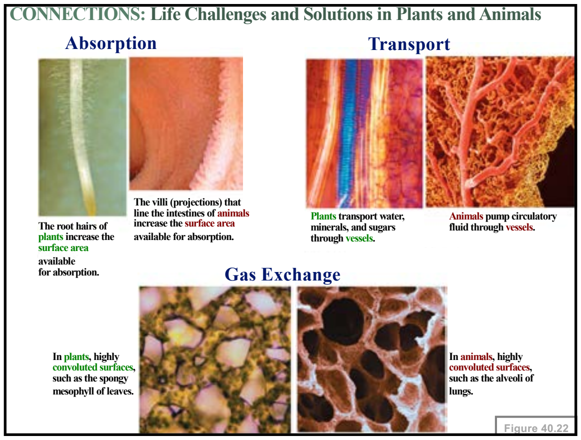
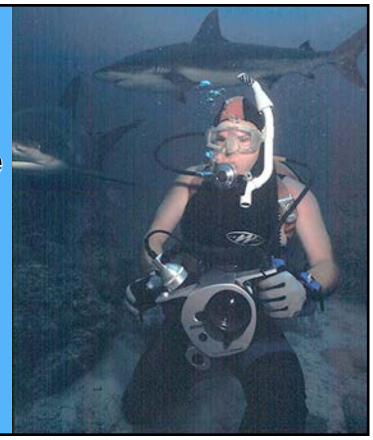


Gas Exchange in Animals



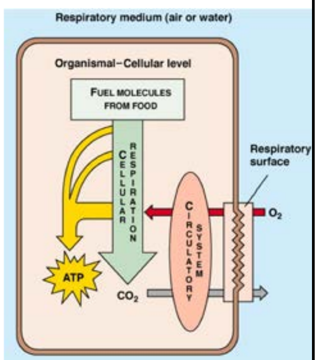
WHY RESPIRE?

- Mitochondria need O_2 to make ATP.

$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O$ + Energy

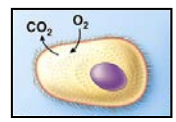
ATP ↲

- CO_2 by-product must be removed



"Organismal Respiration" vs. "Cellular Respiration"

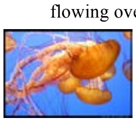
- External gas exchange:
  - environmental gases / tissues
- Internal gas exchange
  - tissues / tissues
  - Cell membranes are permeable to **simple diffusion** of **dissolved** O_2 and CO_2

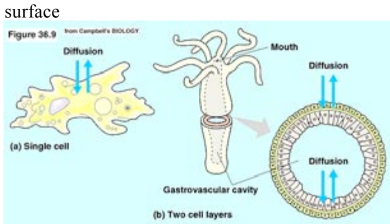


- Cellular Respiration: using the oxygen to drive ATP production
  - The more cells (more body mass), the more O_2 needed (**oxygen demand**)

SIZE MATTERS

- Small organisms have high s/v ratios & use cutaneous exchange (protozoans, sponges, cnidarians, flatworms)
- Ciliated epidermal & gastrodermal tissues keep fresh water flowing over surface





- Surfaces must be moist for exchange to occur!

How do animals get enough O_2?

- Size matters!
- So does activity level.
- **Larger, faster animals need tricks to speed up exchange of gases between environment & tissues.**

Thunnus thunnus

Diffusion of Dissolved Gases

- ***FICK'S LAW***
- GILLS vs. LUNGS
- AQUATIC RESPIRATION
- TERRESTRIAL RESPIRATION
- RESPIRATORY PIGMENTS

FICK'S LAW

Adolf Fick, 1858

Fick's law of diffusion of a gas across a fluid membrane:

Rate of diffusion = $KA(P_2–P_1)/D$

Wherein:

- K = a *temperature-dependent* diffusion constant.
- A = the surface area available for diffusion.
- $(P_2–P_1)$ = The difference in concentration (partial pressure) of the gas across the membrane.
- D = the distance over which diffusion must take place.

FICK'S LAW

Fick's law of diffusion of a gas across a fluid membrane:

Rate of diffusion = $KA(P_2–P_1)/D$

Therefore, since:

- The diffusion is of **dissolved** gases across a **fluid** membrane
  - ➢The respiratory surface must stay wet!

FICK'S LAW

Fick's law of diffusion of a gas across a fluid membrane:

Rate of diffusion = $KA(P_2–P_1)/D$

Therefore, since:

- K = a *temperature-dependent* diffusion constant.
  - ➢Temperature is important!

FICK'S LAW

Fick's law of diffusion of a gas across a fluid membrane:

Rate of diffusion = $KA(P_2–P_1)/D$

Therefore, since:

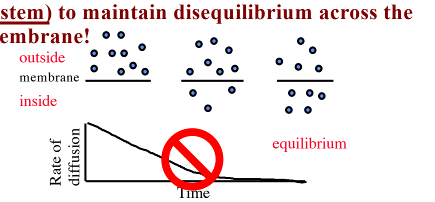
- A = the surface area available for diffusion.
- D = the distance over which diffusion must take place.
  - ➢How can gas exchange rate be increased?
  - ➢Increase surface area and decrease thickness of respiratory surfaces as much as possible!

FICK'S LAW

Rate of diffusion = $KA(P_2–P_1)/D$

Therefore, since:

- (P_2-P_1) = The difference in concentration (partial pressure) of the gas across the membrane.
  - ➢ **Continually replenish the respiratory fluid (ventilation system) and body fluid (circulatory system) to maintain disequilibrium across the membrane!**



Gas Concentrations

Concentration of a gas in a mixture measured as partial pressure
= % of total gas x total gas pressure

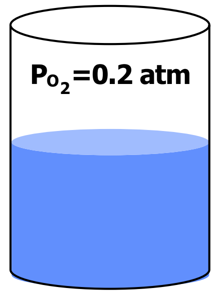
Air: composition & partial pressures

Dry air at 1 atm total pressure (sea level)

- **N_2: 78%; P_{N_2}= 0.78 atm**
- **O_2: 21%; P_{O_2}= 0.21 atm**
- **CO_2: 0.03%; P_{CO_2}= 0.0003 atm**
- **Other gases bring total up to 1 atmosphere**

Dissolved Gas Concentrations

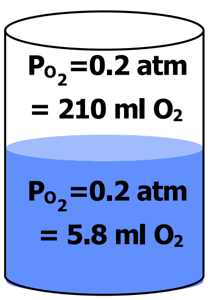
Still measured as partial pressure
= amount of that gas dissolved in water at equilibrium with a gas having that partial pressure (at STP)



- **cylinder contains 1 liter water and 1 liter air**
  (total 1 atm at 25° C)
- **Oxygen diffuses between air & water.**

Dissolved Gas Concentrations

Still measured as partial pressure
= amount of that gas dissolved in water at equilibrium with a gas having that partial pressure (at STP)

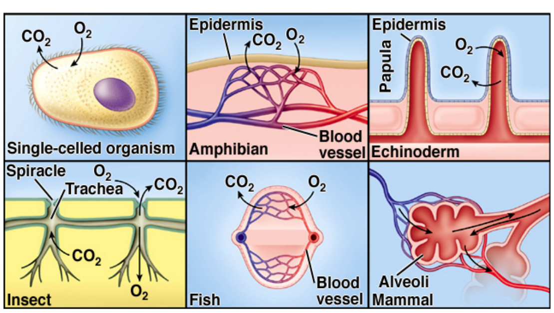


- **The air & water are at equilibrium ∴ they have the same P_{O_2}**
- **The amount of a gas dissolved in water depends on its solubility.**
  - **↑ temp → ↓ gas solubility**

RESPIRATION

- FICK'S LAW
- *GILLS vs. LUNGS*
- AQUATIC RESPIRATION
- TERRESTRIAL RESPIRATION
- RESPIRATORY PIGMENTS

Respiratory Surfaces



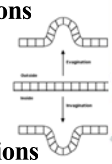
↑surface area / ↓distance between environment and tissues

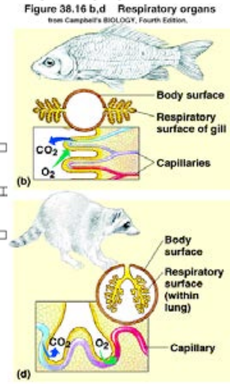
GILLS vs. LUNGS

Figure 38.16 b,d Respiratory organs from Campbell's BIOLOGY, Fourth Edition.

Maximizing the respiratory surfaces:

- **Evaginations** (gills)
- **Invaginations** (lungs)





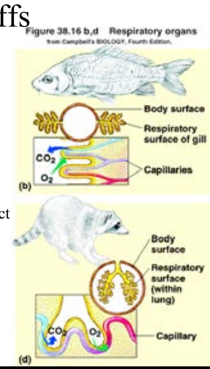
Terrestrial vs. Aquatic Respiration

	5° C	35° C	% metabolism for ventilation
% O_2 in air	21%	21%	1%
% O_2 in water	0.9%	0.5%	20% *
O_2 in air/water	25x	40x	

* Water is ~800x more dense & 50x more viscous than air!

Terrestrial vs. Aquatic Respiration — the Trade-offs

- Hence, in low-oxygen environments (i.e., in water), need large, wet respiratory surface exposed to the respiratory medium.
  - Gills!
- But, in dry environments (i.e., in air), large, wet respiratory surface would dry out and result in excessive water loss.
  - No gills!
- In dry, high-oxygen environments (i.e., in air), contact of the wet respiratory surface with the respiratory medium can be restricted to protect from drying out.
  - Lungs!
- But, in viscous, low-oxygen environments (i.e., in water), restricted contact provides inadequate gas exchange.
  - No lungs!



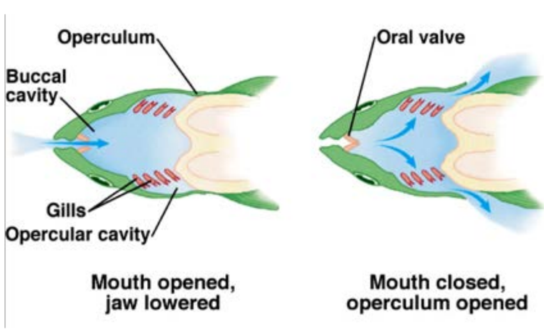
Aquatic Respiration Structures

Animal	Gill type	Ventillation
Fish	Pharyngeal gills	Buccal pumping
Polychaete worm	Parapodia	Gill movement
Aquatic mollusk	Ctenidia	Cilia
Echinoderm	Dermal branchia	Cilia
Crustacean	Gills	Gill bailer
Horseshoe crab	Book gills	Gill movement

Fish usually need more oxygen than invertebrates; they have more gill area than most invertebrates.

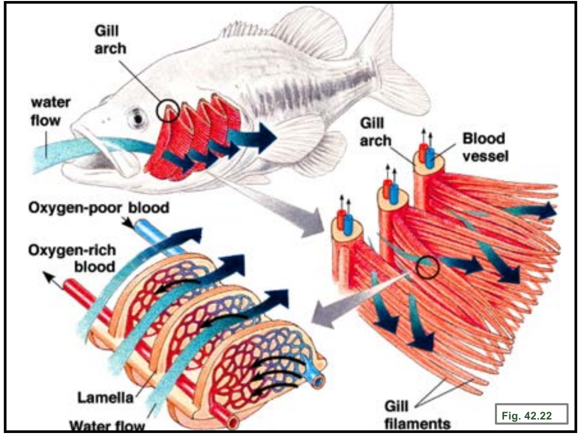
Buccal pumping

1-way flow of water across gills

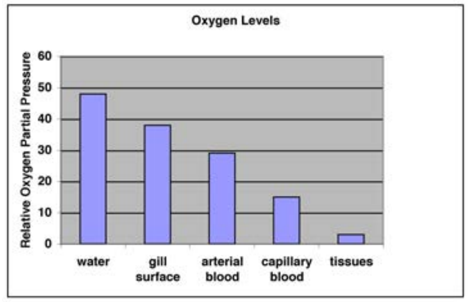


Fish ventilation

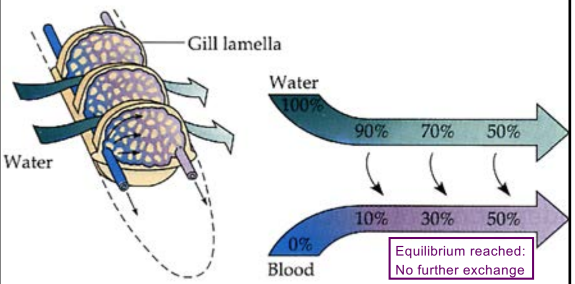
- **Fish use energy to pump water across gills (ventilation).**
- **At low speed, buccal pumping is used.**
- **At higher speed, ram ventilation (swimming with mouth & operculum open) is more efficient (but still costs energy).**



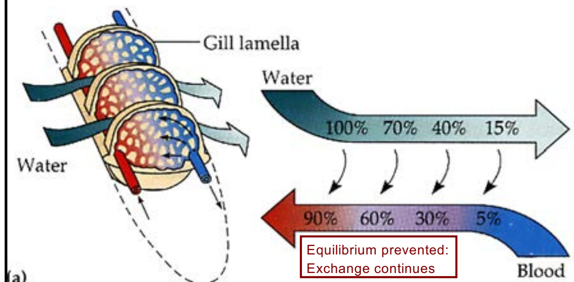
O_2 diffuses from high concentration to low concentration.



If fish used **Concurrent Exchange**:



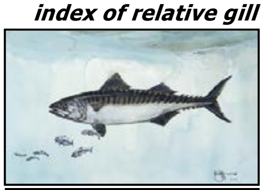
So fish use **Countercurrent Exchange**.



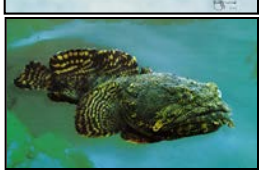
c.f., Campbell **Fig. 42.22**

More active fish have bigger gills.

index of relative gill surface area/body mass



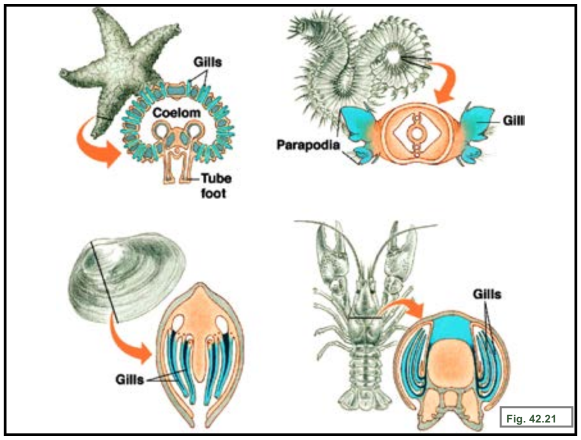
Mackerel: 2551



Toadfish: 137

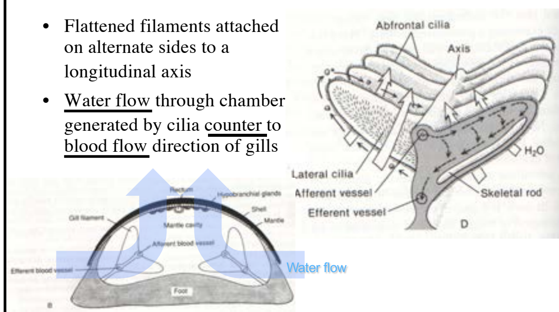
Aquatic Respiration Structures

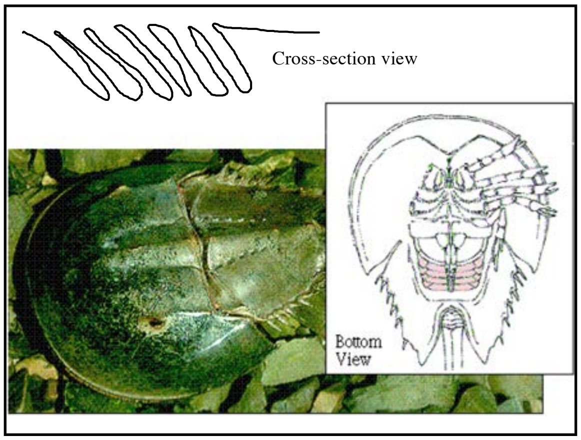
Animal	Gill type	Ventillation
Fish	Pharyngeal gills	Buccal pumping
Polychaete worm	Parapodia	Gill movement
Aquatic mollusk	Ctenidia	Cilia
Echinoderm	Dermal branchia	Cilia
Crustacean	Gills	Gill bailer
Horseshoe crab	Book gills	Gill movement



Counter-current exchange in mollusc ctenidia

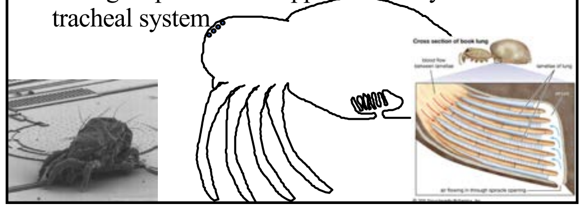
- Flattened filaments attached on alternate sides to a longitudinal axis
- Water flow through chamber generated by cilia counter to blood flow direction of gills



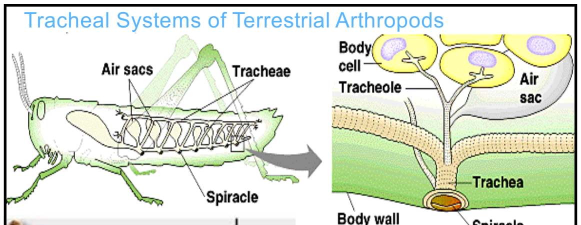


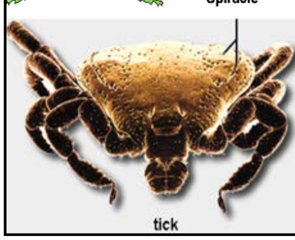
ARACHNIDS & BOOK LUNGS

- Page-like structure
- In larger species it's supplemented by a tracheal system



Tracheal Systems of Terrestrial Arthropods



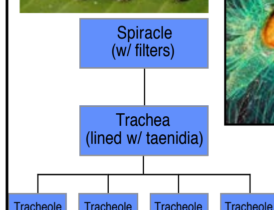


- Ventilated by air sacs in larger or more active species.

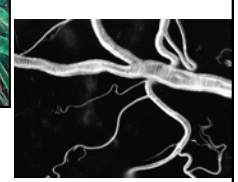
Fig. 42.23

Terrestrial Arthropod Tracheal System

– Insects, millipedes, onycophorans, and big arachnids.



silkworm spiracle & tracheae



cockroach trachea

Flight muscles have very high aerobic demand —Tracheoles end near mitochondria in each cell.

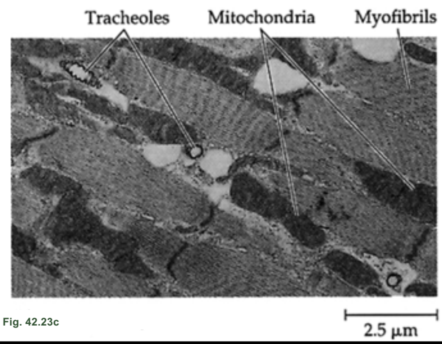
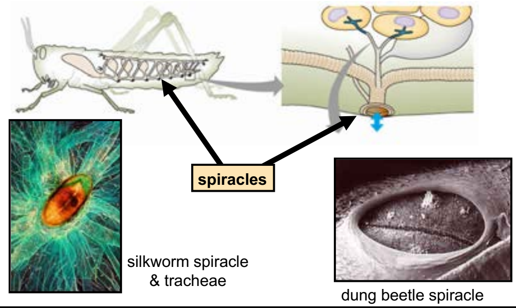


Fig. 42.23c

Insect gas exchange:

- Spiracles can close to limit water loss.

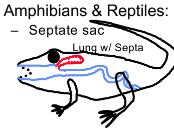


Terrestrial snails & slugs have:

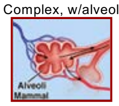
- lost their ctenidia from mantle cavity
- vascularized mantle cavity acting as lung

Vertebrate Lungs

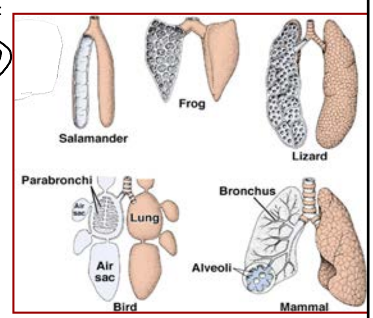
- Amphibians & Reptiles:
  - Septate sac



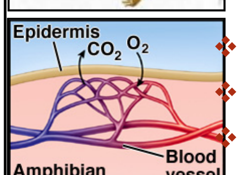
- Mammals:
  - Complex, w/alveoli



- Birds:
  - Elaborate flow-through system w/ parabronchi



Lungless salamanders

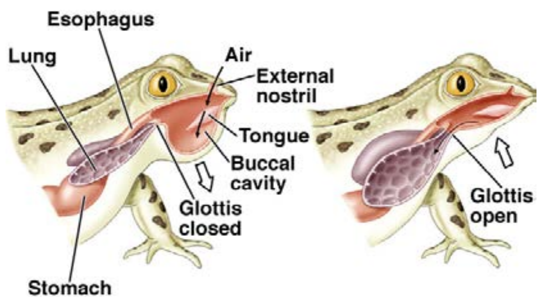


- Gas exchange through skin; blood gets oxygenated when if flows near skin.
- Small, slender bodies.
- They dry out easily.
- Cold bodies; don't use much O_2.

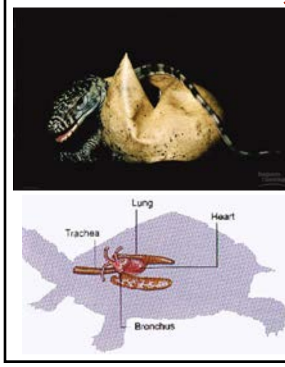
Amphibians with lungs

- Frogs and larger salamanders do gas exchange through skin and lungs.
- Usually most O_2 is absorbed in the lungs, but most CO_2 is eliminated through the skin.

Frogs: positive-pressure breathing forces air into lungs



Reptiles

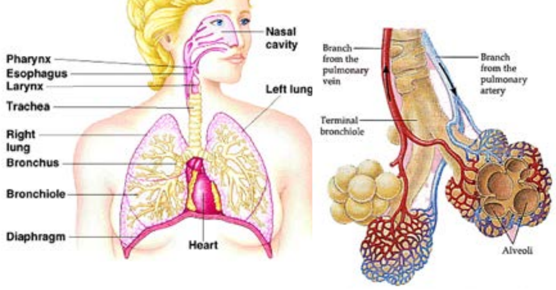


- Reptiles have impermeable skin; gas exchange happens in lungs.
- Most have fairly low oxygen requirements. Breathing is not continuous.
- Body temperature is usually near ambient; this keeps water loss low compared to warm-bodied animals.

Mammalian Lung — 300 Million Alveoli

Fig. 42.24

Human lung:
- Surface area = 100 m^2
- Only 0.2 μm between air/blood



Negative pressure breathing

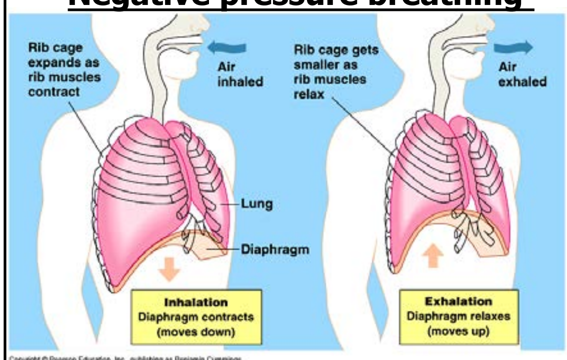
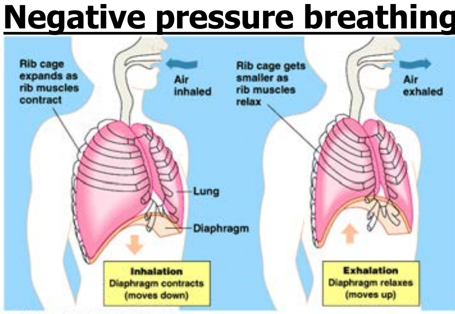


Fig. 42.27

Negative pressure breathing



- Dead space: 150 ml
- Tidal volume (resting): 500 ml
- Tidal volume (exercise): 3000 ml

O_2 & CO_2 diffuse from high concentration to low concentration.

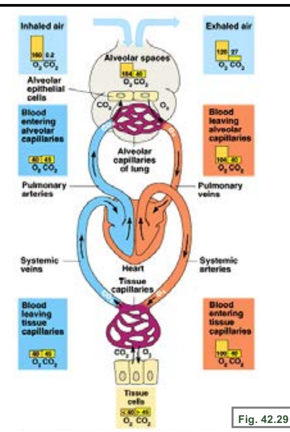
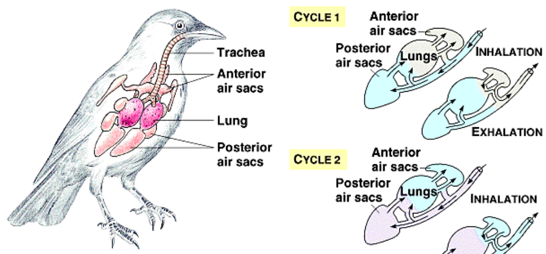


Fig. 42.29

The avian respiratory system

Air Capillary Lung of Birds



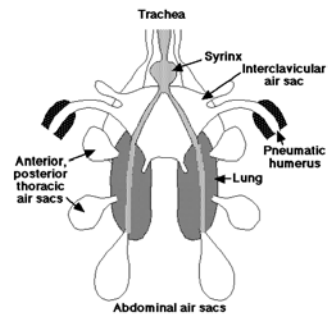
(a)

Constant air flow through rigid lungs
- Negative pressure ventilation during inhalation
- Positive pressure ventilation during exhalation
- Two ventilation cycles needed for inhaled air to be exhaled

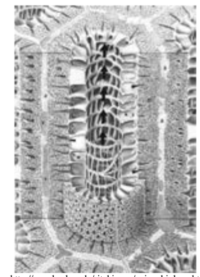
Fig. 42.26

Both Positive- & Negative-Pressure Breathing

expand & contract rib cage (no diaphragm)



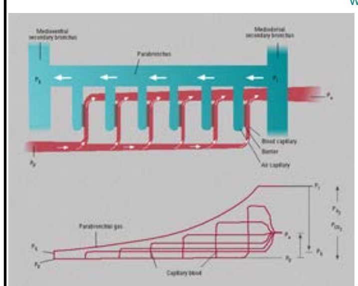
Parabronchi: continuous, one-way, flow-through exchange

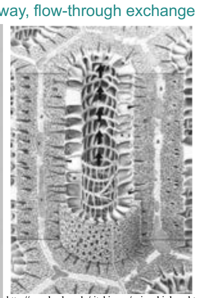


http://people.eku.edu/ritchisong/avian_biology.htm

Counter-current exchange between air capillaries and blood capillaries

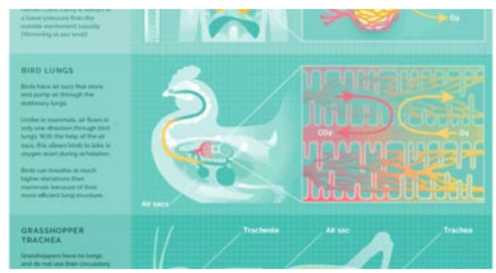
- **Parabronchi**: continuous, one-way, flow-through exchange



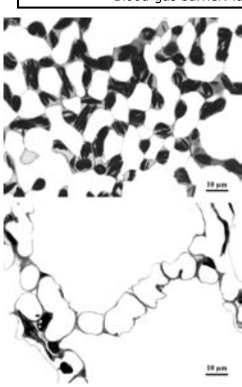


http://people.eku.edu/ritchisong/avian_biology.htm

http://tabletopwhale.com/2014/10/24/3-different-ways-to-breathe.html



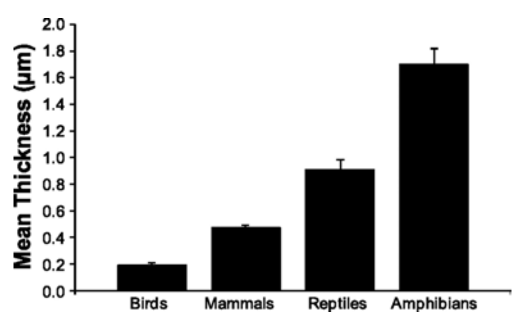
Blood-gas barrier: lung cross-sections



Bird parabronchi

Mammal alveoli

Blood-gas barrier thickness



Diffusion & exchange is of ***dissolved*** *O_2 only!*

How much O_2 can be carried dissolved in blood fluids alone?

Terrestrial vs. Aquatic Respiration

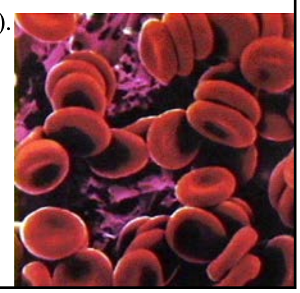
O_2 Level	5°C	35°C	% Metab. for Resp.
Air	21%	21%	1%
Water	0.9%	0.5%	20%
O_2 in air vs. water	25X	40X	

RESPIRATION

- FICK'S LAW
- GILLS vs. LUNGS
- AQUATIC RESPIRATION
- TERRESTRIAL RESPIRATION
- RESPIRATORY PIGMENTS

Respiratory Pigments Carry O_2

- Proteins with a metal core, giving it color.
- E.g., Hemoglobin (Hb).



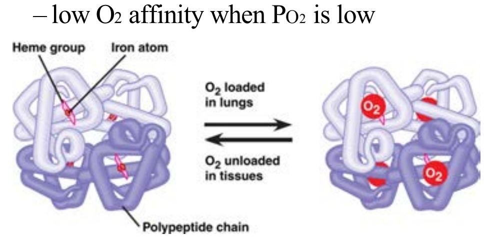
- Pigment protein packed in blood cells (RBCs) reduce viscosity of high-protein solution.

Other Respiratory Pigments

Name	Metal	Color	Animal
Chlorocruorin	Iron	Green	Sedentary Polychaetes
Hemocyanin	Copper	Blue	Arthropods and Molluscs
Myoglobin	Iron	Red	Marine Mammals, Waterfowl

Hb affinity for O_2 shifts w/ blood oxygen content

- Hemoglobin has
  - high O_2 affinity when P_{O_2} is high
  - low O_2 affinity when P_{O_2} is low



O_2 -Dissociation Curve for Hb

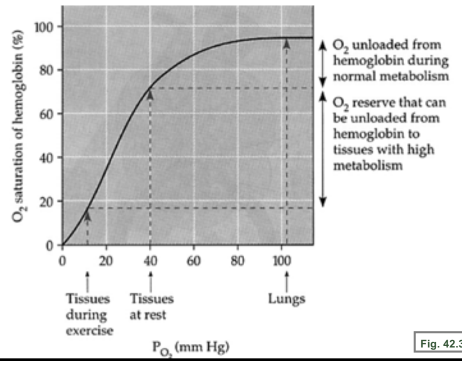
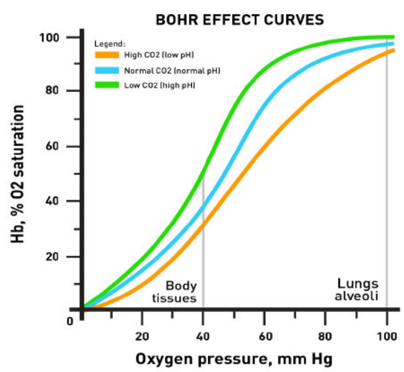


Fig. 42.30a

Blood temperature & pH also influence hemoglobin's affinity for O_2.

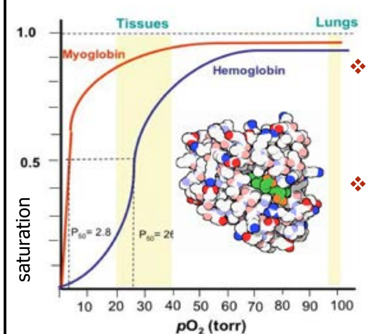
The **Bohr Shift**

- CO_2 dissolved into blood forms carbonic acid, lowering pH.
- Gives O_2 up easier when pH is lower at cells (more carbonic and lactic acid present)
- Grabs O_2 at alveoli where CO_2 levels are lowest due to exhalation



c.f., Fig. 42.30b

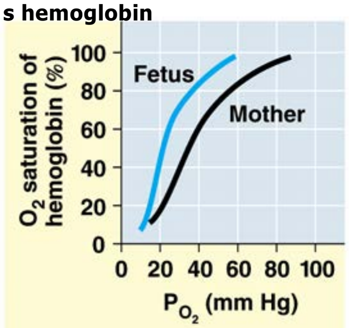
Myoglobin



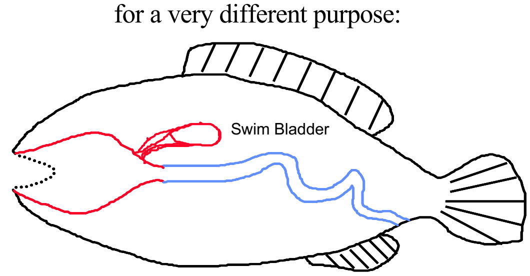
- Myoglobin: another O_2 carrier, found in muscle.
- Single subunit; no cooperativity

Fetal hemoglobin

O_2 binding affinity of fetal hemoglobin vs. mother's hemoglobin



The Bohr shift is used elsewhere …
for a very different purpose:



Oxygen [swim] bladder as a buoyancy control organ

- ↑pH → bind O_2 to Hb → deflate → sink
- ↓pH → offload O_2 from Hb → inflate → rise