AQUATIC ADAPTATIONS

Lecture 2

Aquatic Adaptations

- Adaptation is an evolutionary process whereby an organism becomes increasingly well suited to living in a particular habitat. It is not a quick process!

- Natural selection over many generations results in helpful traits becoming more common in a population. This occurs because individuals with these traits are better adapted to the environment and therefore more likely to survive and breed.

- In other words, an adaptation is a feature of an organism that enables it to live in a particular habitat.

When animals live in the water, they must have special adaptations to help them survive in an aquatic habitat. The more time an animal spends in the water, the more adaptations the animal will have for an aquatic life. Below are examples of some of these adaptations:

1. Streamlined body reduces friction when the animal moves through the water.
2. Smooth, almost furless body helps aquatic mammals move through the water with little friction.
3. Dense fur helps streamline the bodies of some aquatic mammals and keeps them warm.
4. Dense waterproof feathers keep cold water away from bird's skin and prevent wetting of the feathers.

5. Webbed feet, formed from thin skin between the toes, work like paddles.
6. Long legs and necks keep the bodies of wading birds out of the water and are thin, light, and easy to move, and the long neck helps the birds to reach the water, or below it, for food.
7. Strainers in the mouth filter food particles from the water.
8. Flippers provide a large surface for pushing against water and act like paddles.
9. Eyes positioned on top of the head allow animals to hide almost fully submerged in water and still detect predators or prey above the water.
10. Nostrils positioned near the top of the head allow animals to come to the surface to breathe while only a small part of
the body can be seen.
11. Nostrils close when the animal goes under the water.
12. Blubber, a thick layer of fat or oil stored between the skin and muscles of the body, provides insulation.
13. Transparent eyelids cover the eyes of animals swimming underwater.
14. Flattened tails serve as paddles.

Freshwater vs. Marine Habitats

The obvious difference when comparing these two extremes is the salinity of the water, and the differences associated with that salinity.

One obvious consequence of the difference in salinity is the change in osmoregulatory strategy that must take place.

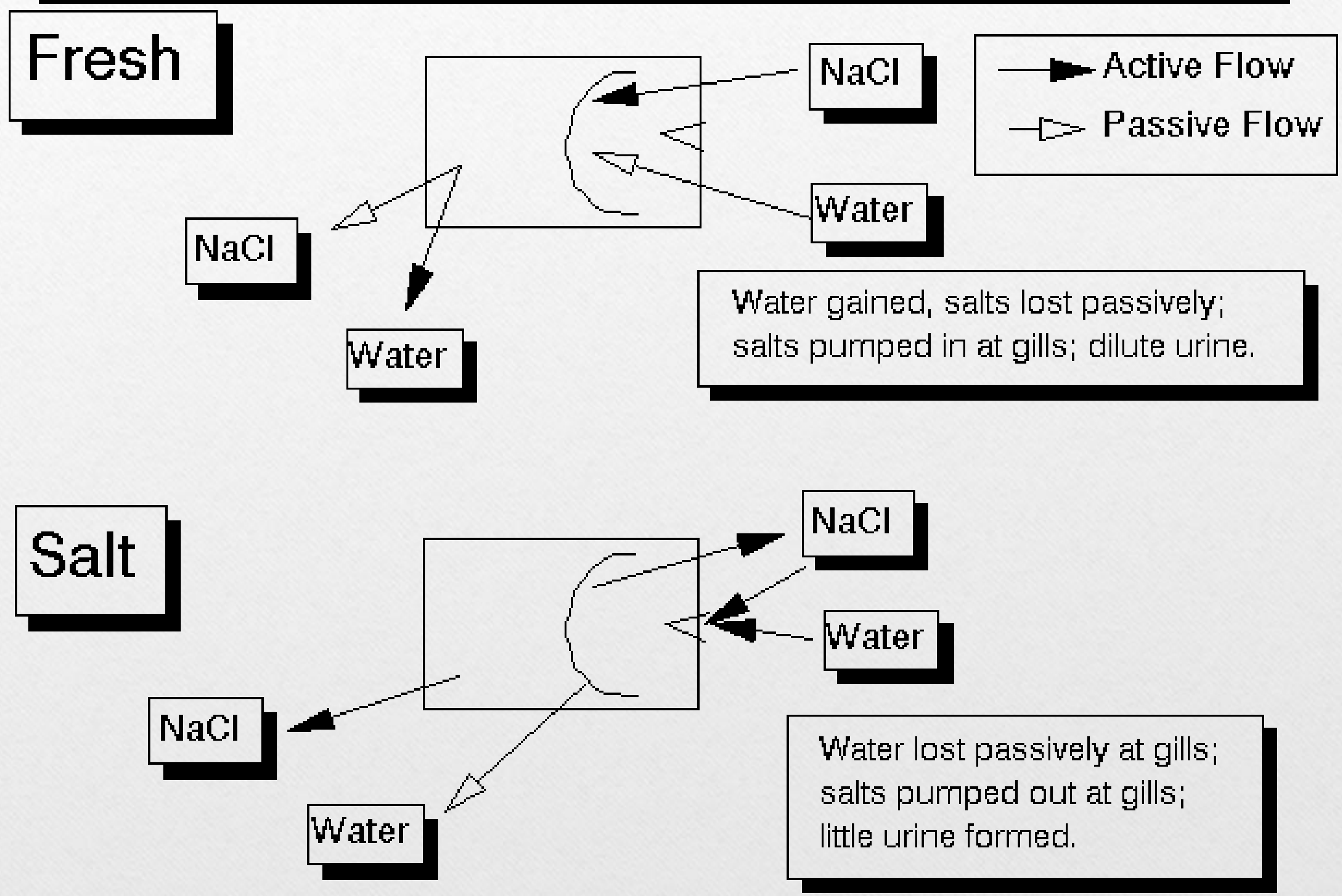
Many organisms in salt water are osmoconformers, essentially isotonic in relation to the seawater, although they may regulate certain ions at levels different from those of the surrounding ocean.

E.g . Osmoconformers : **Hagfish** internal salt concentration = seawater. However, since they live in the ocean....no regualtion is required.

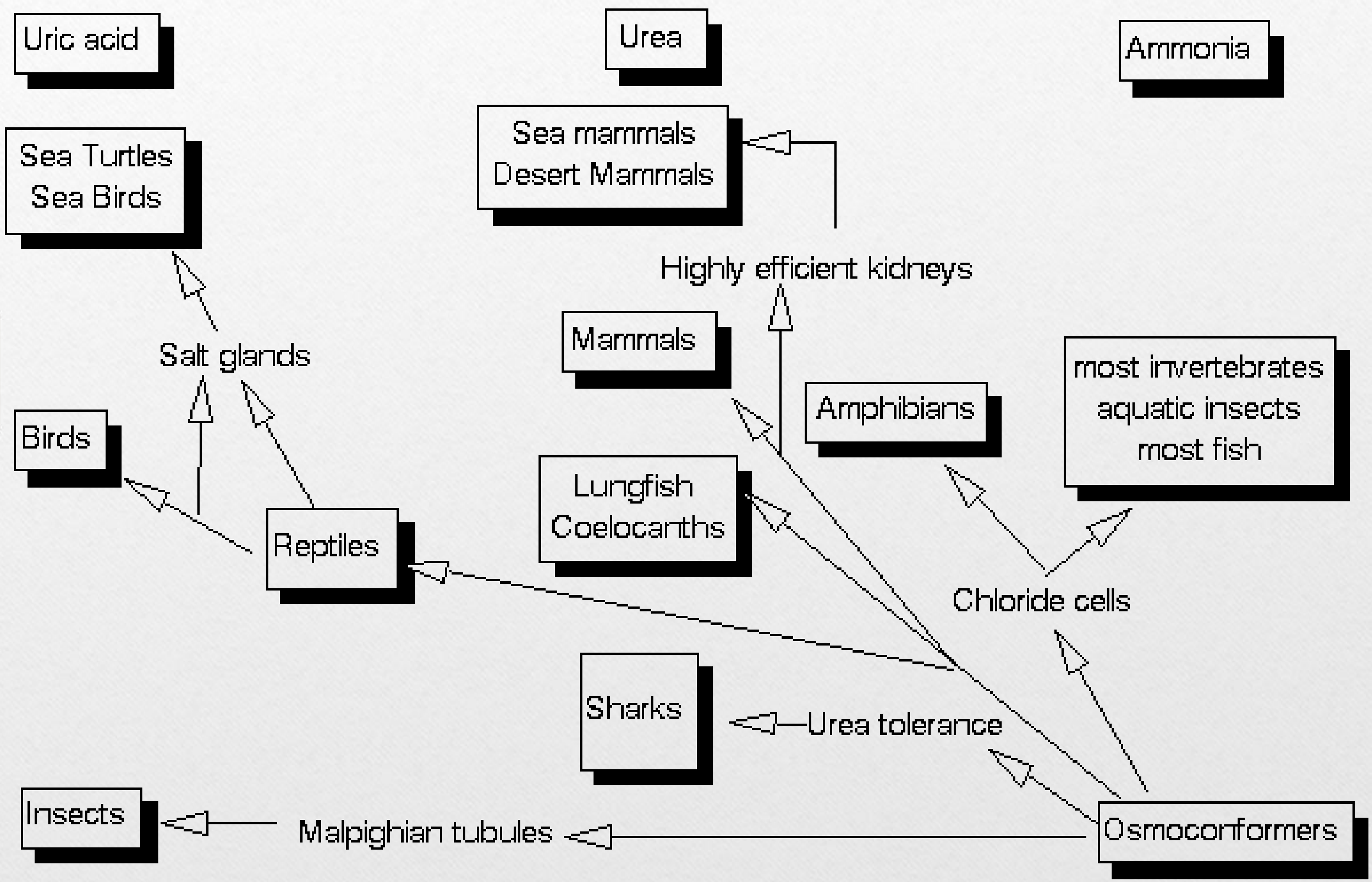
Osmoregulation = aquatic animals

- Question : why is this important
  - Low solute concentration: cells shrink
  - High solute concentration: cells burst
  - Cells need proper ion balance to function
    - Muscle, nerve cells; Na+/K+ pump
  - Problem: solution
  - Freshwater fish
    - Water gain: produce lots of dilute urine
    - Salt loss: pump salt in through chloride cells in gills
  - Marine fish
    - Osmoconformers: no regulation
    - ionoconformers: increase plasma solutes—Urea
    - Osmoregulators
      - Lose water: drink lots of sea water, produce little urine
      - Gain salt: Chloride Cells in gills
  - Marine birds
    - Gain salt: excrete salt in salt glands
  - Marine mammals
    - Gain salt: excrete hi solute urine

Osmotic Regulation in Fresh and Salt Water



Evolution of excretory and osmoregulatory strategies



- There are two main types of osmoregulatory environments in which aquatic animals live: freshwater and marine.

- Aquatic animals are either euryhaline or stenohaline, depending on their ability to tolerate different salinities.

- Animals that maintain an osmotic difference between their body fluid and the surrounding environment are osmoregulators. Freshwater animals (all osmoregulators) include invertebrates, fishes, amphibians, reptiles, and mammals.

- Cartilaginous fishes such as sharks, rays, and skates, have plasma that is approximately isosmotic to seawater.

- This unusually high osmotic concentration (compared to that of other vertebrates) is maintained by high levels of urea and trimethylamine oxide (TMAO) in the blood.

- In most vertebrates, levels of urea this high would damage proteins, but the presence of the TMAO helps to stabilize these protein molecules against the adverse effects of urea.

- Excess inorganic electrolytes, such as Na+ and Cl- which diffuse into the blood at the gills, are excreted by way of the kidneys and also by means of a special excretory organ called the rectal gland that is located at the end of the alimentary canal.

- The freshwater animals are generally hyperosmotic to their environment.

- The problems that they face because of this are that they are subject to swelling by movement of water(endosmosis) into their bodies owing to the osmotic gradient, and they are subject to the continual loss of body salts to the surrounding environment (which has a low salt content).
- The way these animals deal with these problems is to produce a large volume of dilute urine.
- The kidney absorbs the salts that are needed, and the rest of the water is excreted. Another way these animals deal with lack of salt is by obtaining it from the food they ingest.

- A key salt replacement mechanism for freshwater animals is active transport of salt from the external dilute medium across the epithelium into the interstitial fluid and blood. Amphibian's skin and fish gills are active in this process.

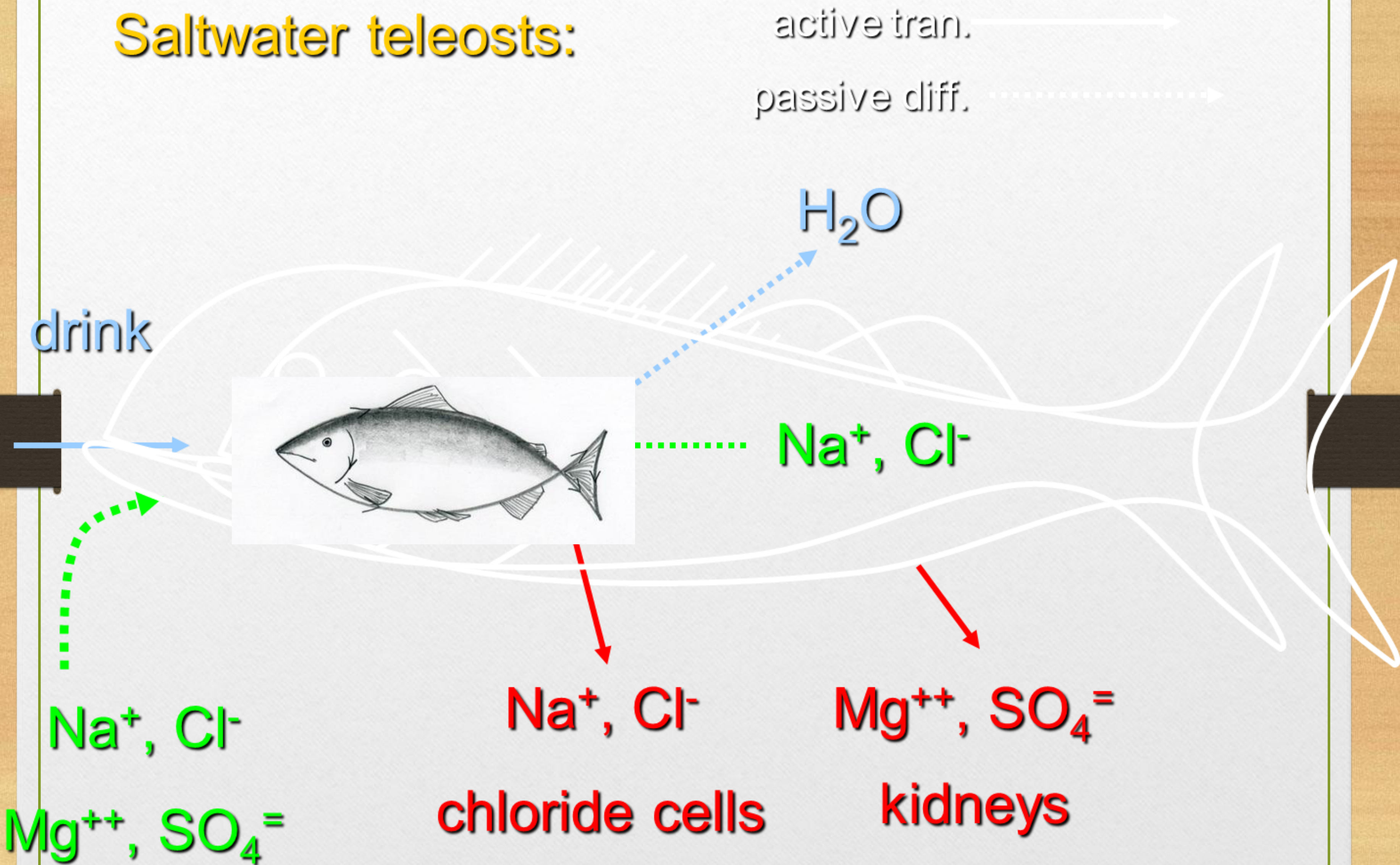
- Among marine animals, most invertebrates are osmoconformers whereas most vertebrates are osomoregulators.

- There is a tendency for marine fishes to lose water to the environment through the gill epithelium. The net result of combined osmotic work of the gills and kidneys in the marine teleosts is a net retention of water by the kidneys.

- Marine reptiles (iguanas, sea turtles, crocodiles, and sea snakes) drink seawater to obtain a supply of water but are unable to produce a concentrated urine that is significantly hyperosmotic to their body fluids. They compensate for this by the use of specialized glands for the secretion of salts in a strong hyperosmotic fluid.

- Salt glands are generally located above the orbit of the eye and nose in lizards. The salt glands of marine reptiles secrete a sufficiently concentrated salt solution to enable them to drink saltwater even though their kidneys are unable to produce urine more concentrated than seawater.

Saltwater teleosts:



- The body fluids of marine teleosts, like those of higher vertebrates, are hypotonic to seawater, so there is a tendency for these fishes to lose water to the environment, especially across the gill epithelium.

- To replace the water, they drink salt water and actively secrete the excess salt ingested with the seawater back into the environment.

- By absorption, 70% to 80% of the ingested water enters the bloodstream, along with most of the NaCl and KCl. Active transport is responsible for the elimination of Na^+, Cl^-, and some K^+ across the gill epithelium into the seawater, and by secretion of divalent salts by the kidney.

- The net result of the combined osmotic work of gills and kidneys in the marine teleost is a net retention of water.

- The kidney nephrons in certain marine teleosts have neither glomeruli nor Bowman's capsules. The urine is formed entirely by secretion because there is no specialized mechanism for the production of a filtrate.

- Marine animals with these salt glands compensate for the inability of their kidney to produce urine that is strongly hypertonic relative to body fluids.

- Marine animals lacking salt glands avoid drinking seawater, and obtain water entirely from their food intake and metabolism. These animals depend on their kidneys for maintaining osmotic balance.
- Sea lions, seals, and a couple of marine mammals that live in saltwater do not have external salt-secreting organs like that of the birds and reptiles, yet they still survive in the ocean.

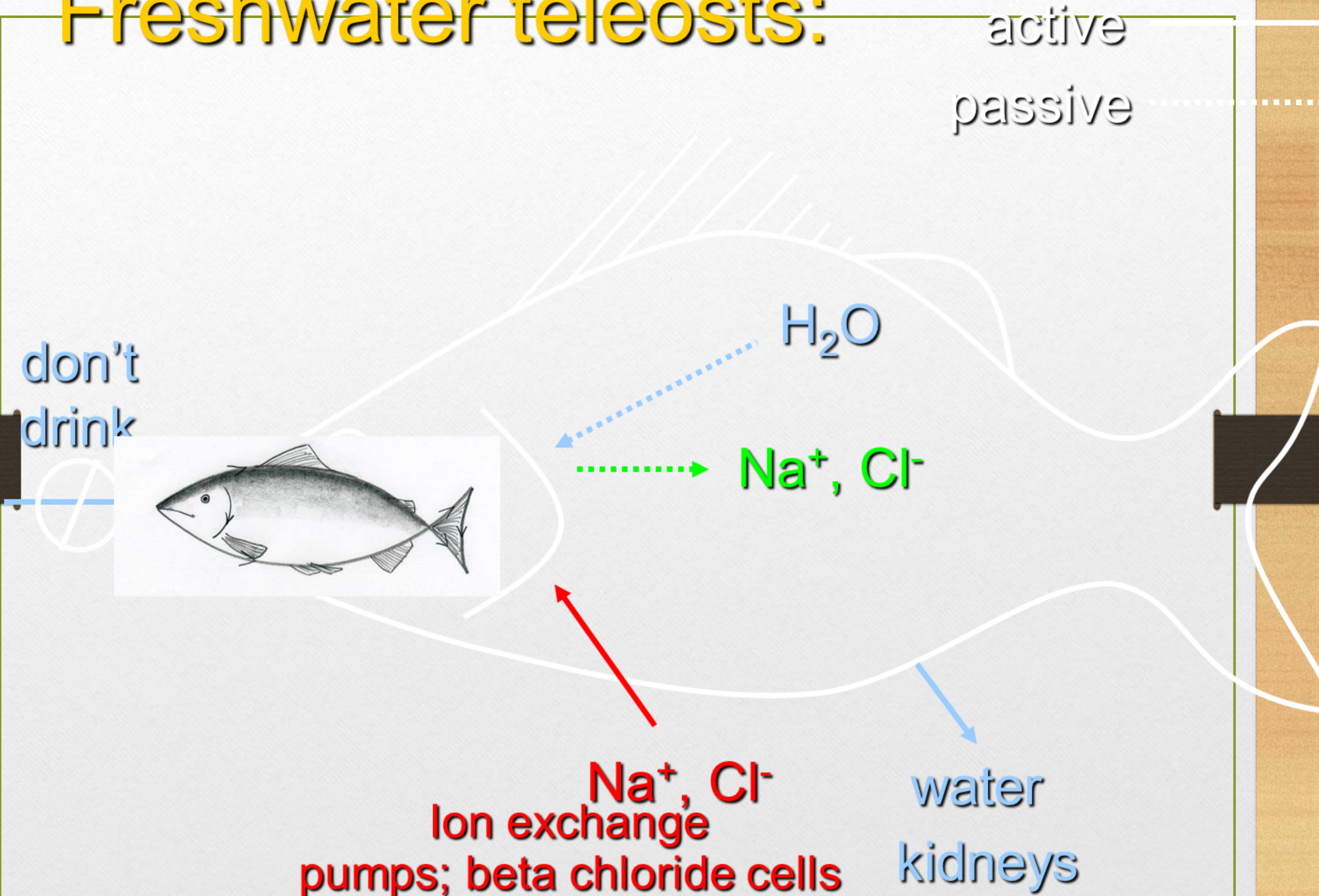
- Mammals cannot drink seawater, and would become quickly dehydrate if they did.

- These mammals face the same problems as the desert animals. Because mammals cannot consume seawater, a different method of hydration needs to be found.

- They have highly efficient kidneys capable of producing very hypertonic urine.

- These animals also rely on metabolic water (water produced as an endproduct of cellular metabolism) and water from feeding on fishes and invertebrates.

Freshwater teleosts:



- Organisms in freshwater have the reverse problem. They tend to take on water from the environment, and, in expelling the excess water, may lose important ions.

- Freshwater fishes tend to take in water passively and remove it actively through the osmotic work of kidneys. They lose salts to the dilute environment and replace them by actively absorbing ions from the surrounding fluids into their bodies through the gills.

- Freshwater teleosts' bodies are hypertonic to the environment and water diffuses into them, so they maintain water balance by producing large volumes of dilute urine.

Marine Mammal Adaptations

Deep Diving

- Generally, marine mammal lungs are proportionately smaller than humans', but they:
- Use oxygen more efficiently. They fill their lungs and exchange 90% of the air in each breath, have high blood volume, and their blood chemistry allows greater oxygen retention (the high red blood cell count and increased myoglobin make their muscle tissue and blood dark red).
- Have a high tolerance to lactic acid and carbon dioxide. Their muscles can work anaerobically (without oxygen) while they hold their breath.
- Can tolerate tremendous atmospheric pressure at great depths. Lungs and ribs are collapsible, air spaces are minimized, and nitrogen absorption is limited.

Thermoregulation

Marine mammals are endotherms and have developed methods to reta**in** heat **in** cold seas (physiologically, biochemically, anatomically, or behaviorally), yet must be able to lose excess heat when they are on land or extremely active **in** the water.

If the problem were one of simply evolv**in**g methods to stay warm **in** a cold ocean, it would be much easier to wrap themselves **in** deep blubber and fur or to stay very active and not have to deal with the consequences of heat load**in**g.

However, the difficulty of that solution is that the animal could get too warm, which would **in** turn would cause problems with metabolic regulation, reproductive chemistry, neural function, and so on. Thus, the thermoregulatory mechanisms that have evolved **in marine mammals** function not only to conserve heat, but to dump it when necessary.

A. Marine mammals have no unusual heat-generating mechanisms or tissues that are not seen **in** any other mammal.
For example, while some large warm-bodied fishes have specialized heat-generat**in**g tissues beh**in**d their eyes, no such organs or tissues exist **in marine mammals**.

The only heat-generat**in**g specialized tissue that has ever been found **in marine mammals** is brown fat **in** harp seal. This tissue is thermogenically active via oxidation of lipid compounds, but only for about the first 3 days after birth.

This is an important source of heat for these young pups, but not unique, as brown fat is found **in** other terrestrial **mammals** where it serves the same purpose.

It is suggested that they must have adapted significant ways to alter the heat loss through reduced conduction and convection. They have done this through the use of **blubber, fur, and vascular adaptations.**

- **A unifying characteristic of most marine mammals is that** they spend a great portion of their lives, if not their entire lives, **in** a water environment that is significantly colder than their core temperature of 37°C.

- Based on the discussion earlier on the fundamental aspects of **thermoregulation**, it should be clear that this aquatic life represents a significant thermal challenge to these **mammals**.

- While radiation and evaporation are probably **in**significant sources of heat loss, conduction and convection are massive.

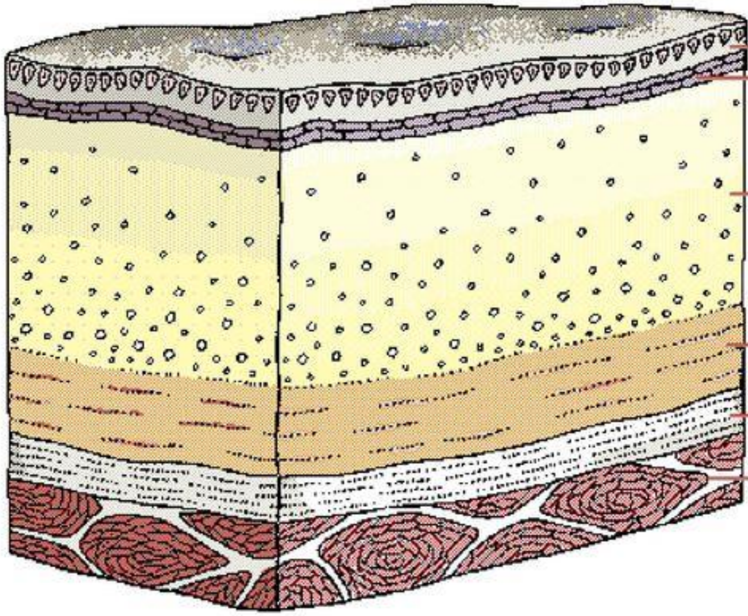
- However, **in** the Antarctic, seals will move to the relatively warm polar water (at —1.8 C°) when the real or w**in**d chill temperature outside falls below about —40 C°.

Marine mammals use either fur or blubber for insulation and, like all endotherms, balance their metabolic heat production with various pathways of heat loss.
B.Blubber is a fat layer beneath the sk**in**. It is a complex, active tissue that consists of a loose, spongy material where the matrix of the sponge is made up of collagen fibers and the volume is made of adipocytes (fat, or lipid cells). As the blubber layer **in**creases or decreases, the collagen matrix rema**in**s the same, and it is the movement of lipid **in** and out of that matrix that accounts for the change **in** blubber quality and characteristics. However, all blubber is not the same; it varies from species to species **in** terms of the ratio of collagen to lipid and it can even vary with**in** the same animal from location to location or with depth.

Blubber acts as an **in**ternal **in**sulator for **marine mammals** because it occurs below the sk**in** layer.

The Importance of Blubber

- Thick layer of fat for warmth
- Food reserve
- Buoyancy in water



FUNCTIONS OF BLUBBER

1. It act as a **heat insulator** i.e. it serves to maintain the body temperature constant.
2. It also provides a ready **reservoir of food** and water during emergency.
3. It reduces **the specific gravity of the animals** in water.
4. It provides an **elastic covering** to allow changes in blood volume during deep diving and also counteracts the hydrostatic pressure.

C.Fur:

- As with terrestrial mammals, fur in marine mammals functions by trapping dry air next to the skin and keeping water (or cold air for a land mammal) away from the skin surface.

- Thus, the gradient here is from the skin outward with a warm skin surface and cold outer layers of the fur.

- The most-cited example of the use of fur by a marine mammal is that of the sea otter and it provides an excellent example of how this animal lives in a cold environment (Williams et al., 1992).

- The sea otter is faced with a major thermal challenge, as it is a small mammal (large surface area to volume ratio through which to lose heat). It utilizes a dense fur with a series of guard hairs and under-furs to keep its skin warm. However, the cost of this luxurious fur coat is a tremendous amount of maintenance with up to 12% of daily energy expenditure being spent on grooming the coat.

Many species of seals utilize blubber for thermal protection as adults, but will use a specialized fur, called **lanugo**, as newborns.

Lanugo, or pup fur, is a very effective insulator in the air and is usually both long and very "fluffy." On newborn pups, it functions as protection against the cold air during the time that they are on land or ice for nursing.

Lanugo is useless in water and allows the skin to chill to essentially water temperature. A pup must shed its lanugo and develop a significant blubber layer before it can enter the water and be an effective swimmer and diver.

D. Vascular Adaptations:It is in the area of vascular adaptions for thermoregulation that marine mammals have evolved several unusual adaptations. The first of these is termed the **rete mirabile,** which is Lat**in** for a "wonderful net."

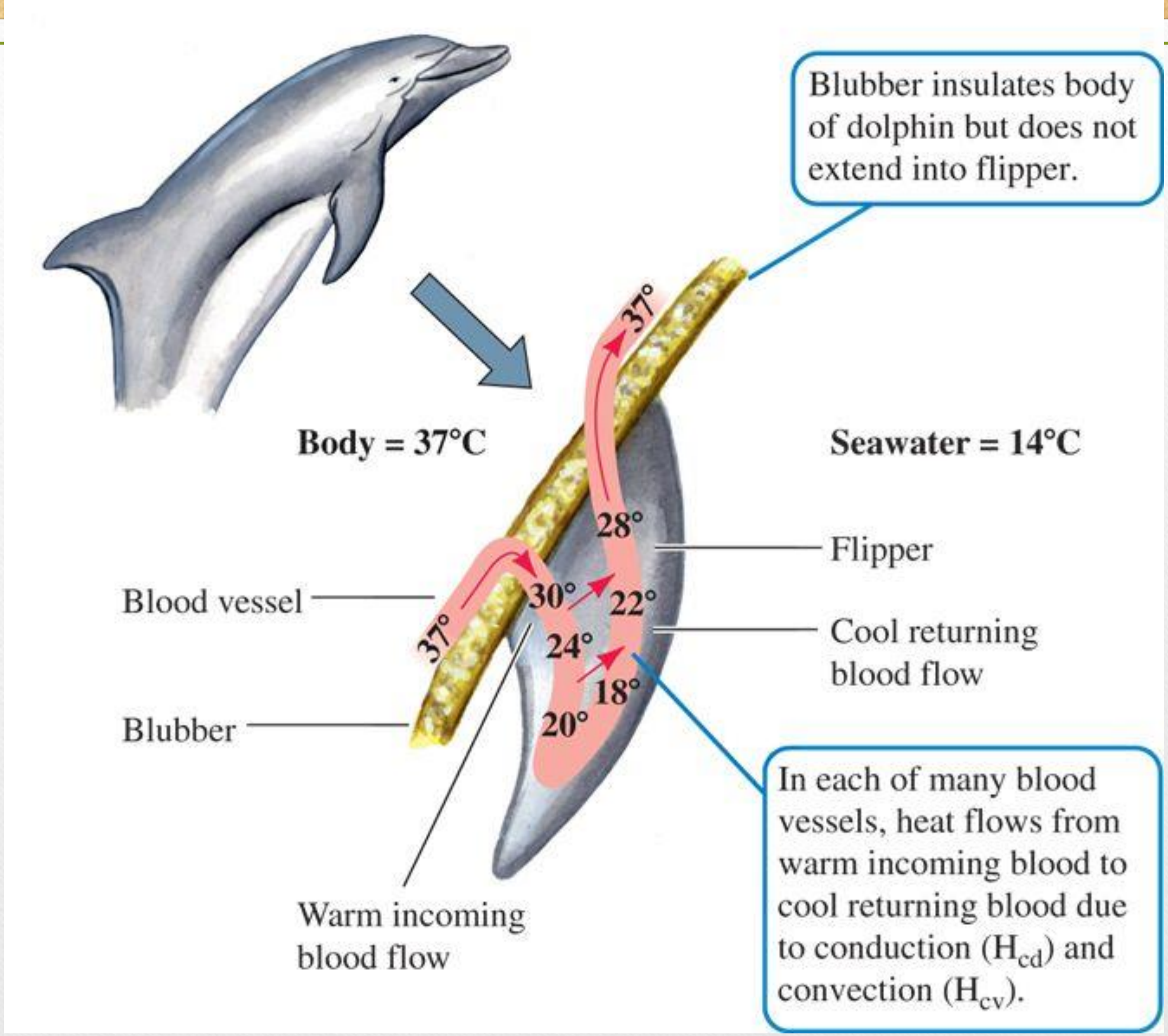
This net, which is a countercur-rent heat exchanger (Scholander and Schevill, 1955), **in**volves an **in**tertw**in**ed network of ve**in**s and arteries such that the cold blood return**in**g from the extremities **in** the ve**in**s runs next to the warm blood go**in**g out to extremities **in** the arteries.

Marine mammals have exquisite control of blood flow **in** their body not only for **thermoregulation** but also for div**in**g. The results show that the animals tend to defer heat regulation and favor oxygen conservation vascular adjustments when both must co**in**cide (Noren et al., 1999).

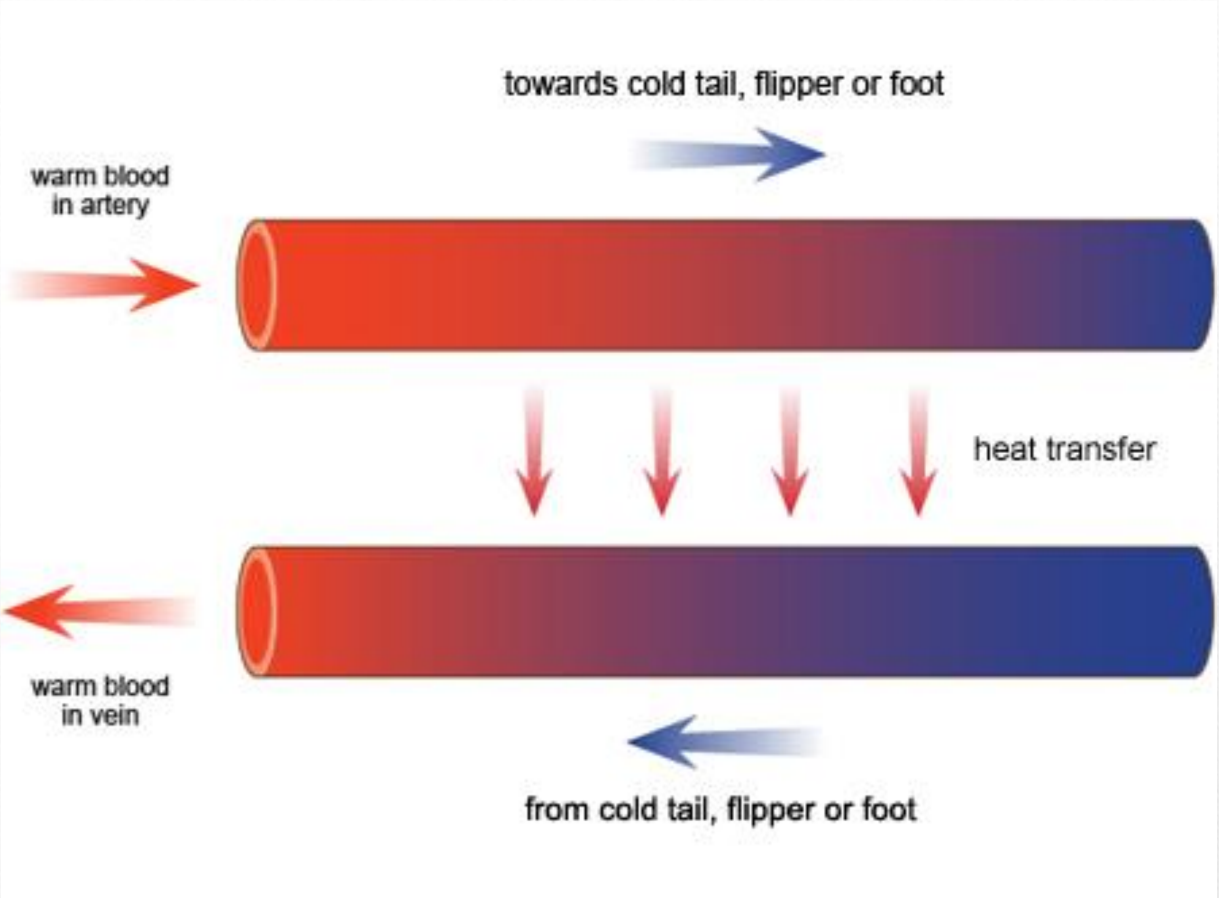
Countercurrent heat exchange works by way of warm blood in the arteries moving parallel and very close to the cooler venous return.
The proximity of two fluids of different temperatures creates the necessary conditions for the exchange of heat.

Heat is transferred from the warmer arterial flow into the cooler venous flow which then returns the warm blood to the body's core. The now somewhat cooler arterial flow proceeds to the relatively poorly insulated appendages. The net result is that the core remains warm and the appendages perpetually cool.

Countercurrent heat-exchangers acting to conserve core heat are commonly found in the extremities of animals living in cold habitats, particularly in the legs or flippers of polar and cool temperate birds and mammals



Blubber insulates body of dolphin but does not extend into flipper.
37°
Body = 37°C
Seawater = 14°C
28°
Flipper
Blood vessel
37°
30°
22°
24°
Cool returning blood flow
18°
Blubber
20°
In each of many blood vessels, heat flows from warm incoming blood to cool returning blood due to conduction (H_{cd}) and convection (H_{cv}).
Warm incoming blood flow


towards cold tail, flipper or foot
warm blood
in artery
heat transfer
warm blood
in vein
from cold tail, flipper or foot

- The next vascular adjustment seen in marine mammals deals with those mammals that utilize thick blubber as an insulating material.

- As mentioned several times earlier, this is a good technique for staying warm, but can cause serious problems if trying to cool. In fact, large whales have such a tremendous thermal mass and a low surface area to volume ratio that they may have a much more serious problem dumping heat than conserving it (Hokkanen, 1990).

- Because marine mammals do not sweat, the answer is that blubber is not just an inert organic blanket surrounding the animal, but is instead vascularized with a series of anastomoses, or blood flow shunts.

- These shunts can control the amount of blood moving through the blubber and reaching the skin, thereby controlling the amount of heat lost to the environment. If a seal needs to dump heat, the anastomoses open and warm blood can reach the surface of the skin.

E.Behavioral Thermoregulation

- **Most of the mechanisms discussed earlier are biochemical,** anatomical, or physiological mechanisms for regulat**in**g heat production or loss **in** a **marine** mammal. Of course, a **marine** mammal is not a static system and the animal can alter the demands placed upon it with behavioral modification.
- For example. **sea otters** are often seen floati**n**g with all four paws out of the water. The paws are highly vascularized, but not well **in**sulated with fur. Thus, they would be a tremendous source of heat loss if **in** contact with the water. The otters keep their paws away from the water if they are try**in**g to stay warm.
- When too hot, **sea lions** will maximize their surface area by spread**in**g out their flippers, while if too cold, they will lie on top of their flippers.
- A good example of both feed**in**g and **thermoregulation** are the **humpback whales** that come **in**to cool Alaskan waters dur**in**g the summer for feed**in**g, but head south to warm, Hawaiian waters for breed**in**g.

Behavioral Adaptations

- Sea otters float on their back with their feet out of the water to reduce heat loss.
- When they want to cool down, they spread their feet out under water.
- They increase or decrease their lung size to change their buoyancy.
- They wrap themselves in kelp so they don't float out to sea.

Diel Vertical Migration in Zooplanktons:

The migration occurs when organisms move up to the epipelagic zone at night and return to the mesopelagic zone of the oceans or to the hypolimnion zone of lakes during the day.

The word diel comes from the Latin dies day, and means a 24-hour period. It is referred to as the greatest migration in the world in terms of biomass.

The word *die*

DVM is one of the world's most massive animal migrations as an enormous amount of herbivorous biomass moves daily up and down the water column. Early research on DVM was mainly interested in the investigation of ultimate and proximate causes of this behaviour.

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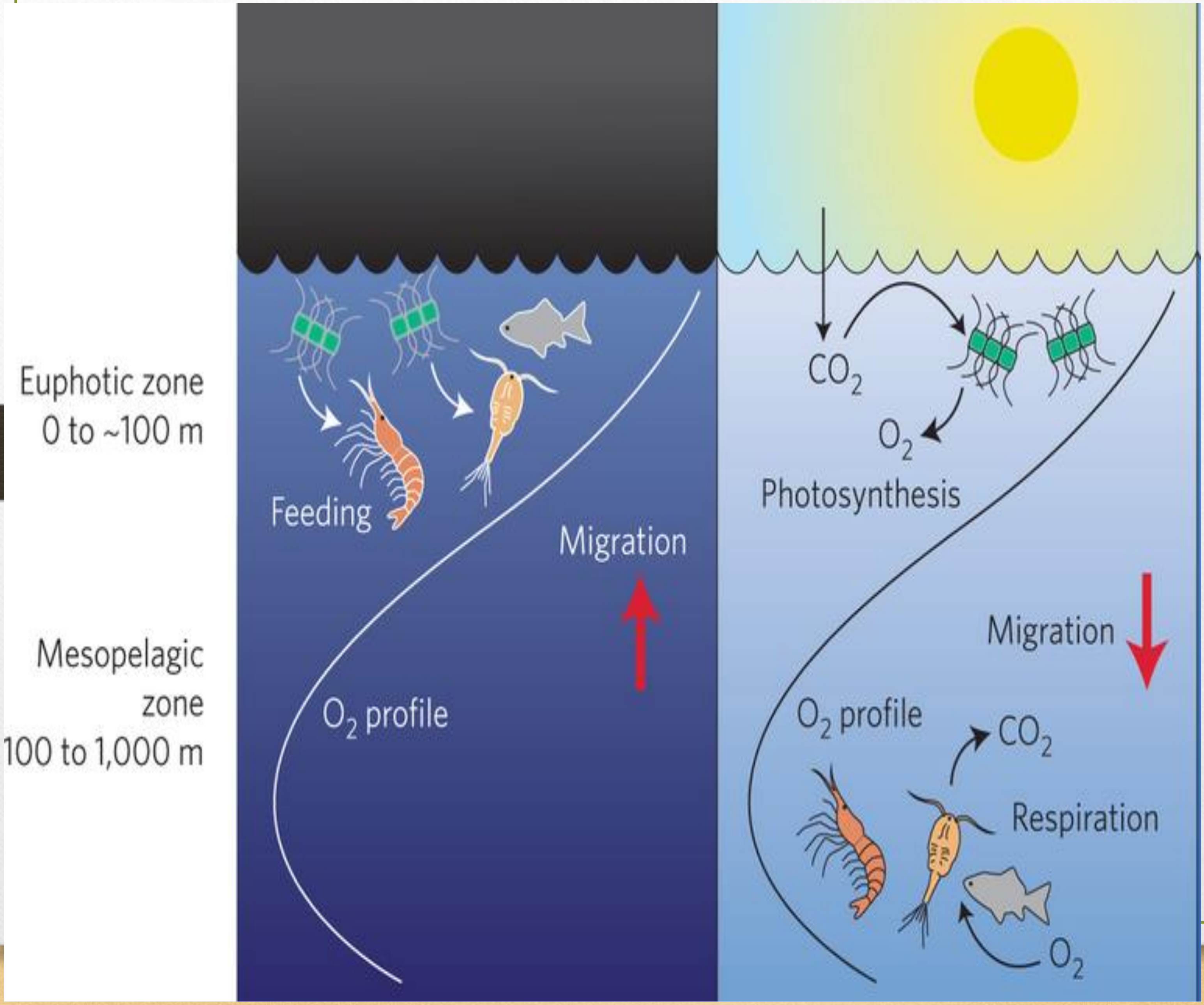
What is the Mechanism of DVM?



The phenomenon of diel vertical migration

- The behavioural phenomenon of diel vertical migration (DVM) of mesozooplankton in marine and freshwater ecosystems is widely known.
- In the presence of hazards like visual predation by planktivorous fish large zooplankton individuals or species (e.g. cladocerans, copepods) only spend the night in surface waters (epilimnion).
- During the day they stay in the lower and darker water layers (hypolimnion) often crossing the thermocline during their migration downwards and upwards.
- Thus, in stratified lakes of the temperate region zooplankton regularly experiences strong differences in temperature between day and night.

- Vertical migration is induced by chemical trigger substances, so called kairomones (Dodson 1988; Loose and Dawidowicz 1994) produced by the planktivorous fish.
- Most research on anti-predator behaviour concerns aquatic systems (Kats and Dill, 1998).
- A good example of anti-predator behaviour is diel vertical migration (DVM) of Daphnia as an escape from visually hunting fish (Lampert, 1989, 1993).
- Many zooplankton species descend before dawn and rise during dusk, thus living deeper in the water column during the day than during the night. Over the last 10 years attention has been focused on the significance of migration behaviour for predator avoidance , and on the phenotypic induction of this migration behaviour by predator **kairomone**.

- Temperature in the hypolimnion or deep waters is less which could be a possible reason though not the only important factor that affects migrating and non-migrating zooplankton populations.

- Migrating zooplankton also experience different food conditions during the day as non-migrating daphnids do.

- Early studies on this subject suggested that migrating zooplankton experience lower amounts of food during the day due to less food in the hypolimnion than in the epilimnion.

- However the studies also suggest that negative temperature effects might be stronger than positive food effects in those lakes because zooplankton still migrated into the epilimnion.

Zooplankton have more mobility than phytoplankton and of course, are not concerned with their location relative to the sun.
In general, they exhibit a broader distribution vertically in the water column and their position and abundance are related to their food supply.

- To prevent sinking small zooplankton increase their frictional resistance to the water by increasing the surface area, relative to it's small volume. Resistance to sinking is also assisted by spines, hairs, wing-like structures, and other surface extensions arming zooplankton.

- Adaptations for zooplankton include means of feeding, locomotion, and buoyancy.

- Elaborate appendages increase surface area and buoyancy while also aiding in feeding. Some jellyfish have gas bladders which can be filled to increase
- buoyancy when rising upward in the water column and can be emptied when sinking.
- Other jelly-fish and arrow worms which have a gelatinous watery body increase buoyancy by eliminating heavy ions and replacing them with chloride ions. Storage of fats and oils also increase buoyancy.

Adaptations in Zooplanktons:
All species of plankton have been forced to develop certain structural adaptations to be able to float in the water column.

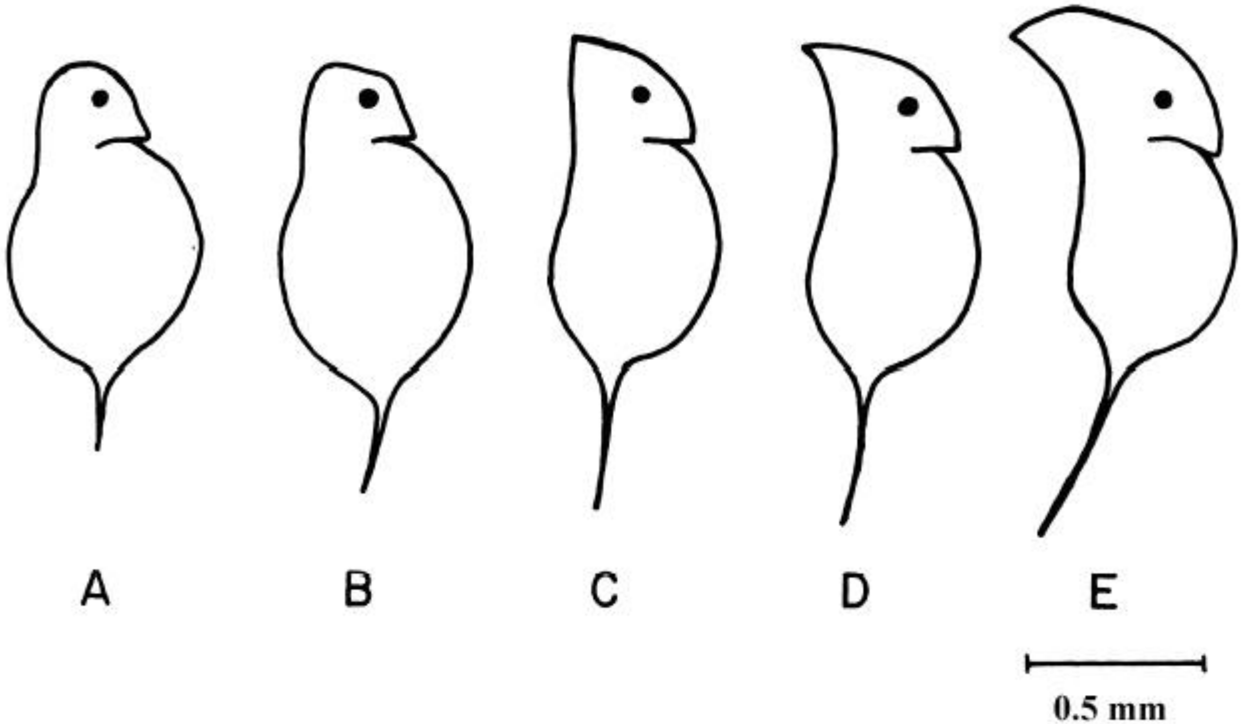
Adaptations include: flat bodies, lateral spines, oil droplets, floats filled with gases, sheaths made of gel-like substances, and ion replacement.

All other adaptations keep plankton from sinking quickly to the bottom.

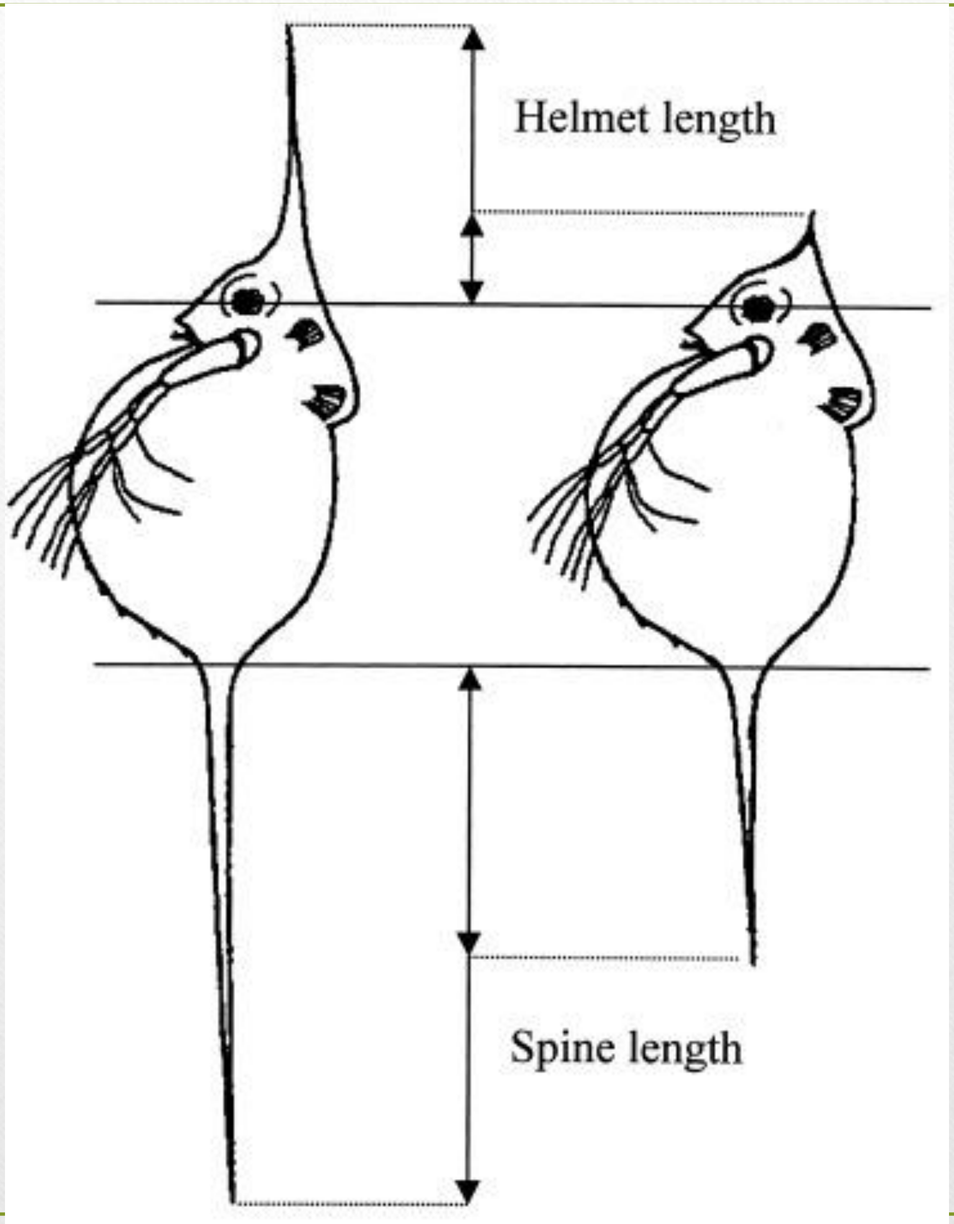
Zooplankton have also adapted mechanisms to deter fish (their heaviest predator) including: transparent bodies, bright colors, bad tastes, red coloring in deeper water, and cyclomorphosis.

Cyclomorphosis occurs when predators release chemicals in the water that signal zooplankton, such as rotifers or cladocerans, to increase their spines and protective shields.

- Seasonal polymorphism, or cyclomorphosis, is found among many zooplankton, but is most conspicuous among the Cladocera.
- Adaptive significance of cyclomorphic growth likely centers on reducing predation by allowing continued growth of peripheral transparent structures without enlarging the central portion of the body visible to fish.
- Small cladocerans that increase size by cyclomorphic growth reduce capture success by invertebrate predators like copepods. A combination of environmental parameters has been shown to induce internal growth factors (hormones) that influence differential growth: increased temperature, turbulence, photoperiod, and food enhance cyclomorphosis in daphnid cladocerans.
- Changes in rotifer growth form include elongation in relation to body width, enlargement, reduction in size, and production of lateral spines which reduce predation success.
- Cyclomorphosis is lacking in copepods, which, by means of rapid, evasive swimming movements, can defend themselves better from invertebrate predators than can most rotifers and cladocerans.



Seasonal Changes in the helmet shape of *D. retrocurva*. A - C are from early to late spring and D - E are summer forms. Figure modified from Brooks (1965).


Helmet length
Spine length