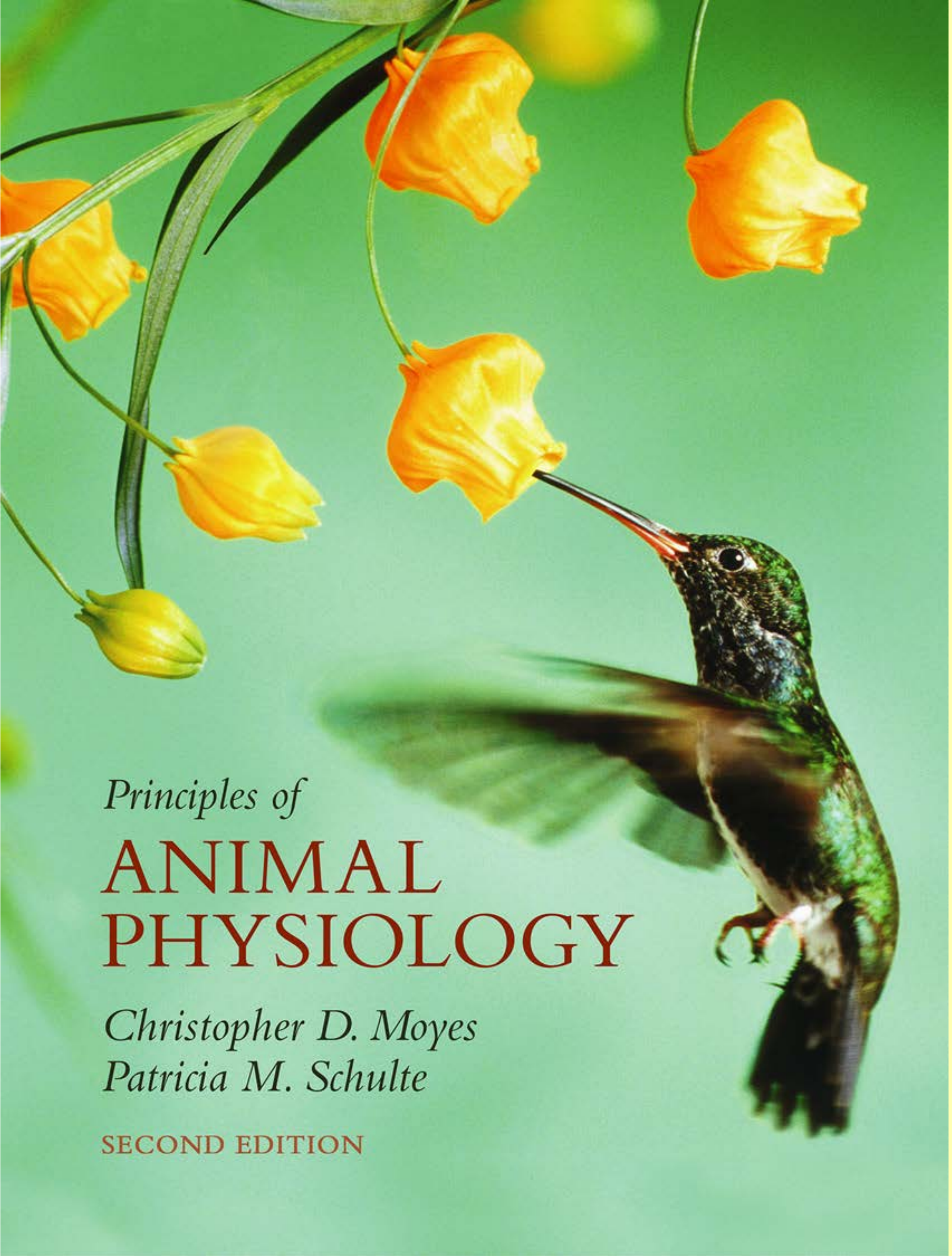


CHAPTER

9

Respiratory Systems

Extra Information

- **Chris' drop-in hours**: Tues – 12:00pm – 2:00pm
- **Additional Help**: Use the Blackboard Discussion Board which will have Respiratory and Cardiovascular threads monitored by Chris. Please do not e-mail lecture or lab questions.

BIO271: Lecture Topic Overview - Garside

Lecture 6: ***Respiratory Systems: strategies; physics; types; ventilation and gas exchange in air vs water***

Lecture 7: Respiratory Systems: gas transport to and from tissues; regulation of vertebrate respiratory systems

Lecture 8: Circulatory Systems: overview; components; diversity

*Lecture 9**:** Circulatory Systems: physics; the heart*

Lecture 10: Circulatory Systems: regulation of blood pressure and flow; blood composition

Review Lecture 11: Questions posed on Blackboard

Final Exam April 15: 2:00 pm – 4:00 pm

Month	**Date**	**Lecture and Topic**	**Required Readings**
February	26	***Lecture 6*** Respiratory Systems: strategies; physics; types; ventilation and gas exchange in air vs water	p. 412-435 (not echinoderms or chelicerates)
March	05	***Lecture 7*** Respiratory Systems: gas transport to and from tissues; regulation of vertebrate respiratory systems	p. 435-462 (not box content)
March	12	***Lecture 8*** Circulatory Systems: overview; components; diversity	p. 350-362 (not box content)
March	19	***Lecture 9*** Circulatory Systems: physics; the heart	p. 363-378
March	26	***Lecture 10*** Circulatory Systems: regulation of blood pressure and flow; blood composition	p. 378-403
April	02	***Review Session:*** Questions posed on Blackboard will be reviewed	

BIO271: Lecture 6 Overview

- **Overview**
- The physics of respiratory systems
- Respiratory strategies, ventilation and perfusion
- Water-breathing animals

- Air-breathing animals
- Ventilation in mammals
- Gas transport
  - Oxygen
  - Carbon dioxide
- Regulation of respiration

Produces a lot of ATP
A substrate that is required in mitochondria
Needs a low conc of oxygen
Always a gradient for oxygen from high conc to low con in the mitochondria

PH regulation and carbon dioxide
Respiratory system getting oxygen in and carbon dioxide out
Temperature regulation is important for the lungs

Overview

- *Respiration ("external respiration")*
  - Sequence of events that result in the exchange of oxygen and carbon dioxide between the external environment and the mitochondria

Different from cellular respiration
External respiration is required for cellular respiration to happen, need that oxygen for cellular respiration

- *Mitochondrial respiration*
  - Production of ATP by oxidation of carbohydrates, amino acids, or fatty acids;

Partial pressures don't change

  - Oxygen is consumed and carbon dioxide is produced
    - Concentration gradient of oxygen and carbon dioxide; these gases diffuse down their concentration gradients

Overview

Small thin organism, unicellular or multicellular, can rely entirely based on diffusion
Larger organisms need to rely on combination of diffusion like bulk flow
Two types of bulk flow and two types of diffusion

- Unicellular and small multicellular organisms rely on diffusion for gas exchange
- Larger organisms must rely on a combination of bulk flow and diffusion for gas exchange

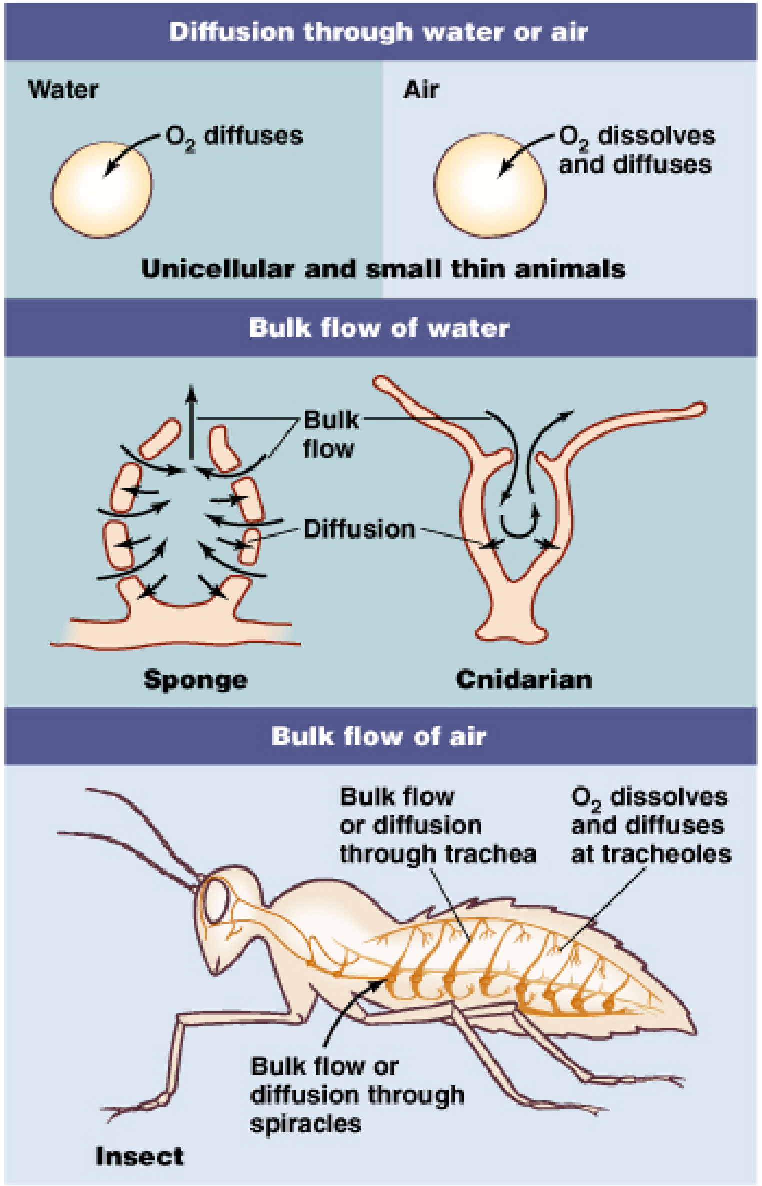
- **Bulk flow**
  - Ventilation
    Movement of external environment
    - Moving medium (air or water) over respiratory surface (lung or gill)
    Pulmonary diffusion gets into circulation and will be carried around the body and take in oxygen and take waste out
  - Circulation
    - Transport of gases in the circulatory system

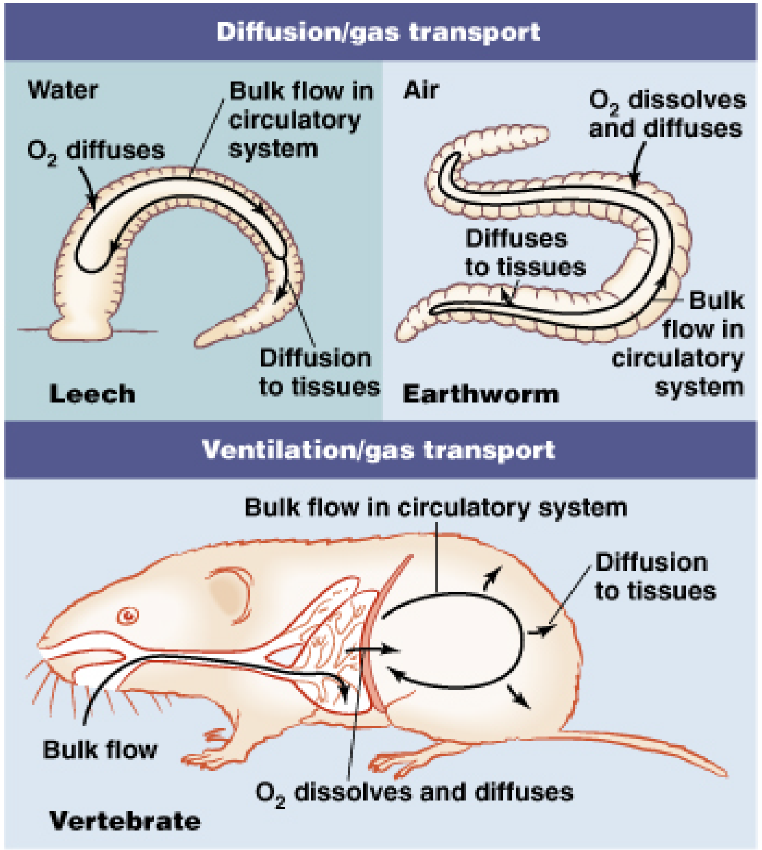
Peripheral gas exchange - gas exchange again

Overview

Unicellular organism living in water
Oxygen diffuses in towards mitochondria
Always a gradient for o2 to come in

Ventilating
Make sure you don't get stagnant





1. Ventilation
2. Pulmonary gas exchange
3. Circulation - bulk flow
4. Peripheral gas exchange

1,3 cause energy - expensive - increase metabolic rate - powering bulk flow steps
For bulk flow to occur, you need a gradient, high gradient to low gradient, diffusion just happens

2,4 we have some control over

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Physics of Fluid Flow

Bulk flow is like things moving through tubes

Increases length of tube, you increase resistance

Law of bulk flow: $Q = \Delta P/R$

Q = flow

ΔP = pressure drop

R = resistance (due to friction)

Flow is proportional to partial pressure
Increase resistance you decrease flow
Decrease resistance you increase flow

$R = 8L\eta/\pi r^4$

Increase viscosity, increase resistance
Changing radius of tubes significantly influence resistance
If you half the tube, he will have to increase lessee difference 16x to get the same volume

L = length of the tube

η = viscosity of the fluid

r = radius of the tube (greatest effect)*

Think effects of vasoconstriction or vasodilation

Poiseuille's equation: $Q = \Delta P \pi r^4 / 8L\eta$

- More detailed version of law of bulk flow

The Physics of Respiratory Systems

- ***Fick Equation*** (for diffusion rate)

How quickly does this occur?

How much is moving in a specific of time

$$dQ/dt = \frac{D \times SA \times dC}{dx}$$

Diffusion coefficient has to do be viscosity of acid, size of particles, temperature etc

dQ/dt = Rate of diffusion
D = diffusion coefficient (*D*)
SA = surface area of the membrane (*A*)
dC = energy gradient

- Difference in pressure (not concentration)

dx = Diffusion distance

- Rate of diffusion will be greatest when the diffusion coefficient (*D*), surface area of the membrane (*A*), and energy gradients (*dC*) are large, but the diffusion distance (*dx*) is small

Consequently, gas exchange surfaces are typically thin, with a large surface area

Dalton's Law of Partial Pressure

- In a gas mixture each gas exerts its own *partial pressure*

Each gas contributes to the total pressure
Based of its proportion to the total amount of gas

- The sum of all partial pressures is equal to the total pressure of the mixture
- Air is a mixture of gases
  - Nitrogen (78%), oxygen (21%), argon (0.9%), and carbon dioxide (0.03%)

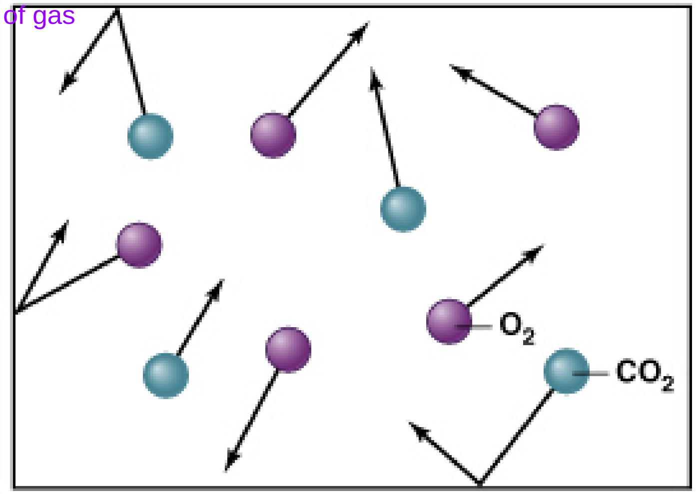
160mm/Mg in sea level

- The pressure exerted by a gas is related to the number of moles of the gas and the volume of the chamber
- Ideal gas law

$$PV = nRT$$

As gases are coming inside the chamber, they are bouncing the walls

Partial changes are not going to change but comic of gases do



(a) Ideal gas law

$$PV = nRT$$

$$P_{O_2} V_{O_2} = n_{O_2} RT$$

$$P_{CO_2} V_{CO_2} = n_{CO_2} RT$$

$$P_{total} = P_{O_2} + P_{CO_2}$$

$$n/V = P/RT$$

- ↑ temp, ↑ volume, ↓ [gas], while pressure is constant

Henry's Law describes how gases dissolve in liquids

- Gas molecules in air must first dissolve in liquid to diffuse into a cell
- The concentration of gas in a liquid is proportional to its partial pressure

Gas molecules in air must first dissolve in liquid to diffuse into a cell
Henry's law and diving - people can die from the bubbles in blood stream, it has to do with solubility and pressure
Everyday example of Henry's law can be the champagne, they add in extra yeast and sugar for a second fermentation

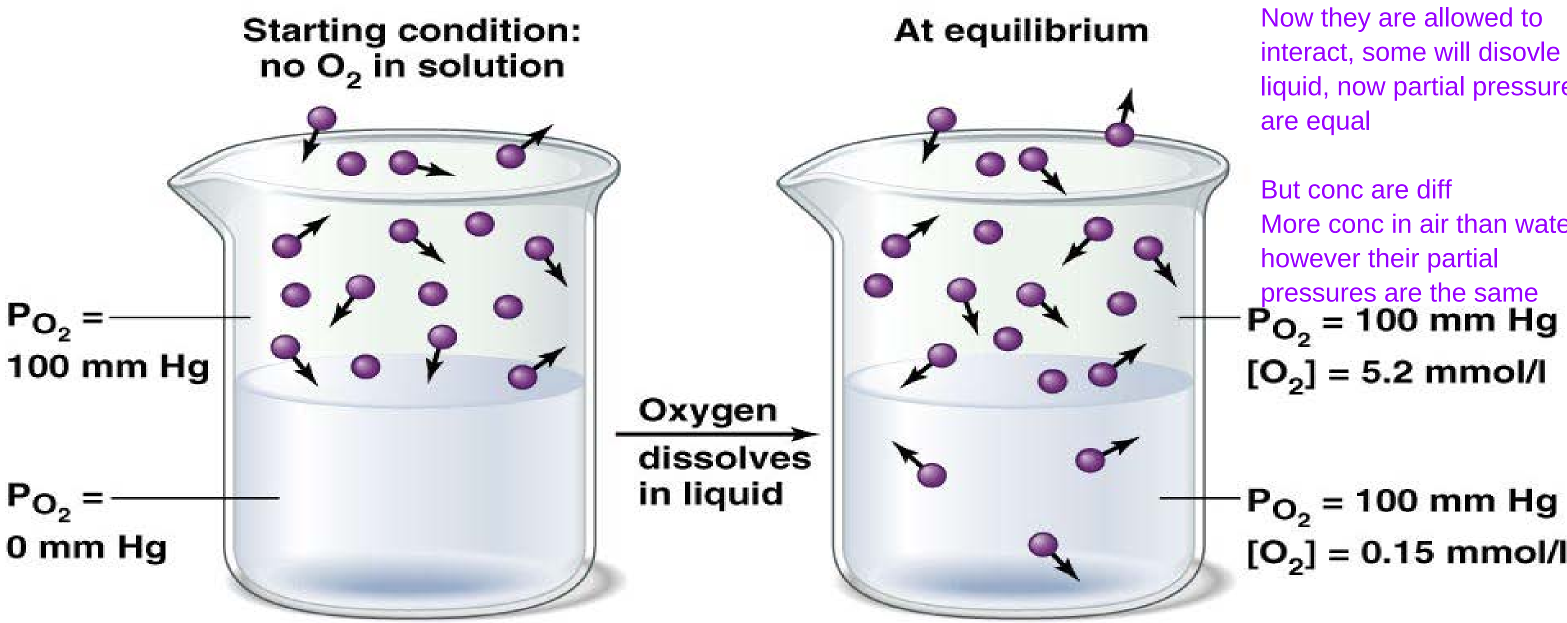
Henry's law: $[G] = P_{gas} \cdot S_{gas}$

where, $[G]$ = concentration of the gas, P_{gas} = partial pressure of the gas,

S_{gas} = solubility of the gas (note: this is also affected by temp and [ionic])

Varies in different elements

Before they have allowed gas to interact with liquid



(b) Henry's law

Now they are allowed to interact, some will disovle in liquid, now partial pressures are equal

But conc are diff
More conc in air than water, however their partial pressures are the same

The effects of solubility, like temperature, are why we express the Fick equation in terms of pressure rather than concentration.

Diffusion Rates of Gases

Graham's law

- Diffusion rate is proportional to $S_{gas}/\sqrt{MW}$ → $\frac{\sqrt{32}}{\sqrt{44}}$

- Combining the Fick equation with Henry's law and Graham's law
  - Diffusion rate of a gas molecule

$$dQ/dt = \frac{\mathbf{D \times A \times \Delta P_{gas} \times S_{gas}}}{\mathbf{X \times \sqrt{MW}}}$$

Graham's law with Henry's law

- *Thus, At a constant temp, rate of diffusion is proportional to*:
  - Partial pressure gradient (ΔP_{gas}), Surface area (A), and Solubility of the gas in the fluid (S_{gas})

And Inversely proportional to:

- Diffusion distance (*X*) and Molecular weight of the gas (MW)

Gases diffuse at dif rates in water and air

Table 9.1 The physical properties of air and water and their effects on the respiratory gases.

Property	Air (20°C)	Water (20°C)	Ratio (water/air)
Oxygen diffusion coefficient ($m^2/sec \times 10^{-9}$)	20,300	2.1	~1:10,000
Carbon dioxide diffusion coefficient ($m^2/sec \times 10^{-9}$)	16,000	1.8	~1:10,000
Oxygen solubility (ml/l)	1000	33.1	1:30
Carbon dioxide solubility (ml/l)	1000	930	~1
Oxygen concentration (mM) (at 1 atm)	8.7	.3	1:30
Carbon dioxide concentration mM (at 1 atm)	.01	.01	~1
Density (kg/m^3)	1.2	998	~800:1
Viscosity (poise $\times 10^{-2}$)	.02	1	50:1

Oxygen diffuses ~300,000 X more slowly in water than air!

Bulk Flow of Gases

- Fluids flow from areas of high pressure to areas of low pressure
- For gases, changes in pressure are related to changes in volume
- *Boyle's law*:

Basically stating that:

Modification of the ideals law

Production of pressure and volume of ideal gas are constant

$$P_1V_1 = P_2V_2$$

Temperature will also affect this

Increase pressure, volume must decrease
Decrease pressure, volume must increase

  - P_1V_1 = initial pressure and volume of the gas
  - P_2V_2 = final pressure and volume of the gas
- For example, if you increase the volume of a chamber of gas, the pressure of the gas will decrease
- Temperature is constant

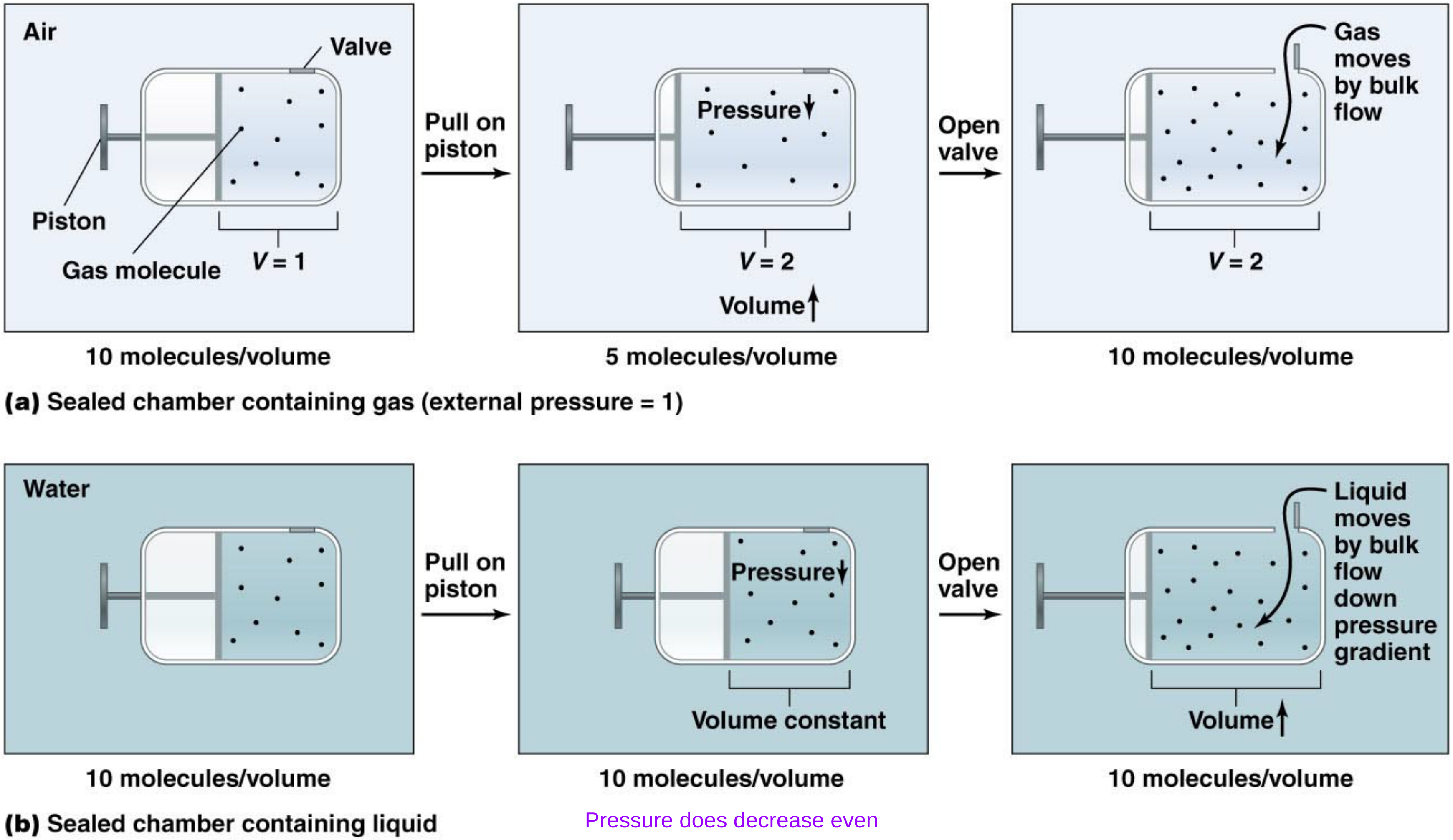
Bulk Flow of Gases

Gases have neither fixed shape nor volume

Gas moves in down conc gradient and comes to eq.

Valve is closed in this case
So given amount in a given volume

Increase volume, pressure decrease
Boyles law



Pressure does decrease even though volume is constant

Figure 9.3

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  - Carbon dioxide
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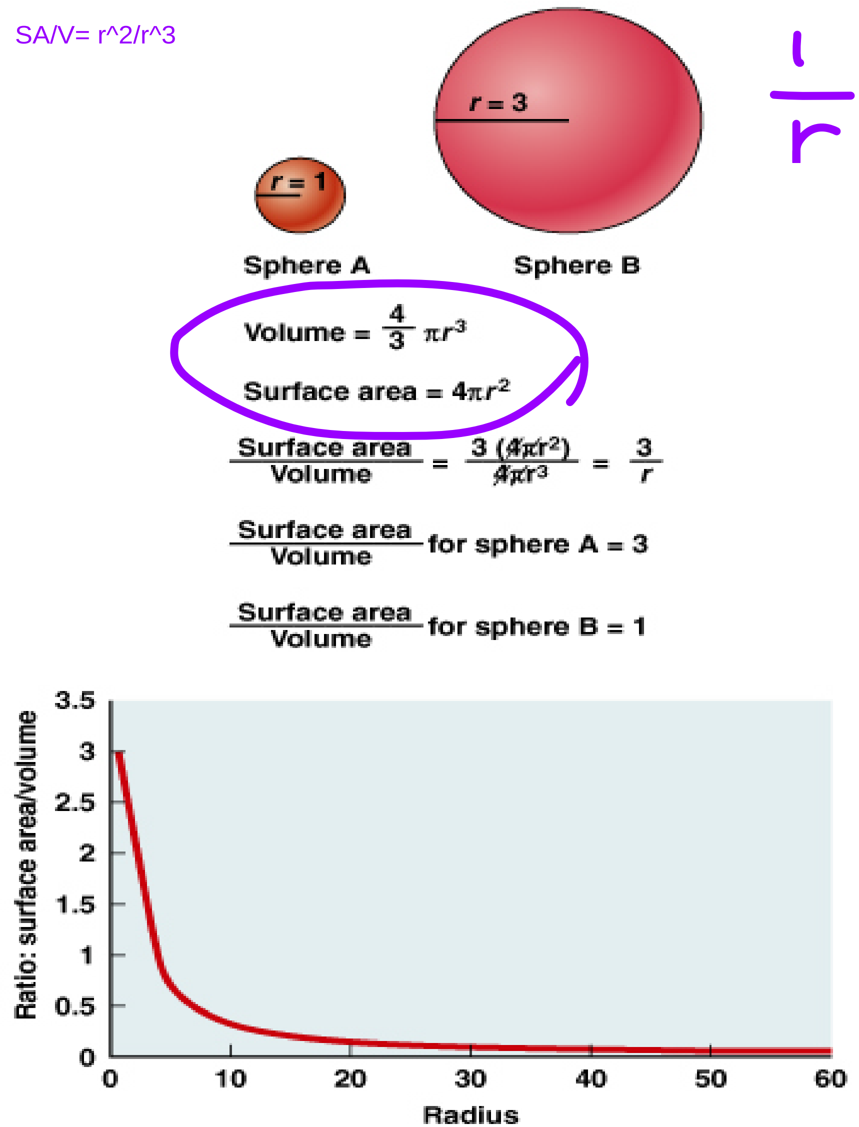
Surface Area to Volume Ratio

- As radius increases, volume ↑ faster than surface area
- As organisms grow larger, the ratio of surface area to volume decreases
- Larger size limits the surface area available for diffusion and increases the diffusion distance
- Only very small organisms can rely solely on the diffusion of oxygen to support metabolism
    - Larger animals must transport oxygen by bulk flow

SA/V= r^2/r^3



Max metabolic rate per gram of tissue must ↓
BUT
Diffusion rate can be ↑ by movement of medium

Respiratory Strategies

- Animals more than a few millimeters thick use one of three respiratory strategies
  1. Circulating the external medium through the body
     - Sponges, cnidarians, and insects
  2. Diffusion of gases across the body surface accompanied by circulatory transport
     - *Cutaneous respiration*
     - Skin must be thin and moist
     - Most aquatic invertebrates, some amphibians, eggs of birds
  3. Diffusion of gases across a specialized respiratory surface accompanied by circulatory transport
     - Gills (evaginations) or lungs (invaginations)

Respiratory Strategies (2)

Eastern west selamender doesn't have a lung

Significantly increases SA

Ventilation

- Ventilation of respiratory surfaces reduces the formation of static boundary layers
- Types of ventilation
  1. *Nondirectional*
     - Medium flows past the respiratory surface in an unpredictable pattern
  2. *Tidal*
     - Medium enters and exits chamber through same passageway
  3. *Unidirectional*
     - Medium enters the chamber at one point and exits at another

Patterns of Ventilation

- The rate or pattern, but not the direction, of ventilation can change with environmental or metabolic conditions

Direction of flow never changes but rate or pattern changes

Table 9.2 Patterns of ventilation

Term	Definition	Examples
Eupnea	Normal breathing	
Apnea	No breathing	During diving in air breathers
Hyperpnea	Increased ventilation frequency or volume associated with increased metabolism	Exercise
Tachypnea	Increased ventilation frequency, usually with a decrease in ventilatory volume	Panting
Dyspnea	Difficult, labored, or uncomfortable breathing	Anxiety or panic attacks, excessive exercise, various diseases (e.g., emphysema)
Hyperventilation	Increased ventilation in excess of that required to meet metabolic needs	Anxiety or panic attacks, response to blood acid-base disturbance
Hypoventilation	Decreased ventilation	Asthma, various lung diseases

Perfusion of Respiratory Surface

- Gases enter the blood at the respiratory surface

  Gases have to come into contact with the fluid
- Movement of the medium at the respiratory surface and movement of blood through the respiratory surface (perfusion) affects the efficiency of gas exchange
- Compare P_{O2} in the medium and blood as they enter and leave the respiratory surface…

Important to think of ventilation and perfusion

Orientation of Medium and Blood Flow

No specific direction or path for this one
But a well mixed medium in the tidal one - good movement

Non-directional

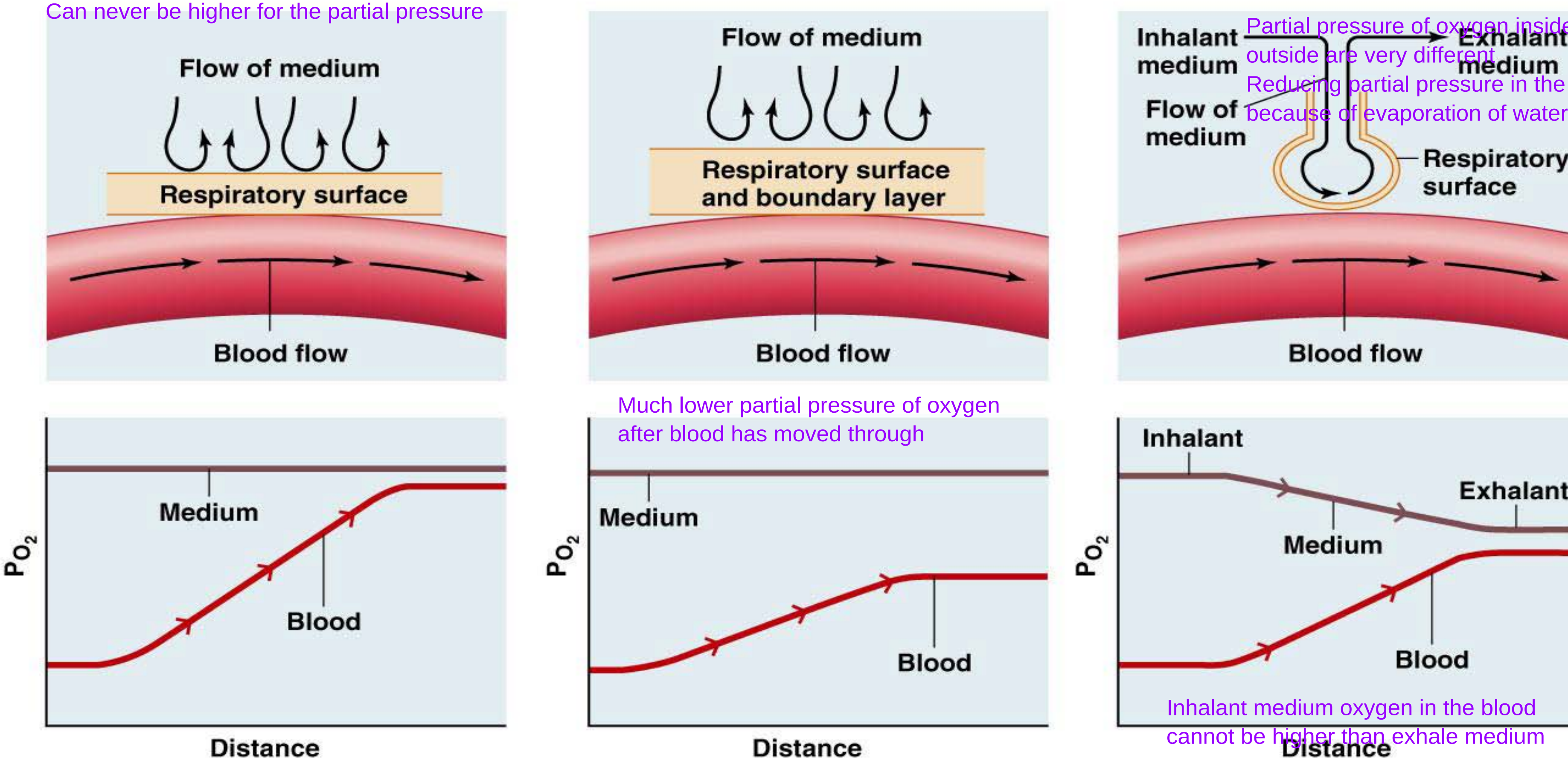
Tidal

Increase partial pressure in the blood
Can never be higher for the partial pressure

Partial pressure of oxygen inside and outside are very different
Reducing partial pressure in the lung because of evaporation of water

Much lower partial pressure of oxygen after blood has moved through

Inhalant medium oxygen in the blood cannot be higher than exhale medium



(a) Nondirectional ventilation (fully mixed medium and thin respiratory surface)

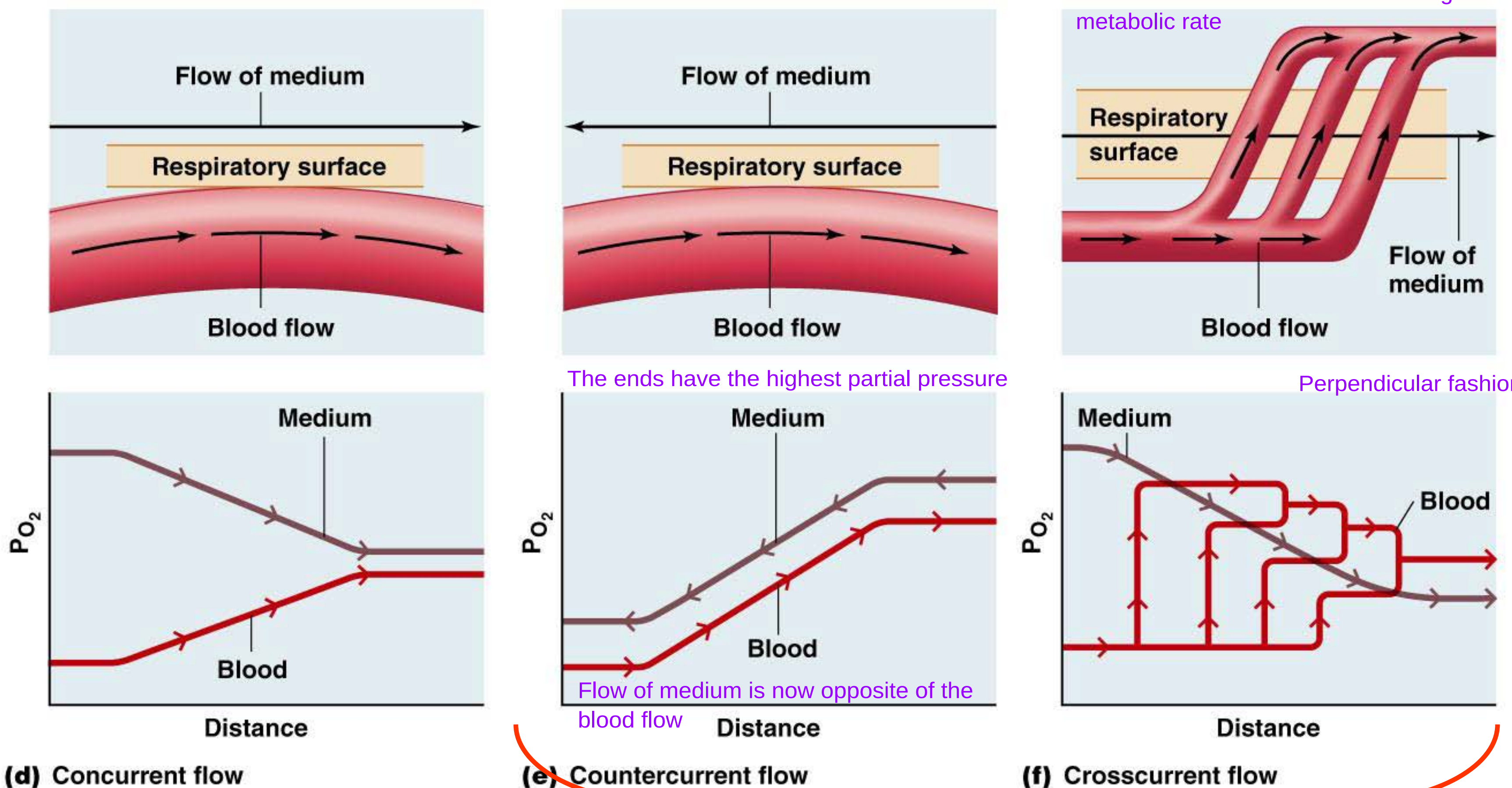
(b) Nondirectional ventilation (poorly mixed medium or thick respiratory surface)

(c) Tidal ventilation

Orientation of Medium and Blood Flow

- With unidirectional ventilation, the blood can flow in three ways relative to the flow of the medium

See in birds whom vertebrates of highest metabolic rate



The ends have the highest partial pressure

Perpendicular fashion

Flow of medium is now opposite of the blood flow

Important for water breathing

Pp of the blood can be higher than pp in the medium flow

Figure 9.6d–f

Velocity of flows is particularly important

All are important to maintain gradients

Ventilation of Water and Air

Because of the different physical properties of air and water, animals use different strategies depending on the medium in which they live

Differences

- $[O_{air}]$ is 30X greater than $[O_{water}]$
  - 30 times more water than air must be ventilated to get the same amount of oxygen
- Water is more dense and viscous than air
  - It is more difficult to ventilate water
    - High energy expenditure

Much more work to pump water in respiratory system than pumping air

Ventilatory strategies

- Unidirectional
  - Most water breathers
  - Allows for countercurrent exchange
- Tidal
  - Air-breathers
  - Air flows easily; it would require too much work for tidal ventilation of water
- Air-filled tubes
  - Insects
  - High diffusion rates of gases in air

Don't forget that gases still have to be dissolved and diffused in these systems

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Sponges and Cnidarians (1)

- Circulate external medium through an internal cavity
- Sponges
  - Flagella of choanocytes move water in through *ostia* and out through the *osculum*
- Cnidarians
  - Muscle contractions move water in and out through the mouth
- Gases diffuse directly in and out of cells

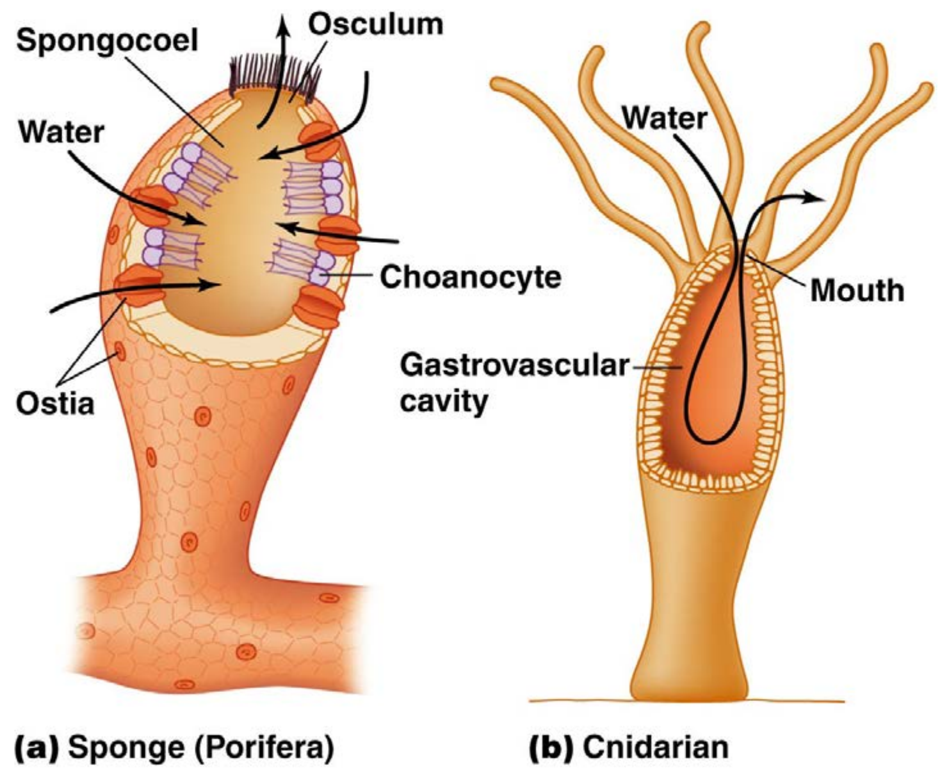
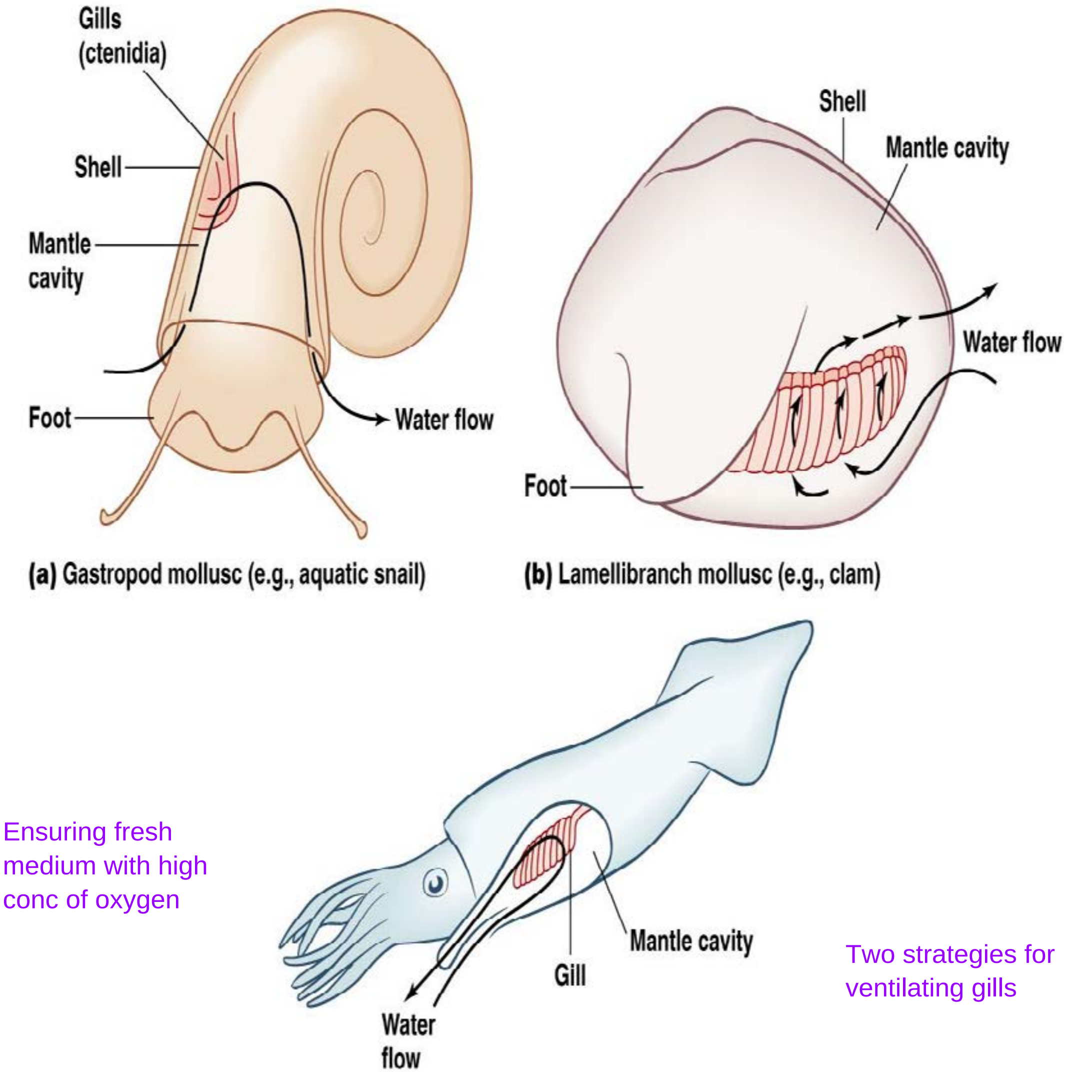


Figure 9.7

Molluscs

- Two strategies for ventilating gills (ctenidia)
  - Snails and clams
    - Cilia on gills move water across the gills unidirectionally
    - Flow is countercurrent
  - Cephalopods
    - Muscular contractions of mantle propel water unidirectionally past the gills in the mantle cavity
    - Flow is countercurrent

Push fluids out of the mantle



(a) Gastropod mollusc (e.g., aquatic snail)

(b) Lamellibranch mollusc (e.g., clam)

(c) Cephalopod mollusc (e.g., squid)

Ensuring fresh medium with high conc of oxygen

Two strategies for ventilating gills

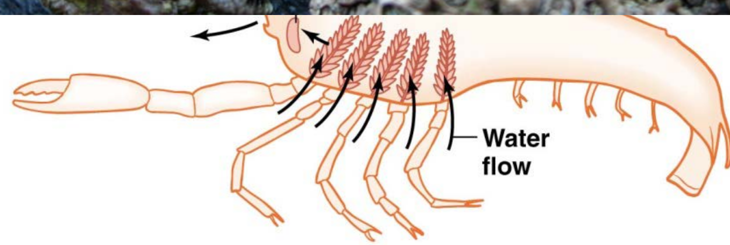
Crustaceans

The more inactive you are, the less oxygen you need so they don't need as much oxygen

- Filter feeding (barnacles) or small species (copepods) lack gills and rely on diffusion
- Shrimp, … erived from mo… nchial cavity
- Moveme… out of branchia… ucks water across g…

Shrimps, crabs, and lobsters have gills derived from modified appendages within a bronchial cavity

Movement of gill bailer properly water out of branchial chambers, negative pressures sucks water across gills

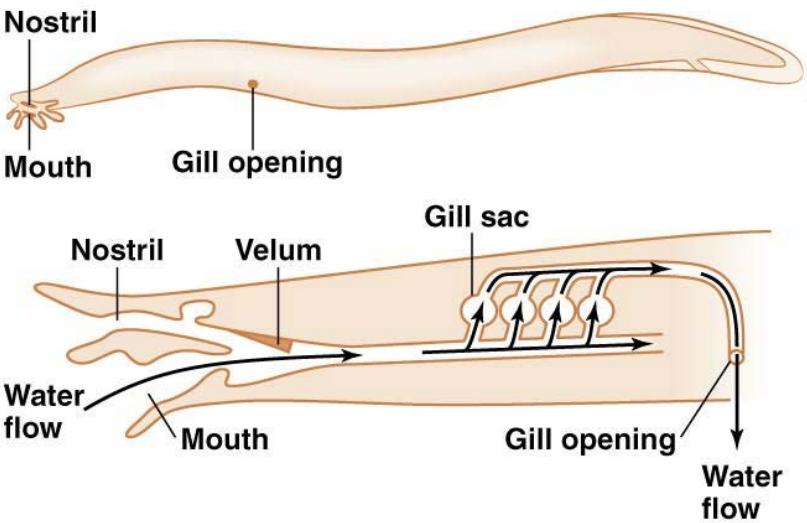


Decapod crustacean (crayfish)

Figure 9.9

Jawless Fishes

- Lamprey and hagfish have multiple pairs of gill sacs
  - Hagfish
    - Muscular pump (*velum*) propels water through respiratory cavity
    - Water enters the mouth and leaves through the gill opening
      - Flow is unidirectional
    - Blood flow is countercurrent



(a) Hagfish (side view and longitudinal section)

Figure 9.11a

Jawless Fishes – cont’d

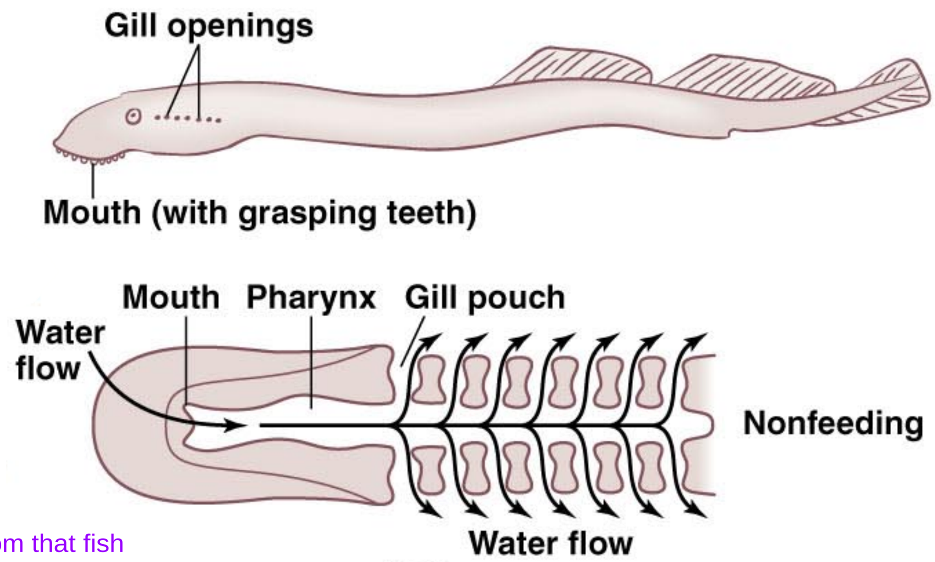
They are believed to breath when they are not feeding

- Lamprey
  - When not feeding, ventilation is similar to hagfish
  - When feeding, the mouth is attached to a prey

Extract blood from that fish

    - Ventilation is tidal through gill openings

Water can be pulled in and out though gills opening when lampreys are breathing



Retrieved from http://www.arkive.org/river-lamprey/lampetra-fluviatilis/image-A5122.html, 24/02/2014

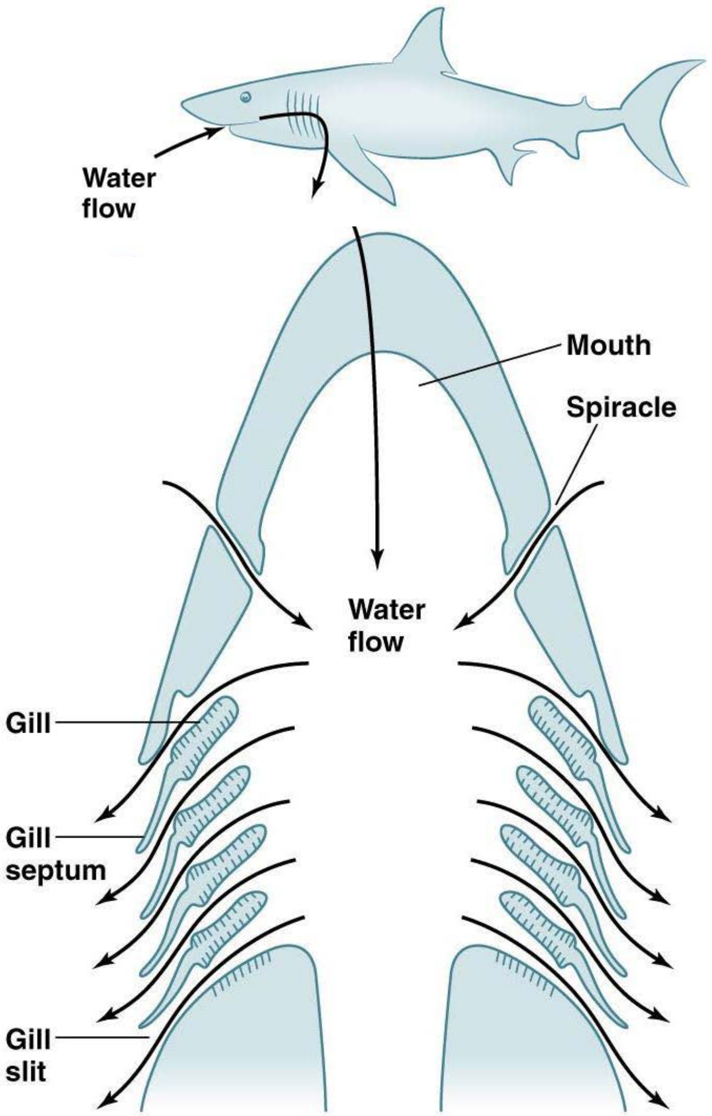
Figure 9.11b

Elasmobranchs

Use suction pumps - expand buccal cavity

- Steps in ventilation
  - Expand *buccal* cavity
    - <u>Suction pump</u>
  - Mouth and spiracles close
  - Muscles around the buccal cavity contract
    - <u>Pressure pump</u>
- Blood flow is countercurrent

Push on fluid although volume doesn't change, increasing pressure but the buccal cavity isn't entirely closed yet



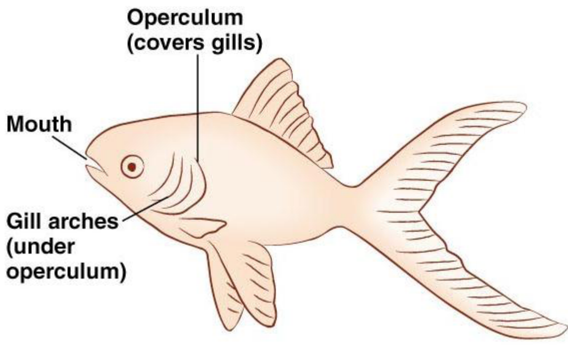
Shark's head (horizontal section)

Teleost Fishes

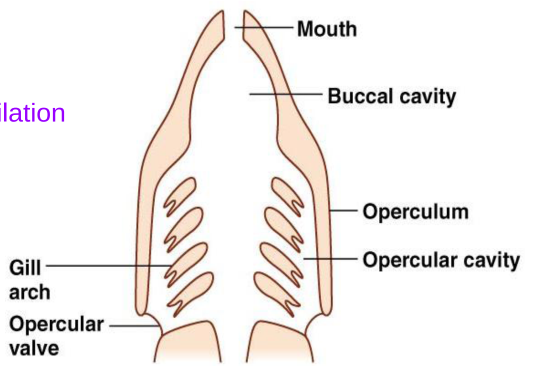
- Gills are located in the *opercular* cavity protected by the flaplike *operculum*
- Ventilatory keys
  - Buccal pressure pump and opercular suction pump
  - Generally
    - Opercular pump sucks while buccal pump fills
    - Buccal cavity pumps when opercular cavity empties

Just a little bit of back flow near the end
They don't want back flow, they want fresh ventilation

  - Unidirectional and nearly continuous
- Active fish can also use *ram ventilation*
  - Swimming with mouth and opercular valve open

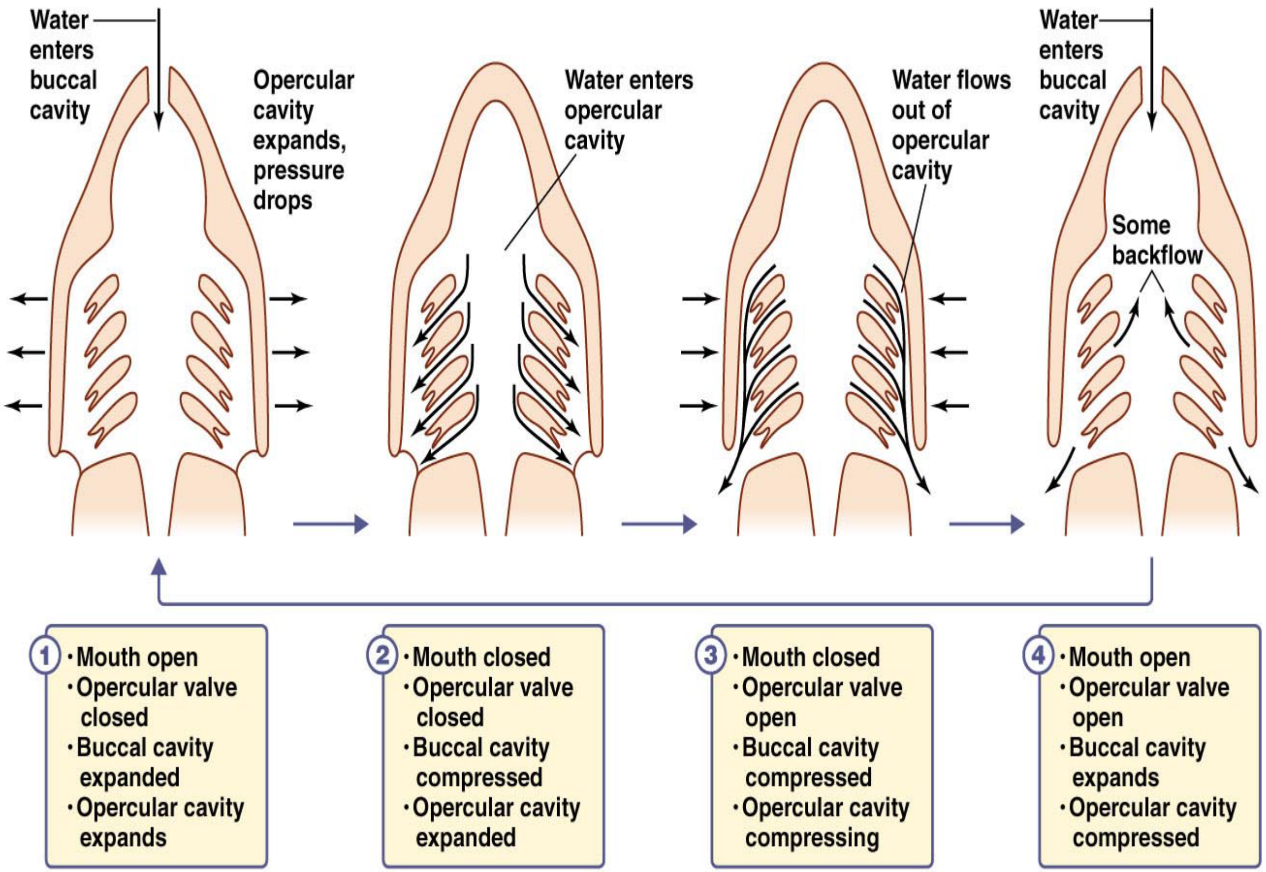


(a) Teleost fish (lateral view and horizontal section)

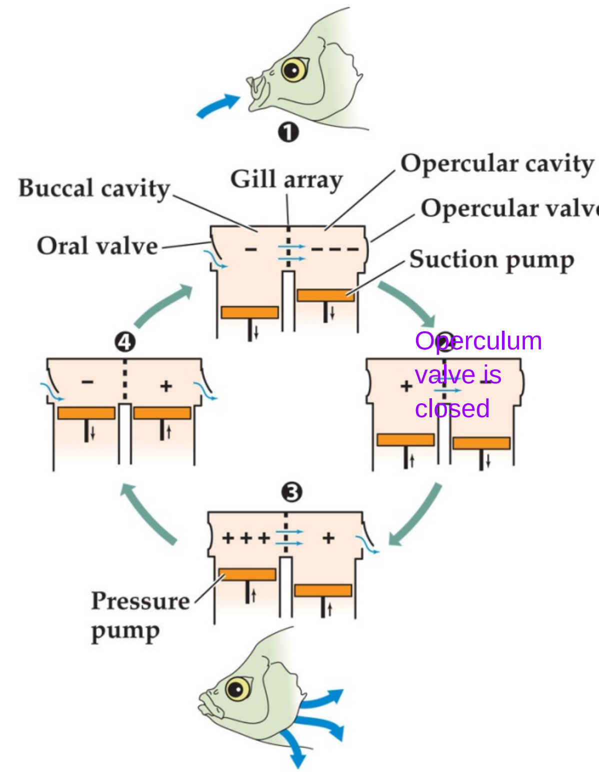


Teleost Fishes

Unidirectional - fluids continue to move in one direction - continuous



(b) Ventilatory cycle of teleosts



ANIMAL PHYSIOLOGY 3E, Figure 23.11
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Little bit of back flow before suction pump kicks in

Considered as very efficient even though there is a little of back flow

Think Boyle's Law

Hill, Wyse, and Anderson, Animal Physiology, 3rd edition, 2012.

Figure 9.13

Countercurrent Flow in Fish Gills

Gill filaments contain blood flow

- Fish gills are arranged for countercurrent flow
  - Complex with large SA
  - Very efficient when flow of medium and blood are matched

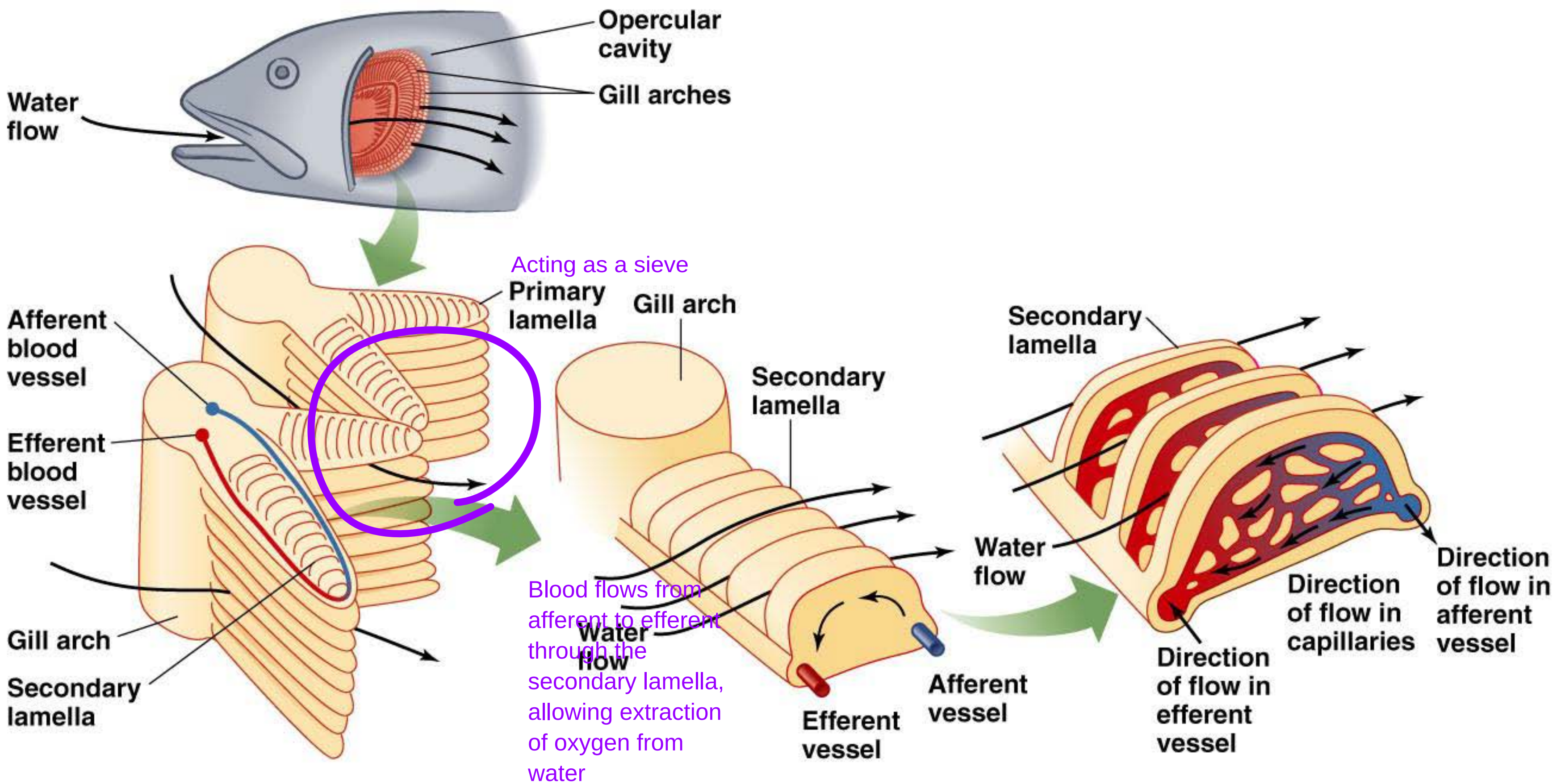


Figure 9.14

Ventilation and Gas Exchange in Air

- Two major animal lineages have colonized terrestrial habitats
  - Arthropods
    - Crustaceans
    - Chelicerates
    - Insects
  - Vertebrates
    - Fish
    - Amphibians
    - Reptiles
    - Birds
    - Mammals

Respiratory organs are typically very thin and must be kept moist

Insects

- Have an extensive *tracheal system*
  - Air-filled tubes called *tracheae*
  - Open to outside via spiracle
  - *Tracheae branch* to form *tracheoles*
  - Ends of tracheoles are filled with *hemolymph*
    - *Cells seldom < 100 μm from tracheole*
  - Gases diffuse in and out
    - rem: air has a high diffusion coefficient
    - Moist and high SA

Tracheoles interdidterate between the myofibrils

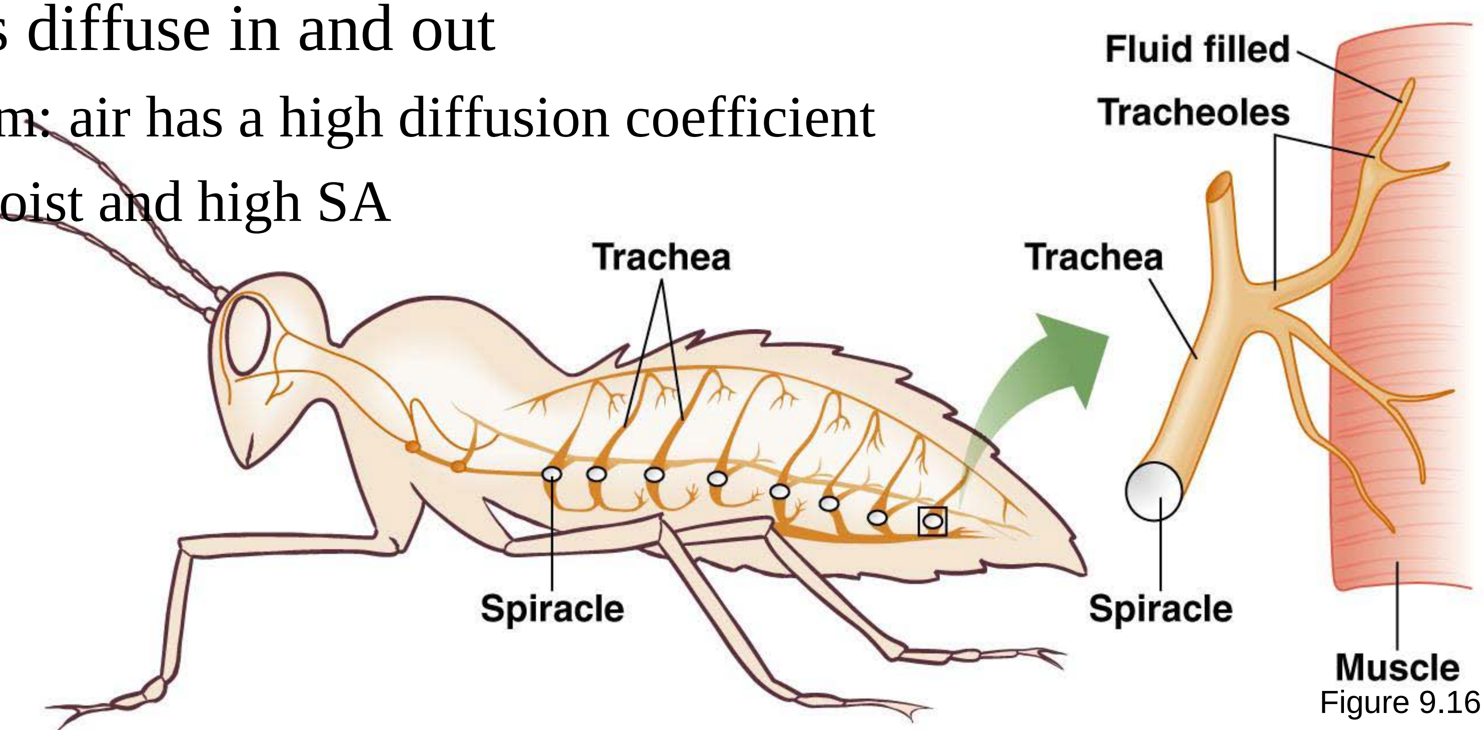
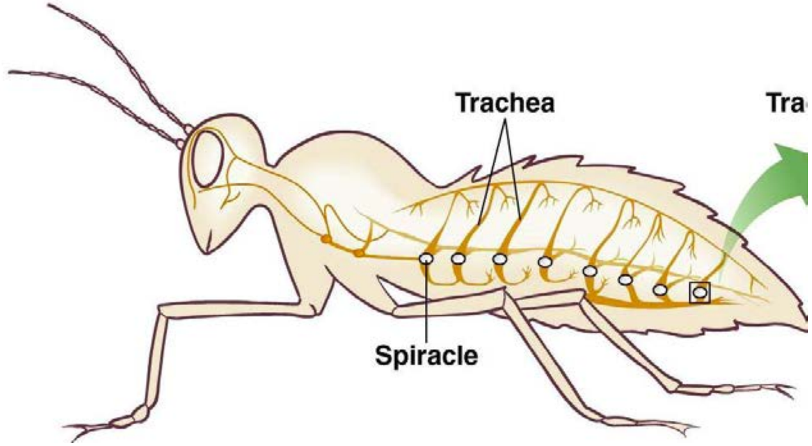


Figure 9.16

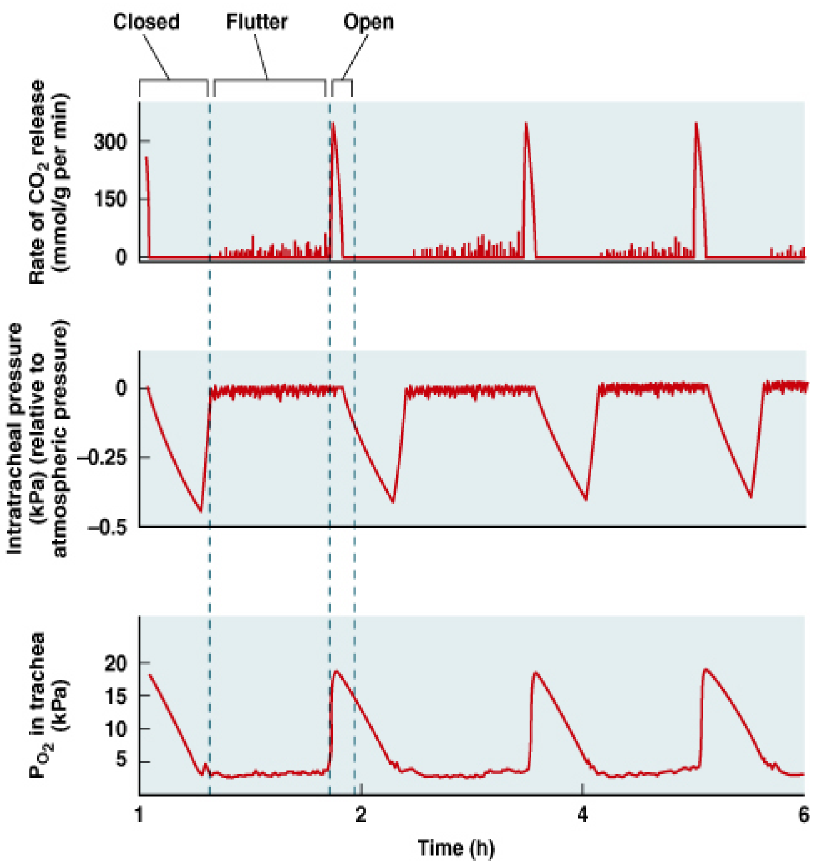
Insect Ventilation

- Mechanisms
  - Contraction of abdominal muscles or movements of the thorax
    - *Tidal*
      - Air flows in and out of same spiracles
    - *Unidirectional*
      - Exit at the posterior spiracles
      - enter anterior spiracles and exit abdominal spiracles
  - *Ram ventilation* (*draft ventilation*) in some flying insects



Discontinuous gas exchange

- Phase 1 (closed phase):
  - Spiracles closed; no gas exchange with environment;
    Close off from any gas coming in or out
  - O_2 used and CO_2 converted to HCO_3^-; ↓ in total P in trachea
    But oxygen is reducing
- Phase 2 (flutter phase)
  - Spiracles open and close in rapid succession
    Allows more oxygen to move in down pressure gradient to produce ATP, still storing co2 as bicarbonate
  - Air enters trachea
    Co2 can no longer be stored, bicarbonate can no longer be stored as well
- Phase 3:
  - Excess CO_2 can no longer be stored as HCO_3^-
  - Total pressure in trachea ↑
  - spiracles open and CO_2 is released
- Adaptive value unknown

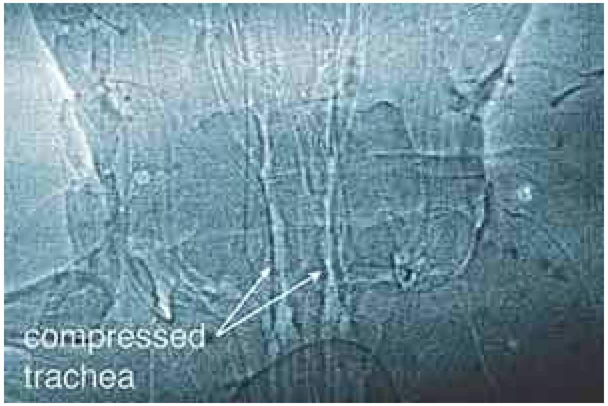


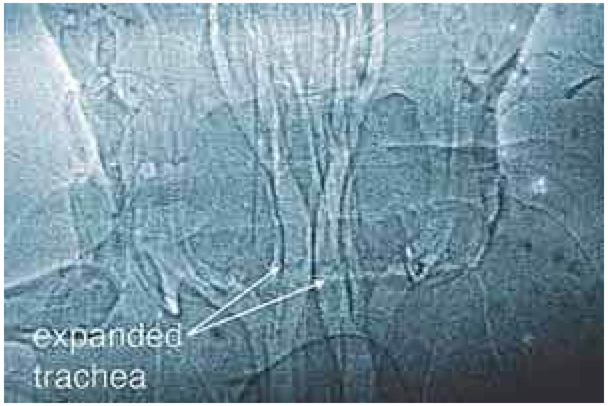
$CO_2 + H_2O \leftrightarrow H_2SO_3 \leftrightarrow HCO_3^- + H^+$

Insects – cont'd

Do Insects breathe by lung ventilation like humans?

X-ray synchrotron at Argonne





Look at trachea through cuticles in animals

Trachea seems to be compressing and expanding when they are moving around

This was not happening when they took the pics

Looks like ventilation in human

(.avi)

Retrieved from http://www.aps.anl.gov/News/APS_News/2003/20030127a.htm, 06/03/06

Air breathing in fish

- Air breathing has evolved multiple times in fishes

Important for fish that live in ponds

- Types of respiratory structures – most highly vascularized
  - Reinforced gills that do not collapse in air

Supported by dense water

  - Vascularized mouth and pharyngeal cavity
  - Vascularized stomach

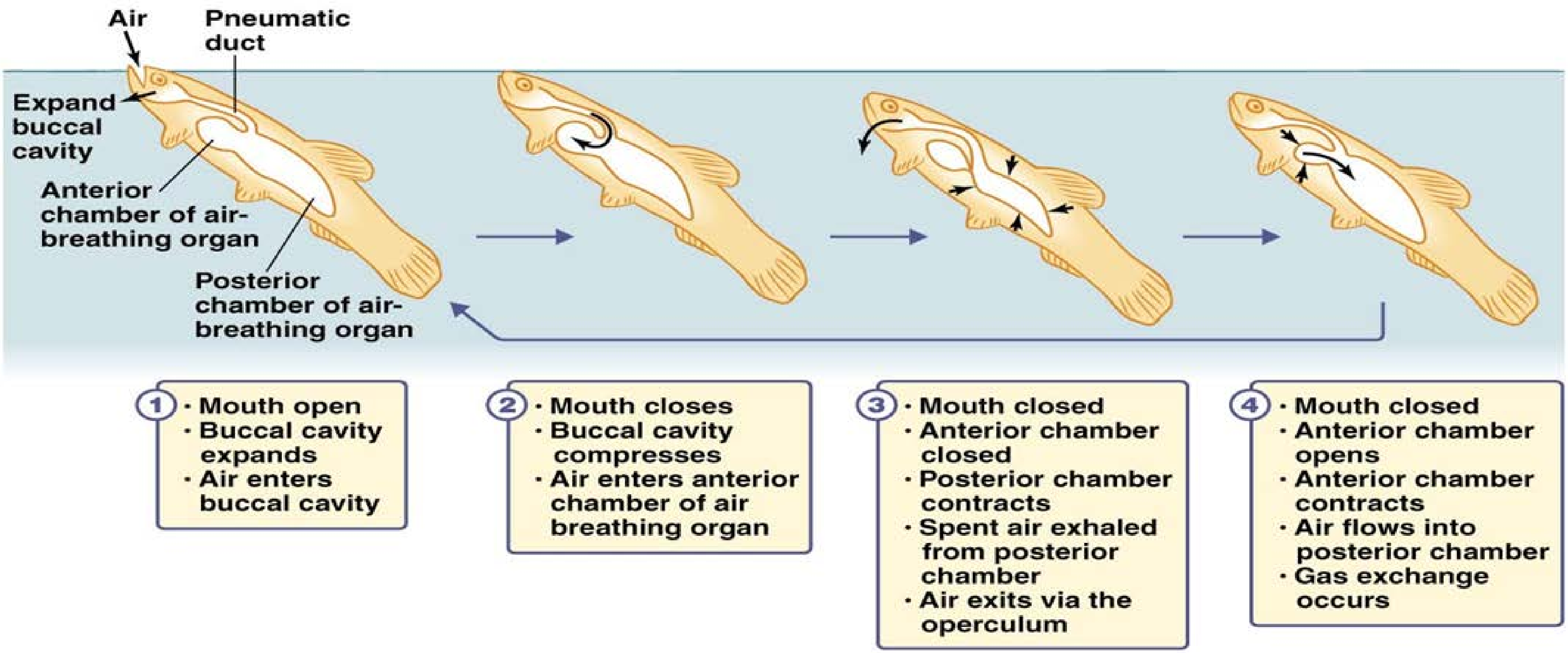
Able to open and close off different chambers, so fresh air and get in and old air can get out

They use buccal pressure pump to swollen air

  - Specialized pockets of the gut

Air breathing in fish

- Ventilation is tidal (unidirectional in water breathing fish) using buccal pressure pump similar to other fish
  - Essentially swallow air!



Amphibians

- Types of respiratory structures
  - Cutaneous respiration
  - External gills
  - Simple bilobed lungs
    - More complex lungs in terrestrial frogs and toads
- Ventilation is tidal using a buccal pressure pump

Amphibians

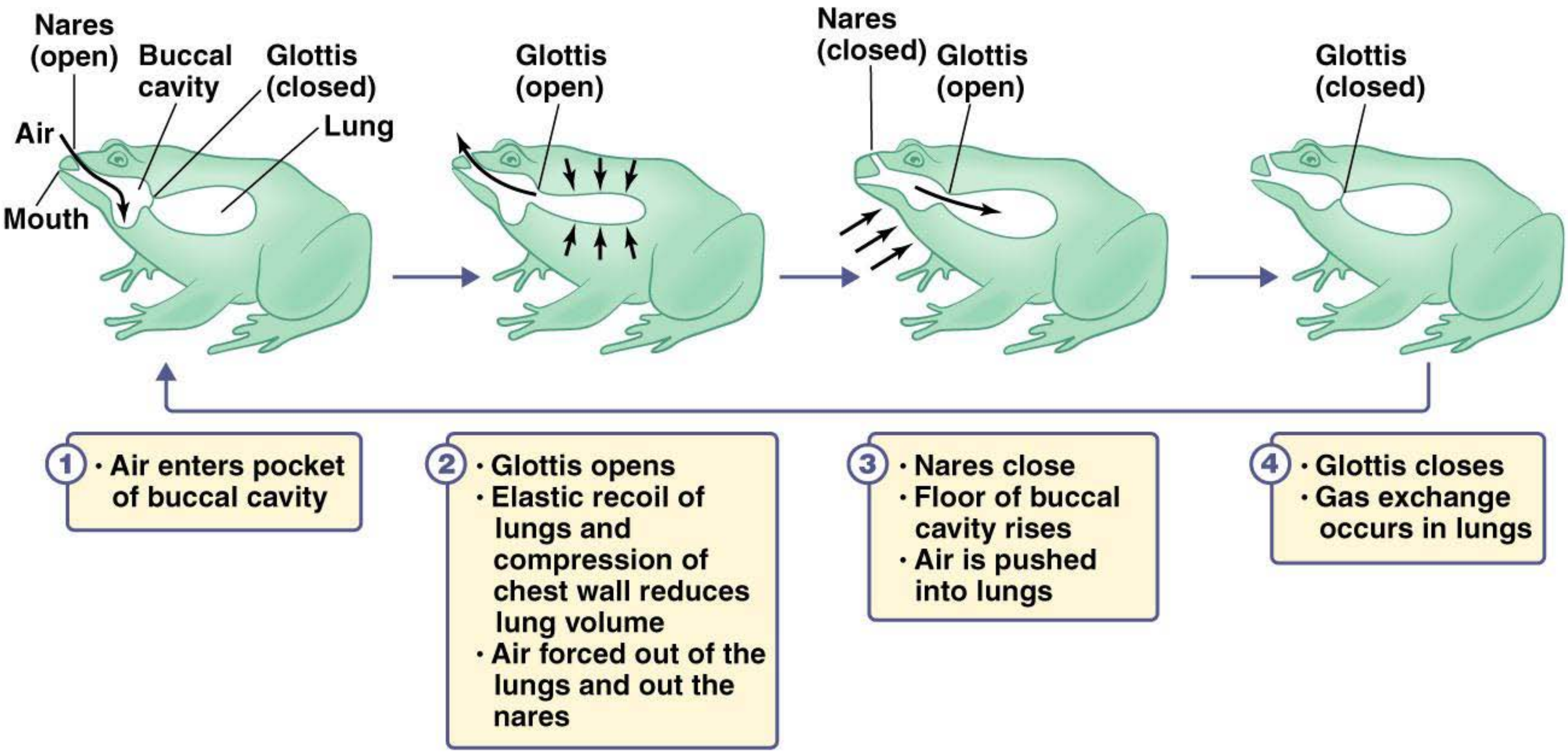


Figure 9.20