

# Gas Exchange



## WHY RESPIRE?

- Mitochondria need O<sub>2</sub> to make ATP.
   

$$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O + \text{Energy}$$
  
 ATP
- CO<sub>2</sub> 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<sub>2</sub> and CO<sub>2</sub>
- Cellular Respiration: using the oxygen to drive ATP production
  - The more cells (more body mass), the more O<sub>2</sub> 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!

## SIZE MATTERS

- Amphibians use skin & oral cavity/lungs.

Newborn Julia Creek Dunnart get 90% of O<sub>2</sub> from skin.

Size of rice grain

## How do animals get enough O<sub>2</sub>?

- ❖ **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:

$$\text{Rate of diffusion} = KA(P_2 - P_1) / D$$

Wherein:

- K = a *temperature-dependent* diffusion constant.
- A = the surface area available for diffusion.
- (P<sub>2</sub>-P<sub>1</sub>) = 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:

$$\text{Rate of diffusion} = KA(P_2 - P_1) / D$$

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:

$$\text{Rate of diffusion} = KA(P_2 - P_1) / D$$

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:

$$\text{Rate of diffusion} = KA(P_2 - P_1) / D$$

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!

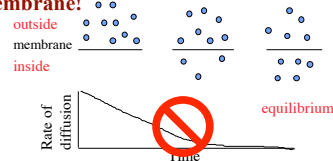
### FICK'S LAW

$$\text{Rate of diffusion} = KA(P_2 - P_1) / D$$

Therefore, since:

- (P<sub>2</sub>-P<sub>1</sub>) = 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 Exchange

## Gas Concentrations

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

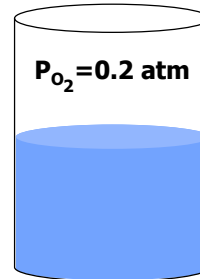
### Air: composition & partial pressures

**Dry air at 1 atm total pressure (sea level)**

- ❖ **N<sub>2</sub>: 78%; P<sub>N<sub>2</sub></sub> = 0.78 atm**
- ❖ **O<sub>2</sub>: 21%; P<sub>O<sub>2</sub></sub> = 0.21 atm**
- ❖ **CO<sub>2</sub>: 0.03%; P<sub>CO<sub>2</sub></sub> = 0.0003 atm**
- ❖ **Other gases bring total up to 1 atmosphere**

## Dissolved Gas Concentrations

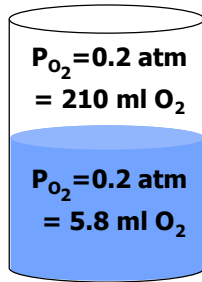
Still measured as **partial pressure**  
 = amount of that gas dissolved in water at equilibrium with a gas having that partial pressure (at STP)



- ❖ **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)



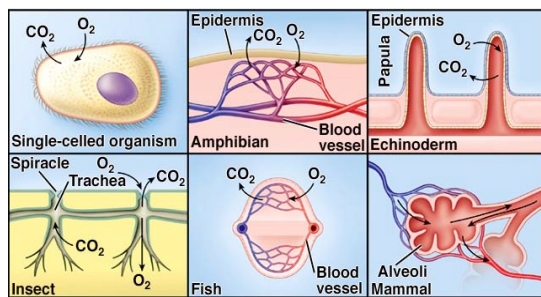
- ❖ **The air & water are at equilibrium**  
 □ they have the same P<sub>O<sub>2</sub></sub>
- ❖ **The amount of a gas dissolved in water depends on its solubility.**

□ ↑ temp □ □ gas solubility

## RESPIRATION

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

## Respiratory Surfaces



## GILLS vs. LUNGS

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

Maximizing the respiratory surfaces:

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



# Gas Exchange

## Terrestrial vs. Aquatic Respiration

	5°C	35°C	% metabolism for ventilation
% O <sub>2</sub> in air	21%	21%	1%
% O <sub>2</sub> in water	0.9%	0.5%	20% *
O <sub>2</sub> 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!**

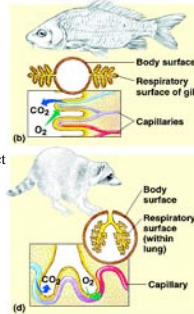
• In dry, high-oxygen environments (i.e., in air), contact of the wet respiratory surface with the respiratory medium can be restricted to protect from drying out.

• **Lungs!**

• But, in viscous, low-oxygen environments (i.e., in water), restricted contact provides inadequate gas exchange.

• **No lungs!**

Figure 38.16 b,d Respiratory organs



## RESPIRATION

- FICK'S LAW
- GILLS vs. LUNGS
- **AQUATIC RESPIRATION**
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## Aquatic Respiration Structures

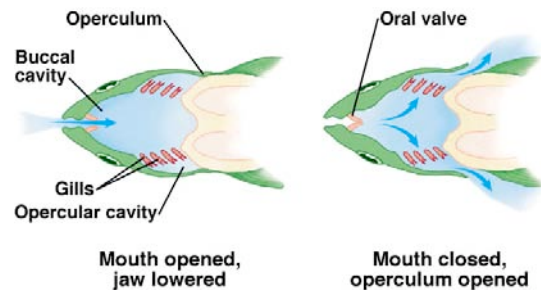
Animal	Gill Type	Ventilation
<b>Fish</b>	<b>gills</b>	<b>buccal pumping</b>
Polychaetes	gills or parapodia	gill movement
Marine Molluscs	ctenidia	cilia
Echinoderms	dermal branchiae & tube feet	cilia
Crustaceans	gills	gill bailer
Horseshoe Crabs	book gills	gill movement



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

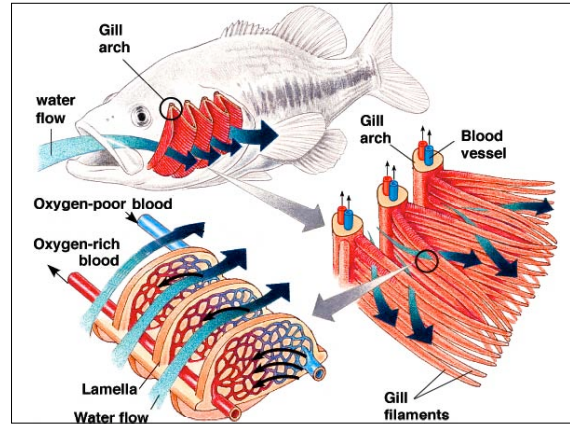
## Buccal pumping

### 1-way flow of water across gills

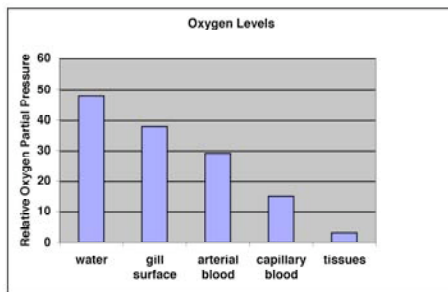


**Fish ventilation**

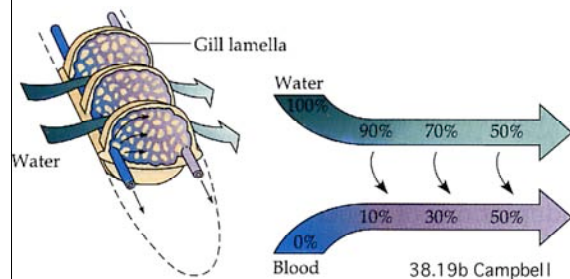
- ❖ Fish use energy to pump water across gills (ventilation).
- ❖ At low speed, buccal pumping is used.
- ❖ At higher speed, ram ventilation (swimming with mouth & operculum open) is more efficient (but still costs energy).



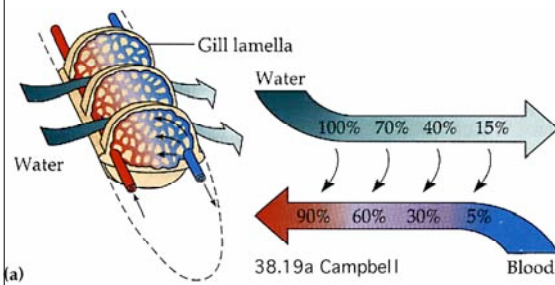
**O<sub>2</sub> diffuses from high concentration to low concentration.**



If fish used **Concurrent Exchange**:



Fish use **Countercurrent Exchange**.



**More active fish have bigger gills.**

*index of relative gill surface area/body mass*



**Mackerel: 2551**

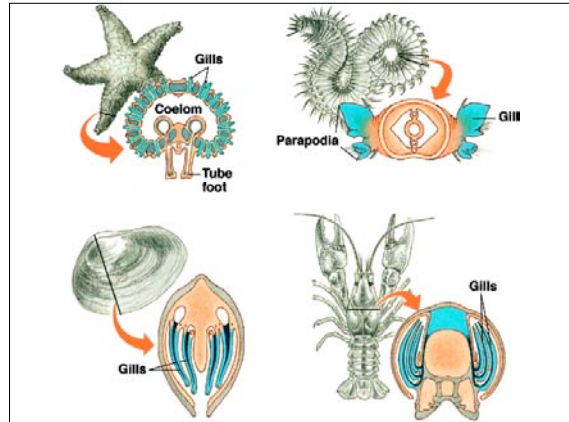


**Toadfish: 137**

# Gas Exchange

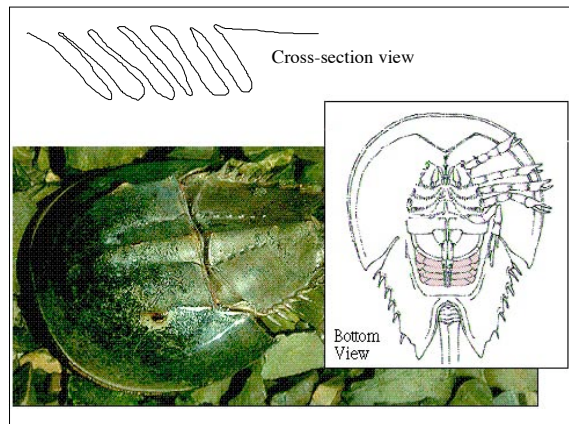
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- ## RESPIRATION
- FICK'S LAW
  - GILLS vs. LUNGS
  - AQUATIC RESPIRATION
  - **TERRESTRIAL RESPIRATION**
    - Arthropods: Book Lungs & Tracheal System
    - Vertebrate Lungs
  - RESPIRATORY PIGMENTS

## ARACHNIDS & BOOK LUNGS

- Homolog is book gill
- Page-like structure
- In larger species it's supplemented by a tracheal system

# Gas Exchange

## Arthropod Tracheal System

– Insects, millipedes, onychophorans, and big arachnids.

Diagram illustrating the structure of the tracheal system:

- Spiracle (w/ filters)
- Trachea (lined w/ taenidia)
- Tracheole

Images show: silkworm spiracle & tracheae, and cockroach trachea.

**Figure 38.20 Tracheal systems**  
from Campbell's BIOLOGY, Fourth Edition.

Labels: Air sacs, Tracheae, Spiracle, Body cell, Tracheole, Air sac, Trachea, Body wall, Spiracle.

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

tick

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

Labels: Tracheoles, Mitochondria, Myofibrils.

(b) 38.20b Campbell

2.5 μm

## Insect gas exchange:

- ❖ Spiracles can close to limit water loss.

Labels: spiracles, silkworm spiracle & tracheae, dung beetle spiracle.

## Terrestrial snails & slugs have:

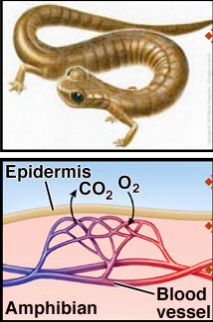
- lost their ctenidia from mantle cavity
- vascularized mantle cavity acting as lung

## Vertebrate Lungs

- Amphibians & Reptiles:
  - Septate sac
- Mammals:
  - Complex, w/alveoli
- Birds:
  - Elaborate flow-through system w/ parabronchi


Labels: Salamander, Frog, Lizard, Parabronchi, Lung, Air sac, Bronchus, Alveoli, Bird, Mammal.

### Lungless salamanders



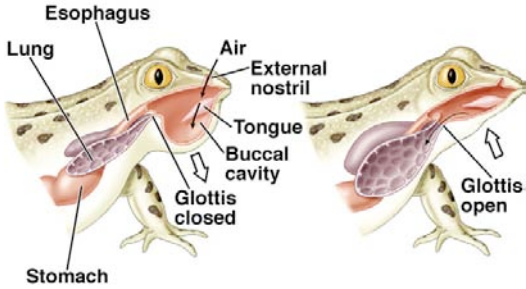
- ❖ Gas exchange through skin; blood gets oxygenated when it flows near skin.
- ❖ Small, slender bodies.
- ❖ They dry out easily.
- ❖ Cold bodies; don't use much O<sub>2</sub>.

### Amphibians with lungs



- ❖ Frogs and larger salamanders do gas exchange through skin and lungs.
- ❖ Usually most O<sub>2</sub> is absorbed in the lungs, but most CO<sub>2</sub> is eliminated through the skin.

### Frogs: positive-pressure breathing forces air into lungs

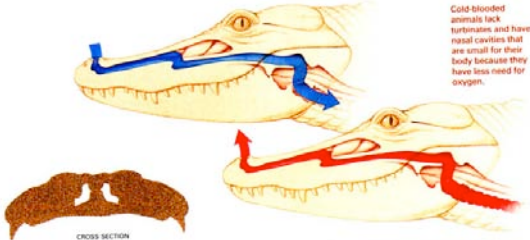


### Reptiles



- ❖ Reptiles have impermeable skin; gas exchange happens in lungs.
- ❖ Most have fairly low oxygen requirements.
- ❖ Body temperature is usually near ambient; this keeps water loss low compared to warm-blooded animals.

### Reptiles don't lose as much water to evaporation as mammals do, because:



Cold-blooded animals lack turbinates and have nasal cavities that are small for their body because they have less need for oxygen.

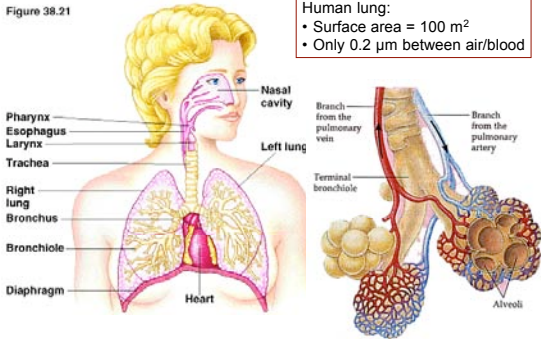
- ❖ They don't need to breathe as much
- ❖ Their bodies are close to ambient temperature

### Mammalian Lung — 300 Million Alveoli

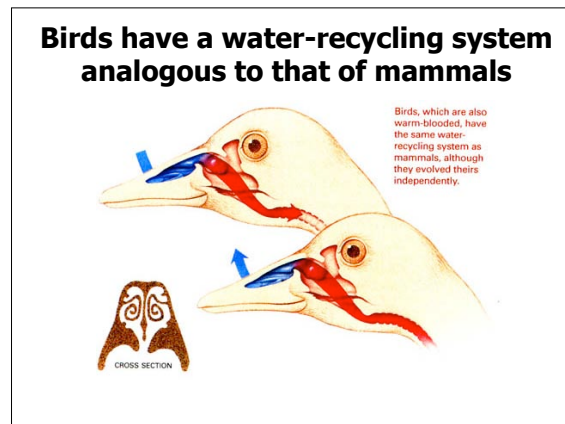
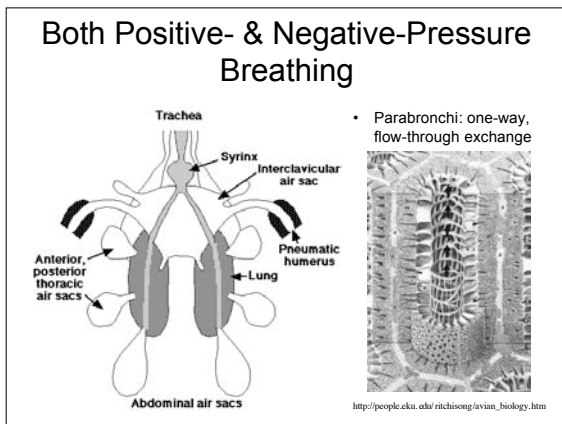
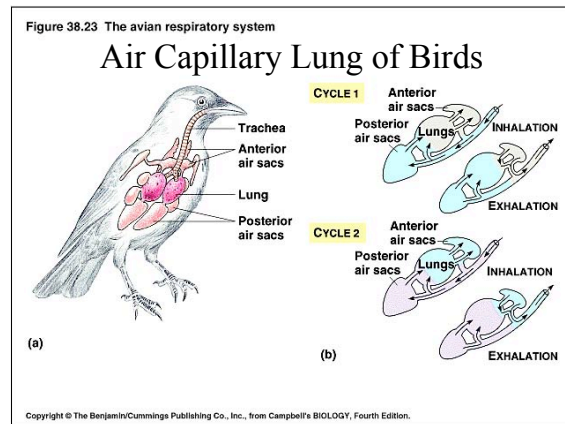
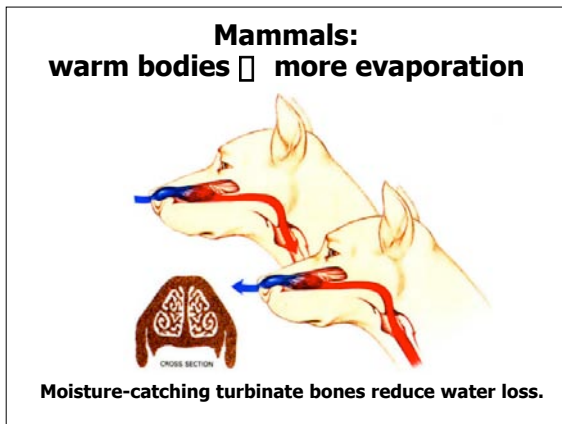
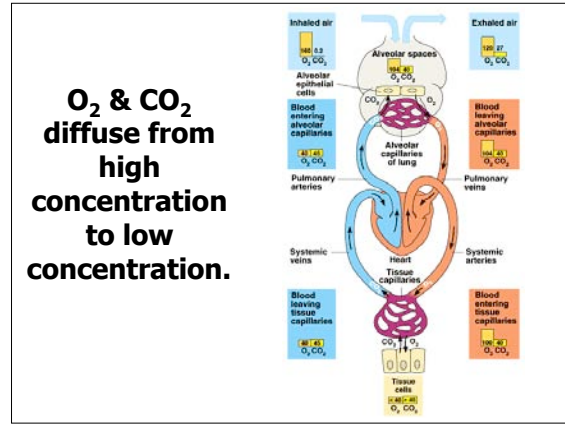
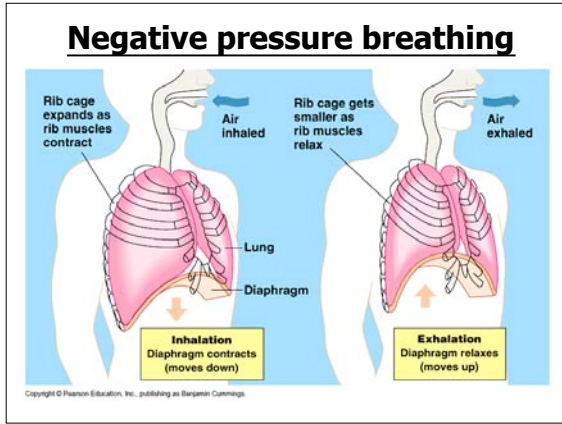
Figure 38.21

Human lung:

- Surface area = 100 m<sup>2</sup>
- Only 0.2 μm between air/blood



# Gas Exchange



*How much O<sub>2</sub> can be carried dissolved in blood fluids alone?*

Terrestrial vs. Aquatic Respiration

O <sub>2</sub> Level	5°C	35°C	% Metab. for Resp.
Air	21%	21%	1%
Water	0.9%	0.5%	20%

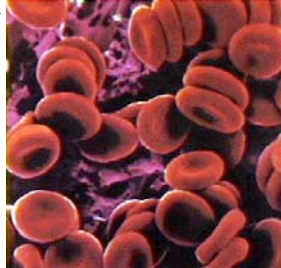
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O<sub>2</sub> in air vs. water    25X    40X

- RESPIRATION**
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**Respiratory Pigments Carry O<sub>2</sub>**

- 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.

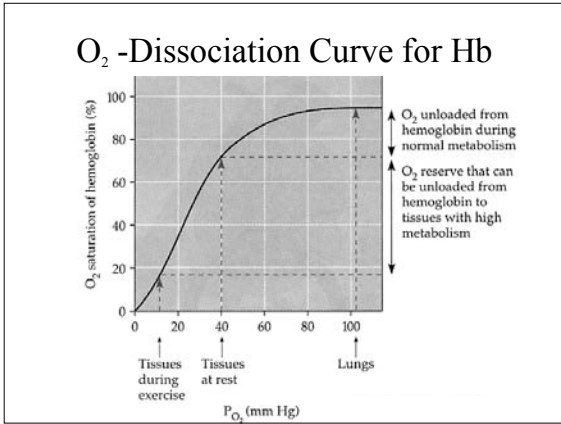


**Other Respiratory Pigments**

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<sub>2</sub> shifts w/ blood oxygen content**
- Hemoglobin has
    - high O<sub>2</sub> affinity when P<sub>O<sub>2</sub></sub> is high
    - low O<sub>2</sub> affinity when P<sub>O<sub>2</sub></sub> is low
  - Blood O<sub>2</sub> content is measured as its partial pressure.

# Gas Exchange



### The Bohr Shift

- CO<sub>2</sub> dissolved into blood forms carbonic acid, lowering pH.
- Gives it up easier when pH is lower at cells (more carbonic and lactic acid present)
- Grabs it at alveoli where CO<sub>2</sub> levels are lowest due to exhalation

