styrofoam	0.029	0.20
Water	0.61	4.2
Wood (pine)	0.11	0.78

*Temperature range 0°C to 100°C.

A 1 m rod of gold is connected to a 1 m rod of silver. The gold end is placed in boiling water and the silver end is placed in ice water. Where is it 50°C ?

1. **At the midpoint**
2. **Near the midpoint but closer to the gold end**
3. **Near the midpoint but closer to the silver end**

Heat flow $H = -kA\frac{dT}{dx}$

$k_{Gold} = 310\ W\ m^{-1}K^{-1}$
$k_{Silver} = 418\ W\ m^{-1}K^{-1}$

A 1 m rod of gold is connected to a 1 m rod of silver. The gold end is placed in boiling water and the silver end is placed in ice water. Where is it 50°C ?

Heat energy is flowing from the boiling water to the ice at a rate H

Larger conductivity k implies smaller temperature gradient dT/dx

Temperature drop is smaller over the silver than the gold

Temperature passes 50 degrees in the gold

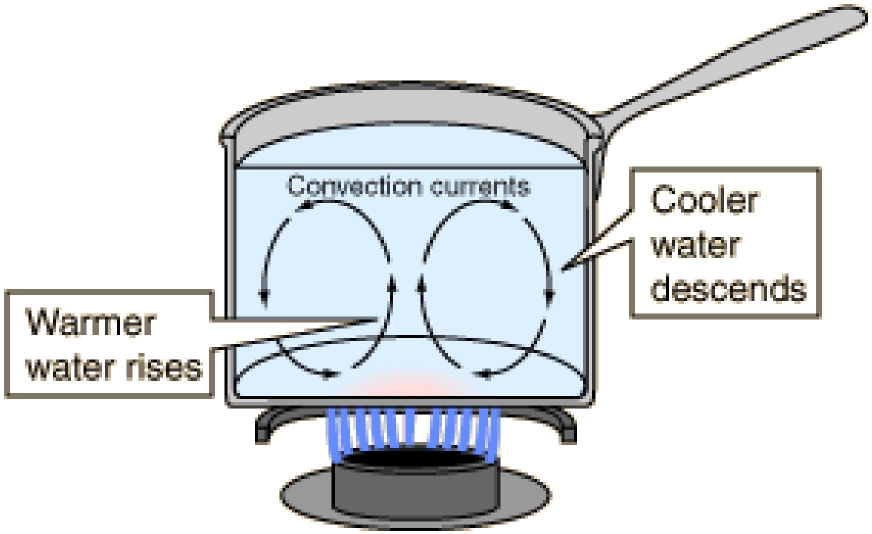
Heat flow $H = -kA\frac{dT}{dx}$

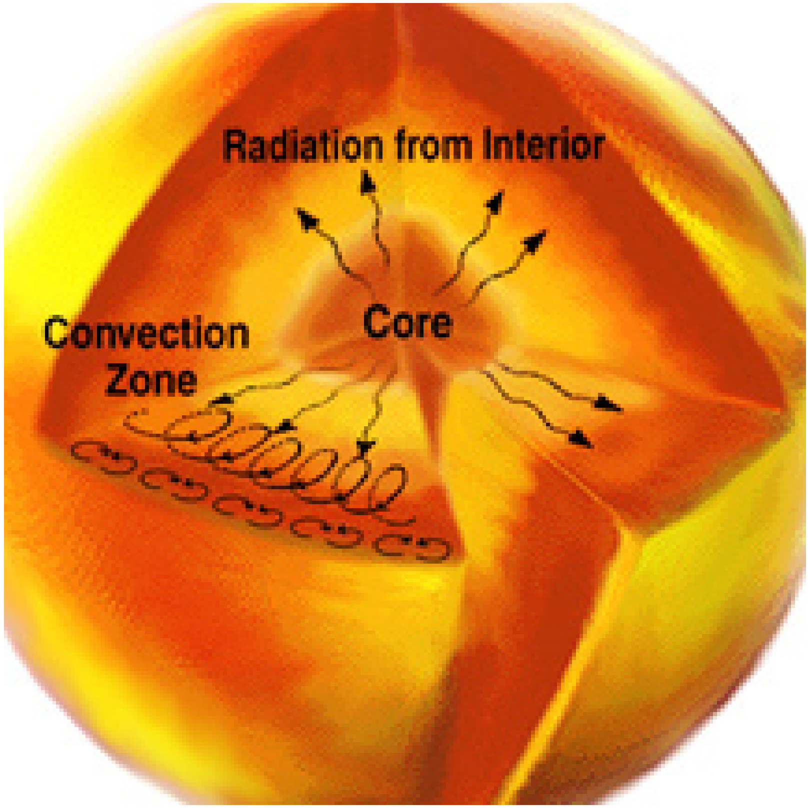
$k_{Gold} = 310\ W\ m^{-1}K^{-1}$

$k_{Silver} = 418\ W\ m^{-1}K^{-1}$

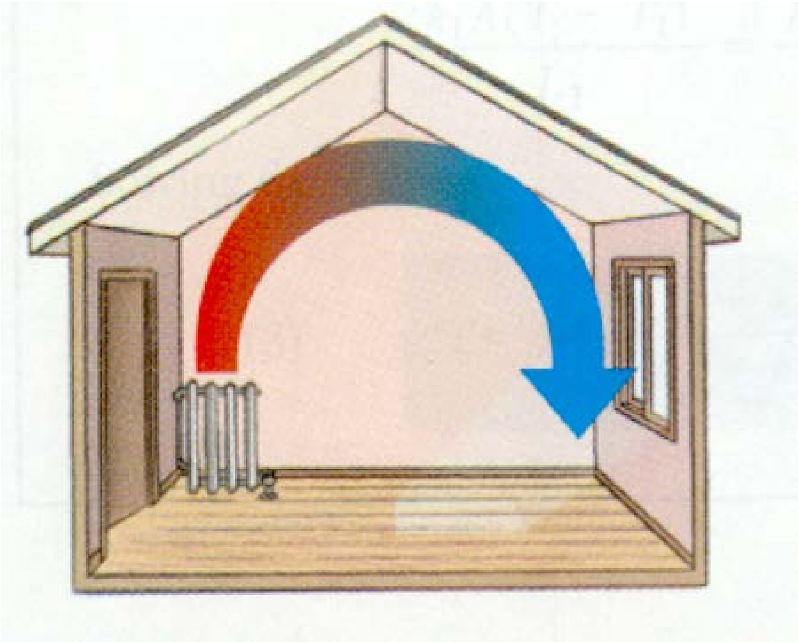
Convection

- Heat transfer by **bulk motion of a fluid**

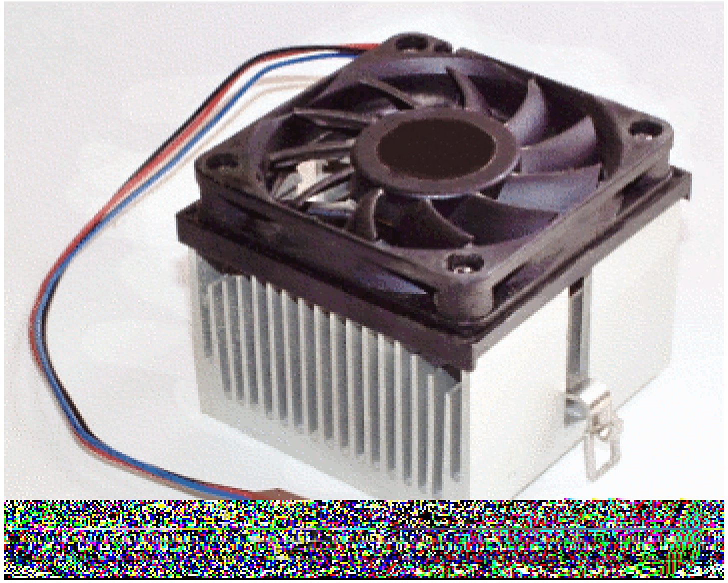




Convection



Natural convection relies on the buoyancy effect alone to move the fluid.



Forced convection drastically increases the fluid movement by using a fan or pump.

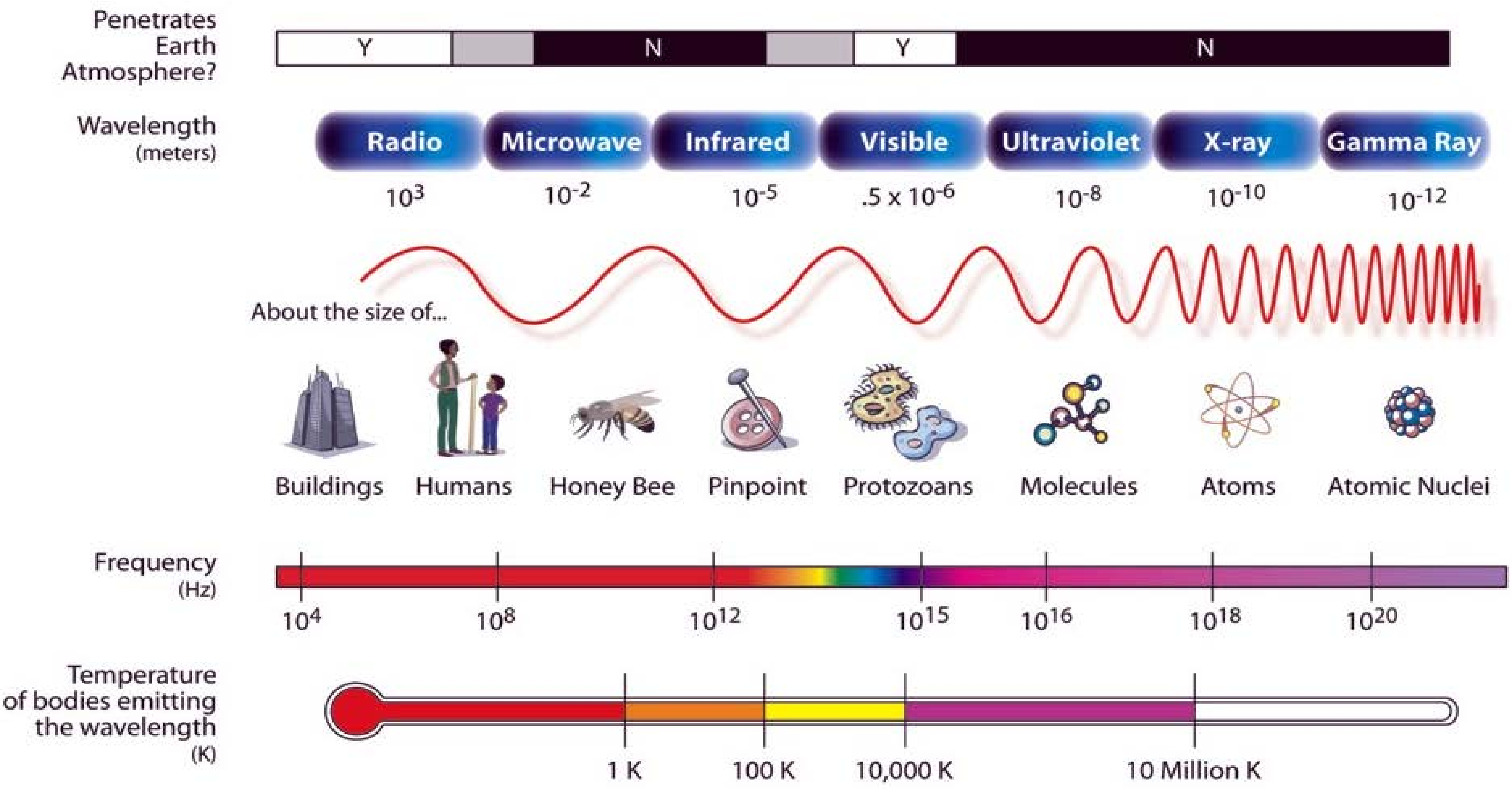
Calculations for convection are **extremely complicated** due to fluid dynamics and remains one of the important unsolved problems in science.

Radiation

- Heat transfer by **electromagnetic radiation**

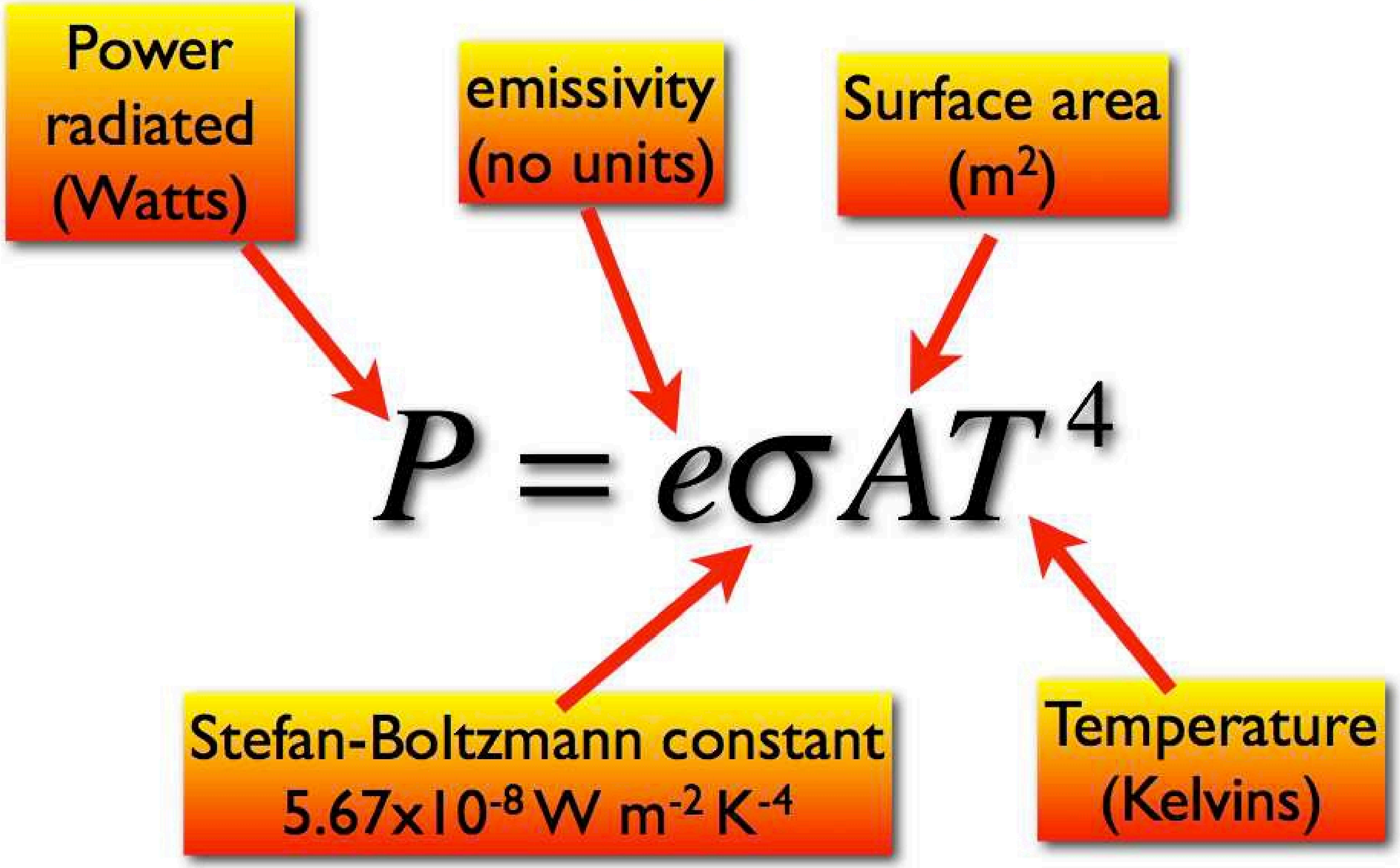
Radiation

- Electromagnetic radiation?



Radiation

Stefan-Boltzmann Law



$$P = e\sigma A T^4$$

Radiation

- **Emissivity** usually assumed to be e=1 in our problems – sometimes called "black body emission"

$$P_{emitted} = \sigma\, A\, T_{body}^{4}$$

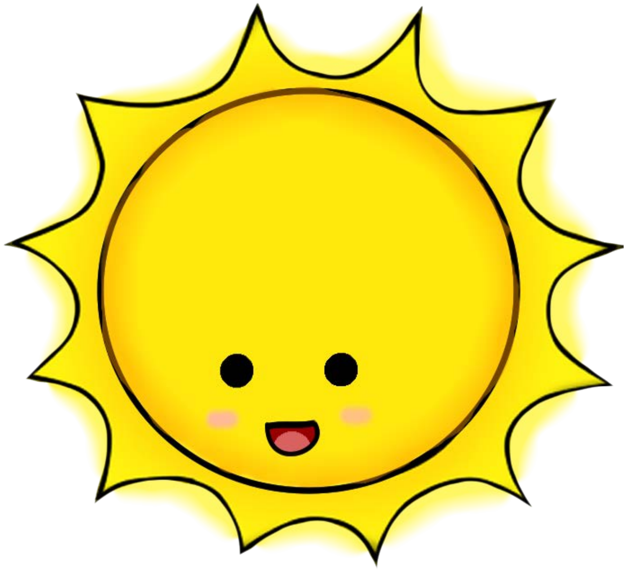
- Objects also **absorb energy** from surroundings at a rate given by the same law

$$P_{absorbed} = \sigma\, A\, T_{ambient}^{4}$$

$$P = power\ in\ W, \qquad \sigma = 5.67 \times 10^{-8}\ W m^{-2} K^{-4},$$
$$A = area\ in\ m^2, \qquad T = temperature\ in\ K$$

Radiation

The Sun radiates energy at the rate P = 3.9 x 10^{26} W, and its radius is R = 7 x 10^{8} m. Assuming the Sun is a perfect emitter (e=1), what is its surface temperature?



$$P = \sigma A T^4$$

$$A = 4 \pi R^2$$

$$P = \sigma 4\pi R^2 T^4$$

$$T^4 = \frac{P}{\sigma 4\pi R^2} = \frac{3.9 \times 10^{26}}{5.67 \times 10^{-8} \times 4\pi \times (7 \times 10^8)^2}$$

$$\rightarrow T = 5800\, K$$

Thermal Energy Balance

A poorly insulated water heater loses heat by conduction at the rate of 120 W for each degree Celsius difference between the water and its surroundings. It's electrically heated at 2.5 kW in a basement of 15°C. What is the water temperature if the heating element operates continuously ?

Water receives energy from heating element, and loses it by conduction at the same rate

Gain rate = 2500 W, Loss rate = (T – 15) x 120 W

Gain rate = Loss rate when T = 36 ^{o}C

Thermal Energy Balance is where the heat gains are equal to the heat losses and the system stays in equilibrium.

Temperature and Heat - Summary

- Difference in **temperature** T causes **heat energy** Q to flow
- **Specific heat capacity** of a material

$$Q = m\,c\,\Delta T$$

- Heat energy flow by **conduction**

$$\frac{\Delta Q}{\Delta t} = -k\,A\,\frac{\Delta T}{\Delta x}$$

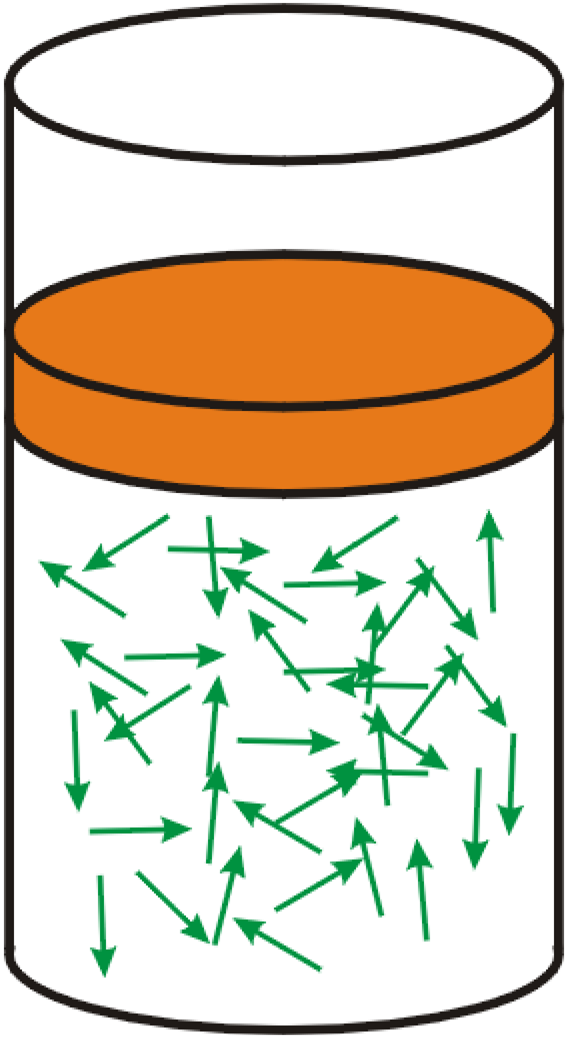
- Heat energy flow by **radiation**

$$P = \sigma\,A\,T^4$$

Chapter 17 : Thermal Behaviour of Matter

- *How does matter respond to heating?*
- A gas may undergo changes in **pressure** or **volume**
- These may be understood in terms of **molecular motion**
- A material may **change phase**, releasing energy
- A material may undergo **thermal expansion**

Ideal gas law



- Pressure P
- Volume V
- Temperature T
- N molecules

$$PV = Nk_BT$$

Boltzmann's constant

$$k_B = 1.38 \times 10^{-23}\ JK^{-1}$$

Ideal gas law

- Ideal gas law with Boltzmann's constant:

$$PV = Nk_BT \qquad k_B = 1.38 \times 10^{-23}\, JK^{-1}$$

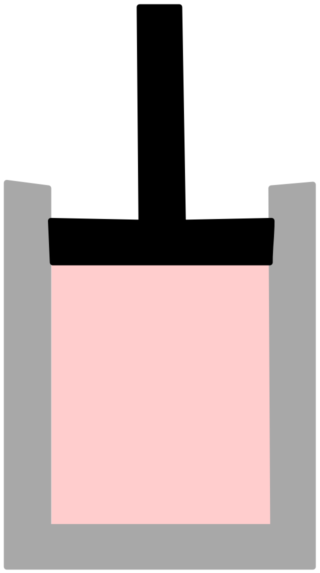
- The number of molecules N may be measured in moles n using **Avogadro's number** N_A

$$1\, mole = N_A = 6.022 \times 10^{23}\, molecules$$

- The ideal gas law may also be expressed in terms of number of moles n using the **universal gas constant** R

$$PV = nRT \qquad R = 8.314\, JK^{-1}mol^{-1}$$

I double the volume of the cylinder and reduce the absolute pressure from 1 atm to 0.5 atm. How does the final temperature compare to the initial ?



0%

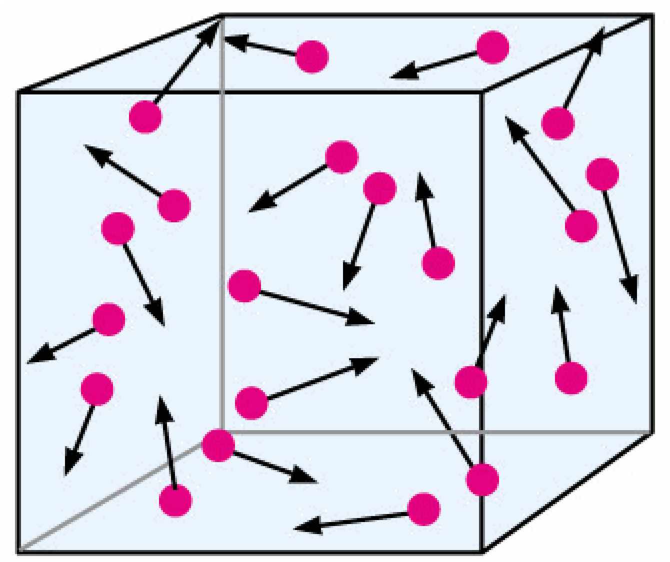
1. $T_f > T_i$
2. $T_f = T_i$
3. $T_f < T_i$
4. **Can't tell without *n***

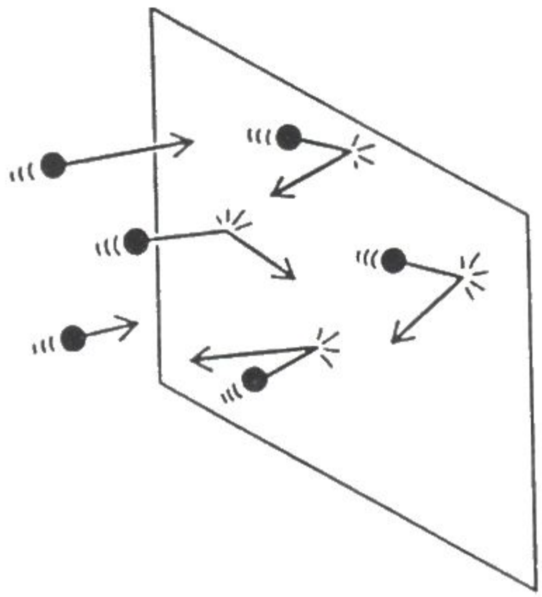
1 2 3 4

If quantity of gas is fixed (n, m or N constant) then the equation of state relating initial and final properties reduces to

$$\frac{P_i V_i}{T_i} = \frac{P_f V_f}{T_f}$$

Kinetic theory of gases





- On a microscopic level, a gas consists of *moving molecules*
- **Pressure** is generated by molecules *colliding with the walls*
- **Temperature** is described by the molecules' *kinetic energy*

Kinetic theory of gases

- We can relate the pressure to the molecular velocity!

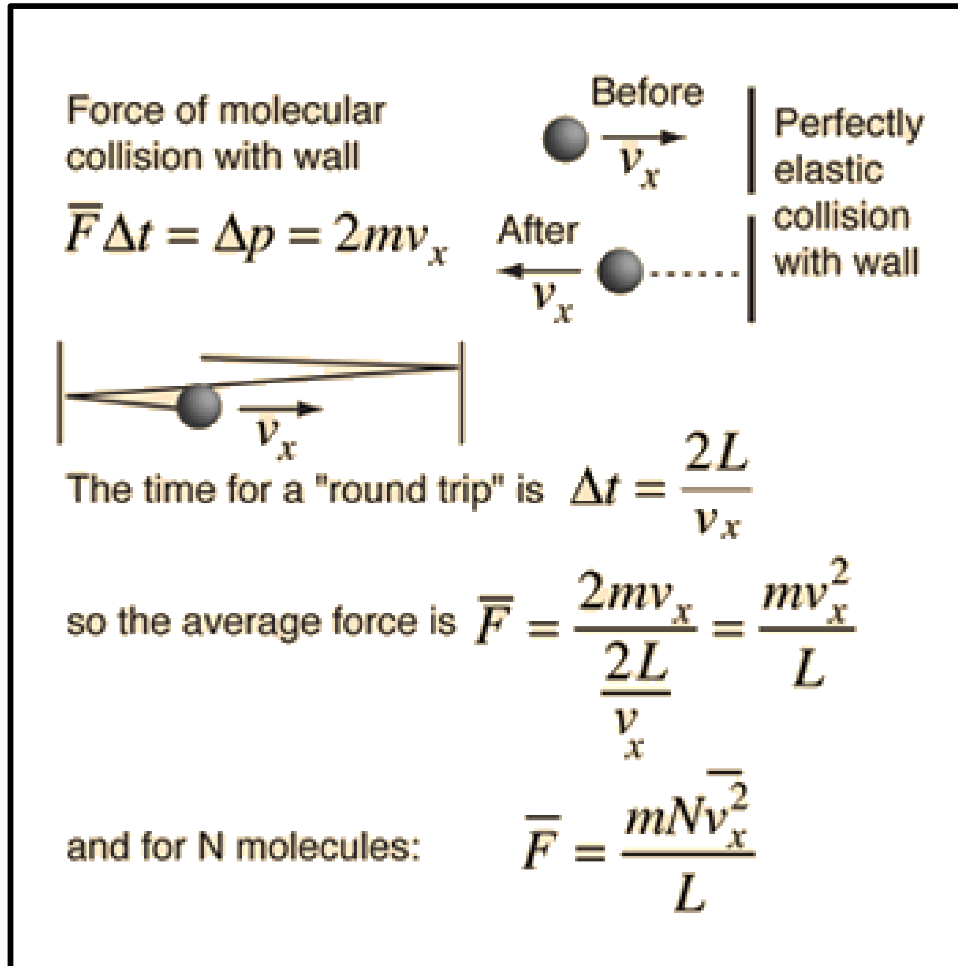
(calculation in textbook)

$$P = \frac{F}{A} = \frac{mN\overline{v^2}}{3V}$$

$$But: \; PV = Nk_BT$$

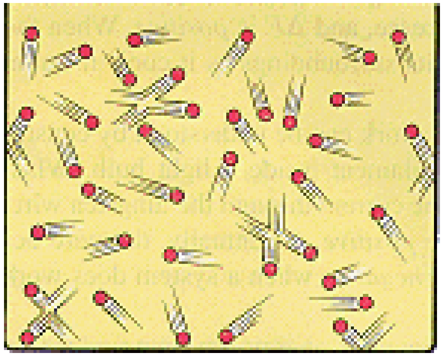
$$So: \; \frac{1}{2}m\overline{v^2} = \frac{3}{2}k_BT$$

Temperature measures the average kinetic energy!

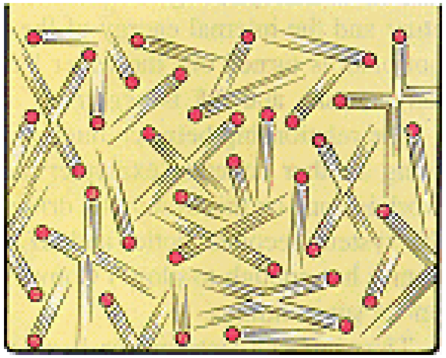


Kinetic theory of gases

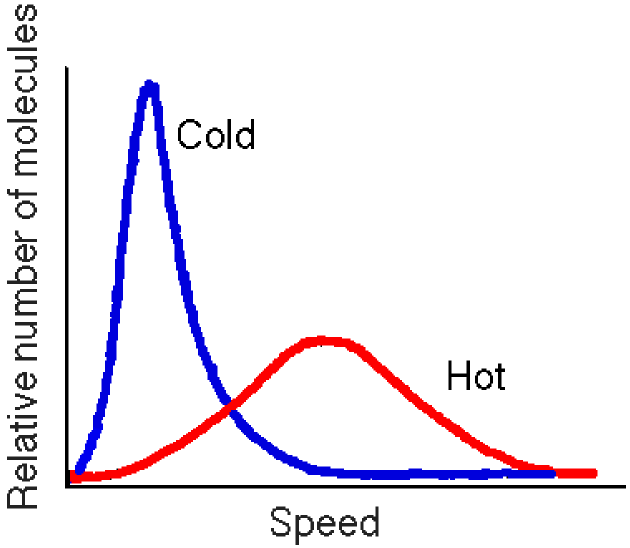
Temperature measures the **average kinetic energy** associated with random translational motion of an atom



Low Temperature



High Temperature



Two identical cylinders, one with H_2 and one with N_2, have **different** gauge pressures but the same temperature. Which cylinder has the fastest molecules.

1. **The high pressure vessel**
2. **The low pressure vessel**
3. **The one with Hydrogen**
4. **The one with Nitrogen**
5. **Insufficient information to tell**

Two identical cylinders, one with H_2 and one with N_2, have **different** gauge pressures but the same temperature. Which cylinder has the fastest molecules.

$$\frac{1}{2}m\overline{v^2} = \frac{3}{2}k_B T$$

Temperature and mass dictate velocity

Temperature is the same, but mass(H_2) < mass(N_2)

So speed(H_2) > speed(N_2)

Molecular Energy and Speed

Find the average kinetic energy of a molecule of air at room temperature ($T = 20°\text{C}$) and determine the speed of a nitrogen molecule (N_2) with this energy.

$$Average\ kinetic\ energy = \frac{1}{2}m\overline{v^2} = \frac{3}{2}k_B T$$

$$T = 293K \rightarrow \overline{KE} = \frac{3}{2} \times 1.38 \times 10^{-23} \times 293 = 6.07 \times 10^{-21}\ J$$

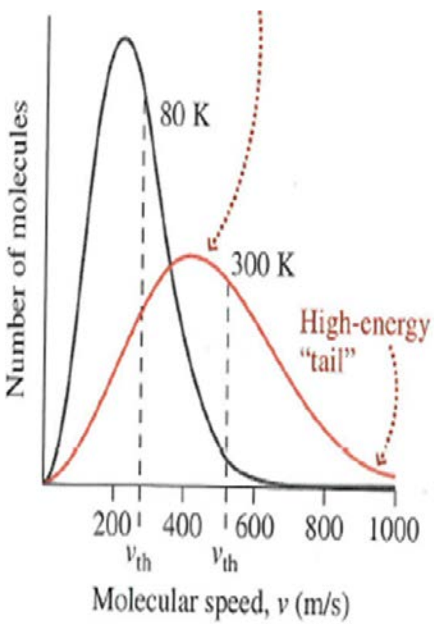
$$KE = \frac{1}{2}mv^2 \rightarrow v = \sqrt{2 \times KE/m}$$

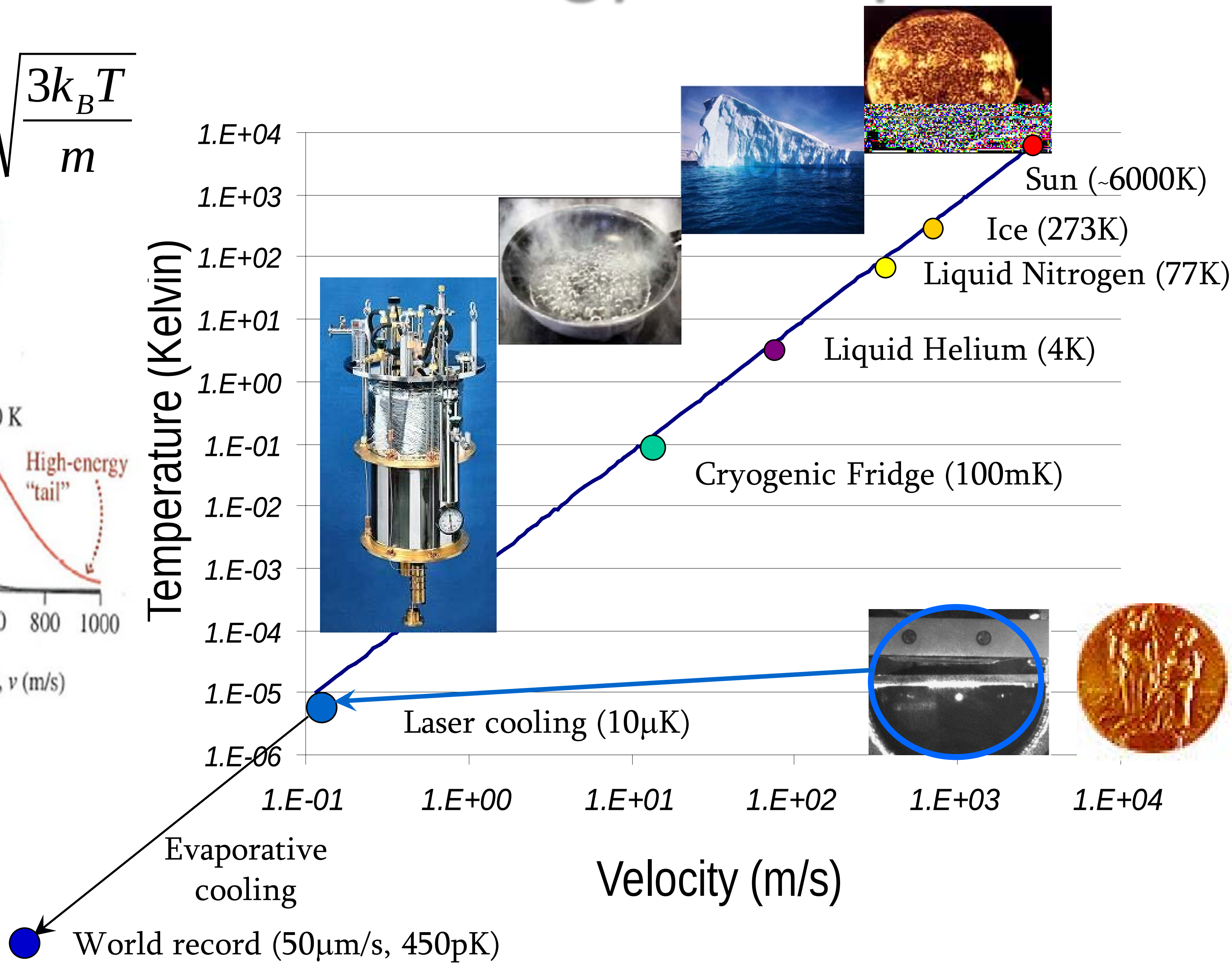
$$m = 2 \times 14 \times 1.66 \times 10^{-27}\ kg = 4.65 \times 10^{-26}\ kg$$

$$\rightarrow v = \sqrt{2 \times 6.07 \times 10^{-21}/4.65 \times 10^{-26}} = 511\ m/s$$

Molecular Energy and Speed

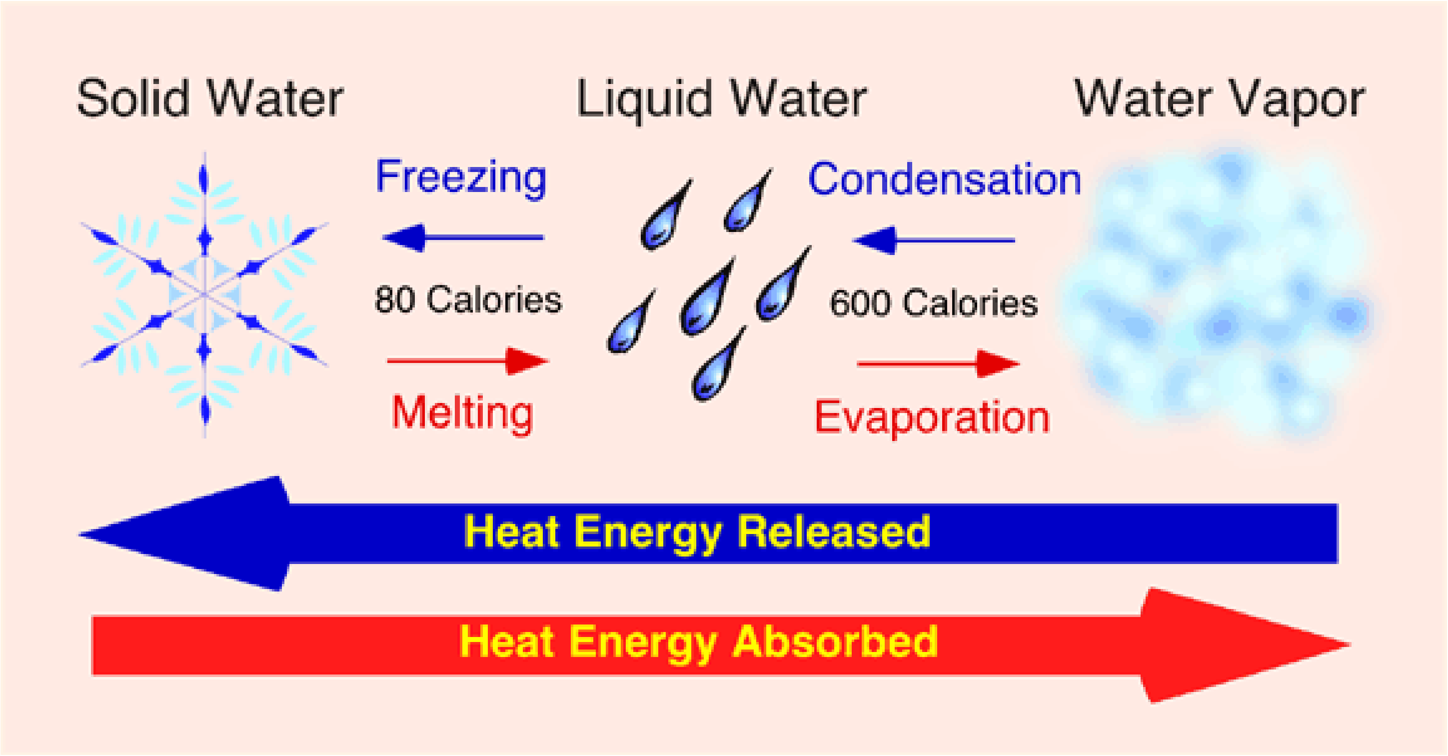
$$v_{thermal} = \sqrt{\frac{3k_B T}{m}}$$





Phase Changes

- *Phase changes* (solid, liquid, gas) are accompanied by **release** or **absorption** of heat energy



Phase Changes

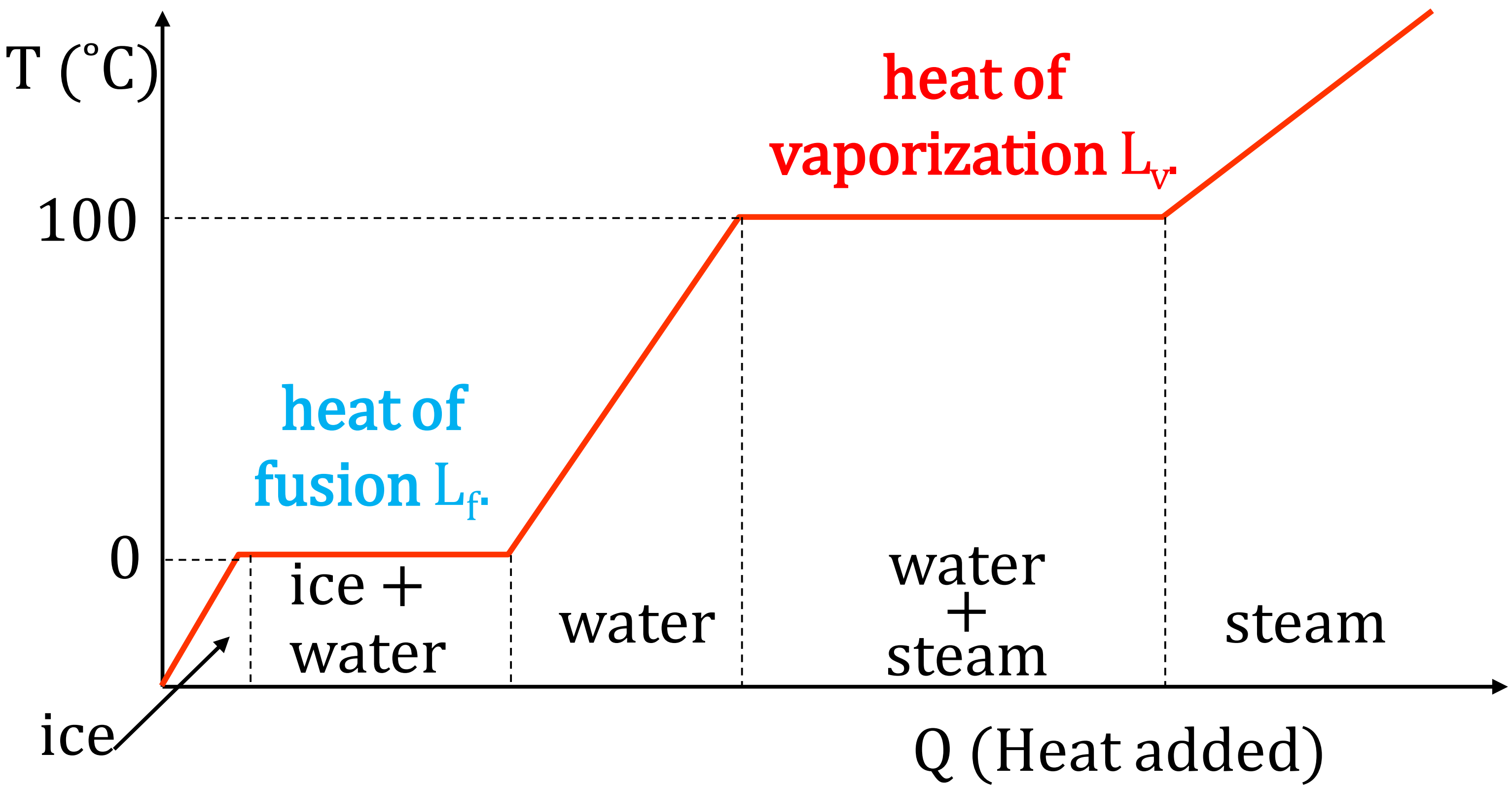
- The amount of energy involved, per unit mass, is known as the **latent heat**

$$Q = m\,L$$

Q = heat energy absorbed/released [J]
m = mass of substance [kg]
L = latent heat [J/kg]

Phase Changes

eg. adding heat to ice, initially with T=-20 °C at 1 atm.



The energy per unit mass to change a phase is called the **latent heat of transformation** L. For solid-liquid change its heat of fusion L_f, for liquid-gas change its heat of vaporisation L_v.

Phase Changes

- Values given in Table 17.1 of the textbook (page 326 of 3rd ed.)

TABLE 17.1 Heats of Transformation (at Atmospheric Pressure)

Substance	Melting Point (K)	L_f (kJ/kg)	Boiling Point (K)	L_v (kJ/kg)
Alcohol, ethyl	159	109	351	879
Copper	1357	205	2840	4726
Lead	601	24.7	2013	858
Mercury	234	11.3	630	296
Oxygen	54.8	13.8	90.2	213
Sulfur	388	38.5	718	287
Water	273	334	373	2257
Uranium	1406	82.8	4091	1875

$$Q = mL$$

Take the energy required to melt 1 kg of ice and instead heat 1 kg of water. How much has the temperature of the water changed by ?

1. 80°C
2. 539°C
3. 13°C
4. 2°C
5. Insufficient Information

$$Q = mc\Delta T \qquad c_{water} = 4184\ J\ K^{-1}\ kg^{-1}$$

$$Q = mL \qquad L_v = 2257\ kJ\ kg^{-1}\ L_f = 334\ kJ\ kg^{-1}$$

Take the energy required to melt 1 kg of ice and instead heat 1 kg of water. How much has the temperature of the water changed by ?

Energy required to melt 1 kg of ice = 334 kJ

$$Q = mc\,\Delta T \rightarrow \Delta T = \frac{Q}{c} = \frac{334{,}000}{4{,}184} = 80\text{ K}$$

However, it depends on initial T, since water may boil!

$Q = mc\Delta T$ $\quad$ $c_{water} = 4184\ J\ K^{-1}\ kg^{-1}$

$Q = mL$ $\quad$ $L_v = 2257\ kJ\ kg^{-1}\ L_f = 334\ kJ\ kg^{-1}$

Phase Changes

A 20 g ice cube at – 3°C is placed in a polystyrene cup containing 0.20 kg water at $T = 20\,^{\circ}C$). What is the final temperature of the water?

Energy is required to: (1) heat the ice cube to 0°C, (2) melt the ice cube

$$Q_1 = mc_{ice}\Delta T = 0.02 \times 2050 \times 3 = 123\ J$$

$$Q_2 = mL = 0.02 \times 334{,}000 = 6680\ J$$

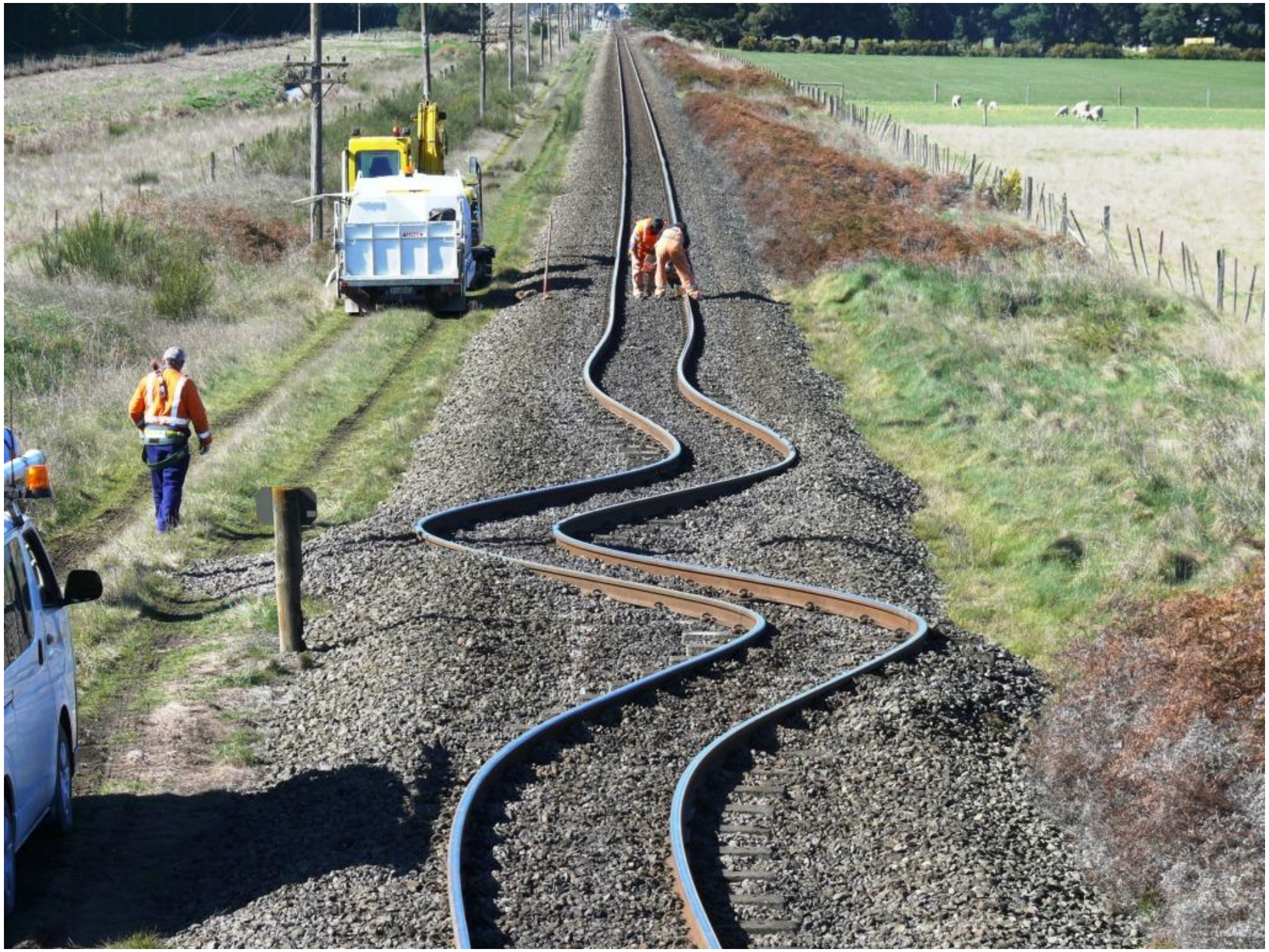
Total energy = 123 + 6680 = 6803 J

$$Q_{tot} = mc_{water}\Delta T \rightarrow \Delta T = Q_{tot}/mc_{water}$$

$$\Delta T = \frac{6803}{0.2 \times 4184} = 8K \rightarrow T_{final} = 12°C$$

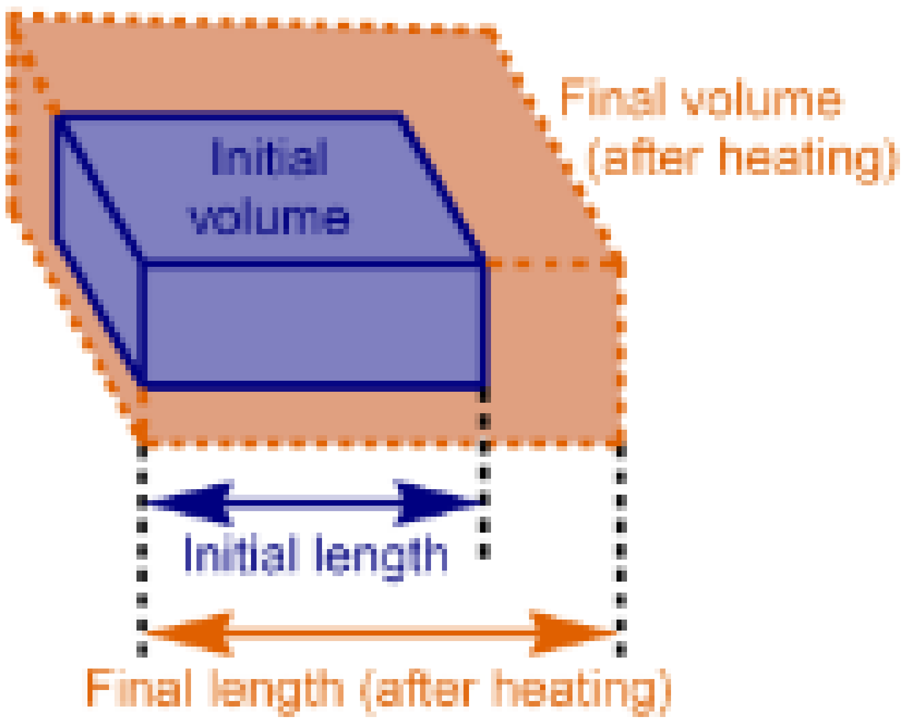
Thermal Expansion

- Solids **expand** when heated



Thermal Expansion

- The fractional change in *length* or *volume* as T increases is described by **coefficients of expansion**



Fractional length change:

$$\frac{\Delta L}{L} = \alpha\, \Delta T$$

[coefficient of linear expansion]

Fractional volume change:

$$\frac{\Delta V}{V} = \beta\, \Delta T$$

[coefficient of volume expansion]

Thermal Expansion

- Values given in Table 17.2 of the textbook (page 328 of 3rd ed.)

Coefficient of linear expansion $\alpha = \frac{\Delta L/L}{\Delta T}$

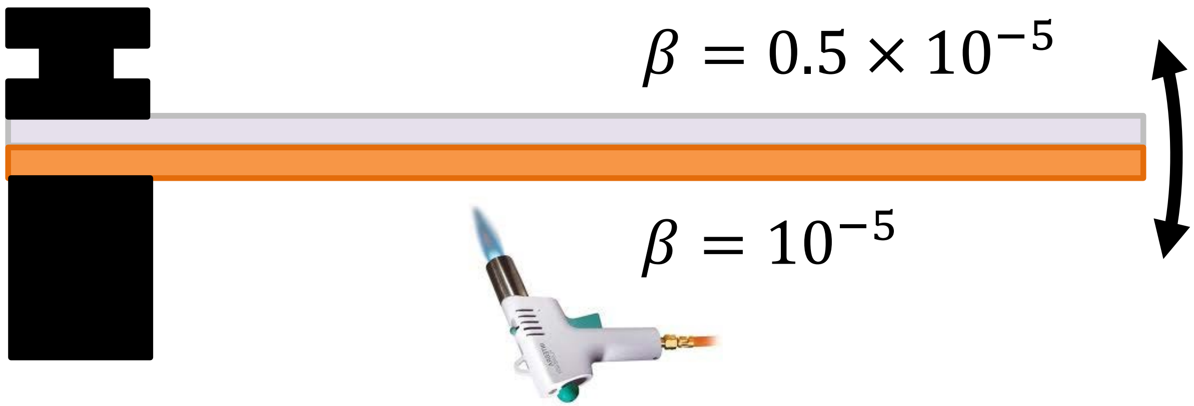
Solids	α (K^{-1})
Aluminum	24×10^{-6}
Brass	19×10^{-6}
Copper	17×10^{-6}
Glass (Pyrex)	3.2×10^{-6}
Ice	51×10^{-6}
Invar†	0.9×10^{-6}
Steel	12×10^{-6}

Coefficient of volumetric expansion $\beta = \frac{\Delta V/V}{\Delta T}$

Liquids and Gases	β (K^{-1})
Air	3.7×10^{-3}
Alcohol, ethyl	75×10^{-5}
Gasoline	95×10^{-5}
Mercury	18×10^{-5}
Water, 1°C	-4.8×10^{-5}
Water, 20°C	20×10^{-5}
Water, 50°C	50×10^{-5}

Often only care about the **change in 1 dimension** or looking at long thin objects (railway).

A bimetallic strip is made of dissimilar metals with different coefficients of volumetric expansion (shown). When heated the strip bends



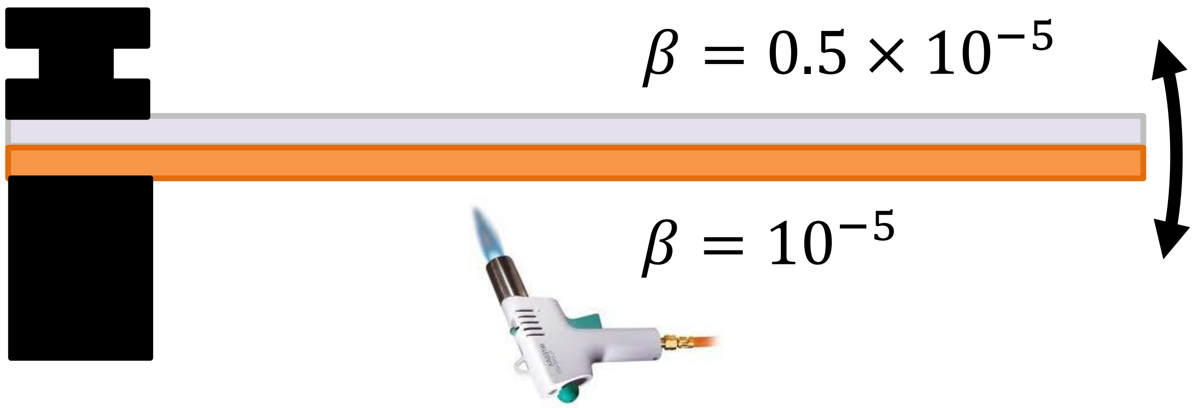
0%

1. upwards
2. downwards
3. it stays level and lengthens
4. Insufficient information

$$\Delta V = V\,\beta\,\Delta T$$

1 2 3 4

A bimetallic strip is made of dissimilar metals with different coefficients of **volumetric** expansion (shown). When **heated** the strip bends



The lower metal will expand more, causing the strip to bend upwards

$$\Delta V = V \, \beta \, \Delta T$$

Thermal Behaviour of Matter - Summary

- Ideal gas law

$$PV = Nk_BT \qquad PV = nRT$$

- Gas may be analysed in terms of molecular motion

$$\frac{1}{2}m\overline{v^2} = \frac{3}{2}k_BT$$

- Latent heat of transformation of phases

$$Q = m\,L$$

- Coefficients of thermal expansion

$$\frac{\Delta L}{L} = \alpha\,\Delta T \qquad \frac{\Delta V}{V} = \beta\,\Delta T$$