# PRINCIPLES OF MEASUREMENT

(a) ***To explain mathematical concepts such as exponential functions, integration and differentiation.***

Function:

- Defines a value of "y" (dependent variable) for a given value of "x" (independent variable)

$$y = f(x)$$

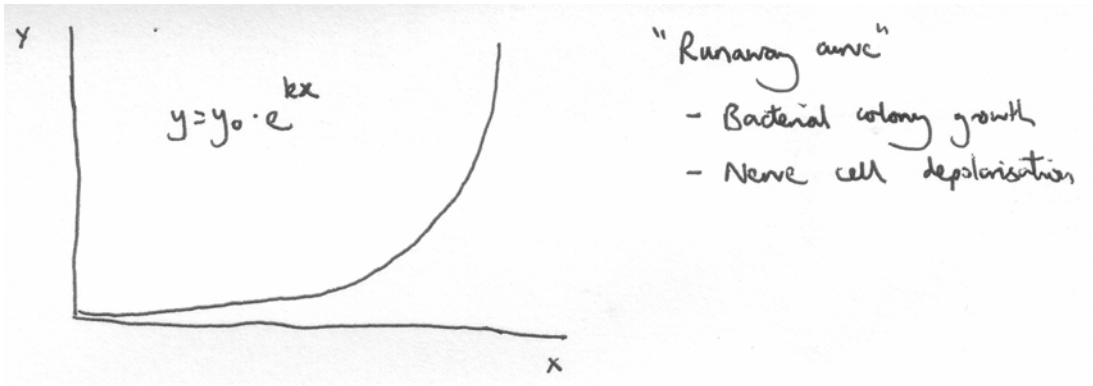
Exponential function:

- Characteristic of exponential function → rate at which the dependent variable (y) changes is dependent on the value of the independent variable (x) at that time

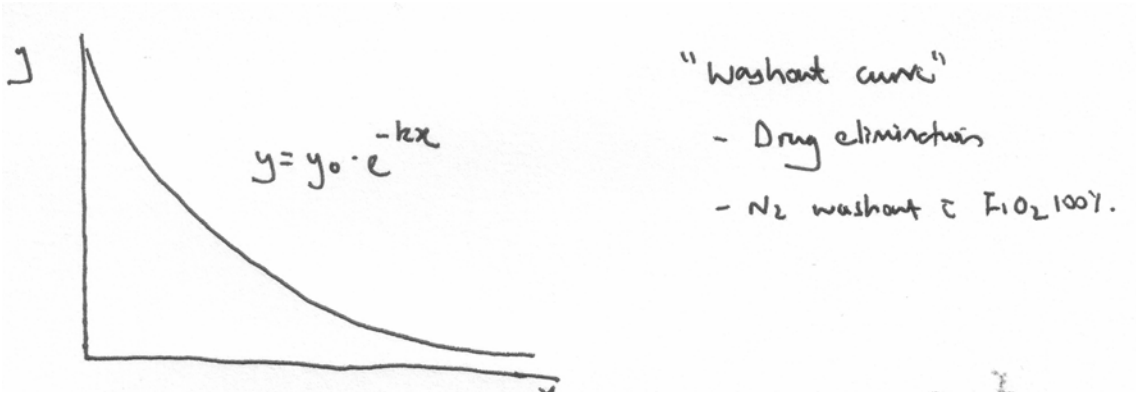
$$Y = An^{ax}$$

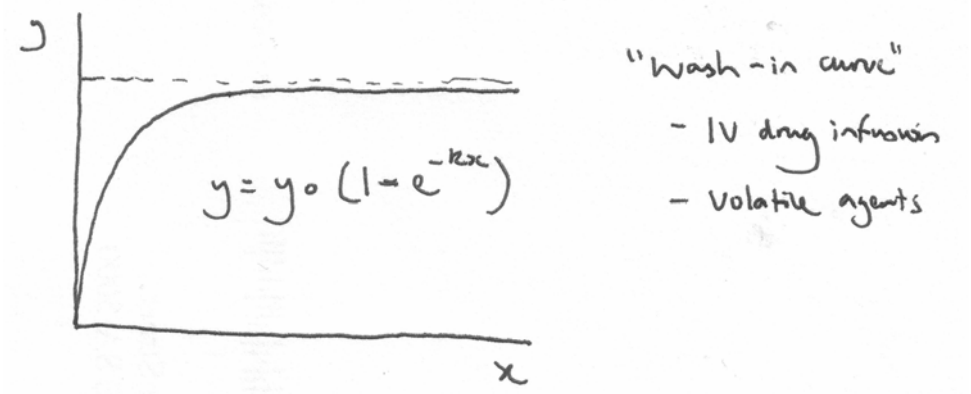
A = Y-intercept (constant)
a = rate constant → determines steepness of exponential curve)
n = base → usually natural number ("e")
x = independent variable
y = dependent variable

- Types of exponential functions:
  - (1) Positive → rate of change in "y" INCREASES with a rise in "x"




  - (2) Negative → rate of change in "y" DECREASES with a rise in "x"



Note – Negative exponential functions are defined by "Asymptotes" (Eg. zero or steady state) → reached after:

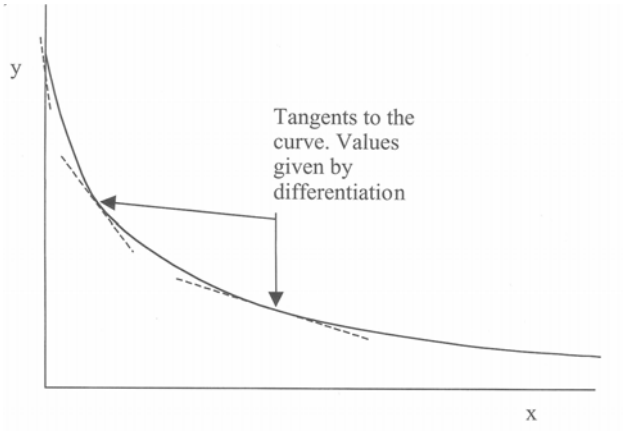
- (i) 5x t ½ (reaches 96.87% of process) → where 1x t ½ = 50%
- (ii) 3x time constants (reaches 97.4% of process) → where 1x TC = 63%

Differentiation:

- Mathematical process used to find an expression that determines the rate of change of a dependent variable (y) relative to change in an independent variable (x)

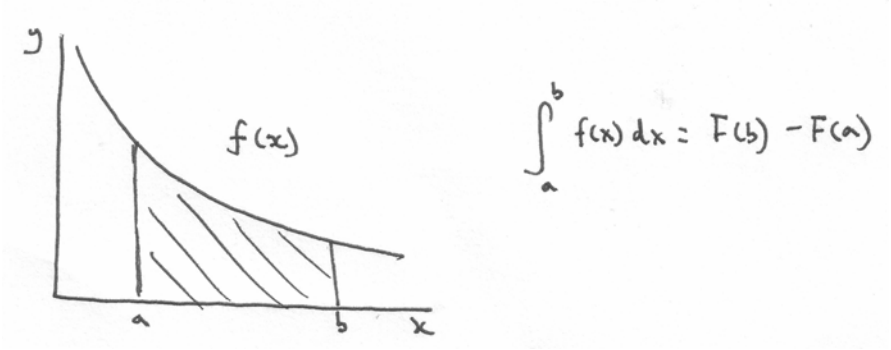
Given function y = f(x) → differentiation of this is "dy/dx"

- This expression gives the slope of tangent of the curve at a defined value of "x"




Integration:

- Mathematical process used to calculate the area under a curve described by the function between two variables of "x"



(b) ***To explain electrical concepts such as current, potential difference, resistance, impedance, inductance and capacitance as they relate to biomedical apparatus.***

Current:

- Defined as the flow of charge through a medium → typically carried by moving electrons in a conductor (Eg. wire)
- SI unit is "Ampere" (A) → measured as the charge flowing through a point in a circuit per unit time → Coulombs/second
- This can be – (i) Unidirectional (DC) or (ii) Bidirectional (AC)

Potential difference:

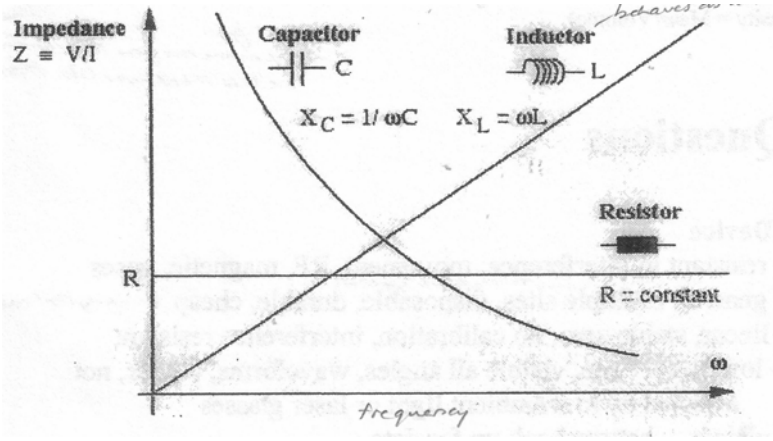
- Defined as the difference in electric potential energy per unit charge between 2 points → when applied across a conductor (Eg. wire), it produces an electrical current!
- SI unit is "Volts" (V) → measured as the work done by an external force to move a unit of charge against an electric field → Joules/coulomb

Resistance:

- Defined as the opposition to the passage of an electrical current within a circuit → as per Ohm's Law, where V = IR such that R = V/I (assuming a DC circuit)
- SI unit is "Ohm" (Ω) → measured as potential difference required to generate a unit of current → Volts/ampere
- The resistance of an object (assuming uniform cross-section) is: $R = L\varrho / A$
  - (i) proportional to resistivity ($\varrho$) and length (l)
  - (ii) inversely proportional to its cross-sectional area (A)
- Resistance in series ($R = R_1 + R_2 + R_3 + \ldots$) vs. parallel ($1/R = 1/R_1 + 1/R_2 + 1/R_3 + \ldots$)

Impedance:

- Defined as the frequency-dependent form of resistance within an AC circuit → measured in "Ohm" (Ω)
- It is the sum of – (i) resistance (resistor), (ii) capacitive reactance (capacitor), and (iii) inductive reactance (inductor or coils)
- As frequency of AC current ↑, this has effects on impedance of certain components of the circuit:
  - Capacitor – Impedance ↓ exponentially
  - Resistor – Impedance remains unchanged
  - Inductor – Impedance ↑ linearly




Inductance:

- Defined as the ability of an inductor (Ie. wire coil) to store energy in a magnetic field
- SI unit is "Henry" (H)
- Basis – Inductor produces an electromagnetic field in an opposite direction to current flow → a change in current through the inductor is resisted by it (Ie. ↑ current through

inductor = ↑ opposition to flow through it = ↑ EMF produced) → this causes energy to be stored as a magnetic field which is then released slowly

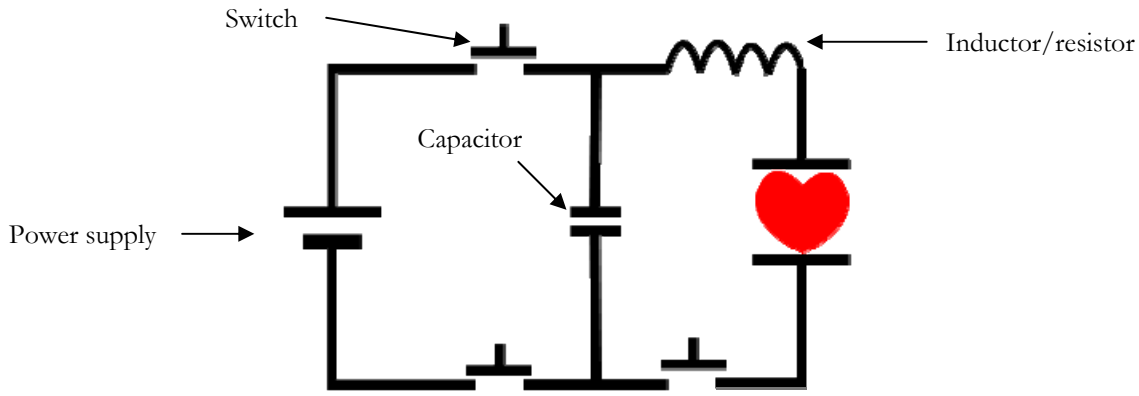
Capacitance:

Defined as the ability of an object to store charge for an applied electrical potential → where C = Q/V

- SI unit is "Farad" (F) → 1 F is the ability to store 1 C of charge for an applied potential difference of 1 V
- It is dependent on – (i) Size of conducting plates, (ii) Separation of plates, and (ii) Material used
- Energy stored by capacitor → $E = \frac{1}{2} CV^2$ → so, a ↑ potential difference requires ↑ energy to store the same amount of charge

Aside: Defibrillator

- Consist of a (i) power supply, (ii) large capacitor, (iii) inductor/resistor, and (iv) switches
- Process:
  - (1) Power supply is used to store an electrical charge within the capacitor → amount of energy stored depends on (i) charge to be stored, (ii) capacitance of system and (iii) potential difference required (as $E = \frac{1}{2} CV^2$)
  - (2) Electrodes placed on chest → then stored energy in capacitor is released in a controlled fashion (via a switch mechanism)
  - (3) Current pulses through chest → heart → causes synchronous myocardial contraction and refractory period → restores normal beats
  - (4) Inductor ensures → (i) electrical pulse delivered has optimum shape and waveform, and (ii) not all the energy stored in capacitor is delivered (Ie. it absorbs some energy)



(c) ***To explain the SI system of units.***

"SI units" (Systeme Internationale d'Unites) was derived in 1960 → comprises of 7 "base units" and several "derived units" → devised around convenience of "base 10"

SI "base" units:

| Quantity | Base unit | Symbol | Reference |
|---|---|---|---|
| Length | Metre | m | Distance that light travels in a vacuum in 1/299,792,45$^{th}$ of a second |
| Mass | Kilogram | kg | Mass of 1 kg platinum iridium kept in France |
| Time | Second | s | Frequency of radiation emitted from cesium$^{133}$ atom |
| Temperature | Kelvin | K | 1/273.16 of the triple point of $H_2O$ (where $H_2O$ exists in equilibrium as solid, liquid and gas) |
| Electrical current | Ampere | A | Current that produces a force of $2x10^7$ Newtons between 2 conductors 1 m apart in vacuum |
| Luminous intensity | Candela | cd | Luminous intensity of a surface of 1/600,000 $m^2$ of a black body radiator at temperature of freezing platinum under pressure of 101.325 kPa |
| Amount of substance | Mole | mol | Amount of substance that contains as many elementary particles as there are atoms in 0.012kg of $C^{12}$ |

SI "derived" units:

| Quantity | Derived unit | Symbol | Relation to other units |
|---|---|---|---|
| Force | Newton | N | 1 N = 1 kg.($m/s^2$) |
| Energy and work | Joule | J | 1 J = 1 N.m |
| Power | Watt | W | 1 W = 1 J/sec |
| Pressure | Pascal | Pa | 1 Pa = 1 $N/m^2$ |
| Frequency | Hertz | Hz | 1 Hz = 1/sec |
| Electrical charge | Coulumb | C | 1 C = 1 A/sec |
| Electrical potential | Volt | V | 1 J/C |
| Electrical resistance | Ohm | Ω | 1 Ω = 1 V/A |
| Radiation activity | Becquerel | Bq | 1 Bq = 1/sec |
| Volume | Cubic metre | $m^3$ | 1 $m^3$ |
| Speed | Metre per second | m/s | 1 m/s |
| Acceleration | Metre per second squared | $m/s^2$ | 1 $m/s^2$ |
| Density | Kilogram per cubic metre | $kg/m^3$ | |
| Etc. | | | |

Aside:

- Gauge (non-SI) → standard gauge based on Birmingham Wire Gauge with each step a multiple of 4/1000 of an inch (where ↑ gauge number = ↓ smaller diameter)
- French Gauge (non-SI) → 1 FrG = 1/3 mm

(d) ***To outline the conversion between the different units of pressure measurement.***

(I) Definition of pressure:
- Defined as force applied to or distributed over a surface
- SI unit: Pascal (Pa) → force of 1 N acting over an area of 1 $m^2$ (1 $N/m^2$)

(II) Conversion of pressure measurements:

| **1 atmosphere is equal to:** |
|---|
| 101.325 kPa (or 101325 $N/m^2$) |
| 760 mmHg |
| 988 $cmH_2O$ |
| 1.01 bar |
| 1013 millibar (or dynes/$cm^2$) |
| 14.7 psi |

Note:
- **1 kPa** = 10.2 $cmH_2O$ = 7.5 mmHg
- **1 bar** = 100 kPa = 750 mmHg

(III) Types of pressure:

Absolute pressure = Gauge pressure + Ambient atmospheric pressure

- (1) Absolute pressure → equals sum of gauge pressure and ambient atmospheric pressure
- (2) Gauge pressure → equals absolute pressure minus ambient atmospheric pressure
  - Used to measure pressures relative to ambient atmospheric pressures → "background" pressure (Ie. $P_{ATM}$) is considered as a zero reference pressure, and measured pressure (Ie. gauge pressure) is a pressure relative to it
  - Measured by a pressure gauge (Eg. aneroid manometers, IABP transducer, Etc.)

Nb. BP of 120/80 is "gauge pressure" → "absolute pressure" is 880/840 (with $P_{ATM}$ = 760 mmHg)

(IV) Measurement of pressure:
- (1) Manometer:
  - Measuring unknown pressure of a system against a known pressure from a column of liquid

    Pressure of column of liquid = (height) x (density) x (gravity)

  - Higher pressure measured with higher density fluid (Eg. Hg), while lower pressure measured with lower density fluid (Eg. $H_2O$) → note that Hg is read from top of meniscus, while $H_2O$ is read from bottom of meniscus
- (2) Aneroid gauge → gauges that do not contain liquid
  - (i) Bourdon gauge (Eg. pressure gauge in $O_2/N_2O$ cylinders)
    - Consists of a coiled tube (flattened cross-sectionally) connected to a high pressure source → ↑ pressure in tube causes tube to uncoil slightly → movement measured by pointer moving across a calibrated pressure scale
    - Advantages – Ideal for high pressures (cf. manometer), no liquids to spill, no power supply required, rugged and robust
    - Issues – Not suitable for low pressures, requires calibration
  - (ii) Bellow gauge (Eg. sphygmanometer)
    - Consists of a bellow → when ↑ pressure within bellow → causes outward movement of bellow wall → sensed by mechanism that moves pointer over a calibrated pressure scale
- (3) Electric pressure transducer

- Strain gauge transducer connected to elastic diaphragm → pressure changes cause diaphragm to move → causes strain gauge wire to stretch/compress and change its resistance → change in current through circuit related to pressure change
- Strain gauge commonly incorporated into Wheatstone bridge circuit to ↑ sensitivity of pressure readings

(e) ***To describe the laws governing the behaviour of gases and liquids.***

(I) **Gas Laws**:

Boyles law: At a constant temperature, volume of a given mass of gas varies inversely with its absolute pressure → $V \propto 1/P$ → so $PV = K$

Charles law: At a constant pressure, volume of a given mass of gas varies directly with its absolute temperature → $V \propto T$ → so $V/T = K$

3rd perfect gas law: At a constant volume, absolute pressure of a given mass of gas varies directly with its absolute temperature → $P \propto T$ → so $PT = K$

Universal gas constant and Ideal gas law:

- Based on Boyles law ($PV = K$), Charles law ($V/T = K$) and 3rd perfect gas law ($PT = K$):

  For 1 mole of a gas → $PV/T = K$ → where K = "Universal gas constant" (R)

- "Ideal gas law" is → $PV = nRT$ (where n = # moles of gas)

> Relevance – Amount of gas left in a cylinder is proportional to its pressure → this is b/c gas cylinders have a fixed volume, R is constant, and temperature is generally constant → thus, $P \propto n$ based on the "Universal gas law"

Avogadro's hypothesis:

- States that equal volumes of gas at the same temperature and pressure contain equal number of molecules

> Note:
> - 1 mole of substance → defined as quantity of substance containing same # particles as atoms in 0.012 kg of $C^{12}$ → contains $6.02 \times 10^{23}$ molecules (Avogadro's number)
> - 1 mole of gas at STP (273.15 K (0°C) and 101.325 kPa (1 atm)) → occupies 22.4 L

Dalton's Law of partial pressures:

- States that in a gas mixture, the pressure exerted by each gas (which is referred to as its "partial pressure") is the same as that which it would exert if it alone occupied the container

Total pressure = ∑ of partial pressures of each gas

Partial pressure of a gas = (total pressure) x (fractional [ ] of gas)

> Note: For humidified gases (Eg. alveoli) → $H_2O$ vapour pressure must be accounted for when determining the partial pressure of a gas → so partial pressure of a gas = (total pressure – $P_{H2O\ VAPOUR}$) x (fractional [ ] of gas)

> Note – Arterial blood exists at equilibrium with alveolar gas:
> - Alveolar gas → total pressure is 760 mmHg ($PO_2$ 100 mmHg, $PCO_2$ 40 mmHg, $P_{H2O}$ 47 mmHg, $PN_2$ 573 mmHg)
> - Arterial blood → 713 mmHg (∑ of $PO_2$, $PCO_2$, $PN_2$) → does not contain dissolved $H_2O$ vapour ($P_{H2O}$) as it does not make sense for $H_2O$ vapour to be dissolved in $H_2O$

Critical temperature: Temperature above which a gas cannot be liquefied by pressure alone (Eg. $O_2$ → -119 °C; $N_2O$ → 36.5 °C)

> Note – Gas and Vapour are defined based upon a substance in gaseous state with respect to its critical temperature:
> - Gas → defined as a substance in a gaseous state when ambient temperature is ABOVE its critical temperature
> - Vapour → defined as a substance in a gaseous state when ambient temperature is AT or BELOW its critical temperature

Critical pressure: Pressure at which a gas liquefies at its critical temperature (Eg. $N_2O$ → 73 bar at 36.5 °C; $O_2$ → 52 bar @ 20 °C)

Pseudo-critical temperature: For a mixture of gas at a specific pressure, it is the specific temperature at which the individual gases may separate from gaseous phase (Eg. Entonox (50% $N_2O$:50% $O_2$) → -5.5 °C for cylinders (117 bar); -30 °C for piped gas)

Adiabatic changes: Refers to a change in physical state of a gas WITHOUT the transfer of heat energy to or from the surrounding environment

Thus,
- Rapid gas expansion → energy required to overcome Van de Waal attractive forces is gained from the kinetic energy of molecules (and NOT from heat energy of environment)
- Rapid gas compression → energy is transferred to kinetic energy of molecules (and NOT lost as heat energy into surroundings)

Azeotrope: Mixture from which the component liquids vapourise in the same proportions as the molar ratios in the mixture

> Example:
> - Ether and halothane form azeotrope when volume [ ] and molar [ ] ratios are both 1:2
> - EtOH and water form azeotrope when volume % EtOH is 96%

Raoult's Law: Depression of vapour pressure of a solvent is proportional to the molar concentration of solute

> Note: ↑ solute [ ] → causes ↓ vapour pressure (less volatile) → results in ↑ boiling point and ↓ freezing point

(II) **Solubility**:

Solubility:
- Solubility of gas in a liquid:
  - Dictated by Henry's Law → at a constant temperature, amount of gas dissolved in a liquid is directly proportional to the partial pressure of that gas in equilibrium with the liquid at its surface

Amt of gas dissolved = K x (partial pressure of substance in gas phase)

K (Henry's constant) → specific to gas (solute), liquid (solvent) and temperature

Note – With ↑ temperature → gases have ↓ solubility in liquids

Note – Meaning of $PaCO_2$ 40 mmHg → means if arterial blood was exposed to gas phase with $PCO_2$ 40 mmHg, equilibrium for $CO_2$ would be present (Ie. amt of $CO_2$ leaving blood into gas phase = amt of $CO_2$ entering blood from gas phase) → and amount dissolved in blood = 0.03 x 40 mmHg = 1.2 mmol/L!

Solubility coefficient:

- Solubility of gas expressed as a volume of gas dissolved in a unit volume of solvent → but as gas volume depends on (i) temperature and (ii) pressure → there are two types:
  - (1) Bunsen solubility coefficient → volume of gas that dissolves in one unit volume of liquid at STP (at 1 atm and 0°C)
  - (2) Ostwald solubility coefficient → volume of gas that dissolves in one unit volume of liquid at a stated the temperature and partial pressure

Partition coefficient:

- Ratio of the amount of substance present in each of the two phases at equilibrium, which occurs when the volumes (and partial pressures, if substance is a gas) are equal between the two phases at a state temperature

For example, a blood-gas partition coefficient of 0.47 for $N_2O$ means that at equilibrium, an volume of blood will contain 0.47 as much as an equal volume of alveolar gas when partial pressures are the same at 37°C

(III) **Diffusion and Osmosis**:

Diffusion:

- Passive process by which molecules in a gas or solution move spontaneously (as a result of their random thermal motion) along their thermodynamic activity gradient (Ie. down its [ ] gradient from ↑ [ ] to ↓ [ ]) until the [ ] is equally distributed throughout the medium and equilibrium is reached
- Rate of diffusion is determined by "Fick's Law of diffusion":

$$J = -\frac{D \times A \times \Delta C}{t} \quad ; \quad D = \frac{\text{Solubility}}{\sqrt{\text{MWT}}}$$

J – Net rate of diffusion
D – Diffusion coefficient (which is the solubility of the substance in the boundary, divided by the square-root of the substance's MWT
A – Cross-sectional area of boundary
ΔC – [ ] or partial pressure gradient across a unit area
t – Thickness of boundary

- "Time for diffusion" is proportionate to the square of the diffusion distance

Osmosis:

- A passive process by which a solvent (such as $H_2O$) moves across a semi-permeable membrane due to a thermodynamic activity gradient for that solvent
- This thermodynamic activity gradient is established by a $P_{OSMOTIC}$ gradient across the membrane → causes solvent to flow from a solution of ↓ $P_{OMSOTIC}$ (hypotonic solution) to one of ↑ $P_{OSMOTIC}$ (hypertonic solution) until the $P_{OSMOTIC}$ gradient dissipates

(III) **<u>Benoulli Effect, Venturi Effect and Coanda Effect</u>**:

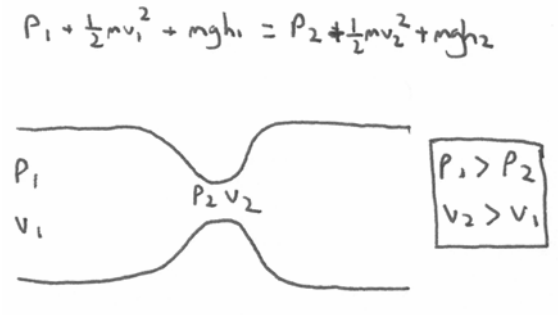
<u>"Bernoulli effect"</u>:

- For a non-compressible, non-viscous fluid undergoing laminar flow → total energy of fluid flow is conserved at all points along the line of flow (Ie. ∑ of potential energy (due to gravity and pressure) and kinetic energy (due to motion) is constant throughout)

Potential energy of pressure (PV) + Potential energy of gravity (mgh) + Kinetic energy of motion (½ $mv^2$) = constant

Nb. With laminar flow → frictional loses as heat is negligible (cf. turbulent flow → ↑ frictional loss as heat)

- Effect of narrowing of tube on fluid flow:
  - At site of constriction:
    - There is a significant ↑ in fluid velocity → a/w ↑ kinetic energy of motion
    - Due to conservation of energy → (i) ↓ potential energy of pressure → such that pressure is at its lowest at the narrowest point of constriction (often below $P_{ATMOSPHERIC}$), and (ii) ↓ potential energy due to gravity
  - At site of widening → opposite of above occurs




<u>"Venturi Effect"</u>:

- Using the above example → if there was a hole at the constriction point of a tube, air or fluid can be entrained through side-tube due to the pressure drop (occasionally sub-atmospheric) caused by an increase in fluid velocity at that point (Eg. nebuliser, AS with decreased pressure at coronary ostia)

<u>"Coanda effect"</u>:

- Using the above example → if the tube diverges, the fluid stream may adhere to either wall → diverts flow to one or other lumen (Ie. unequal distribution of gas flow in pulmonary tree)

(IV) **<u>LaPlace's Law</u>**:

For straight tubes: $P = (T.h) / r$

For spheres (with one surface): $P = (2T.h) / r$

(with two surfaces): $P = (4T.h) / r$

T = Tangential force (N/m) acting along wall)
h = Wall thickness
r = Radius

Note:

- As radius of tube (vessel) or sphere (alveoli) ↓↓↓ → collapsing force (due to surface tension) will ↑↑↑ → leads to vessel or alveolar closure at low pressures ("critical closing pressure")
- In the lung → the ↑ in collapsing force due to surface tension is minimised by surfactant

(f) ***To describe the principles of measurement employed by apparatus in clinical use, including transducers, and to describe their calibration.***

Function of a measurement system:

- Convert value of some physical quantity (Eg. pressure, temperature, Etc.) into a form that can be observed and recorded

Components of a measurement system:

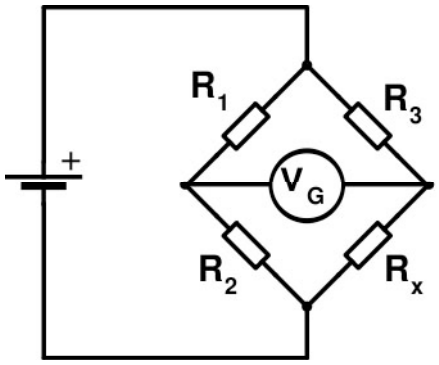
- (1) Electrode or detector → detects a range of physiological variables
- (2) Transducer → device that converts energy from one form to another (Ie. pressure to electrical energy) → includes strain gauge, piezoelectric crystal, thermistor, Etc.

> Aside – Strain gauge:
> - A wire whose resistance varies with stretch or compression
> - It is commonly used as a transducer (Ie. as a pressure transducer → strain gauge is connected to diaphragm at one end and to a fixed point at the other → pressure changes cause diaphragm to move resulting in stretching/compression of strain gauge → changes its resistance → produces a current change across strain gauge that is measured → proportional to pressure change)

- (3) Signal conditioning unit → includes amplifier, processor, filter, recorder
- (4) Display

Important to note → "Wheatstone bridge circuit"

- Role – Used to ↑sensitivity of a strain gauge
- Components:
  - Common source of electrical current (battery)
  - Two parallel circuit branches that contains four resistors:
    - One branch contains two resistors of fixed known resistances ($R_1$ and $R_2$)
    - Other branch contains one resistor of variable but known resistance ($R_3$), and one resistor with variable and unknown resistance ($R_X$ – this is the "strain gauge" that is exposed to the deforming force)
  - Galvanometer that connects the two parallel branches (forms the "bridge")
- Principle:
  - Changes in resistance of strain gauge ($\Delta R_X$) are proportional to changes in deforming force (Ie. pressure)
  - $R_X$ is determined by varying the resistance of $R_3$ to "balance" the two branches in the circuit such that there is no potential difference (and no current flow) across the galvanometer or the "bridge" → this implies that $(R_1/R_2) = (R_3/R_X)$

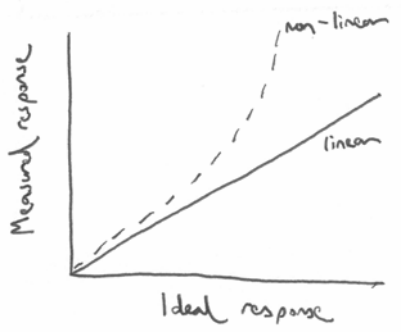



Calibration of a measurement system:

*Linearity*:

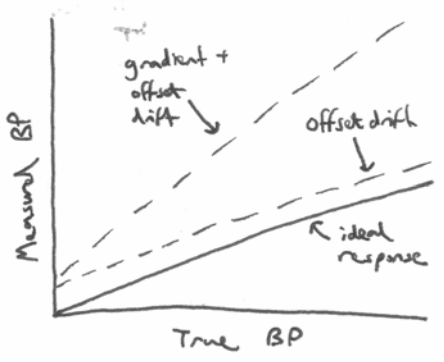
- Measure of degree to which displayed value is proportional to true value

- Ideally → relationship is linear, sensitive and accurate throughout measurement range → this allows 2 point calibration




*Drift*:

- A measure of degree to which the displayed value changes over a period of time when the true value is constant → this is why measurement systems be kept constantly calibrated
- Two types:
    - Offset drift → each point of measured response differs from ideal response by a fixed margin → measured response can be easily corrected by 1-point calibration
    - Gradient drift → each point of measured response differs from ideal response by a varied margin (Ie. ↑ variation with ↑ quantity of ideal response) → can only be corrected by 2-point calibration
- Factors that commonly cause drift → (i) temperature variations (Ie. causes transducer diaphragm to expand), and (ii) dirt/contamination (Ie. blood gas electrodes)




*Static and dynamic response*:

- Static response → response of a measuring system when the measured value is not changing or changing slowly

Calibration for static response:
- Setting the zero reference point
- Checking gain (sensitivity)
- 2 point calibration (if required for linearity)
- Checking for time stability

- Dynamic response → response of a measuring system when the measured value is consistently changing (more common)

Types:
- Zero-order response → displayed value tracks with value that is being measured immediately
- First-order response → displayed value approaches the value being measured in an exponential manner (Eg. temperature probe)
- Second-order response → response resemble that of 1st order or may oscillate about the true value (Eg. resonance and damping with IABP)

(g) ***To describe the measurement of flow, pressure and velocity of fluids.***

(I) Definition of a Fluid, Viscosity and Density:

- "Fluid" → a substance that continually that deforms (or flows) by action of an applied shear stress → includes gases and liquids
- " Viscosity" ($\eta$) → indicates the fluid's internal resistance to flow (Pa.sec) → thought of as a measure of friction of a substance
- "Density" ($\varrho$) → relates the mass of substance to its volume ($kg/m^3$)

> Nb. For ideal gases → $\varrho \propto P$, while $\varrho \propto 1/T$

(II) Physics of Fluid Flow:

*Overview of flow*:

- "Flow" → quantity of fluid (gas or liquid) passing a point per unit time → L/sec
- Fluid flow occurs when there is a pressure gradient present → occurs from a region of higher pressure to a region of lower pressure

*Types of flow*:

- (1) Laminar flow:
  - Occurs when "viscous" forces (viscosity) predominate → Re < 2000:
    - (i) Tubes with small radius, absence of bends and smooth lining
    - (ii) Low fluid flow velocity
    - (iii) Fluid is highly viscous and/or low density (Eg. heliox)
  - Characterised by:
    - (i) Steady flow with no eddie currents or turbulence
    - (ii) Parabolic velocity profile → velocity greatest at centre of flow (2x the mean flow), and falls off rapidly to zero as wall approached
    - (iii) Resistance of flow obeys Hagen-Poiseuille's equation:

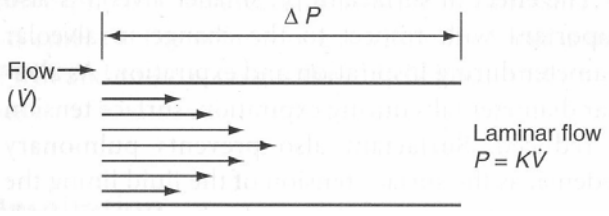
$$R = \frac{8nl}{\pi r4}$$

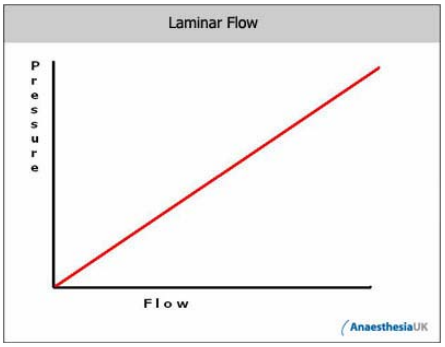
n = viscosity
l = length
r = radius

    - (iv) ↓↓↓ resistance to flow and driving pressure required (cf. turbulent flow)
    - (v) Driving pressure is directly proportional to flow rate:

$$P = K \bullet V = R \bullet V$$

K = Constant
P = Driving pressure
V = Flow rate
R = Airway resistance



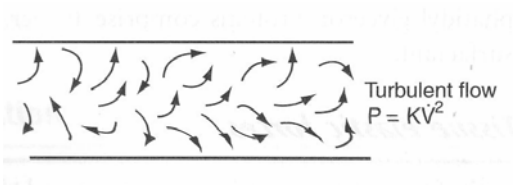

  - Thus, flow rate (V) is:

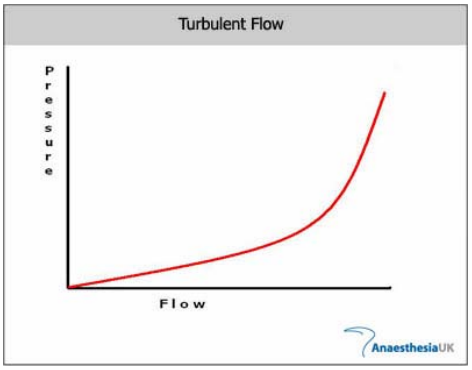
$$V = \frac{P}{R} = \frac{P \times (\pi r^4)}{(8nl)}$$

> - Flow rates are proportional to → (i) Pressure gradient generated and (ii) Radius to the 4th power
> - Flow rates are inversely proportional to → (i) Length and (ii) Viscosity

- (2) Turbulent flow:
  - Occurs when "inertial" forces (density) predominate → Re > 2000:
    - (i) Tubes with large radius, sharp bends or corrugated lining
    - (ii) High fluid flow velocity
    - (iii) Fluid with high density and/or low viscosity
  - Characterised by:
    - (i) Flow occurs in disorganised stream lines and eddie currents are present
    - (ii) Absence of velocity profile
    - (iii) Resistance of flow does NOT obey Hagen-Poiseuille's equation
    - (iv) ↑↑↑ resistance to flow and driving pressure required (cf. laminar flow)
    - (v) Driving pressure is proportional to the square of flow rate

$$P = K \bullet V^2 = R \bullet V^2$$




  - Thus, flow rate (V) is: $V = \frac{k.r^2.\sqrt{P}}{\varrho.L}$

*Nature of fluid flow*:
- "Reynolds number" (Re) is the ratio of inertial to viscous forces of fluid → dimensionless

$$Re = \frac{2\ rvd}{\eta}$$

r = radius
v = velocity of gas flow
d = density of gas
η = viscosity of gas

- It determines the pattern of fluid flow:
  - Turbulent flow is likely if Re > 2000
  - Laminar flow is likely if Re < 2000

Nb. "Critical velocity" → velocity of fluid where Re = 2000 (Ie. transition of laminar to turbulent flow) for a given set of conditions

Clinical relevance of fluid flow:
- Respiratory flow is generally laminar flow → EXCEPT during peak flow (Eg. deep breathing, coughing, talking, Etc.)
- Within respiratory tract, turbulent flow occurs in large AW (Eg. trachea) while laminar flow occurs in smaller AW (Eg. bronchioles)
- Mixture of gases influences type of fluid flow → warmed humidified gases and use of Heliox → ↓ gas density → ↑ critical velocity → promotes laminar flow
- Use of rugged tubing, sharp bends/curves (Eg. ETT connectors), large tube sizes and high gas flow → promote turbulent flow

(III) Measurement of fluid pressure:

- See section on "Pressure measurement" above

(IV) Measurement of fluid velocity:

- See section on "Bernoulli effect" above

(V) Measurement of fluid flow:

- (1) Blood flow measurement
  - See "Cardiovascular Physiology – Measurement of CVS function"
- (2) IV fluid infusion measurement

$$\text{IV infusion rate} = (\text{drop volume}) \times (\text{rate of drops})$$

  - (a) Drop volume:
    - Dependent on – (i) surface tension, (ii) density, (iii) size and shape of tube, and (iv) rate at which liquid is flowing
    - Note – Density and surface tension are dependent on temperature and the type of solution
  - (b) Rate of drops → determined:
    - (i) Visually → observe # of drops in chamber over time
    - (ii) Using infusion pumps (Eg. TCI/TIVA machines) → # of drops passing through drip chamber are determined by passing a light source (Eg. IR) through it → inversely proportional to light intensity received at photodetector

(h) ***To describe the basic physics of ultrasounds and the Doppler principle.***

(I) Ultrasound (U/S):

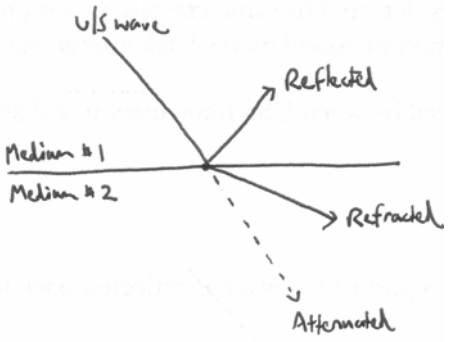
*Definition of U/S*:

- A sound wave with a frequency > 20 kHz → higher than frequency range audible by human ear
- Used medically for diagnostic imaging (ultrasonography) → typically involves frequency range of 2-15 MHz

> Aside → Sound:
> - Defined as a longitudinal wave created by high and low pressure pulse waves travelling through a medium causing it to compress and expand
> - Cannot travel in a vacuum → as sound wave generated by pressure only
> - Sound wave is characterised by:
>  - (i) Frequency (Hz) → rate of change of pressure variations in medium
>  - (ii) Wavelength (mm) → distance b/t points of maximum pressure variations in medium
>  - (iii) Amplitude (Db) → maximum pressure variation of sound wave
>  - (iv) Velocity (mm/s) → $v = f \times \lambda$

*Physical basis of ultrasound*:

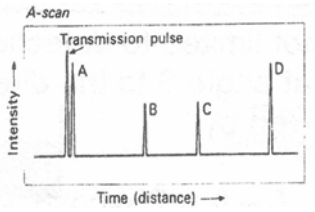
- U/S transducer and receiver rely on "piezoelectric effect" → vibration of a crystal of piezoelectric material (Eg. ferroelectric ceramic crystal) interconverts electrical and sound energy → whereby:
  - U/S generation: Piezoelectric crystal within probe is stimulated by electrical current to vibrate → produce sound wave (Ie. electrical energy transduced into sound energy)
  - U/S detection: Sound wave reflected by medium causes same crystals within probe to vibrate → produce an electrical signal (Ie. sound energy is transduced back into electrical energy)
- Sound waves produced by U/S probe reaches interface b/t two mediums of differing density (or acoustic impedance) → sound wave at interface is either:
  - (1) Reflected → sound wave is reflected back to U/S probe
    - Amount of reflection depends on the ratio of density (or acoustic impedance) b/t two mediums → where ↑ density ratio b/t mediums causes ↑ reflection
    - Nb. "Acoustic impedance" = (tissue density) x (acoustic velocity) → it is unique to tissue type (Eg. fat, bone, Etc.)
  - (2) Refracted → sound wave is deflected within the medium
  - (3) Attenuated
    - Intensity and velocity of sound wave falls when it passes through tissues of differing density or acoustic impedance → this is caused by absorption of sound energy by tissue, which is converted into heat
    - Nb. Attenuation ↑ linearly with frequency in soft tissue → thus, ↓ frequency provides better tissue penetration → BUT at expense of ↓ resolution



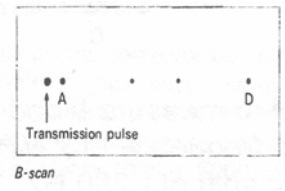
- Image is formed by reflection of U/S waves from tissue back to the probe → depends on:
  - (i) Intensity of reflected sound wave energy → ↑ intensity of wave = ↑ density difference b/t two mediums
  - (ii) Time interval b/t U/S generation and detection at probe

> Note: Resolution of U/S
> - Defined as the ability to differentiate b/t structures that are closely related
> - Resolution is ↑ with either:
>   - (i) ↑ frequency (or ↓ wavelength) of sound wave → but this ↓ tissue penetration
>   - (ii) ↑ amplitude of sound wave → but this ↑ artefact
>   - (iii) ↑ gain → but this ↑ noise

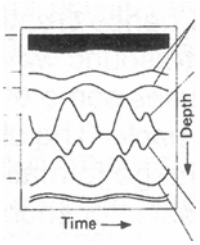
*Modes of ultrasound*:
- A (amplitude scan): Amplitude of U/S signal plotted against time → provides information about tissue depth (BUT is no longer used)
- B (brightness): Depth recorded as bright spot (rather than a spike as in A-mode) → amplitude of U/S signal is proportional to brightness
- M (motion): B-mode plotted against time (Ie. assess heart valve movement over time)
- 2-D: Sequential B-mode across 90° (most commonly used) → requires an array of crystals
- Doppler: Uses "Doppler shift" to establish velocity of moving object which is reflecting sound waves → superimposed on 2D mode with colours representing direction of movement (red = towards, blue = away)




A-scan




B-scan




M-scan

(II) <u>Doppler principle</u>:

*Doppler effect*:
- Describes the change in frequency and wavelength of a sound wave when it moves towards or away from the detector
- Since the velocity of sound wave through a medium is constant (Ie. 1560 m/s in air) and related to product of frequency and wavelength ($v = f \times \lambda$) → then:
  - When a sound wave travels towards a detector → interval b/t high pressure sound waves decreases → so ↓ λ and ↑ frequency
  - When a sound wave travels away from a detector → interval b/t high pressure sound waves increases → so ↑ λ and ↓ frequency

*Doppler shift*:
- "Doppler shift" is the difference in frequency of incident and reflect U/S wave against a moving object → it is determined by the "Doppler equation"

*Doppler equation*:
- Doppler shift is determined by (i) velocity of moving object, (ii) incident angle at which U/S beam strikes the object, and (iii) velocity of sound through a medium (~ 1560 m/s)

$$F_d = \frac{2F_t V \cos\theta}{C}$$

$F_d$ = frequency shift
$F_t$ = transimitted freqeuncy
V = velocity of flow
cosθ = cosine of the angle of transmitted freqeuncy to flow
C = velocity of sound through medium (approx 1560 m/s)