Back to basics

Key equations and concepts in respiratory physiology

CRFS Workshop – Gold Coast 2015

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Equations you should understand…

Basic physics	Graham's Law of gas diffusion	**Measurement**	Vtg by plethysmography
	Henry's Law of gas solubility		TLCO, VA
	Fick diffusion equation		Roughton and Forster model
			Hb correction for TLCO
	Gas Laws (Boyle's, Charles', Avogadro's)		Shunt fraction
	Ideal gas equation		Gas dilution/washout TLC (mass balance)
	Dalton's Law of Partial Pressures		Fick cardiac output
	Water vapour - a non-ideal gas		Vd/Vt
	Condition correction equations (eg BTPS)		Calibration equations
Flow	Resistance/conductance	**Blood gases**	Alveolar gas equation
	Poiseuille's equation		A-a PO2 gradient
	Turbulent flow equation		Oxygen content
	Integration/differentiation		PCO2 equation
			Henderson-Hasselbach equation
Elasticity	Compliance/elastance (static/dynamic)	**Miscellaneous**	Z-scores
			Basic stats (mean/median/sd/cv etc)
			Predicted norms, LLN

Gas laws

Questions

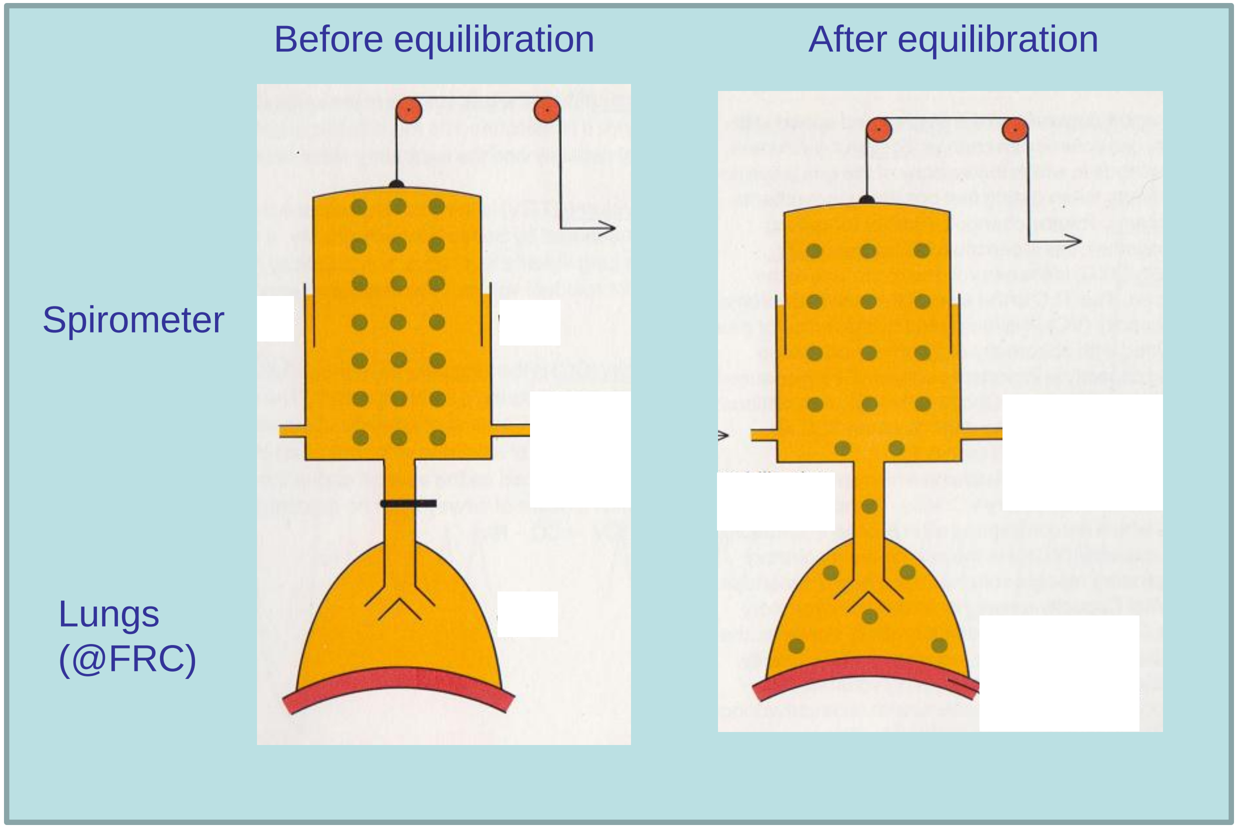
- What happens to a volume of gas as it moves from the interior of the lungs to the interior of a flow sensor? Why? How can you calculate the effect size?
- How can the gas laws be used to calculate FRC in a body plethysmograph? By inert gas dilution?
- What effect does passing expired gas at BTPS through permapure tubing? Why? How can you calculate the effect on gas concentration?
- What effect does passing dry calibration gas through permapure tubing? Why? How can you calculate the effect on gas concentration?
- Why does water vapour behave differently to other gases such as O2 and CO2?
- etc






The Gas Laws

Q. A patient has FRC measured by Helium dilution. The initial circuit volume and Helium concentration is 4L and 10% respectively. After equilibration, the final circuit Helium concentration is 6%. Calculate FRC.



		Spirometer	Lungs
Before	Helium	10.0%	0.0%
	Volume	4.0L	FRC
After	Helium	6.0%	6.0%
	Volume	4.0L	FRC

What approach to use?

⇩

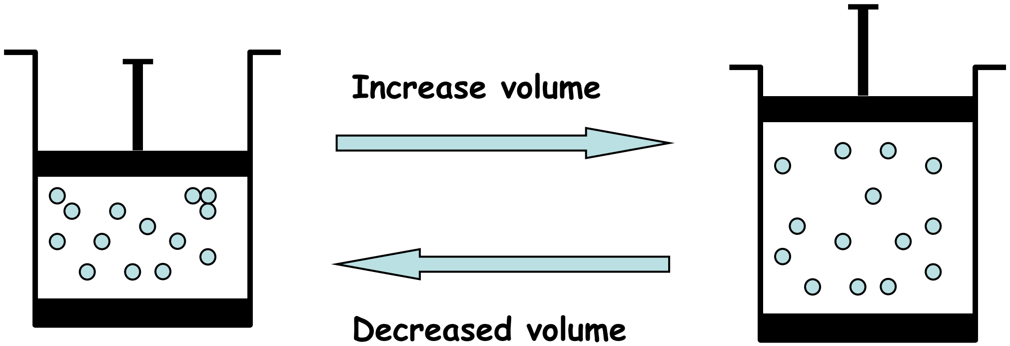
Principle of mass balance

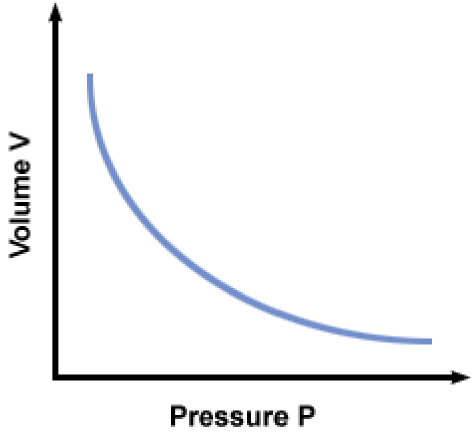
PLUS

Ideal gas equation

1. Boyle's Law

Boyle's law: $V \propto \frac{1}{P}$ (constant n, T)

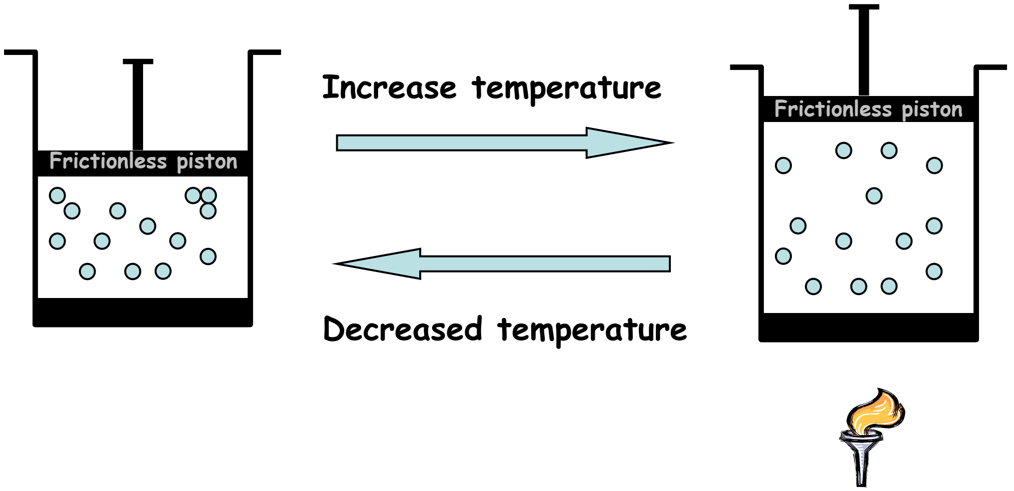


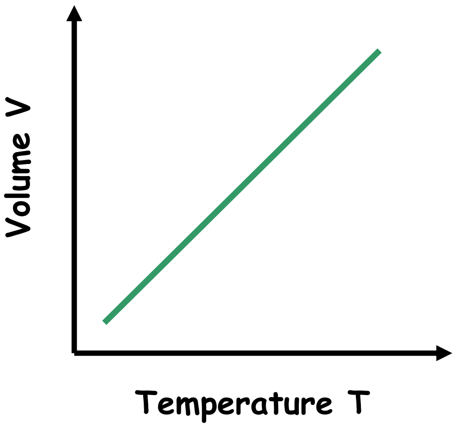


As gas volume decreases, molecules are closer together and more collisions occur. Therefore, pressure rises (and vice-versa).

2. Charles' Law

Charles' law: $V \propto T$ (constant n, P)

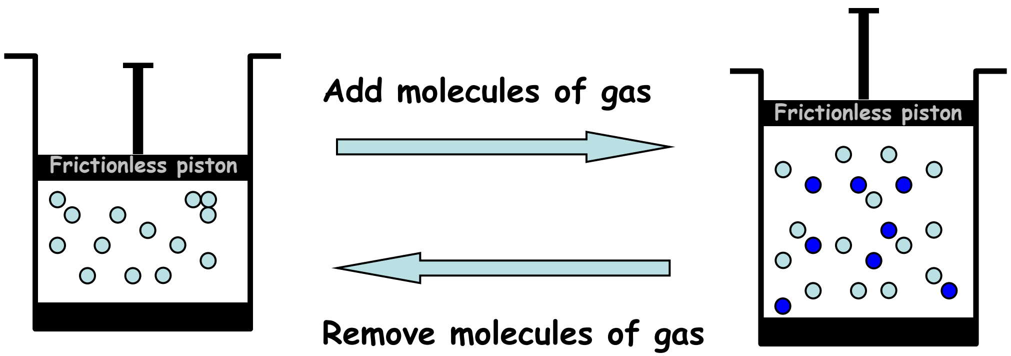


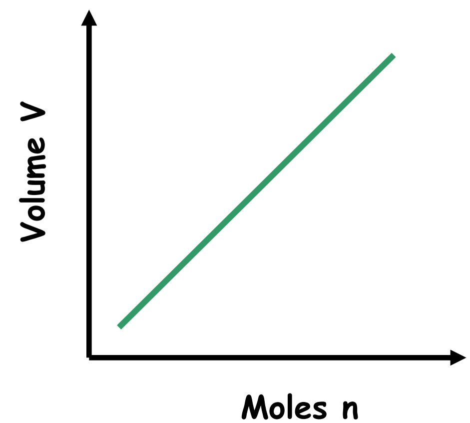


As gas temperature rises, the velocity of molecules and so the force of their collisions increases. Therefore, pressure rises (and vice-versa).

3. Avogadro’s Law

Avogadro's law: $V \propto n$ (constant P, T)





Equal volumes of different gases, at the same temperature and pressure, contain the same number of molecules.

The Ideal Gas Equation: PV = nRT

– the 3 gas laws combined

$$\left.\begin{array}{ll} \text{Boyle's law:} & V \propto \dfrac{1}{P} \quad (\text{constant } n,\ T) \\ \text{Charles's law:} & V \propto T \quad (\text{constant } n,\ P) \\ \text{Avogadro's law:} & V \propto n \quad (\text{constant } P, T) \end{array}\right\} \Rightarrow$$

$$V \propto \frac{nT}{P}$$

$$V = R \times \frac{nT}{P}$$

$$\boxed{PV = nRT}$$

Points to note –

- The value and units of R depend on the units used for P, V, n and T
- Temperature expressed on absolute-temperature scale (°Kelvin = °Celsius + 273)

Ideal Gases– not always ideal!

"Ideal gas" molecules –

1. Occupy negligible volume
2. Do not attract each other
3. Undergo elastic collisions
   (no loss of kinetic energy)

⇒ Insignificant inter-molecular forces

"Real" gases and the ideal gas equation –

- Acceptable accuracy for most respiratory gases at physiological temp's and pressures
- Most accurate for monatomic gases eg Helium
- Ideal gas laws don't explain
  - condensation of gases
  - vapourisation of liquids

A word about water vapour

- Gases in equilibrium with their liquid phase will (appear to) **disobey** the gas laws.

- Water vapour is a gas often in **equilibrium** with its liquid phase (ie water).

  Examples:

  1) in the lungs
  2) inside a water filled spirometer
  3) any situation where there is 100% saturation of a gas with water vapour.

- Water vapour pressure depends **only** **on temperature** (non-linear)

- Ideal gases are also affected by pressure.

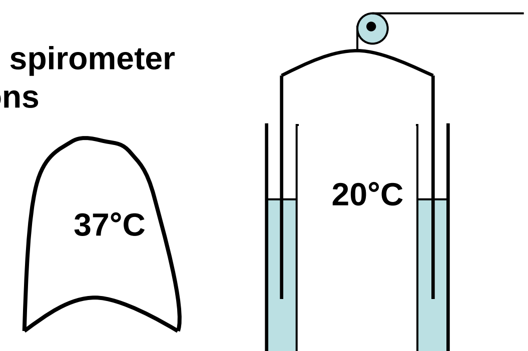
A word about water vapour ….

- Gases in equilibrium with their liquid phase **disobey** the gas laws.
- Water vapour pressure depends ***only*** **on temperature**, unlike ideal gases.

The lungs at sea level vs altitude

	Pb (mmHg)	PAO2 (mmHg)	Alveolar temp	PAH2O (mmHg)	FAH2O
Sea level	760	106	37°C	47	6.2%
20,000 ft	350	46	37°C	47	13.4%

Lung vs spirometer conditions



	Temp	Pb (mmHg)	Saturated with H2O?	PH2O
Lungs	37°C	760	Yes	47
Spirometer	20°C	760	Yes	18

Back to our question …

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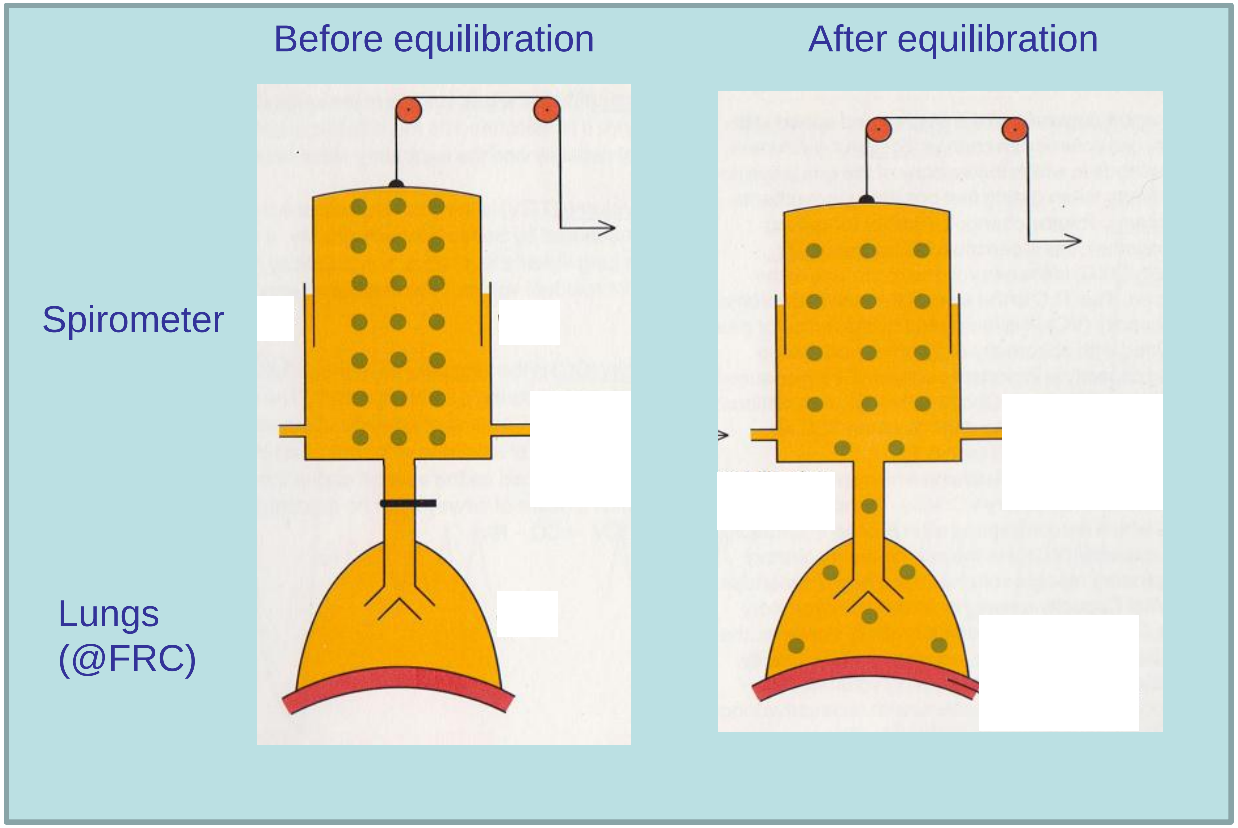

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What approach to use?

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Principle of mass balance
PLUS
Ideal gas equation

Ideal gas equation: $PV = nRT$ or $n = PV/RT$

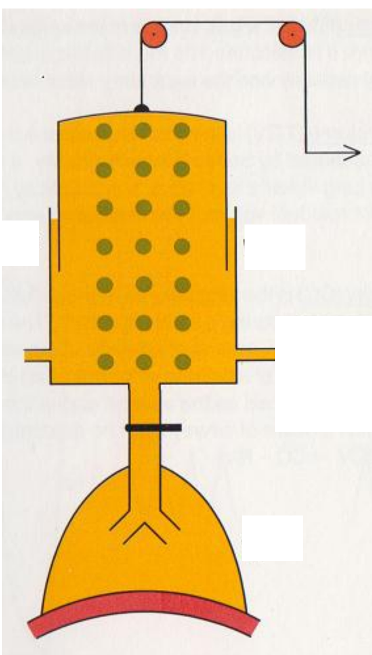
<u>Assumption</u>: The number of molecules of helium before and after equilibration remains the same i.e. mass is conserved (or balanced).

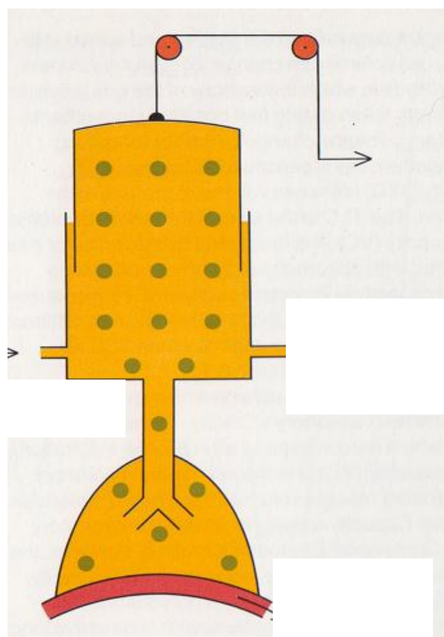
Before equilibration

$$n = \frac{Pb.F_1He.Vs}{R.T}$$

After equilibration

$$n = \frac{Pb.F_2He.(Vs + FRC)}{R.T}$$





$$\frac{Pb.F_1He.Vs}{R.T} = \frac{Pb.F_2He.(Vs + FRC)}{R.T}$$

$$F_1He.Vs = F_2He.(Vs + FRC)$$

$$\boxed{FRC = Vs.(F_1He - F_2He) / F_2He}$$

$$FRC = 4 \times (10-6) / 6$$
$$= 2.67 \text{ L}$$

(adjust for system deadspace and correct to BTPS)

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Airflow resistance - flow through a tube

Questions

- How does airway diameter influence flow resistance?
  eg. If airway diameter is halved? quartered?

- Does changing gas density and/or viscosity alter resistance to airflow?
  eg By breathing Heliox (21%O_2, balance helium)?

- How does the pattern of airflow change from the large bronchi to the small terminal airways? What causes the change? What is the effect on airflow resistance?

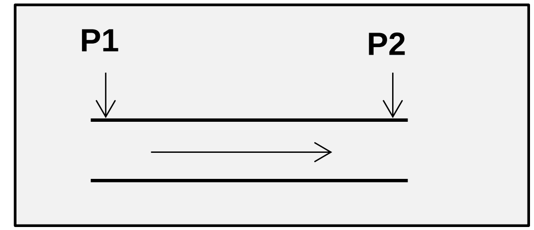
- What effect does the composition of a gas mixture have on the calibration of flow sensors? Why?
  eg. 100% inspired O_2 during a nitrogen washout test

- What are examples of gases used in respiratory physiology that have –
  - density > air
  - viscosity < air

- etc

Airflow resistance - flow through a tube

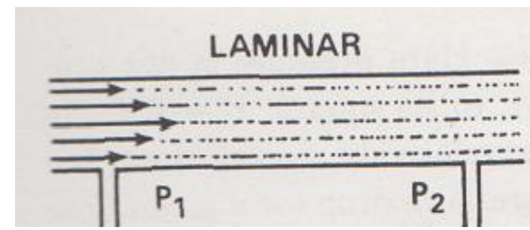
Ohm's law: $Flow = \frac{Pressure\ (\Delta P)}{Resistance\ (R)}$ or $R = \frac{\Delta P}{Flow}$



- *Laminar* versus *turbulent* pattern of flow
- Laminar flow – described by Poiseuille's equation

$$Flow = \frac{P.\pi.r^4}{8.n.l} \qquad (n = viscosity)$$

or $$Resistance = \frac{P}{Flow} = \frac{8.n.l}{\pi.r^4}$$

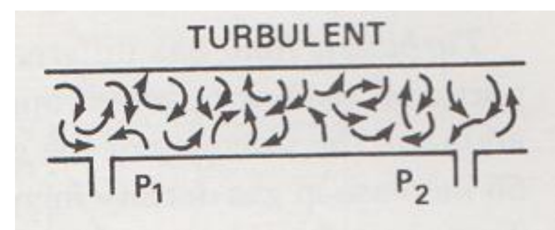


- Turbulent flow – higher P (ie more energy) needed to produce a given flow

$$P \propto Flow^2$$

- Transition to turbulent flow when Reynold's number > ~2000

$$Re = \frac{2.r.v.d}{n} \qquad (d = density,\ v = velocity,\ n = viscosity)$$



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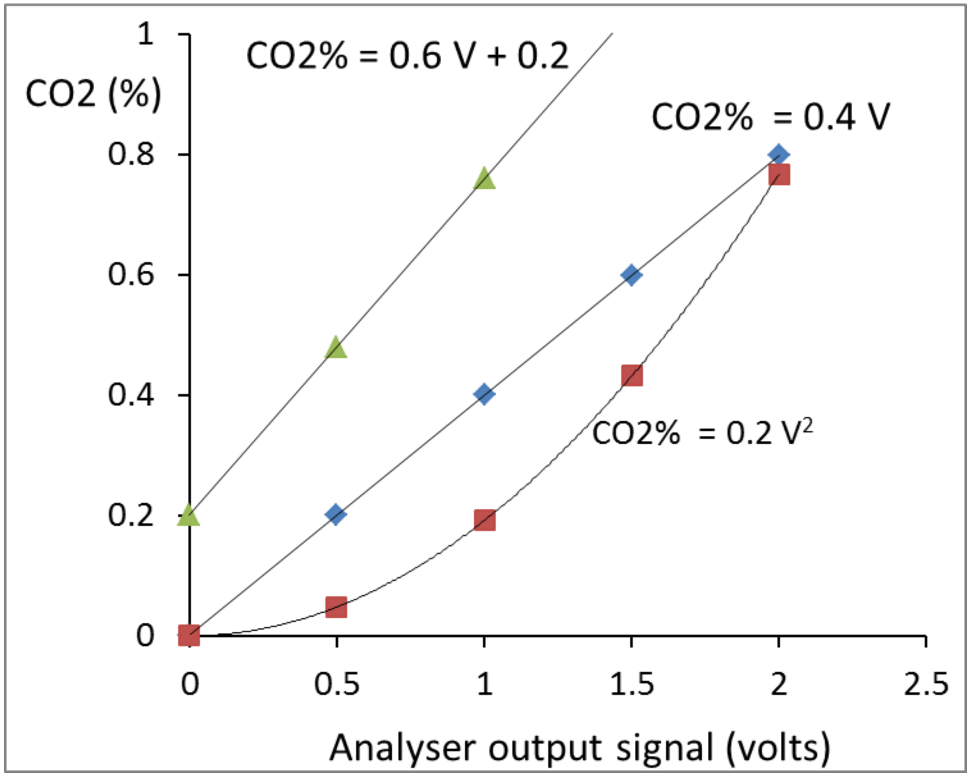
Calibration equations

Questions

- What is the purpose of calibration?
- How is calibration different from quality control?
- How is a transducer’s output voltage converted to an accurate reading in the units of interest?
- Why are non-linear transducers more complicated to calibrate than linear transducers?
- How is it possible to accurately calibrate a flow transducer with a syringe of known volume but unknown flows?
- etc



Linear devices:

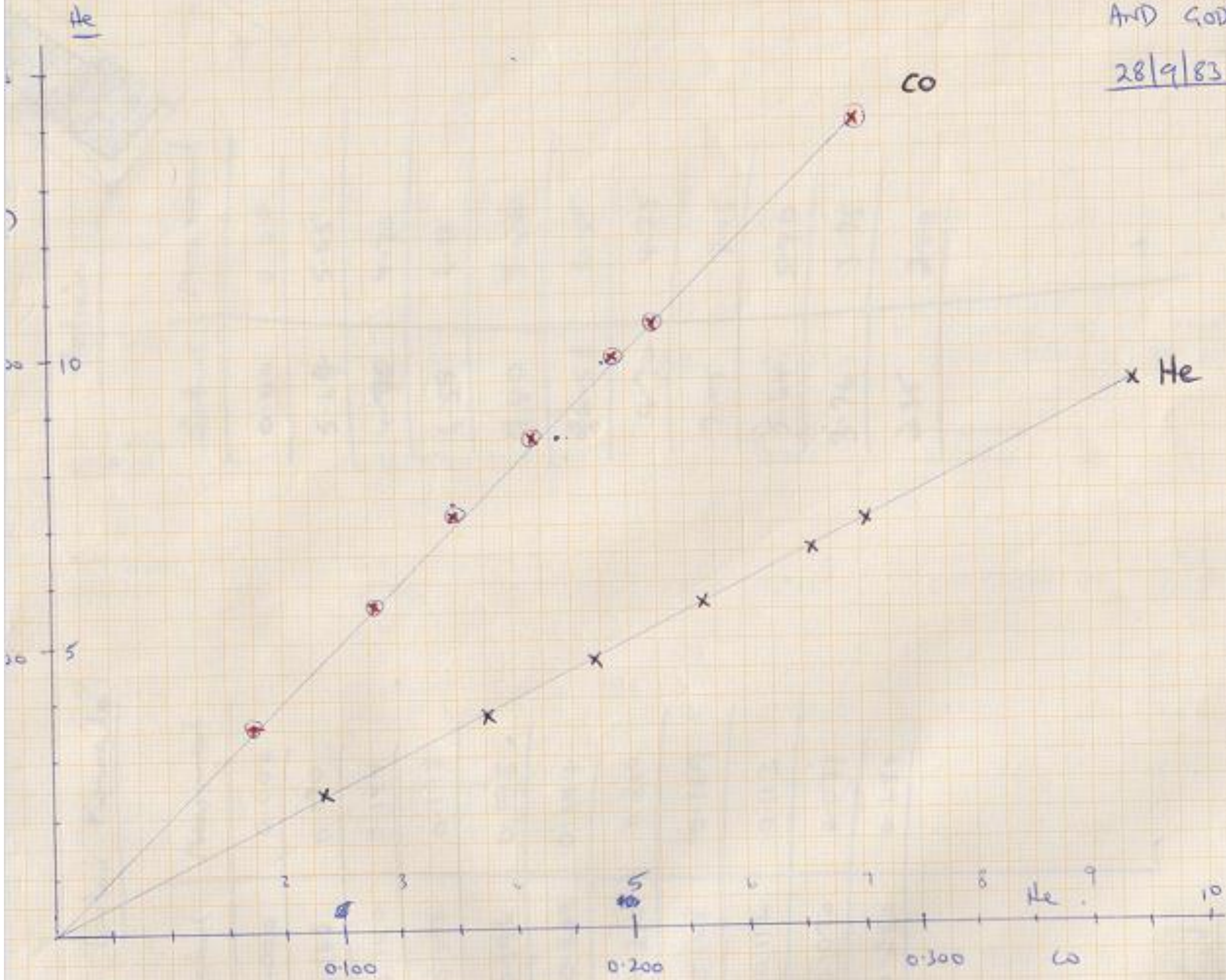
- Straight line cal equation
- Y=mX + c
- 2 point cal sufficient if linearity is known

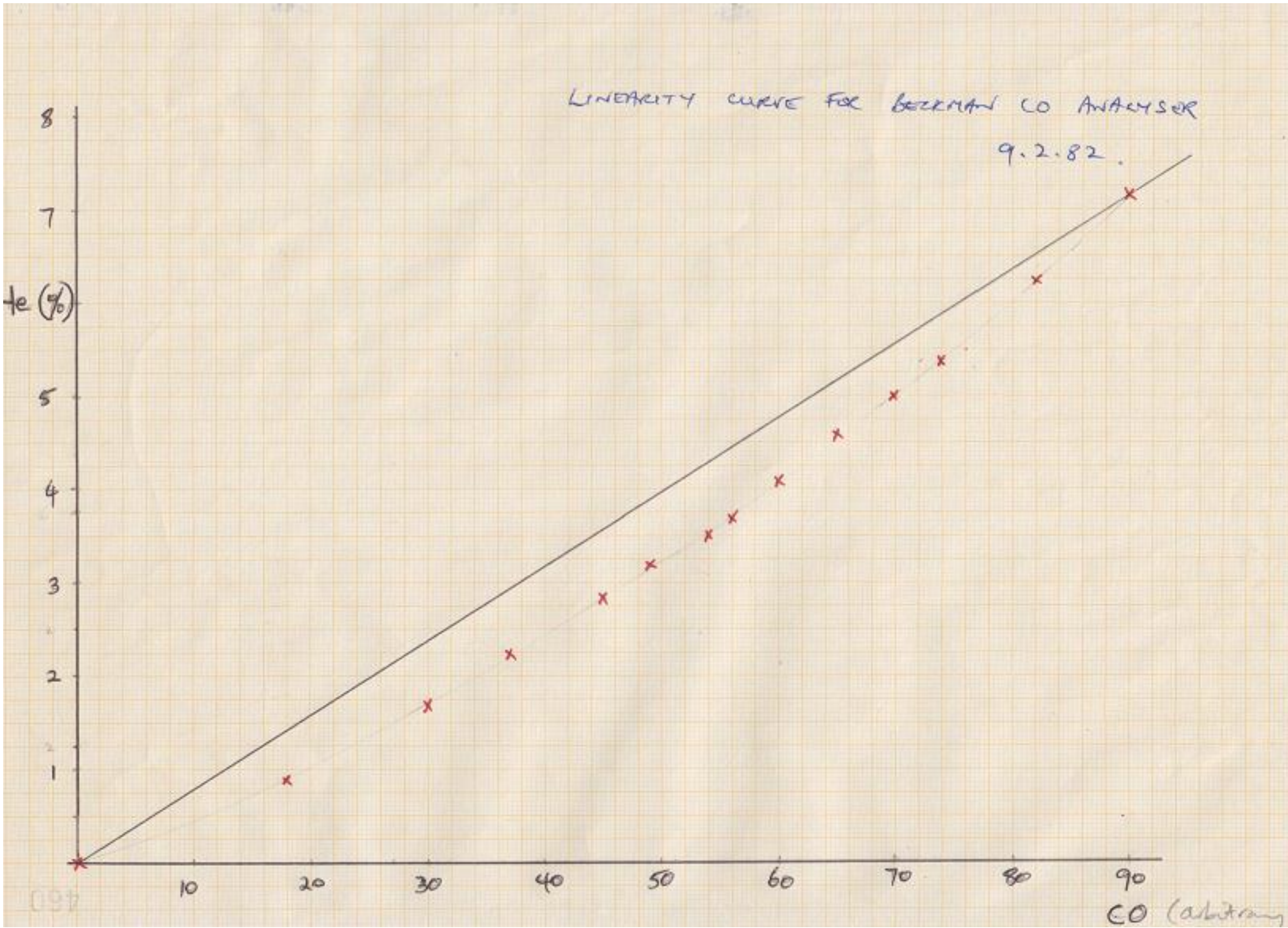
Non-linear devices:

- Variety of regular profiles
- Polynomials, square root, exponential etc
- Profiles not well fitted by an equation
  – use lookup tables
- Multi-point point cal required

LINEARITY CHECK
ON MORGAN CO ANALYSER
AND GODART He ANALYSER

28/9/83




LINEARITY CURVE FOR BECKMAN CO ANALYSER
9.2.82.
te (%)
8
7
5
4
3
2
1
10
20
30
40
50
60
70
80
90
CO (arbitrary