Part II Non-Amniotic Vertebrates: Fishes and Amphibians

~ Chapter 4 ~

Living in Water

Non-Amniotic Vertebrates

1) Vertebrates originated in the sea, and there are more than 27,000 species of extant **cartilaginous** & **bony fishes** living in water. Diversity of fishes indicates diverse habitats.
2) Life in water poses challenges as well as opportunities for vertebrates.
3) Some fishes produce a large number of **eggs**; others only few but provide parental care.
4) Males of some species are **larger** than females; in others females are larger, and some species have no males. Some species change sex.
5) Feeding mechanisms have been an important aspect in the evolution of fishes, and **modern fishes** are specialized for different modes of feeding such as swallowing or extending their jaws like a tube to suck up minute invertebrates.

Living in Water

1) Physical properties of water may be difficult for living, but aquatic animals are adapted to live in this media.
2) To live in open water, a vertebrate must adjust its **buoyancy** to remain at a selected depth & force its way through a **dense medium** to pursue prey or to escape its own predators.
3) Heat flow & maintaining body temperature are also difficult.
4) Ions & water molecules move readily between **external env.** & animal's internal body fluids, so maintaining a stable internal environment can be difficult.
5) On the plus side, **ammonia** (*toxic, metabolic waste product*) is extremely soluble in water so disposal of nitrogenous waste products is easier in aquatic environments than on land.
6) Oxygen concentration is **lower** in water than in air, and this can cause problems unless a special solution is developed.

Q) What are the main properties of the aquatic environment that make aquatic animals live in it?

4.1 The Aquatic Environment

Main Chapter Question: What is the main specialization needed by aquatic animals in order to survive in water?

1. Obtaining Oxygen in Water – Gills

1) Most aquatic vertebrates have gills where oxygen and CO_2 exchange between water & blood takes place.
2) Gills which are covered by the **opercular cavities** allow unidirectional water flow, and flaps just inside the mouth or on the edge of the **operculae** prevent backflow.
3) Respiratory surfaces of gills extend from the **lateral side** of each gill arch.
4) From each gill arch, gill filaments (primary lamellae) extend and from these smaller filaments (secondary lamellae) project. The gas exchange occurs in the secondary lamellae.
5) Two columns of gill filaments (**primary lamellae**) extend from each gill arch and from these, smaller filaments (**secondary lamellae**) project. Gas exchange occurs in secondary lamellae.
6) Respiratory current is created by the pumping action of mouth & opercular cavities (**buccal pumping**) which creates a positive pressure across the gills, allowing water to flow easily.
7) Some filter-feeding fishes & many open-ocean fishes **e.g.** shark and tuna lost the ability of pumping, so they create a respiratory current by swimming with the mouths open (**ram ventilation**). These fishes must swim continuously.

   #### What is Ram Ventilation?

   A respiratory current across the gills; created by swimming with the mouth open.

8) Arrangement of blood vessels in gills maximises oxygen extraction from water. Each gill filament (primary lamellae) has two arteries; an **afferent vessel** from gill arch to filament tip & an **efferent vessel** returning blood from the tip back to the arch.
9) The blood flow and the water flow are in opposite direction and this is called Counter Current Exchanger.
10) Direction of blood flow through lamellae is opposite to direction of water flow across the gill. This arrangement is called **countercurrent exchanger** & assures that as much oxygen as possible diffuses into the blood.
11) **What is the advantage of the Countercurrent Exchanger?**

    Fluid streams flowing in opposite directions in adjacent vessels to promote exchange of heat or dissolved substance.

12) More **active** fishes such as tunas have larger gills and skeletal tissues in their gill filaments. Also their blood can carry more oxygen per millilitre.

Obtaining Oxygen from Air – Lungs & Other Respiratory Structures

1) Fishes that live in water with **low** oxygen levels cannot obtain enough oxygen via gills alone.

2) These fish obtain additional O_2 from the air via lungs or accessory air respiratory surfaces e.g.

- Enlarged **lips** to take up air
- Variety of internal **structures**

3) Air is sucked into the mouth & transferred to a specialized structure for gas exchange.

4) Many of these fishes are **facultative air breathers**; they switch oxygen uptake from their gills to accessory respiratory structures when oxygen in the water becomes low.

5) Others (e.g. electric eel) are **obligatory air breathers**; cannot live using the gills alone so they must go to the surface to breathe air.

6) Lungs of freshwater species of early vertebrates (**e.g.** placoderms) are an ancestral character for both bony fishes & their tetrapod descendents.

7) Lungs develop **embryonically** as evaginations of the pharyngeal region of the digestive tract, originating from its ventral or dorsal surface.

8) The lungs of **lungfish** & **tetrapods** originate from the ventral surface of the gut, whereas the lungs of **gars** (group of primitive bony fish) & the lungs of derived bony fish (**teleosts**) originate from its dorsal surface.

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2. Adjusting Buoyancy

1) Fishes use the lungs as **swim bladders** that regulate a fish's position in the water.

2) Many bony fishes are **neutrally** buoyant (i.e. have the same density of water). These fish do not have to swim to maintain their vertical position in the water column.

3) The only movement they make when at rest is **backpedalling** of the pectoral fins to counteract the forward thrust produced by water as it is ejected from the gills & a gentle undulation of the tail fin to keep them level in the water. They have well-developed swim bladders.

Figure 4-3: Swim bladder of bony fishes

4) Where is the swim bladder located in bony fishes?

Swim bladder is located between the peritoneal cavity & the vertebral column.

5) Size of swim bladder is larger in freshwater fishes because salt water is **denser**, so a smaller swim bladder is needed.

6) Swim bladder wall, composed of interwoven **collagen** fibers, is virtually impermeable to gas.

7) Neutral buoyancy produced by a swim bladder works as long as a fish remains at one depth, but must be adjusted when the fish moves to another depth. The **hydrostatic pressure** which increases with depth forces the bladder to change its volume.

8) What happens to fish buoyancy when swimming towards the surface? How does the fish regulate the volume of its swim bladder? *Answer on p.81 of new edition*

9) Primitive teleosts have a **connection** between the gut & swim bladder. This allows them to gulp air at the surface to fill the bladder & to burp gas out to reduce its volume. These fishes are called **physostomous** e.g. goldfish.

Fig. 4-3 (a): Swim bladder retains its ancestral connection to gut via pneumatic duct.

10) **Pneumatic duct** is absent in adult teleosts, a condition termed **physoclistous**. Physoclists regulate swim bladder volume by secreting gas from the blood into the bladder.

11) Physostomes & physoclists have a **gas** gland located in anterior ventral floor of swim bladder.

Fig. 4-3 (b): Vascular connections of physoclistous swim bladder

12) Underlying the gas gland is a network of capillaries arranged to help move the gas (which is mainly oxygen) from the blood into the bladder. This capillary bed is called **rete mirabile**.

13) Gas gland secretes oxygen by releasing **lactic acid** and CO_2 to acidify the blood in the rete mirabile. Acidification causes hemoglobin to release oxygen into solution (**the Bohr and Root effects**).

14) Oxygen **accumulates** in the rete mirabile until its pressure exceeds the oxygen pressure in the swim bladder. Oxygen **diffuses** into the bladder, increasing its volume.

15) Physoclists have **no connection** between swim bladder & gut, so they cannot burp to release excess gas from the bladder.

- Instead, they open a muscular valve (**ovale**) located in posterior dorsal region of bladder adjacent to a capillary bed.
- High internal pressure of oxygen in the bladder opens the valve to release the gas.

Cartilaginous Fishes

1) Cartilaginous fishes (sharks, rays, and ratfish) **do not** have swim bladders. These fish use the **liver** to create neutral buoyancy.

2) **Shark liver** has high oil content; nitrogen-containing compounds in the blood also contribute to their buoyancy.
3) Urea & trimethylamine oxide in the blood and muscle tissue provide **positive buoyancy**.
4) Many deep-sea fishes have lipids distributed throughout the body to provide **static lift** (neutral buoyancy).
5) A **long** rete mirabile is needed to secrete oxygen at high pressures, and the gas gland in deep-sea fishes is very **large**.
6) Air–breathing vertebrates must **breathe air** into their lungs to become buoyant.

4.2 Water and the Sensory World of Fishes

1) Light is **absorbed** by water molecules and scattered by suspended particles.
2) Objects become invisible at a distance of a few hundred meters even in clear water.
3) So fishes supplement vision with other senses, some of which can **operate only in water**
4) Most important of these aquatic senses is **mechanical**, and **electric sensitivity,** that depend on water properties & do not operate in air.

3-1 Vision

1) Vision is different in water & air because of the different refractive properties of the two media.
2) All vertebrates have well-developed eyes, but the way an image is focused on the **retina** is different in **terrestrial** and **aquatic** animals.
3) **Refractive index** of air is less than that of water, so underwater objects appear closer to an observer in air than they really are.
4) **Cornea** of terrestrial vertebrate plays a substantial role in focusing an image on the retina.
5) The **lens** plays the major role in focusing light on the retina of an aquatic vertebrate, and fish have spherical lenses with **high** refractive indexes.
6) The entire lens is moved towards or away from the retina to focus images.
7) Terrestrial vertebrates have **flatter lenses**, & eye muscles change the lens shape to focus images. Aquatic mammals have **spherical lenses** like those of fishes.

3-2 Taste

1) Fishes have **taste-bud organs** in the mouth & around the head and anterior fins.

2) In addition, **receptors** detect substances that are only slightly soluble in water, & **olfactory organs** on the snout detect soluble substances.

3) Sharks and salmon can detect odours at very low concentrations.

3-3 Touch

1) Mechanical receptors detect touch, sound, pressure, and motion.

2) Internal ear (**the labyrinth organ**) detects changes in speed & direction of motion.

3) Fishes also have **gravity detectors** at the base of the semicircular canals that allow them to distinguish up from down.

4) In fishes & aquatic amphibians, clusters of hair cells and associated support cells form **neuromast** organs that are located in a series of canals on the head and body. This system is called the **lateral line system**.

Fig. 4-4: Lateral line systems (and hair cells)

5) Lateral line systems are **found only in** aquatic vertebrates, because air is not dense enough to stimulate the neuromast organs.

6) Terrestrial vertebrates that have returned to the water (**e.g**. **whales**) lack lateral line systems.

3-4 Detecting Water Displacement

1) Neuromast hair cells are arranged in pairs with the **kinocilia** on opposite sides of adjacent cells. **Kinocilium:** a sensory cell located in neuromast organs.

2) Neuromast has two **afferent nerves**:
   - One transmits impulses from hair cells with kinocilia in one direction.
   - Other carries impulses from cells with kinocilia positions reversed by 180 degrees.

3) This arrangement allows a fish to determine the direction of **displacement** of the kinocilia.

4) Lateral line system also responds to **low frequency** sound.

3-5 Electric Discharge

1) Unlike air, water conducts electricity, and **seawater** is a better conductor than fresh water.

2) Electrical activity used to **detect** prey, and also used for **defence** and **signals**. *So how do fish produce electricity?*

3) Electric fish use modified muscles to produce electricity.

- Cells (called **electrocytes**) of these modified muscles lost the capacity to contract & are specialised for generating an **ion current flow**.
- They are arranged in **stacks** like batteries in flashlight, & produce high voltages.

4) Most electric fishes are found in **tropical freshwaters** of Africa & South America (e.g. South American electric eel).

Electroreception by Sharks and Rays

1) Many fishes, especially sharks, are able to detect electric fields.

2) Sharks have special structures called **ampullae of Lorenzini** on their heads, and rays have them on the pectoral fins as well. The ampullae are electroreceptors.

Fig. 4-7: Ampullae of Lorenzini

3) Canal connecting the receptor to the surface pore is filled with an electrically conductive **gel**, & the canal wall is **nonconductive**.

4) Many sharks track temperature gradients at sea using the glycoprotein gel.

5) Sharks may use **electroreception** for navigation as well. Electromagnetic field at the Earth's surface produces tiny voltage gradients, but larger voltage gradients cannot be detected by **ampullary organs**.

Electrolocation by Teleosts (bony fishes)

1) Unusual arrangements of electrocytes are present in bony fishes that produce weak electrical discharges. Use their discharges for **electrolocation** & **social communications**.

2) When a fish discharges its electric organ, it creates an **electric field** which may extend outwards for some distance in freshwater.

3) Electric fish detects the location of objects (e.g. prey) by sensing where on its body maximum distortion of its electric field occurs, & because of a change in distribution of electric potential.

Fig. 4-9: Electrolocation by fishes

4) **Electroreceptors** of teleosts are modified lateral line neuromast receptors. They also have double innervation (an **afferent** channel that sends impulses to the brain & an **efferent** channel that causes inhibition of the receptors).

5) Electroreception ability appeared in early vertebrates.

4.3 Internal Environment of Vertebrates (Point 4)

1) 70-80% of body mass of most vertebrates is water, & the chemical reactions that **release** energy or **synthesise** new chemical compounds take place in solutions (aqueous environ.).

2) Body fluids contain ions and other solutes. Some ions are **cofactors** that control the rates of metabolic processes; others regulate pH, cell homeostasis, or the electrical activity of nerves.

3) Everything that happens inside the body involves water, & maintaining the **balance** of water and solutes is crucial.

4) Freshwater vertebrates – esp. fishes & amphibians – face the threat of **excess water** entering their bodies, while saltwater vertebrates must prevent **water loss** from their bodies.

5) **Temperature** is another critical factor for living organisms because chemical reactions are temperature sensitive. In general, chemical reaction rates increase as temperature increases. Also, **permeability** of cell membranes is sensitive to temperature change.

6) Water temperature is more stable than air temperature because water has a much higher **heat capacity** than air. This helps in maintaining a **constant** body temperature, as long as the body temperature the animal needs is the same as the temperature of the water around it.

7) However, an aquatic animal has a hard time maintaining a body temperature different from water temperature because water conducts heat so well.
    - ❖ Heat flows out of the body if an animal is warmer than the surrounding water.
    - ❖ Heat flows into the body if the animal is cooler than the water.

4.4 Exchange of Water and Ions

- ➢ Vertebrates use both active and passive exchange to regulate their internal concentrations of ions and water.

5-1 The Vertebrate Kidney

1) Protein breakdown end product is **ammonia** which is toxic and must be removed. Kidney plays a crucial role in this process.

2) Adult kidney consists of hundreds to millions of tubular **nephrons** that produce urine.

3) **Primary function** of nephron is removing excess water, salts, waste, & foreign substances from the blood.

4) Blood is first filtered through the **glomerulus**, a structure unique to vertebrates.

Fig. 4-10: Typical mammalian glomerulus

5) Each glomerulus is composed of capillary bed encapsulated within a **sieve-like filter**.

6) Arterial blood pressure forces fluid into the nephron to form an **ultrafiltrate** composed of blood minus blood cells & larger molecules.

7) Ultrafiltrate is then processed to return essential **metabolites** (e.g. glucose) & water to blood.

8) Fluid that is left after this processing is the **urine**.

5-2 Regulation of Ions and Body Fluids

1) Marine invertebrates & hagfishes have body fluids that are in osmotic equilibrium with seawater – they are **isosmolal** to seawater; i.e. they have similar ionic *(salt*) concentrations.

2) In contrast, salt levels are *greatly reduced* in the blood of all other vertebrates.

3) **Solute** = a small molecule that is dissolved in water or blood plasma; examples: salt ions, urea, & some small carbohydrate molecules.

4) Presence of solutes lowers the **kinetic** activity of water.

5) Therefore, water flows from a dilute solution (*high kinetic activity of water*) to a more concentrated solution (*low kinetic activity*) – a phenomenon called **osmosis**.

6) Body fluid concentrations in marine **teleosts** & **lampreys** are less concentrated than seawater, so water flows outwards from their blood to the sea (i.e. from a region of high kinetic activity of water to a region of lower kinetic activity.

- They are **hyposmolal** – lower solute concentrations than the surrounding water.

7) Cartilaginous fishes retain urea and some other compounds, raising the **osmolality** of their blood above that of seawater so water flows from the sea into their bodies.

- They are **hyperosmolal** – higher solute concentrations than the surrounding water).

8) Most fishes are **stenohaline** – they inhabit either freshwater or seawater & cannot tolerate (large) changes in salinity.

9) Some fishes are **euryhaline** – they move between freshwater and seawater, & tolerate large changes in salinity.

Q) How are water and ions balanced in freshwater and seawater animals?

Freshwater Organisms – Teleosts & Amphibians

1) Several mechanisms are involved in salt & water regulation of freshwater fishes & amphibians

- Body surface (skin) of fishes has low permeability to water and to ions.
- However the **gills**, which must be permeable to oxygen and CO_2, are also permeable to water. As a result, most water & ion movements take place across the gill surfaces.

2) Water is gained by osmosis, and ions are lost by diffusion.

3) **<u>Freshwater teleost</u>** does not drink water because osmotic water movement is already providing more water than it needs.

- Kidney produces a large volume of (diluted) urine but salts are actively reabsorbed.

4) Freshwater teleosts have large glomeruli; the glomerular ultrafiltrate is **isosmolal** to the blood & contains essential blood salts.

5) **Reabsorption** is an active process that consumes metabolic energy. Chloride cells in the gills actively transport chloride ions.

6) **<u>Freshwater amphibians</u>** face the same osmotic problems as freshwater fishes.

7) Entire body surface of amphibians is involved in the active uptake of ions from the water. They also do not drink water and lose ions by diffusion.

8) Skin contains cells that actively take up ions from the surface water. **Acidity** causes death in both amphibians & fishes because it inhibits the active transport of ions.

<u>Marine Organisms – Teleosts & Other Fishes</u>

1) Osmotic and ionic gradients of **seawater** vertebrates are the opposite of those in freshwater.

2) Seawater is more concentrated than body fluids of vertebrates, so there is a net **outflow** of water by osmosis & a net **inward** diffusion of ions.

<u>*Teleosts*</u>

1) As in freshwater teleosts, the **integument** (skin) of marine fishes is highly impermeable to water, so that most osmotic & ion movements occur across the gills.

2) Kidney glomeruli are small, & glomerular **filtration** rate is low. Urine volume is small and more concentrated.

3) *To compensate for **osmotic dehydration***, marine teleosts drink seawater. Sodium and chloride ions are actively absorbed across the lining epithelium of the gut. Water flows by osmosis into the blood.

4) *To compensate for influx of sodium & chloride ions*, chloride cells in the gills pump chloride ions outwards against a concentration gradient.

Hagfishes and Cartilaginous Fishes

1) Hagfishes have few problems with ion balance because they regulate only **divalent ions** (when an atom loses or gains two electrons, **e.g.** Ca^{2+}) & reduce osmotic water movement by being nearly **isosmolal** to seawater (*maintaining similar internal concentration*).

2) Cartilaginous fishes retain urea & trimethyleamine oxide to produce osmolalities that are slightly **hyperosmolal** (*above*) to seawater. As a result, they gain water by osmotic diffusion across the gills and do not need to drink seawater.

3) Urea is not soluble across the gills of cartilaginous fishes & the kidneys reabsorb urea. These fishes do not have **salt-excreting cells** in the gills. Instead, they achieve ion balance by secreting salts from the rectal gland.

Freshwater Sharks, Rays, and Marine Amphibians

1) Some **cartilaginous fishes** are euryhaline, e.g. In seawater, sharks retain high levels of urea but in freshwater their blood urea levels decline.

2) During seawater exposure, **marine frog** allows its blood ion concentrations to rise & thus reduces the ionic gradient. Also, ammonia is converted to urea & released into the blood.

3) In these frogs, water is absorbed osmotically like in sharks. But frog skin (unlike that of sharks) is permeable to urea, so urea is rapidly lost. *To compensate for this loss*, the activity of **urea-synthesising enzymes** is very high.

4) Frog larvae, tadpoles, have salt-excreting cells in the gills – just like fishes (teleosts)

Nitrogen Excretion by Aquatic Vertebrates

Q) How is nitrogen excreted by aquatic vertebrates?

1) When protein is metabolised, the nitrogen is reduced to ammonia through a process called **deamination**. Ammonia is very soluble in water but extremely toxic.

2) Nitrogen is eliminated by vertebrates as **ammonia**, **urea**, or **uric acid**. Many vertebrates excrete all three of these substances in different proportions.

3) Urea is synthesised from ammonia in a cellular enzymatic process called the **urea cycle**.

4) Urea synthesis requires more energy than does ammonia production, but is less toxic.

5) Urea has two advantages:

i. Retained by some marine vertebrates to counter osmotic dehydration.

ii. Detoxification of ammonia when there is not enough water available to allow it to be excreted as fast as it is produced.

4.5 Responses to Temperature (Point 6)

1) Vertebrates occupy habitats from cold polar latitudes to hot deserts.
2) Living and nonliving systems are similar because they are both subject to the laws of physics & chemistry.
3) Chemical reaction rates increase or decrease when the **temperature** changes.
4) Q_{10} is the **ratio** of the rate at one temperature compared to the rate at a temperature 10°C higher or lower. So a Q_{10} of 1.0 means that the rate **stays the same**, a Q_{10} greater than 1 means the rate **increases**, and a Q_{10} less than 1.0 indicates a **decrease** in rate (**Fig. 4-13**).
5) Q_{10} can be used to describe the effect of temperature on whole animals down to molecules.

6-1 The Standard Metabolic Rate (SMR)

1) The SMR of an organism is the **minimum** rate of oxygen consumption needed to sustain life.
2) SMR includes all the activities necessary to maintain life but does not include activities like locomotion or growth.
3) SMR is **temperature sensitive**; the energy cost of living is affected by changes in body temperature, **e.g.**
   - If the SMR of a fish is 2 joules per minute at 10^{o}C and the Q_{10} is 2, the fish will use 4 joules per minute at 20^{o}C and 8 joules per minute at 30^{o}C.
   - That increase in energy use means more food consumption.

6-2 Controlling Body Temperature – Ectothermy & Endothermy

1) Maintaining temperature differences requires **thermoregulatory** mechanisms, & these are well developed among vertebrates.
2) In the past, vertebrates were classified as **poikilotherms** (Gr. *variable heat*) & **homeotherms** (Gr. *the same heat*).
3) But this terminology has become less appropriate because **poikilothermy** & **homeothermy** describe variability of body temperature, & these terms cannot be used for groups of animals.

4) **Example:** mammals have been called homeotherms & fishes poikilotherms, but some mammals allow their body temperatures to drop 20^oC or more from their normal levels at night & in the winter, **whereas** many fishes live in water that changes temperature less than 2^oC in an entire year.

5) That example shows that it is not correct to state that a homeotherm experiences 10 times as much variation in body temperature as a poikilotherm.

6) Most biologists prefer the terms **ectotherm** and **endotherm**.

7) These terms are *not* synonymous with poikilotherm & homeotherm because, instead of referring to variability of body temperature, they refer to the **sources of energy** used in thermoregulation.

8) **Ectotherms:** gain their heat from external sources, e.g. by basking in the sun.

   Endotherms: depend on metabolic production of heat to raise their body temperatures.

9) Terrestrial ectotherms (like **lizards** & turtles) and endotherms (like **birds** & mammals) **all** have activity temperatures ranging from 30 to 40^oC.

10) Many animals use endothermy and ectothermy in combination.

Regional Heterothermy – Warm Fishes

1) **Regional heterothermy** is a term used to refer to different temperatures in different parts of an animal's body.

2) This is found in fishes that maintain some parts of their bodies at temperatures 15^oC warmer than surrounding water. Mechanism used to retain heat is a **countercurrent system** of blood flow in **retia mirabilia**.

3) As **cold arterial** blood from the gills enters the warm part of the body, it flows through a rete & is warmed by heat from the **warm venous** blood that is leaving the tissue.

4) **Example:** Tuna have an arrangement of retia that retains heat produced by **myoglobin-rich** swimming muscles near vertebral column. Brains & eyes are warmer than water temperature.

6-3 Warm Bodies, Cold Seas – Marine Mammals and Sea Turtles

1) Air breathing aquatic **tetrapods** have lungs instead of gills, which are obstacles to whole-body endothermy for fish.

2) In addition, **fully aquatic mammals** have a layer of insulation that helps to retain metabolic heat in the body.

3) Mammals are endotherms. A **furry body** covering traps metabolic heat in spaces between hairs, but a fur coat works in air not in water.

4) The most specialised marine mammals (**e.g.** whales and dolphins) use **blubber** (a layer of fat beneath the skin) rather than fur for insulation.

5) Aquatic mammals also have countercurrent exchange systems in their flippers that allow them to **retain** heat in the body or **release** it to the ocean.

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7. Body Size and Surface-to-Volume Ratio

1) Body size is important in the **exchange** occurring between an organism & its environment.

2) For objects of the same shape, volume increases as the **cube** of linear dimensions, whereas surface area increases only as the **square** of linear dimensions.

3) **Example:** Consider a cube that is 1 cm on each side. Each face of the cube is **1 cm^2** and a cube has six faces, so total surface area is **6 cm^2**. Volume is **1 cm^3** and surface to volume ratio is **6 cm^2 / 1 cm^3**.

Fig. 4-15: Relationships between linear dimensions, surface area, and volume of an object.

If we double the linear dimensions of the cube to **2 cm** long, each face has a surface area of **4 cm^2**, and total surface area is **24 cm^2**. Volume is **8 cm^3** and ratio is **3 cm^2 / 1 cm^3**. Thus the larger cube has only **half** as much surface area per unit volume as the smaller cube.

4) As an object gets larger, it has progressively **less** surface area in relation to its volume.

5) Exchange between an animal and its environment occurs through its body surface, and **larger species** have proportionally less area for exchange in relation to the volume (or mass) of their bodies. Smaller species exchange energy with the environment more **rapidly**.

6) Being big makes temperature regulation in water easier, **e.g.** leatherback sea turtles can keep their body temperature **18^{o}C** higher than the water.

- **a)** Turtles have **lower** metabolic rates than mammals.
- **b)** Nonetheless, the combination of large body size & small surface-to-volume ratio with countercurrent heat exchangers in the flippers allows leatherback sea turtles to retain the heat produced by muscular activity.
- **c)** Smaller sea turtles cannot maintain a large difference between their body temperatures and water temperature.

The properties of water offer both advantages and disadvantages for aquatic vertebrates.