PRE-U REVISION NOTES.

THERMAL PHYSICS (I)

TEMPERATURE & HOW TO MEASURE IT
IDEAL GASES. LATENT HEAT OF FUSION & VAPORIZATION. COOLING CURVES

$\boxed{\text{Thermodynamics}}$ is the physics of heat, what it is and how it is transported. Heat is the kinetic energy associated with the random motion of a large number of molecules which constitute a gas, liquid or solid. It is a statistical theory ie. properties such as pressure, temperature and density are averages.

The $\boxed{\text{Kelvin}}$ scale of temperature (T) is proportional to the mean kinetic energy of molecules

For a gas:

$$\boxed{U = \alpha \times \tfrac{1}{2} n R T}$$

Internal energy

Degrees of freedom of molecular motion (x, y, z so $\alpha = 3$ for most gases)

moles of gas

Molar gas constant $8.314\ \text{J mol}^{-1}\ \text{K}^{-1}$

'Absolute' temperature /K

ie where we can ignore the effect of intermolecular forces as molecules are moving too fast and density is low ie mean free path >> molecular dimensions

1 mole = N_A molecules

$$\boxed{N_A = 6.02 \times 10^{23}}$$

(Avogadro's number)

$\boxed{\text{Celsius}}$ scale is based upon the freezing (0°C) and boiling (100°C) points of water at at 1 atmosphere (101,325 Pa)

$$\boxed{T_C = T - 273}$$

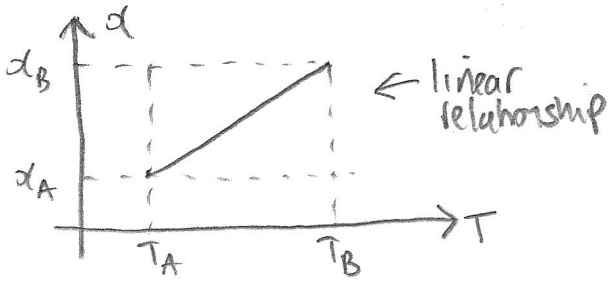
Fahrenheit is based upon cold brine (0°F) and the human body temperature (37°C or 100°F)

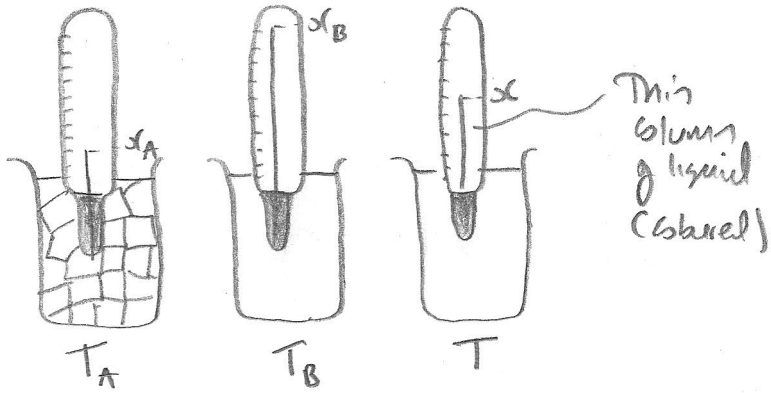
$$\boxed{T_F = \frac{9}{5}(T - 273) + 32}$$

when $\boxed{T_C = -40°C}$, $T_F = \frac{9}{5}(-40) + 32 = -40$ ie $\boxed{T_C = T_F}$

To $\boxed{\text{measure temperature}}$, we ideally require a sensor that varies (in a measurable quantity) in a linear fashion between two fixed points of known temperature (eg 0°C and 100°C).

Example: **In-glass thermometer**





e.g. T_A = Iced water (0°C)
T_B = 100°C

$$T = T_A + (T_B - T_A) \times \frac{x - x_A}{x_B - x_A}$$

So measure rise of liquid $x - x_A$ as a proportion of whole range $x_B - x_A$, and you have the proportional temperature rise from T_A over the range $T_B - T_A$

Enhance <u>sensitivity</u> ($\text{ie } \frac{\Delta x}{\Delta T}$) by

* Reduce diameter of liquid column
* Increase volume of liquid

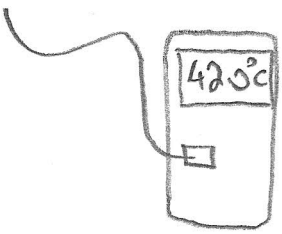
[But this might make the thermometer too big for practical use]

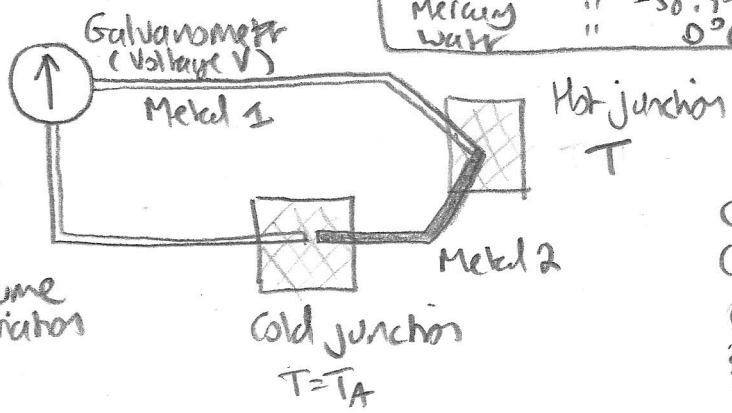
* CHOOSE LIQUID SO IT IS A LIQUID!

Alcohol	Melt −114.4°C	Boil 78.3°C
Mercury	" −38.9°C	" 356.6°C
Water	" 0°C	" 100°C

Example: **Thermocouple**

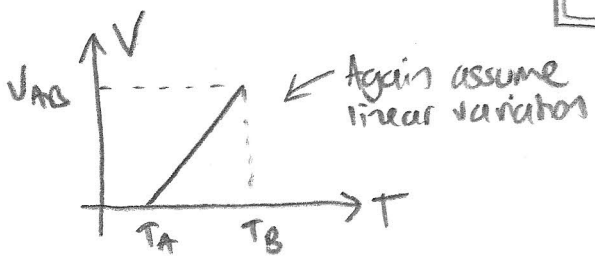
↳ Based upon **thermoelectric effect**





90% Ni
10% Cr

Chromel-Alumel* (K type) are common pairs {but not Nickel is magnetic Curie temp 356°C}

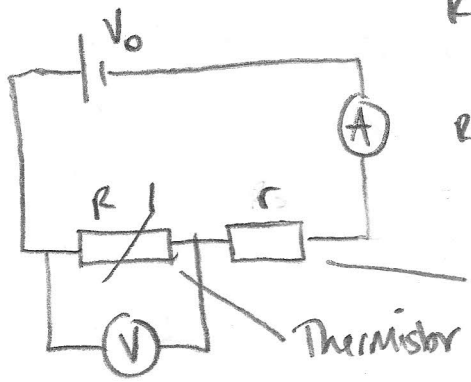


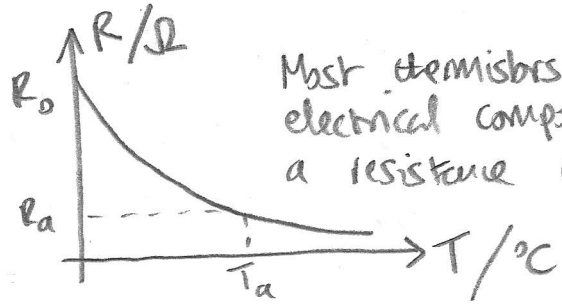
So $$T = T_A + (T_B - T_A) \times V/V_{AB}$$

* High melting point so much greater range of T than in-glass.
* Can be made very small
* Responds fast as small thermal mass
* Can be robust to harsh environments

(2) * 95% Ni, 2% Al, 2% Mn, 1% Si

Example: $\boxed{\text{Thermistor}}$





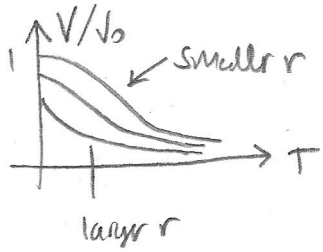
Most thermistors (a semiconductor electrical component) will have a resistance that exponentially decays with temperature

ie $\boxed{R = R_0 e^{-kT}}$ *

[Find k from $R_a = R_0 e^{-kT_a}$ so $\ln\left(\frac{R_a}{R_0}\right) = -kT_a$

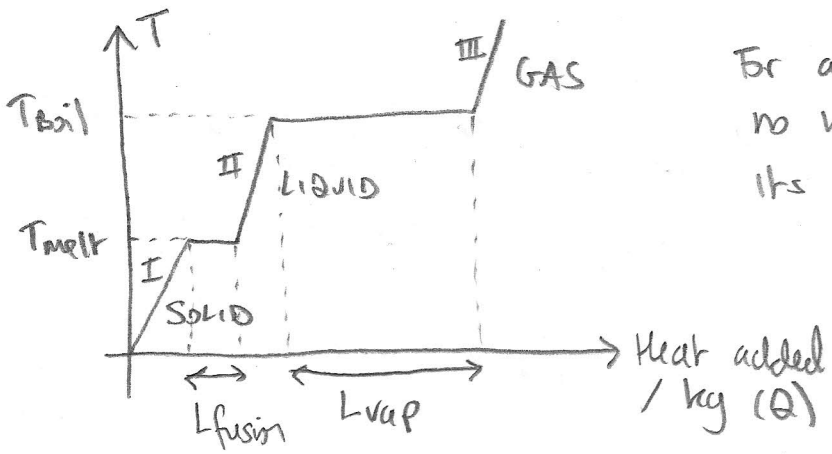
$\therefore k = \frac{\ln R_0/R_a}{T_a}$] ← ie find (R, T) at a fixed point via measurement.

Note $\boxed{V = V_0 \frac{R}{R+r}}$



Compared to thermocouple and in-glass thermometer a thermistor is highly non-linear

$\boxed{\text{LATENT HEAT}}$ ← the amount of energy required to overcome intermolecular forces and ∴ change the state of a substance from solid to liquid to gas.



For an insulated substance (ie no heat loss) which is heated from its solid phase

I : $\frac{dQ}{dT} = C_{solid}$ ← ie 1/gradient

C_{solid} ← $\boxed{\text{Specific heat capacity}}$

II : $\frac{dQ}{dT} = C_{liquid}$

III : $\frac{dQ}{dT} = C_{gas}$

Specific means 'per unit mass'

L_{fusion} is the specific $\boxed{\text{latent heat of fusion}}$ (solid ↔ liquid)

L_{vap} " " " " " " $\boxed{\text{vaporization}}$ (liquid ↔ gas)

which occurs at constant T

So when gas → liquid ENERGY IS RELEASED. This drives many weather systems such as hurricanes. (ie when water vapor condenses as it rises to form clouds).

* or at least decays strongly with temperature T

	$T_{melt}/°C$	$T_{boil}/°C$	L_{fus}/Jkg^{-1}	L_{vap}/Jkg^{-1}	C_{solid}	C_{liq}	C_{gas}
Water	0	100	33.5×10^4	22.6×10^5	2090	4186	1930
Alcohol (Ethyl)	-114	78.3	10.8×10^4	8.55×10^5	970	2440	1900
Copper	1083	2566	20.7×10^4	47.3×10^5	385	386	380

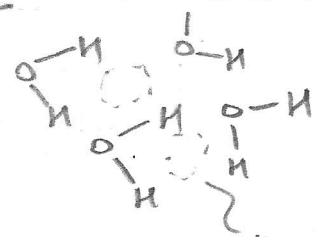
* Note $L_{vap} \gg L_{fus}$
* Note $C_{liq} > C_{solid}$ for water & alcohol

C in $Jkg^{-1}K^{-1}$

This can be explained by the nature and structure of the water and alcohol molecules e.g hydrogen bonding, more modes of motion than translation

etc

which explains why liquid water is more dense than solid water



"gaps" appear in solid water.

In each particular state

$$\boxed{\Delta Q = cM\Delta T}$$

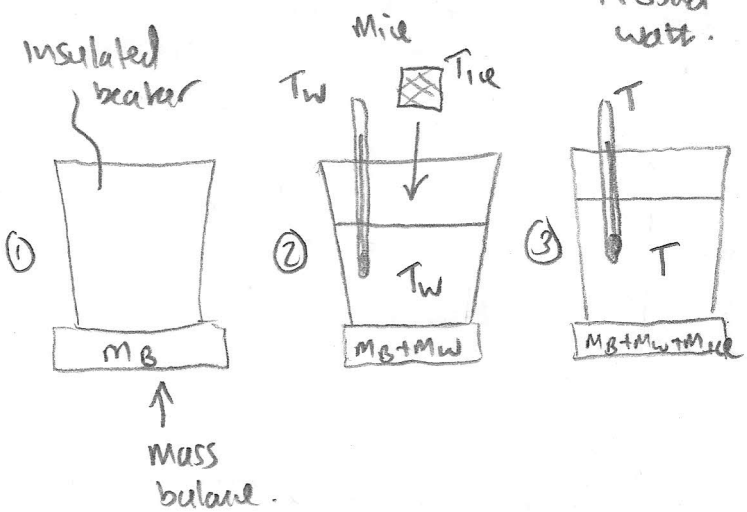
Temperature change

Total heat added (to M kg now!)

Specific heat capacity

mass

Calculating L_{fus} for water



* Determine mass of beaker
* Add warm water, record temperature, record new mass
* Add an ice cube of known temperature (assume 0°C)
* Wait till melted, record T and total mass.

← You can do this more dynamically using a thermocouple inside the beaker

A add warm water
B add ice cube
C ice cube melted
D heat loss, system temp → room temperature

Heat balance (assume no loss)

$\boxed{\text{ICE}}$ $M_{ice}L + cM_{ice}(T - T_{ice})$
(energy added)

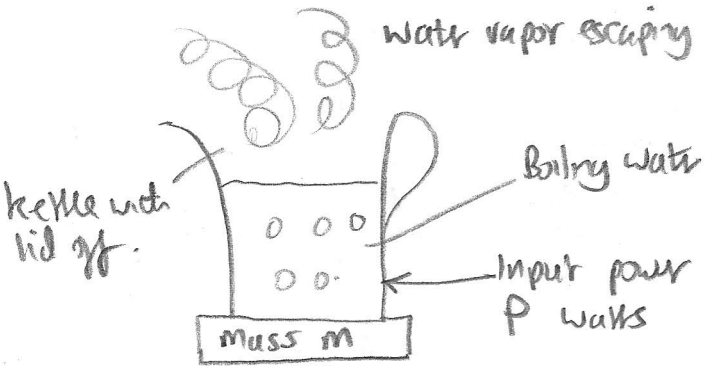
$\boxed{\text{WATER}}$ $cM_W(T_W - T)$
(energy lost to ice cube)

ie ice cube melted AND raised to temp T.

So $$\boxed{L = \frac{C M_w (T_w - T) - C M_{ice} (T - T_{ice})}{M_{ice}}}$$

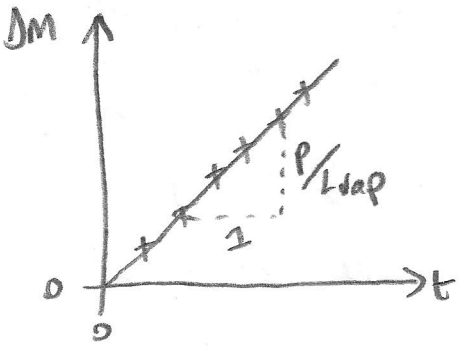
For water $L \simeq 335$ kJ/kg

Calculating L_{vap} for water



* Heat water in kettle
* once boiling has started, zero mass balance and log mass lost (the balance will read -ve) vs time.
* If no heat loss (there will be some!)

$$\boxed{\underbrace{Pt}_{\text{heat input from electrical supply}} = \underbrace{\Delta m \times L_{vap}}_{\text{Energy required to vaporize } \Delta m \text{ kg of water.}}}$$



Wincott 2018
$P = 1.04$ kW
$\Rightarrow L_{vap} = 2480$ kJ/kg

So $$\boxed{\frac{d\Delta m}{dt} = \frac{P}{L_{vap}}}$$

∴ Find gradient of Δm vs t line of best fit and $$\boxed{L_{vap} = \frac{P}{\text{gradient}}}$$

Since non-negligible heat loss, expect measurement L_{vap} to be an over-estimate. For water $L_{vap} \simeq 2260$ kJ/kg

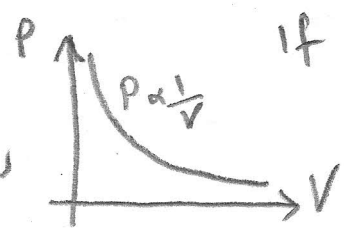
IDEAL GASES

$$\boxed{pV = nRT}$$

* Neglect intermolecular forces
* Assumes fast moving 'point particles' colliding elastically
* Mean free path of molecules prior to collision ≫ molecular size

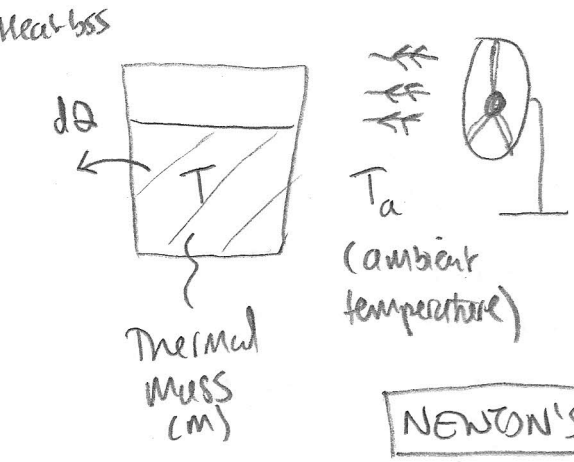
p pressure
V volume
n # moles of gas
R molar gas constant $8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$
T Temperature/K

T, n constant: $\boxed{pV = \text{const}}$ Boyle's law



If p, n constant $\boxed{V \propto T}$ Charles' law.

Cooling Curves



If one can prevent localized heating of the surrounding air (eg by use of a fan) and T is low enough for $\boxed{\text{radiative}}$ heat transfer to be ≈ negligible $\boxed{\text{CONDUCTION}}$ is the main mechanism for heat transfer to ambient.

$\boxed{\text{NEWTON'S LAW OF COOLING}}$ (based upon Fourier's law of conduction – ie $\boxed{\text{heat flux} \propto \text{temperature gradient}}$)

Heat flow ∝ temp. difference

$$\frac{dQ}{dt} = -\alpha (T - T_a)$$

(α will be ∝ to surface area of thermal mass and ∝ $\frac{1}{\text{thickness}}$ of any walls) ← Δx

$$dQ = mc\,dT$$

m ← mass; c ← specific heat capacity

Note $\boxed{\frac{kA}{\Delta x} = \alpha}$

k is the THERMAL CONDUCTIVITY

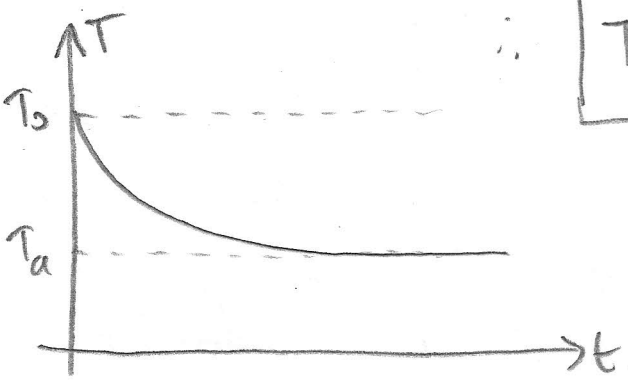
So

$$mc\frac{dT}{dt} = -\alpha (T - T_a)$$

$$\int_{T_0}^{T} \frac{dT}{T - T_a} = -\frac{\alpha}{mc}\int_0^t dt \quad \therefore \quad \Big[\ln(T - T_a)\Big]_{T_0}^{T} = -\frac{\alpha t}{mc}$$

$$\int \frac{f'(x)}{f(x)}\,dx = \ln|f(x)| + c$$

$$\therefore \quad \ln\left(\frac{T - T_a}{T_0 - T_a}\right) = -\frac{\alpha t}{mc}$$

$$\therefore \quad \boxed{T = T_a + (T_0 - T_a)e^{-\alpha t/mc}}$$

$\boxed{\frac{mc}{\alpha} = \tau}$ is the 'characteristic time'