Respiration

- Most terrestrial vertebrates have internal lungs that must be ventilated through *bidirectional* movement of air to replenish the oxygen (O_2) supply

- Most fish have external gills that are ventilated by a *unidirectional* flow of water, by pumping or swimming

- Fine sieve structure of gills very efficiently extracts O_2 from water.

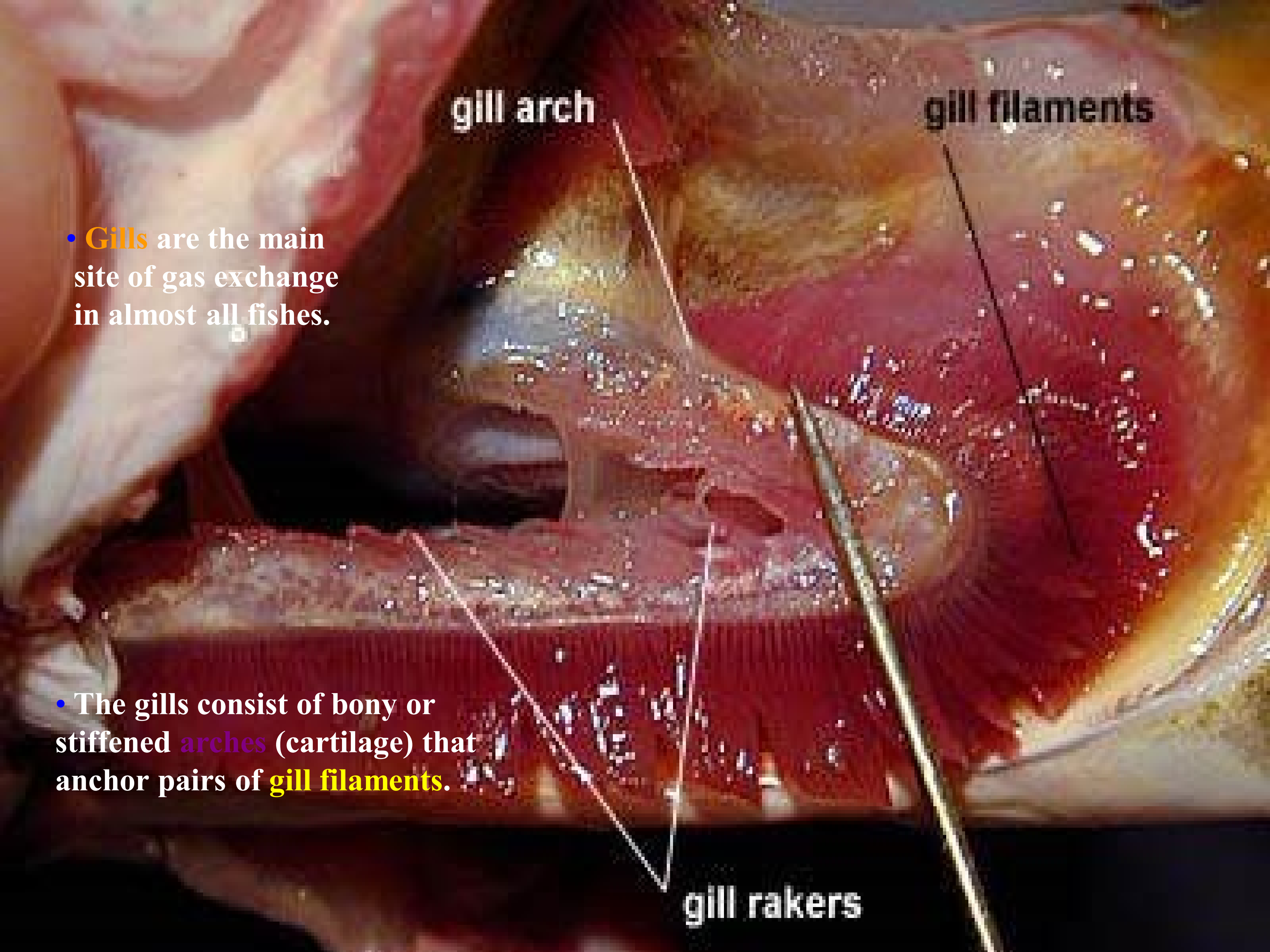
- Efficient O_2 uptake is vital to fish because of its low water solubility.

- Solubility <u>decreases</u> with <u>increased</u> temperature & salinity

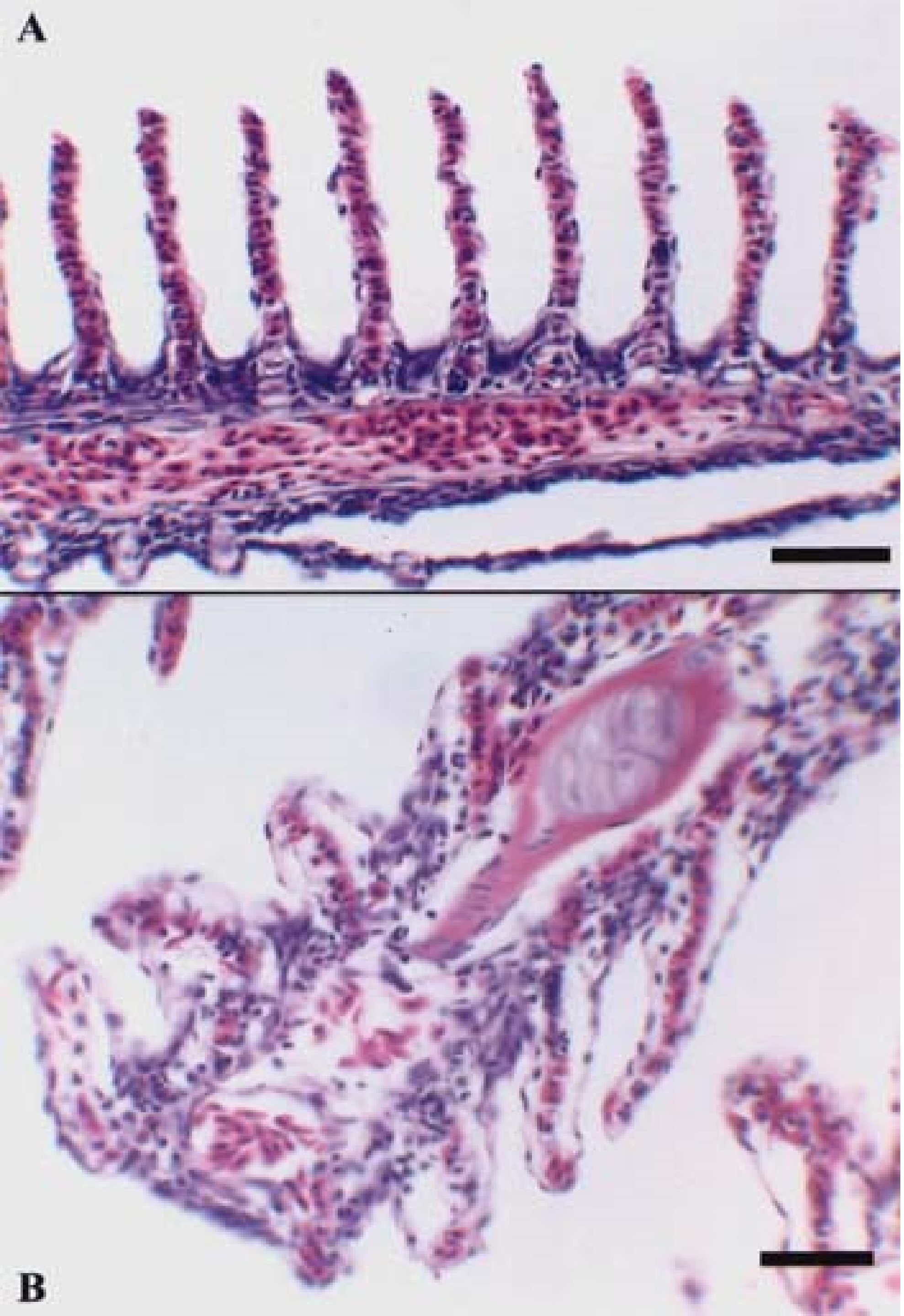
Oxygen solubility determined by temperature

Temp (°C)	O_2 con. at sat. (mg/l) – Fresh	O_2 con. at sat. (mg/l) – Salt
0	10.3	8.0
10	8.0	6.3
20	6.5	5.3
30	5.6	4.6

Gills



- Gills are the main site of gas exchange in almost all fishes.
- The gills consist of bony or stiffened arches (cartilage) that anchor pairs of gill filaments.

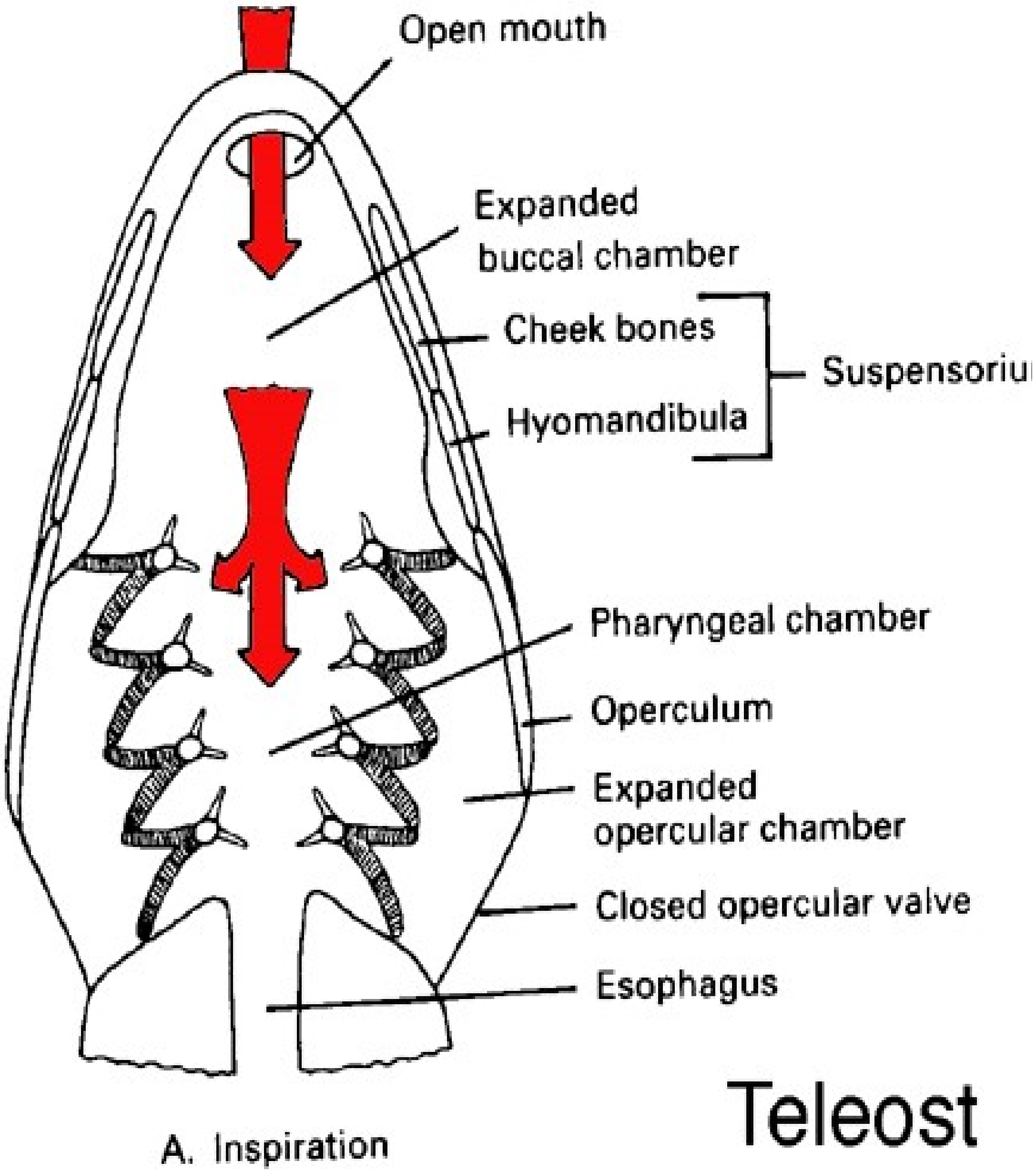


Microscopic gill structure: showing gill filament and lamellae (Red blood cells evident.)

How can fish remove 80 - 90% of O_2 available from water?

- Short diffusion distance at gill site
- Large surface area for diffusion at gill site
- Counter current exchange of gases at gill site
- Large volume of water passes over gills

Gill Ventillation



Teleost

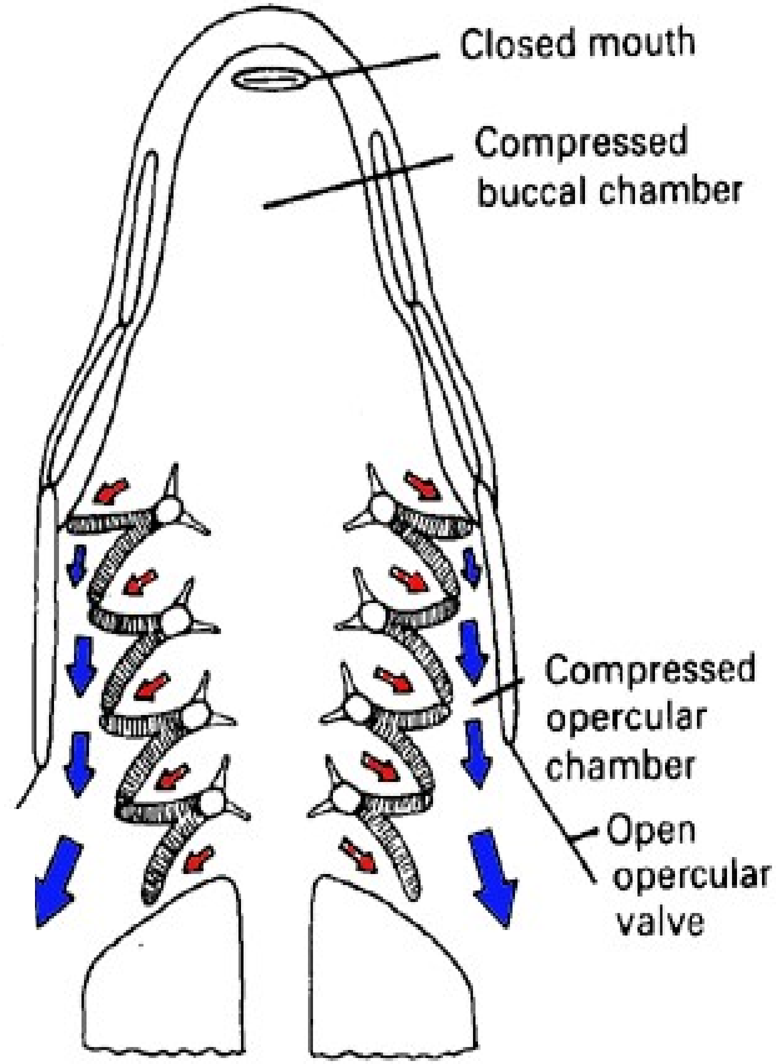
1. Fill mouth cavity (open mouth, expand volume of mouth, expand volume of gill chamber with operculum closed)

2. Fill gill cavity (close mouth, squeeze mouth cavity, expand gill cavity, with operculum closed)

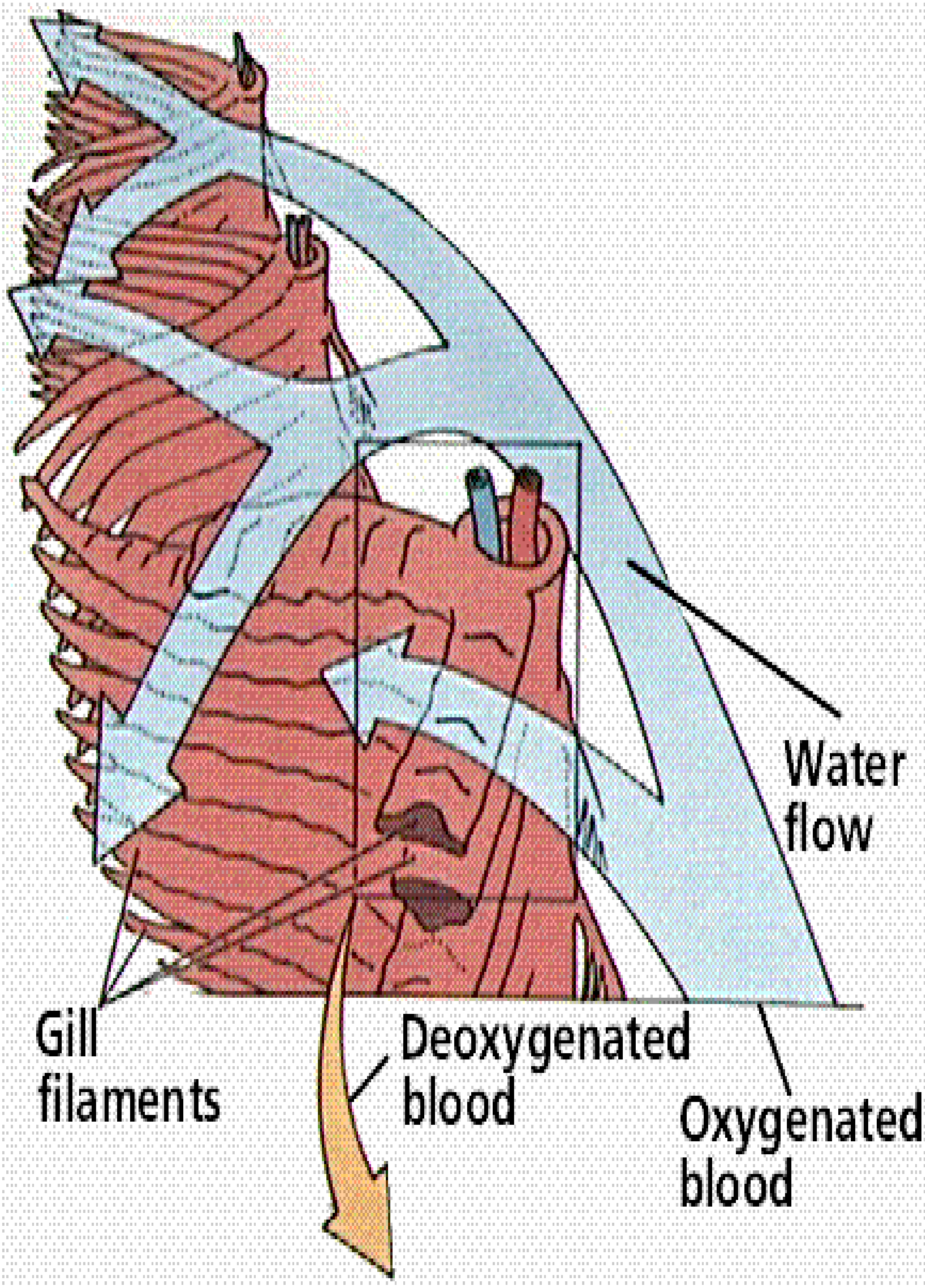
Gill Ventillation

3. Expel water from gill cavity (squeeze mouth and gill cavities, open operculum)

4. Reset for next cycle



B . Expiration



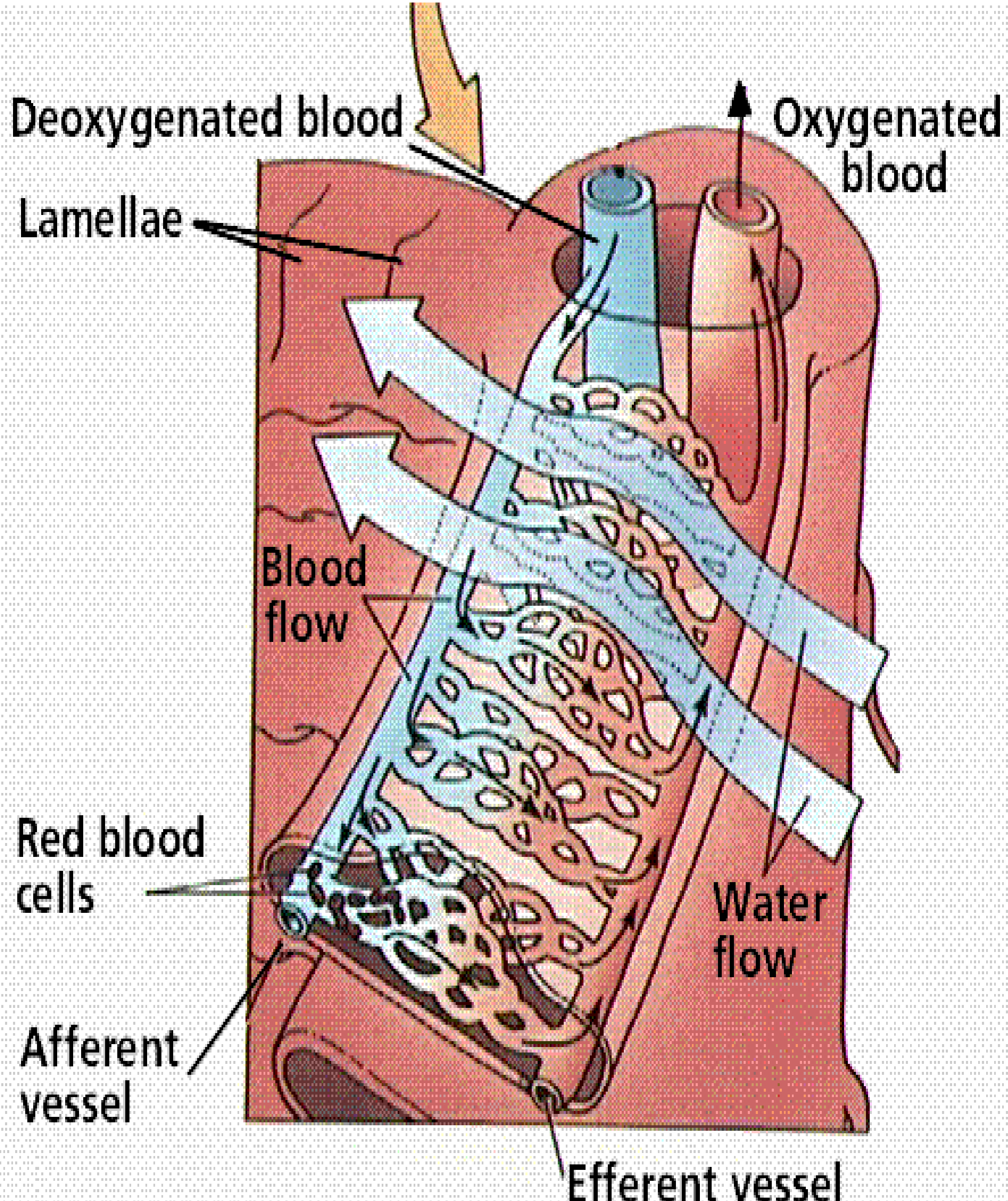
Oxygen Exchange in Fish

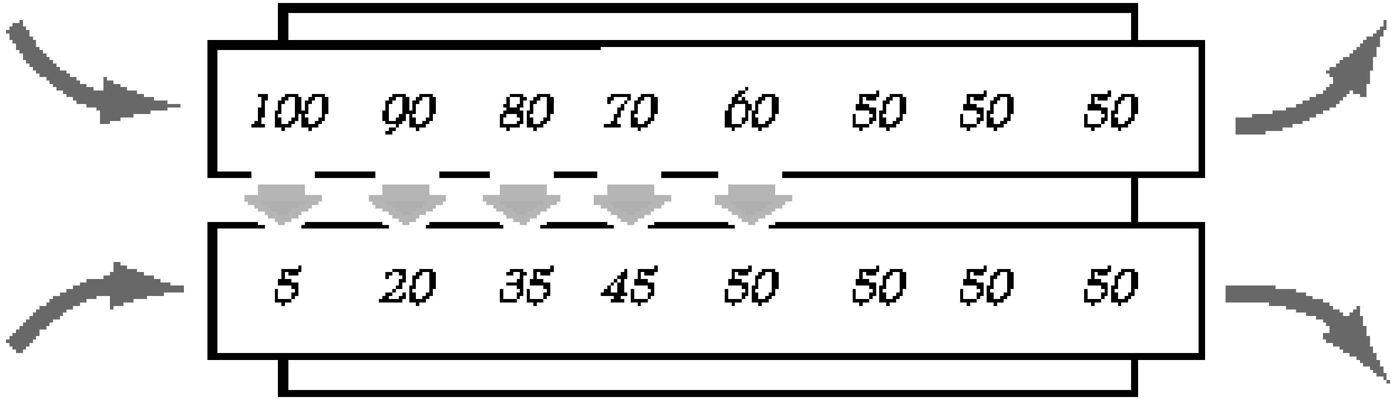
- Fish employ the *countercurrent system* to extract O_2 from the water.
- This system moves water flowing across the gills, in an *opposite* direction to the blood flow creating the maximum efficiency of gas exchange.

Countercurrant* Close-up

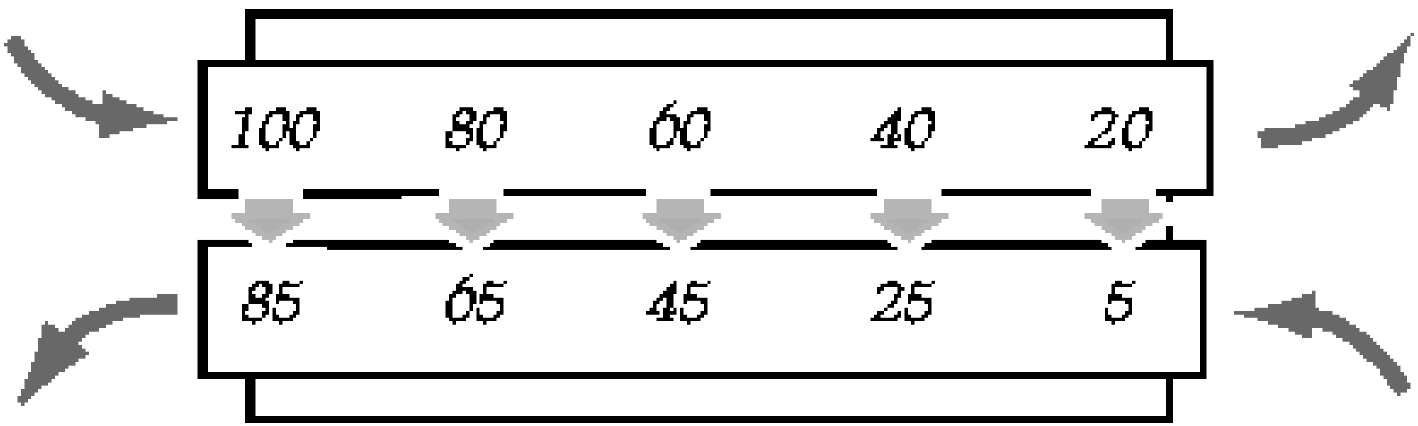
- Blood flow through lamellae is from posterior to anterior.
- Water flow over lamellae is from anterior to posterior.
- Counter-current allows for diffusion from high O_2 in water to low O_2 in blood across entire length of lamella.

* When he blood and water flows in the same direction, the *co-current system*, it will initially diffuses large amounts of oxygen but the efficiency reduces when the fluids start to reach equilibrium.





Co-current



Counter-current Exchange

4 gill arches on each side of body

2 rows of gill filaments on each arch (demibranchs)

100's filaments per demibranch - closely spaced

1000's lamellae per gill filament

gill area = 10 to 60 times that of body surface area, depending on species

HUGE potential to extract Oxygen from water

Auxiliary Respiratory Structures

- Skin - diffusion of oxygen from water into dense network of capillaries in skin (eels), *Thin skin (larval fish) supplies 50% of* O_2 *needed.*
- Swim bladder - vascularized physostomous swim bladders (gars)
- Lungs - modified swim bladder (lungfishes)
- Mouth - vascularized region in roof of mouth (electric eel, mudsuckers)
- Gut - vascularized stomach or intestinal wall (armored catfish, loaches)

Branchial vs. Ram Ventilation

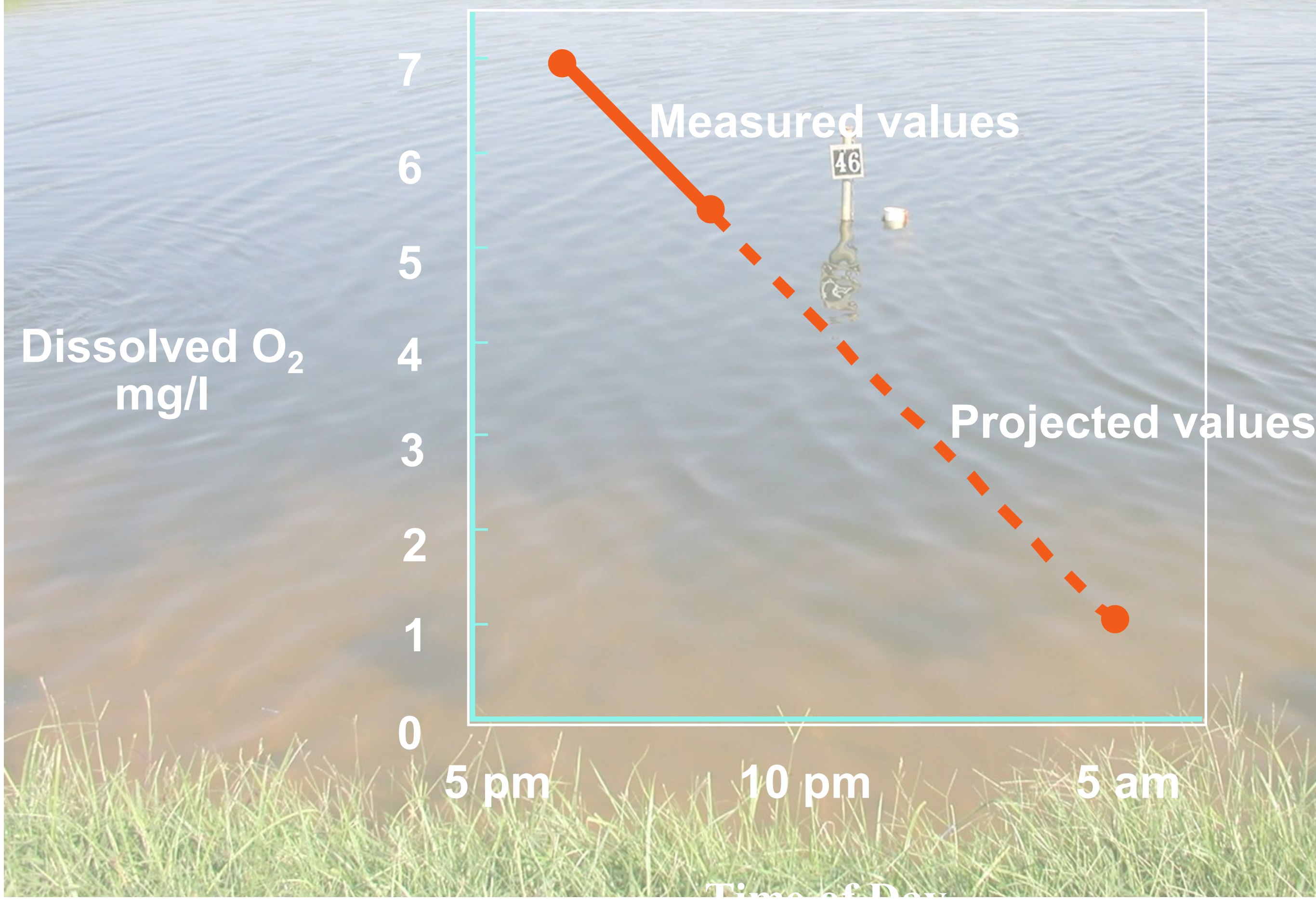
Branchial

- Mouth
- Pharynx
- Operculum
- Branchiostegals (filaments, lamella)

Ram

- Uses same parts, but not the pumping energy required. Sharks primarily. Once swimming speed is achieved...no need to actively vent buccal cavity. However, this can only be used consistently by strong swimmers (sharks, tuna).

Practical Application of This Knowledge
Projected Dissolved Oxygen Levels



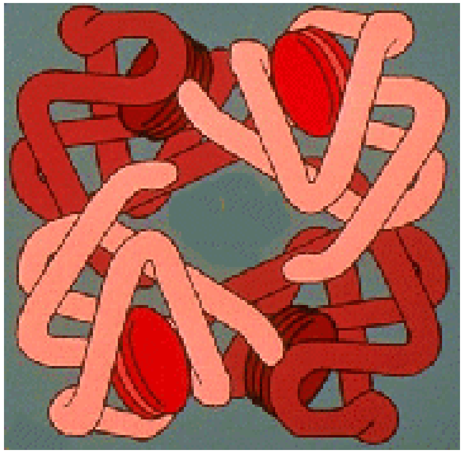
Gas Transport in Fishes

Hemoglobin (Hb) of Fish Erythrocytes

- Primary means for transporting oxygen
  - In some fish up to 15% may be in plasma

- A few fish have no Hb (rare situation)

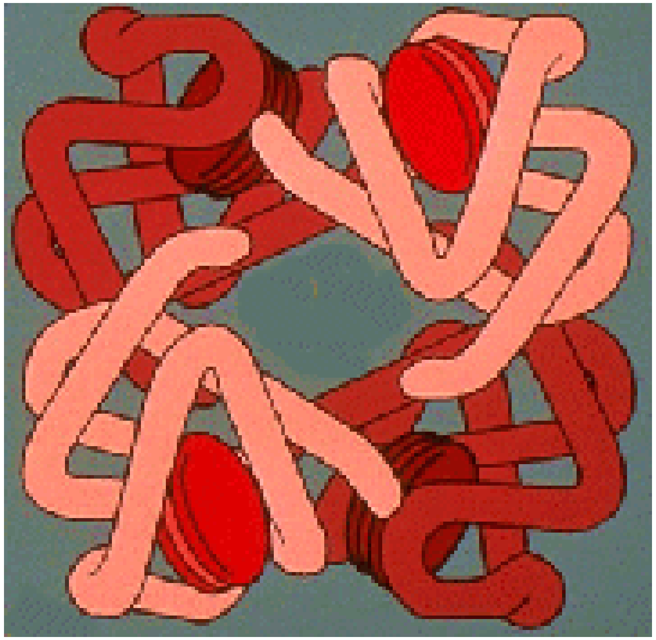
  - Environmental oxygen high
  - Low metabolic requirements
  - Special cardiovascular adaptations



Fish Hemoglobin Characteristics

- Structure is different in different fish
  - Monomeric
  - Single-heme peptide molecules
  - Found in Agnatha

- Tetrameric
  - Four peptide chains



Fish Hemoglobin Characteristics

- **May differ in many features**
  - **Composition of amino acids**
  - **Affinity for oxygen**
  - **Some salmonids have up to 18 different Hbs**

Having Different Hemoglobin Types

- **Different Hbs have different responses to:**
  - **temperature**
  - **oxygen absorption**

- **Allows fish to deal with changing conditions**
  - **Important for migratory species**

- **Some fish gain or lose types as they age**

Blood Oxygen Affinity

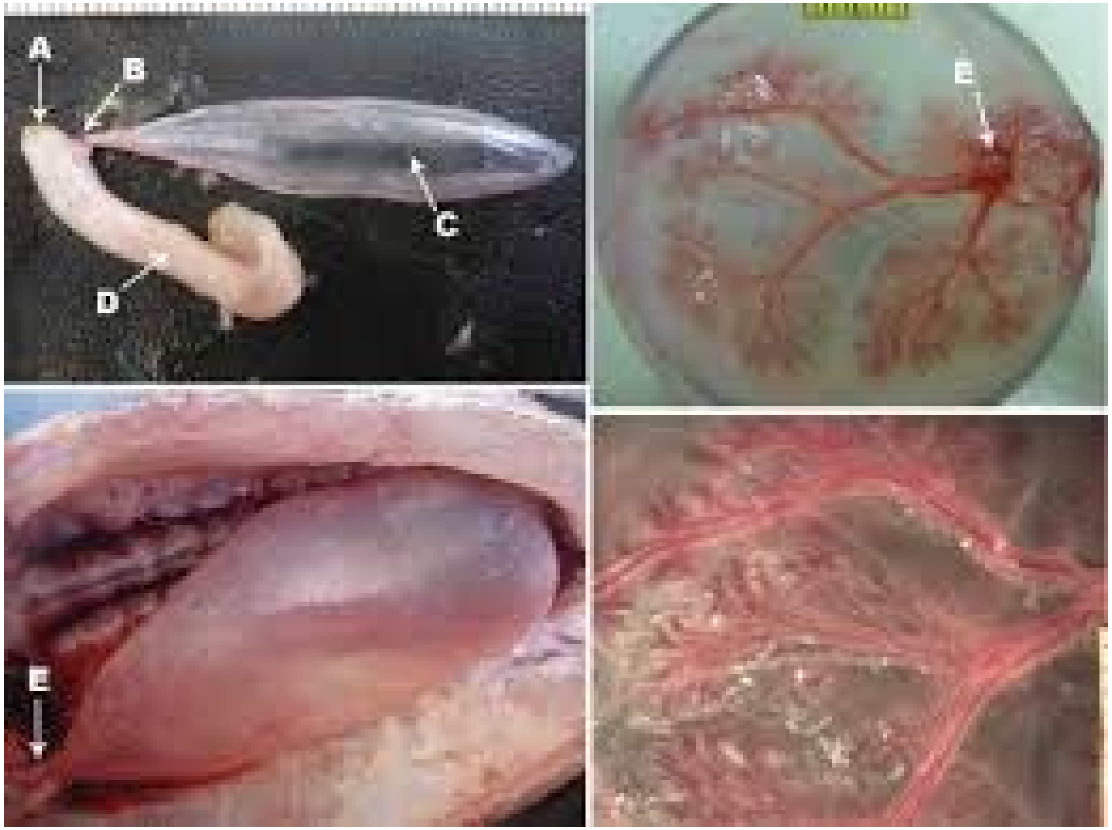
- pH
  - Decreasing pH decreases Hb affinity for O_2
  - Often associated with carbon dioxide
- Carbon dioxide
  - Increase in CO_2 drives off O_2 (Bohr effect)
  - Decrease in blood pH magnifies Bohr effect

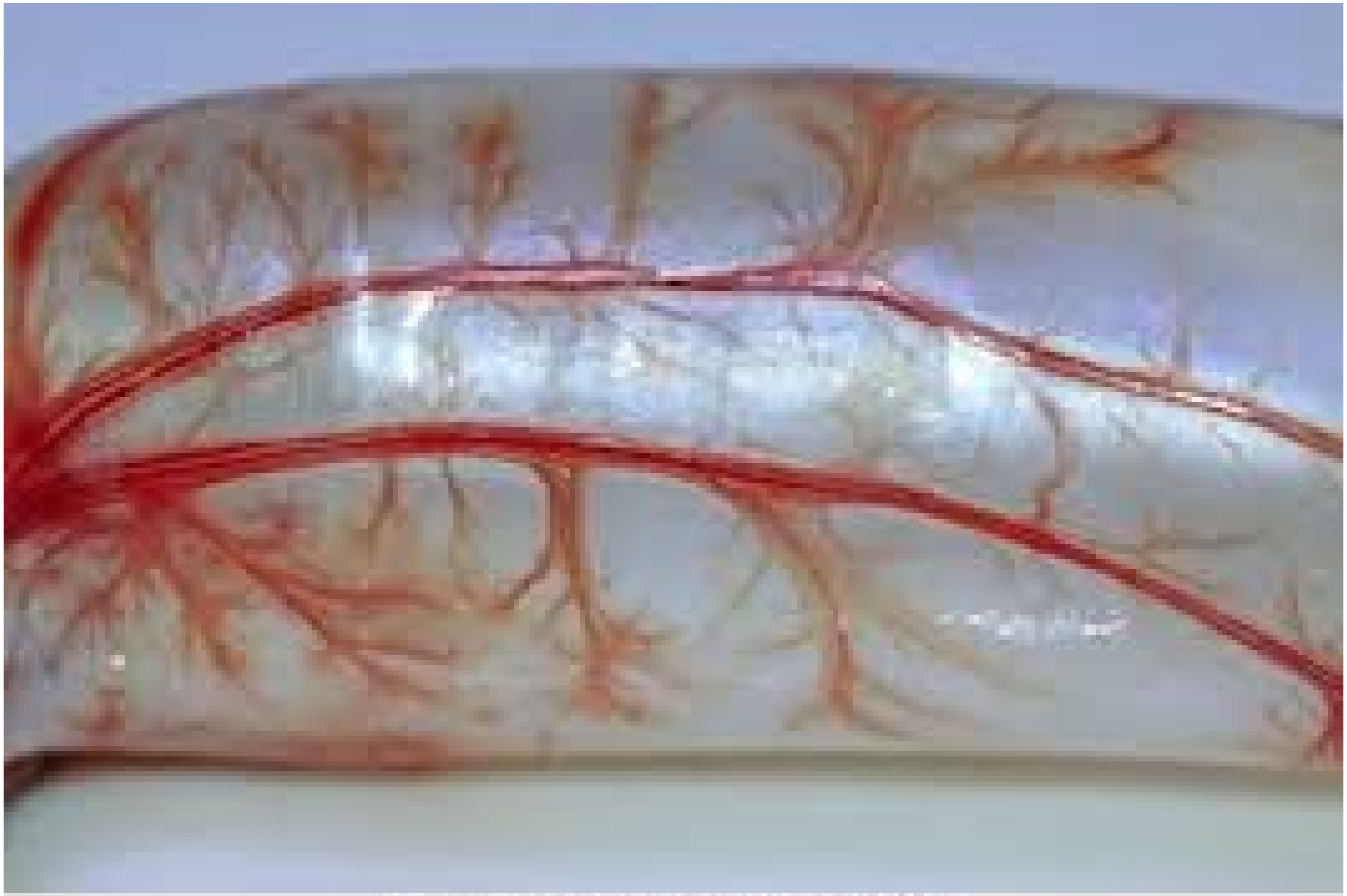
Blood Oxygen Affinity

- **Temperature**
  - **Increase in temperature depresses oxygen affinity and capacity**
  - **Results in fish having narrow temperature tolerances**
- **Organic phosphate**
  - **ATP depresses O_2 affinity**
  - **Urea increases O_2 affinity**

Swim bladder

- low density
- adjustable
- most osteichthians
- lost secondarily in some species


A
B
C
D
E
E



Two types of swim bladders:

- Physostomous
  - pneumatic duct
  - soft-rayed teleosts--herrings, salmonids, catfishes, cyprinids, eels, etc.
- Physoclistous
  - blood/circulatory system
  - spiney-rayed teleosts--Acanthopterygii, sunfishes, perch, most marine fishes

Effects of depth on swim bladder volume

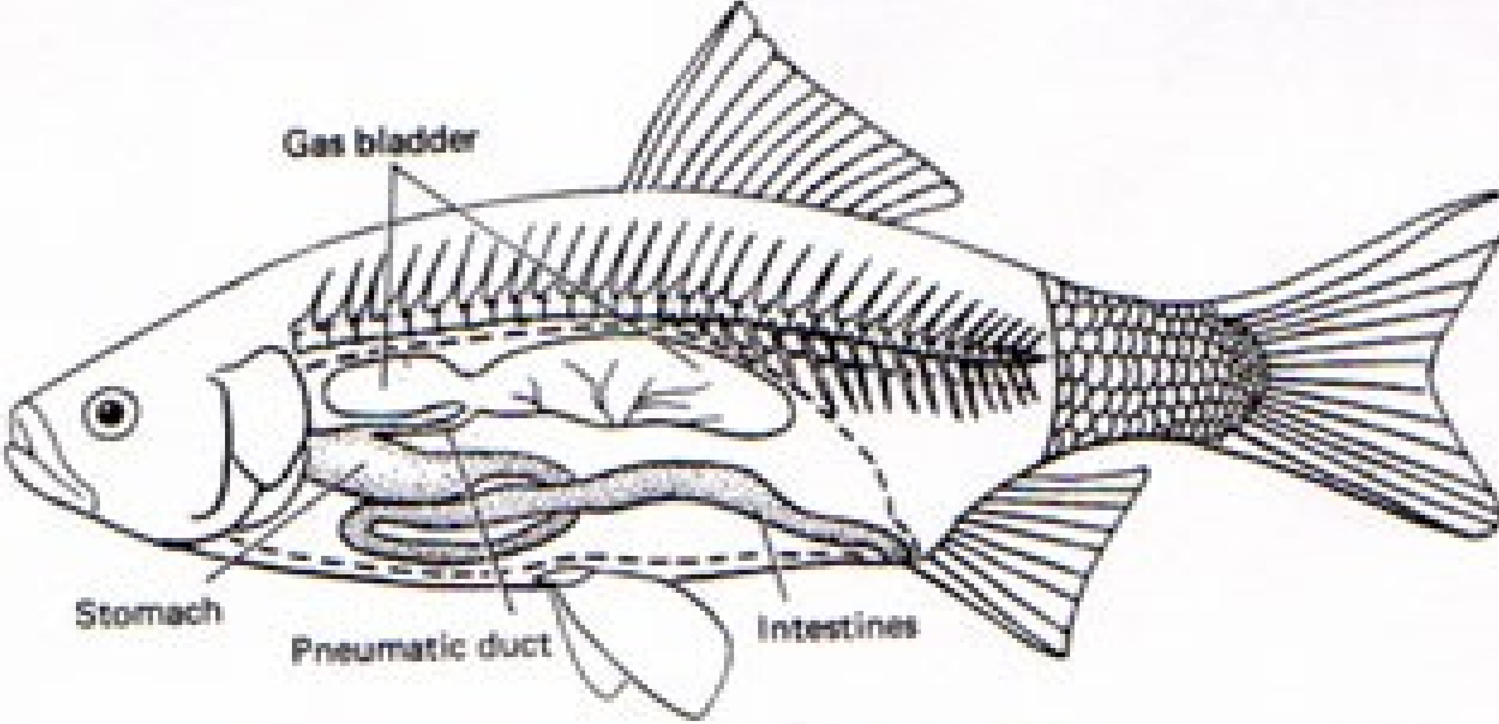
- pressure increases 1 ATM/10m
- swim bladder must be adjustable
- Physostomous fishes adjust volume by gulping or spitting air.
  - mostly shallow water species
  - gas-spitting reflex
  - gulp air at surface

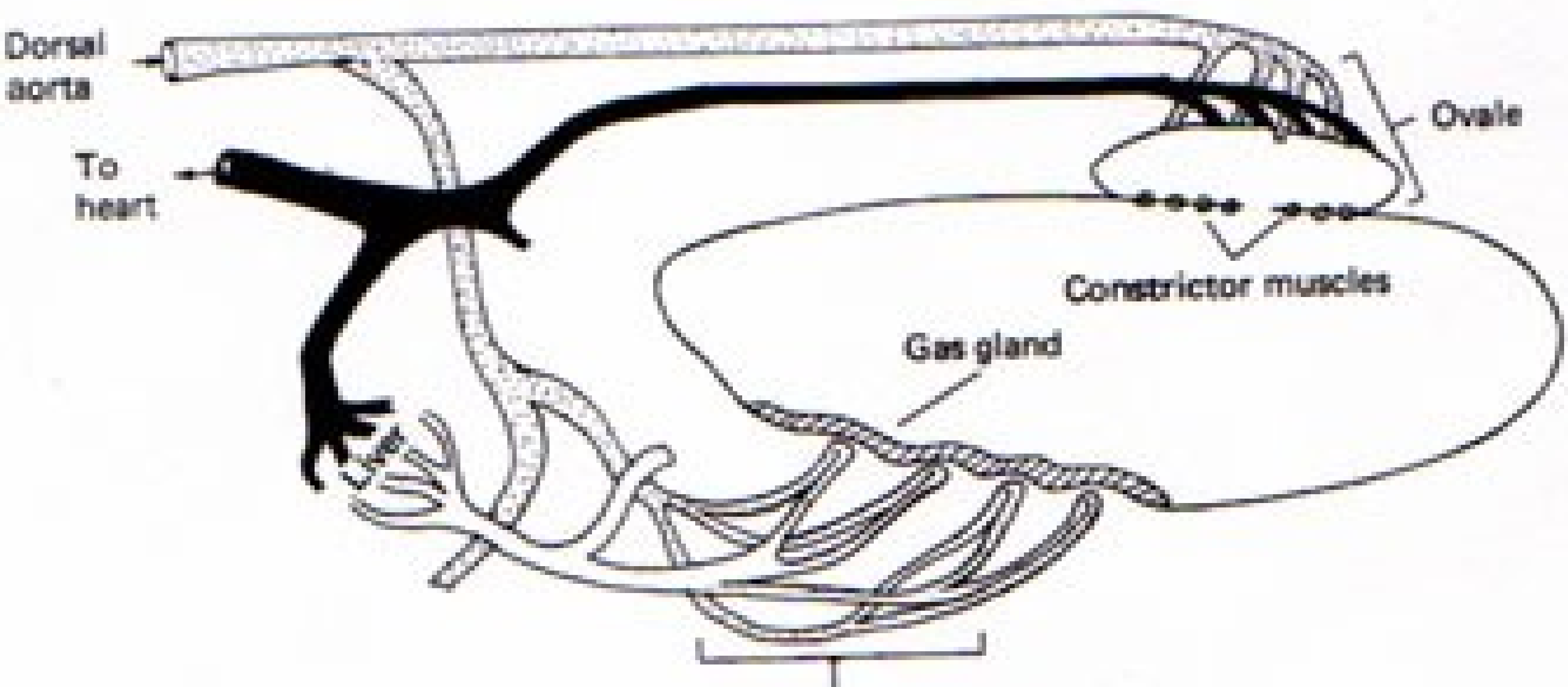
Physoclistous inflation/deflation

- circulatory system--source of gases
- rete mirabile (wonderful net) --inflation
- oval window--deflation
- Problem: fish need greater pressure in swim bladder than is achieved by equilibrium with blood gases

Physoclistous swim bladder

- Pressures up to 300 ATM in some deep sea fishes
- Gases mostly O_2, some CO_2 and N_2
- Guanine crystals in SB wall reduce permeability
- Deflation occurs at oval window
  - dense bed of capillaries on SB wall
  - gasses diffuse into blood
  - mucus layer covers window during inflation


Gas bladder
Stomach
Pneumatic duct
Intestines


Dorsal aorta
To heart
Ovale
Constrictor muscles
Gas gland

How do you inflate a swim bladder?

- Gas gland is location of action in wall of swim bladder (rete mirabile “wonderful net” and surrounding tissues)
- Need to pry O_2 molecules from Hb molecules in gas gland
- Need to accumulate enough O_2 ($>pO_2$) in solution in blood plasma to generate a diffusion gradient from distal end of rete mirabile into lumen of swim bladder

Prying O_2 from Hb

- **Change of pH in blood causes change in bond strength of Hb for O_2**

- **Bohr effect--decrease in affinity of Hb for O_2 due to decreasing pH or increasing pCO_2**
  affinity: strength of attraction of Hb for O_2

- **Root effect--decrease in capacity of Hb for O_2 due to decreasing pH or increasing pCO_2 (extreme Bohr effect)**
  capacity: total quantity O_2 of that Hb can carry

- **more active species tend to have greater Bohr & Root effects**

How to cause pH to drop in tissues of gas gland?

- Regular metabolic processes result in release of H^+, either from glycolysis (lactic acid) or aerobic metabolism (CO_2)

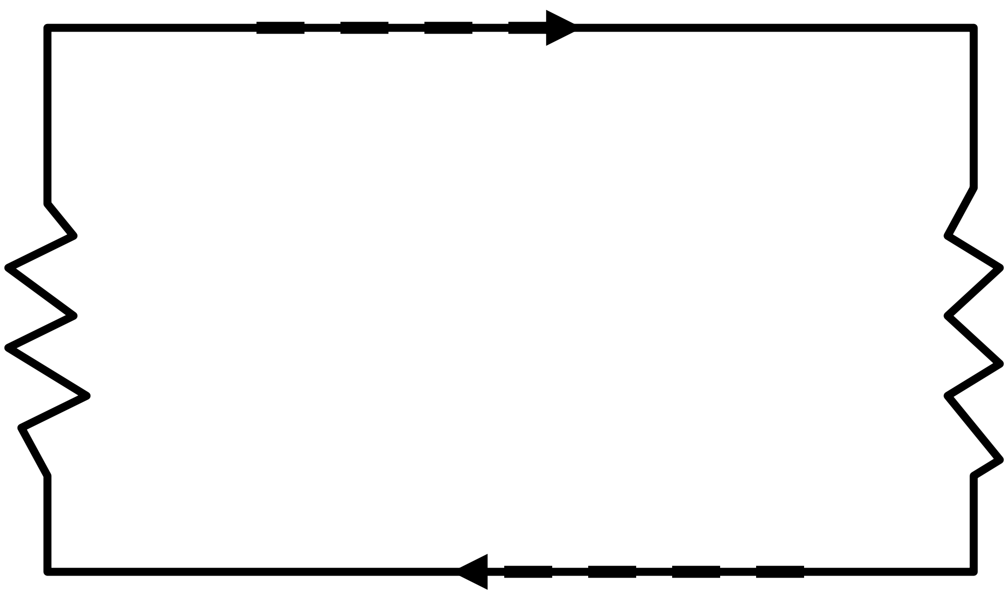
- Increase metabolic activity in tissues surrounding rete mirabile = decrease of pH

How to cause free O_2 to accumulate in distal end of rete?

- Another counter-current exchange system:
  - **long capillaries that fold back on self**
  - **<u>afferent</u> (incoming) part of capillary experiences drop in pH, Hb loses O_2**
  - **<u>efferent</u> (outgoing part of capillary has higher partial pressure (concentration) of dissolved O_2 than afferent, so**
  - **O_2 diffuses into afferent arm, causing supersaturation of blood at distall end of rete with O_2**

Advantage of Bohr Effect

blood circulation



<u>Gills</u>

pH higher

pCO_2 lower

no lactic acid

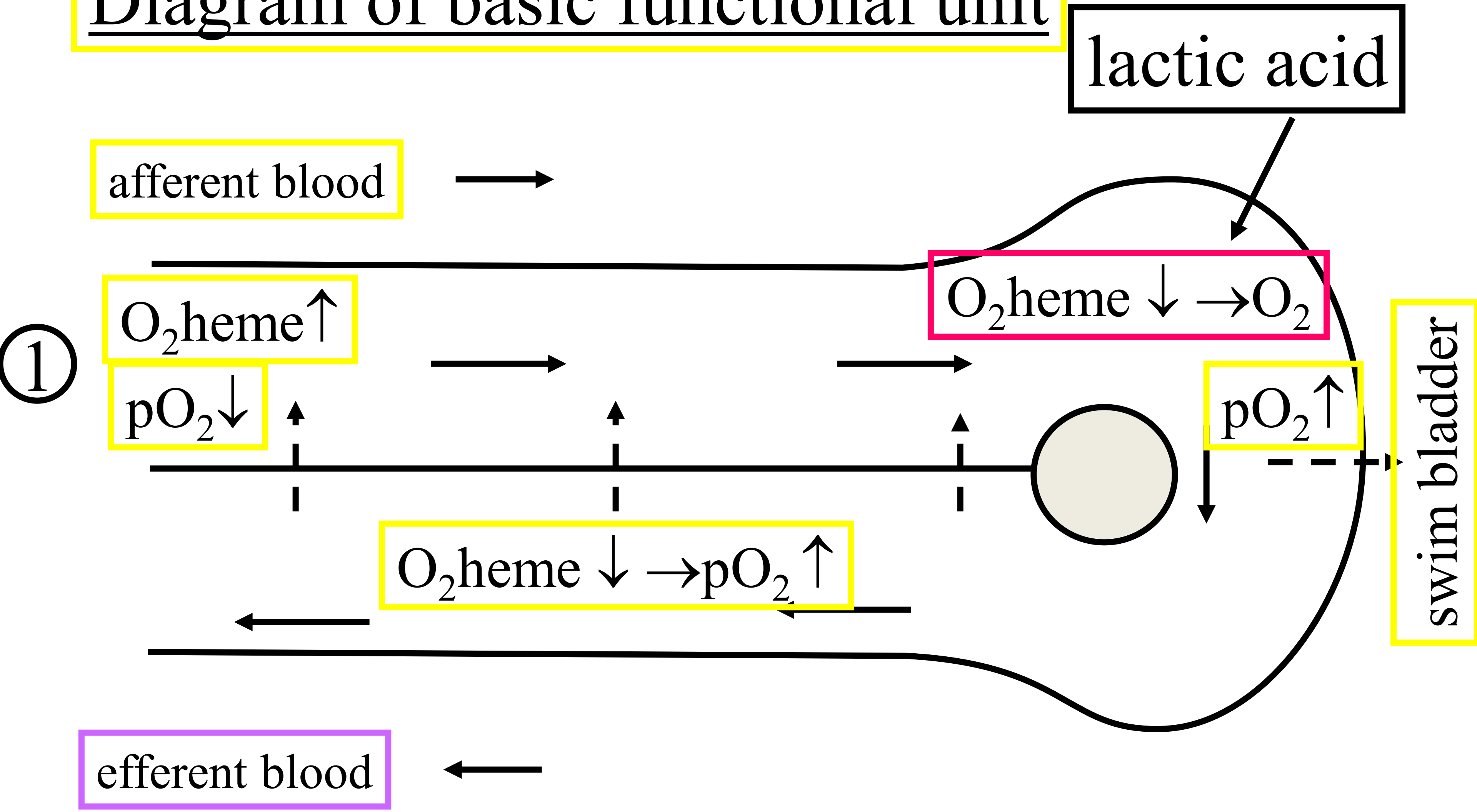
<u>Tissues</u>

pH lower

pCO_2 higher

lactic acid

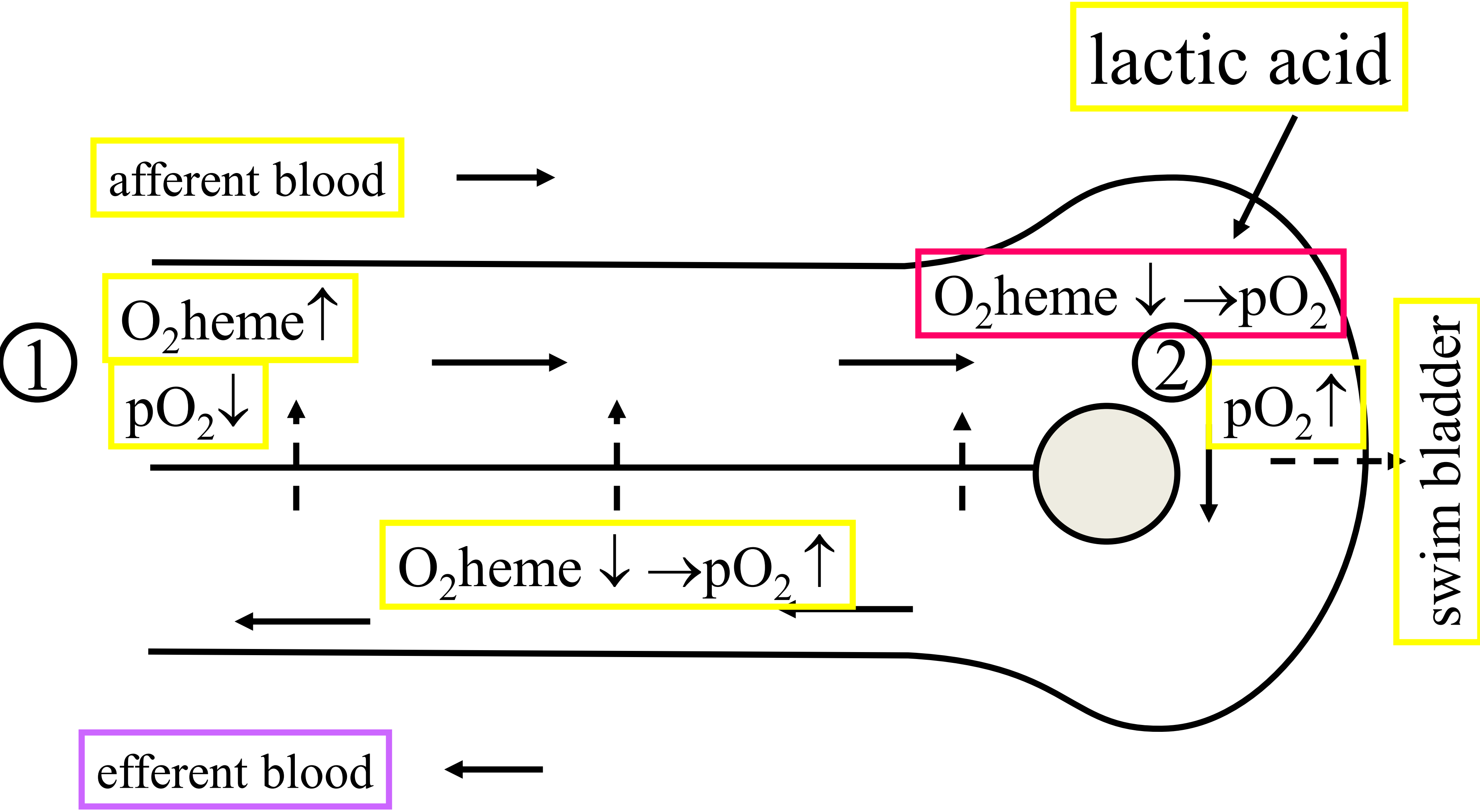
Diagram of basic functional unit



Function of Rete Mirabile

1. Hemoglobin saturated with O_2 (O_2 heme) plasma O_2 low (p O_2)

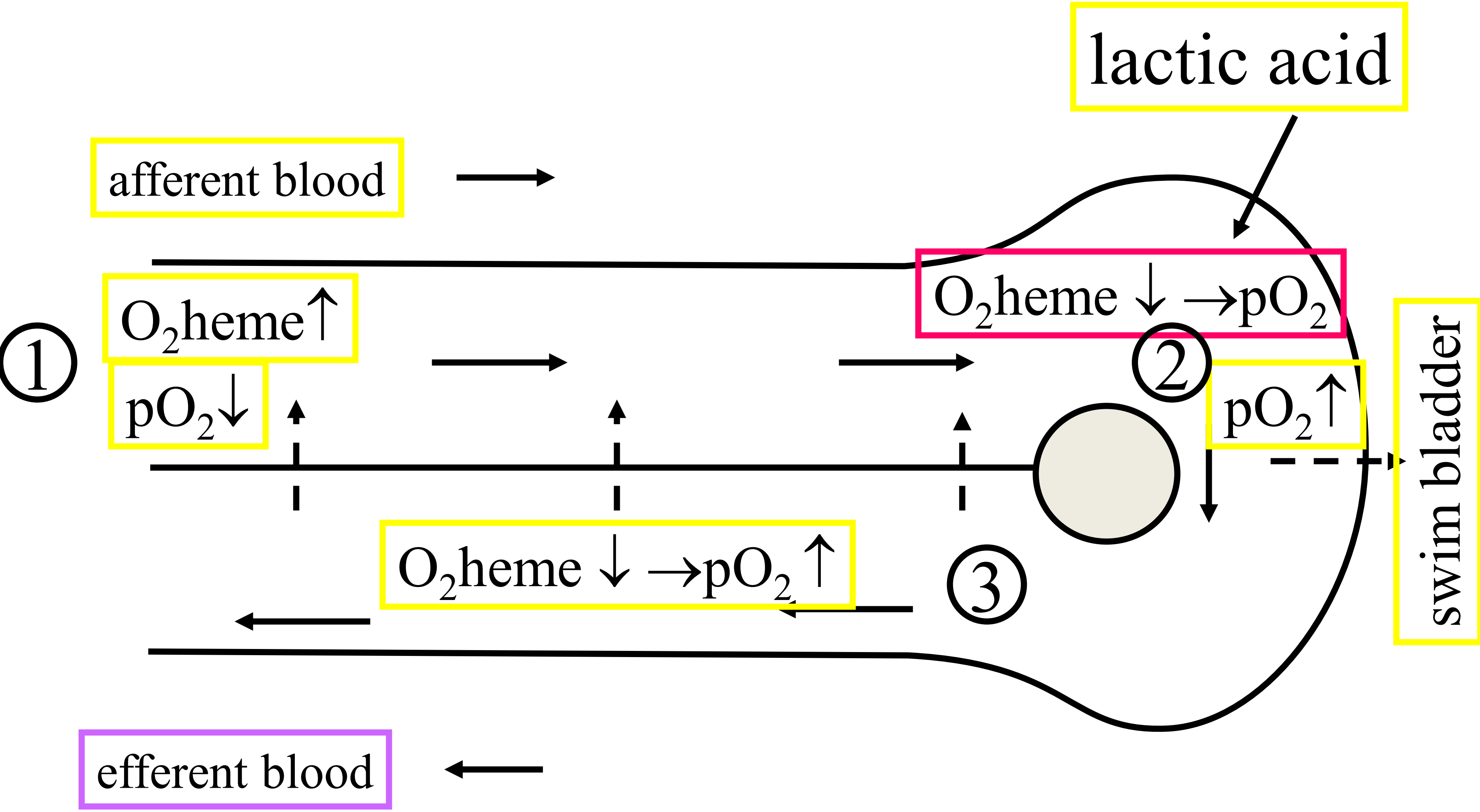
Counter-current multiplication system



Function of Rete Mirabile

2. Lactic Acid Secretions
   heme dumps O_2 to plasma
   pO_2 diffuses into swim bladder to equil.

Counter-current multiplication system

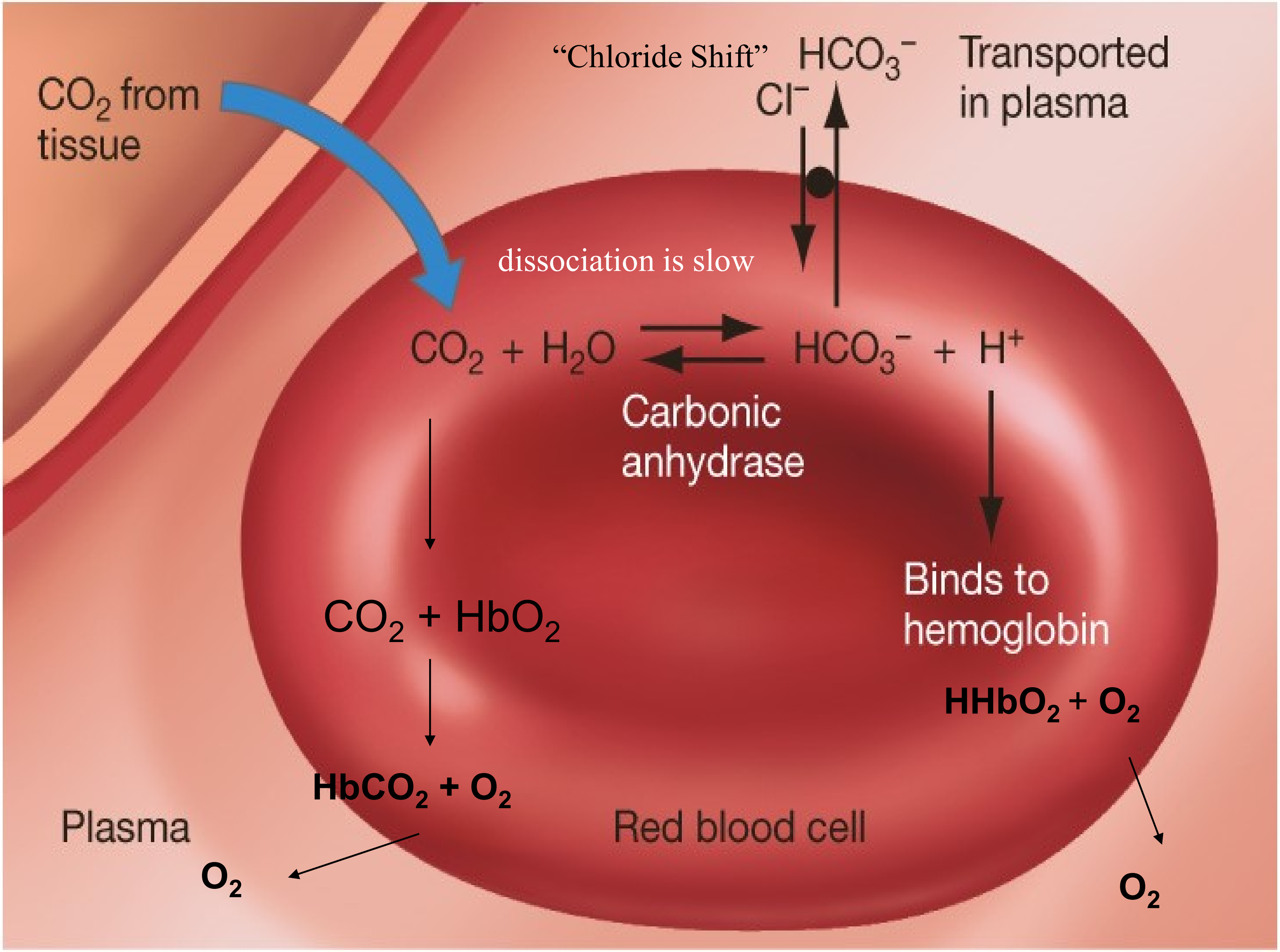


Function of Rete Mirabile

3. Multiplying effect: pO_2 diffuses from efferent capillary to afferent cap. Also, longer capillaries yield more efficient exchange of oxygen, higher pressures

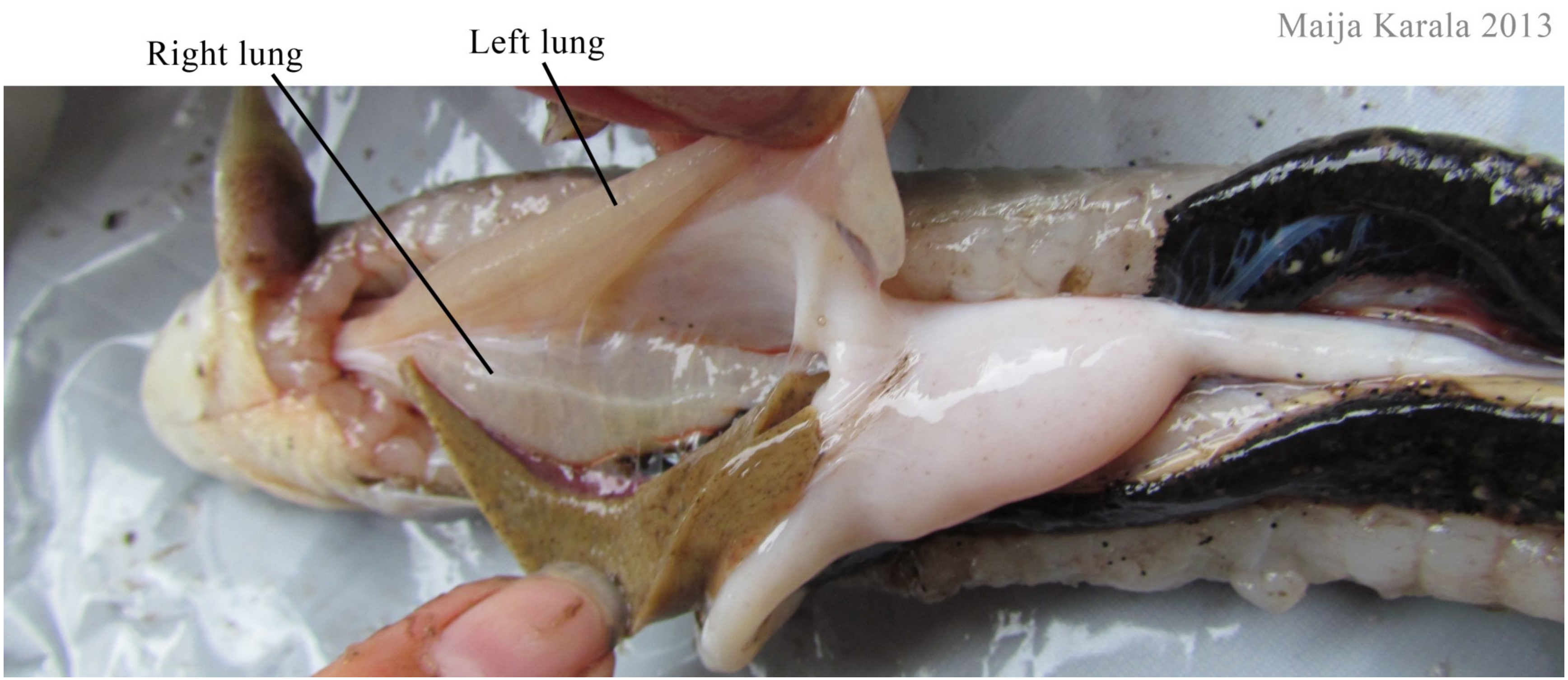
What about CO_2?

- the O_2 inside...how do the CO_2 outside
- Again, blood also is involved in CO_2 transport.
- Three mechanisms to move CO_2 outside cell to be excreted.
  (1) Simple dissolution in plasma
  (2) Binding to proteins/formation of carbamino groups.
  (3) Dissociation into carbonic acid by pH change (greatest
  amount of CO_2 transformed this way.)



CO2 from tissue
"Chloride Shift"
HCO3−
Cl−
Transported in plasma
dissociation is slow
CO2 + H2O ⇌ HCO3− + H+
Carbonic anhydrase
CO2 + HbO2
Binds to hemoglobin
HHbO2 + O2
HbCO2 + O2
Plasma
Red blood cell
O2
O2

Lungs



Buoyancy strategies

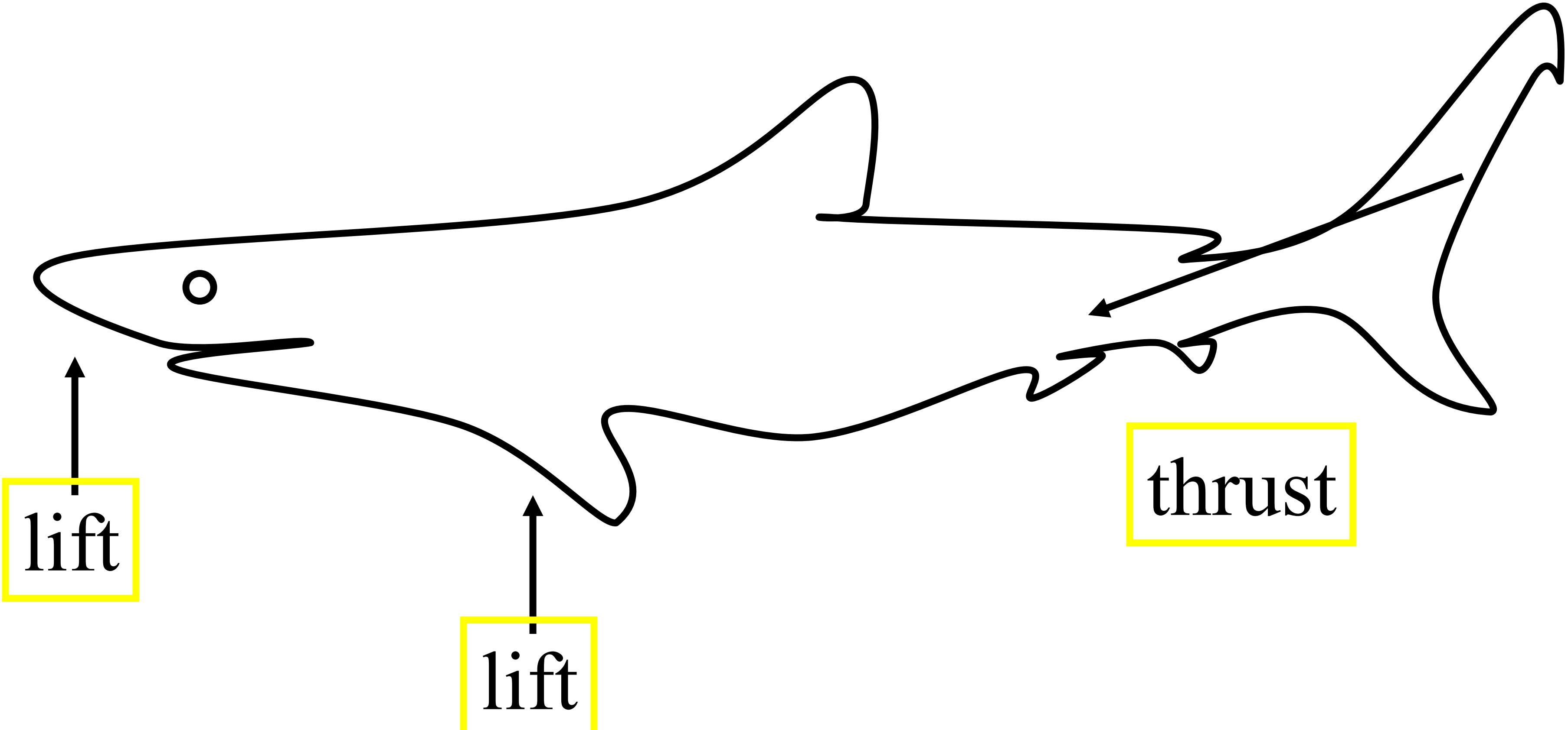
1. Low density compounds
2. Lift generated by swimming
3. Reduction of heavy tissues
4. Swim bladder (air bladder)

1. Low density compounds:

Substance	Specific Gravity
Bone	2.0
Muscle	1.05
Cartilage	1.1
Freshwater	1.002 @20C
Saltwater	1.072 @20C
Lipids	0.9-0.92
Squalene	0.86

Advantages/disadvantages

2. Lift generated by swimming:



sharks

Advantages/disadvantages

umbrella mouth gulper *Eurypharynx pelecanoides*

Summary:

- Diffusion of O_2; controlled by structure & function
- Relationship O_2 bound to Hb vs. O_2 in plasma
- Effect of pH on affinity/capacity of Hb for O_2
- Counter-current multiplier
  - length of capillaries
  - counter-current flow of blood

Growth:

- Longevity
  - unconfirmed reports of carp 200-400 yr.
  - authenticated records for carp 50 yr.
  - large fish-few > 12-20 yr.
  - some marine spp > 100 yr. thornyspines, orange roughy
  - many small spp-2 yr. or less (sardines, anchovies)

Note: aging with scales, bones, otoliths

Many Generalities:

- Sexual Dimorphism: females can be larger than males
- Growth rate a function of temperature
- Longevity inversely proportional to temperature
- Stress reduces growth
- Dominance hierarchies - dominant get food
- Overcrowding can lead to stunting
- Indeterminate growth - grow throughout life
- Growth highly variable - decreased weight gain

Bioenergetic Definition of Growth

- energy accumulation (calories) vs. length or weight

Bioenergetics continued:

- Energy Budget:

$$I = M + G + E$$

where: I = ingested energy

M = energy expended for metabolism

G = energy stored as growth

E = energy lost to environment

Bioenergetics continued:

Ex: E = energy in feces

ammonia, or urea

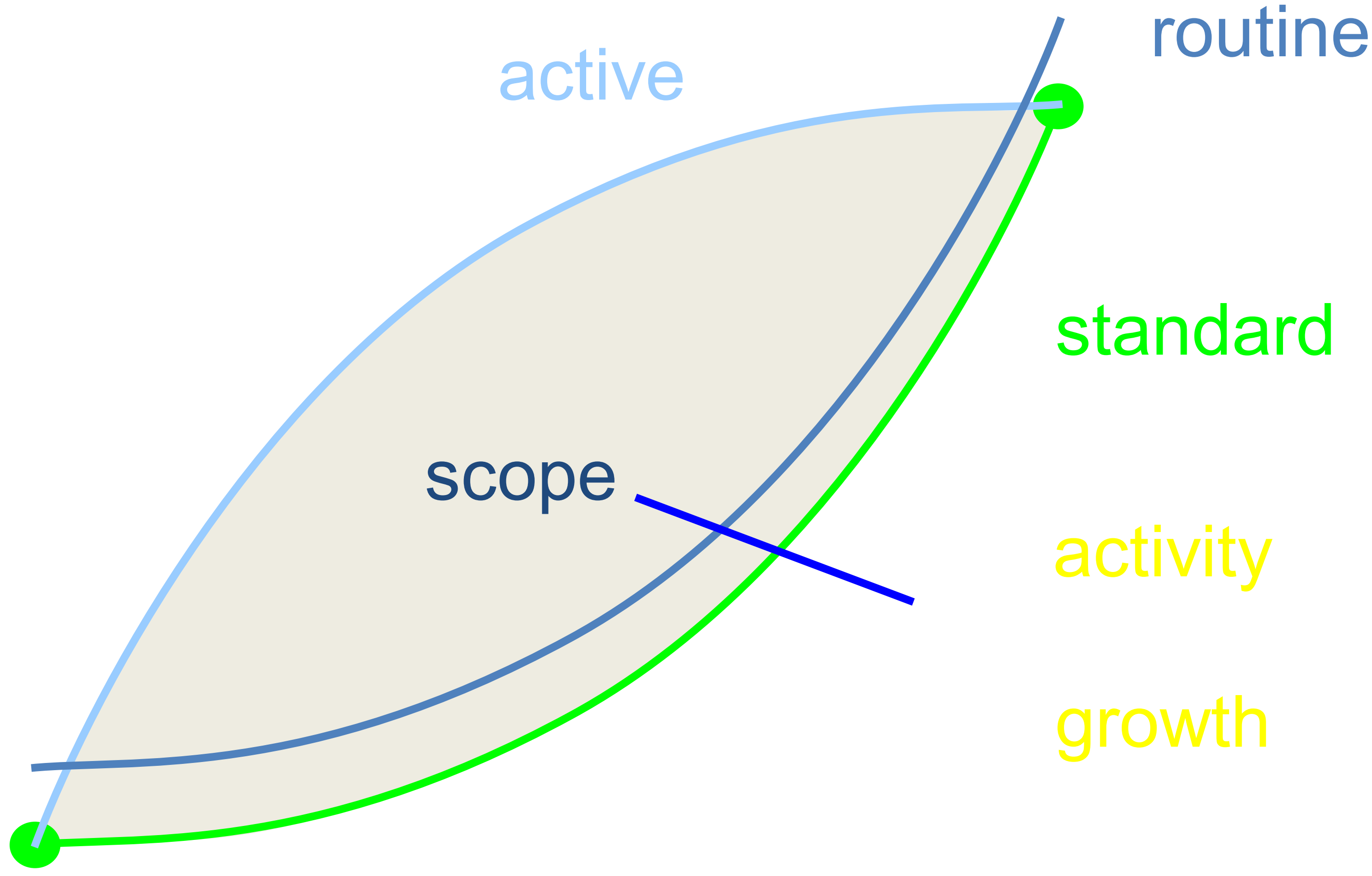
mucus

epidermal cells

Terms:

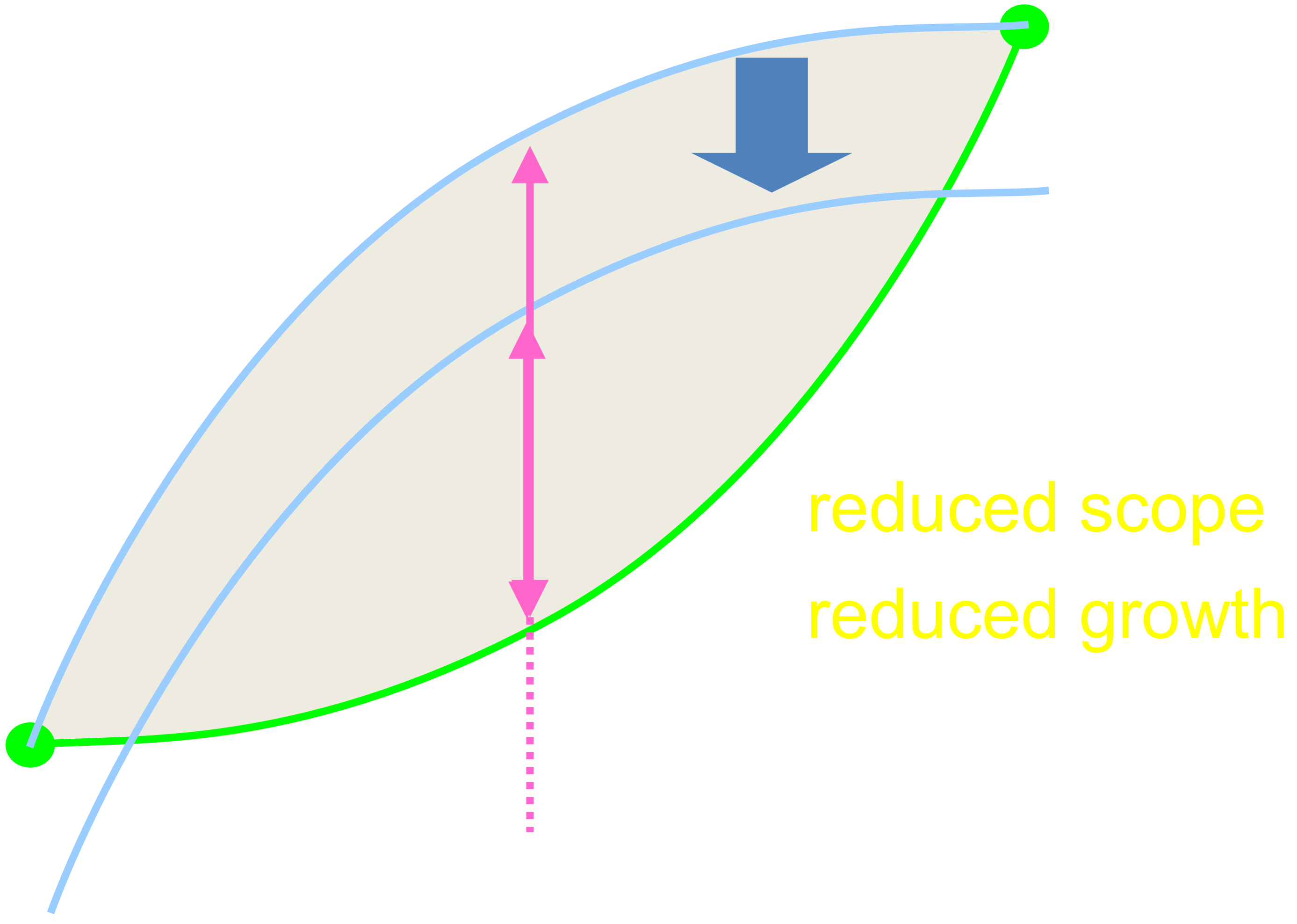
- Standard Metabolic Rate
  - maintenance met.; no growth, no activity
- Routine Metabolic Rate
  - typical met.; routine growth & activity
- Active Metabolic Rate
  - max. aerobic metabolism

Factors Affecting Growth:



Where would growth be best?

Factors Affecting Growth:



Factors Affecting Growth: