Thermal Physics EE1

Lecture 1

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Recommended books

- Benson – University Physics
  - Chapters 18-20 and parts of 21
- Extra info in C.B.P. Finn - Thermal Physics

Thermodynamics

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

WilliamThompson
(Lord Kelvin)

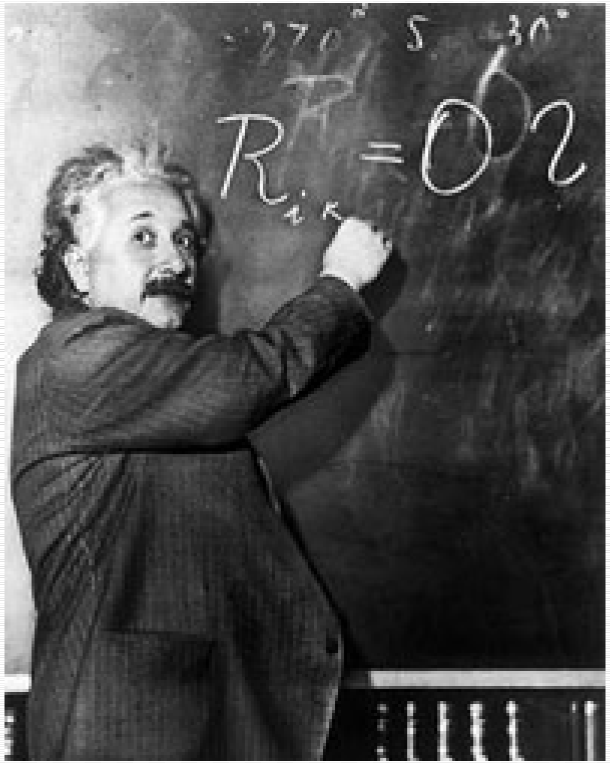
Why study thermal physics???

- Temperature affects material properties, dimensions
- Electrical or electronic components need cooling
  - Transformers
  - ICs
- Thermodynamic effects often used
  - E.g. heat pump in refrigeration
- Efficiency - why can't I turn all my energy into useful work???

What is it all about?

- Describe a system in terms of simple *State Variables*
  - E.g. Temperature, pressure, volume, amount of substance
- Independent of microscopic structure
- But consistent with microscopic understanding
- Very powerful for all sorts of systems!!

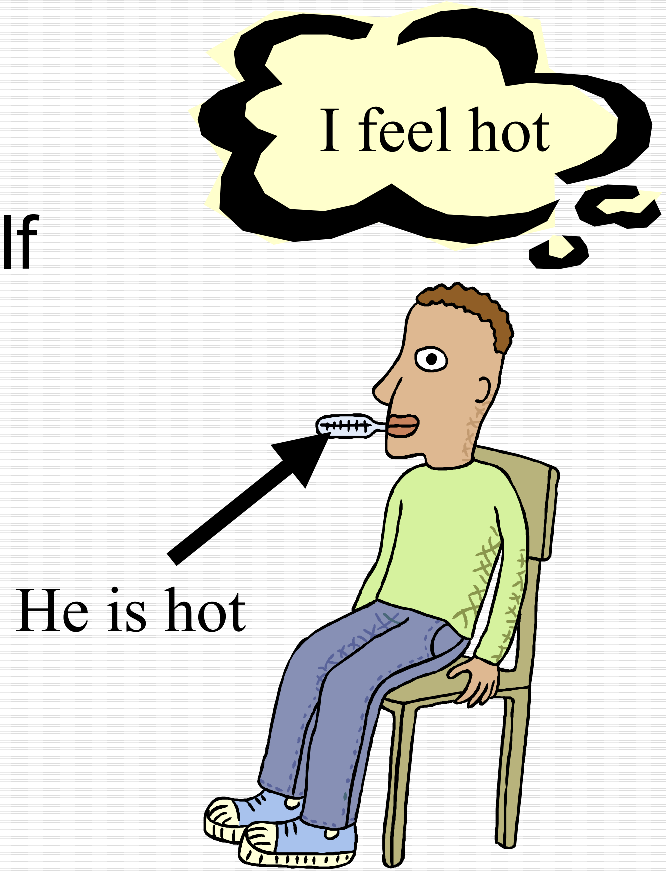
Einstein thought:



A theory is the more **impressive** the greater the **simplicity** of its premises, the more **varied** the kinds of things it relates and the more **extended** the area of its applicability. Therefore classical thermodynamics has made a **deep impression** upon me. It is the only physical theory of **universal** content which I am convinced, within the areas of the applicability of its basic concepts, will **never be overthrown**.

What is Temperature?

- Perception as to hot and cold defined relative to our own body temperature, i.e. object is hotter or colder than oneself
- Own perception misleading
  - Door and doorhandle
  - 21°C air and water
  - Hand in hot then lukewarm water
  - Hand in cold then lukewarm water



What is Temperature - 2?

- 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
  - Electrical Resistance

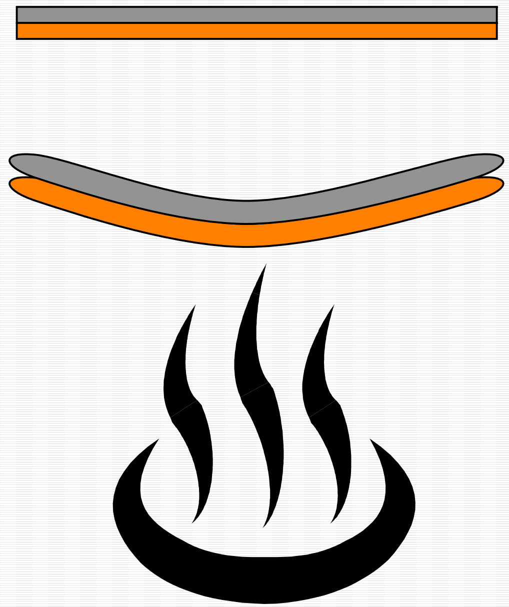
Hotter things become longer

- Most 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

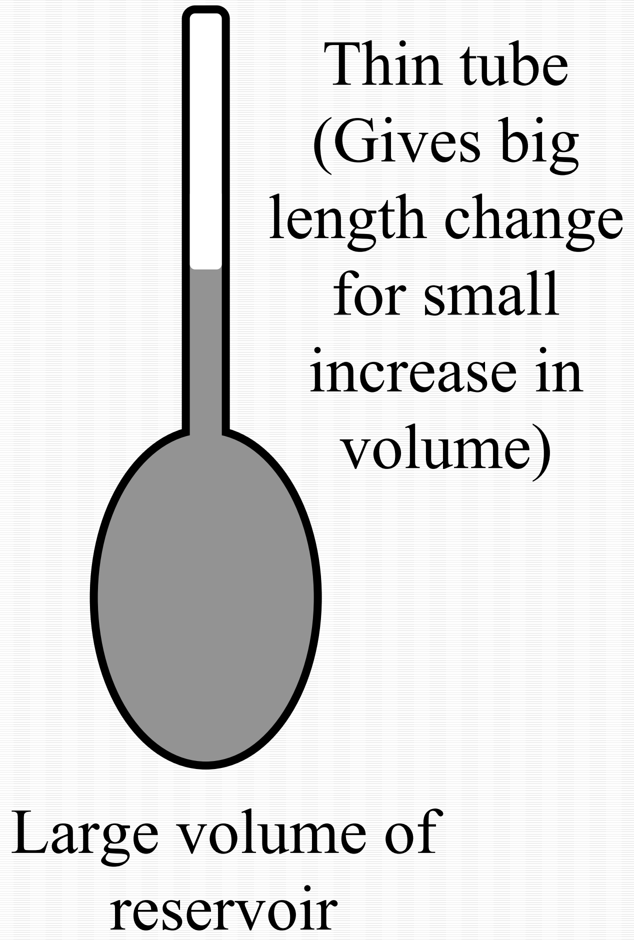
- Join two metals with different coefficient of thermal expansion



e.g. fire alarm

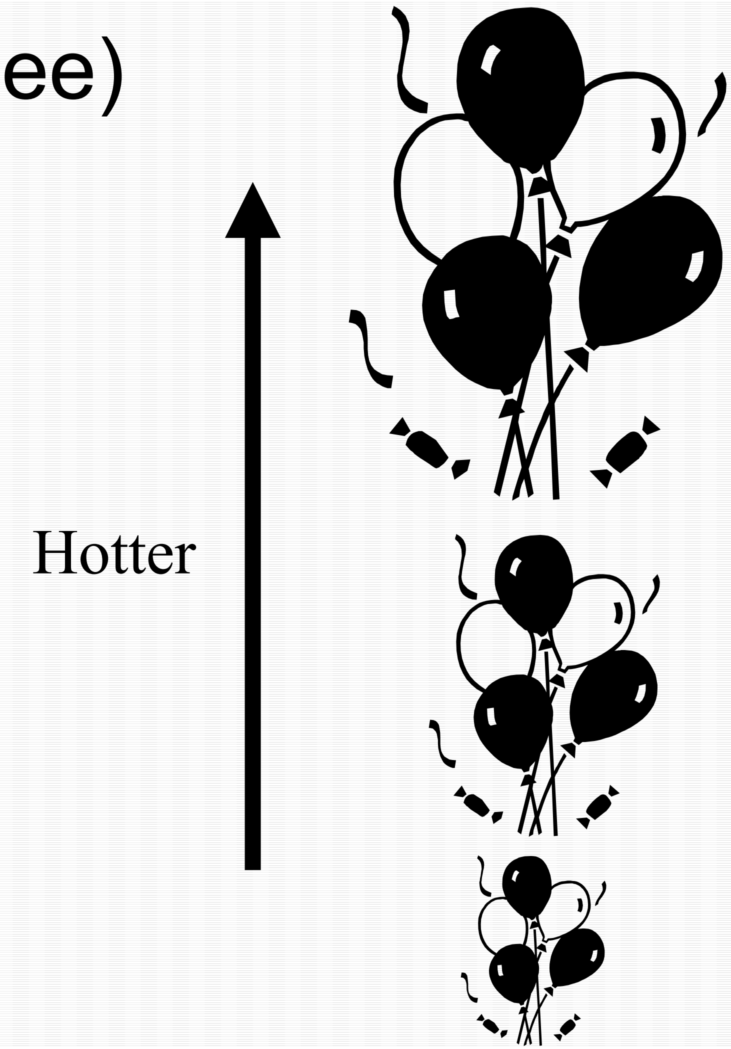
Hotter things take up more volume -1

- 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)



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
- Hotter (undoped) semiconductors have a lower electrical resistance
  - key distinction between metals and insulators!
- Superconductors lose all electrical resistance at low T

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)

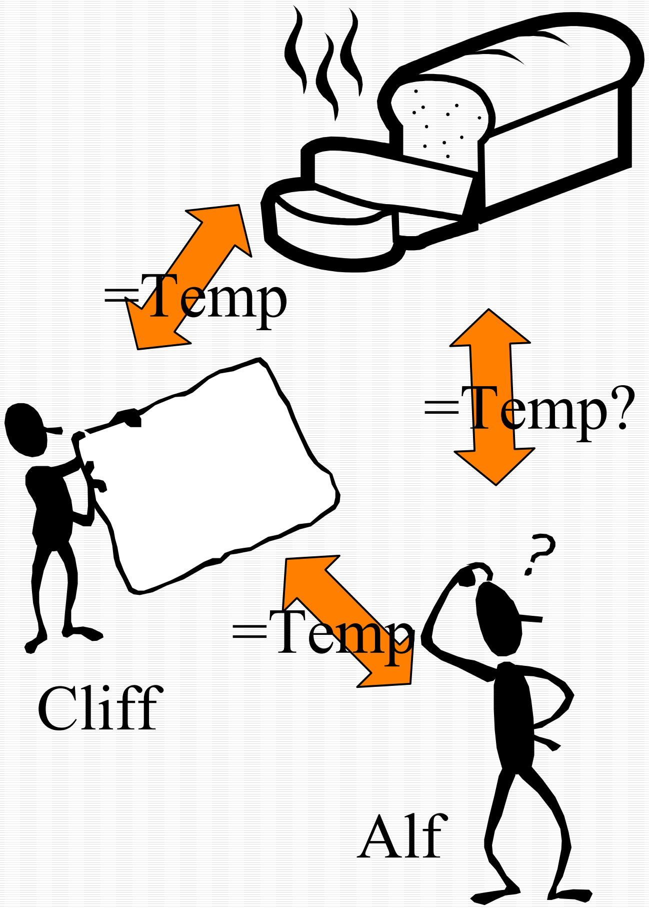
Ask a friend if it’s cool enough to eat

- 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 them, 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.



So what is temperature?

- A *State Variable*
  - *Independent of structure, path to current state etc.*
- Describes thermal equilibrium
- Two objects in thermal contact will reach thermal equilibrium only when they have the same temperature
- Microscopically – to do with motion or vibration of atoms and molecules

Temperature and scales

- We need a linear scale for temperature
- Could use any two fixed points
- Temperature scales in historical order (melting & boiling of water)
  - Degrees Fahrenheit (MP 32° F BP 212°F)
    - 0° F – cold day, 100° F – body temperature (with a cold!!)
  - Degrees Celsius (MP 0°C 100°C)
  - Degrees Kelvin (MP 273.15 K BP 373.15 K)

Converting between scales

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

Example

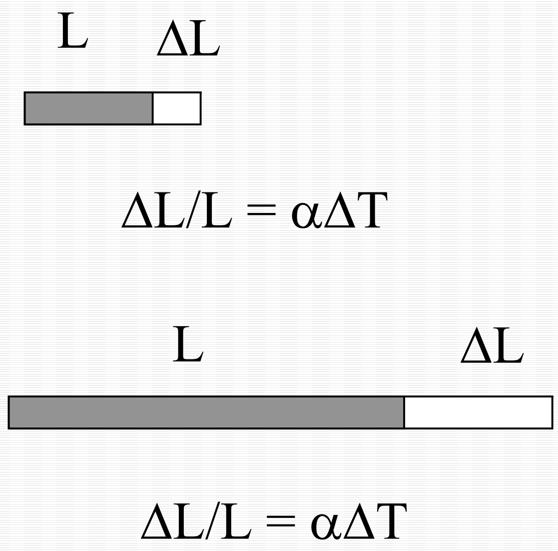
- Convert the following temperatures into °F and K
- Boiling water, 100°C — 212°F, 373.15K
- Freezing water, 0°C — 32°F, 273.15K
- Absolute zero, -273.15°C — -460°F, 0K

Types 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)
- Thermocouple

Linear expansion

- Objects get longer when they get hotter
- Approximately linear over small range
- 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, $\alpha = 2.4x10^{-5}\ K^{-1}$
- Steel, $\alpha = 1.2x10^{-5}\ K^{-1}$
- Glass, $\alpha \approx 5\ x10^{-6}\ K^{-1}$
- Invar, $\alpha \approx 9\ x10^{-7}\ K^{-1}$
- Quartz, $\alpha \approx 4\ x10^{-7}\ K^{-1}$

Example

- Metre rules are calibrated at 20°C
- What is the error in a measurement of 500mm if made at 45°C?
- $\alpha_{steel} = 1.2 \times 10^{-5}\ K^{-1}$

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

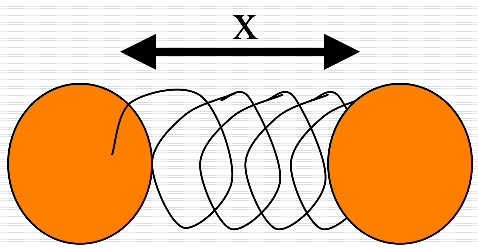
$$\Delta L = L\ \alpha\ \Delta T$$

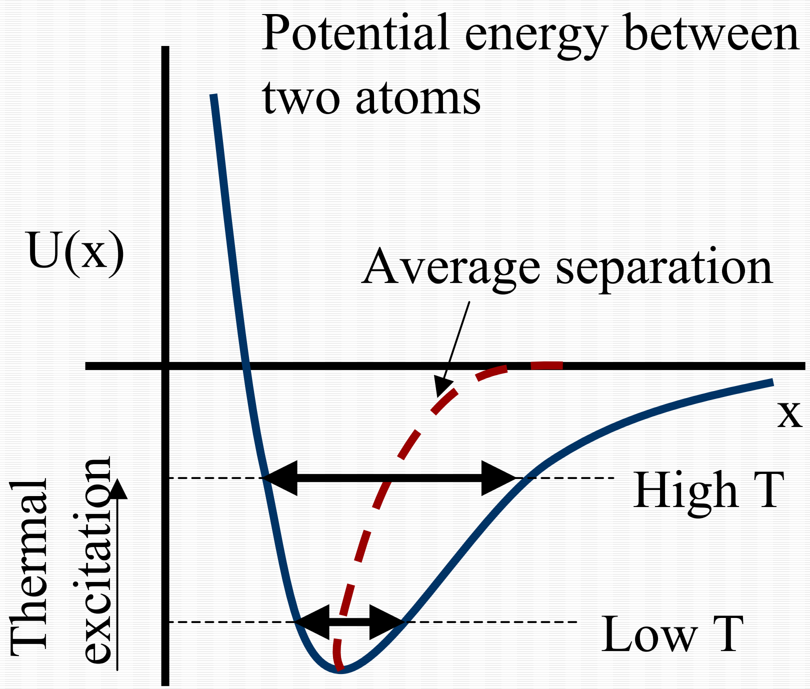
$$\Delta L = 500\ x10^{-3}\ x\ 1.2x10^{-5}\ x\ 25$$

$$\Delta L = 1.5x10^{-6}m = 1.5\mu m$$

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





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Lecture 2

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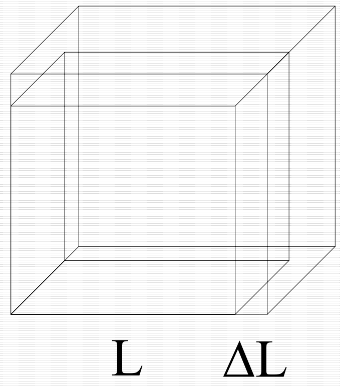
Volume Expansion

- 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
  - $V_{new} = (L + \Delta L)^3 \approx L^3 + 3L^2\,\Delta L$
- But $\Delta L = L\alpha\,\Delta T$
  - $V_{new} = L^3 + 3L^2\,\Delta L = L^3 + 3L^2\,\alpha L \Delta T = L^3 + 3L^3\,\alpha\Delta T$
  - $\Delta V = 3L^3\,\alpha\Delta T$
  - $\Delta V / V = 3\alpha\,\Delta T$ 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?
  - $\beta_{glass} = 2x10^{-5}\ K^{-1}$
  - $\beta_{whisky} = 75x10^{-5}\ K^{-1}$

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

$$V_{bottle@10°C} = 1\ (1 - 10\ x\ 2x10^{-5})$$

$$V_{bottle@10°C} = 0.9998\ \text{litres}$$

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

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

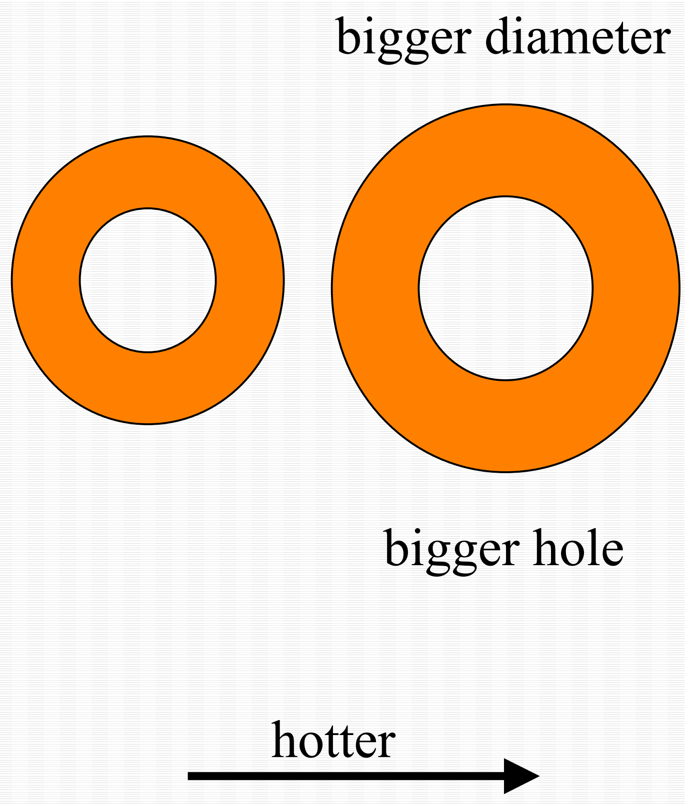
$$V_{whisky@20°C} = 0.9998\ (1+10\ x\ 2x10^{-5})$$

$$V_{whisky@20°C} = 0.9998\ (1+10\ x75x10^{-5})$$

$$V_{whisky@20°C} = 1.0073\ \text{litres}$$

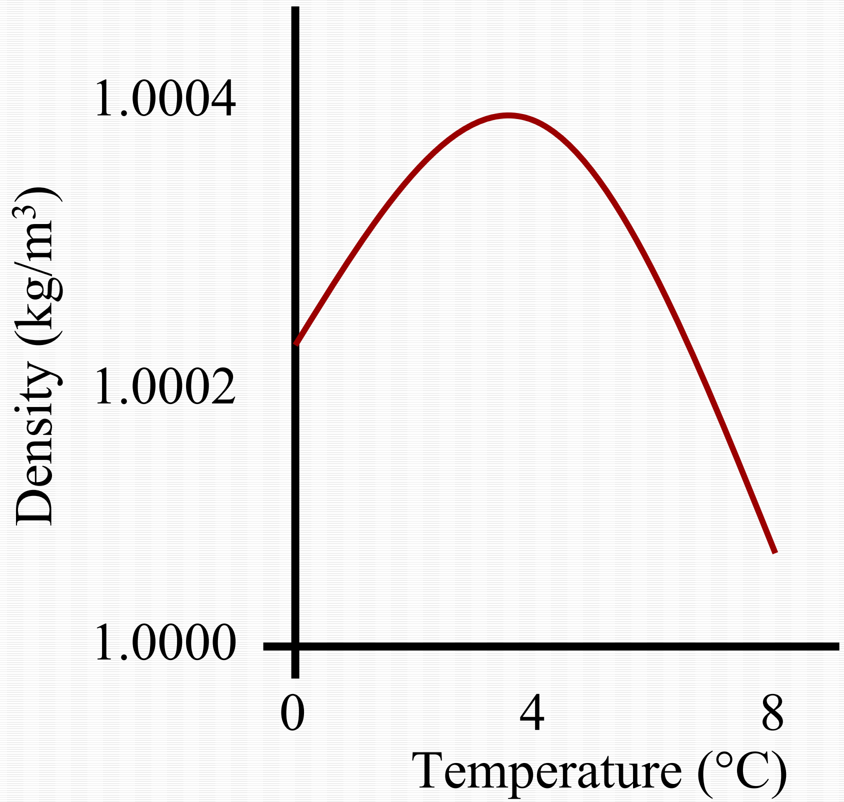
Shape change on expansion

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



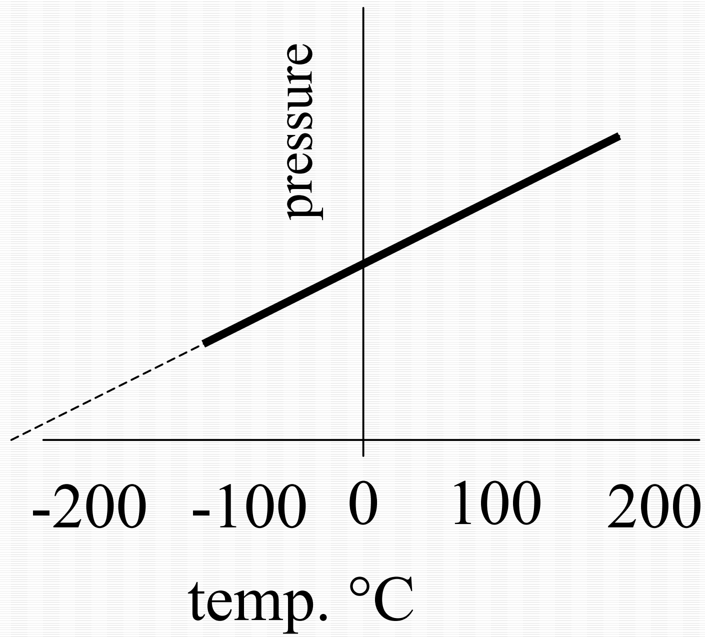
Thermal expansion of water

- 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 at surface



Volume and pressure of a gas

- Gases (at constant pressure) expand with increasing temperature
  - ideal gases tend to zero volume at - 273.15°C!
- Gases (at constant volume) increase pressure with increasing temperature
  - ideal 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 $N/m^2 = Pa$
- 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
  - $1atm \approx 1 \times 10^5 N/m^2 = 0.1 MPa$

Volume and Pressure of a Gas

- Ideal gas law:
  - P V = const.
- Can define PV = NkT
  - Where N is the number of molecules
  - And k is Boltzmann's constant, 1.38×10^{-23} J K^{-1}
- Alternatively PV = nRT
  - Where n is the number of moles of a gas
  - $N = n N_A$
  - where N_A is Avogadro's number, 6.02×10^{23} mol^{-1}
  - $R = k N_A = 8.314$ J mol^{-1} K^{-1}

Volume and pressure 2

- Any two temperatures defined by the ratio
  - $P_1 T_2 = P_2 T_1$ or $V_1 T_2 = V_2 T_1$
- Can use this to calculate volume or pressure changes with temperature

Example

- A bottle of hair spray is filled to a pressure of 1 atm 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 1

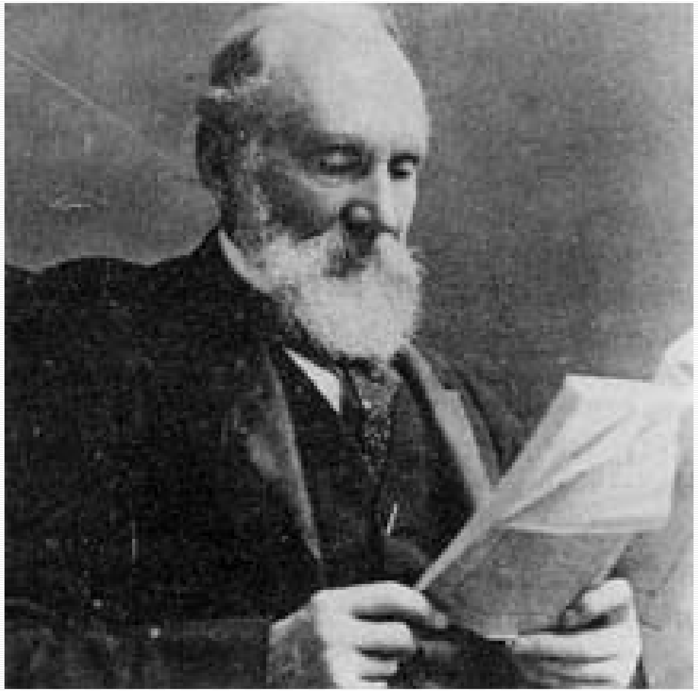
- On the Kelvin scale, the lowest possible temperature is 0 K. (zero volume and zero pressure)
- The zero point is fixed -
  - Absolute Zero (≈ -273.15°C)
- Additional point defined at triple point of water (occurs at one temp and pressure where ice, steam and liquid all coexist (≈ 0.01°C and 0.006 atm)
- T_{triple} = 273.16K
- $T = 273.16 \quad x\ (p/p_{triple})$

Absolute zero 2

- Ideal gas has zero volume
- Resistance of metal drops to zero (superconductivity cuts in above 0K)
- Brownian motion ceases (kinetic energy due to thermal excitation ≈ 3/2 kT, see later)
- But lowest temperature yet attained in lab is ≈ 10^{-9}K
- Very difficult to get really cold!!!

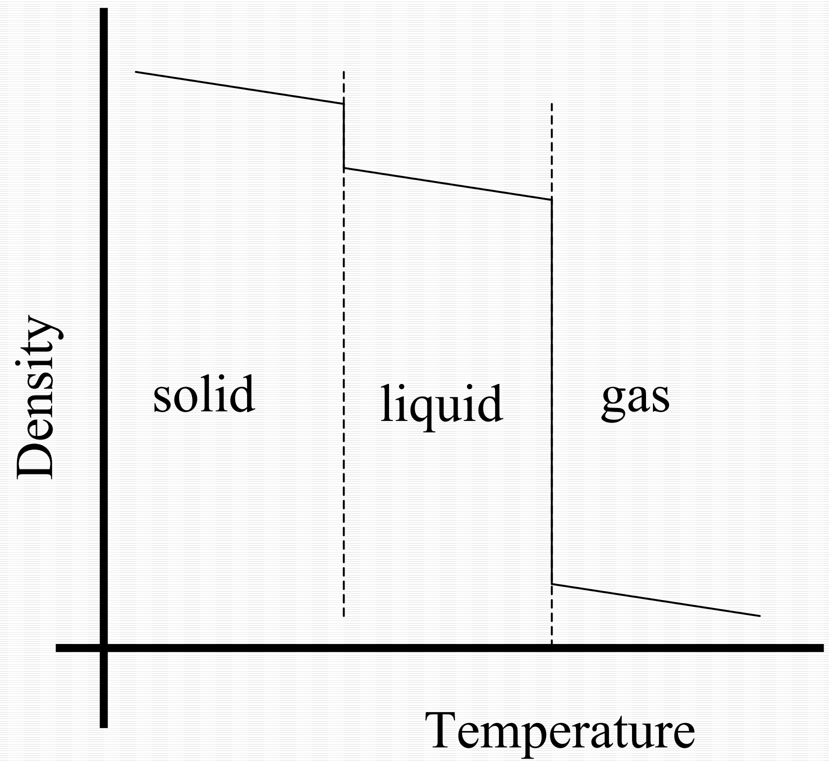
Lord Kelvin

- 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 solid-liquid-gas

- Normally, density (ρ) changes as

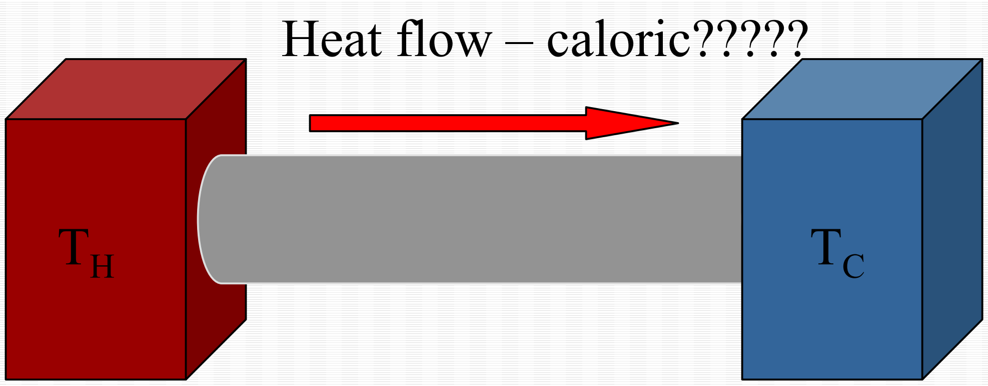


How much energy required to heat object?

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

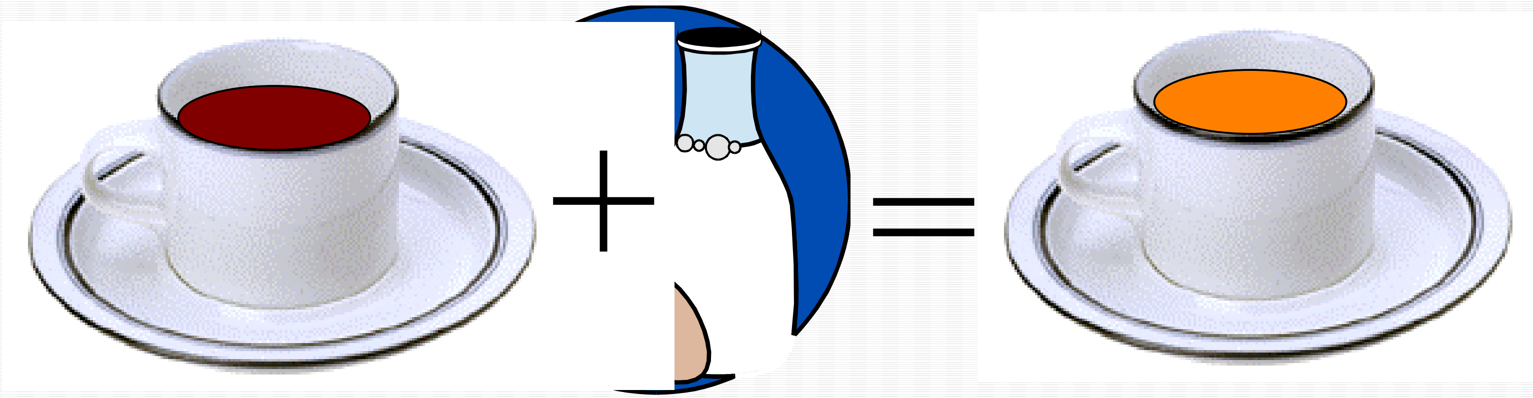
What is heat?

- Heat flows from hot bodies to cold bodies until the temperature of the two is the same
- Early researchers thought it was a substance called caloric



Equilibrium

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



Hot black coffee   Cold milk   Warm white coffee

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

Sir James Joule 2

- Heat and energy are the same thing
- Measured in Joules (J)
- Sometimes measured in calories
  - One cal raises one gram of water from 14.5°C to 15.5°C
  - 1 cal - 4.186J

1st Law of Thermodynamics Heat transfer = energy transfer

- Doing work on something usually makes it hot
  - Splash in the bath and the water will get warmer!
- 1st law of thermodynamics heat and work are both forms of energy
- $\Delta U = Q - W$
- Same as conservation of energy
  - Can neither be created nor destroyed, just changes form

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Lecture 3

Heat capacity and heat transfer

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How quickly do things get hot?

- If you give heat to something
  - T increases
  - How fast?
  - Depends on the substance
  - Alcohol heats quicker than water
  - Also depends on how much you have of the substance

Specific heat capacity

- $Q = mc\,\Delta T$
  - Q is heat required
  - m is the mass of substance
- c is called the specific heat capacity
  - $c_{water} = 4190\ J\ kg^{-1}\ K^{-1}$ - very difficult to heat
  - $c_{ice} = 2000\ J\ kg^{-1}\ K^{-1}$
  - $c_{ethanol} = 2428\ J\ kg^{-1}\ K^{-1}$ - easier to heat
  - $c_{mercury} = 138\ J\ kg^{-1}\ K^{-1}$ - very easy to heat
- The higher c is, the more energy we need for heating

Example – heat capacity

- "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

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

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

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

Example 2 – heat capacity

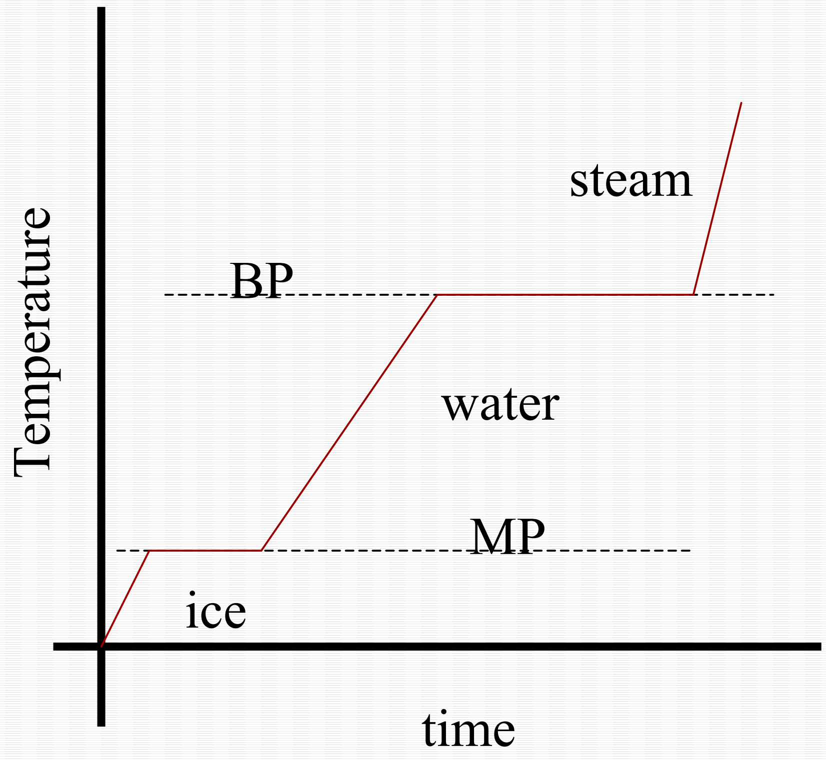
- A 2.5 kg steel bar is heated to 1000 °C
- It is then dropped into a 10 l tank of cold water at 10 °C (approx 10 kg water)
- What is the final temperature of the water?
- $c_{steel} = 420 \text{ J kg}^{-1} \text{ K}^{-1}$
- $c_{water} = 4190 \text{ J kg}^{-1} \text{ K}^{-1}$
- $m_{water}\, c_{water}\, \Delta T_{water} = - m_{steel}\, c_{steel}\, \Delta T_{steel}$
- $\Delta T_{steel} / \Delta T_{water} = -39.9$
- $\Delta T_{water} - \Delta T_{steel} = 990$
- $\Delta T_{water} + 39.9\, \Delta T_{water} = 990$
- $\Delta T_{water} = 990/40.9 = 24.2\ °C \Rightarrow T_{final} = 34.2\ °C$
- $\Delta T_{steel} = -990/1.025 = 965.8\ °C$!!!!!!

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 ($J\ mol^{-1}\ K^{-1}$)
- $Mc \approx 25\ J\ mol^{-1}\ K^{-1}$ 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
  - Need heat to convert
    - Solid to liquid
    - Liquid to vapour



Energy required for phase change

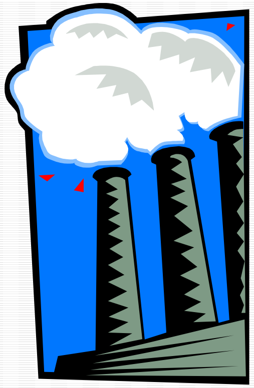
- Heat of fusion (Q), solid -> liquid
  - $Q = mL_f$ (L_f is latent heat of fusion)
    - $L_{f\ (water)} = 334 \times 10^3$ J/kg
    - $L_{f\ (mercury)} = 11.8 \times 10^3$ J/kg
- Heat of vapourisation (Q), liquid -> gas
  - $Q = mL_v$ (L_v is latent heat of vapourisation)
    - $L_{v\ (water)} = 2256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

Other phase changes

- Magnetic transitions
  - Iron is paramagnetic at high temperature
    - Can be magnetised
    - Not permanently magnetised
  - Is ferromagnetic at lower temperatures
  - Change happens at the *Curie Temperature*
- Changes in crystal structure, ferroelectrics etc.
- May also have latent heats associated

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
- Same idea with sweating
  - Sweat forms on the skin
  - It evaporates and this requires energy
  - Your skin gets cooler



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

Transferring heat energy

- 3 mechanisms
  - Conduction
    - Heat transfer through material
  - Convection
    - Heat transfer by movement of hot material
  - Radiation
    - Heat transfer by electromagnetic radiation (light, IR, etc.)

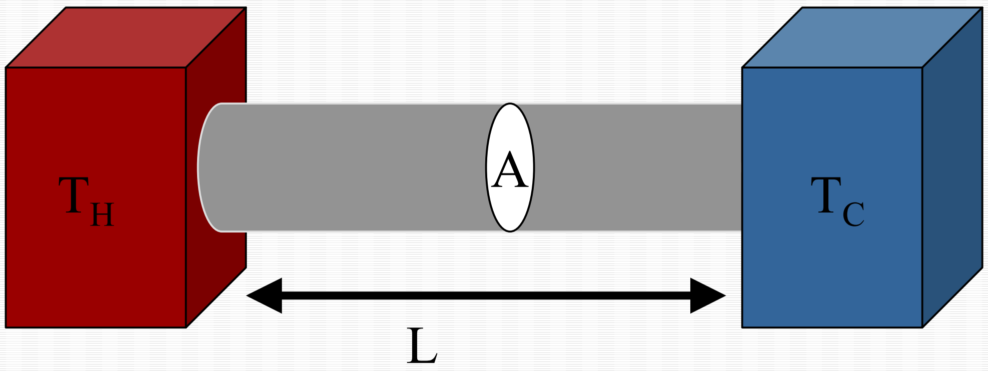
Conduction of heat

- Conduction in solids
  - Heat energy causes atoms to vibrate, a vibrating atom passes this vibration to the next and so on
- Conduction in metal
  - Have free electron "gas"
  - Conduction electrons can move where they wish
  - Heat energy causes electrons to gain energy
  - This energy is rapidly spread out through entire free electron gas
    - 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 (κ)
    - k $_{(copper)}$ = 385 W/(m K)
    - k $_{(glass)}$ = 0.8 W/(m K)
    - k $_{(air)}$ =0.02 W/(m K)

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



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

- Can also use thermal resistance, R

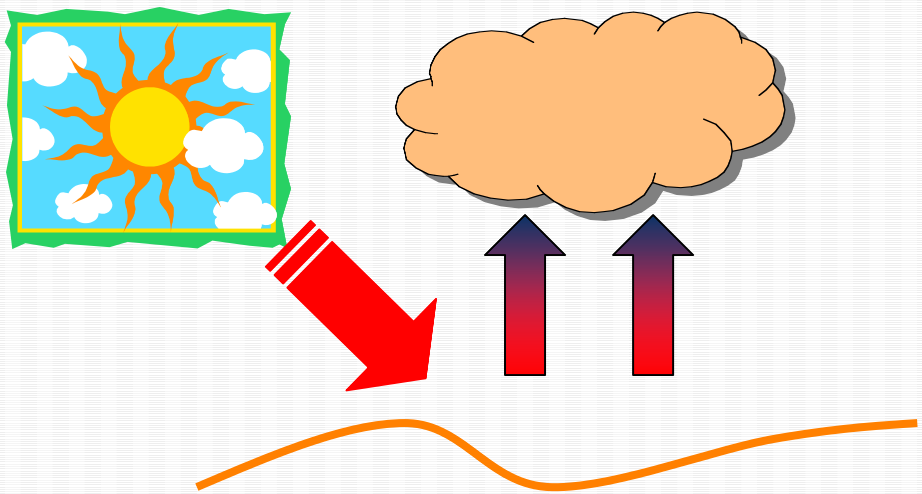
$$H = \frac{dQ}{dt} = \kappa A \frac{T_H - T_C}{L} = A \frac{T_H - T_C}{R} \qquad i.e.\ \ R = \frac{L}{\kappa}$$

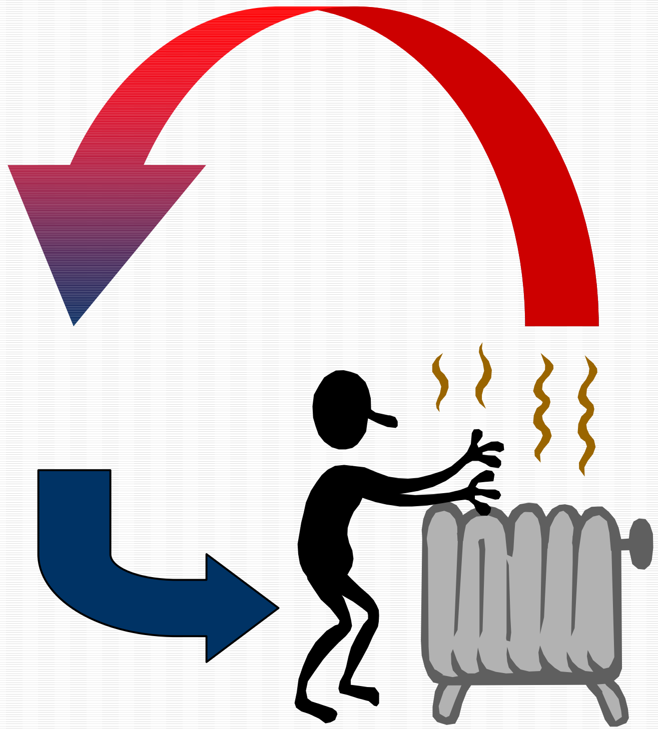
- R values often quoted for household insulation (in absurd imperial units!!)
- Can make equation of heat flow more general

$$H = \frac{dQ}{dt} = \kappa A \frac{dT}{dx}$$

Convection of heat

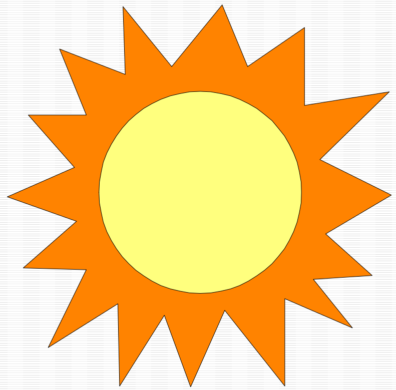
- “Hot air rises” (and takes its heat with it!)
  - Radiators
  - Cumulus clouds





Radiation of heat

- Don't confuse with radioactivity
- Instead realise that EM radiation (light etc.) carries heat (e.g. the sun heats the earth)
- Anything above absolute zero radiates heat
  - Heat energy emitted $\propto T^4$



Not all things emit heat the same

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

Example

- Estimate the upper limit to the heat emission of the sun
  - Sun's surface temperature 6000k
  - Sun's radius 7×10^8m

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

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

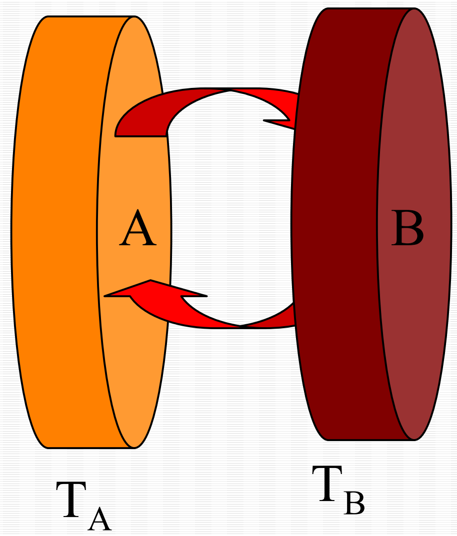
Emissivity ≈ 1

$H = 6.2 \times 10^{18} \times 5.6 \times 10^{-8} \times 6000^4$

Sun's output = 4.5×10^{26} W

Are heat emitters 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 with A, i.e. heat in = heat out
  - Area $\eta_B \sigma T_A^4$ = Area $e_B \sigma T_B^4$
  - $T_A = T_B$ therefore $e_B = \eta_B$



The “colour” of heat

- Peak wavelength of EM radiation 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 red)
  - 3000° - peak in blue (but includes green and red light hence appears white)
  - 2.7K peak in microwave (background emission in the universe left over from the Big Bang)

Thermal Physics – EE1

Lecture 4

Ideal gases

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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 = *n*M
    - 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^{-1} K^{-1}) 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 weight of air ≈ 32 g

$pV = nRT$

Atmospheric pressure = 10^5 Pa
Atmospheric temp. = 300 K

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 ≈32 g mol^{-1}

$pV/T = nR$

$n = pV/RT$

Balloon has constant volume and constant pressure

$n_{cool} = 10^5 x150 / (8.3\ x293) = 6168$

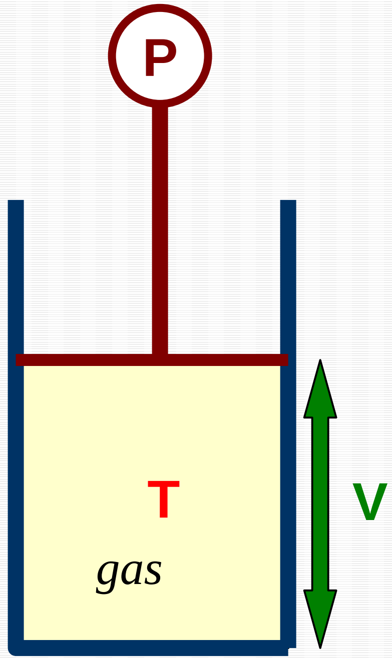
$n_{hot} = 10^5 x150 / (8.3\ x333) = 5427.1$

$\Delta n = 7409$ moles

$\Delta M = 740.9\ x\ 0.032 = 23.7kg$

Work on and by gases

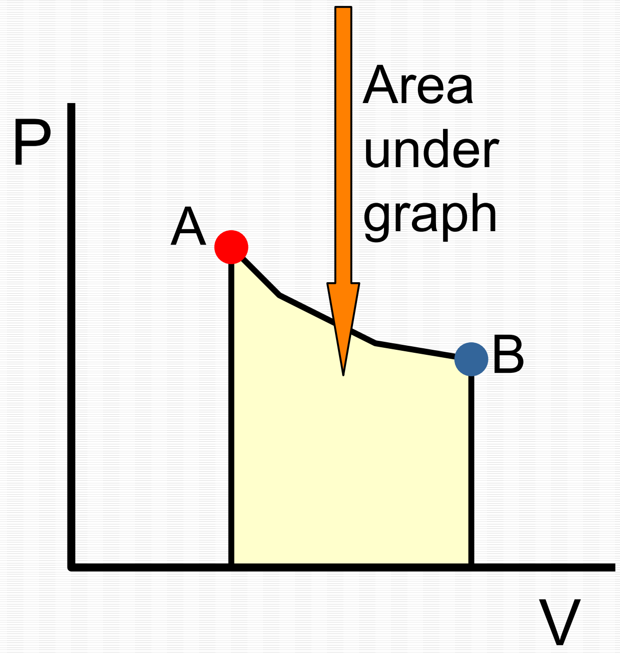
- Compress
  - V → V-dV
  - Work done on the gas by the piston
  - W is -ve
- Expand
  - V → V+dV
  - Work done on the piston by the gas
  - W is +ve



Work done on/by gas

- $dW = F\,dx$
- $P = F/A$
- $dW = P\,Adx$
- $Adx = dV$
- $dW = PdV$
- $P = nRT/V$ so P depends on V

$$W = \int PdV$$

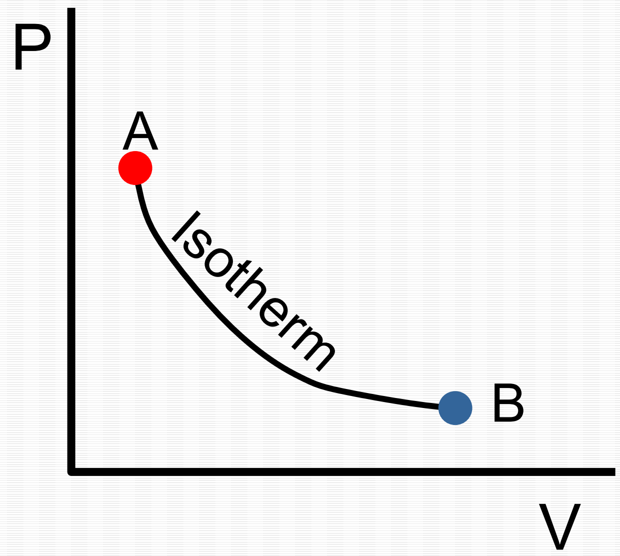


Change of State processes

- How to get “there” from “here”
- Isothermal
  - Same temperature
- Isobaric
  - Same pressure
- Isovolumetric
  - Same volume
- Can relate to first law of thermodynamics
  - $\Delta U = Q - W$

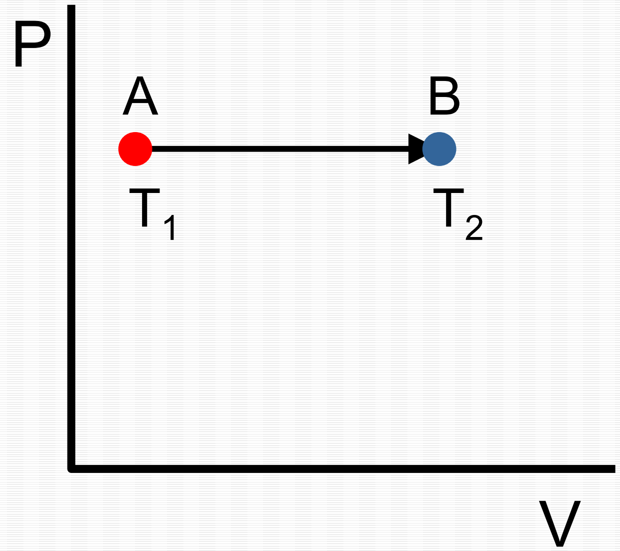
Isothermal

- Iso – same
- Thermal – temperature
- Pressure and volume change inversely
- PV = const
  - Boyle's law
- For ideal gas, if T is constant, U is constant
- $\Delta U=0=Q-W \Rightarrow Q = W$
- Heat input = Work done



Isobaric

- Iso – same
- Baric – pressure
- V increases with T or vice versa



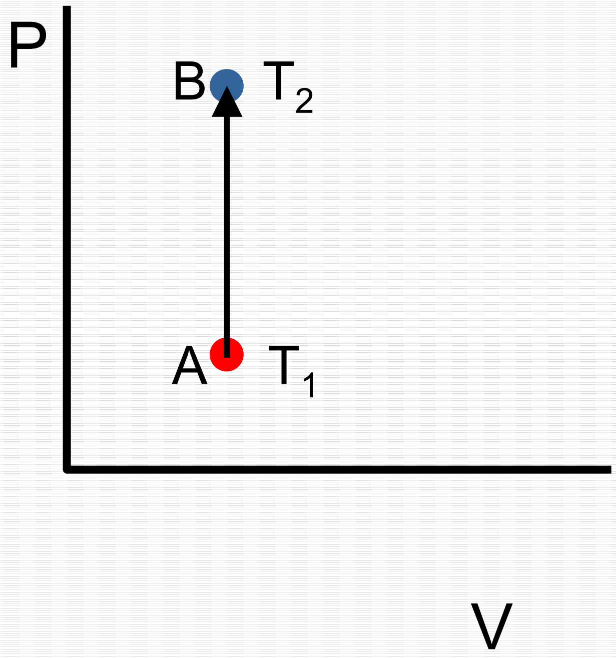
Isovolumetric

- Iso – Same
- Volumetric – volume
- As P increases, T increases
- $V_1=V_2$

$$W = \int PdV = 0$$

$$\Delta U = Q$$

- All heat converted to internal energy

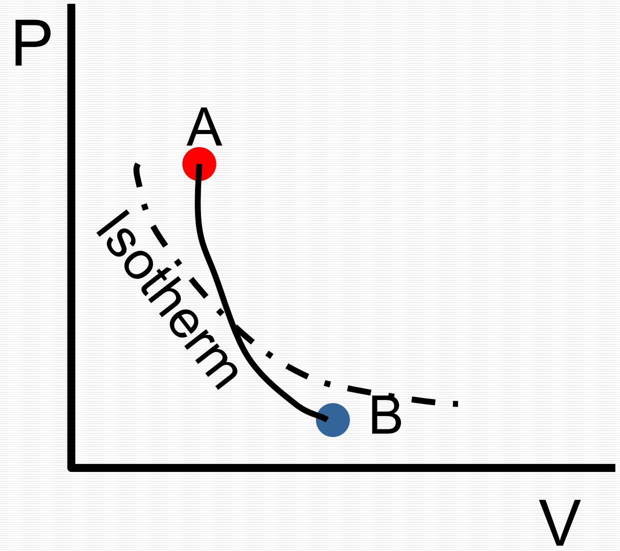


Adiabatic

- A – not
- Dia – through
- Batic – passable
- i.e. No heat flow
- $Q = 0 \Rightarrow \Delta U = -W$
- Process occurs fast

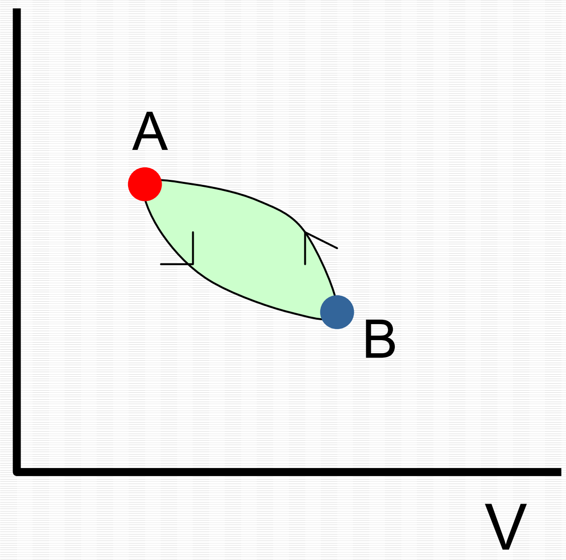
or

- Container is well insulated
- Adiabats obey PV^{γ} = const.



Cyclic processes

- Go from one state (point) to another and return by different route
- Net work: area of cycle (shaded)

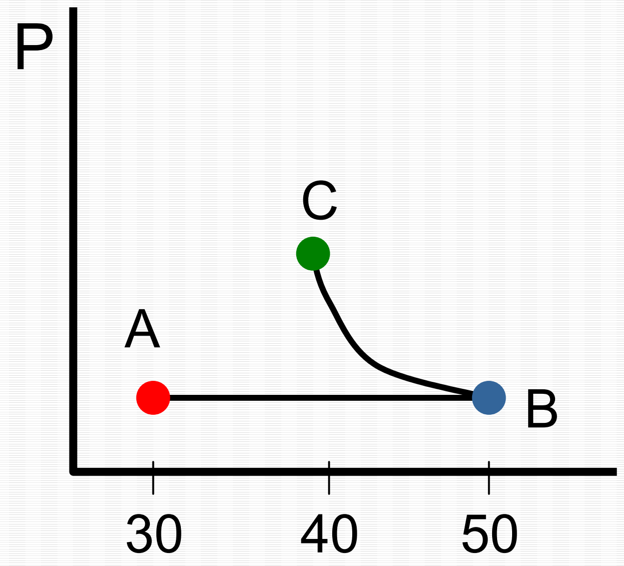


- Quasistatic process
  - Slow change in state variables P, V, T

Example

- Ideal gas expands isobarically at P = 120 kPa from A to B
- It is then compressed isothermally from B to C
- Find the work done

$$W = \int P dV$$



- A to B: P const

$$W = P\int dV = P(V_2 - V_1)$$

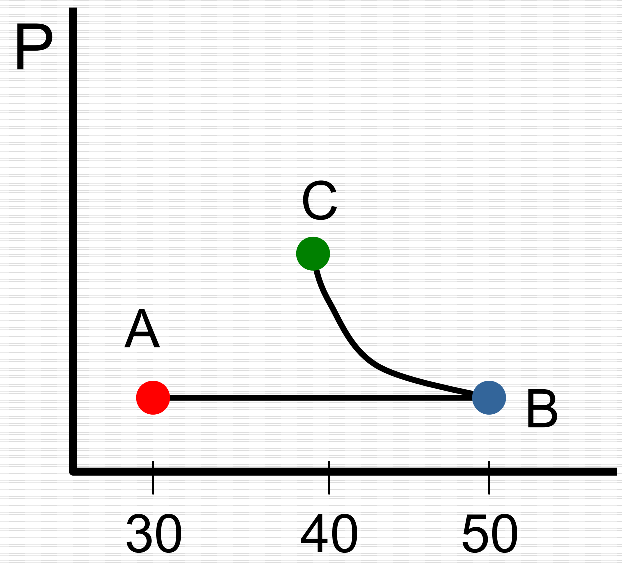
$$= 120x10^3 x(50 - 30)x10^{-3} = 2400J$$

Example continued

- B-C: T constant

$$W = \int_{V_1}^{V_2} PdV = nRT\int_{V_1}^{V_2} \frac{dV}{V}$$

$$= nRT(\ln V_2 - \ln V_1)$$



- At B

$$PV = 120x10^3 x50x10^{-3} = 6000J = nRT$$

$$W = 6000(\ln V_2 - \ln V_1) = 6000\ln\frac{V_2}{V_1} = -1339J$$

$$W_{total} = 2400 - 1339 = 1061J$$ **Done by the gas**