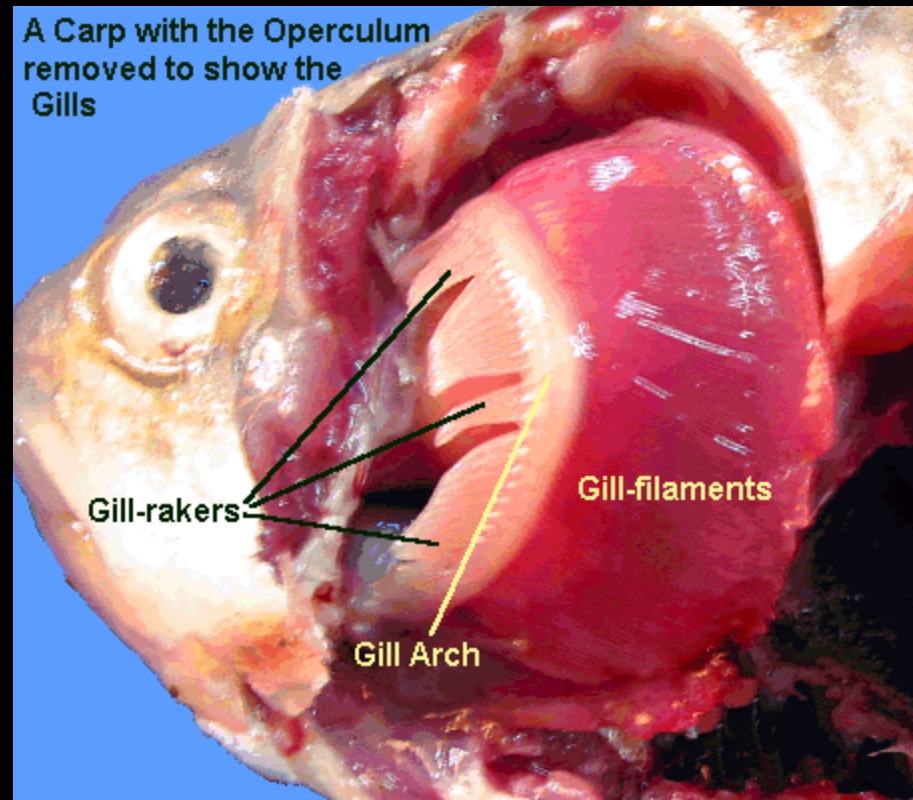# Respiratory system

1. Respiration: the capture of O_2 and elimination of CO_2
2. The buccal and opercular pumps
3. The structure and function of gills
4. Respiration and blood circulation
5. Air-breathing fishes

A Carp with the Operculum removed to show the Gills

Gill-rakers

Gill-filaments

Gill Arch

Respiration: the capture of O_2 and elimination of CO_2

- Oxygen is more readily available to terrestrial vertebrates than fishes:
- 1 l of air contains 210 cc of oxygen
- 1 l of water contains 10 cc of oxygen
- Fishes get oxygen by creating a continuous flow of water (800x more dense than air) over the gills. The steadier the flow the more oxygen is removed.
- Fish have a high oxygen removal efficiency (Tuna remove up to 80% of the oxygen in water, compared with humans that remove only 25% of the oxygen from air).
- How is this done and how is the consistent flow of water created and maintained?

The buccal and opercular pumps

In contrast to terrestrial vertebrates in which oxygen flow across the lungs is **bidirectional**—inflow and outflow associated with dead air space—oxygen flow in fishes is **unidirectional**. Water is almost always sucked in through the **mouth** and exits by way of the **opercular openings** on each side of the head. This unidirectional flow pattern negates the waste associated with dead air space and makes possible the opportunity to maintain a **constant gradient** for oxygen to diffuse from the water into the blood by way of the gills.
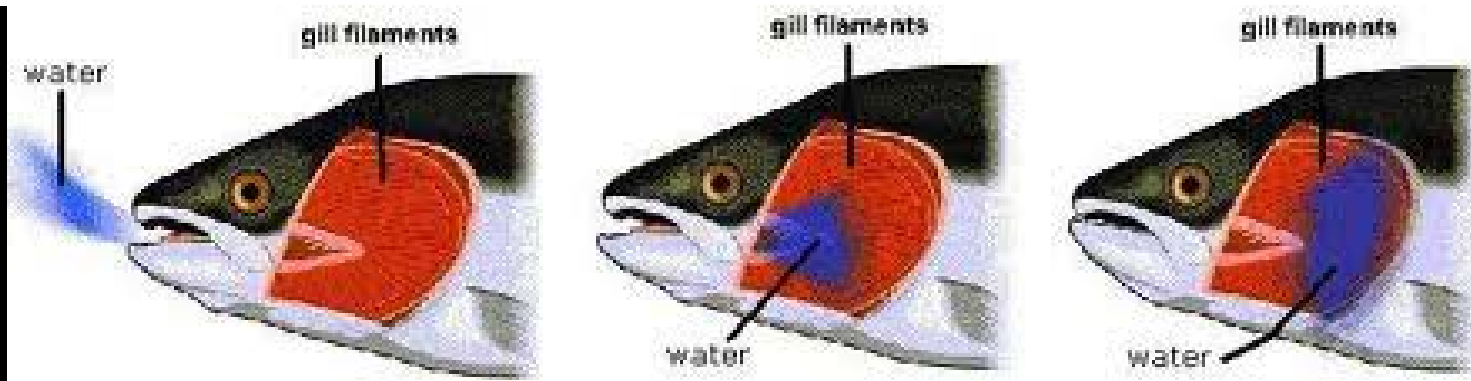
Within the pattern, however, can be seen a definite cycle of breathing that may be divided into a number of phases, two major phases and two minor phases:
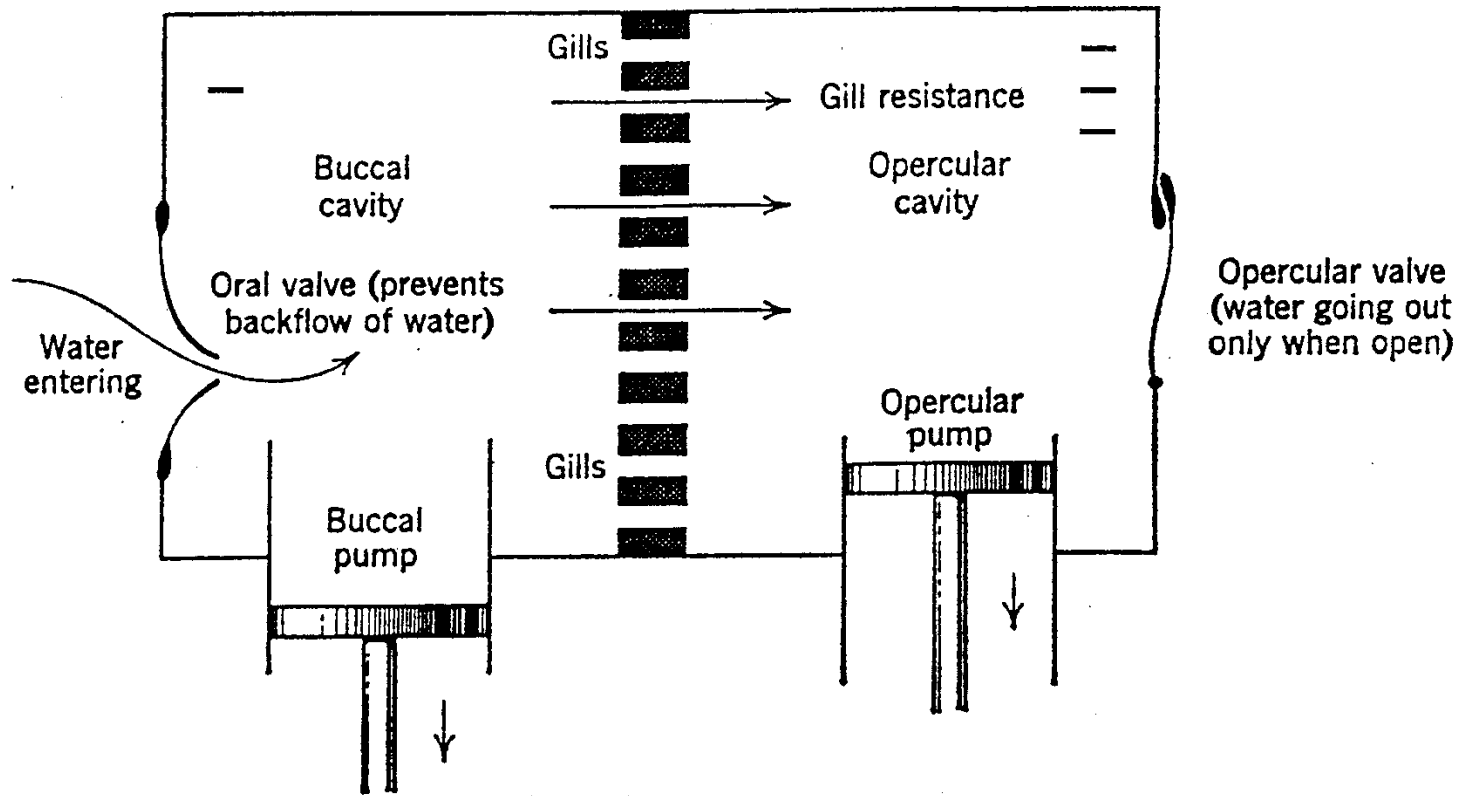
Phase 1:   the **Opercular Suction Pump**

Phase 2:   when the pressure is reduced

Phase 3:   the **Buccal Pressure Pump**

Phase 4:   when the pressure is reversed

Gills

Gill resistance

Buccal cavity

Opercular cavity

Oral valve (prevents backflow of water)

Opercular valve (water going out only when open)

Water entering

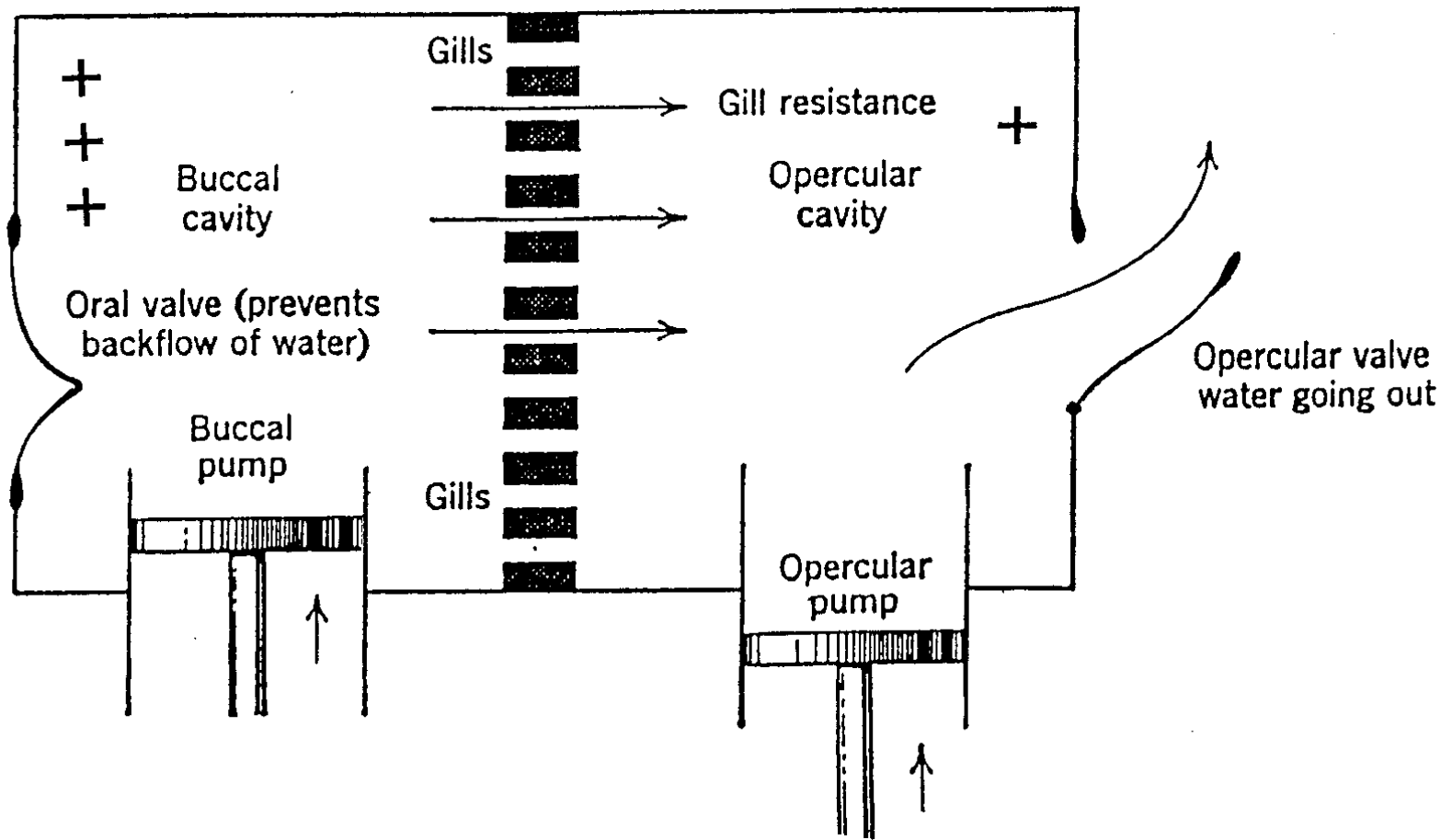Opercular pump

Buccal pump

Gills

Phase 1: The **Opercular Suction Pump**: both the Buccal and Opercular cavities expand creating negative pressure in both cavities. But, as these volume expansions take place, there is strong differential pressure, the opercular cavity being considerably more negative than the buccal cavity. Water is sucked in through the mouth (the **buccal** or **oral valve**). The opercular opening (**opercular valve**) is held tightly closed.
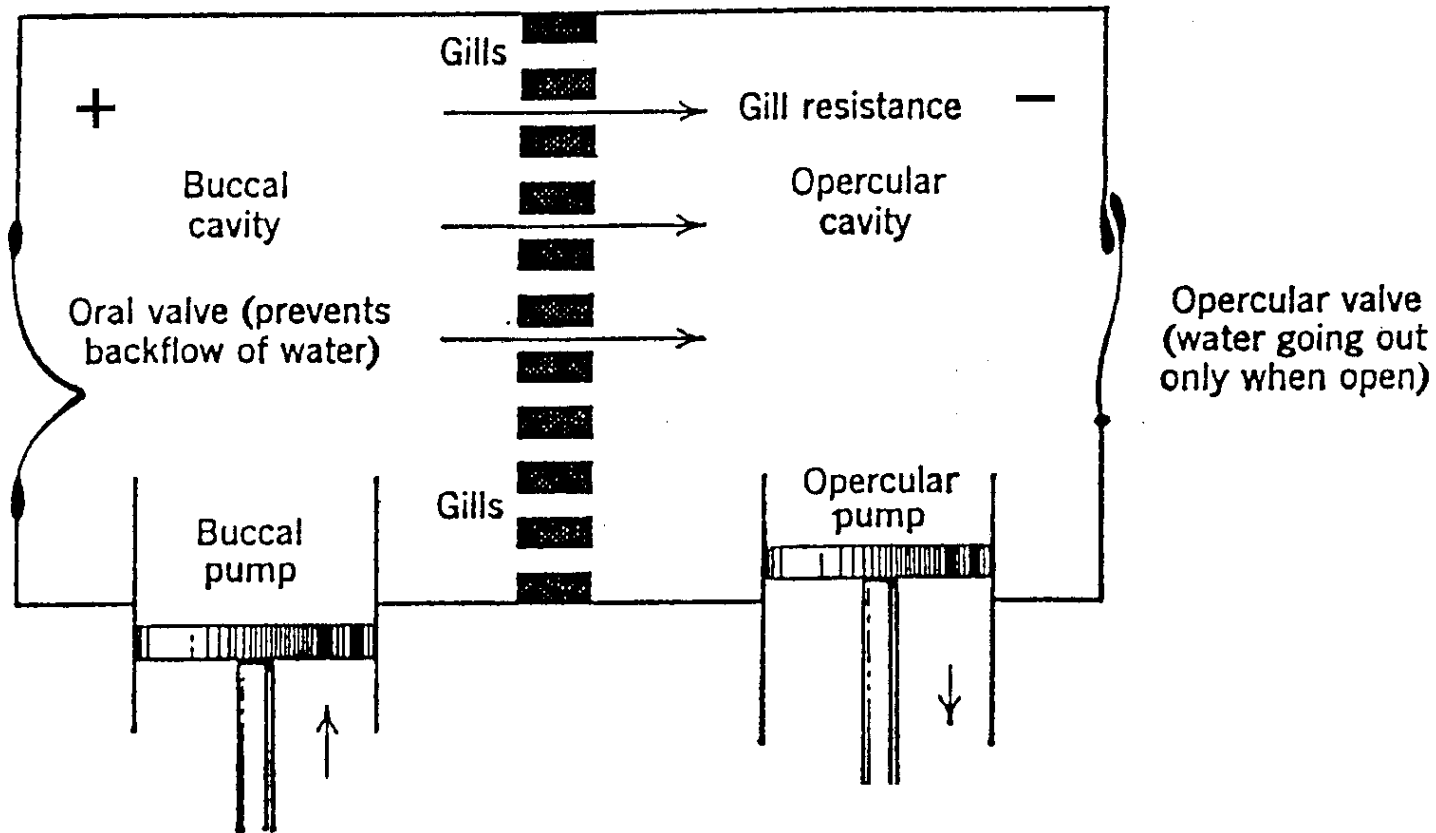
Phase 2: The mouth closes and the buccal cavity contracts, creating positive pressure in the buccal cavity and causing a reduced pressure differential between the two cavities. This phase is of very short duration.
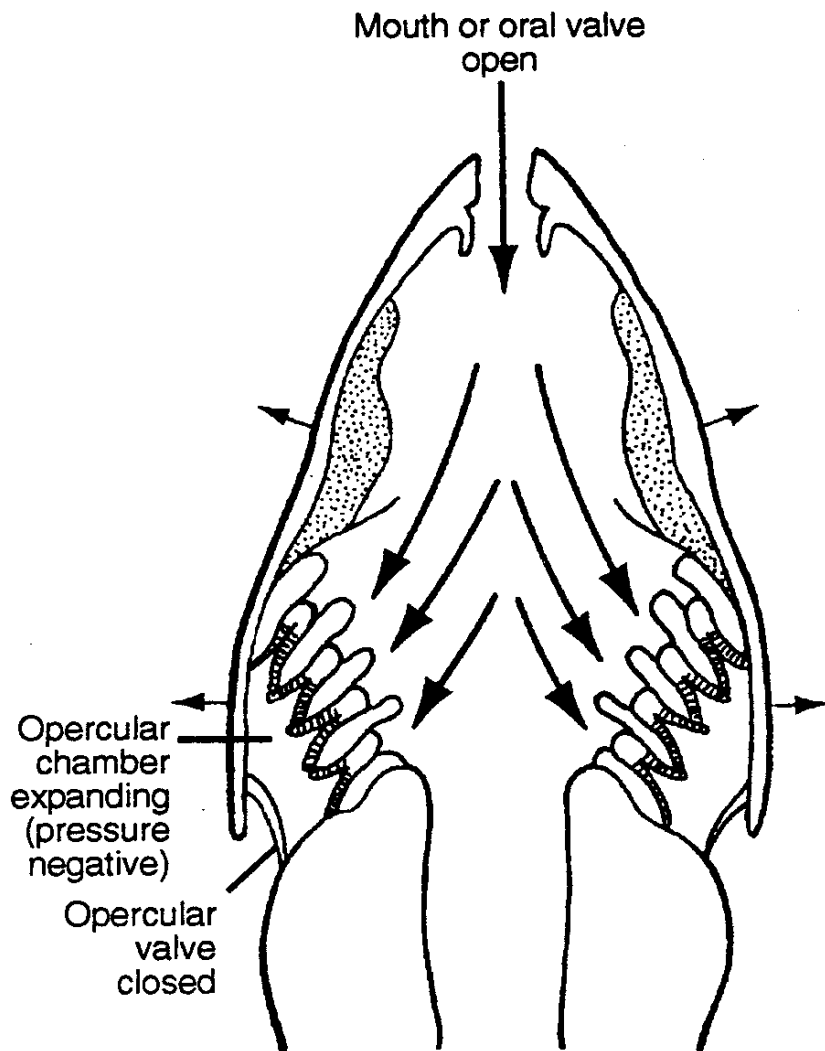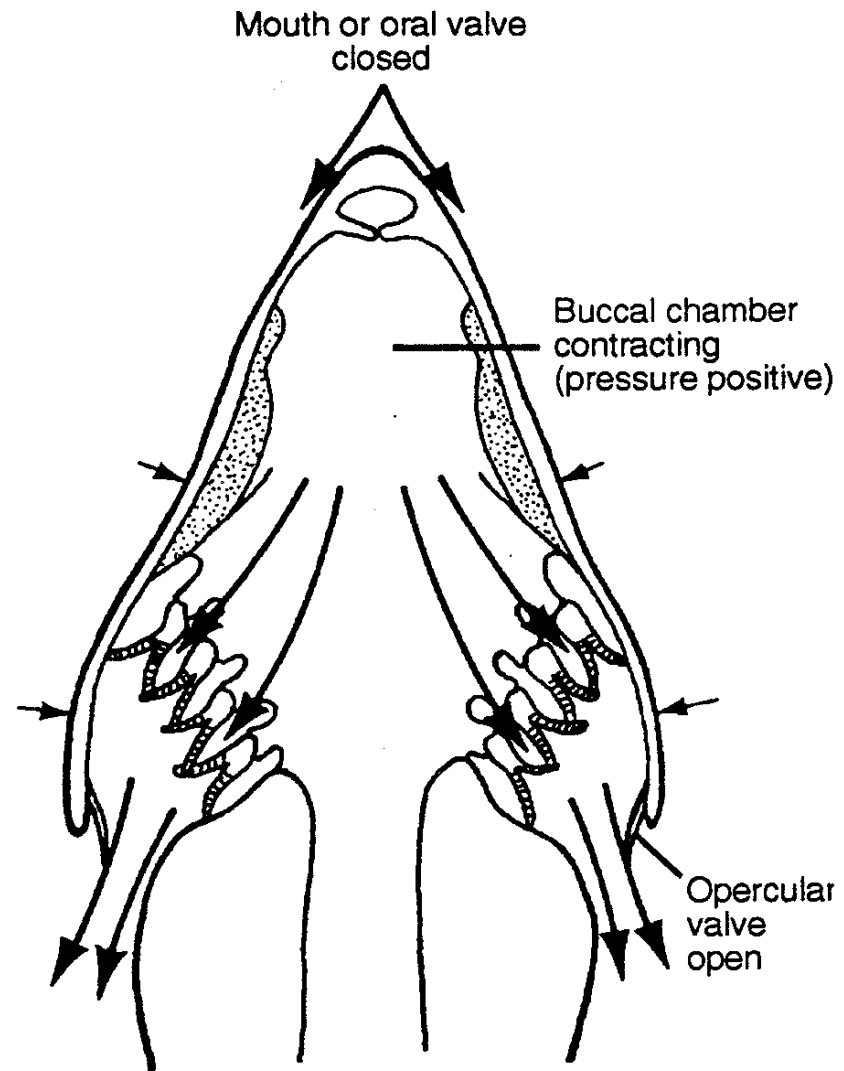
Phase 3: The **Buccal Pressure Pump**: the buccal cavity is further compressed, while the opercular cavity is being compressed as well, causing water to be pushed out through the opecular opening. Pressure is positive in both cavities, but the pressure differential between the two cavities is maximized.
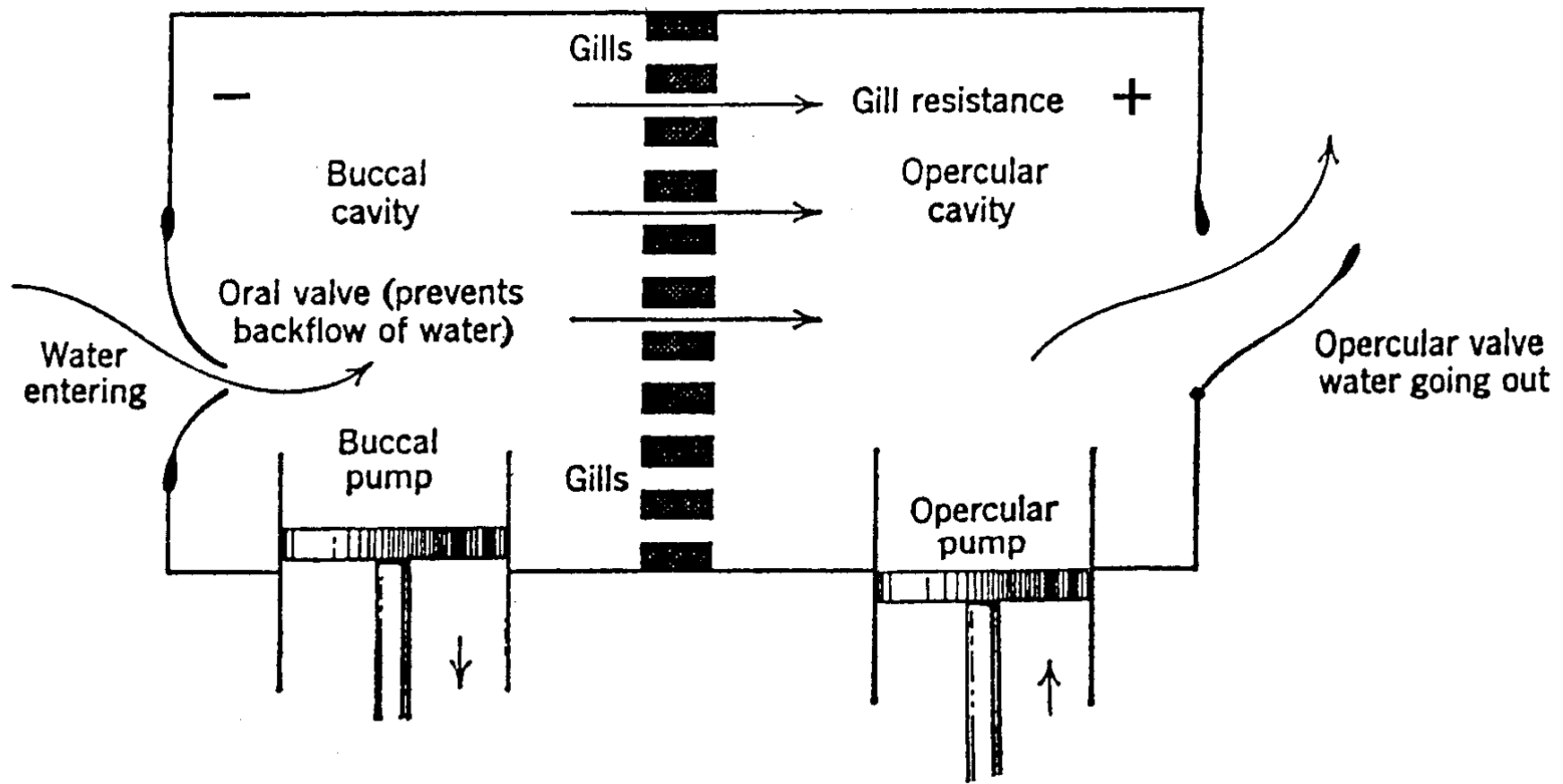
Phase 4: The buccal cavity expands while the opercular cavity is still being compressed. There is a slight reversed differential pressure between the two cavities, but this lasts for only a very short time.

Mouth or oral valve open

Mouth or oral valve closed

Buccal chamber contracting (pressure positive)

Opercular chamber expanding (pressure negative)

Opercular valve closed

Opercular valve open

Suction pump phase

Pressure pump phase

The timing of the expansion and contraction of the buccal and opercular cavities ensures that the pressure in the buccal chamber exceeds that of the opercular chamber throughout nearly all of the respiratory cycle. This creates a nearly steady flow of water from the buccal chamber to the opercular chamber, passing over the gill lamellae, which have blood flowing through them in the opposite direction

The application of modern, sensitive, and stable **pressure transducers** has resulted in accurate pressure measurements in both the **buccal** and **opercular cavities**. The recordings show that the gills have an appreciable resistance to water flow so that a differential pressure is always present, usually with the gradient from buccal to opercular cavity. In other words, pressure in the buccal cavity is nearly **always positive** with respect to pressure in the opercular cavity.

With sensitive pressure transducers we can also record the **time course** of the differential pressure between the two cavities. In a typical perch-like fish, for example, a wrasse of the genus *Crenilabrus* (family Labridae), the two pumps are balanced. That is, Phase 1 and Phase 3 have more-or-less equal time duration:
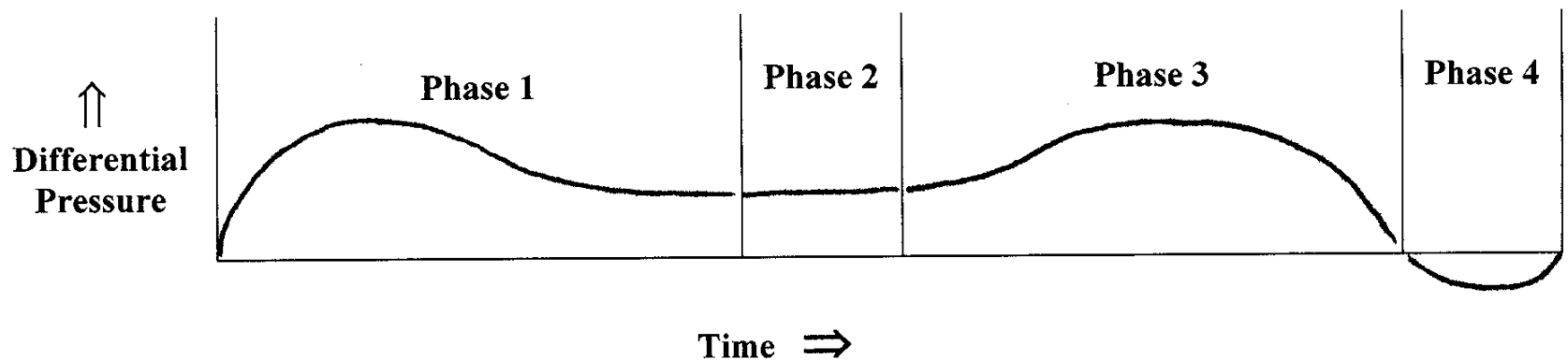
But, the time duration varies tremendously among fishes, depending on the **speed** with which they move through the water, or on **oxygen availability** in the particular environment to which they are adapted. In more slowly swimming species like various cods (family Gadidae), the opercular pump predominates. In faster swimming forms like jacks (family Carangidae), the buccal pump predominates.

In other pelagic forms, the pumps may not be used at all. For example, in fishes like mackerels and tunas (family Scombridae), which swim continuously at a good rate of speed, moving long with the mouth open and allowing the water to flow in and through the buccal and opercular cavities is enough to supply adequate oxygen to the gills. The stream of water can be regulated simply by the degree of mouth opening.

In many bottom living fishes, there is a tendency to increase the duration of the **inspiratory phase**, that is, the opercular pump phase. Thus phase 1 is of long duration, while phase 3 is relatively short:
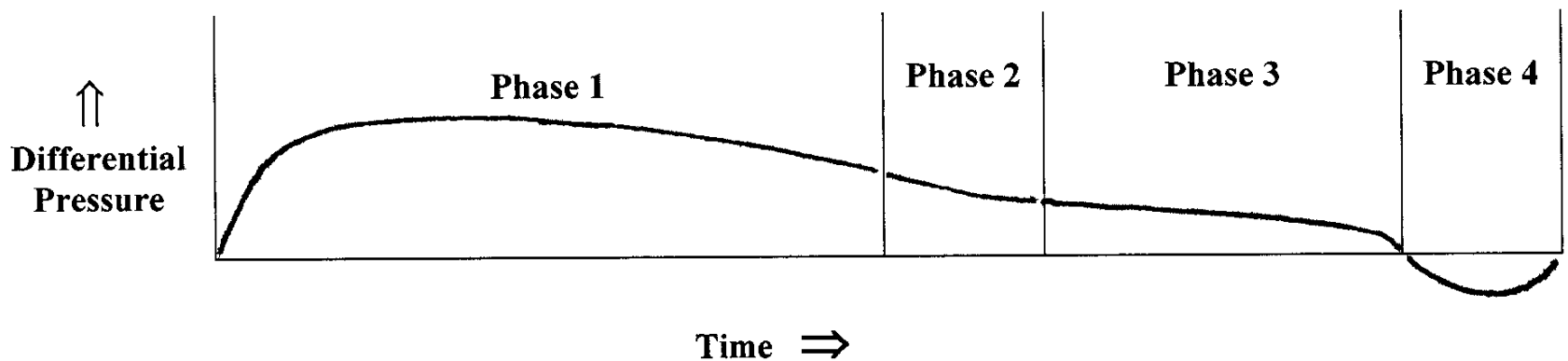
In truly benthic forms, especially those highly modified for existence on the bottom, like flatfishes, an accessory pump has evolved, the **Branchiostegal Pump**.

In these forms, the **branchiostegal apparatus** plays an important role in respiration forming an accessory pump that works along with the opercular pump. The buccal pump plays a relatively minor role.

The **inspiratory phase** (the time taken to draw water in through the mouth) is increased. Combining the accessory pumping action of the **branchiostegal rays** with the opercular suction pump completely eliminates the reversal of differential pressure usually characteristic of phase 4.
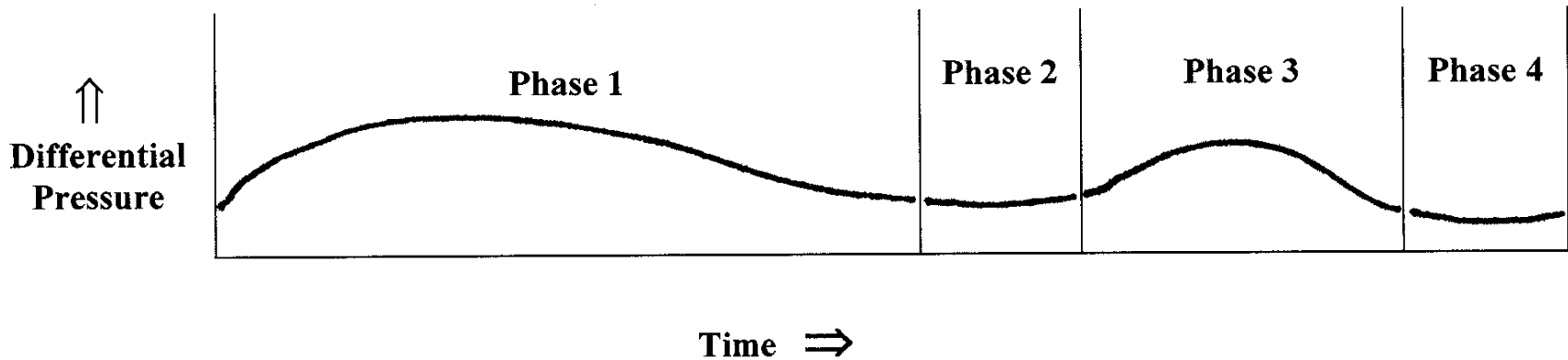

This is a great advantage for a fish with limited time spent progressing forward and with limited opportunity to meet new oxygenated water. Many benthic habitats, where currents may be relatively slow moving, are oxygen limited to begin with—anything that would increase the efficiency of extraction of oxygen would provide a distinct advantage.

Structure and function of the gills

The gills of a sieve-like structure in the path of the respiratory flow. They produce resistance to water flow, which, in turn, creates a differential pressure between the buccal and opercular cavities.
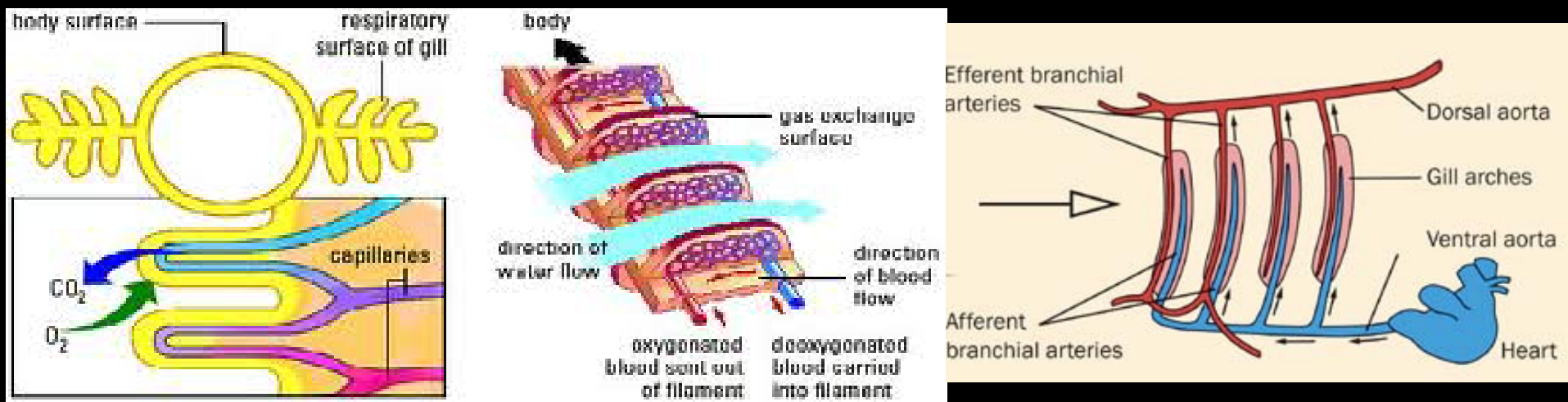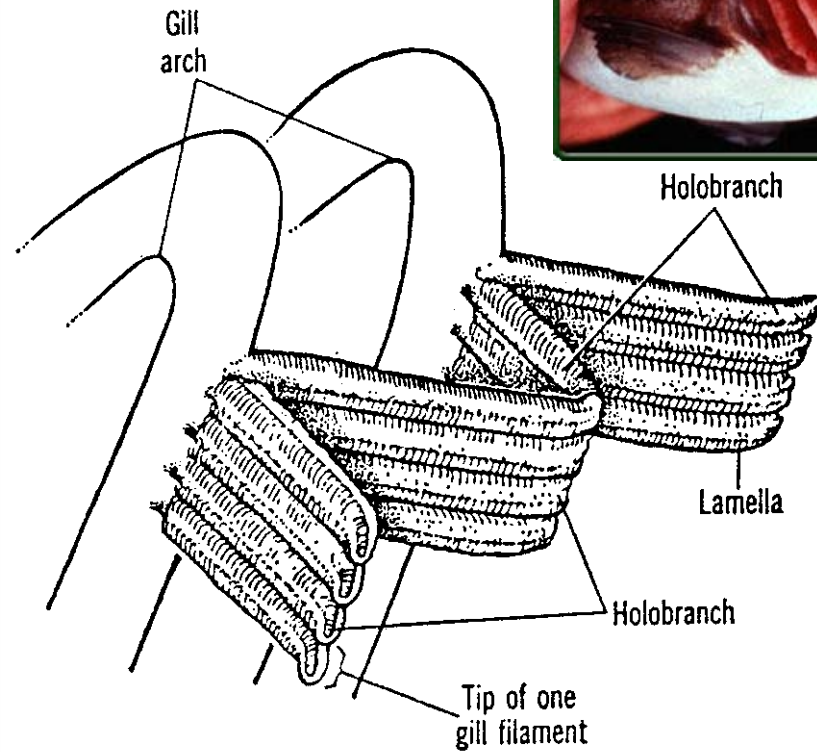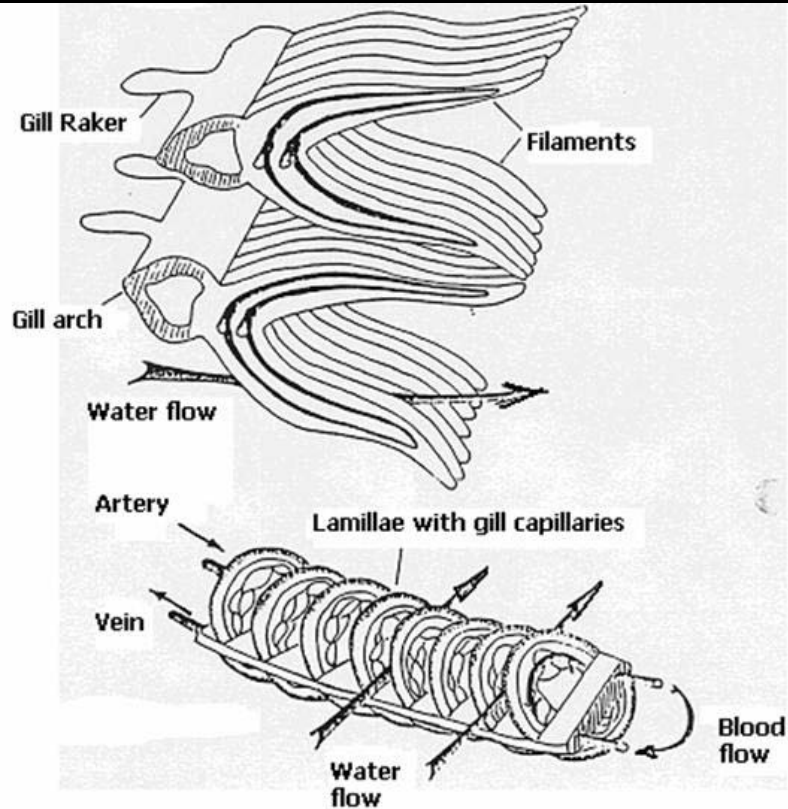
Several abducted gill filaments on two adjacent gill arches. Note that each gill filament or holobranch is paired, consisting of two hemibranchs. Note Also that the tips of adjacent holobranchs come into contact with each other at the distal tips.

Each gill arch bears a number of **gill filaments** or **holobranchs**, each of which is made up of two halves, called **hemibranchs**. Each hemibranch bears many fine subdivisions called **gill lamellae**. It is the gill lamellae that form the major part of the sieve through which water passes. They are primarily responsible for creating the resistance to water flow and which represent the major respiratory portion of the gills. The total surface area of the gill lamellae averages about 5 cm^2 per gram of body weight.

In all bony fishes there are **muscles** that move the bases of the **hemibranchs**, that is, each **holobranch** can open and close. In this way, the tips of the hemibranchs of adjacent gill arches can come into contact with one another to create **maximum resistance** to water flow or they can be separated to protect the gills against excess water flow.
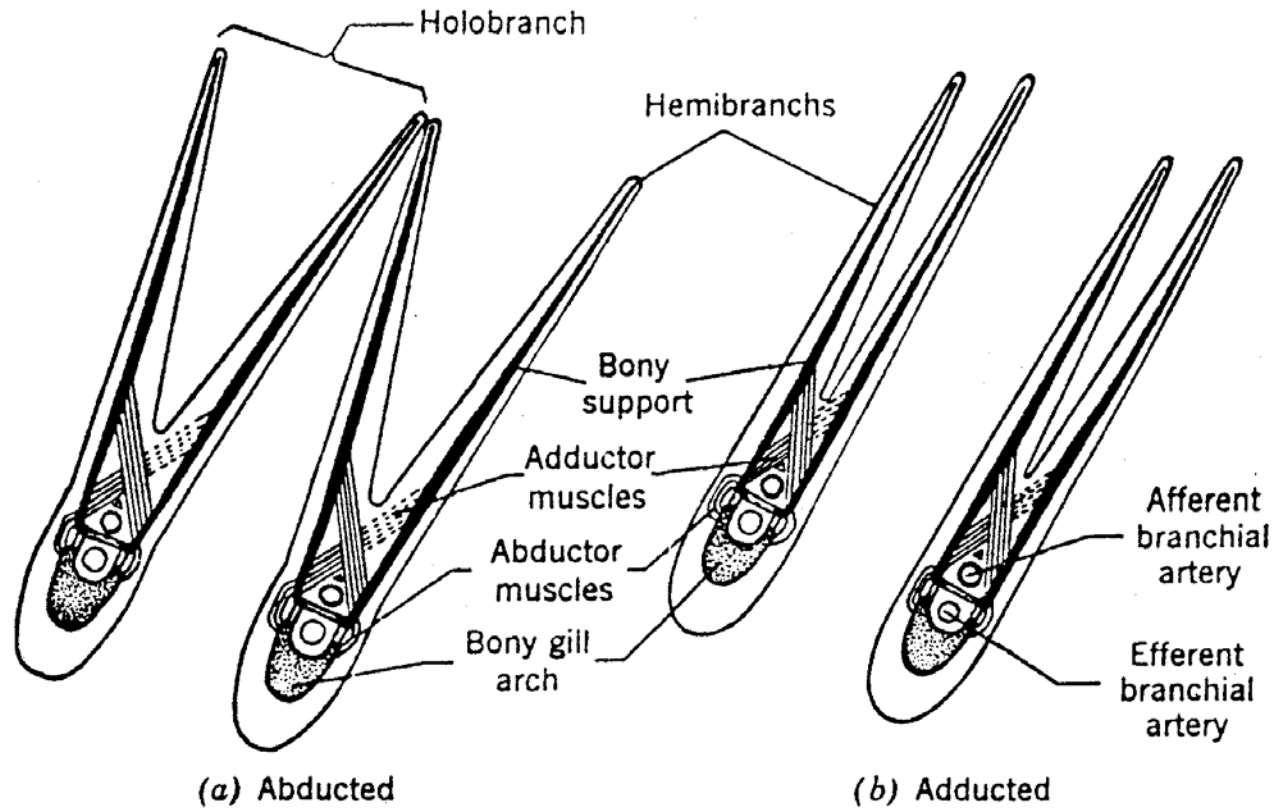
Diagrammatic cross sections through adjacent holobranchs of a bony fish showing supporting and muscular elements that enable (a) abduction and (b) adduction. These muscles thus perform a regulatory function whereby resistance of flow by the gills can be actively varied and regulated.

Air breathing fishes

In all tropical regions of the world, **deoxygenation** is frequent in shallow and stagnant waters. Whenever water is slow-moving, covered with vegetation, and heavily shaded so that **photosynthesis** is slight, and where cooling at night is not sufficient to produce overturn, **deoxygenation** is bound to occur.

The only oxygen in these waters gets there by **diffusion** from the air. Usually freshwater habitats are the only ones effected, but also estuarine habitats are susceptible, especially mangrove swamps. Deep lakes like those of the East African Rift Valleys can also be affected. In marine habitats, entire deep basins may be deoxygenated, for example, the Cariaco Trench off the coast of Venezuela.

Many bony fishes inhabiting such waters have evolved special **air-breathing structures** to cope with these unusual conditions. Others have evolved ways to live out of the water for extended periods of time.

List of Air-breathing Fishes Arranged Phylogenetically

Preteleostei:
  Amia, airbladder functions as a lung
  Lepisosteus, airbladder functions as a lung
Teleostei:
  Osteoglossomorpha:
    Arapaima, airbladder
    Heterotis, airbladder
    Clupisudis, airbladder
    Notopterus, airbladder
  Elopomorpha:
    Megalops, airbladder
    Anguilla, skin and pharynx
  Euteleostei:
    Ostariophysi:
      Cyprinoids:
        Misgurnus, intestine
        Cobitis, intestine
      Characoids:
        Erythrinus, airbladder
        Hypopomus, gill chamber
        Electrophorus, pharynx
      Siluroids:
        Clarias, pharynx
        Dinopterus, pharynx
        Doras, intestine
        Callichthys, intestine
        Plecostomus, stomach
        Ancistrus, stomach
        Heteropneustes, outgrowths of the branchial chamber
        Saccobranchus, outgrowths of the branchial chamber
    Acanthopterygii:
   Anabantoidei, specialized structures in the branchial chamber
      Ophicephalidae, pharynx
      Periopthalmus, pharnyx
      Synbranchiformes, esophagus and skin

The **accessory air-breathing structures** of bony fishes are all modifications of the **epithelia** of the **alimentary canal**, or **gill chamber**, or diverticula emerging from these parts. This includes a host of structures: the mouth, pharynx, gill chamber, esophagus, airbladder, stomach, and intestine. Here is an example:
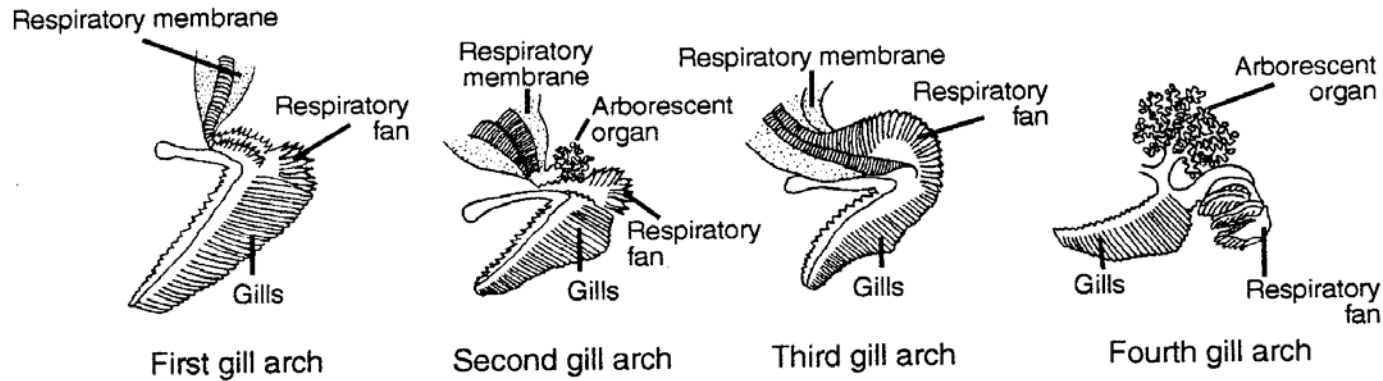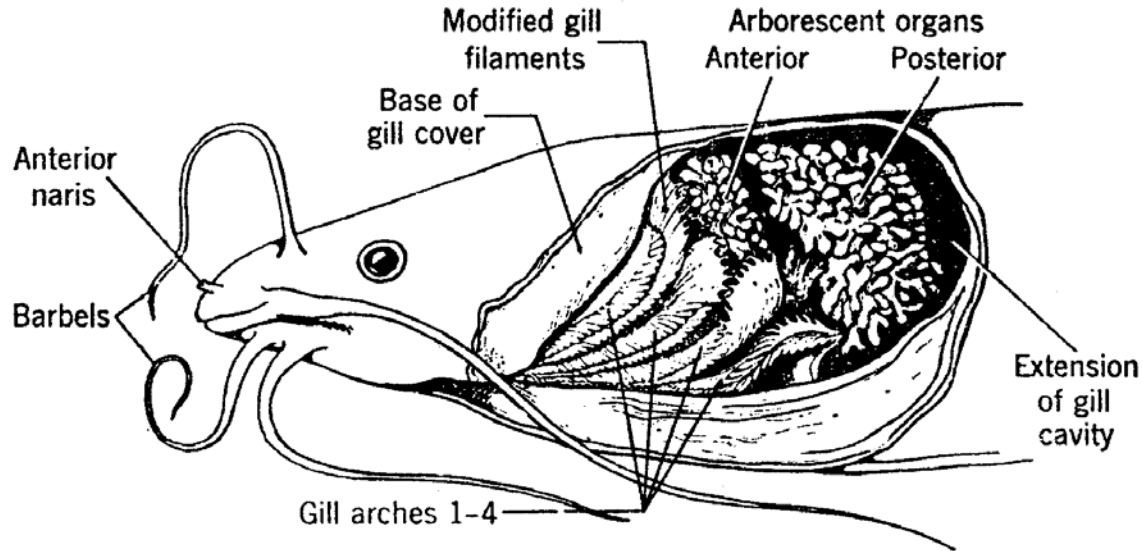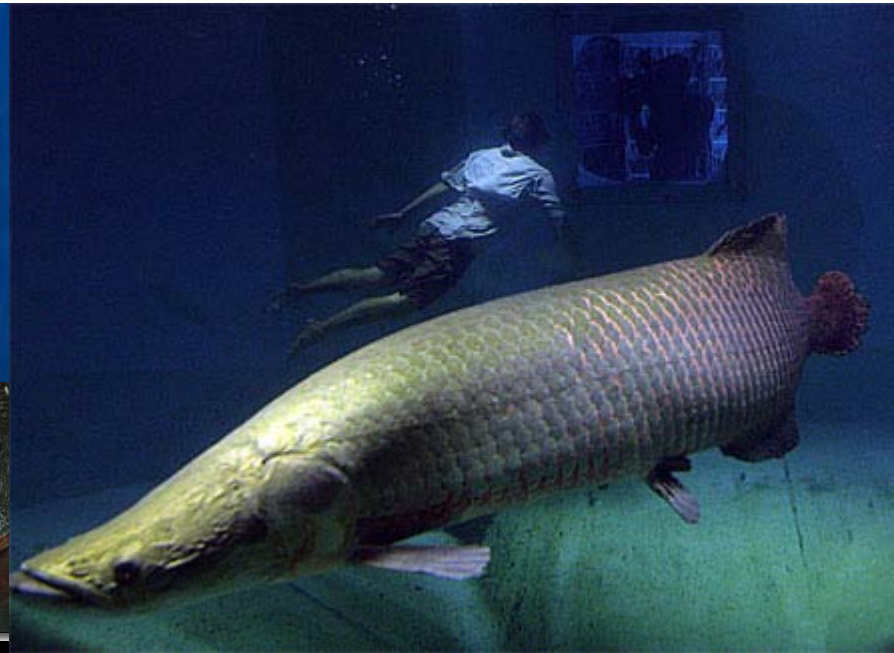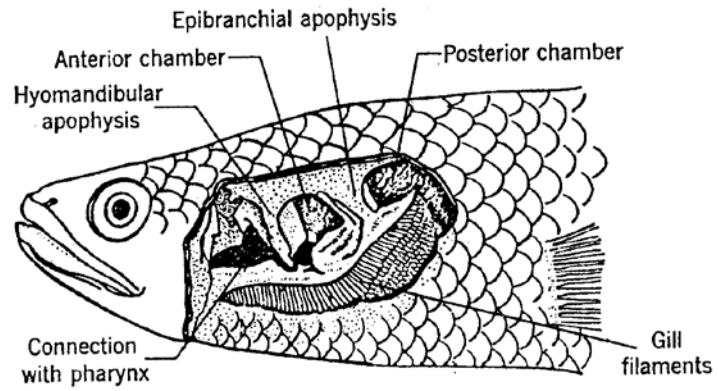

Lateral views of the gill arches of the walking catfish (*Clarias batrachus*) showing the respiratory fans, respiratory membranes of the suprabranchial chamber, and tree-like extensions that permit the fish to extract oxygen from air when it is out of water.

All have in common a specialized **epithelium** that is often equipped with branched, tree-like **outgrowths** to increase the **surface area**. Lying underneath this thin epithelial layer is always a rich network of **blood capillaries**.
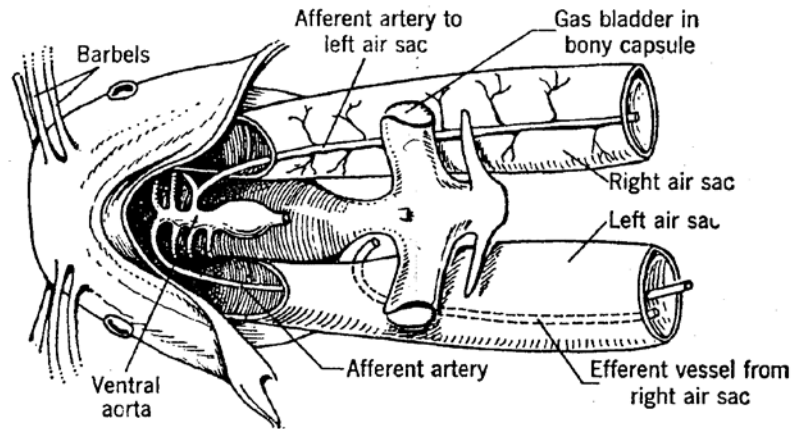
Gills are never used for air breathing because they are poorly adapted for it. The **gill lamellae** are not stiff enough to support themselves and collapse when out of water. The surface area is lost and the fish suffocates.

All air-breathing organs function just as absorbers of **oxygen**, they never have anything to do with **carbon dioxide**. The gills and/or the skin take care of the excretion of carbon dioxide.
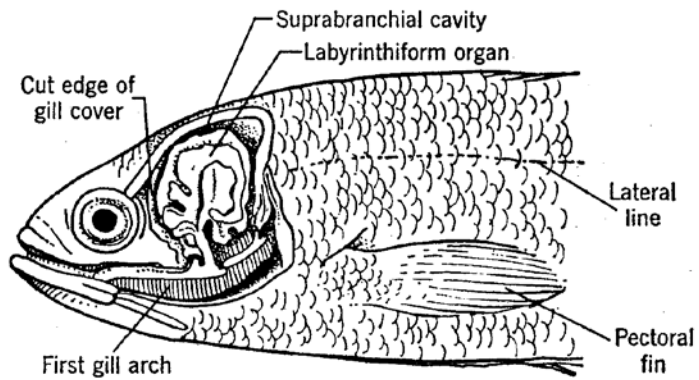
Epibranchial apophysis

Anterior chamber

Posterior chamber

Hyomandibular apophysis

Connection with pharynx

Gill filaments

Snakehead, genus *Ophicephalus*

Barbels

Afferent artery to left air sac

Gas bladder in bony capsule

Right air sac

Left air sac

Ventral aorta

Afferent artery

Efferent vessel from right air sac

Airsac catfish, genus *Heteropneustes*

Suprabranchial cavity

Labyrinthiform organ

Cut edge of gill cover

Lateral line

First gill arch

Pectoral fin

Climbing perch, genus *Anabas*

Adaptive strategies: a trend toward the separation of the organs dealing with oxygen uptake and carbon dioxide discharge.

Most air-breathers have evolved a new organ by modifying some existing structure. This new organ deals with **oxygen** uptake from the air—elimination of **carbon dioxide** is done by way of the gills.

A few air-breathers have evolved a new respiratory organ by modifying an existing structure for oxygen uptake, but, at the same time, the gills have become greatly reduced. Scales are reduced as well and the skin is used for the discharge of carbon dioxide. Synbranchiforms and the goby genus *Periophthalmus* fall into this latter category.

What is the biological significance of air breathing?

1. Survival in oxygen poor habitats

2. Utilization of terrestrial food resources

3. Abandon drying ponds to search for better habitat

4. Invade new territories and thus enhance distribution.