

The Gas Laws and Hypoxia



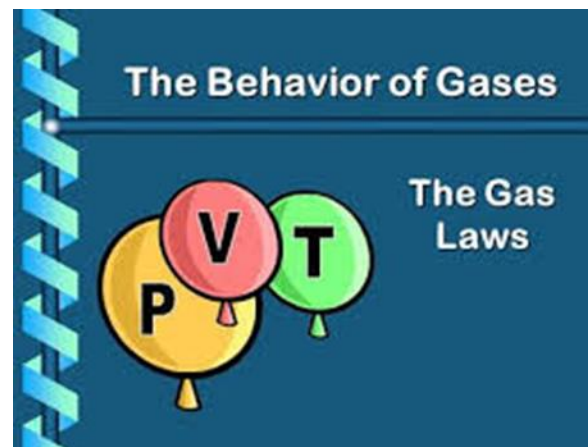
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Aviation Medical Examiner's Course
17 February 2025

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)

$101 \text{ kPa} = 1 \text{ atm} = 760 \text{ mmHg} = 1013.25 \text{ mb or hPa}$
(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

Centigrade Scale

Fahrenheit Scale

Infinite kinetic energy

0 Kelvin = -273.15 °C

Nothing can be colder

No kinetic energy

Electrons stop moving

Superconduction

Convert Celsius to Kelvin as follows:

$$^{\circ}\text{K} = ^{\circ}\text{C} + 273 \text{ e.g., } 11 ^{\circ}\text{C} = 284 ^{\circ}\text{K}$$

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

3. Gas Laws

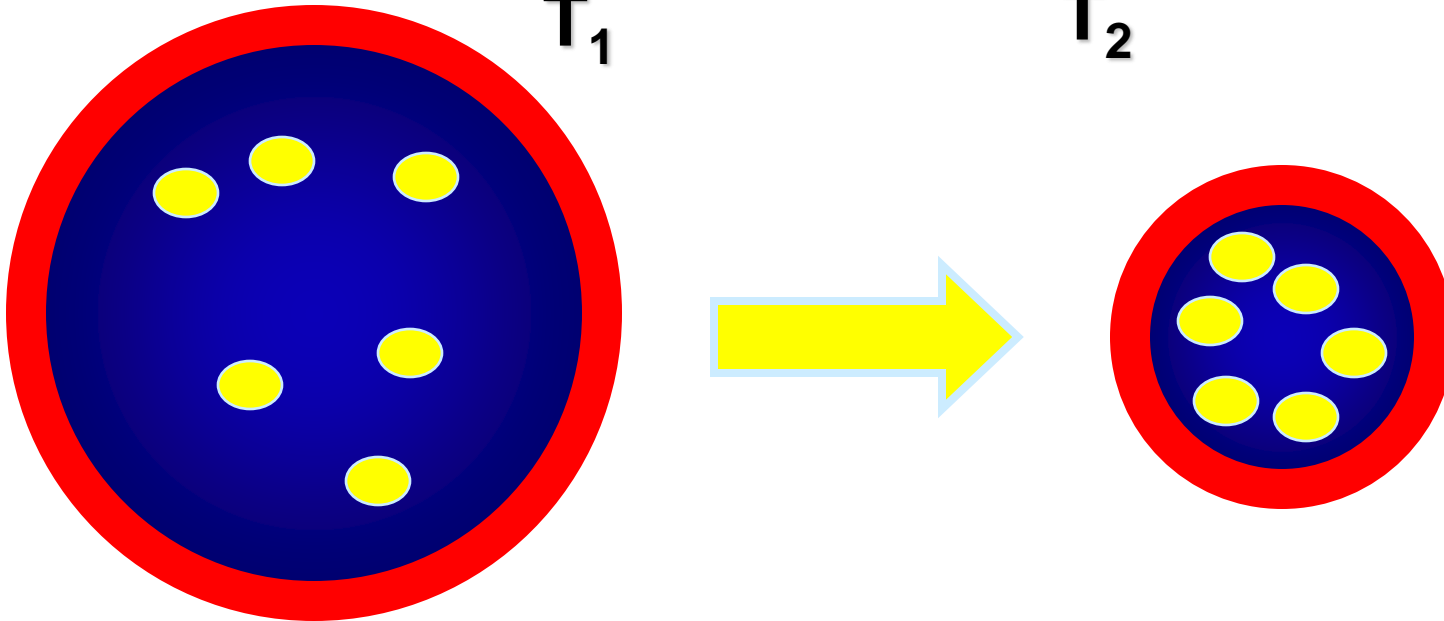
- **The General Gas Law** combines -
Boyle's, Charles' and Gay Lussac's laws which describe the relationship between
 - P: pressure,
 - T: temperature and
 - V: volume, *of a fixed amount* of *a* gas.
- **Dalton's law** describes the behavior of the individual components of a *mixture of gases*

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** proportional 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

Charles's law

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

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

$$P_1 V_1 = P_2 V_2$$

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

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

General law

P

T

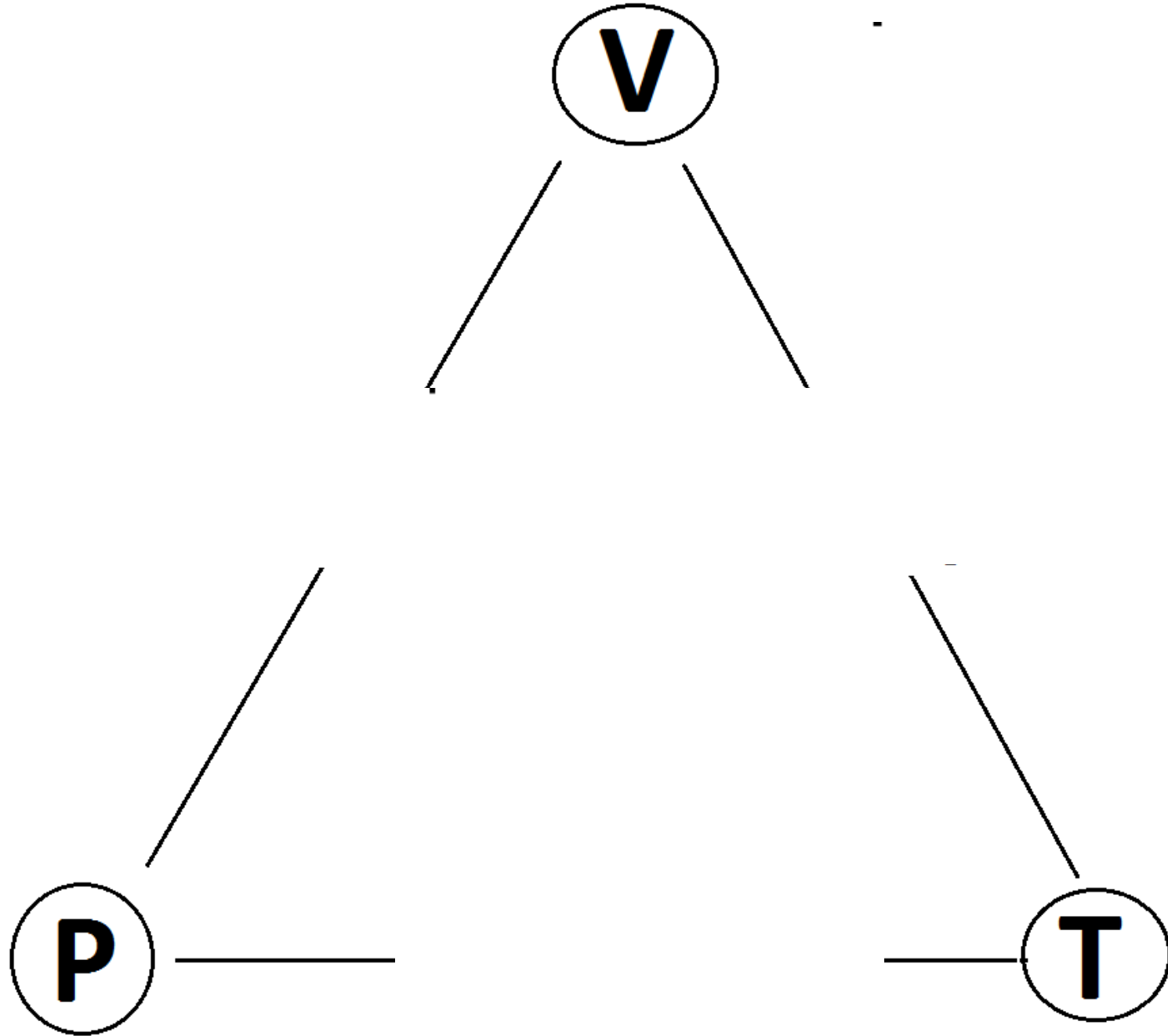
$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

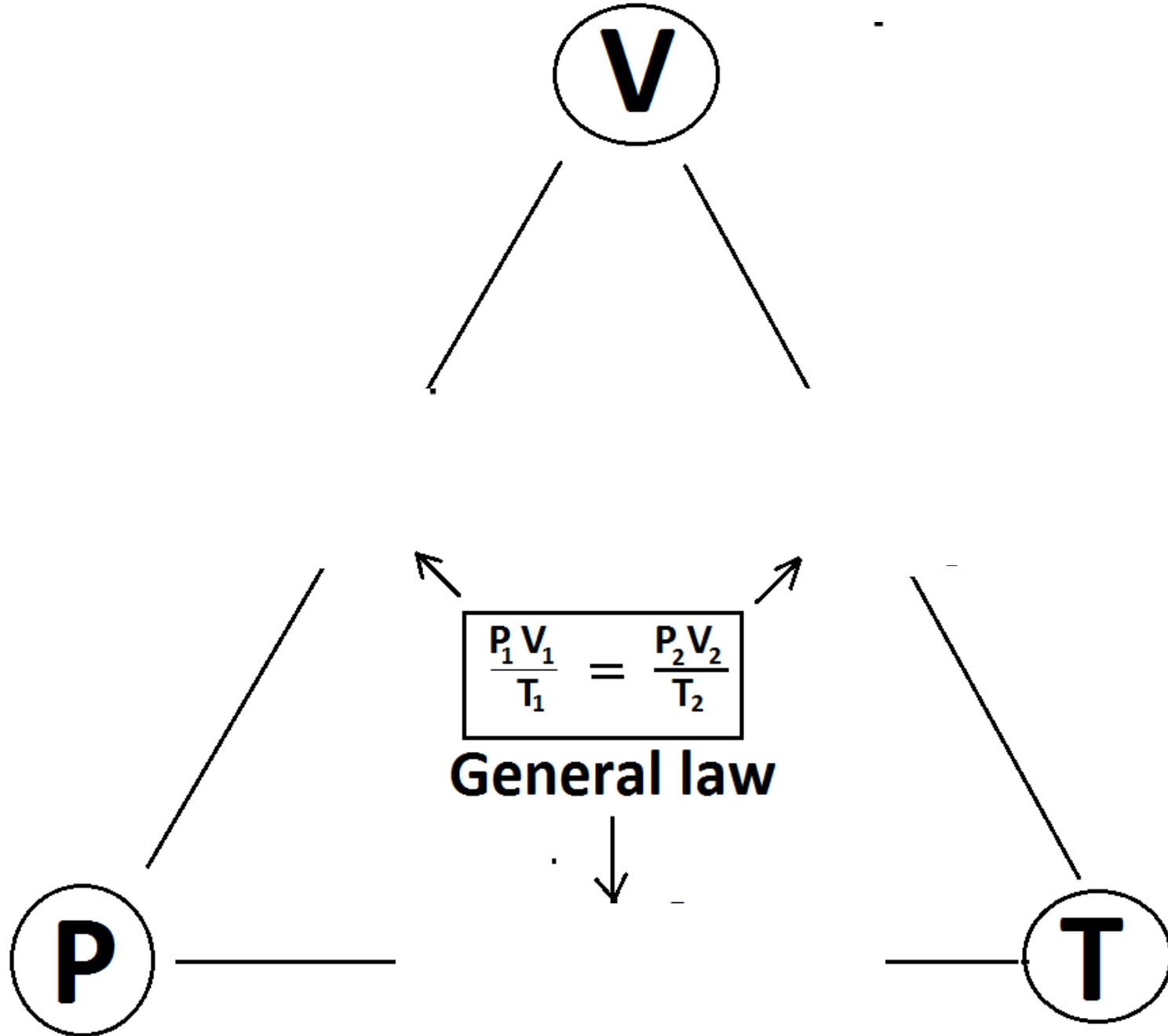
Gay Lussac's law

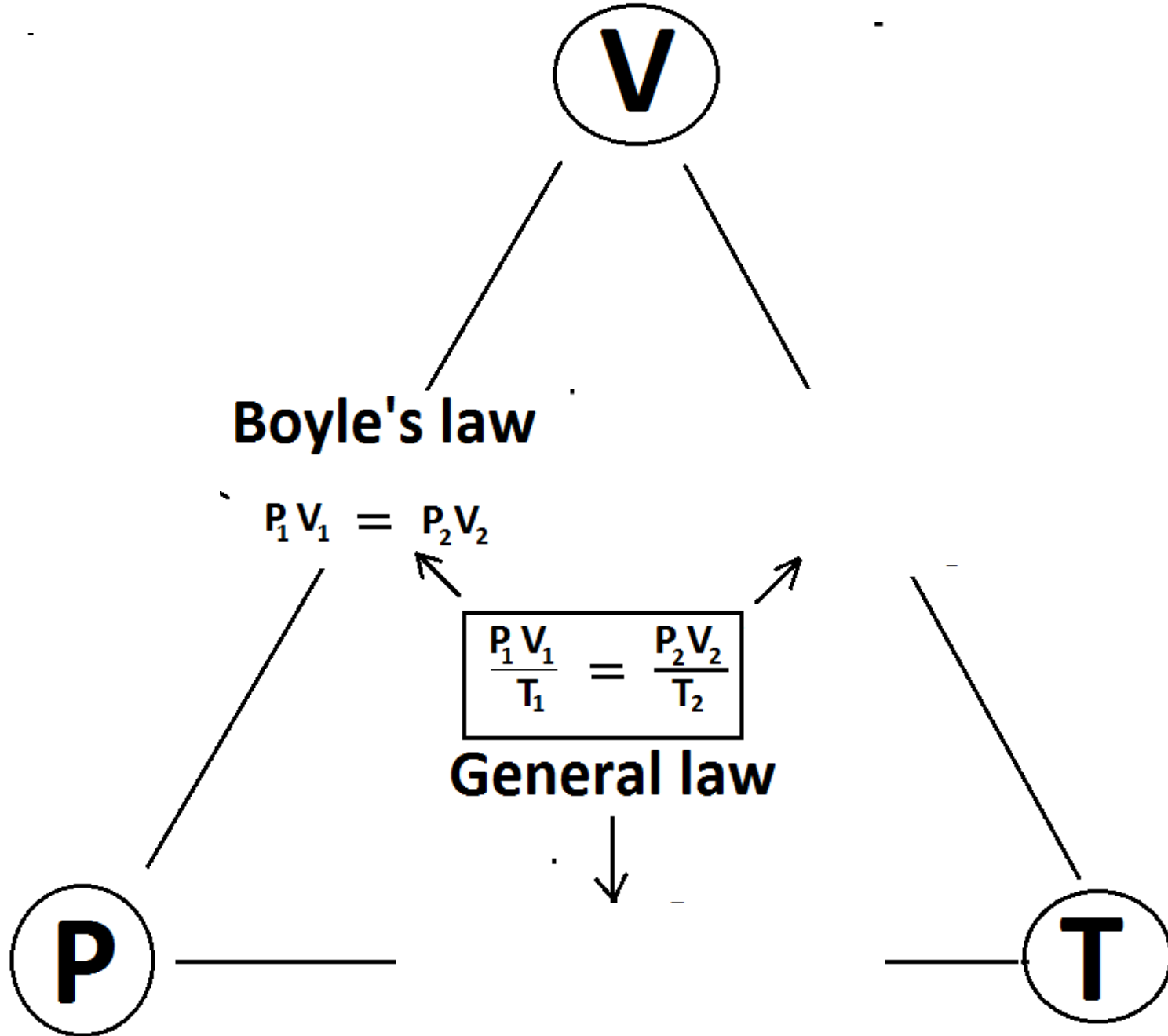


P —

— **T**







V

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

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

Boyle's law

$$P_1 V_1 = P_2 V_2$$

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

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

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

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

Boyle's law

Charles's law

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

$$P_1 V_1 = P_2 V_2$$

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

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

General law

P

T

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

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

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? GAS IN YOUR STOMACH AND BOWELS EXPANDS

Altitude in ft

43,000



34,000



25,000



16,000



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

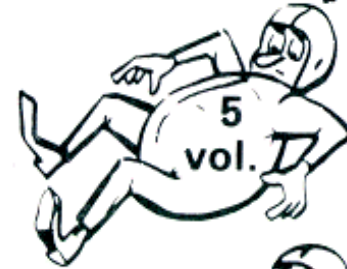
Relevance to flight?

GAS IN YOUR STOMACH AND BOWELS EXPANDS

Altitude in ft
43,000



34,000



25,000



16,000



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?

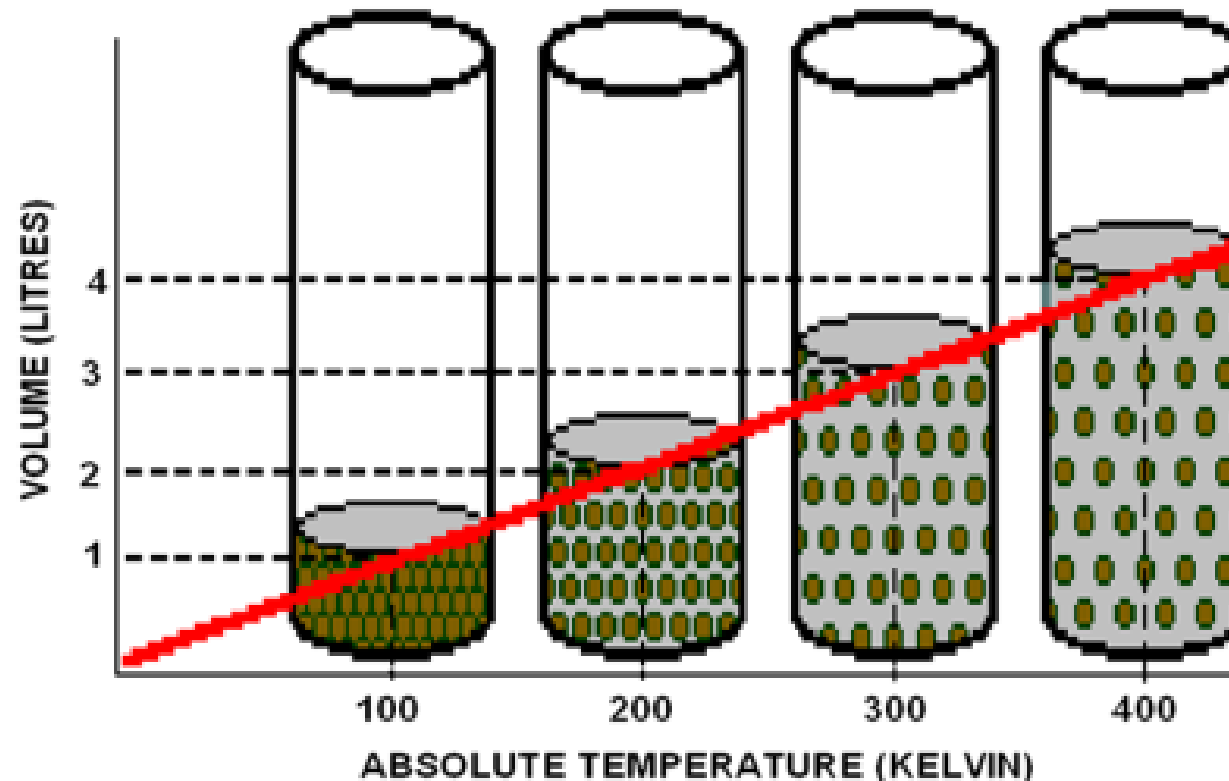
- Teeth (aerodontalgia)
- Sinusses (barosinusitis)
- Patients with pneumothorax
- Lungs (breath holding)
- Middle ear (barotitis media) – is a greater problem during **descent**



Charles' Law

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

$$V_2 = V_1 \times T_2/T_1$$

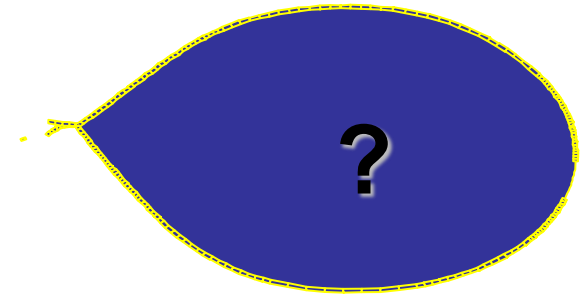


The volume of a gas is directly proportional to its **absolute** temperature at constant pressure.

(Linear relationship between V_2 and T_2)



Question – Charles' Law



$$V_2 = V_1 \times T_2 / T_1$$

37°



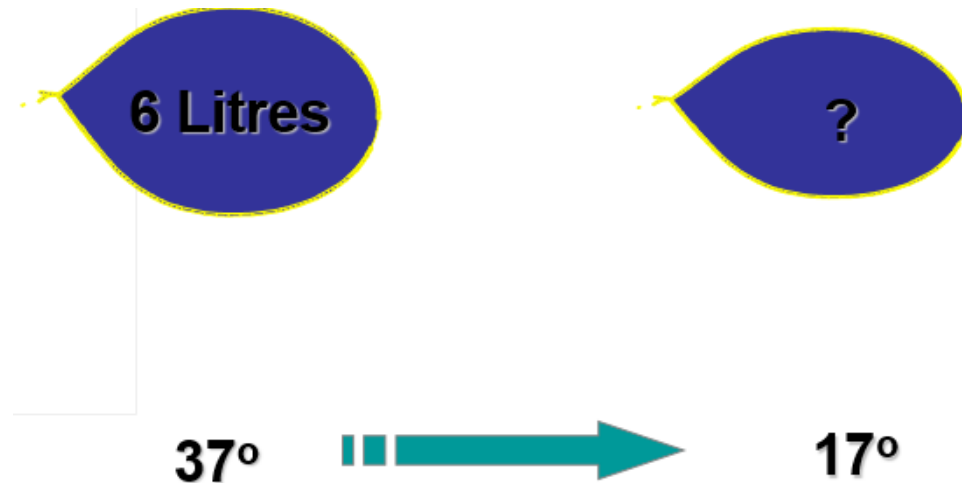
17°

Solution?



- a. 1,83
- b. 2,76 = usual answer
- c. 4,59
- d. 5,61
- e. 6,97

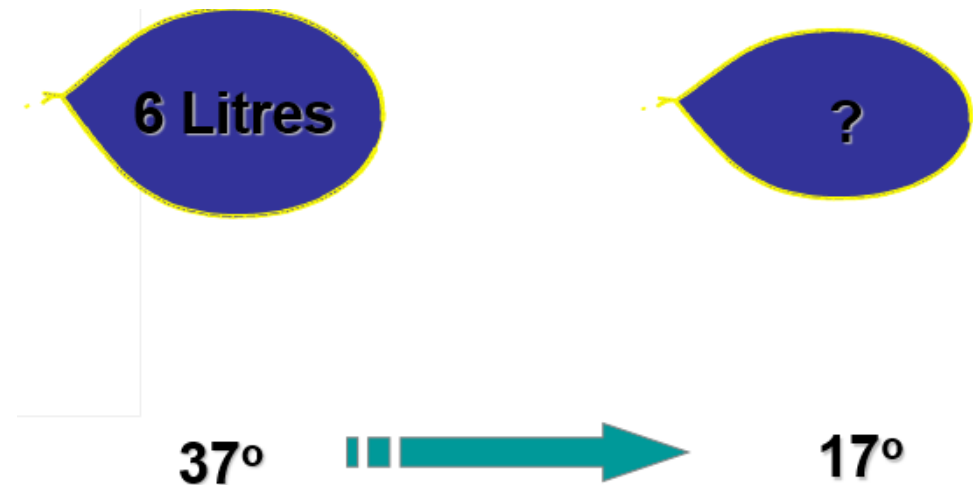
How to get 2,76?





Solution?

- a. 1,83
- b. 2,76 = usual answer
- c. 4,59
- d. 5,61
- e. 6,97



How to get 2,76?

$$V_2 = V_1 \times T_2/T_1$$

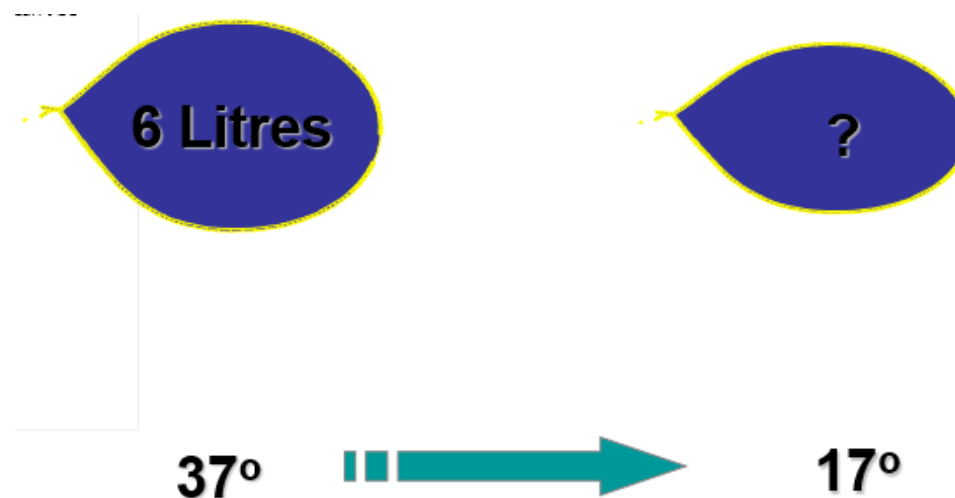
$$V_2 = 6 \times 17/37$$

$$= 2,76?$$



Solution?

- a. 1,83
- b. 2,76
- c. 4,59
- d. 5,61 = correct answer - why???
- e. 6,97

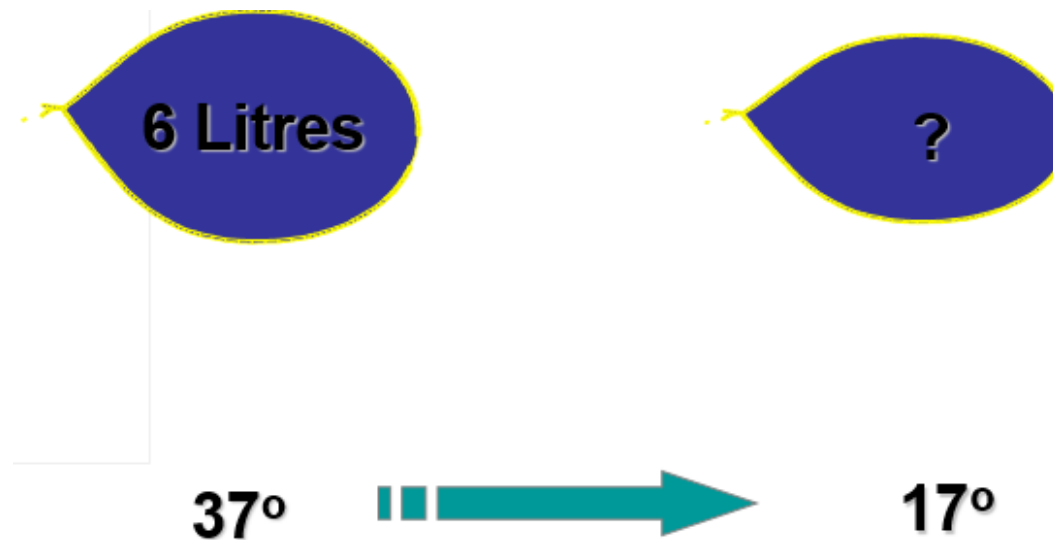


Solution...



- Convert all temperatures to K.

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



Solution (cont...)



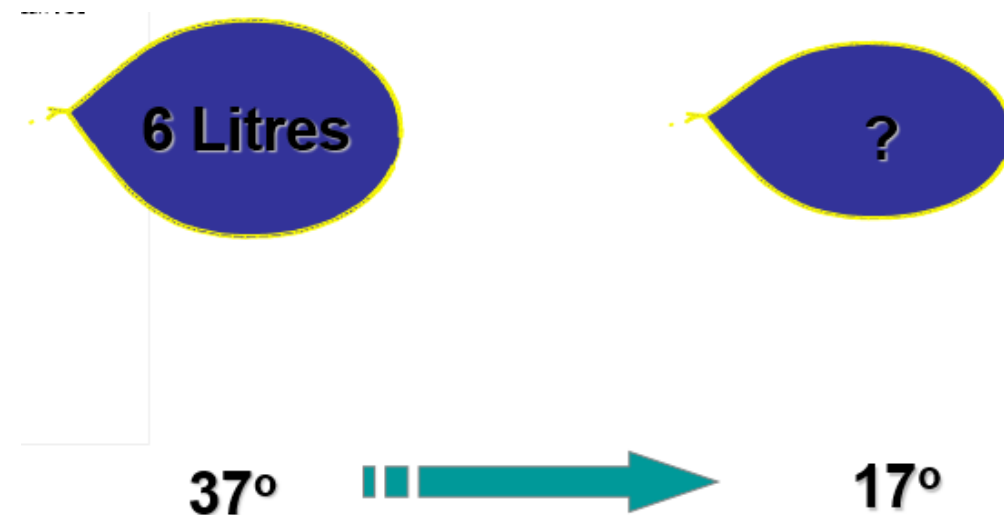
- Convert all temperatures to K.

$$T_1 = 273 + 37 = 310 \text{ } ^\circ\text{K}$$

$$T_2 = 273 + 17 = 290 \text{ } ^\circ\text{K}$$

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

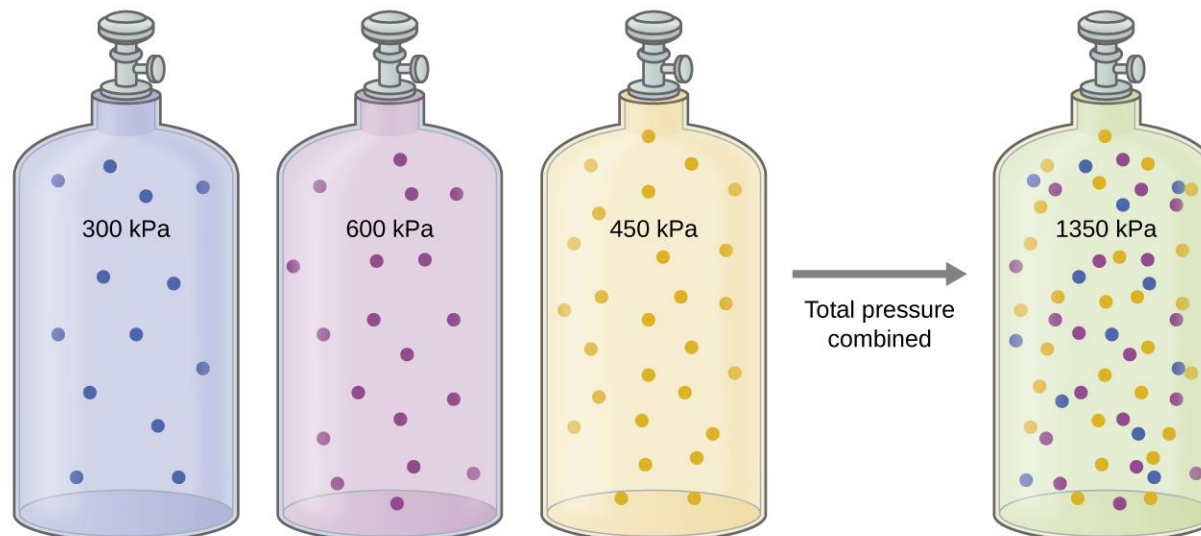
$$V_2 = 6 \times 290/310 = 5,61 \text{ L}$$

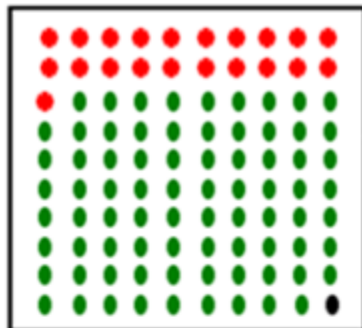


Dalton's Law

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.





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: $f_3 = \frac{1}{100}$

P_{Tot}



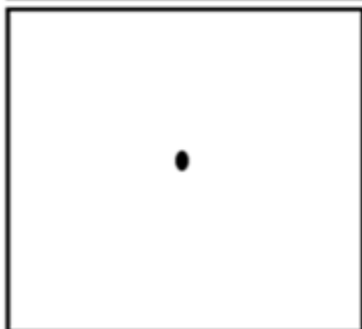
Partial pressure of Oxygen:

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



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...

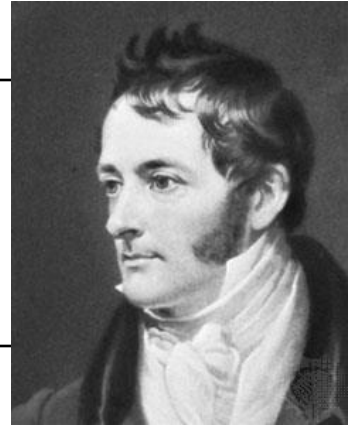


- Partial pressure is responsible for the physiological effects of the individual gas.
- As altitude increases total atmospheric pressure decreases and the partial pressures of the constituents of air also decrease.
- So it becomes more difficult for sufficient oxygen to transfer from the air to the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

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

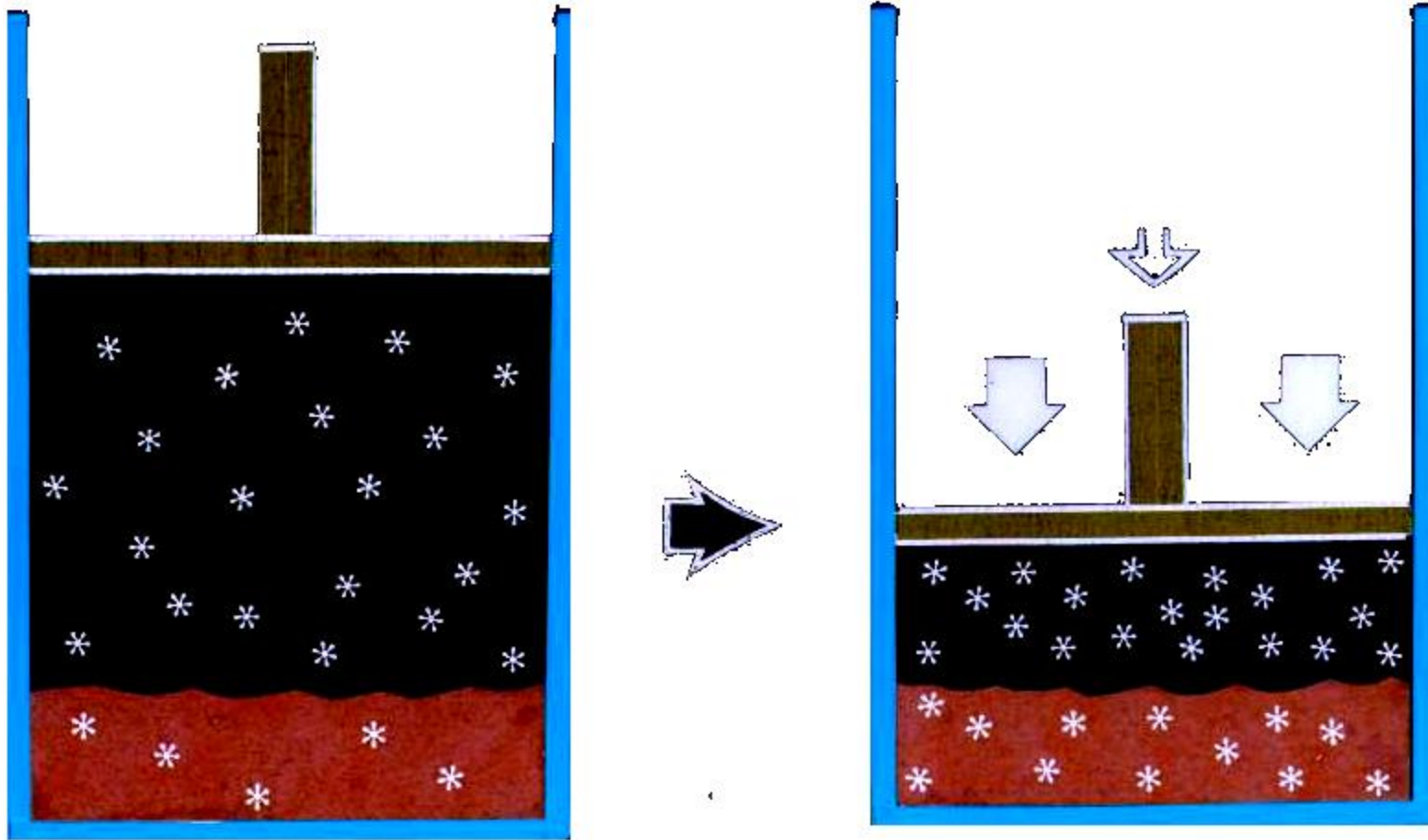
Henry's Law

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 \uparrow 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**

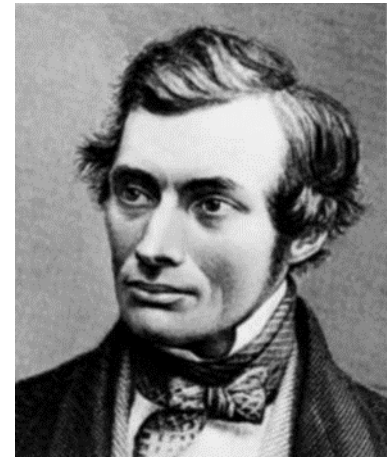
Generally, a gas at a **higher** pressure

- 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 ($P_1 - P_2$), 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.

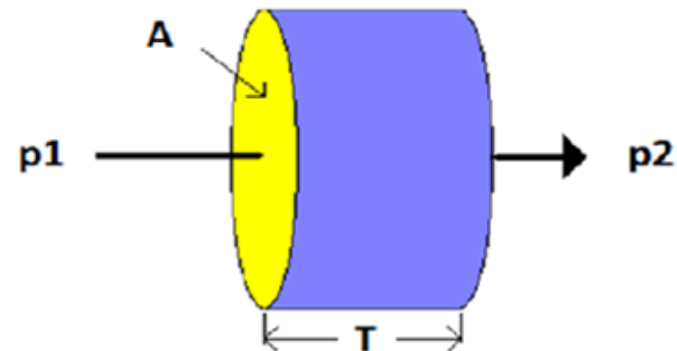
$$\dot{v} \propto \frac{(p_1 - p_2) S}{\sqrt{MW}}$$



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.

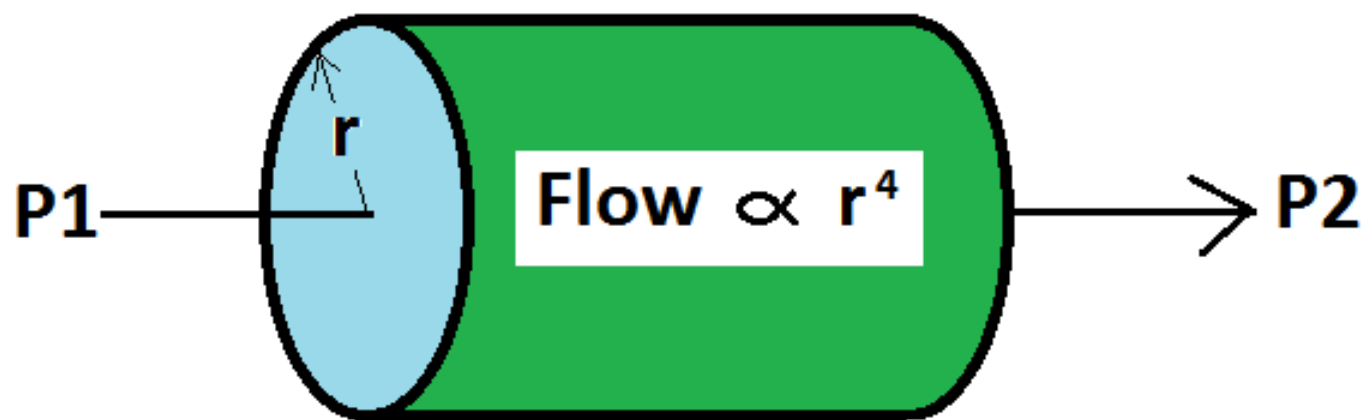
$$\dot{V} \propto \left(\frac{A}{T} \right) (p_1 - p_2)$$



POISEULLE'S LAW

THE FLOW-RATE OF A GAS THROUGH A TUBE IS PROPORTIONAL TO THE 4th 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 next lecture by Dr Frans Cronje

Definitions



Hypoxia

- **Inadequate** supply of oxygen to the **tissues**

Anoxia

- **Complete absence** of oxygen

Hypoxaemia

- **Deficient** oxygenation of blood



Credit: Wikipedia

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.....



Anaemic (Hypoxaemic) Hypoxia – 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**

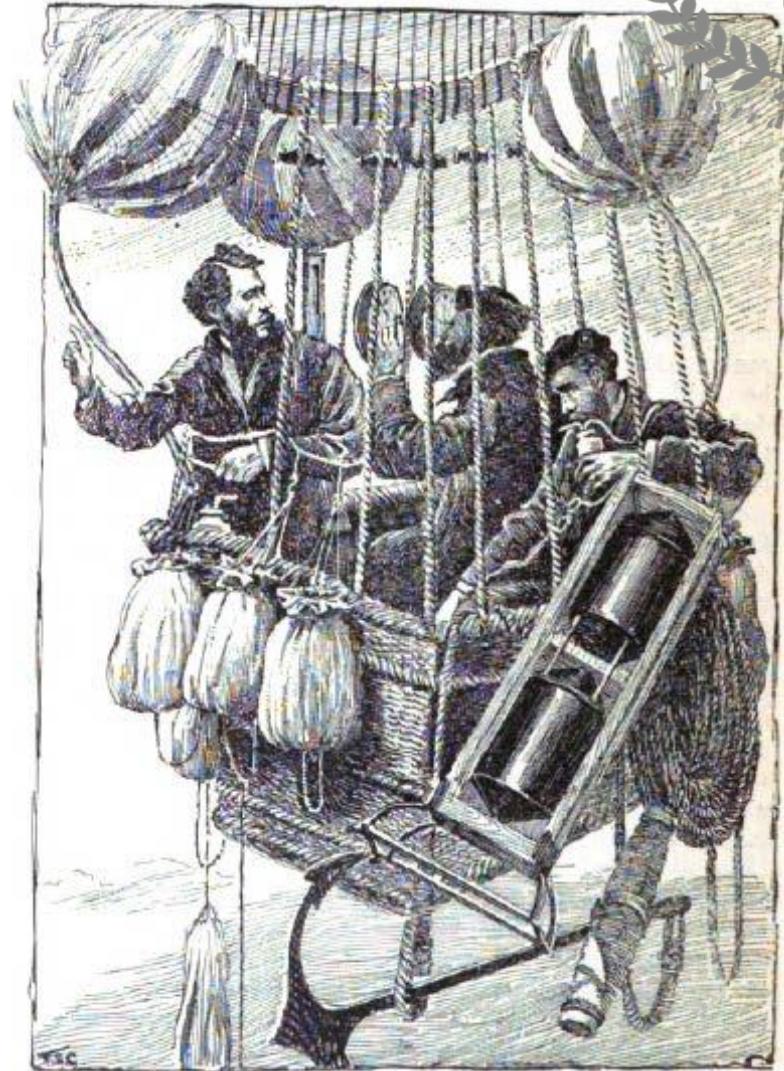
Histotoxic Hypoxia – Interference with the ability of the tissues to utilize oxygen

- Poisoning – cyanide, alcohol, CO, smoking

Hypoxic Hypoxia survivor



- April 1875,
- 3 balloonists who knew about hypoxia
- with bags of O₂
- 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.

Recent Example

- 14 August 2005
- Helios Airways Flight 522
- Pilot error and lack of cabin pressurization causing hypoxia leading to crew incapacitation
- All passengers & crew (121) died in crash due to fuel exhaustion



Hypoxia that is not deep enough to kill you is still enough to make you a danger to yourself and your passengers

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**
 - Very relevant during explosive cabin decompression – See next lecture by Dr Frans Cronje
 - 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

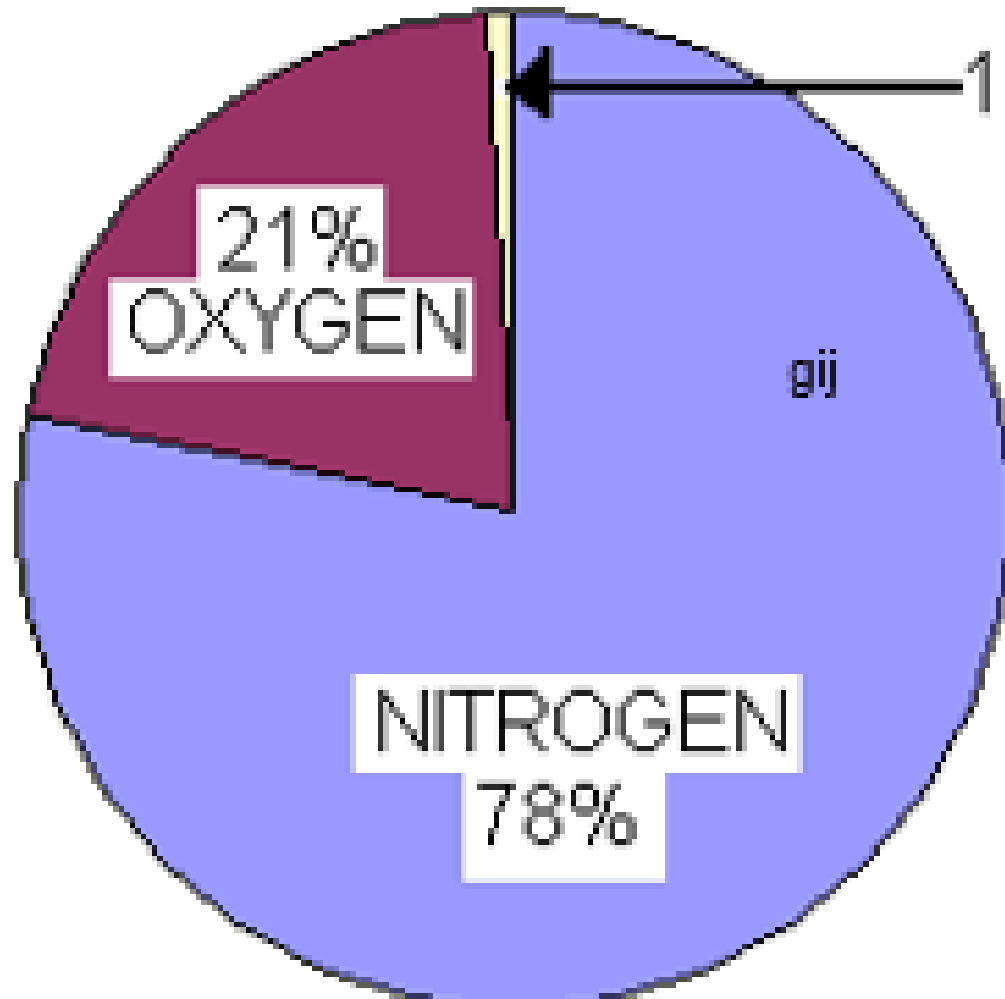
Hypoxia Timeframes...



- 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



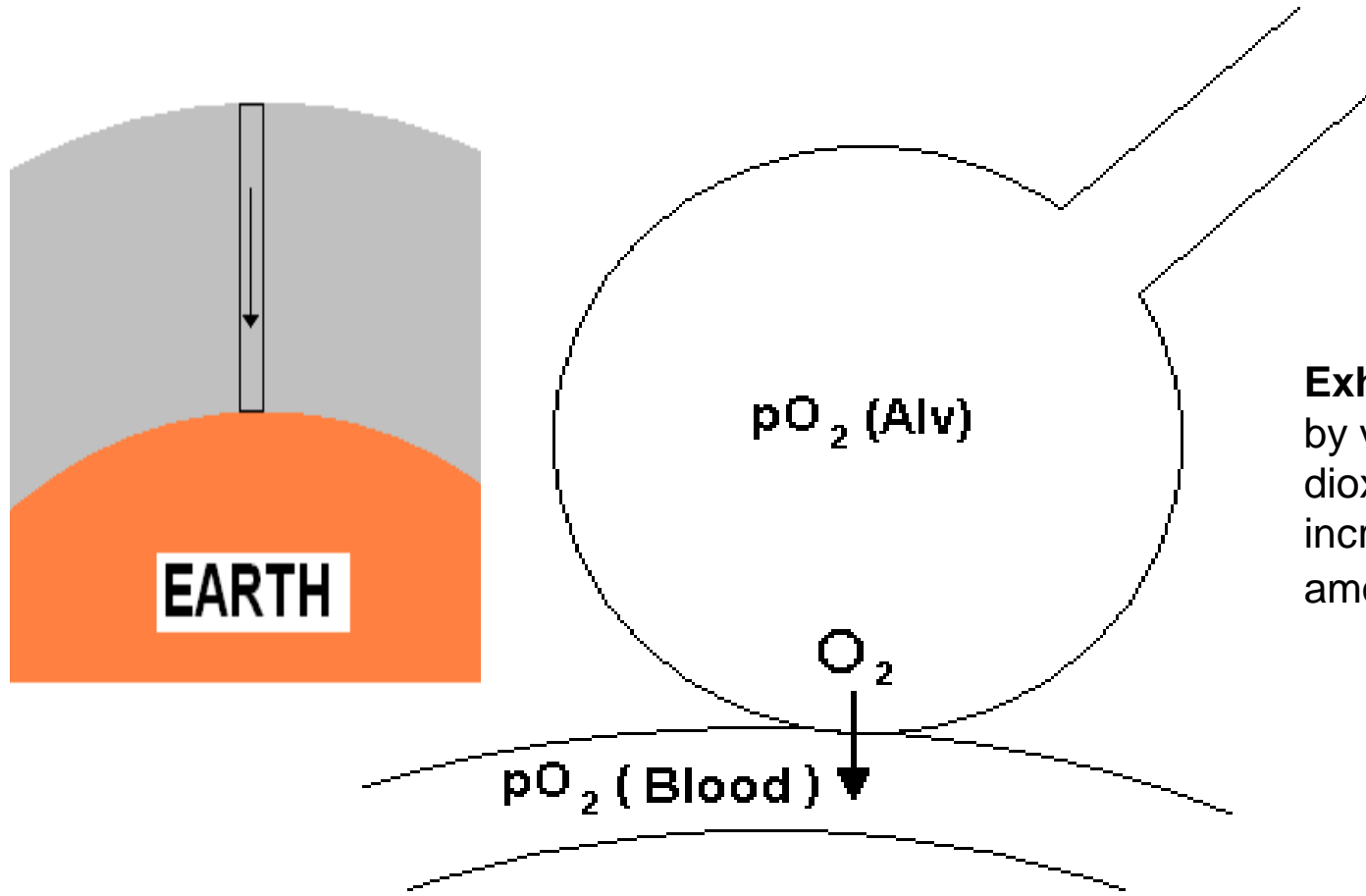
1% TRACE GASES

- Argon
- Hydrogen
- CO₂
- Xenon
- Neon
- Krypton
- Helium

Variable:

- Water vapour
- Ozone

Oxygen partial pressure - role in gas transport



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

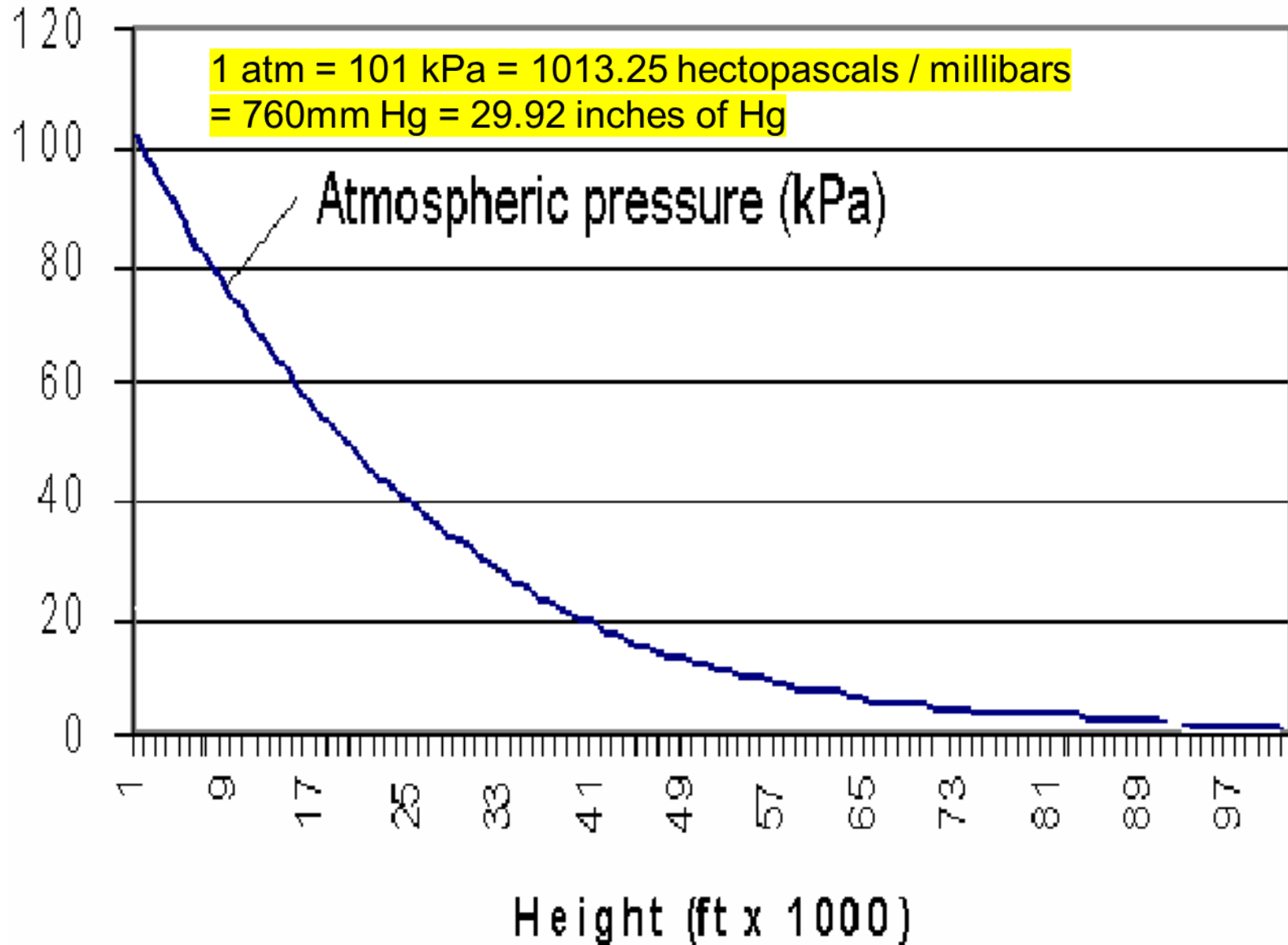
Diffusion OC $pO_2(Alv) - pO_2(Blood)$

Atmospheric pressure vs altitude

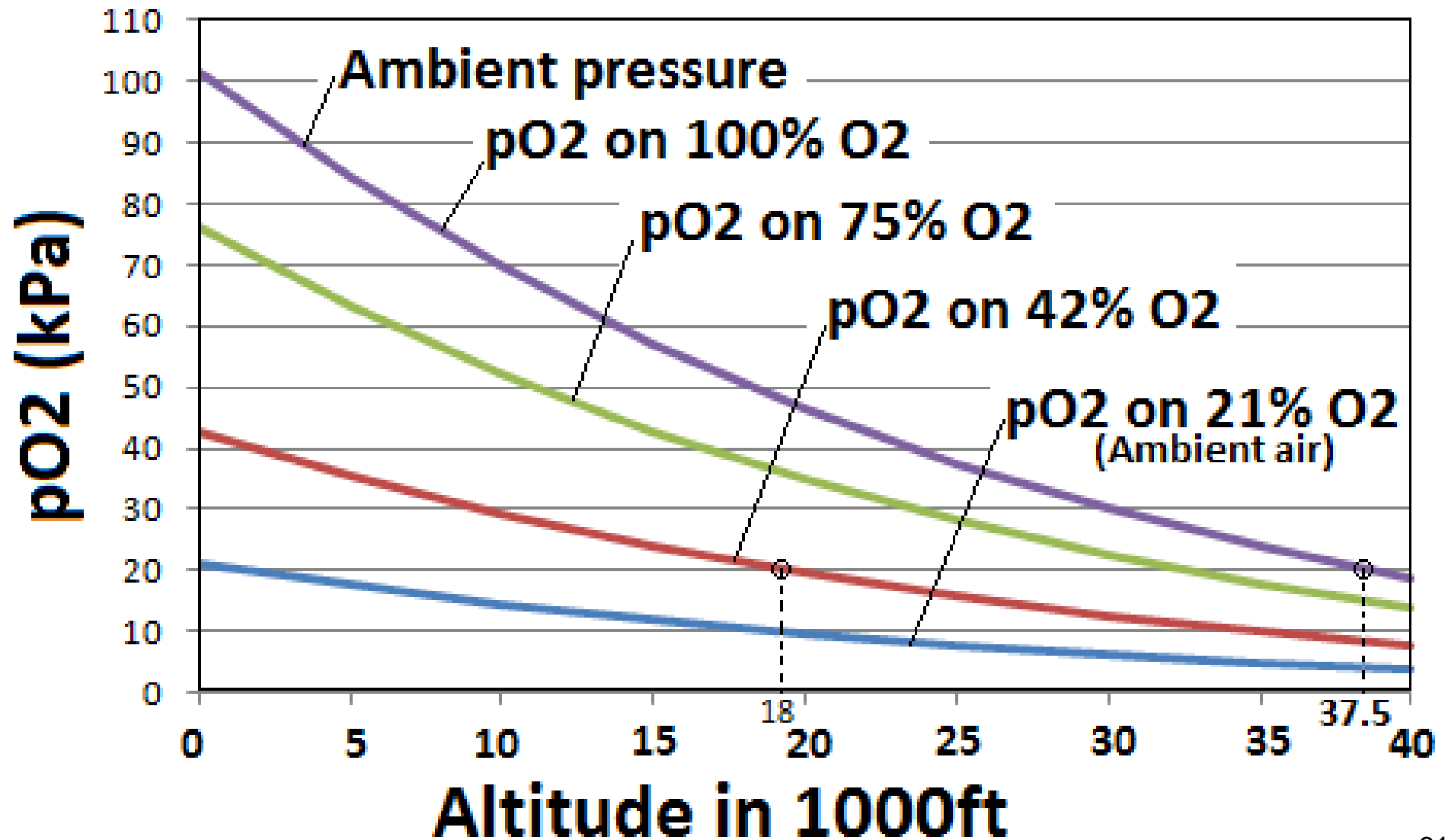
- Pressure decreases exponentially with altitude above mean sea level
- 1 Atmosphere at MSL
- 1/2 Atmosphere at 18 000 ft
- 1/4 Atmosphere at 36 000 ft
- 1/8 Atmosphere at 72 000 ft
- etc



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
- **$pO_2 = O_2 \text{ Fraction} \times \text{Ambient pressure}$**
- $pO_2 = (21/100) \times P_{amb}$
- $pO_2 = 0,21 \times 101 \text{ kPa} = 21,2 \text{ kPa}$ (sea level)

Oxygen partial pressure (cont) - maintaining sufficient pO₂

- Ambient pressure drops with increase in altitude.
- To maintain sufficient pO₂ for alveolar respiration the percentage of oxygen inhaled must be increased.
- By how much?



Maintaining sufficient pO₂



- Eg, at 18000 ft the ambient pressure is **halved** to 50,5 kPa.
- Therefore need to **double** the O₂ fraction to 42%
- $pO_2 = (42/100) \times 50,5 = 21,2 \text{ kPa}$

Compensating for reduced oxygen partial pressure in **non**-pressurised aircraft



Example:

- At 36 000 ft ambient pressure is 21 kPa.
- 100% O₂ is needed to keep the inhaled pO₂ equal to 21 kPa:

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

Oxygen partial pressure (cont)

Problem: Can't give more than 100% O₂.

- 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% O₂ 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





Maintaining sufficient pO₂ at higher altitudes - summary

Ambient pressure decreases as altitude increases

To maintain pO₂ at 21 kPa & SaO₂ at 98%	
Altitude in ft	Inhaled O₂ %
Sea level	21% (ambient air)
18 000	42%
36 000	100%
36 000 – 48 000	Positive Pressure Breathing

Higher than 50 000ft – Pressure suit

Federal Aviation Administration ZONES	ALTITUDES	PRESSURE
Physiological Efficient Zone	Sea Level - 12,500 feet	760 - 523 mm/Hg
<p>General body adaptation. Minor trapped gas problems (ears, sinus, and GI tract) with shortness of breath, dizziness, headaches and fatigue in the upper region if exposure too long</p>		
Physiological Deficient Zone	12,500 - 50,000 feet Mount Everest!!	523 - 87 mm/Hg
<p>Most flying done here. Major physiological problems...hypoxia and decompression sickness if not in a pressurised cabin</p>		
Space Equivalent Zone	50,000 ft - 1000 miles	87 - 0 mm /Hg
<p>Very hostile to humans. "Armstrong's line" at 63,000 feet, unprotected exposure above this level causes ebullism. Need a sealed suit or cabin</p>		

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 ↓ <u>color vision</u>	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



