Thermal Physics
Physics 1X

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Thermodynamics

- Understanding the words
    - Temperature
    - Heat
    - Heat capacity
    - The 0, 1, 2 laws of thermodynamics
- (one of) Kelvin's legacy's

WilliamThompson (Lord Kelvin)

What is Heat?

- Perception as to hot and cold defined relative to out own body temperature, i.e. object is hotter or colder than oneself
- Objective measurement of temperature
  - Macroscopic, display of temperature gauge
  - Microscopic behaviour of atoms and molecules

Measuring temperature

- Properties of materials change with temperature
  - Length
  - Volume
  - Resistance

Hotter things become longer

- All(?) solids get bigger when they get hot
  - A 1 metre long bar heated by 1 degree gets bigger by
    - Steel ≈0.01 mm
    - Glass ≈ 0.001 mm
    - Zerodur ≈ 0.0001mm

Rails expand and may buckle on a hot summer day

A bimetallic strip

- Join two metals with different coefficient of thermal expansion

e.g. fire alarm

Hotter things take up more volume -1

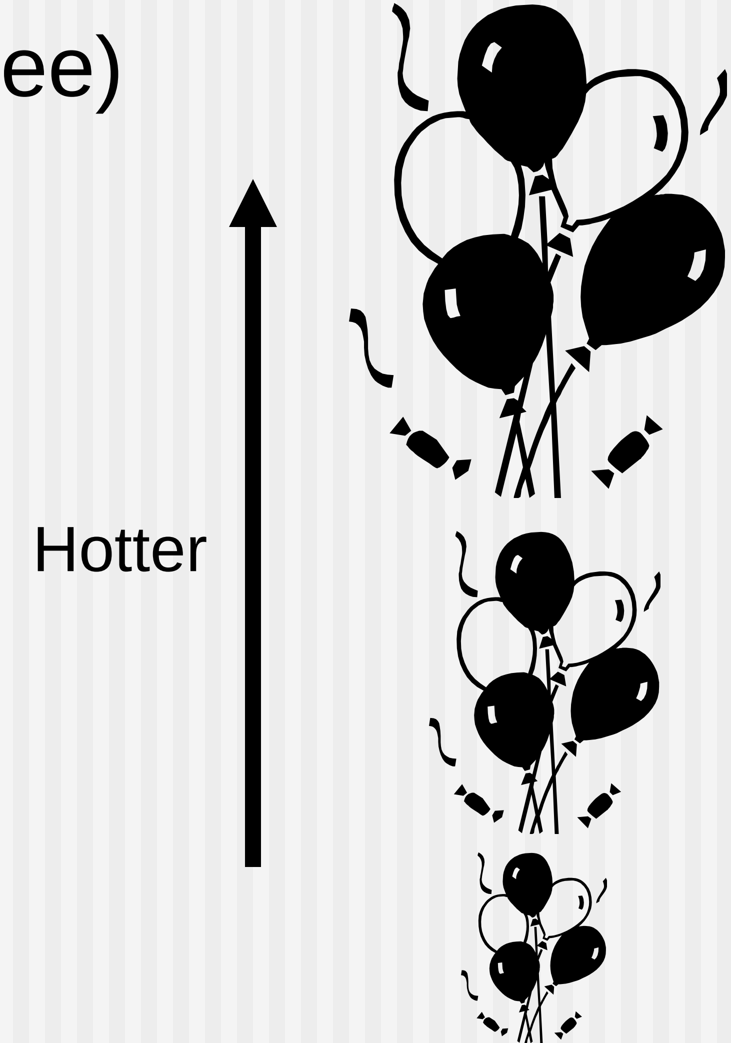
- Most materials get bigger when they get hot (but not water 0°C -> 4°C gets smaller!)
  - Thermometer relies on a thermal expansion of a liquid (e.g.mercury)

Thin tube (Gives big length change for small increase in volume)

Large volume of reservoir

Hotter things take up more volume -2

- Gases (as we will see) can behave near perfectly



Hotter things change their resistance

- All hotter metals have a higher electrical resistance
  - e.g. platinum resistance thermometer
- All hotter semiconductors have a lower electrical resistance
  - key definition between to distinguish metals and insulators!

How long do you have to leave a thermometer in your mouth?

- Hot things stay hot if you insulate them, e.g.
  - coffee in a vacuum flask (keeps things cold too)
  - an explorer in a fur coat
- The mercury in the thermometer must reach the same temperature and you

Insulation

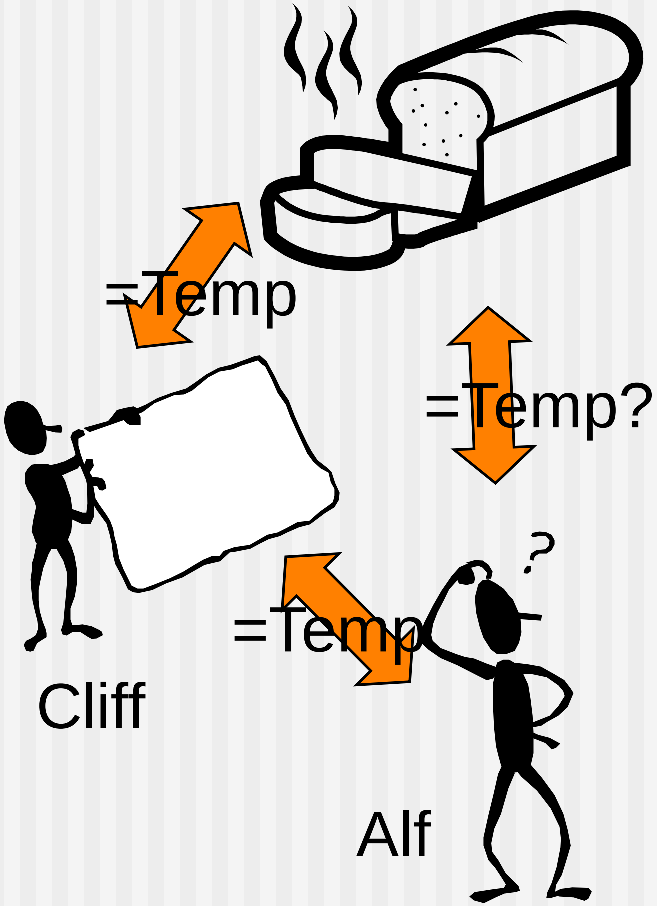
- Example of good (thermal) insulators
  - A vacuum, polystyrene, fibreglass, plastic, wood, brick
  - (low density/foam structure, poor electrical conductors)
- Examples of poor insulators, i.e. good conductors
  - Most metals (but stainless steel better than copper) e.g. gold contact used within IC chips to prevent heating
  - Gases, liquids
  - (high density, “mobile”, good electrical conductors)

Ask a friend if it’s cool enough to eat

- Your friend eats the “hot” loaf and says it cool enough to eat (i.e it is “close” enough to their own temperature that it does not burn)
- Is it safe for you to eat too
- If it is safe for then, it’s safe for you!

The 0th law of thermodynamics

- If A and B are each in thermal equilibrium with C then A and B are in thermal equilibrium with each other
- If Alfred and the Bread are the same temperature as Cliff then Alf is the same temperature as the Bread.



Temperature and scales

- Temperature scales (melting & boiling of water)
  - Degrees Celsius (MP 0°C 100°C)
  - Degrees Kelvin (MP 273.15 K BP 373.15 K)
  - Degree Fahrenheit (MP 32° F BP 212°F)

Converting between scales

- Kelvin to Celsius
  - $K = C + 273.15$
  - $C = K - 273.15$
- Fahrenheit to Celsius
  - $F = C \times (9/5) + 32$
  - $C = (F - 32) \times (5/9)$

Example

- Convert the following temperatures into °F and K
- Boiling water, 100°C

212°F, 373.15K

- Freezing water, 0°C

32°F, 273.15K

- Absolute zero,

  -273.15°C

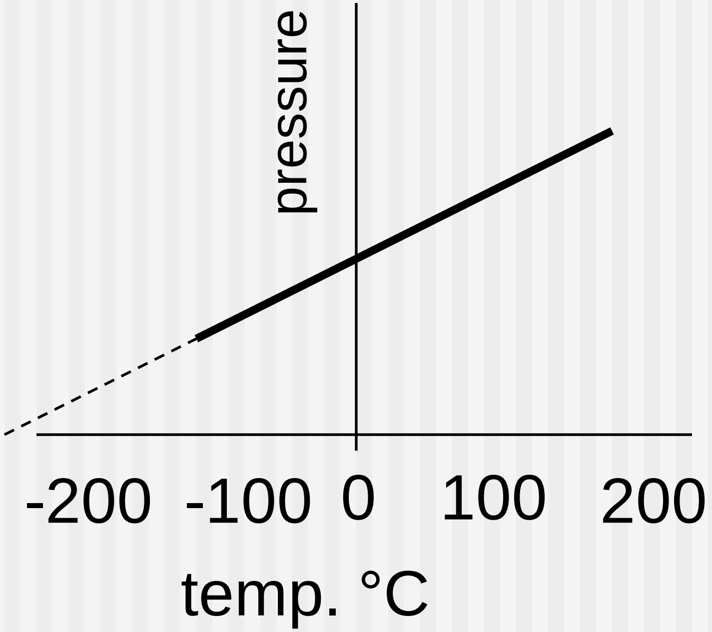
-460°F, 0K

Type of thermometer

- Change in electrical resistance (convenient but not very linear)
- Change in length of a bar (bimetallic strip)
- Change in volume of a liquid
- Change in volume of gas (very accurate but slow and bulky)

Volume and pressure of a gas

- Gases (at constant pressure) expand with increasing temperature
  - all gases tend to zero volume at - 273.15°C!
- Gases (at constant volume) increase pressure with increasing temperature
  - all gases tend to zero pressure at - 273.15°C!
- In reality gases liquefy when they get cold



Pressure

- Pressure is defined as force per unit area
  - Newtons per square metre N/m^2
- The pressure exerted by a gas results from the atoms/ molecules “bumping” into the container walls
  - More atoms gives more bumps and higher pressure
  - Higher temperature gives faster bumps and higher pressure
- At sea level and 20°C, normal atmospheric pressure is
  - 1atm $\approx 1 \times 10^5$ N/m^2

Volume and Pressure of a Gas

- In the kelvin scale, the lowest possible temperature is 0 K. (zero volume and zero pressure)
- Any two temperatures defined by the ratio
  - $p_1 T_2 = p_2 T_1$ or $V_1 T_2 = V_2 T_1$
- The zero point is fixed -
  - Absolution Zero (≈-273.15°C)
- additional point defined at triple point of water (occurs at one temp and pressure where ice, steam and liquid all coexist (≈ 0.01°C and 0.006 atm)
- $T_{triple} = 273.16K$
- $T = 273.16 \quad x\ (p/p_{triple})$

Example

- A bottle of hair spray is filled to a pressure of 1atm at 20°C
- What is the canister pressure if it is placed into boiling water?

$p_1 T_2 = p_2 T_1$

$1 \times 373 = p_2 \times 293$

$p_2 = 373/293$

$p_2 = 1.27$ atm

Absolute zero

- Ideal gas has zero volume
- Resistance of metal drops to zero (actually superconductivity cuts in above 0K)
- Brownian motion ceases (kinetic energy due to thermal excitation ≈ 3/2 kT, see Physics 1Y)
- But lowest temperature attained is ≈ 10^{-9}K

Example

- How fast does a typical average gas atom/molecule travel at room temperature? ($k = 1.38\text{x}10^{-23}$J/K)

$KE = 1/2\ mv^2 = 1/2\ kT$

$v = (kT/m)^{1/2}$

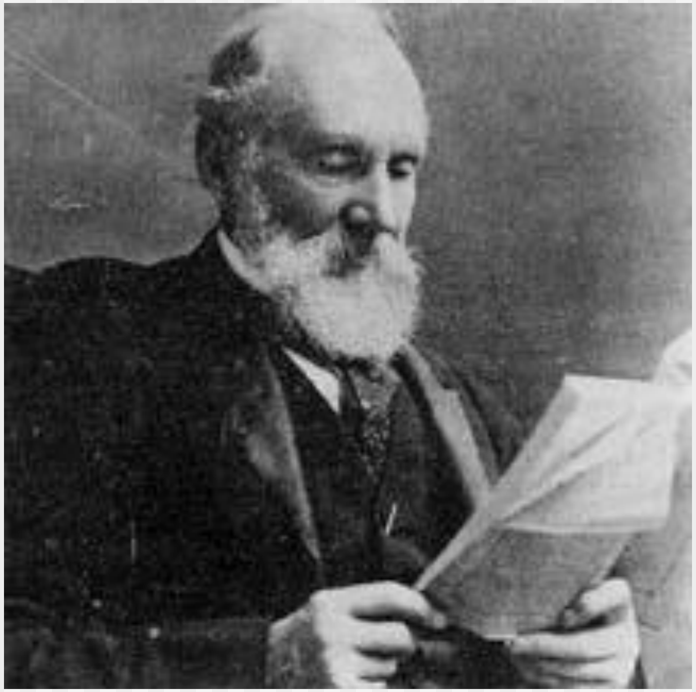
$v = (1.38\text{x}10^{-23} \text{ x } 293/m)^{1/2}$

$m = 0.03/(6.023 \text{ x } 10^{23}) = 5\text{x}10^{-26}$ kg

v = 284 sm/sec

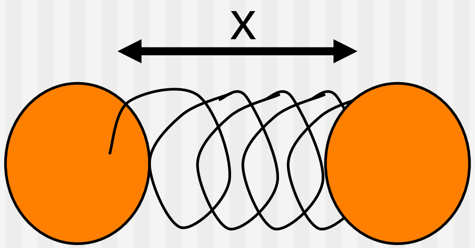
Lord Kelvin

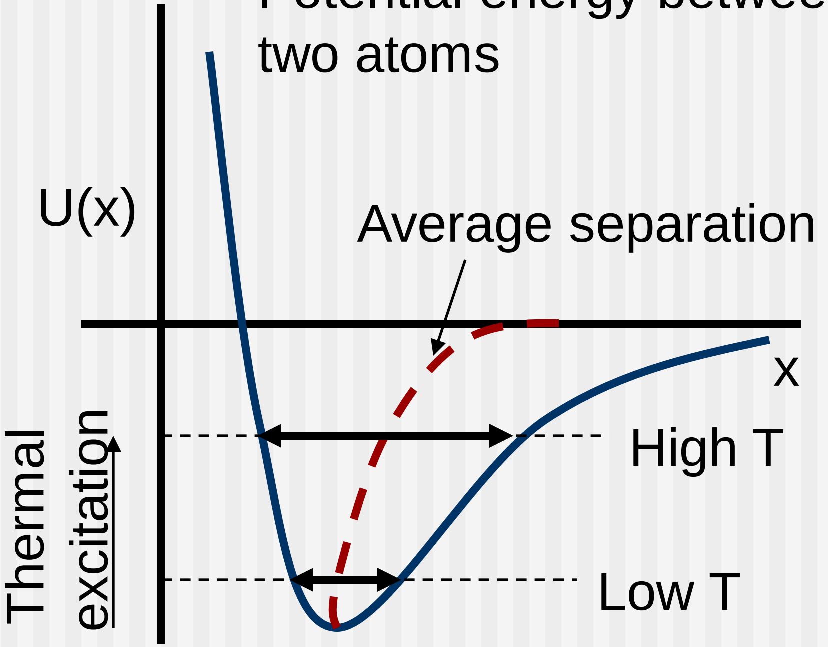
- William Thompson, born Belfast 1824
- Student in Natural Philosophy
- Professor at 22!
- Baron Kelvin of Largs in 1897
- Lived at 11 The Square
- A giant
  - Thermodynamics, Foams, Age of the Earth, Patents galore!



Thermal expansion, why?

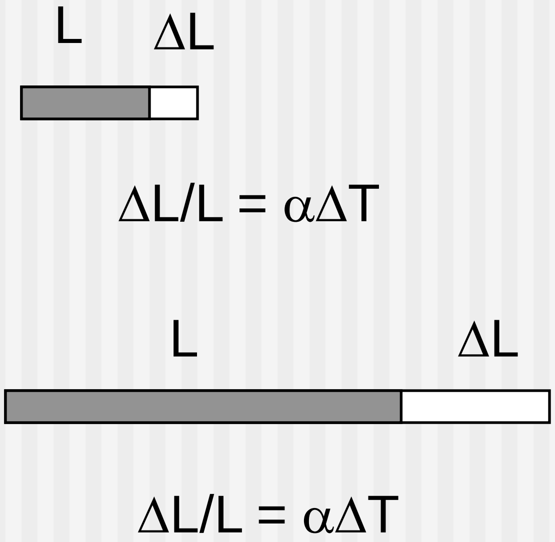
- Every microscopic object moves due to thermal excitation - Brownian motion
- Atoms too vibrate with respect to each other
- Hotter atoms vibrate more
  - Asymmetric potential means average separation increases




Potential energy between two atoms

Linear expansion

- Objects get longer when the get hot
- Their *fractional* change in length is proportional to the change in temperature
  - $\Delta L/L = \alpha\ \Delta T$ or $\Delta L = \alpha\ L\ \Delta T$
  - or $\dfrac{dL}{dT} = \alpha L$



Thermal expansion ($\alpha[K^{-1}]$)

- Aluminium, $\alpha = 2.4\text{x}10^{-5}\ K^{-1}$
- Steel, $\alpha = 1.2\text{x}10^{-5}\ K^{-1}$
- Glass, $\alpha \approx 5\ \text{x}10^{-6}\ K^{-1}$
- Invar, $\alpha \approx 9\ \text{x}10^{-7}\ K^{-1}$
- Quartz, $\alpha \approx 4\ \text{x}10^{-7}\ K^{-1}$

Example

- Metre rules are calibrated at 20°C
- What is the error in a measurement of 500mm if made at 45°C?
- $\alpha_{steel} = 1.2\times10^{-5}\ K^{-1}$

$\Delta L/L = \alpha\ \Delta T$

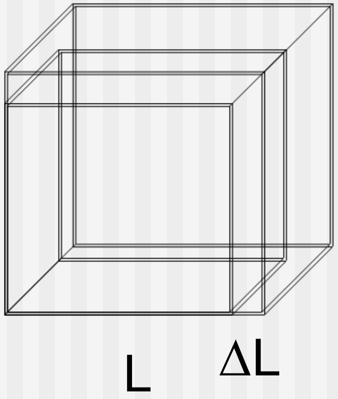
$\Delta L = L\ \alpha\ \Delta T$

$\Delta L = 500\ \times10^{-3}\ \times\ 1.2\times10^{-5}\ \times\ 25$

$\Delta L = 1.5\times10^{-6}m = 1.5\mu m$

Volume Expansion

- Every length goes from L to $L+\Delta L = L + L\alpha\ \Delta T$
- Old volume = L^3
- New volume = $(L + \Delta L)^3$
- Ignore terms like ΔL^2 and ΔL^3
  - $(L + \Delta L)^3 \approx L^3 + 3L^2\,\Delta L$
- But $\Delta L = L\alpha\ \Delta T$
  - $L^3 + 3L^2\,\Delta L = L^3 + 3L^3\,\alpha\Delta T$
  - $\Delta V/V = 3\alpha\ \Delta T$ or $\Delta L = 3\alpha\ V\ \Delta T$
- 3α often called β



Example

- If whisky bottles are made to be exactly 1 litre at 20°C
- but, whisky is bottled at 10°C
- How much whisky do you actually get if it is served at 20°C?
  - β_{glass}= 2x10^{-5} K^{-1}
  - β_{whisky}=75x10^{-5} K^{-1}

$V_{bottle@10°C} = V_{bottle@20°C}\,(1+\Delta T\beta)$

$V_{bottle@10°C} = 1\,(1+ -10 \times 2\text{x}10^{-5})$

$V_{bottle@10°C}$ = 0.9998 litres

What does 0.9998 litres of whisky at 10°C occupy at 20°C?

$V_{whisky@20°C} = V_{whisky@10°C}\,(1 + \Delta T\beta)$

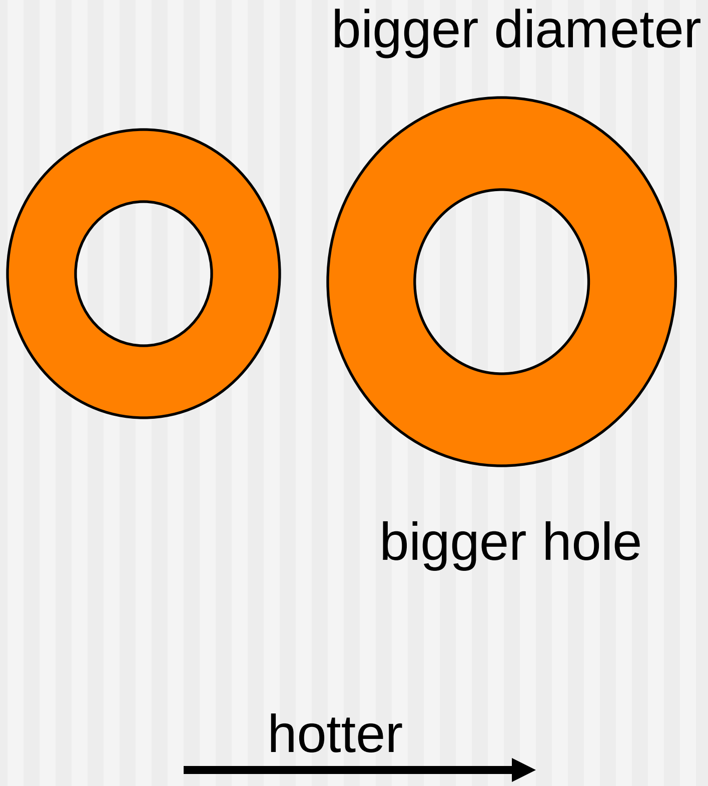
$V_{whisky@20°C} = 0.9998\,(1+10 \times 2\text{x}10^{-5})$

$V_{whisky@20°C} = 0.9998\,(1+10\ \text{x}75\text{x}10^{-5})$

$V_{whisky@20°C}$ = 1.0073 litres

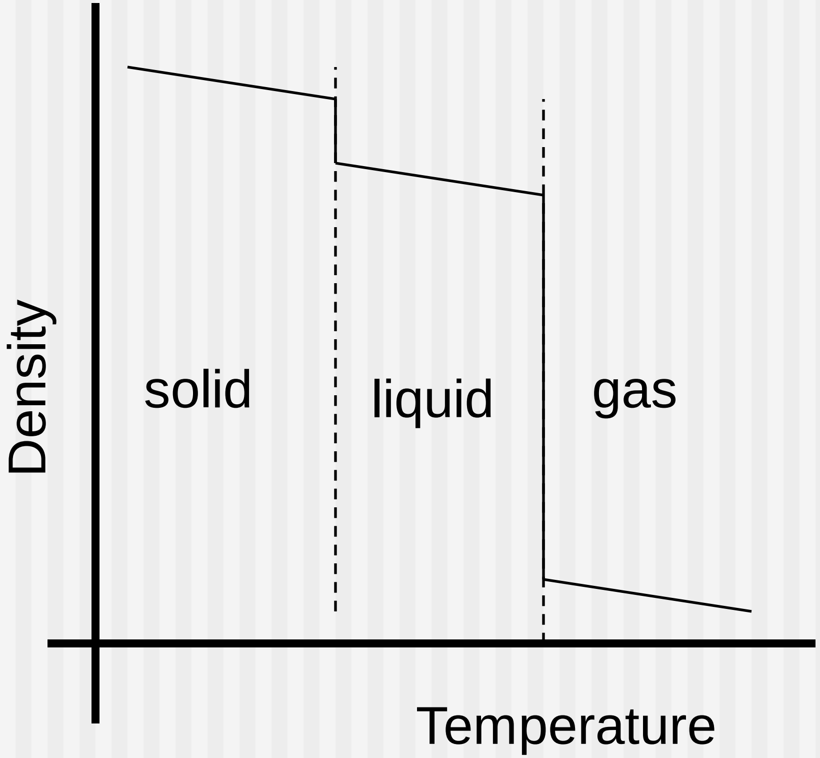
Shape change on expansion

- This can be very complex for mis-matched materials
- Single material (or matched α) much simpler



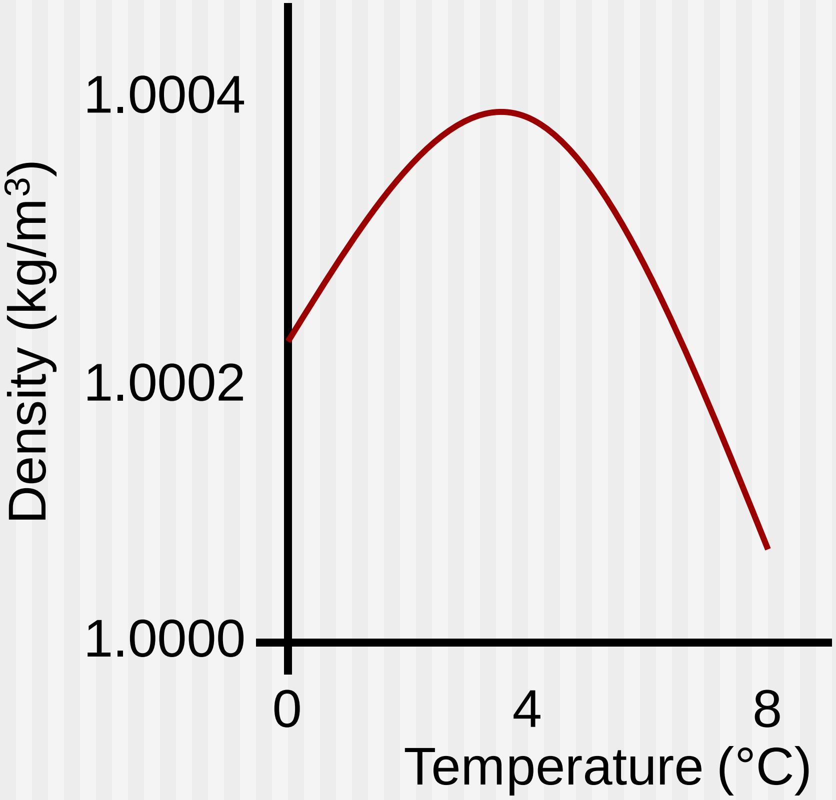
Thermal expansion solid-liquid-gas

- Normally, density (ρ) changes as



Thermal expansion of water

- Density of ice is less than water!!!
  - Icebergs float
- Density of water maximum at 4°C
  - Nearly frozen water floats to the top of the lake and hence freezes

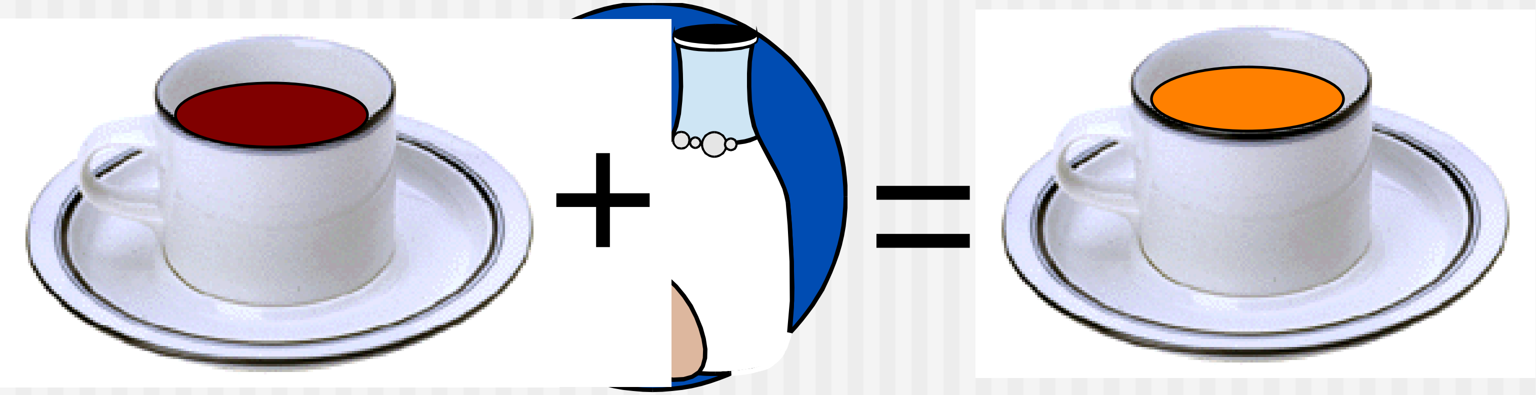


How much energy required to heat object?

- Heat (energy) flows because of temperature difference
  - Bigger temperature difference bigger heat flow
  - Less insulation give more heat flow for the same temperature difference
- Heat will not flow between two bodies of the same temperature

Equilibrium

- Two objects of different temperature when placed in contact will reach the same temperature



Hot black coffee

Cold milk

Warm white coffee

Heat transfer = energy transfer

- Energy measured in Joules but heat often measured in Calories
  - One cal raises one gram of water from 14.5°C to 15.5°C
  - 1 cal - 4.186J
- Doing work on something usually makes it hot
  - Splash in the bath and the water will get warm!
- 1st law of thermodynamics heat and work are both forms of energy

Sir James Joule

- James Joule 1818-1889
- Stirring water made it warm
    - Change in temperature proportional to work done
    - Showing equivalence of heat and energy
- Also that electrical current flow through a resistor gives heating

Some things are easier to heat (specific heat capacity)

- More water in the kettle needs longer time to boil
- Alcohol needs less energy to heat it than water
- Energy required (Q) proportional desired change in temperature (ΔT) x mass (m) of material
  - $Q = mc\,\Delta T$
- c called the specific heat
  - $c_{water} = 4190$ J/(kg K) - very difficult to heat
  - $c_{ice} = 2000$ J/(kg K)
  - $c_{mercury} = 138$ J/(kg K) - very easy to heat
  - $c_{ethanol} = 2428$ J/(kg K) - very easy to heat

Example

- “thrashing” around in the bath should heat up the water.
- How much will the water heat up after one minute of “thrashing”

Estimate volume of water ≈ $0.5m^3$
Estimate power of thrashing ≈ 500W

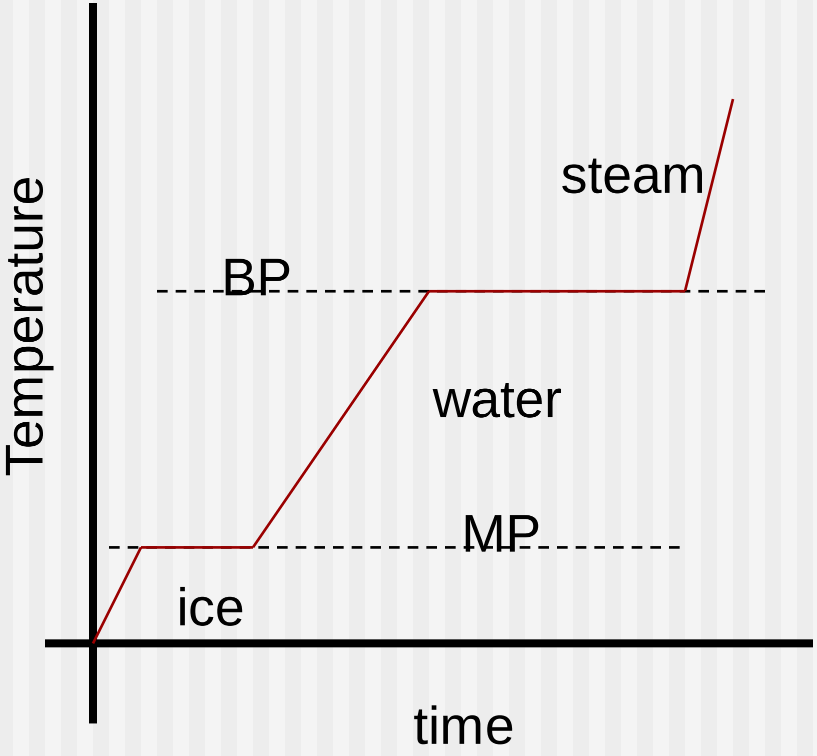
$\Delta T = Q/mc_{water}$
$\Delta T = 500 \times 60 / 500 \times 4190$
$\Delta T = 0.015°C$

Molar heat capacity

- Quote Joules per mole rather than Joules per kilogram
- i.e. $Q = nMc\,\Delta T$
  - n is the number of moles
  - Mc is the molar heat capacity (J/(mol K)
- Mc ≈ 25 J/(mol K) for solids!
  - i.e. energy required to heat one atom of anything is about the same
  - Realised by Dulong and Petit

Phase changes (e.g. solid to liquid)

- When heating ice into water and then into steam the temperature does not go up uniformly
  - Different gradients ($c_{water} > c_{ice}$)
  - Flat bits at phase changes

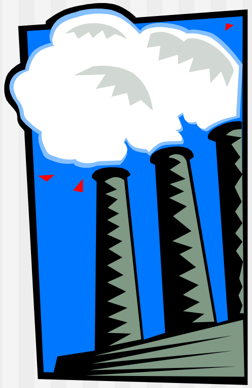


Energy required for phase change

- Heat of fusion (Q), solid -> liquid
  - $Q = mL_f$ (L_f is latent heat of fusion)
    - $L_{f\ (water)} = 334 \times 10^3$ J/kg
    - $L_{f\ (mercury)} = 11.8 \times 10^3$ J/kg
- Heat of vapourisation (Q), liquid -> gas
  - $Q = mL_v$ (L_v is latent heat of vapourisation)
    - $L_{v\ (water)} = 2256 \times 10^3$ J/kg
    - $L_{v\ (mercury)} = 272 \times 10^3$ J/kg
- Heat of sublimation (Q), solid -> gas
  - $Q = mL_s$ (L_s is latent heat of sublimation)

Using condensation to transfer energy

- Steam has two contributions to its stored thermal energy
  - The energy it took to heat it to 100°C
  - The energy it took turn it from water at 100°C to steam at 100°C



Turning water into steam is a thermally efficient way of cooling things down

Example

- If it takes 2 mins for your kettle to begin boiling how much longer does it take to boil dry?
  - Assume kettle is 3kW
  - Starting temp of water 20°C

Work done by kettle = power x time

= 2 x 60 x 3000 = 360 000J

= Work to boil water of mass M

= ΔT x M x c_{water}

= 80 x M x 4190 = 335200 M

-> Mass of water = 1.07kg

Energy to boil water = M x $L_{v\ (water)}$

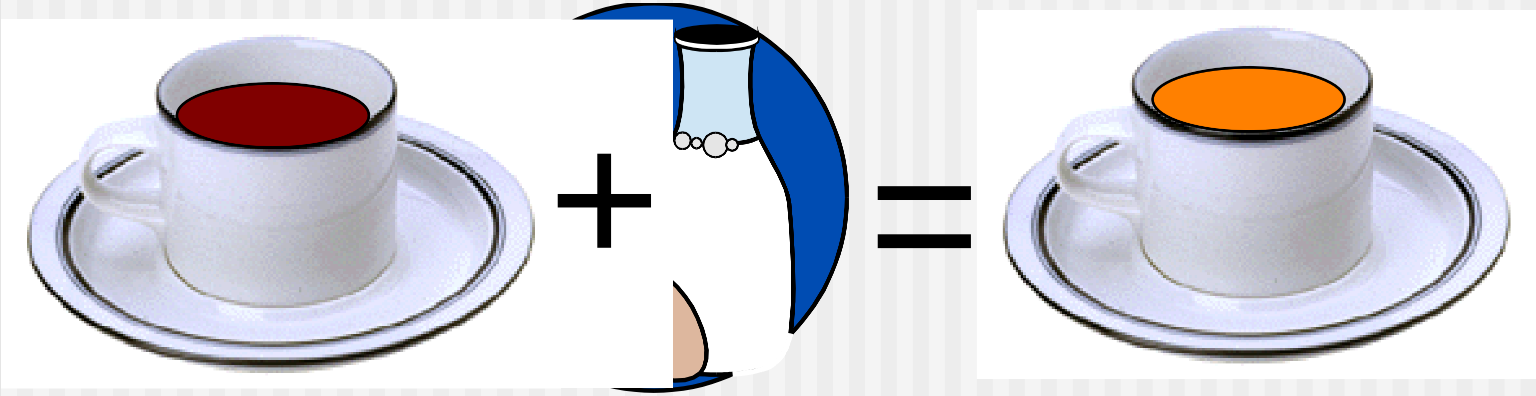
= 1.07 x 2256 x10^3 = 2420 000J

Time required = Energy /power

= 2420 000/3000 = 808 s ≈ 13mins

Reaching thermal equilibrium

- Total energy (heat) of a closed system is constant, $\Delta Q_{coffee} = -\Delta Q_{milk}$ i.e $\Sigma\ \Delta Q = 0$
- By convention heat flowing into a body ΔQ +ve



Hot black coffee at T_H Cold milk at T_C Warm white coffee at T_w

$$(T_H - T_w)m_{coffee}c_{coffee} = -(T_c - T_w)m_{milk}c_{milk}$$

Transferring heat energy

- 3 mechanisms
  - Conduction
    - Heat transfer through material
  - Convection
    - Heat transfer by movement of hot material
  - Radiation
    - Heat transfer by light

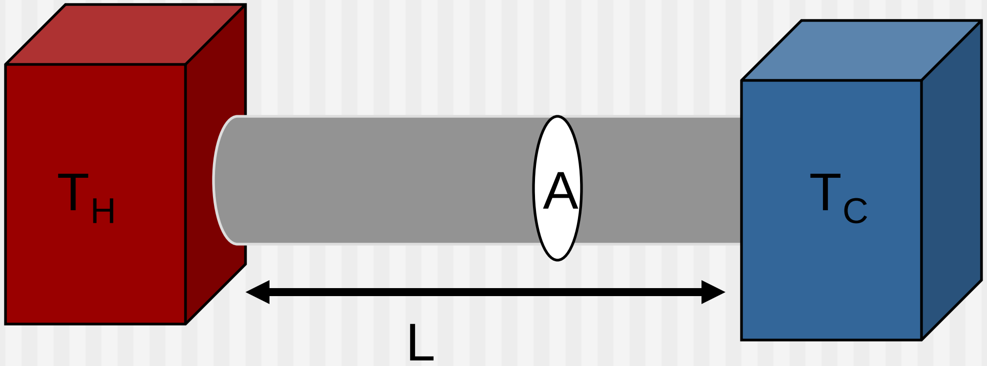
Conduction of heat

- Conduction in solids
  - Heat energy causes atoms to vibrate, a vibrating atom passes this vibration to the next
- Conduction in metal
  - Heat energy causes electrons to gain energy, electrons travel through metal (conduction) and carry heat energy with them
    - Metals are good conductors of both heat and electricity

Rate of heat flow

- Heat flow (H) is energy transfer per unit time, depends on
  - Temperature difference
  - Thermal conductivity (k)
    - $k_{(copper)} = 385$ W/(m K)
    - $k_{(glass)} = 0.8$ W/(m K)
    - $k_{(air)} = 0.02$ W/(m K)

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



Example

- You poke a 1.2m long, 10mm dia. copper bar into molten lead
- How much heat energy flows through the bar to you?
  - Lead melts at 600K

Temperature difference along rod

$\Delta T = 600 - 311 = 289K$

$H = k_{copper} A (\Delta T/L)$

$A = \pi \times r^2 = 3.142 \times 0.005^2$
$= 0.000078 m^2$

$H = k A (\Delta T/L) = 7.3$ units?

Units = $\{W/(mK)\}\ m^2\ K / m$ = Watts

Thermal conduction vs thermal resistance

- Also can use thermal resistance, cf

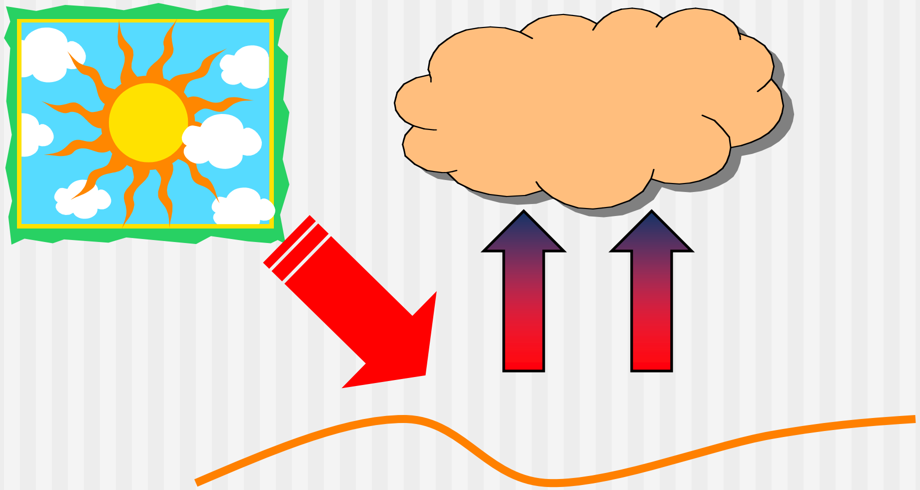
$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L} = \frac{T_H - T_C}{R} \qquad i.e. \quad R = \frac{L}{kA}$$

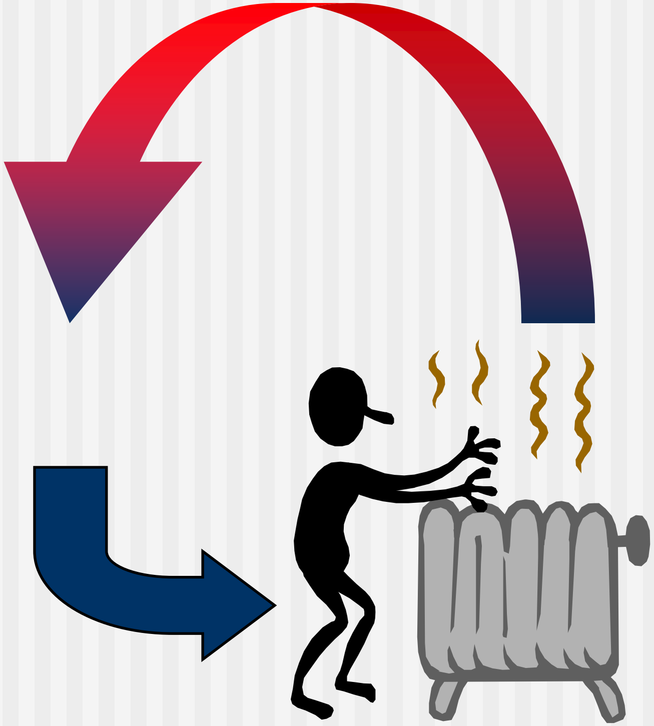
- Can make equation of heat flow more general

$$\mathrm{H} = \frac{\mathrm{dQ}}{\mathrm{dt}} = \mathrm{kA}\frac{\mathrm{dT}}{\mathrm{dx}}$$

Convection of heat

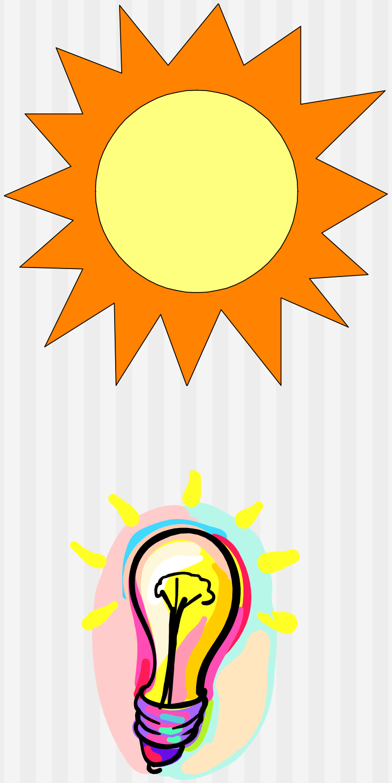
- “Hot air rises” (and takes its heat with it!)
  - Radiators
  - Cumulus clouds





Radiation of heat

- Don’t confuse with radioactivity
- Instead realise that light carries heat (e.g. the sun heats the earth)
- Anything above absolute zero radiates heat
  - Heat energy emitted αT^4



Not all things emit heat the same

- Heat emission from an object area A
  - $H = Ae\sigma T^4$
    - σ = Stafan's constant = $5.6\text{x}10^{-8}$ W/(m^2 K^4)
    - e = emissivity of a body, 0 -1
    - $e_{\text{copper}} = 0.3$
    - $e_{\text{carcoal}} \approx 1$

Example

- Estimate the upper limit to the heat emission of the sun
  - Suns temperature 7000k
  - Sun's radius 7×10^8m

Emission, $H = Ae\sigma T^4$

Area = $4\pi r^2 = 6.2 \times 10^{18}$ m^2

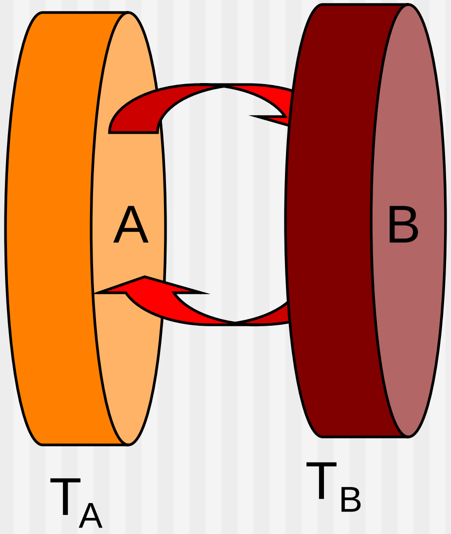
Emissivity ≈ 1

$H = 6.2 \times 10^{18} \times 5.6 \times 10^{-8} \times 7000^4$

Sun's output = 8.3×10^{26} W

Are heat emitter also good absorbers?

- Two bodies close
  - All heat emitted from A hits B
  - All heat emitted from B hits A
  - A is a perfect absorber & emitter
  - B emissivity *e*, absorptivity η
- B in thermal equilibrium, i.e. heat in = heat out
  - $Ae\sigma T_A^4 = A\ \eta\ \sigma T_B^4$
  - $T_A = T_B$ therefore $e = \eta$



The “colour” of heat

- Peak wavelength of light emitted depends on temperature
- Spectrum includes all wavelength longer than the peak but not many above
    - 20°C - peak in infrared (need thermal imaging camera to see body heat)
    - 800°C - peak in red (electric fire glows reds)
    - 3000° - peak in blue (but includes green and red light hence appears white)
    - 2.7K peak in micro-wave (background emission in the universe left over from the Big Bang)

Equations of state

- State, identifies whether solid liquid or gas
- Key parameters or state variables
  - Volume, V (m^3)
  - Pressure, p (N/m^2)
  - Temperature, T (K)
  - Mass, M (kg) or number of moles, *n*
- Equation of state relates V, p , T, m or *n*

Equation of state for a solid

- Increasing the temperature causes solid to expand
- Increasing the pressure causes solid to contract (0 subscript indicates initial value)
  - $V = V_0 [1 + \beta(T - T_0) - k (p - p_0)]$
    - β = thermal (volume) expansion coefficient
    - k = pressure induced volume expansion coefficient

Amount of gas

- Better to describe gas in terms of number of moles (we shall see that all gases act the same!)
- Mass, m related to number of moles, n
  - $m = nM$
    - M = molecular mass (g/mole, 1mole = $6x10^{23}$ atoms or molecules

Equation of state for a gas

- All gases behave nearly the same
  - $pV = nRT$
    - R = 8.3 J/(mol K) for **all** gases (as long as they remain a gas)
    - T is in K!!!!!!
- Re-express
  - $pV = (m/M)\, RT$
- Density $\rho = (m/V)$
  - $\rho = pM/RT$

Example

- What is the mass of a cubic metre of air?
  - Molecular weigh of air ≈ 32g

$pV = nRT$

Atmospheric pressure = 10^5 N/m^2
Atmospheric temp. = 300K

For a volume of 1 m^3

$n = pV/RT = 10^5 / (8.3 \times 300)$
$= 40$ moles

$M = 40 \times 0.032 = 1.3$kg

Constant mass of gas

- For a fixed amount of gas, its mass or number of moles remains the same
  - $pV/T = nR = \text{constant}$
- Comparing the same gas under different conditions
  - $p_1V_1/T_1 = p_2V_2/T_2$
    - Hence can use pressure of a constant volume of gas to define temperature (works even if gas is impure - since all gases the same)
    - Must use T in K!!!!!!

Example

- A hot air balloon has a volume of 150m^3
- If heated from 20°C to 60°C how much lighter does it get?
  - Molecular weight of air ≈32g

$pV/T = nR$

$n = pV/RT$

Balloon has constant volume and constant pressure

$n_{cool} = 10^5 \times 150 / (8.3 \times 293) = 61680$

$n_{hot} = 10^5 \times 150 / (8.3 \times 333) = 54271$

$\Delta n = 7409$ moles

$\Delta M = 7409 \times 0.032 = 237$kg

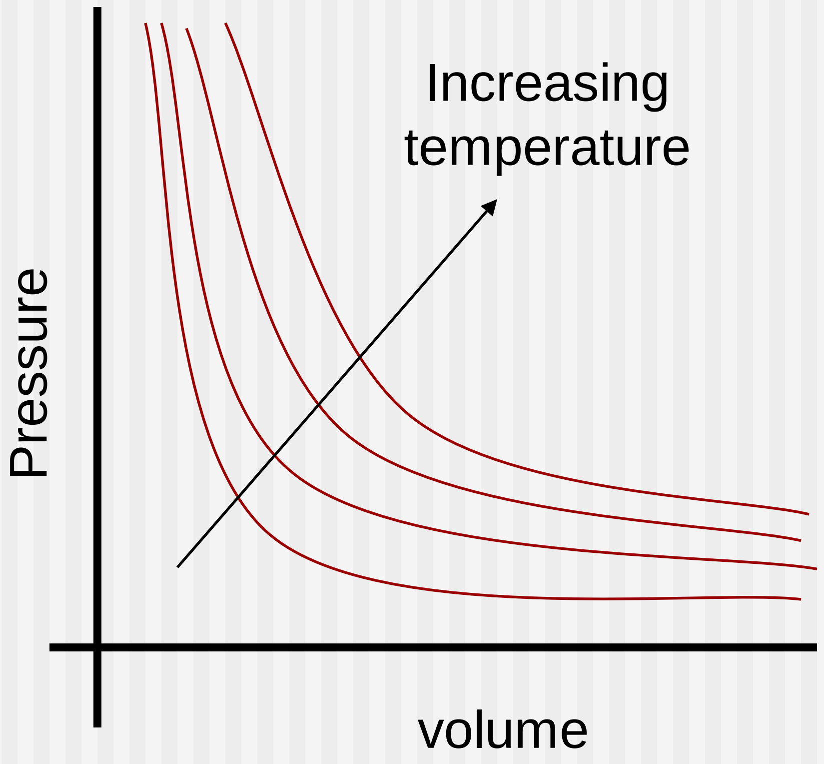
Molecules have finite size

- Cannot reduce volume of gas to zero!
  - When you try, it becomes a liquid
  - Slightly increases the measured volume
- Atoms/ molecules always attract each other
  - Slightly reduces the measured pressure
- Van de Waals equation
  - a and b are measured constants

$$\left(p+\frac{an^2}{V^2}\right)(V-nb)=nRT$$

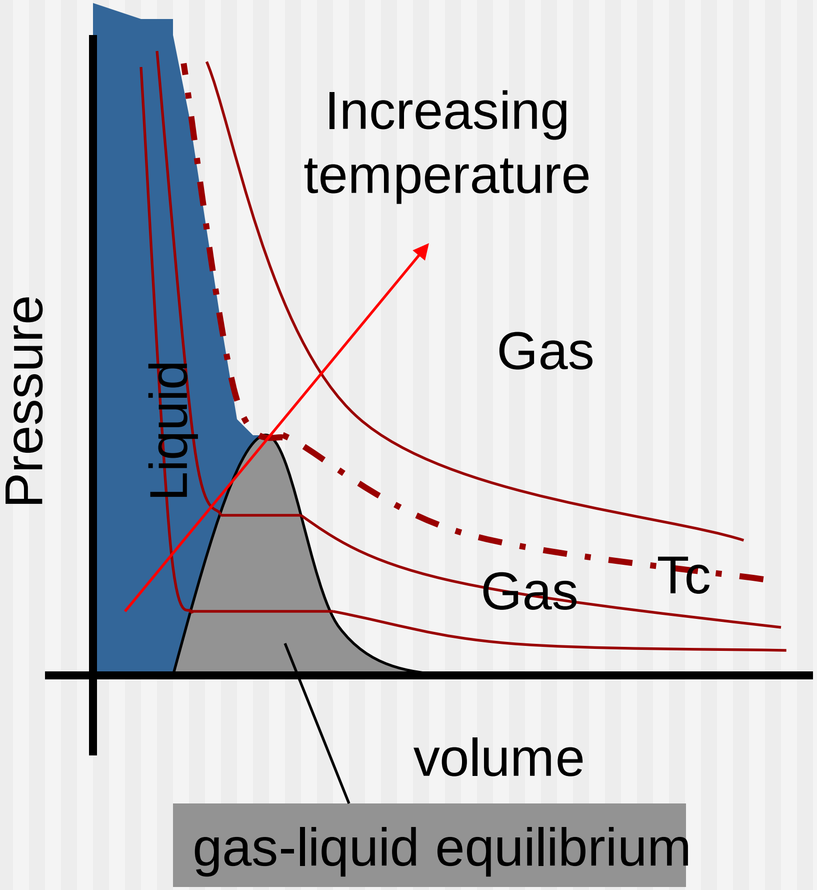
p-V diagrams (for gases)

- Useful to consider the pressure/volume changes at constant temperature
  - Isotherms are p-V values for a fixed amount of gas at constant volume
  - p α 1/V



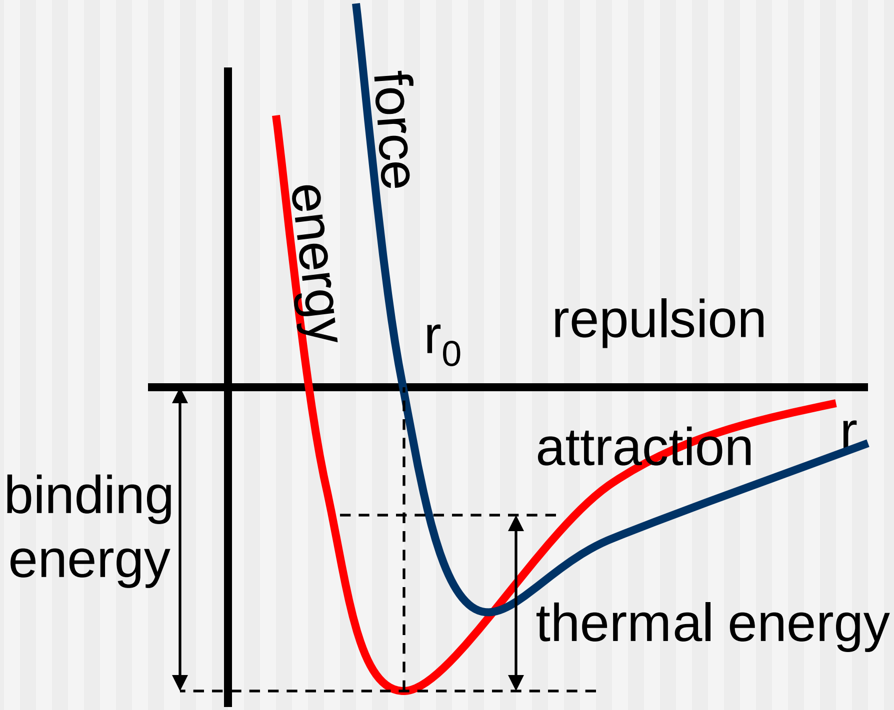
p-V diagrams (including state change)

- Compressing gas into a smaller volume can cause it to liquefy
- At temperatures above Tc, gas cannot be liquefied - even at high pressure
- At temperatures below Tc gas and liquid can co-exist in equilibrium



Bulk vs molecules

- Consider force between two molecules
- At absolute zero
  - No thermal energy
  - Molecules sit at r_0
- Above absolute zero
  - Some thermal energy
  - Molecules are at $r > r_0$ (thermal expansion)
- At high temperature
  - Thermal energy > binding energy
  - Molecules form a gas



$$F(r) = -\frac{dU(r)}{dx}$$

Molecules in a gas

- Gas atoms/molecules move in a straight line
  - velocity due to thermal energy
    - $1/2\ m\ v_x^2 \approx 1/2\ kT$
- Atoms hitting the walls gives (force) pressure
  - $F_{impact} = m\ v_x$