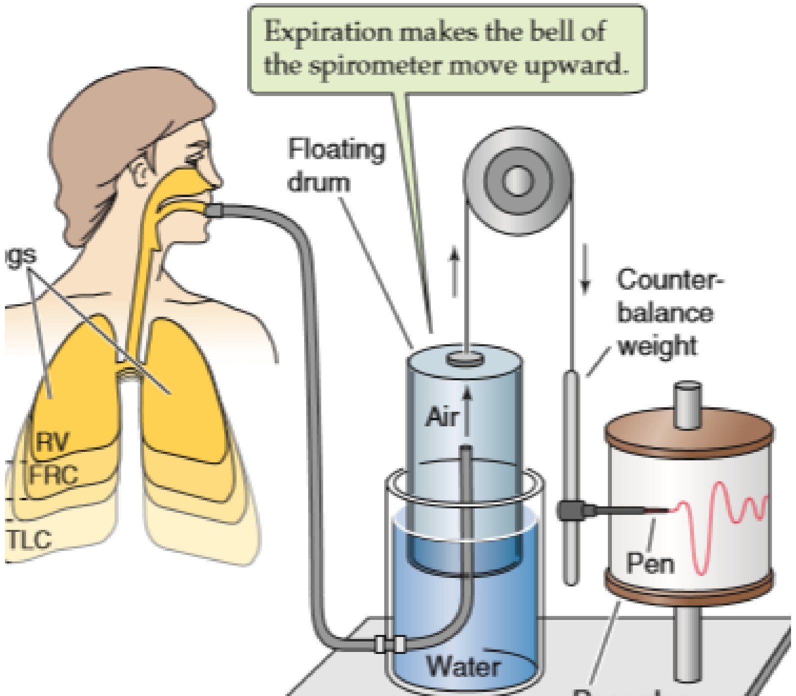
Lung volumes
and
Alveolar ventilation

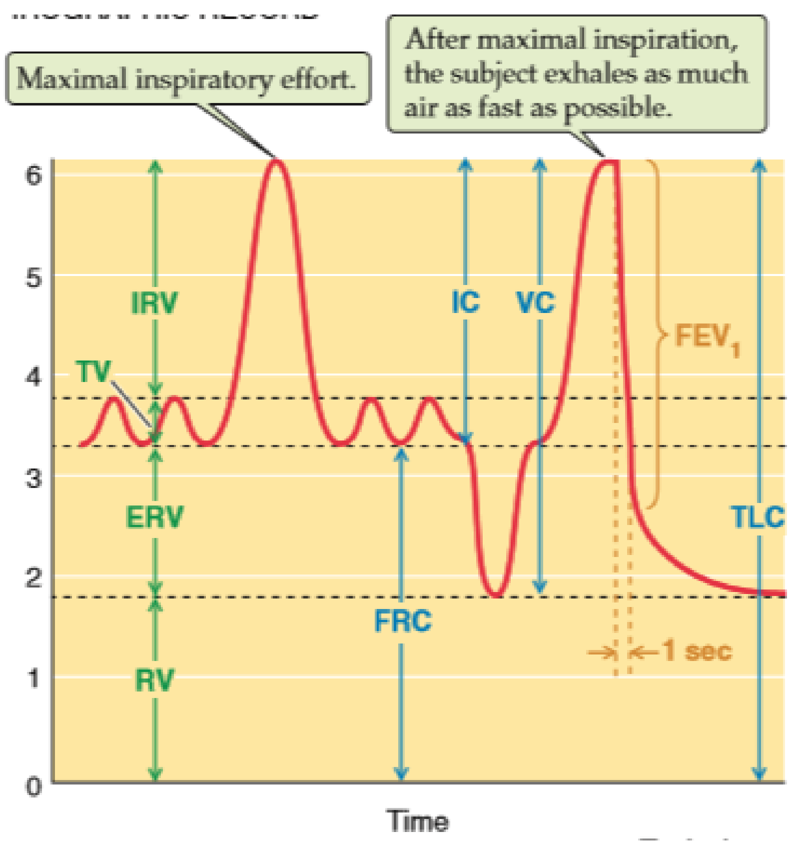
Static Lung volumes: Spirometer

- A spirometer is composed of two vessels: one contains water and the other floats upside down in the first. As the subject breathes through the attached tube, air flows in and out of the inner vessel, which consequently moves up and down.
- This up-and-down motion is recorded as a spirogram which is calibrated to reflect changes in volume of the inner vessel.
- During exhalation, the bell goes up and the pen down, marking a moving chart. The **slope** of the spirogram on the moving drum measures rate of airflow, and the amplitude of the deflection measures the volume of air. **Volume is plotted on the vertical axis (y axis), and time is plotted on the horizontal axis (x axis).**



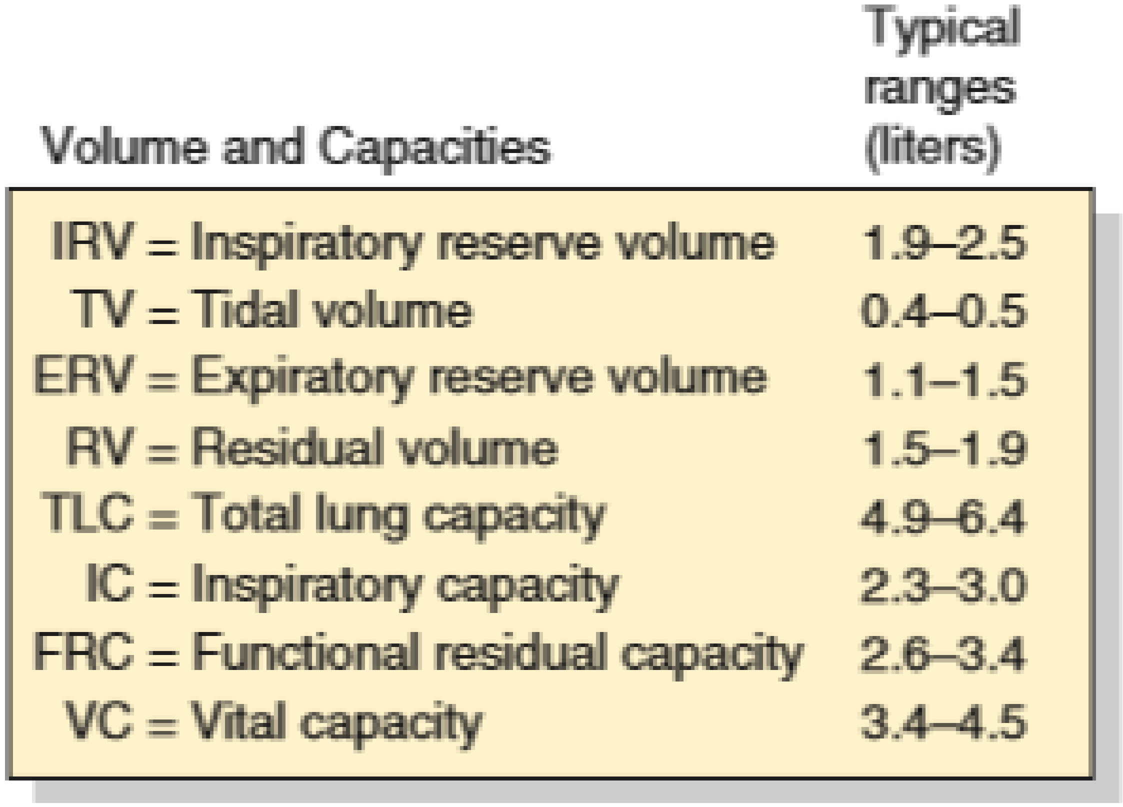
*A **'capacity'** usually refers to a measurement comprised of more than one **'volume**.'*

There are four standard lung volumes and four standard lung capacities, which consist of two or more standard lung volumes in combination



Maximal inspiratory effort.

After maximal inspiration, the subject exhales as much air as fast as possible.



Volume and Capacities	Typical ranges (liters)
IRV = Inspiratory reserve volume	1.9–2.5
TV = Tidal volume	0.4–0.5
ERV = Expiratory reserve volume	1.1–1.5
RV = Residual volume	1.5–1.9
TLC = Total lung capacity	4.9–6.4
IC = Inspiratory capacity	2.3–3.0
FRC = Functional residual capacity	2.6–3.4
VC = Vital capacity	3.4–4.5




1. Doing spirometry **2.** A modern USB PC-based spirometer. **3.** Device for spirometry. The patient places his or her lips around the blue mouthpiece. The teeth go between the nubs and the shield, and the lips go over the shield. A noseclip guarantees that breath will flow only through the mouth. **4.** Screen for spirometry readouts at right. The chamber can also be used for body plethysmography.

First, normal breathing is measured **(tidal volume).**
Next, the subject takes a maximal inspiration and followed this by a maximal expiration. The exhaled volume is called **the vital capacity.**
However, some gas remained in the lung after a maximal expiration; this is the **residual volume.**
The volume of gas in the lung after a normal expiration is the **functional residual capacity (FRC).**
Certain lung volumes, particularly the **FRC**, are determined by elastic forces. It is a **convenient starting point** at which to consider the various lung volumes and their subdivision

https://wikivisually.com/wiki/Alveolar_gas_equation

Pulmonary Volumes

Pulmonary Capacities

Tidal volume: Volume of air inspired or expired during a normal inspiration or expiration

Inspiratory reserve volume: The additional volume a subject is *capable* of inhaling after a normal, quiet inspiration

Expiratory reserve volume: The additional volume a subject is *capable* of exhaling after a normal, quiet expiration.

Residual volume: Volume of air remaining in respiratory passages and lungs after the most forceful expiration

Total lung capacity (TLC): The volume of gas in the lungs after maximal inspiration.
Vital capacity (VC): The maximum volume of air that a subject can exhale after maximal inspiration. **Functional residual capacity (FRC):** The volume remaining in the lungs after expiration during normal, quiet breathing.
Inspiratory capacity (IC): The maximum volume that can be inspired after expiration during normal, quiet breathing.

- ❑ *Total lung capacity is the sum of four of the described volumes:*

  TLC = RV + ERV + VT + IRV

- ❑ *Vital capacity, functional residual capacity, and inspiratory capacity can be equated to the sums of particular lung volumes:*

  VC = IRV + VT + ERV
  FRC = ERV + RV
  IC = VT + IRV

THE TIDAL VOLUME

- It is determined by the activity of the respiratory control centers in the brain as they affect the respiratory muscles and by the mechanics of the lung and the chest wall.
- V_T of a 70-kg adult is about 500 mL/ breath.
- It can increase, for example, during exercise.

THE RESIDUAL VOLUME

- It is determined by the force generated by the muscles of expiration and the inward elastic recoil of the lungs as they oppose the outward elastic recoil of the chest wall. Dynamic compression of the airways during the forced expiratory effort is an important determinant of the RV as airway collapse occurs, thus trapping gas in the alveoli.
- The RV of a healthy 70-kg adult is about 1.5 L.
- The RV is important to a healthy person
- (1) **RV optimizes energy expenditure**: After an airway collapses, an unusually high pressure is required to reinflate it
- (2) Blood flow to the lungs and other parts of the body is continuous, even though ventilation is episodic. If the RV were 0, the composition of blood leaving the lungs would oscillate widely between a high PO2 at the peak of inspiration and a low PO2 at the nadir of expiration

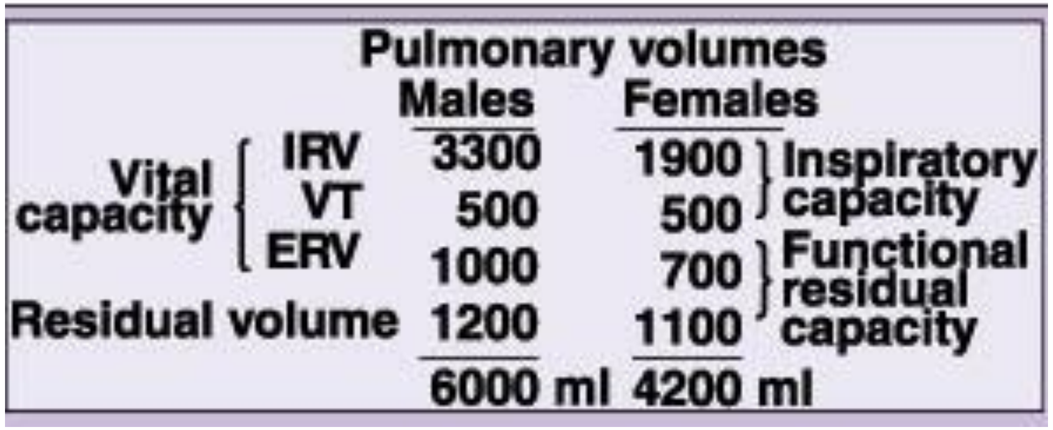
THE EXPIRATORY RESERVE VOLUME : It is determined by the difference between the functional residual capacity (FRC) and the RV. The ERV is about 1.5 L in a healthy 70-kg adult.

THE INSPIRATORY RESERVE VOLUME: It is determined by the strength of contraction of the inspiratory muscles, the inward elastic recoil of the lung and the chest wall, and the starting point, which is the FRC plus the VT. The IRV of a normal 70-kg adult is about 2.5 L.

THE INSPIRATORY CAPACITY: It is therefore equal to the VT plus the IRV. The IC of a normal 70-kg adult is about 3 L.

THE TOTAL LUNG CAPACITY: It is determined by the strength of contraction of the inspiratory muscles and the inward elastic recoil of the lungs and the chest wall. The TLC consists of all four lung volumes: the RV, the VT, the IRV, and the ERV. The TLC is about 6 L in a healthy 70-kg adult.

THE VITAL CAPACITY : equal to the TLC minus the RV, or about 4.5 L in a healthy 70-kg adult. The VC is also equal to the sum of the VT and the IRV and ERV. It is determined by the factors that determine the TLC and RV.



Pulmonary volumes

		Males	Females	
Vital capacity	IRV	3300	1900	Inspiratory capacity
	VT	500	500	
	ERV	1000	700	Functional residual capacity
Residual volume		1200	1100	
		6000 ml	4200 ml	

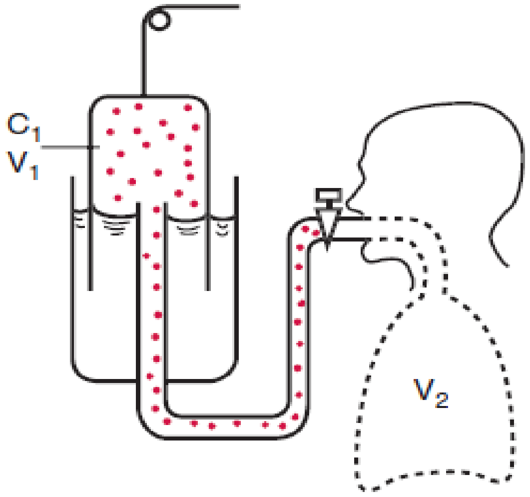
THE FUNCTIONAL RESIDUAL CAPACITY (FRC)

- The FRC represents the balance point between the inward elastic recoil of the lungs and the outward elastic recoil of the chest wall.
- The FRC > relaxation volume if the next inspiration occurs before the relaxation volume is reached (high breathing rates or high resistance to expiratory airflow in the larynx or peripheral airways or active contraction of the inspiratory muscles at end expiration).
- We cannot use a spirometer to measure residual volume or any capacity containing RV (i.e., FRC or TLC), we can use two general approaches to measure RV, both based on the **law of conservation of mass**.

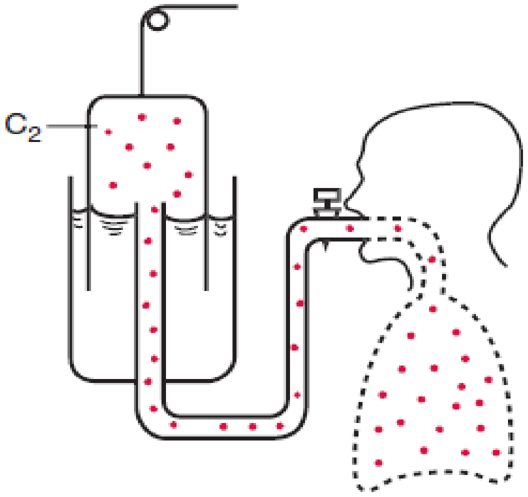
1. RV is computed from the volume of distribution of either helium (He) or nitrogen (N_2)
2. RV is computed by use of Boyle's law.

Helium dilution technique

- A small volume of helium is added to the spirometer before the subject begins the test, resulting in a known initial helium concentration within the volume of the system.
- When the subject begins breathing (beginning at FRC), this initial helium concentration becomes diluted, as the gas equilibrates between the lungs of the subject and the spirometer.
- Because helium does not diffuse through the alveolo-capillary membrane and is inert, a stable equilibrium is reached quickly.
- After some breaths, the helium concentrations in the spirometer and lung become the same.
- This final concentration is dependent only on the initial concentration of helium within the spirometer and the volume of the spirometry system plus FRC.



Before equilibration



After equilibration

Because no helium has been lost, the amount of helium present before equilibration (concentration times volume) is

C1*V1

and equals the amount after equilibration: C1*C2 (V1+V2)

- Volumes and capacities are normally defined for a subject seated in an upright posture wearing loose clothes so that the movement of the lungs is not restrained. The volumes can be represented on a spirogram
- With a typical Western diet, metabolism consumes more O2 (250 mL/min) than it produces CO2 (200 mL/min), the volume of air entering the body with each breath is slightly greater (∼1%) than the volume leaving. The expired lung volume (V_E) is used to describe volumes.

Timing of test

- Starting the test at precisely the right time is important.
- If the test begins at the end of a normal tidal volume (end of expiration), the volume of air remaining in the lungs represents **functional residual capacity**.
- If the test begins at the end of a **forced vital capacity**, then the test will measure residual volume.
- Similarly, if the test starts after a maximal inspiration, then **TLC** is measured.
- Carbon dioxide is absorbed and oxygen is added to the spirometer to make up for the oxygen consumed by the person during the test.
- The helium dilution technique has a major limitation in patients whose lungs are poorly ventilated because of plugged airways or high airway resistance. In these diseased lungs, helium gives a falsely low FRC value

Whole-body plethysmography

- is based on **Boyle's law,** which states that the product of pressure and volume for a gas is constant:

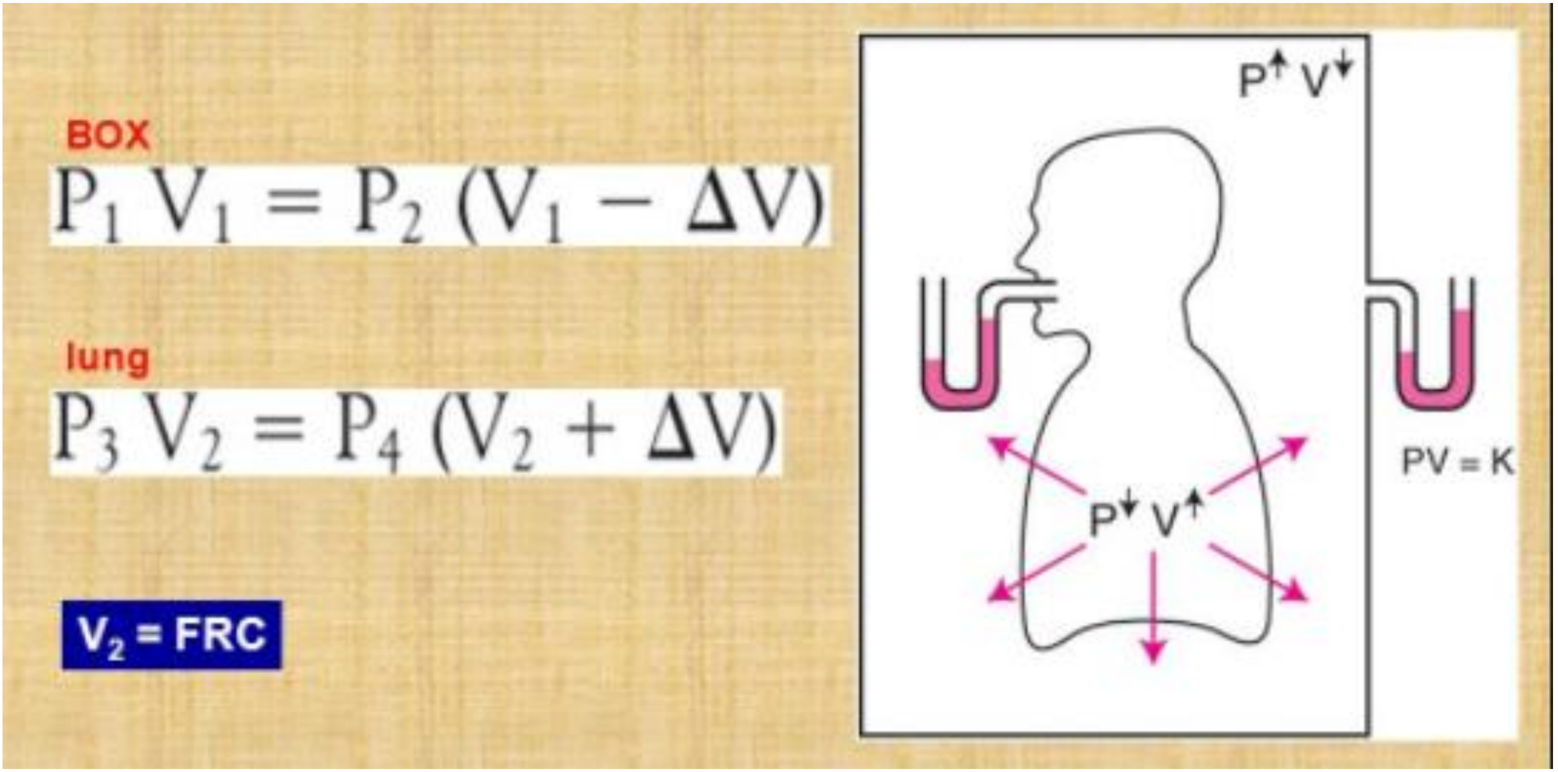
$$P_1V_1 = P_2V_2$$

- the subject is put into an airtight box equipped with a mouthpiece through which he breathes outside air. During normal, quiet breathing, the subject is asked to stop and relax after a normal, quiet exhalation.
- At that point, the mouthpiece is closed, and the subject attempts to inhale through the closed mouthpiece.
- This attempt causes the air in the lungs (FRC) to expand due to the negative pressures created by the expansion of the chest wall, and results in an equal reduction of the volume of the air in the box outside the patient's body.
- The pressure of the air in the box increases due to this reduction in volume. Changes in pressure in the box are used to calculate the change in volume in the box using Boyle's law.
- This change in volume is the same as the change in volume of the lungs from the resting value (FRC).
- Based on the change in pressure in the respiratory system (measured at the mouthpiece during the attempt to inhale) and the change in volume of the lungs, the initial volume (FRC) can be calculated using Boyle's law.
- Therefore, if the pressures in the box before and after the inspiratory effort are P1 and P2, respectively, V1 is the preinspiratory box volume, and ΔV is the change in volume of the box (or lung), we can write

$$P_1V_1= P_2 (V_1+ \Delta V)$$

Thus, ΔV can be obtained.

- Next Boyle’s law can be applied to the gas in the lung.
- $P_3V_2 = P_4(V_2+\Delta V)$ where P3 and P4 are the mouth pressures are the mouth pressures before and after the inspiratory effort and V2 is FRC. Thus FRC can be obtained.



Factors Affecting Static Lung Volumes

1. *Body size.* FRC and other lung volumes are linearly related to subject height.
2. *Sex.* For the same body height, females have a FRC about 10% less than males and a smaller forced vital capacity (FVC), the latter resulting from males having less body fat and a more muscular chest.
3. *Age.* FVC, FRC and RV all increase with age. FRC increases by around 16 ml per year approx.
4. *Posture. A* significantly reduced FRC is seen when supine. The changes are caused by the increased pressure of the abdominal contents on the diaphragm in the supine position, displacing it in a cephalad direction and reducing thoracic volume.
5. *Ethnic group.*
6. *Obesity.* With the exception of tidal volume, obesity causes a reduction in all static lung volumes, particularly expiratory reserve volume and FRC

Minute ventilation and Alveolar ventilation

- Taking an average rate of 15 breaths per minute, the **minute ventilation** is

$$\dot{V}_E = R*V_T$$

where R is the respiratory rate and VT is the tidal volume.

Thus, 15 breaths/min × 500 mL yields a V_E of 7500 mL/min (7.5 L/min).

- . **Alveolar ventilation < the minute ventilation** because the last part of each inspiration remains in the conducting airways and does not reach the alveoli.
- The last part of each expiration remains in the conducting airways and is not expelled from the body.
- No gas exchange occurs in the conducting airways for anatomic reasons: The walls of the conducting airways are too thick for much diffusion to take place; mixed venous blood does not come into contact with the air: the **anatomic dead space.**
- **Thus, with each 500-mL inspiration, only the initial 350 mL of fresh air entering the body reaches the alveoli. With each 500-mL expiration, only the final 350 mL of air exiting the body comes from the alveoli. One 150-mL bolus of fresh air shuttles back and forth between the atmosphere and conducting airways. Another 150-mL bolus of stale air shuttles back and forth between the conducting airways and alveoli.**

Alveolar ventilation

- Because anatomical dead space is approximately 150 mL, this **dead space ventilation** (VD) is roughly 150 mL ×15/min, or 2250 mL/min. Alveolar ventilation is calculated by the formula:

$$VA= R(VT-VD)$$

where R is respiratory rate, VT is tidal volume, and VD is dead space volume.

Of the 500 mL tidal volume, only 350 mL is entering the alveoli with each breath, and of the 7500 mL/min minute ventilation, only the alveolar ventilation of 5250 mL/min (7500 mL/min − 2250 ml/min) is available for gas exchange.

Stated another way,

$$\dot{V}_A=\dot{V}_E-\dot{V}_D$$

- The dot over the letter V indicates per minute.
- **The symbol $\dot{V}_E$ is used because expired gas is usually collected. There is a difference between the volume of gas inspired and the volume of gas expired because as air is inspired, it is heated to body temperature and humidified and also because normally less carbon dioxide is produced than oxygen is consumed.**

Effect of rate and depth of respiration on alveolar ventilation

- **At the same minute ventilation**, deep, slow breathing yields greater alveolar ventilation than rapid, shallow breathing. Comparing alveolar ventilation when respiratory rate is 15/min and tidal volume is 500 mL to alveolar ventilation at a respiratory rate of 30/min and tidal volume of 250 mL:

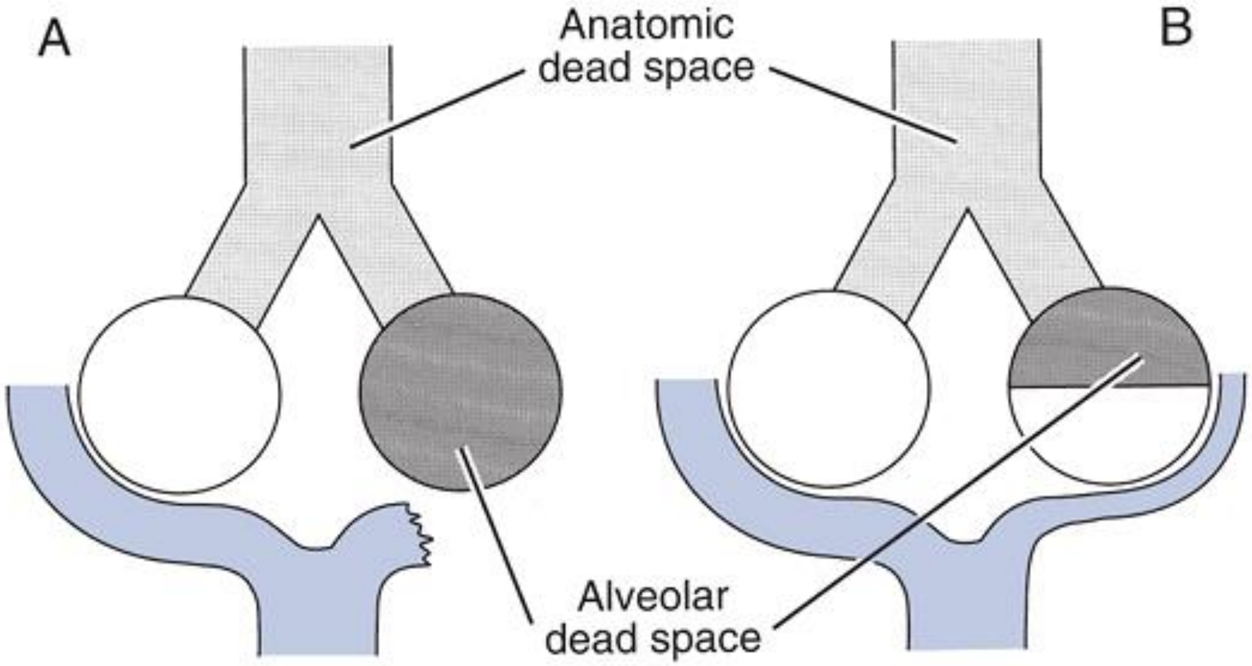
$$VA=15\ /\mathrm{min}\ (500\ \mathrm{mL}-150\ \mathrm{mL})= 5250\ \mathrm{mL/min}$$

$$VA= 30/\mathrm{min}\ (250\ \mathrm{mL}-150\ \mathrm{mL})=3000\ \mathrm{mL/min}$$

Slower, deeper ventilation produces greater alveolar ventilation than more rapid ventilation at proportionally less tidal volume.

Anatomic dead space

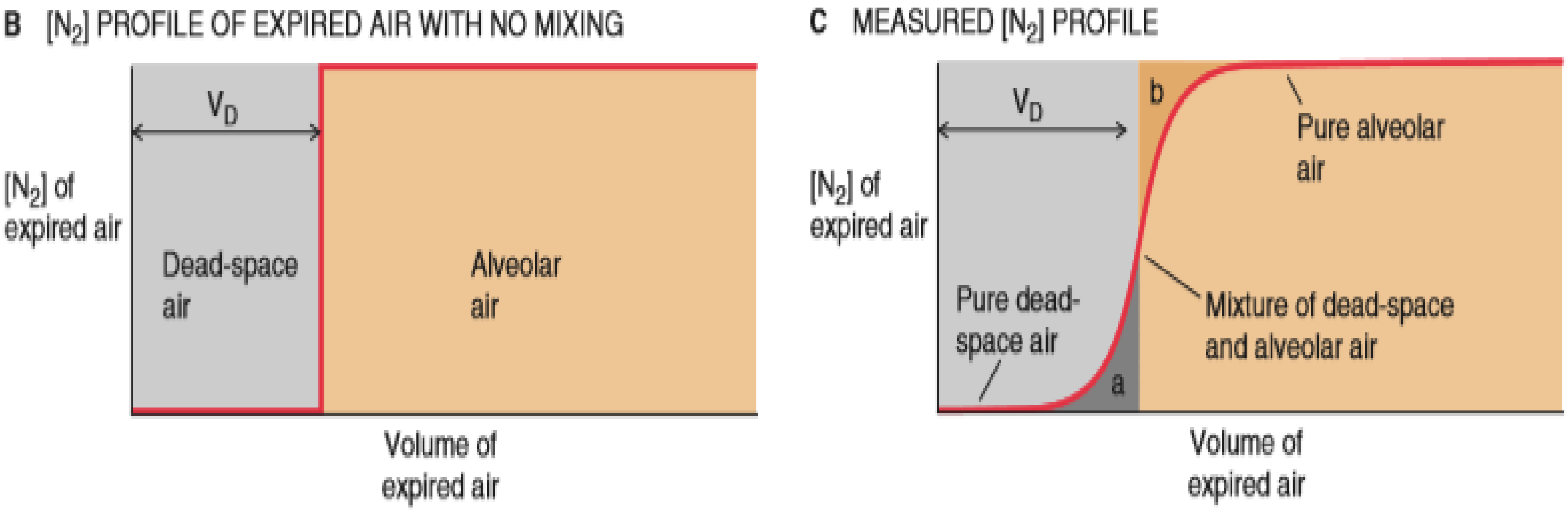
- The normal ratio of dead space volume to tidal volume (VD:VT) is in the range of 0.25 to 0.35.
- About 30% of the tidal volume or 30% of the minute ventilation does not participate in gas exchange and constitutes VD.



Measurement of the anatomic Dead Space Volume: Fowler's method

- The subject suddenly takes a deep single breath of 100% O_2, which fills the entire dead space with pure O_2.
- Some oxygen also mixes with the alveolar air but does not completely replace this air.
- Then the person expires through a rapidly recording nitrogen meter.

I. The first portion of the expired air comes from the dead space regions of the respiratory passageways, where the air has been completely replaced by O_2. Therefore, in the early part of the record, only O_2 appears, and the nitrogen concentration is zero.
II. When alveolar air begins to reach the nitrogen meter, the nitrogen concentration rises rapidly, because alveolar air containing large amounts of nitrogen begins to mix with the dead space air. After still more air has been expired, all the dead space air has been washed from the passages and only alveolar air remains.
III. The recorded nitrogen concentration reaches a plateau level equal to its concentration in the alveoli.



- **Anatomic dead space (respiratory system volume exclusive of alveoli) v/s the total (physiologic) dead space (**nonperfused alveoli; **volume of gas not equilibrating with blood; i.e. wasted ventilation)**
- In healthy individuals, the two dead spaces are identical and can be estimated by body weight.
- In disease states, no exchange may take place between the gas in some of the alveoli and the blood, and some of the alveoli may be overventilated.
- In a person with partially functional or nonfunctional alveoli , the physiological dead space may be 10 times the volume of the anatomical dead space, or 1 to 2 liters.

Physiological dead space

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- *The physiological dead space* is measured in the clinical pulmonary function laboratory by making appropriate blood and expiratory gas measurements and using the following equation, called the Bohr equation:

$$\underline{V_D} = \frac{F_{ACO_2} - F_{ECO_2}}{V_T F_{ACO_2}}$$

- where F= fractional concentration, E = mixed expired, I= inspired, A= alveolar, $VDCO_2$= dead space for CO_2 (physiologic dead space), $FACO_{2=}$ fractional concentration of CO_2 in alveoli that are both ventilated and perfused
- Normal values for the VD/VT ratio are 0.2 to 0.35.
- If a patient has a tidal volume of 500 mL and the VD/VT ratio is 0.35, then the physiological dead space is 175 mL .

- When the physiological dead space is high, much of the *work of ventilation* is wasted effort because so much of the ventilating air never reaches the blood.

ALVEOLAR DEAD SPACE: Bohr method

The principle of Bohr's approach is that the amount of CO2 present in the volume of mixed-expired air (V_E) is the sum of the CO2 contributed by the volume of air from the dead space (V_D) plus the CO2 contributed by the volume of air coming from the alveoli (VE − VD)
After a quiet expiration, the PCO_2 of the alveolar air is virtually the same as the PCO_2 of the arterial blood , (40 mm Hg).

The subject now inhales a normal tidal volume (~500 mL) of room air, although any CO_2-free gas mixture would do.

The first portion enters the alveoli, where it rapidly dilutes the CO_2 and other gases remaining after the previous breath .
The rest (~150 mL) remains in the conducting airways, which now have a PCO_2 of ~0.
When the subject now expires, the first air that exits the body is the CO_2 free gas that had filled the conducting airways, followed by the CO2-containing alveolar air. Thus, the idealized profile of expired [CO_2] is:

1. The amount of CO2 coming from the dead space is the product of VD and [CO2] in this dead-space air. Because [CO2]d is 0, the area beneath VD is also zero.
2. The amount of CO2 coming from alveolar air is the product of (VE − VD) and alveolar [CO2].
3. The total amount of CO2 in the mixed-expired air is the product of VE and the average [CO2] in this air.

Physiologic Variants

- Alveolar dead space typically is negligible in a healthy individual.
- Anatomic, and therefore physiological, dead space normally is estimated at 2mL/kg of body weight and comprises 1/3 of the TV in a healthy adult patient.
- It is even higher in pediatric patients.
- Effectively, 1/3 of a TV of inhaled air is rebreathed due to dead space. At the end of expiration, the dead volume consists of a gas mixture high in CO2 and low in O2 compared to ambient air.

Physiologic factors can influence dead space:

- Respiratory Cycle: Inhalation leads to increases in bronchial diameter and length, effectively increasing the anatomic dead space.
- Positioning: Dead space decreases with the supine position and increases during a sitting position.
- Sleep: Anatomic dead space decreases during sleep and be the primary physiologic cause of observed decreases in tidal volume, minute ventilation, and respiratory rate during sleep.
- Maxilla: Variation also can occur in patients with maxillary defects or those who have undergone maxillectomy procedures.

`https://www.ncbi.nlm.nih.gov/books/NBK442016/`

Function of dead space

The function of a seemingly wasteful design for ventilation that includes dead space is as follows:

1. Carbon dioxide is retained, resulting in a bicarbonate-buffered blood and interstitium.
2. Inspired air is raised or lowered to body temperature, increasing the affinity of hemoglobin for O2 and improving O2 uptake.
3. Particulate matter is **trapped in the mucus** that lines the conducting airways, allowing it to be removed by mucociliary transport.
4. Inspired air is **humidified**, thus improving the quality of airway mucus.

COMPOSITIONS OF ALVEOLAR AIR AND ATMOSPHERIC AIR ARE DIFFERENT

Alveolar air does not have the same concentrations of gases as atmospheric air.
There are several reasons for the differences.

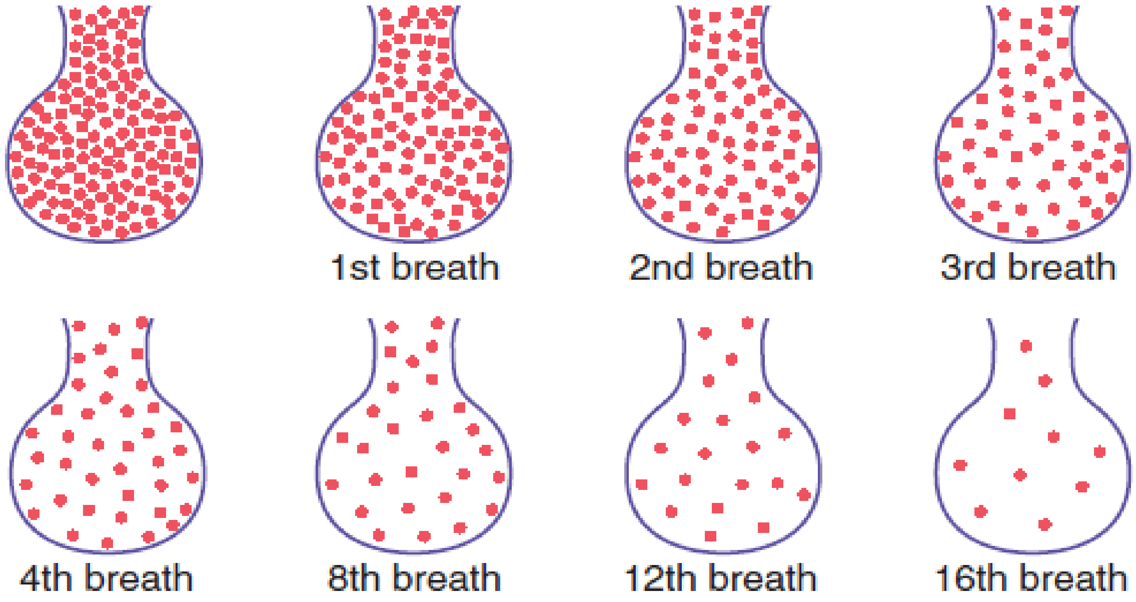
1. The alveolar air is only partially replaced by atmospheric air with each breath.
2. O_2 is constantly being absorbed into the pulmonary blood from the alveolar air.
3. CO_2 is constantly diffusing from the pulmonary blood into the alveoli.
4. Dry atmospheric air that enters the respiratory passages is humidified even before it reaches the alveoli.

Water Vapor Pressure:

1. Depending on the surrounding temperature and pressure, water can exist as a liquid, gas, or solid. Water in the gaseous form is called water vapor, or molecular water.
2. When water vapor is present in a volume of gas, it behaves according to the gas laws and exerts a partial pressure.
3. Because alveolar gas is 100 percent humidified (saturated) at body temperature, the alveolar gas is assumed to have an absolute humidity of 44 mg/L, and a water vapor pressure of 47 mm Hg—regardless of the humidity of the inspired air

Alveolar air is slowly renewed by atmospheric air

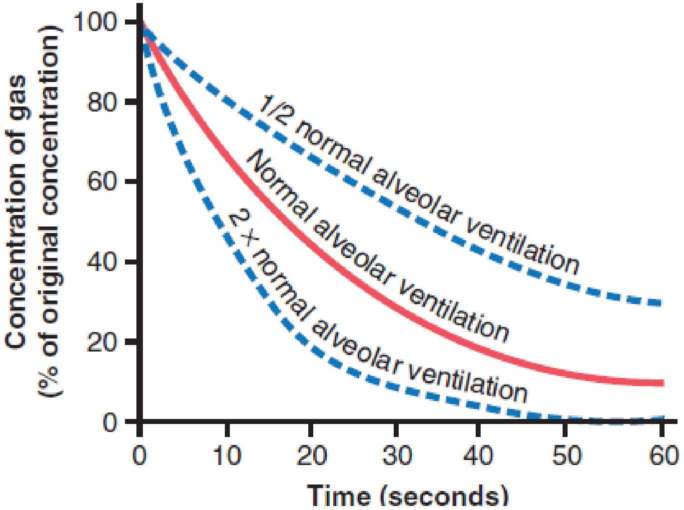
- The average male *functional residual capacity* of the lungs measures about 2300 milliliters.
- Only 350 milliliters of new air is brought into the alveoli with each normal inspiration, and this same amount of old alveolar air is expired.
- The volume of alveolar air replaced by new atmospheric air with each breath is only one seventh of the total.



In the first alveolus of the figure, excess gas is present in the alveoli but even at the end of 16 breaths the excess gas is still present in the alveoli.

The rate at which excess gas in the alveoli is normally removed

- With normal alveolar ventilation, about one half the gas is removed in 17 seconds.
- When a person’s rate of alveolar ventilation is only one-half normal, one half the gas is removed in 34 seconds, and when the rate of ventilation is twice normal, one half is removed in about 8 seconds.



Importance of the Slow Replacement of Alveolar Air:

- prevents sudden changes in gas concentrations in the blood. This makes the respiratory control mechanism much more stable
- it helps prevent excessive increases and decreases in tissue oxygenation, tissue CO2 concentration, and tissue pH when respiration is temporarily interrupted.

Meaningful learning stems from inspiration: to learn, you must be inspired to learn. If anyone can inspire learning in respiratory physiology, it is Wallace Fenn, Hermann Rahn, and Arthur Otis.

Douglas Curran-Everett

Fig. 1. Arthur Otis (1913–), Hermann Rahn (1912–1990), and Wallace Fenn (1893–1971) at the fall 1963 meeting of the American Physiological Society. [Reproduced from Otis and Rahn (5), published in *Pulmonary Gas Exchange*, edited by J. B. West (1980), with permission from Elsevier.]

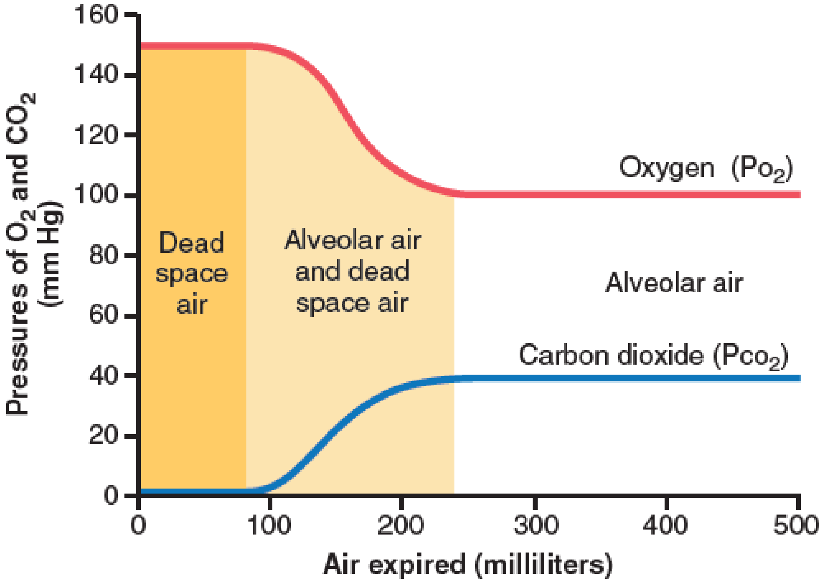
Adv Physiol Educ 30: 58 – 62, 2006;

Sampling expired air

The overall composition of expired air is determined by
(1) the amount of the expired air that is dead space air
(2) the amount that is alveolar air.

- The first portion of this air, the dead space air from the respiratory passageways, is typical humidified air.
- Then, more and more alveolar air becomes mixed with the dead space air till all the dead space air washes out and nothing but alveolar air is expired at the end of expiration.

Normal expired air, containing both dead space air and alveolar air, has gas concentrations and partial pressures i.e., concentrations between those of alveolar air and humidified atmospheric air.



The progressive changes in O_2 and CO_2 partial pressures in the expired air during the course of expiration.

Expired Air Is a Combination of Dead Space Air and Alveolar Air

Sampling alveolar air

Theoretically, all but the first 150 mL expired from a healthy 150 lb man (ie, the dead space) with each expiration is the gas that was in the alveoli **(alveolar air),** but some mixing always occurs at the interface between the dead-space gas and the alveolar air.

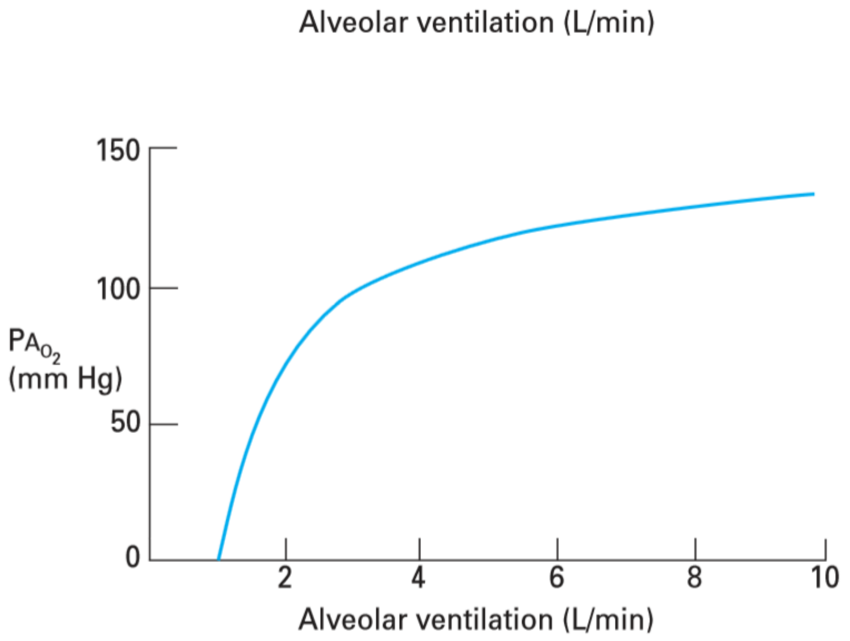
A later portion of expired air is therefore the portion taken for analysis. Using modern apparatus with a suitable automatic valve, it is possible to collect the last 10 mL expired during quiet breathing. The composition of alveolar gas is compared with that of inspired and expired air

Alveolar Ventilation & Oxygen

As alveolar ventilation increases, the alveolar PO_2 will also increase.

Doubling alveolar ventilation, however, cannot double PAO2 in a person whose alveolar PO_2 is already 104 mm Hg because the highest PAO_2 one could possibly achieve (breathing air at sea level) is the inspired PO_2 of about 149 mm Hg. The alveolar PO_2 can be calculated by using the **alveolar air equation**

$$P_{A_{O_2}} = P_{I_{O_2}} - \frac{P_{A_{CO_2}}}{R} + F$$



As alveolar ventilation increases, the alveolar PCO_2 decreases, bringing the alveolar PO2 closer to the inspired PO2.

The alveolar PO2 obtained using the alveolar air equation is a calculated idealized average alveolar PO2.

It represents what alveolar PO2 should be, not necessarily what it is.