The Gas Laws and Hypoxia

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Aviation Medical Examiner's Course

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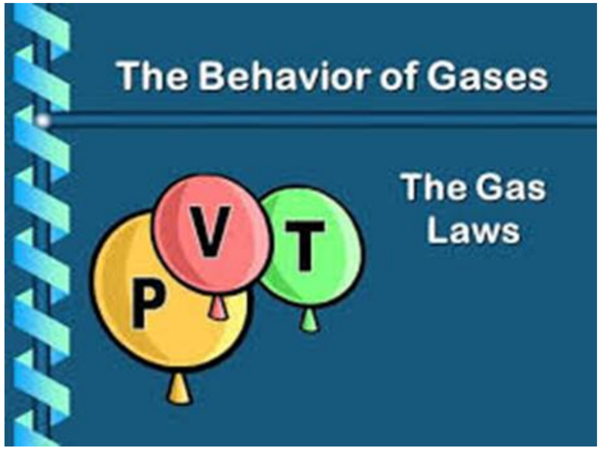
The Gas Laws - Scope

1. Introduction
2. SI Units
3. The Gas Laws
   - The General Gas Law
     - Boyle's Law
     - Charles' Law
     - Gay Lussac's Law
   - Dalton's Law
   - Henry's Law



Scope…

– Laws of Gaseous Diffusion
  - Graham’s Law
  - Fick’s Law
– Law of flow - Poiseuille’s Law

Hypoxia

1. Introduction

The Gas Laws govern the behavior of gases

- in isolation,
- as components of gaseous mixtures and
- as gasses dissolved in liquids,

and have a direct bearing on how changes in altitude affect human physiology.

2. SI Units

- Pressure - the Pascal (Pa)

101 kPa = 1 atm = 760 mmHg = 1013.25 mb or hPa

(millibars or hectopascals)

- Volume - the cubic meter

But can use liters (L) or cubic centimeters (cc)

- Temperature - Kelvin °*K*

Absolute temperature scale: Kelvin…

The SI unit for temperature is Kelvin

0 Kelvin = -273.15 °C

Nothing can be colder

No kinetic energy

Electrons stop moving

Superconduction

Infinite kinetic energy

Convert Celsius to Kelvin as follows:

°K = °C + 273 *e.g., 11 °C = 284 °K*

As common temperature scales are only a portion of the absolute temperature scale these need to be converted to <u>absolute temperature</u> before performing calculations

October 2021: Record - 38 trillionths of a degree above -273.15

3. Gas Laws

- **The General Gas Law** combines -

  Boyle's, Charles' and **Gay Lussac's laws**

which describe the relationship between

  – P: pressure,
  – T: temperature and
  – V: volume, of a *fixed amount* of a gas.

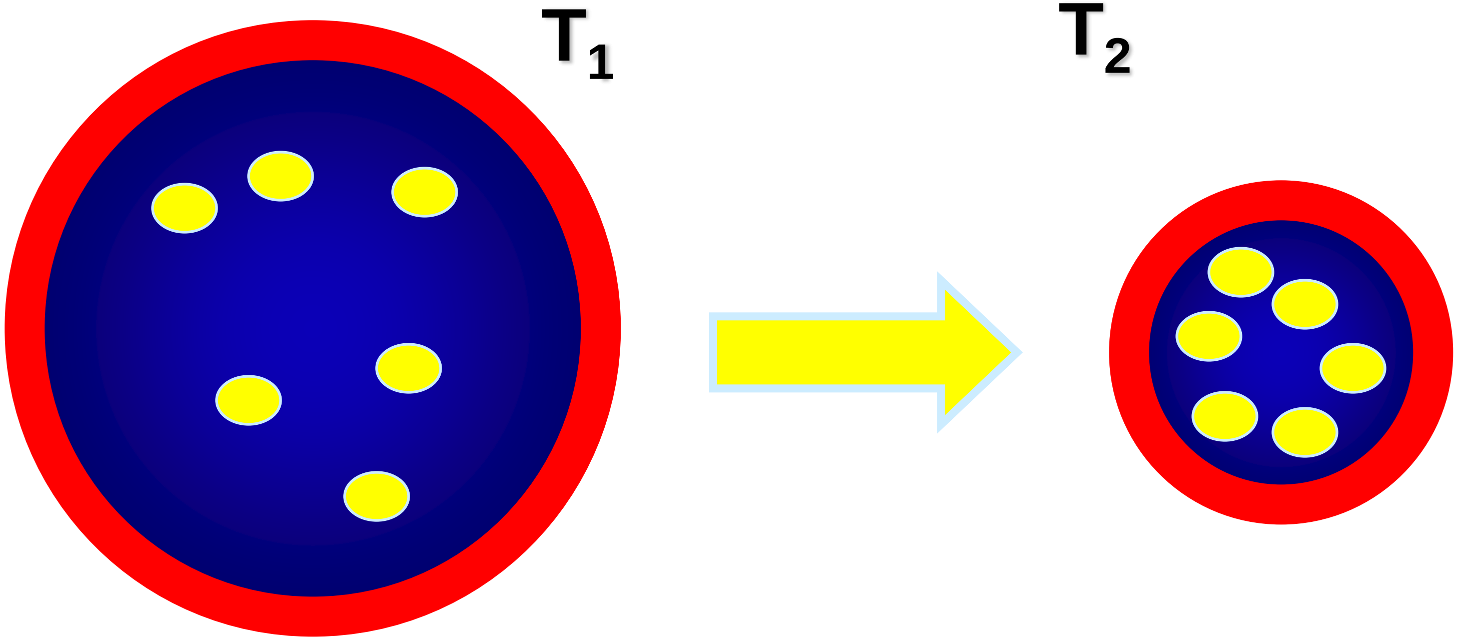
- **Dalton's law** describes the behavior of the individual components of a *mixture* of gases

GAS LAWS OF RELEVANCE TO PHYSIOLOGY

- **Henry's law** describes the behavior of gases *in solution*
- **Graham's law** describes gaseous *diffusion through a liquid or gaseous* mixture
- **Fick's law** describes gaseous *diffusion through a tissue medium*
- **Poiseuille's law** describes *flow through a tube*

The General Gas Law

$$\frac{P_1 V_1}{T_1} = C = \frac{P_2 V_2}{T_2}$$



As long as the mass (ie the number of molecules) of the gas does not change

The volume of a fixed mass of gas is inversely proport-ional to the pressure to which it is subjected, when measured under constant temperature.

The volume of a fixed mass of gas is directly proportional to its absolute temperature, measured under constant pressure. (Temp in Kelvin)

V

Boyle's law

$$P_1V_1 = P_2V_2$$

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}$$

Charles's law

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

General law

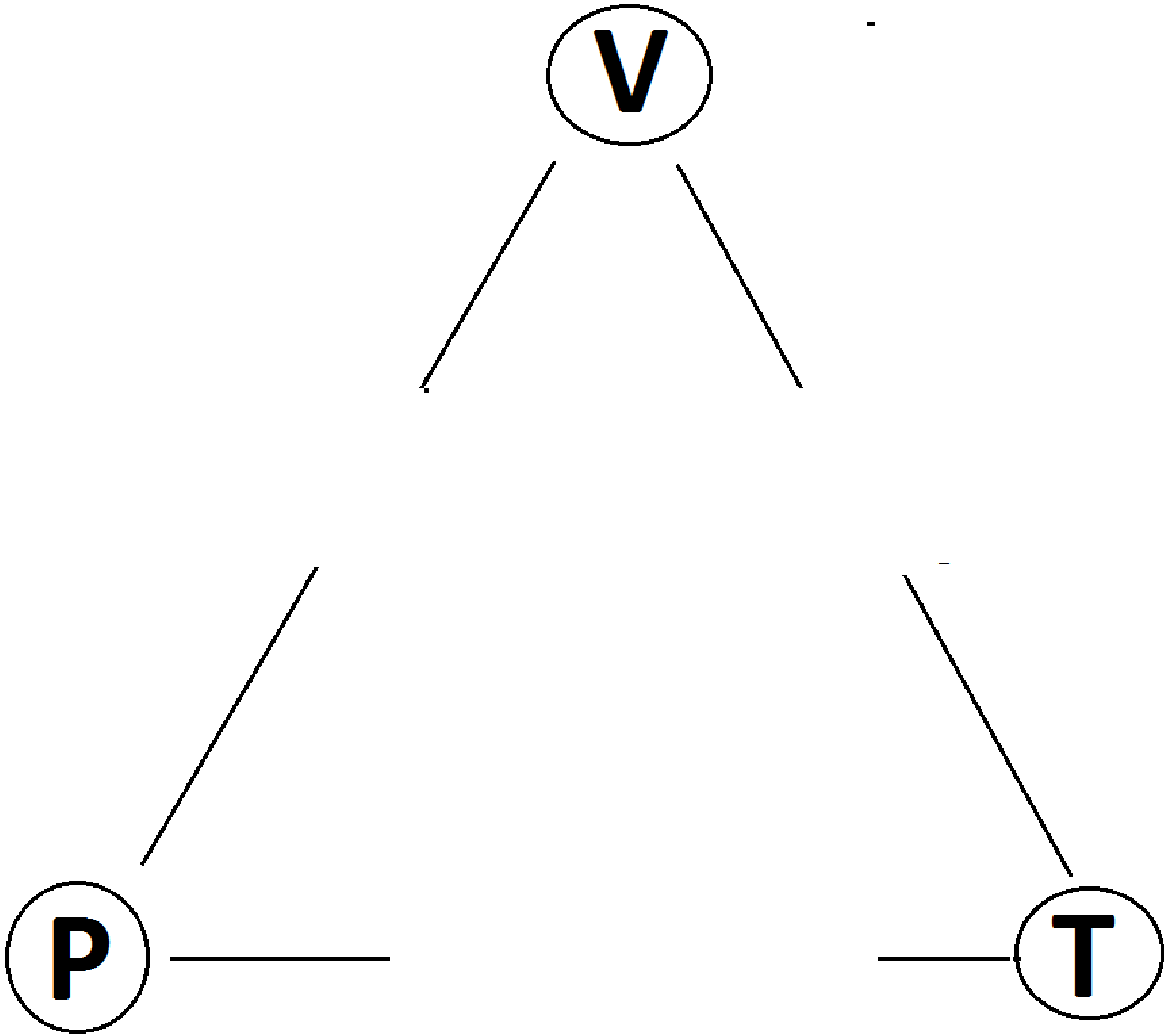
P

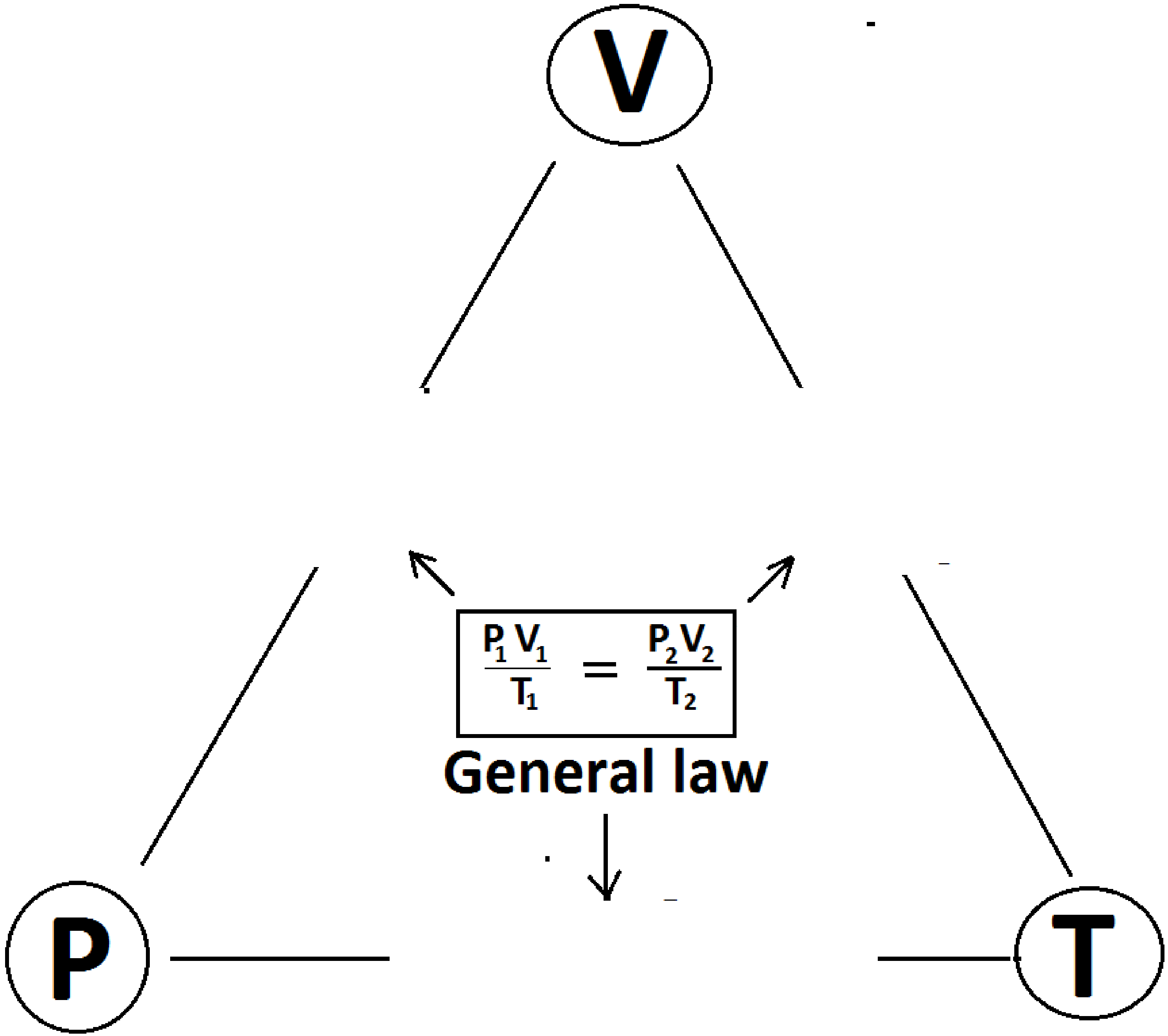
$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

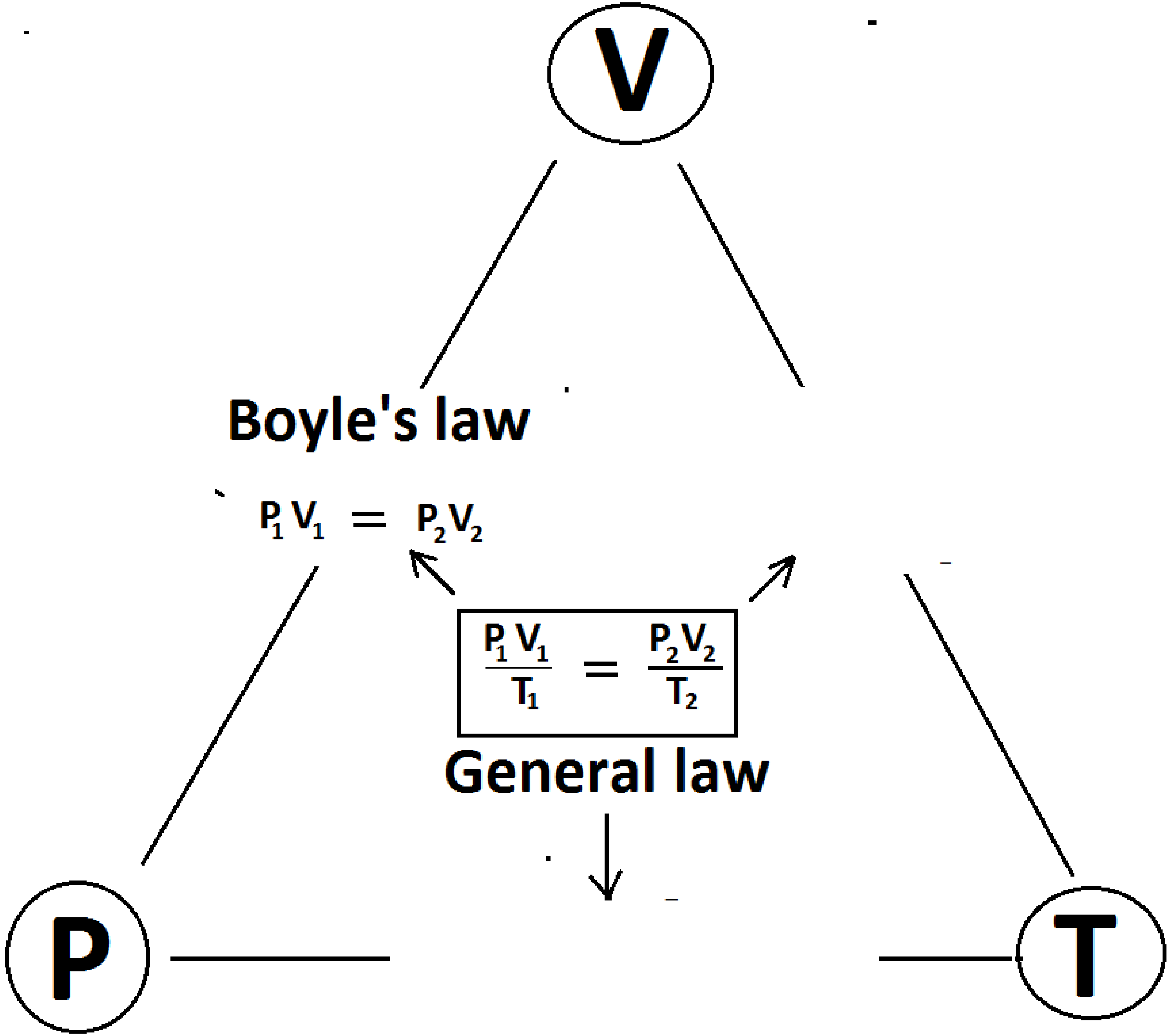
T

Gay Lussac's law


P
T


V
P
T


V
$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
General law
P
T


V
Boyle's law
$P_1V_1 = P_2V_2$
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General law
P
T

The volume of a fixed mass of gas is inversely proportional to the pressure to which it is subjected, when measured under constant temperature.

V

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}$$

Boyle's law

$$P_1V_1 = P_2V_2$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

General law

P

T

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General law

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P

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V

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$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

General law

P — $$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$ — **T**

Gay Lussac's law

Boyle's Law…

TRAPPED GAS

- The volume of a gas is ***inversely*** proportional to the partial pressure at constant temperature.

$$P_1 V_1 = P_2 V_2 \qquad \frac{P_1}{P_2} = \frac{V_2}{V_1}$$

- Relevance to flight – a gas will expand when the pressure on it decreases i.e., at altitude.

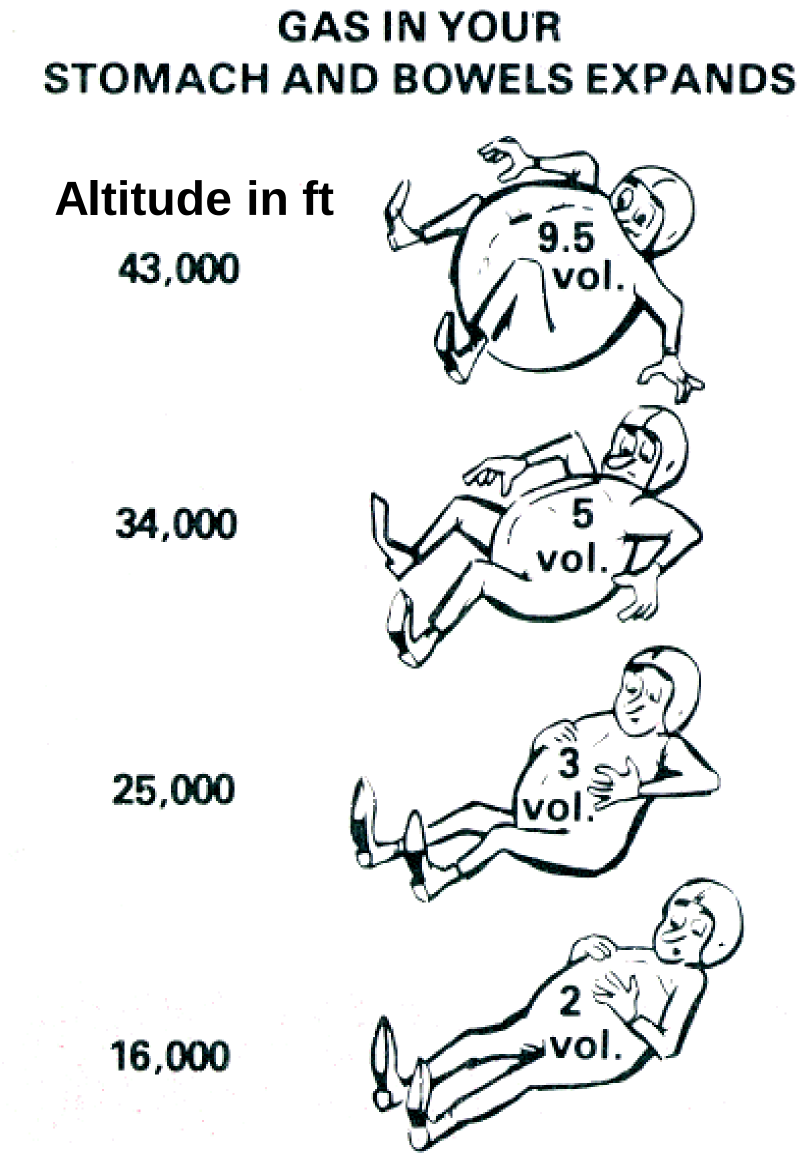
Atmospheric pressure vs altitude

- Pressure decreases exponentially with height above sea level
- 1 atmosphere at msl
- 1/2 atmosphere at 18 000 ft
- 1/4 atmosphere at 36 000 ft (approx)
- 1/8 atmosphere at 72 000 ft (approx)
- etc

Boyle's Law…

Distended bowels -
why so much?

Relevance to flight?



Boyle's Law…

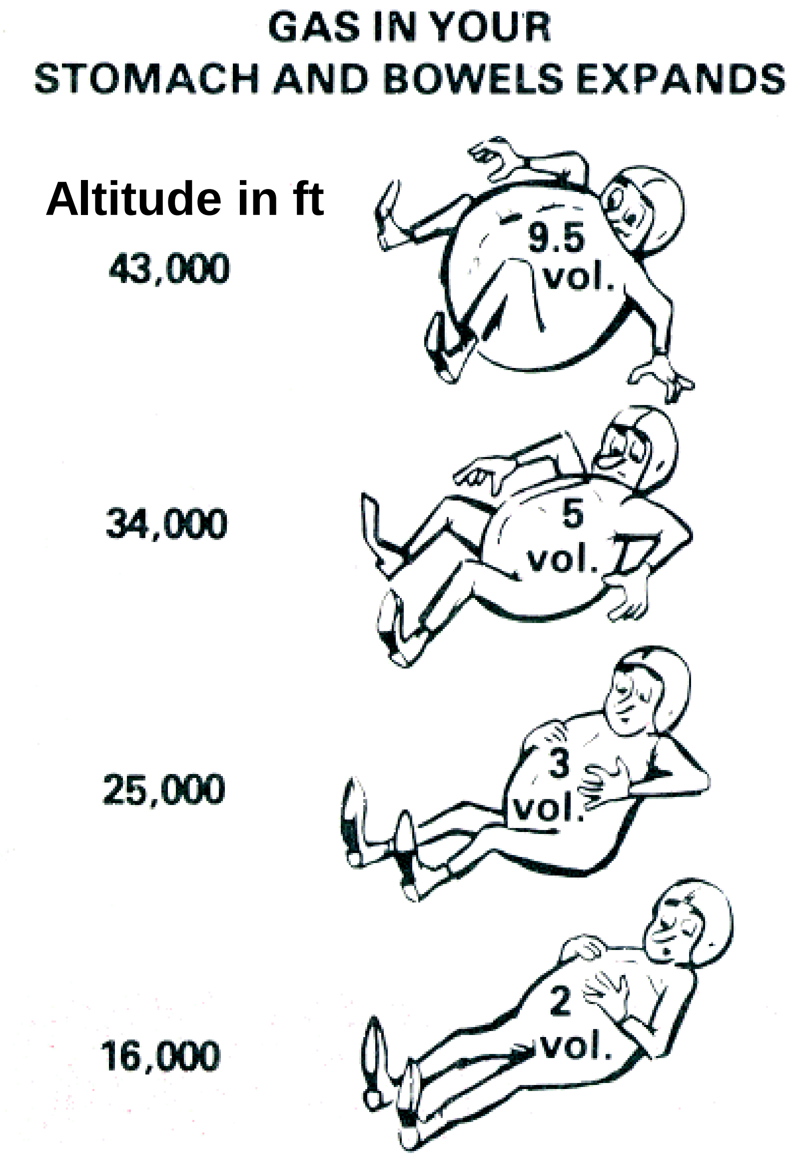
Distended bowels - why so much?

- Boyle's Law, and…
- swallowing & gum chewing,
- production of gas by gut microbes
- diffusion of gas into the intestinal lumen from the bloodstream

Prevention: Avoid -

- gas forming foods (beans, cabbages, peas, etc)
- gassy cool-drinks
- gum chewing

Relevance to flight?



Boyle's Law…

Example:

You inflate an ET cuff with 15cc of air at sea level (1 Atm). What will the volume of air in the balloon be at 18 000 ft?

- What will the expanding cuff do to the trachea?

- How can we prevent this?

Problems during sudden decompression

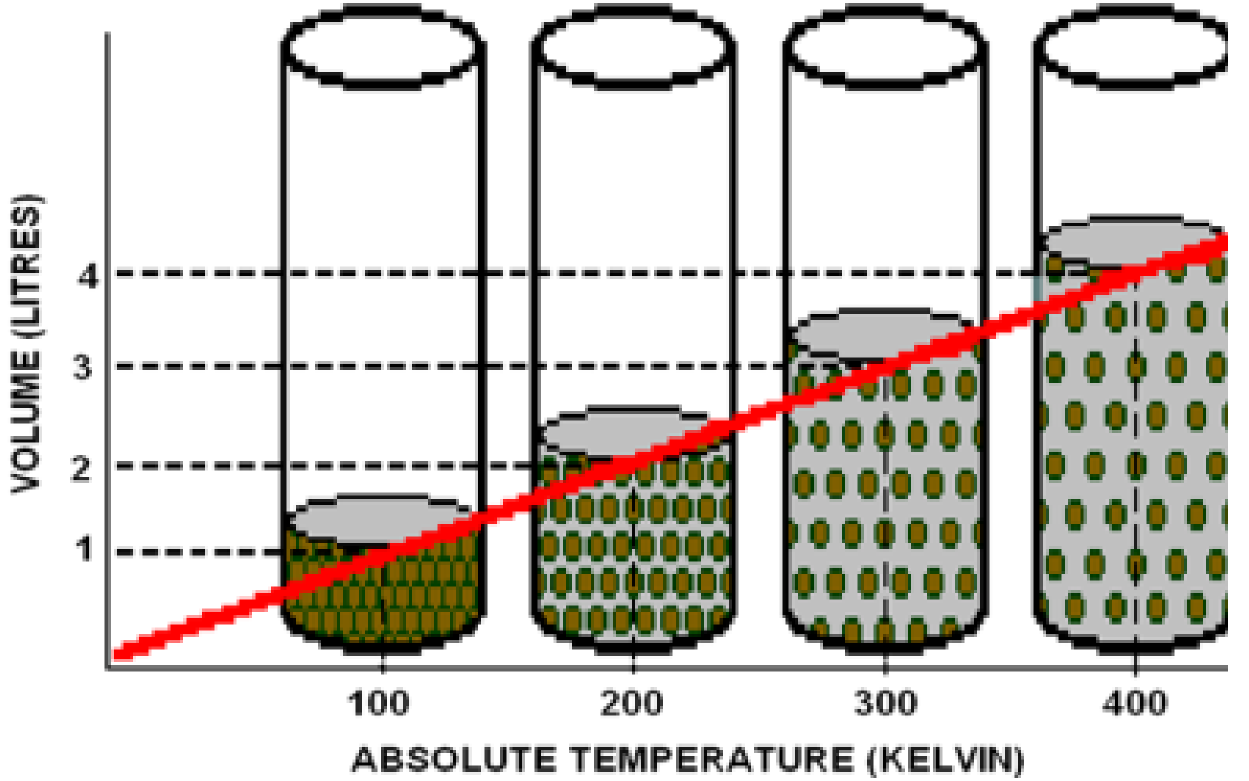
Where else are there isolated quantities of air or gas that may be problematic?

- Teeth (aerodontalgia)
- Sinusses (barosinusitis)
- Patients with pneumothorax
- Lungs (breath holding)
- Middle ear (barotitis media) – is a greater problem during **descent**

Charles' Law

$$\frac{V1}{T1} = \frac{V2}{T2}$$

$V2 = V1 \times T2/T1$



The volume of a gas is directly proportional to its absolute temperature at constant pressure.

(Linear relationship between V2 and T2)

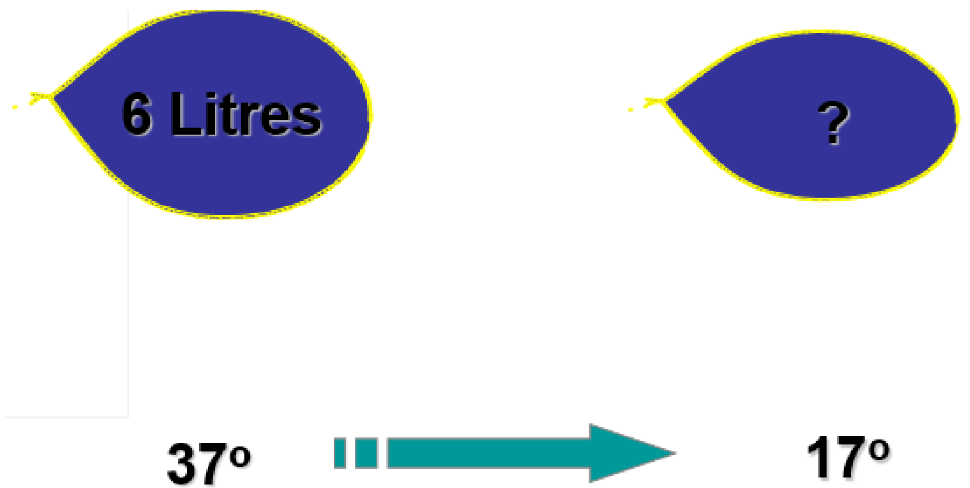
Question – Charles' Law

V2= V1 x T2/T1

37º → **17º**

Solution?

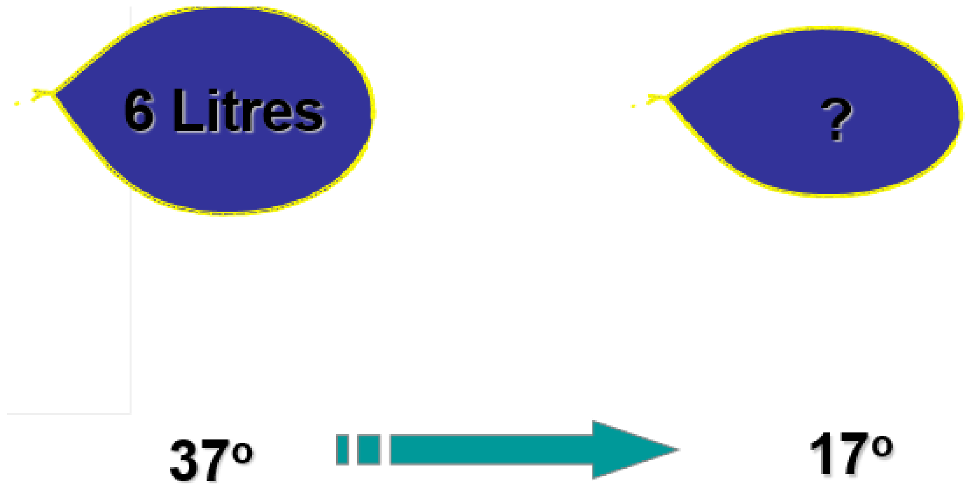
a. I,83
b. 2,76 = usual answer
c. 4,59
d. 5,61
e. 6,97



How to get 2,76?

Solution?

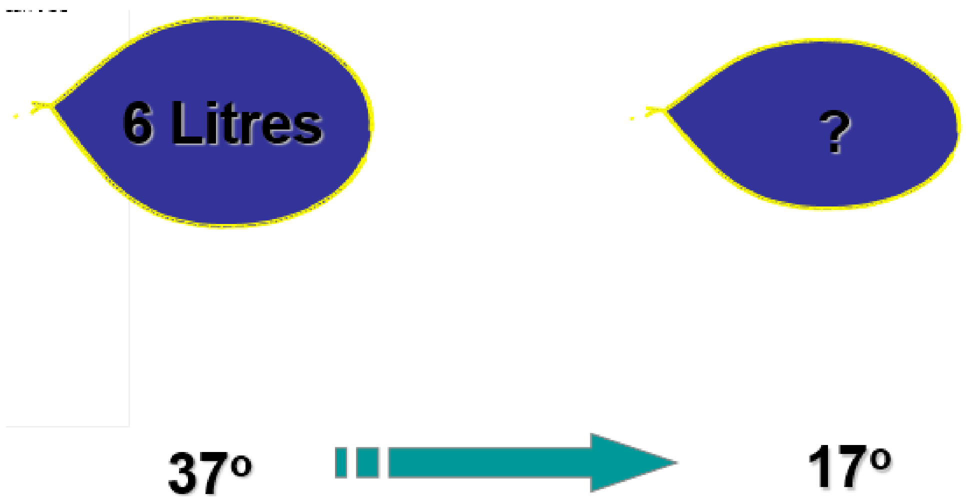
a. I,83
b. 2,76 = usual answer
c. 4,59
d. 5,61
e. 6,97



How to get 2,76?
V2 = V1 x T2/T1
V2 = 6 x 17/37
= 2,76?

Solution?

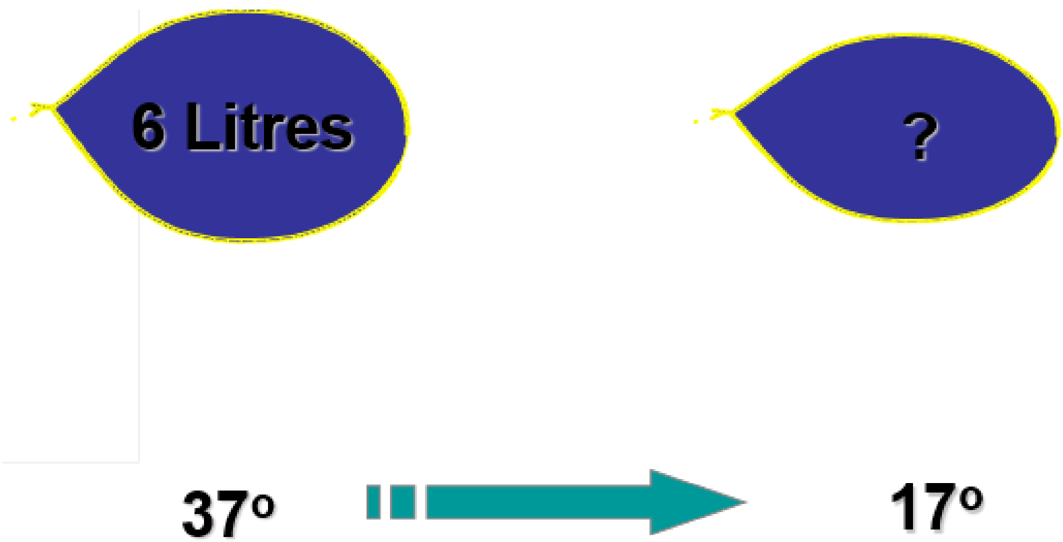
a. I,83
b. 2,76
c. 4,59
d. 5,61= correct answer - why???
e. 6,97



Solution…

- <u>Convert all temperatures to K</u>.

Not doing this is the most common mistake made in solving this type of problem!



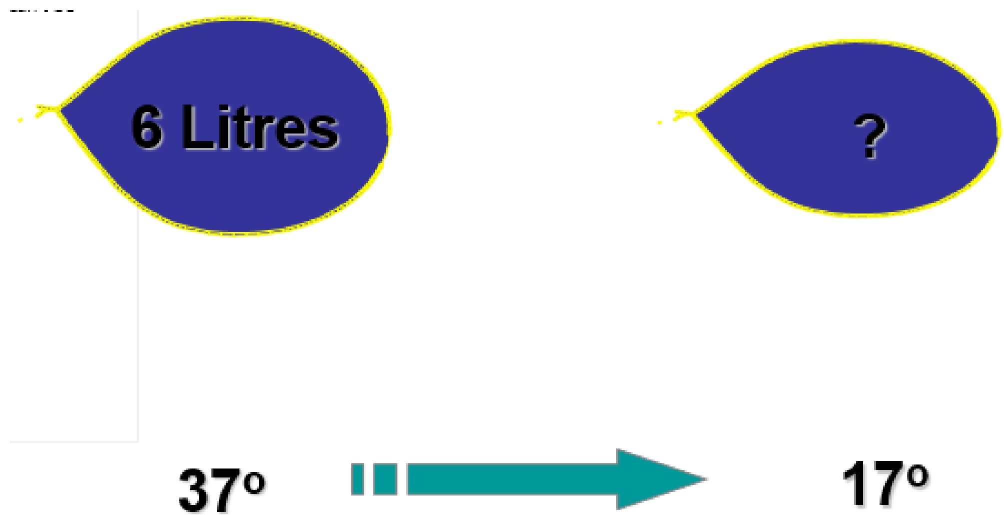
Solution (cont…)

- Convert all temperatures to K.

T_1 = 273 + 37 = 310 °K
T_2 = 273 + 17 = 290 °K

Now find the final volume: $V_2 = V_1 \times T_2/T_1$

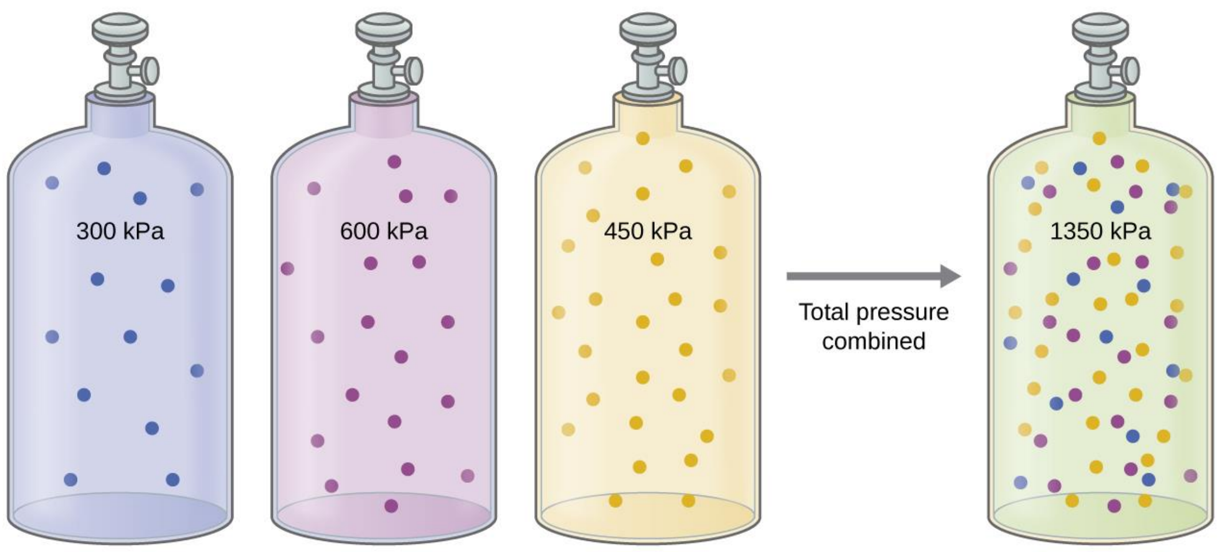
V_2 = 6 x 290/310 = 5,61 L

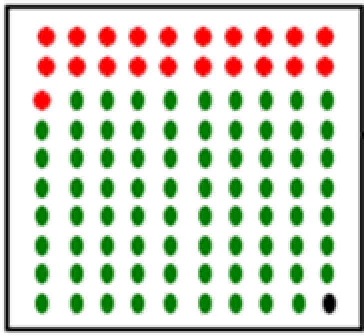


Dalton's Law

HYPOXIA

The total pressure exerted by a *mixture* of gasses is equal to the sum of the pressures that each would exert if it alone occupied the space filled by the mixture.





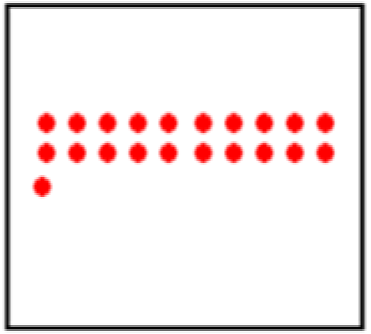
P_{Tot}

Consider 100 units of air in a container with fixed volume V and at constant temperature T

Oxygen fraction : $f_1 = \frac{21}{100}$

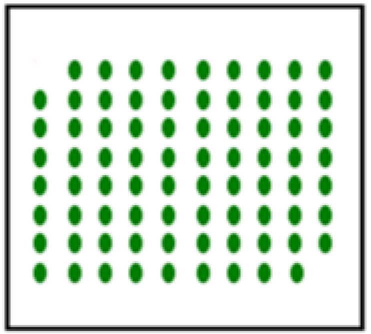
Nitrogen fraction : $f_2 = \frac{78}{100}$

Trace gas fraction : $f_3 = \frac{1}{100}$



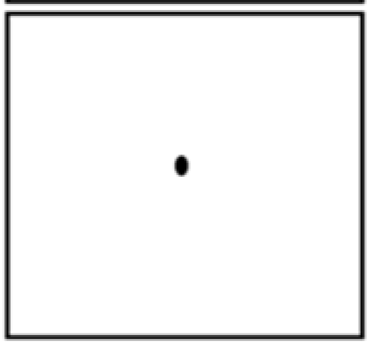
Partial pressure of Oxygen:

$$P_1 = f_1 P_{Tot} = \frac{21}{100} P_{Tot}$$



Partial pressure of Nitrogen:

$$P_2 = f_2 P_{Tot} = \frac{78}{100} P_{Tot}$$



Partial pressure of trace gases:

$$P_3 = f_3 P_{Tot} = \frac{1}{100} P_{Tot}$$

$$P_1 + P_2 + P_3 = \frac{21}{100} P_{Tot} + \frac{78}{100} P_{Tot} + \frac{1}{100} P_{Tot} = \left(\frac{21}{100} + \frac{78}{100} + \frac{1}{100} \right) P_{Tot} = P_{Tot}$$

DALTON'S LAW

$$P_{Tot} = P_1 + P_2 + P_3$$

Dalton's Law…

- Partial pressure is responsible for the physiological effects of the individual gas.
- As altitude increases total atmospheric pressure decreases and the partial pressures of the constituents of air also decrease.
- So it becomes more difficult for sufficient oxygen to transfer from the air to the lungs to the blood.

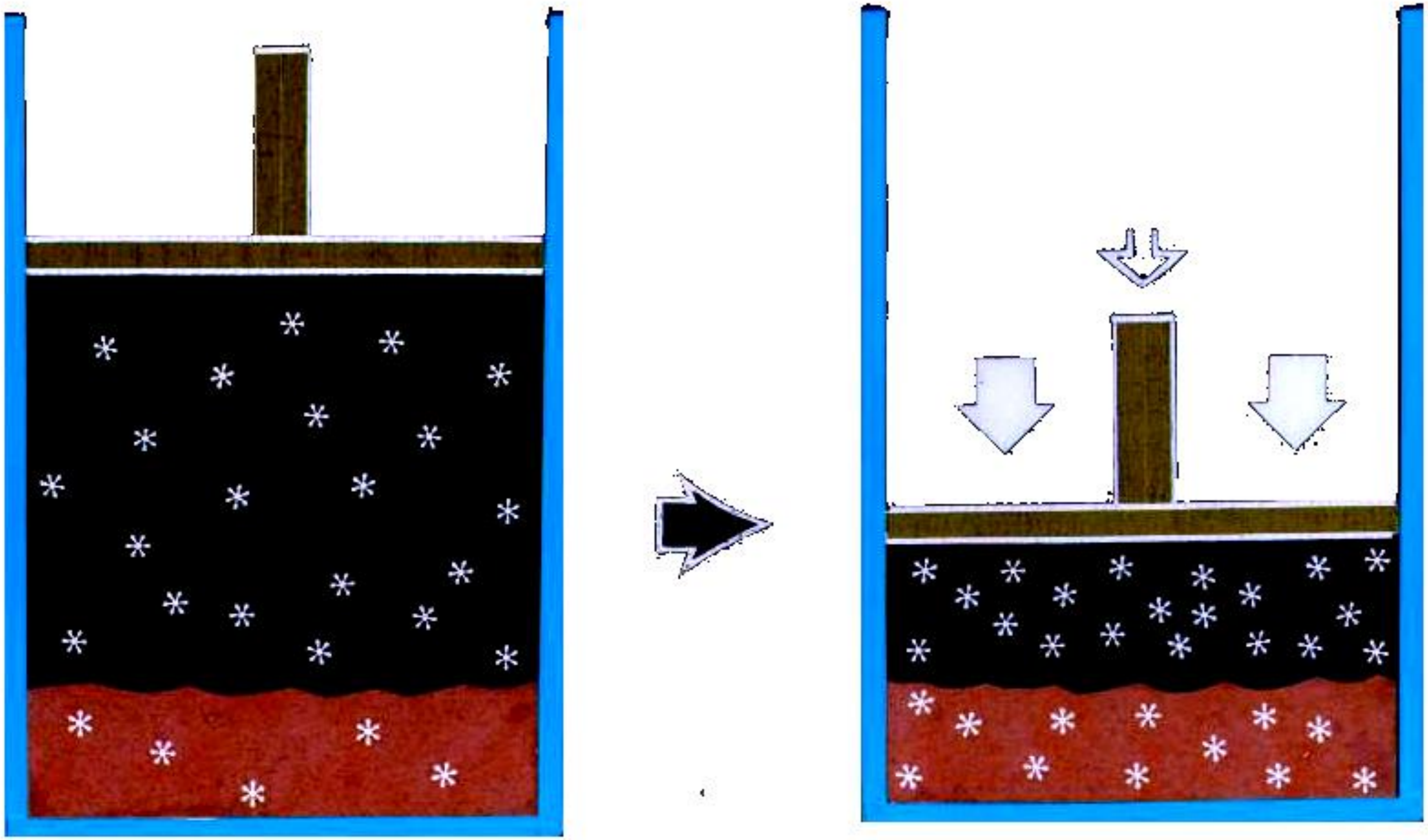
$$P_{Tot} = P_1 + P_2 + P_3$$

Henry's Law

DECOMPRESSION SICKNESS

The volume of gas dissolved in a liquid is directly proportional to its partial pressure *above* the liquid.

Example: "Fizzy" soft drinks are produced by exposing them to ⇧pp CO_2 . They become "flat" again if the caps are left off.



The volume of gas dissolved in a liquid is directly proportional to the partial pressure of the dissolved gas in contact with the liquid

Henry's Law…

Relevance to flight: Risk of decompression sickness at higher altitudes

- Circulatory system – aeroembolisms
- Chest & lungs – the chokes
  - pulmonary decompression sickness
  - sudden, massive blocking of the pulmonary arterial circulation by bubbles
- Muscles & bones – the bends
- Nervous system – various symptoms

Laws of Gaseous Diffusion

- **Graham's law**
- **Fick's law**

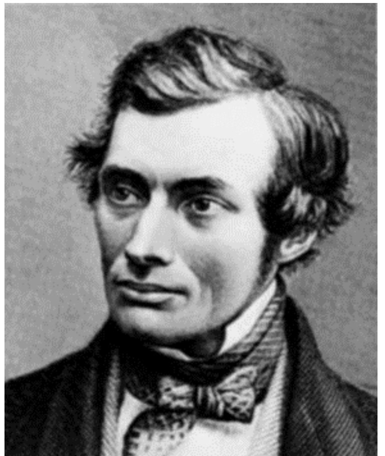
Generally, a gas at a higher pressure

- diffuses through a liquid or gaseous mixture, or a permeable or semi-permeable membrane,
- towards a region of lower pressure.

Graham's Law

- The rate of **diffusion** of a single gas from one point to another point **through a liquid or gaseous mixture**
  - is proportional to the difference between the partial pressures at the two points (P1 - P2), and
  - inversely proportional to the square root of its molecular weight
- In a liquid the rate of diffusion is also proportional to the solubility (S) of the gas in the liquid.

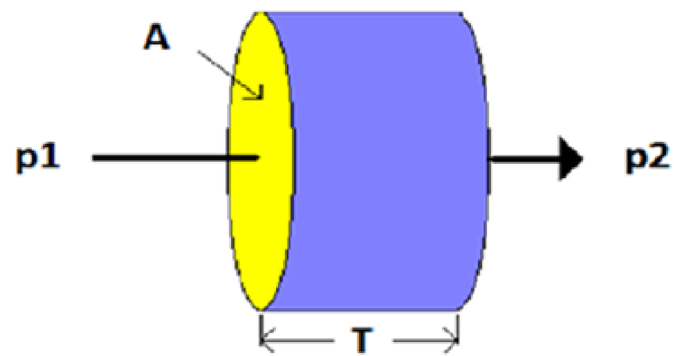
$$\dot{V} \propto \frac{(p1 - p2)\,S}{\sqrt{MW}}$$



Fick's Law

- The **diffusion** of a gas through a **tissue medium** (e.g across a fluid membrane)
  - is proportional to the difference in partial pressures on both sides of the membrane,
  - proportional to the area of the membrane and
  - inversely proportional to the thickness of the membrane.

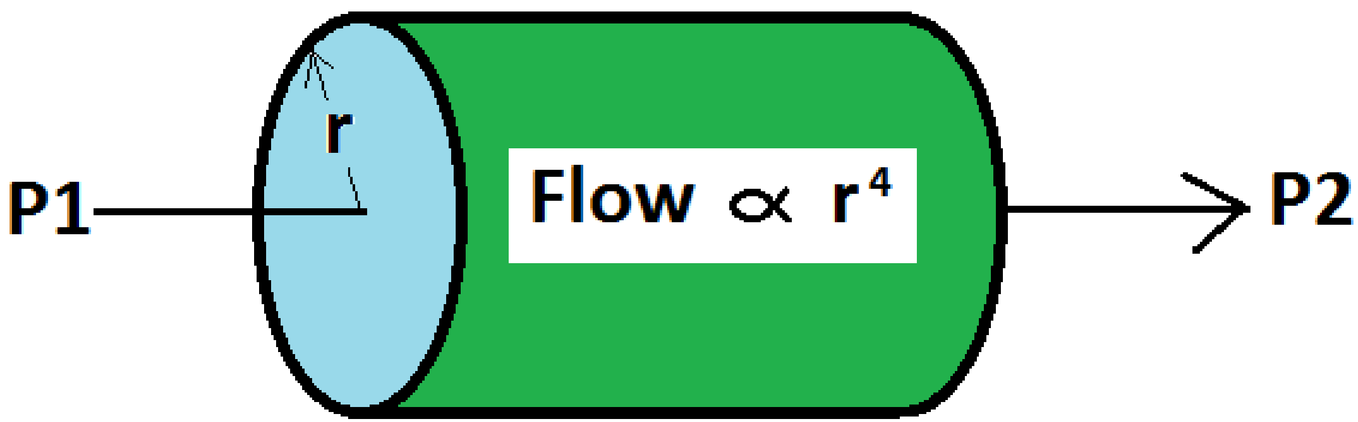
$$\dot{V} \propto \left(\frac{A}{T}\right)(p1 - p2)$$



POISEULLE'S LAW

THE FLOW-RATE OF A GAS THROUGH A TUBE IS PROPORTIONAL TO THE 4'th POWER OF THE RADIUS OF THE TUBE

If you double the radius the flow will increase by a factor of 16.



Application of the Laws of Gaseous Diffusion

- Explains the transfer of gases between the atmosphere and the lungs, the lungs and the blood, and the blood and the cells.
- Confirms that the lungs are a very efficient gas-exchange interface!

Hypoxia in Aviation

Hypoxia - Scope

- Definitions
- Relevance of hypoxia
- Types of hypoxia

  Hypoxic Hypoxia
- Atmospheric composition
- Oxygen partial pressure
- Stages of hypoxia
- TUC & sudden decompression – See lecture by Dr Britz

Definitions

Hypoxia

- Inadequate supply of oxygen to the tissues

Anoxia

- Complete absence of oxygen

Hypoxaemia

- Deficient oxygen-ation of blood

Relevance of hypoxia to anyone flying anywhere

- On the ground, healthy passengers, pilots & aircrew members may function normally

…but…

- Up there, somewhere
- the air is a little thinner, and
- they may *start behaving oddly*

Types of Hypoxia

- Hypoxic / Hypobaric Hypoxia
- Anaemic / Hypoxaemic Hypoxia
- Ischaemic Hypoxia / Stagnant Hypoxia
- Histotoxic Hypoxia

Types of Hypoxia…..

Hypoxic (Hypobaric) Hypoxia

- Reduction in the oxygen pressure at altitude
- Hypoventilatory states:
  - Pulmonary atelectasis
    - High G exposure
    - Trauma / Contusion / Compression
  - Impairment of gas exchange across the alveolar capillary membrane
  - Foreign bodies/gasses
  - Fluids (external/internal)

Types of Hypoxia…..

<u>Anaemic (Hypoxaemic) Hypoxia</u> – reduction in the oxygen carrying capacity of the blood

- Reduced red cell count
- Reduced Hb,
- Reduced oxygen binding capacity

Types of Hypoxia…..

Ischaemic (Stagnant) Hypoxia –

Reduction in blood flow through the tissues

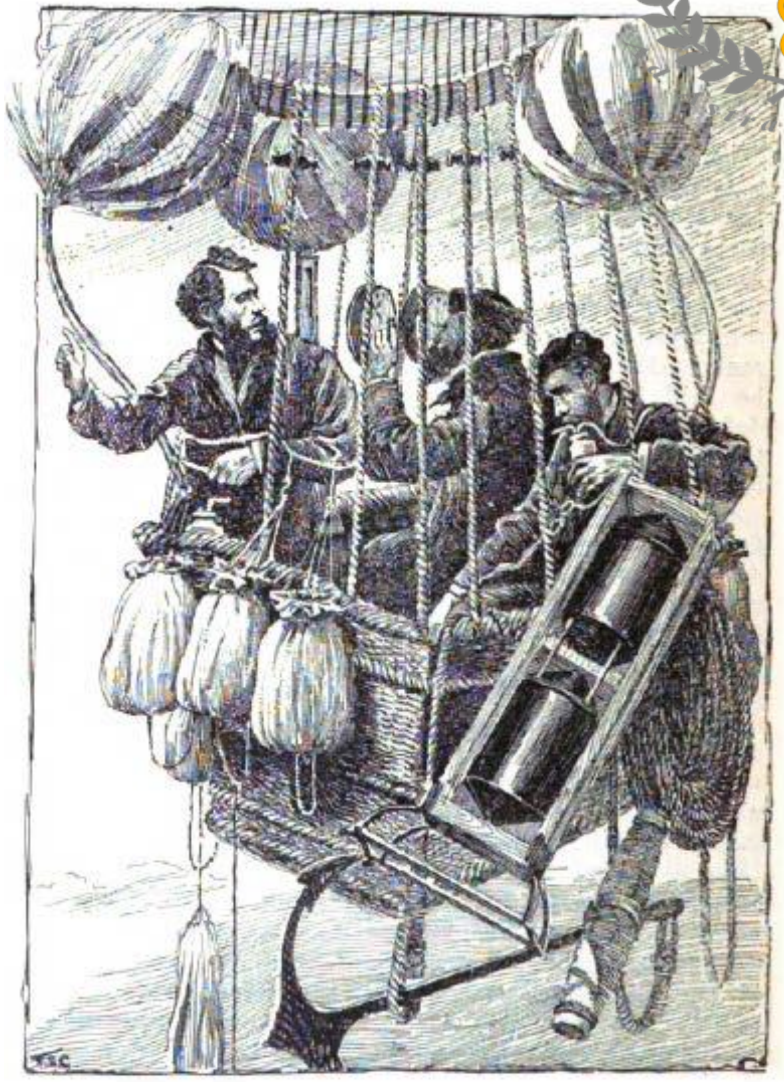
- arteriolar constriction
- general circulatory failure
- DVT, pulmonary embolism
- high G force stresses – pooling

Histotoxic Hypoxia – Interference with the ability of the tissues to utilize oxygen

- Poisoning – cyanide, alcohol, CO, smoking

Hypoxic Hypoxia survivor

- April 1875,
- 3 balloonists
- knew about hypoxia
- with bags of O_2
- flew above 23 000ft
- (to about 28 000ft ?)
- only 1 survived



Hypoxic Hypoxia survivor…

‘One does not suffer in any way; on the contrary. One feels an inner joy, as if filled with a radiant flood of light, one becomes indifferent, one thinks neither of the perilous situation nor of any danger’.

– French pioneering balloonist, Gaston Tissandier, wrote in 1875.

Hypoxic Hypoxia….

- Main aviation hazard, with potential for catastrophic results
  - Most incidents are caused by cabin pressure failure at altitude
  - Also unpressurised aircraft flying too high

- May occur in otherwise healthy people at altitudes less than 10,000ft

Early Signs of Hypoxia

- Impaired judgment
  - Limits aviator's ability to recognize condition or take immediate corrective actions
- Fatigue and hypoglycemia
  - Make hypoxia difficult to recognize
  - Fatigue and hunger also contribute to hypoxia.

Hypoxia Timeframes

- Effective performance time
  - Limited timeframe during which person can function with inadequate level of oxygen

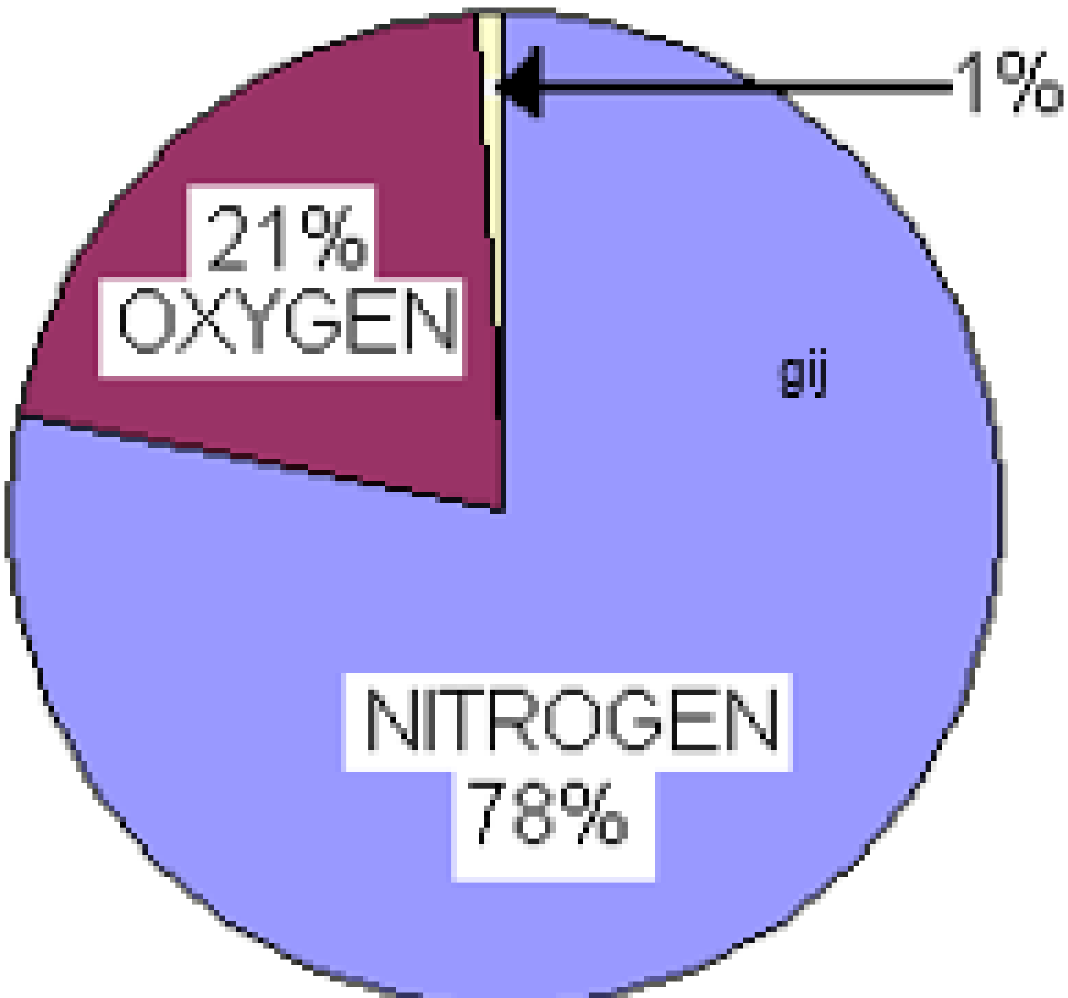
- Time of useful consciousness - **TUC**
  - Period between sudden oxygen deprivation at given altitude and onset of physical and/or mental impairment to a point at which deliberate function is lost

Hypoxia Timeframes…

- Vary by individual depending on:
  - Individual tolerances
  - Method of hypoxia induction
  - Environment before hypoxia
  - Amount of exercise person undertakes
  - Percentage of oxygen prior to hypoxia

Atmospheric composition

Remarkably constant between
sea level and 300 000ft

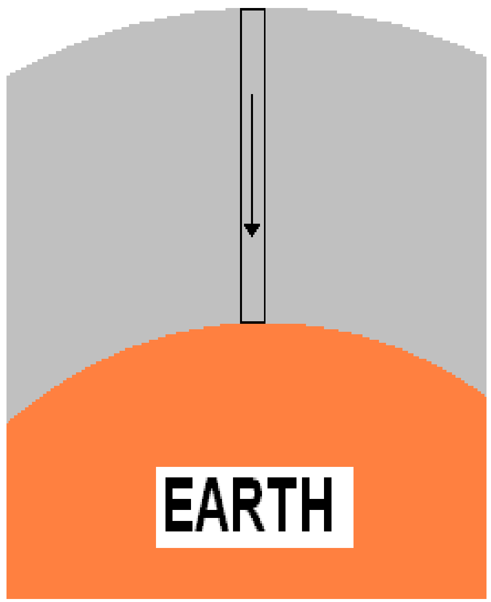


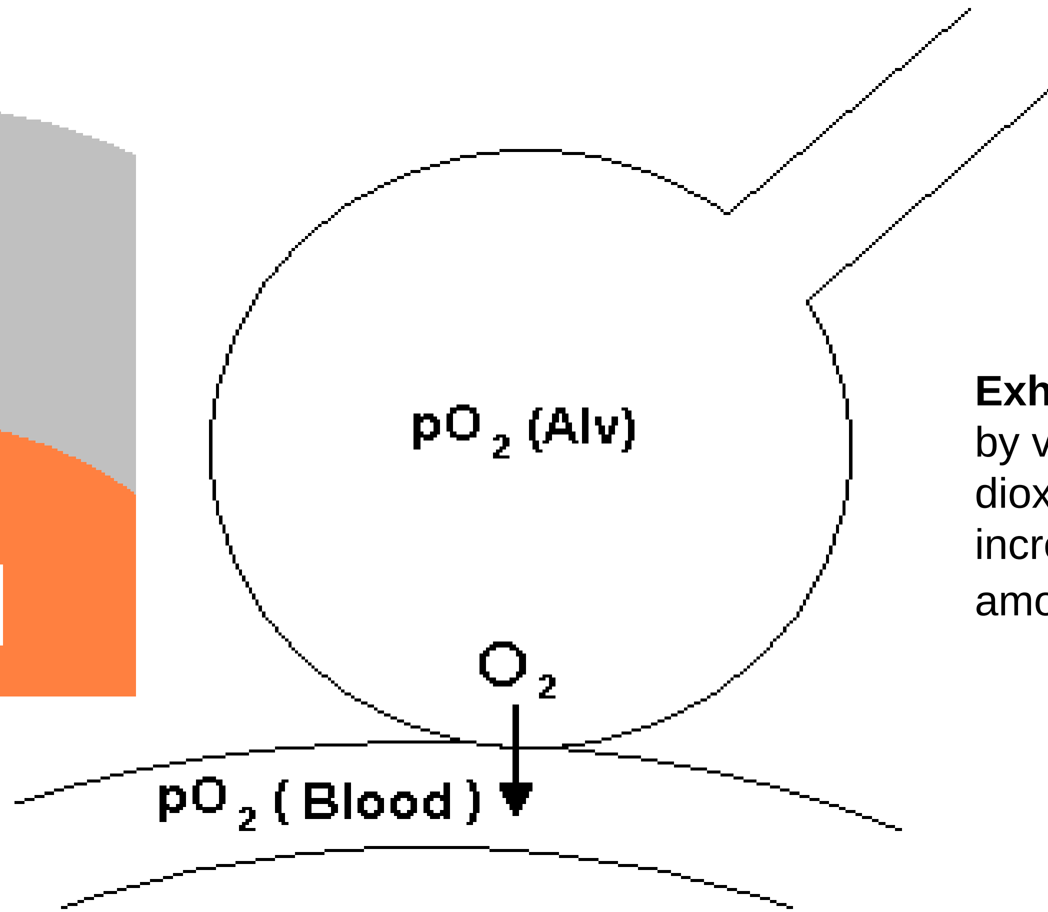
TRACE GASES

Argon
Hydrogen
CO2
Xenon
Neon
Krypton
Helium

Variable:
Water vapour
Ozone

Oxygen partial pressure - role in gas transport





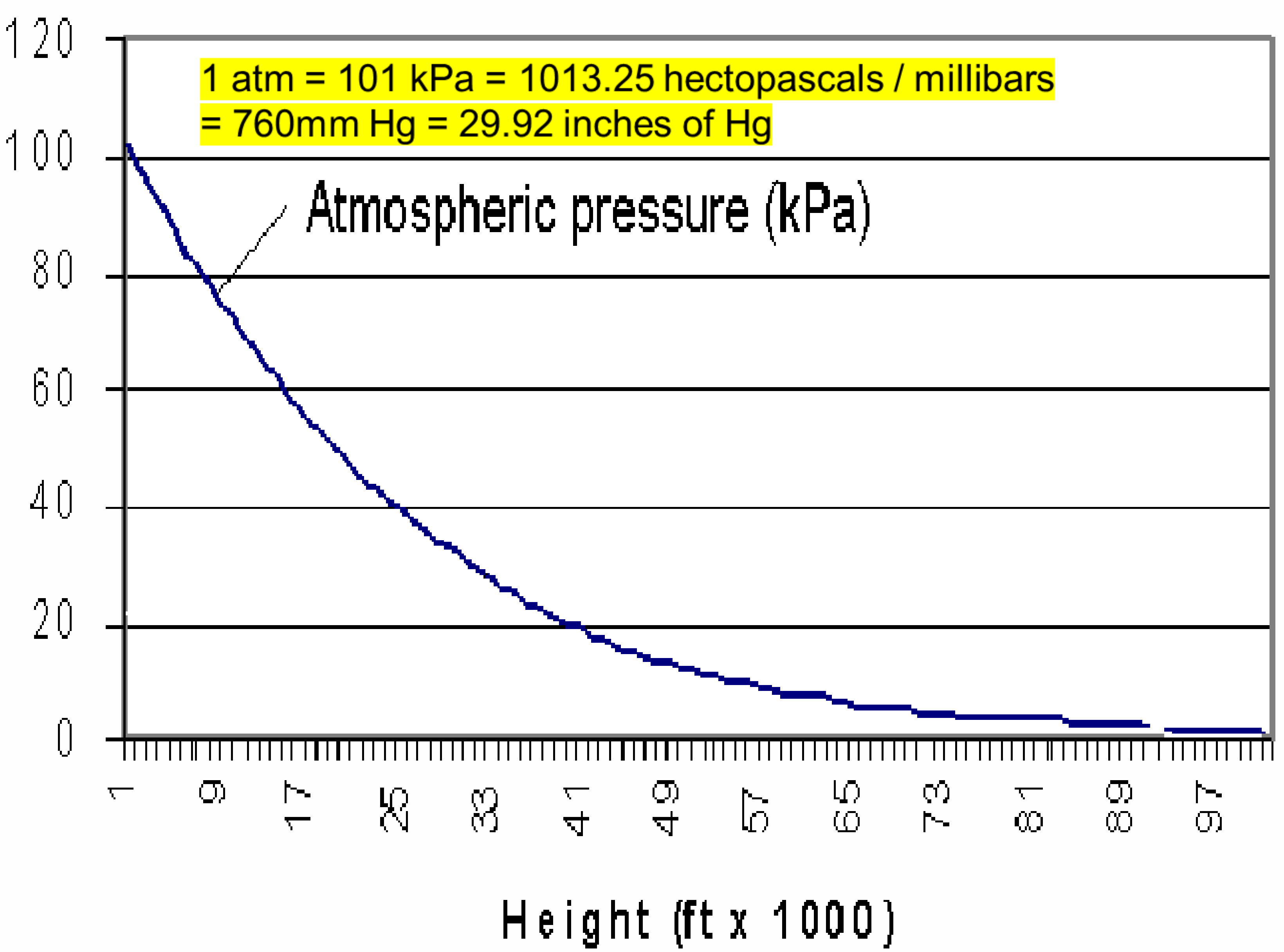
Diffusion $\propto$ pO2(Alv) - pO2 (Blood)

Exhaled CO2 - 4% to 5% by volume of carbon dioxide, about a 100 fold increase over the inhaled amount.

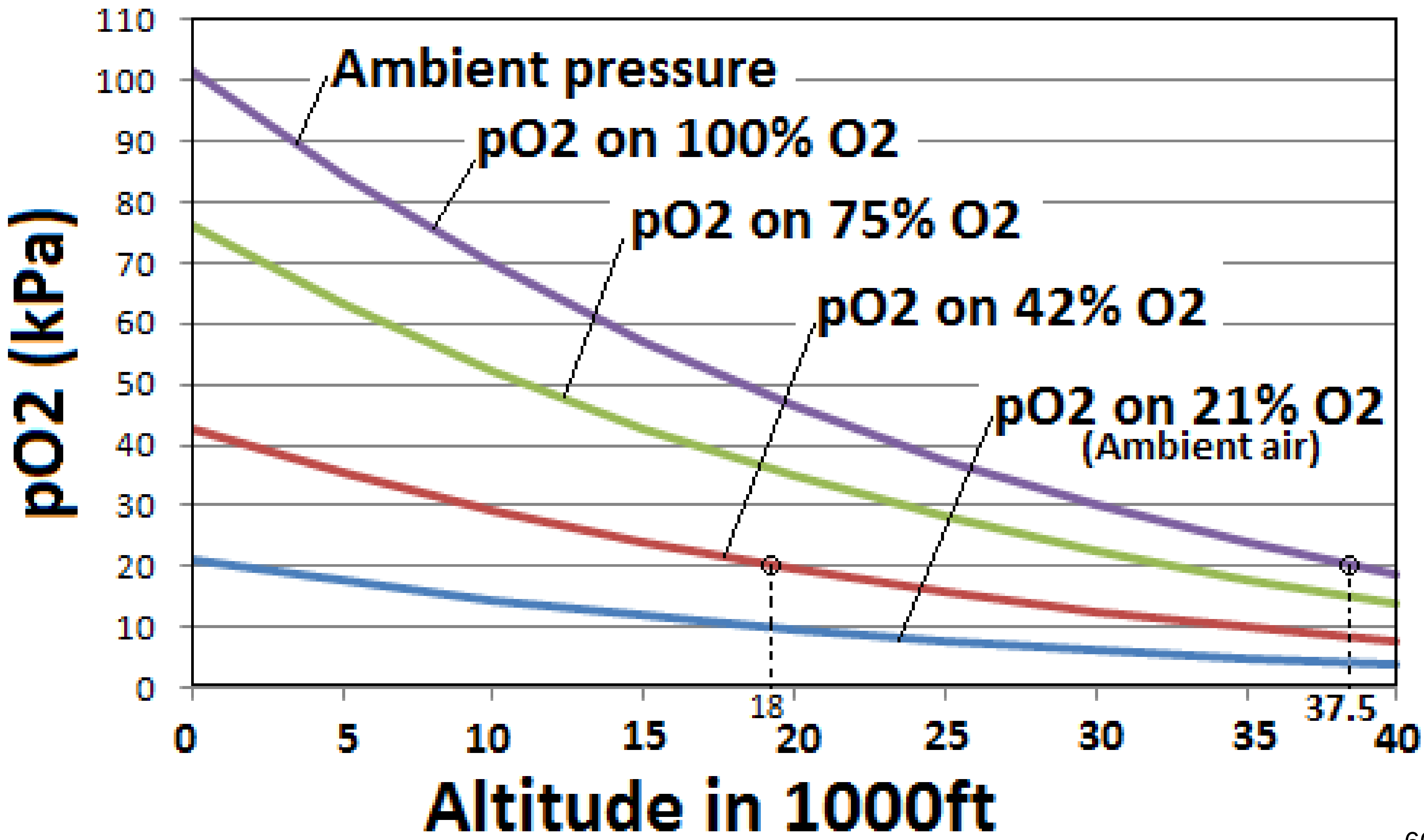
Atmospheric pressure vs altitude

- Pressure decreases exponentially with altitude above mean sea level
- 1 Atmosphere at MSL
- 1/2 Atmosphere at 18 000 ft
- 1/4 Atmosphere at 36 000 ft
- 1/8 Atmosphere at 72 000 ft
- etc

Atmospheric pressure vs altitude…



INHALED pO2 AT ALTITUDE FOR DIFFERENT O2 CONCENTRATIONS



Oxygen partial pressure

- The partial pressure of oxygen (pO_2) in the air is that fraction of the total air pressure that is contributed by O_2
- **pO_2 = O_2 Fraction x Ambient pressure**
- pO_2 = (21/100) x Pamb
- pO_2 = 0,21x101 kPa = 21,2 kPa (sea level)

Oxygen partial pressure (cont) - maintaining sufficient pO_2

- Ambient pressure drops with increase in altitude.
- To maintain sufficient pO_2 for alveolar respiration the percentage of oxygen inhaled must be increased.
- By how much?

Maintaining sufficient pO_2

- Eg, at 18000 ft the ambient pressure is halved to 50,5 kPa.
- Therefore need to double the O_2 fraction to 42%
- pO2 = (42/100)*x 50,5 = 21,2 kPa

Compensating for reduced oxygen partial pressure in non-pressurised aircraft

Example:

- At 36 000 ft ambient pressure is 21 kPa.
- 100% O_2 is needed to keep the inhaled pO_2 equal to 21 kPa:

$$pO_2 = (100/101) \times 21 = 21 \text{ kPa}$$

Oxygen partial pressure (cont)

Problem: Can't give more than 100% O_2.

- Can we safely fly higher than 36 000 ft?
- If so how do we achieve this ?

Breathing above 36 000ft in non-pressurised aircraft

- Above 36 000 ft - increase the pressure of the inhaled 100% O_2 in order to keep the partial pressure at 21 kPa

- Positive Pressure Breathing (PPB) (not to exceed 30 mm/Hg) to 45 000 - 50 000ft

- Thereafter need a pressure (space) suit


2019 Everest traffic jam
11 deaths, 891 summits
SAASMA
Ad Astra per Salus
Credit: AFP

Maintaining sufficient pO2 at higher altitudes - summary

Ambient pressure decreases as altitude increases

To maintain pO2 at 21 kPa & SaO_2 at 98%	
Altitude in ft	**Inhaled O_2 %**
Sea level	21% (ambient air)
18 000	42%
36 000	100%
36 000 – 48 000	Positive Pressure Breathing

Higher than 50 000ft – Pressure suit

Stages of hypoxia

Stages	Indifferent Stage (98%–90% O_2 saturation)	Compensatory Stage (89%–80% O_2 saturation)	Disturbance Stage (79%–70% O_2 saturation)	Critical Stage (69%–60% O_2 saturation)
Altitude (thousands of feet)	0–10	10–15	15–20	20–25
Symptoms	Decrease in night vision ↓ color vision	Drowsiness Poor judgment Impaired coordination Impaired efficiency Euphoria Tingling ↑ respiration rate, heart rate, blood pressure, and cardiac output. Denial is common	Impaired flight control Impaired handwriting Impaired speech Decreased coordination Impaired vision Decreased sensation to pain Impaired intellectual function Decreased memory Impaired judgment Cyanosis	Circulatory failure CNS failure Convulsions Cardiovascular collapse Death

Smokers - night vision ↓ about 20 % at sea level.
- Have a physiological altitude of 5,000 feet at sea level

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