Discuss the various adaptations of vertebrates that enable them to live in marine conditions.

Vertebrates that live in water are said to be aquatic, and naturally over the course of time they have adapted to these marine conditions. They face a number of problems when it come to living in water, which I shall identify later, but have evolved complex and unique ways of dealing with them. Firstly though there must be a distinction between the types of aquatic vertebrates, although they can obviously be classified according to taxa it is more helpful to distinguish how they have adapted to a marine environment. All fishes are primary swimmers-their ancestors also swam. Other swimming vertebrates are secondary swimmers-their ancestors passed through a terrestrial state, and consequently they have structural and physiological handicaps that have prevented most of them from becoming entirely aquatic again.

It is academic to ask about the survival value of, or reason to evolve, an aquatic lifestyle for primary swimmers. It is a successful way of life, and nature has provided no alternative to most of them. A more interesting point is why did secondary swimmers choose to adopt an aquatic lifestyle again after the change to terrestrial life was so profound that it took about 100 million years to complete. The reverse trend back to water has been "easier" and has occurred many times and possible reasons for this reversal could be:

1. To exploit a wide variety of aquatic foods, such as invertebrates, small fish and in one case vegetation.
2. To escape terrestrial predators. They may also subject themselves to aquatic predators of course, but the process of evolution has in specific instances moved in the direction of greater safety.
3. The oceans and major inland waterways are favourable avenues for dispersal and migration.

For whatever the reasons vertebrates have adapted to a marine lifestyle they must all face the same problems. The main categories of problems are motion, homeostasis, acquisition of food, and reproduction.

Motion

Water is a denser medium than air to live in it is harder to move in, and due to is 3-dimensional nature of water much finer control of body orientation is needed. Therefore, all proficient swimmers and divers must:

1. Reduce the resistance that water offers to motions of the moving body.
2. Propel themselves in a relatively dense medium.
3. Control vertical position in the water.
4. Maintain orientation and steer the body.

Reduce the resistance that water offers to motions of the moving body, Drag.

The resistance that a medium (here water) offers to the motion of an object is called drag. There are several sources, or kinds, of drag. They are interdependent, but can best be presented one at a time. First is frictional drag. Imagine a smooth, spindle-shaped, rigid object moving underwater. A film of water wets its surface and moves with it, yet a short distance away, the water does not move with the object at all. Between the object and the still water is the thin boundary layer where successive layers of water slide past one another; those nearest the object move nearly as fast as it does, and those more and more distant move slower and slower. The shearing forces thus produced tend to slow the moving object and are a source of drag. The boundary layer gets thicker toward the posterior end of the moving object. If a smooth spindle-shaped object moves slowly through the water, successive layers or lamina of the boundary layer slip past one another without any eddies. Flow is said to be laminar.

The next form of drag is pressure drag. This is created as the object moves through the water and suction is caused as the water flows back into the gap the object has displaced, disrupting the boundary layer (backfill).

The final form of drag is wave drag. This occurs of the object is moving close to or on the surface. Energy is extracted from the moving object to create the waves and is lost as drag.

Drag increases with body size, but so does the output of the animal's power plant, and these factors nearly cancel one another. The consequence of some rather complicated physiological considerations seems to be that moderately large swimmers have some advantage. The fastest swimmers are large fishes and small whales. There remain the important variables of body shape and the nature of the surface of the body.

Reduction of Drag by Adaptations of Body Form, Streamlining.

Pressure drag is low when the body is long and slender, like that of a snake or eel, because there is then little displacement and backfill. Frictional drag is minimal, however, when the body is short and plump, because surface area is then minimal. The best compromise is a spindle that is circular in cross section and thickest near the centre of its length where its diameter is one-fourth to one-fifth of its length. The bodies of tunas, swordfishes, and dolphins closely approach this shape. Absence of a functional neck (primary swimmers, cetaceans, sirenians), symmetry of the head, shape of thorax and body musculature, and the distribution of fat and blubber all may contribute to streamlining.

Projections from the basic spindle usually cause turbulence and eddies, and increase drag. Accordingly, expert swimmers reduce or eliminate all major projections not needed for propulsion and steering. Swimmers other than mammals have no external ears or external genitalia in their ancestry. Aquatic mammals secondarily lose their external ears and move the testes back into the abdomen. Nipples or teats and the penis may be withdrawn within the body contour when not functioning. Fast primary swimmers have no limb segments between their fins and bodies. Fast secondary swimmers have very short proximal limb segments to again bring the feet or flippers close to the body. The humerus of cetaceans may be only about as long as it is wide; the femur of pinnipeds may be less than twice as long as wide; the femur of diving birds is short and most of the leg musculature is contained within the contour of the body. Cetaceans and sirenians have reduced the pelvic appendages to internal vestiges. For example a 19m whale would have a 41cm pelvis and a 4cm thighbone.

Some other swimmers position the hind limbs in such a way that they do not protrude but instead extend the contour of the spindle shaped body. The knee joints of pinnipeds, beavers, and many diving birds are constructed to allow the necessary reorientation of the limb. Salamanders, crocodilians, and aquatic lizards hold their limbs against the body as they swim with tail and trunk. Lateral fins and flippers that propel the body, on the other hand, must protrude and present a flat surface to the water. Bony fishes also can reduce the area of their fins by folding. Dorsal and anal fins (including the "sail" of the sailfish) may be retracted into grooves on the body surface during fast swimming. Web-footed tetrapods flex their limbs and adduct and curl their toes on the recovery stroke.

These considerations of the drag on a rigid object make it evident that fast-swimming vertebrates require adaptations of body form and of the nature of the surface of the body. However, since swimmers are not rigid, drag can also be reduced by certain behavioural adaptations.

Reduction of Drag by Adaptations of Body Surface and Behaviour.

It is advantageous for most swimmers to achieve laminar flow over as much of the body as possible. To maximize laminar flow, fishes evolve small smooth scales, or none at all, and become covered with slime. The small scale like feathers of penguins and the hair of seals and otters form remarkably smooth coverings. Cetaceans and sirenians (and probably ichthyosaurs and plesiosaurs) are (or were) secondarily naked and slick-skinned.

However a little turbulence can be a good thing. Larger and faster swimmers are unable to do much to prevent turbulent flow over their body but they can turn this around to their advantage. Consider a golf ball, it is not completely smooth; in fact it has hundreds of little dimples on the surface that create small eddies of turbulence when moving. These serve to reduce the separation of the boundary layer and backfill (pressure drag) in the wake of the body. In water the effects of this are even more pronounced and so the aim of aquatic vertebrates is to control turbulence, rather then eliminate it. Many fishes have projections on their scales that are large enough to cause turbulence. These are found even on the sword of the swordfish. Commonly other scales have microrelief that forms longitudinal "runoff grooves" that are thought to control flow in the boundary layer. The skin of cetaceans and the basking shark has a spongy layer that is capable of elastic deformation and probably dampens pulsations of turbulence, as well as providing a resistance to the muscles in high-speed movement. The finlets on the caudal peduncle of many fast-swimming fishes, and the lateral keels on their tails, are described as damping screens and deflectors that direct the flow of water past the caudal fin. It is not only the smoothness of fish slime that reduces drag. Slime is soluble in water but only when stirred and, hence, is not easily washed away. In concentrations as low as l.0% it reduces flow friction by as much as 60%. That is, it reduces the viscosity of water in the boundary layer. Fishes that accelerate fast, such as trout, have the most slime.

Importantly, fast swimmers outperform submarines and torpedoes in ways that involve behaviour. When animals swim just below the surface, as stated before, wave drag increases. Total resistance by as much as five times the minimum. It is unlikely that many vertebrates attempt to swim rapidly in that position. The "playful" leaps of dolphins may be made in part to avoid swimming at the surface while breathing.

Propel themselves in a relatively dense medium.

There are three main types of powered propulsion adopted by marine invertebrates and they are specific to the type of swimmer that they are. Primary swimmers use undulatory motion and transient motion, whilst secondary swimmers use oscillatory motion. All are based on the same basic principle that if a fin (or limb in the case of secondary swimmers) is presented laterally to the water, the subsequent resistance to motion encountered coupled with precise angling of the fin can create a forwards force, thrust.

The evolution of the internal skeleton (to attach muscle to) and subsequently the tail (as a primary source of thrust) was a great adaptation to the movement through water problem. Obviously primary swimmers were the first to obtain this and in terms for evolution it developed from a heterocercal tail where the spinal axis extends into the dorsal, larger lobe (e.g. sturgeon). But this unbalanced tail created downforce with thrust and so fishes evolved towards a more symmetrical tail. This is termed a homocercal tail where the dorsal and ventral lobes are of about the same size and extend beyond the spinal axis (e.g. blue tuna). Secondary swimmers that have adapted to the use of the tail as a main source of thrust have had to re-evolve the extended tail and in the case of cetaceans and ichthyosaurs have shown remarkable convergent evolution towards a high speed lunate tail.

The majority of fishes use undulatory propulsion, a wave like motion from side to side. Their adaptations to this kind of movement involve the use of their spinal columns to act as pivots to the contraction of muscles on either side. Rapid swimmers have stiff spinal columns to increase speed achieved by their centra being elongated or a reduction and increase in size of vertebrae in order to restrict movement. It has been shown that the skin of sharks acts as an external tendon that becomes stiffer as the sharks move faster, however this is not as efficient as the teleost (bony) fishes that have a specialised arrangement of muscles that doesn’t require attachment to the skin and allows for greater flexibility.

Another form of motion used by fishes, mainly in escape from predators is transient propulsion. It is a stop start motion coupled with a change in direction. The fish quickly contracts one side of its body and moves off in a different direction. This type of glide turn glide motion can be seen in trout.

The principle form of motion used by secondary swimmers is oscillatory propulsion. They use their paired appendages for thrust. These pivot as a unit without travelling waves. Oscillatory propulsion may be drag-based or lift-based. In drag-based oscillation the appendages function like oars or paddles. Drag-based oscillatory swimmers include frogs, most turtles, ducks and other birds that swim on the surface, the sea lion, beaver, capybara, polar bear, and various other mammals. Most of these animals manoeuvre well, but do not swim fast. Some fishes use their pectoral fins as oscillatory propulsors when moving slowly. Such fins tend to be of moderate length and constricted at the base. On the power stroke the paddle must be large, broad, and stiff enough to stand against water pressure without muscular effort. Pinnipeds flatten and greatly lengthen the usual complement of metapodials and phalanges, particularly at the leading edge of the flipper. Ichthyosaurs evolved extra digits (hyperphalangeate) to broaden the paddle, one species having nine digits in all. Ichthyosaurs, plesiosaurs, and cetaceans add phalanges to one or more digits, bringing each series to from 4 to as many as 26 units. Pinnipeds extend some of the bony digits with cartilages. Diving birds and cetaceans incorporate the forearm into the paddle; the radius and ulna become short, flat, and positioned in the same plane. Small aquatic mammals usually have fringes of long, stiff hairs that functionally broaden the foot. These paddles are made rigid in various ways, though some resilience remains. In flippers of cetaceans the bones are flat-ended. Spaces between the bony digits are sufficiently filled with firm tissue to brace the digits and make the surface contour of the paddle smooth.

The other kind of oscillatory propulsion is lift-based oscillation. The function of the appendage is similar to that of a wing in air, but here support against gravity is not required and usually propulsion occurs on both the upstroke and downstroke. The angle of incidence between paddle and oncoming water is relatively small. Lift-based swimmers include some skates and rays, teleosts in several families, sea turtles, plesiosaurs, some mosasaurs, penguins, auklets, murres, puffins, diving petrels, and (on occasion) sea lions.

There is also a final type of movement that doesn't require water and is exploited by some swimmers. If the animal can find either motion (velocity field) or a suitable pressure gradient (pressure field), it can then freeload, at least in part. One fish may position itself behind another's slipstream to benefit from the pressure drag. The best example of this however is the wave riding of dolphins alongside ships.

Control of vertical position in the water, Buoyancy .

This again was first tackled by the fish, primarily the chondrichthyes (cartilaginous fishes). As their tissues have a greater density than water they tend to slowly sink in the water. They have overcome this using two methods. Firstly their fins are shaped like an aerofoil, creating higher pressure below the fin and providing lift. This means they must slowly swim all the time, just as tetrapods breathe all the time. Secondly they have the ability to produce two types of oil in their liver, squalene (HC 65%) and lipids (HCO 35%). These oils are of differing densities and by careful control of the amount of production of them they can alter their overall density and therefore their position in the water column.

Teleost fish have a different approach to maintenance of their vertical position in the water. The first is gas gulping, obviously this is not good for deep water diving due to the compression of gas. Another method developed from early Devonian fishes that had a pair of pouched outgrowths from the pharynx that served as lungs. These later developed into swim bladders, gas filled sacs, which can be used to alter the buoyancy of the fish. They work via the root effect where O_2 is pumped from the blood into the cavity by altering the acidity of the blood. A similar selective production of lipids occurs in a number of teleosts, their storage being in muscle, skin, or skull, and in the surviving coelacanth, which has a fat-filled gas bladder.

Secondary swimmers have no such specific adaptations to the buoyancy problem they all rely on simple density adaptations to help them. The bones of diving birds are less pneumatic. Their air sacs are reduced (loons, penguins). They press their feathers against the body to exclude air. Auks bubble constantly when underwater, and the feathers of some diving birds become wet. Penguins achieve a density of 0.98. Mammals that dive deep may hyperventilate before submerging, but they do not fill their lungs. Indeed, they may exhale before diving. Deep-diving whales have relatively small lungs. Sirenia, which may feed while resting on the bottom or standing on their tails, have unusually heavy skeletons; their ribs are swollen and solid. Likewise, the skeleton of the hippopotamus is unusually heavy. Marine turtles such as the leatherback turtle have adapted a softer carapace in order to decrease their overall density. Also the presence of blubber in marine mammals contributes to the overall density as well as playing a role in insulation. A final note is that Odobenidae (walruses) have two large air pouches extending from the pharynx which can be inflated to act like a life preserver to keep the animals head above water whilst sleeping.

Maintain orientation and steer the body.

The major adaptation noted by all truly marine vertebrates is the use of fins to control pitch roll and yaw in the aqueous environment. This has been developed in conjunction with the movement of the centre of buoyancy near the centre of gravity to prevent pivoting unintentionally when manoeuvring. The fins work in the same way as the tail described before, the careful angling of them directing the forces encountered by drag into a desired direction. The best adapted for underwater movement and precision is seen by the teleost fishes, which have fully pivotal pectoral fins, unlike the cetaceans and the chondrichthyes. An example of this could be the use of the pectoral fins of a trout for braking and low speed movement.

Homeostasis.

Being in a fluid medium provides many unique problems too more complex animals when it comes to maintaining a relatively constant internal environment. The fact that there is constantly a medium surrounding the body which is able to infiltrate remove nutrients, water and even heat means that vertebrates have had to make very specific adaptations to this way of life.

Obtaining oxygen is a major concern to life underwater. All primary swimmers use gills for gaseous exchange (rather than feeding) but in order to obtain a greater amount of oxygen they use muscular action to pump water across their gills rather than the cillary action of their predecessors. Secondary swimmers have evolved lungs and none of them have gone back to gills, this means that they must constantly resurface to breathe. Cormorants and pelicans have lost the external nares they simply hold their breath until completely out of the water. However it is not appropriate for all tetrapods to come fully out o the water to breathe if only a small port ion of them can do it. This has two evolutionary implications, it reduces the amount of time at the surface of the water so they can spend more time hunting and it reduces the amount of wave drag they encounter. The external nares of other aquatic tetrapods, from frogs and alligators to beavers, hippopotamuses, and dolphins, are always dorsal in position, and the owner seems always to know when they are barely out of water. A ridge deflects water from the blowhole of many whales. When under water, the nares are automatically tightly closed. This is usually accomplished by sphincter muscles, but baleen whales use a large valvular plug, and toothed whales add an intricate system of pneumatic sacs so that great pressure can be resisted in each direction. Respiratory exchange may be surprisingly rapid: Whales of moderate size require only 1 to 2 sec to exhale and inhale. Tidal air is relatively great and residual air is relatively small.

Because these tetrapods are diving with compressible sacs of air inside them they must also adapt to withstand the great pressures encountered when diving. Sirenia, Cetacea and Pinnipedia that dive to moderate depths, have a succession of 8 to 40 valves of smooth muscle in each bronchiole to hold air in the alveoli against pressure. Lung tissue of whales and manatees is relatively rigid because of the presence of cartilage and muscle. Their tracheas and bronchi are thick and strong. The tracheas of penguins, some petrels, sea lions, and the dugong are braced by a longitudinal partition. Deep-diving mammals do not carry much air down. The lungs are not an oxygen store. If oxygen were exchanged, nitrogen would dissolve in the blood, only to bubble and cause great distress on the return to the surface. Divers call this condition the “bends”. Alveolar collapse is probably complete at 30 m in the Weddell seal and at 70 m in the bottlenose dolphin, forcing the air into larger, stronger, and non-absorbent airways. Whales have a short sternum and few fixed ribs. The remaining ribs have a single head. Thus, the thorax can also 'collapse" without damage. The main oxygen store is then in the blood. Marine mammals have approximately 2.5 times the amount of blood per volume compared to terrestrial mammals and they also have a lot more myoglobin as a reserve store in the muscles.

Maintenance of osmotic balance is important, as seawater is a strongly hypertonic environment. The fact that in fishes their gills have to be exposed to the water in order for gaseous exchange to occur means that they have got to adapt to conserve water. Chondrichthyes solve this problem by maintaining such a high concentration of urea in their blood (2.5% - far higher than the 0.02% of other vertebrates) that it is in osmotic balance with seawater. Teleost fishes have evolved a more complex and efficient kidney to cope with the hypertonic environment. This kidney is obviously continued into the secondary swimmers lineage and that is also how they cope.

Fish are ectothermic creatures and so they have no need to keep a strict internal body temperature (thermoregulation). However certain fish (e.g. the Antarctic fish Trematomus) have adapted to withstand the subzero temperature encountered in Polar Regions. This cold tolerance is provided by the creation of a glycoprotein that acts as an antifreeze by preventing the addition of water molecules to the crystal lattice of ice, and therefore the growth of ice crystals.

The situation is different in endothermic animals. Since the thermal conductivity of water is about 20 times greater than that of air, endothermic aquatic vertebrates must protect themselves from heat loss, particularly when inactive and when in cold seas. Air trapped in plumage or dry underfur (as of the sea otter, beaver, or fur seal) is an effective insulator. Large mammals have relatively little heat loss because of their low surface-to-volume ratio. Blubber is an effective insulator for them, coming, in extreme instances, to ¼ of the body weight. Flippers of cetaceans have slow circulation and countercurrent exchange, so warm outgoing blood gives its heat to the cold incoming blood. It is probable that some whales require moderate activity to

maintain body temperature in arctic waters. Conversely, swimmers must be able to dissipate heat during periods of activity when heat production may rise tenfold. The countercurrent exchange mechanism can be bypassed, and the large flat flippers (which are devoid of blubber) then serve as radiators.
The circulatory physiology of air-breathing vertebrates during dives adjusts so as to supply oxygen to the brain and heart, and otherwise to avoid stress from lack of oxygen or build-up of carbon dioxide and lactic acid. Bradycardia, or slowing of the heart, is universal and occurs on submergence. The rate commonly is reduced to one-tenth or one-fifteenth of normal, and the slowing is in part preventive; its onset is faster when a deep dive is anticipated. The aorta dilates near the heart to help maintain blood pressure during bradycardia, but all arterioles constrict except those of the brain and heart. Excretion stops. The veins of pinnipeds and cetaceans (like those of fishes) have no valves.

Deep divers are usually not very active. Their hearts tend to be relatively small. The metabolic rate falls off a little (pinnipeds, cetaceans, alligators, ducks). The blood of fast-swimming and deep-diving dolphins is able to carry up to three times as much oxygen as that of their less active relatives. The myoglobin content of divers muscles is high. They tolerate twice as much carbon dioxide in the blood as do humans. Lactic acid is stored in the muscles until breathing resumes. These various adaptations are so effective for elephant seals that their long dives are aerobic; lactic acid does not build up and they need only 3 minutes between dives.

Aquistition of food.

In order to effectively locate and capture prey the vertebrates must be able to sense their surroundings. Various adaptations to the senses are required in order for then to function in water and even new methods of sensing have been employed. It is important to note here that the senses are only as complex as they need be, see below for an example.

Vision is the main form of perception on land but it is usually not the main one in water. Light levels decrease the deeper you go and so eyes have to get increasingly more sensitive and larger in order to perceive the environment. Most fishes have large eyes, the eyeball short along its optical axis, the lens large and spherical, and the cornea flattish or elliptical for streamlining. Secondary swimmers have had to re-adapt to looking through a denser optical medium, obtaining secondary characteristics seen before in their primary swimming ancestors. The example mentioned above can be illustrated as so; Sirenians have poor vision, as would be expected from their sluggish habits, stationary (plant) food, and often murky environment. Baleen whales have moderately good eyesight, but have a limited field of vision and cannot see out of water. Their food is passive, and some of them dive below the level of light penetration. The food of toothed whales and pinnipeds is active, and they have excellent vision, both below and above water. It is also interesting to note that the pinnipeds have a much greater control over the shape of their eyeball enabling them to see both in and out of water.

A much more effective method for predation and communication in water is the use of sound. Sound travels much further in water than in air, and vertebrates have used this to their advantage. Sound is essentially changes in the pressure of water over a very localised area. Although fish do not specifically have an ear (an ear is a terrestrial adaptation) they have what is known as a lateral line canal, a series of pressure sensors that extends down the midlines on either side of the fish from anterior to posterior. These are used in order to sense the changes in the water if disturbed by another object e.g. a predator coming towards them. Secondary swimmers have ears, which are designed to work best in the medium of air so adaptations have to be made in order for them to function in the water, it is however the most acute of all of their senses. It can be used in two ways communication and predation, the most evolved type being echolocation. Communication is exemplified by whale song, an amazing repertoire of sounds ranging from low resonant honks to high flutelike tones. In favourable circumstances some whales probably can communicate over distances of 160 km or more, though little is known of their "language." At least most toothed cetaceans and pinnipeds are capable of remarkably discriminating echolocation. They make sounds up to 200,000 Hz emitted in pulses of from 16 to 400/sec. There is indirect evidence that penguins use the cavitation clicks produced by the turbulence of their own swimming as the sound source for echo-ranging (they can quickly locate fish in absolute darkness). Directional hearing of aquatic mammals is excellent and probably is based largely on intensity discrimination. The mechanisms for hearing themselves have been slightly altered, there is no need for a superficial tympanum or external auditory canal, provided that a gas-filled space functions as a resonator, in truly marine vertebrates. Problems are encountered when it comes to secondary swimmers that have both terrestrial and aquatic lifestyles. The gas filled ear must be protected during dives otherwise the ear would collapse under the pressure and render it useless. The external auditory canal can be plugged or furled by pinnipeds. Cetaceans admit water to the outer part of the canal; the inner part grows shut in baleen whales. The middle ear of pinnipeds (and possibly parts of the external canal), and air sinuses communicating with the middle ear of cetaceans, are lined by highly vascular tissue that engorges during dives. The volume lost by compression of air is thus replaced by blood. Furthermore, in cetaceans the sinuses and parts of the middle ear not adjacent to the drum are filled with a foam consisting of small air bubbles in an oil-mucus emulsion. Experiments show that these bubbles do not collapse, even under a pressure of 100 atm.

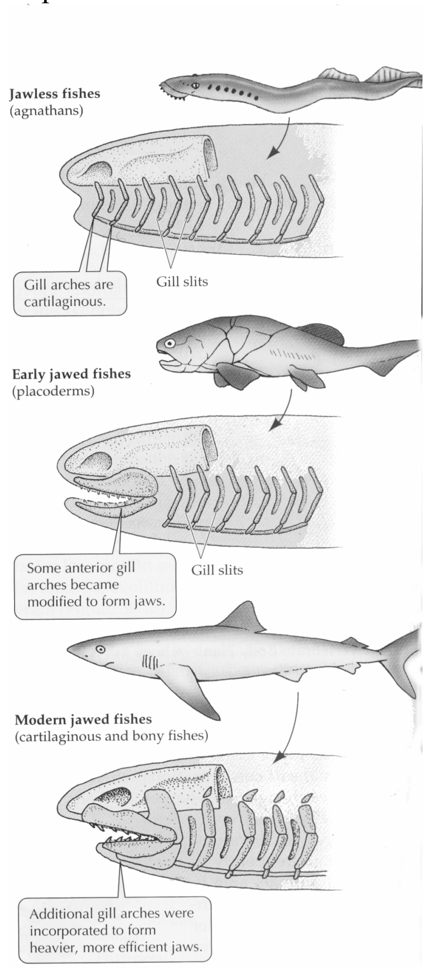
Other adaptations seen in marine vertebrates include a highly developed sense of taste, seen in sharks for location of prey. The hammerhead shark has a very developed sense of smell and the unusual shape of it’s head may be so that it is able to taste “in stereo” due to the wide separation of receptors. The ampullae of lorenzi are used in rays and skates to detect the unique electric signatures given off by fish.

Feeding

Once the food source has been located it has to be consumed. The major adaptation here is the development of the jaw. This adaptation was so profound that it caused Albert Sherwood Romer to comment;

“Perhaps the greatest advances in vertebrate history was the development of jaws and the consequent revolution in the mode of life of early fishes.”

The jaw came about through the adaptation of the gill arches of early fish the aganathans of which today the only surviving member of the group is the Lamprey. See below as to how this adaptation could of come about:



A jaw provides the organism the ability to open its mouth and by causing a pressure difference in the surrounding water "suck" the prey towards it. It also allows the organism to get a firm grasp on its prey and with the addition of teeth it can cut up its prey into smaller pieces and becomes more nutritious. The jaw also allows manipulation of objects such as the ability to dig holes, carry pebbles for a nest and grasp mates.

Reproduction

Due to the hypertonic environment of the sea the chondrichthyes have developed the high urea content of their blood. However this ability does not develop until late embryology and so the eggs of these species cannot simply be released in the sea unlike the teleost fishes. Two solutions are used, both requiring internal fertilisation, in fact chondrichthyes were the first vertebrates to develop this.

1. Enclose the egg in an impervious case filled with isotonic fluid before depositing it in the sea.

2 Retain the eggs and embryos within the mothers body until they are capable of coping with the marine environment, viviparity.

Secondary swimmers also have internal fertilisation and rely on one of the two methods above. Most sea snakes are viviparous and give birth at sea, as did the ichthyosaurs. Other reptiles and all birds lay their eggs or give birth on land. Among aquatic mammals, the walrus and hippopotamus sometimes give birth in the water, and Cetacea and Sirenia always do so. A single, large, precocious young is born at a time. Cetacea deliver rapidly; the calf emerges tail first. The mother whirls in the water, thus snapping the relatively short umbilical cord at a predetermined point of weakness. The newborn swims to the surface and takes its first breaths sometimes aided by the mother.

In summary the adaptations of marine vertebrates display a lot of convergent evolution, showing that within such a homogenous environment as the sea there are not many ways of diversification as there are on land.

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