

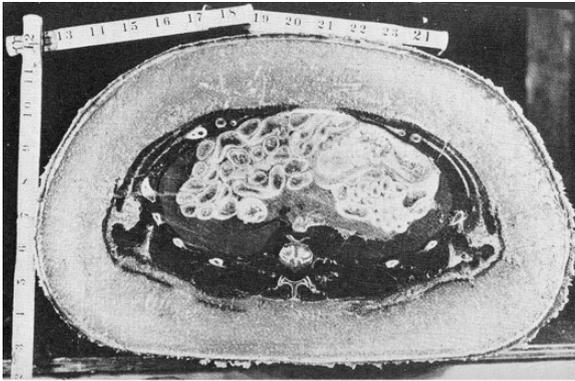
## CHAPTER 21

### RETURN TO WATER AND TO LAND

If one looks at a porpoise or a whale, one realizes that its existence is a conundrum, or puzzle. It lives in the water, which can withdraw heat very rapidly, but it insists on being warm-blooded. Some of the smaller sea-going mammals devote half of their body mass to insulation just to keep warm (Fig. 21.1). It has to come to the surface quite frequently to breathe air. Giving birth is a problem, since the baby is born with no air in its lungs and might sink and so must be lifted to the surface (by “midwife” females) to take its first breath. Nursing or suckling also must be arranged so that the infant can breathe; the mother frequently lies on her back in the water. And yet they are so fish-like, the only difference being that their tails go up-and-down, like a loping mammal, rather than side-to-side like a fish.

These characteristics define a whale or a porpoise as a mammal, but mammals radiated because they were so successful on land. A similar story could be argued for bats: Birds don’t have teeth because of the efficiency of maintaining balance in the air (Chapter 3) but bats, for the most part carnivores, do. Likewise, one advantage of developing a large egg quickly and then laying it is the same reason that airlines charge so much for excess baggage: It is very expensive to carry a large infant around in the air. But bats have true placentas and suckle their young. These questions lead to the more general question of how they arose, and what their ancestry was. The ancestry of the whales has been rather well documented. First, following the discovery of skeletons of what appeared to be the ancestors of whales, the basic scenario was described. Today the similarities of the DNAs confirm the outline, while correcting a few details. Rather than trace the story of analysis in historical sequence, we will pick out some of the details and clues.

First, consider the lifestyles of mammals comfortable in water. They are highly varied but telling. The capybara, a sort of giant, long-legged, South American guinea pig, grazes on land but is also fond of water plants and spends a large part of the night swimming and diving for these plants. It can stay underwater for several minutes. Otherwise it breeds and moves easily on land. Beavers are adapted to water primarily by building underwater entrances to air-filled houses, and having flat tails that like swim fins push it rapidly through water. An otter, a carnivore, does the same, though because of its body shape and flexibility it is more agile and adept in water than it is on land. A hippopotamus grazes on water plants and spends most of its time in water to help it keep cool in the hot, dry lands in which it lives. Next we move to the sea lions, which have ears and a bilobed tail fin that



*Figure 21.1.* Cross section of seal. The total blubber (outer ring) represents 58% of the cross-section. Because water can extract heat much more rapidly and effectively than air can, while mammals are warm-blooded and must maintain temperatures inside their bodies of 98–99° F (37.5° C), marine mammals must maintain very thick insulation. The scale is in inches, Credits: Schmidt-Nielsen, K. *Animal Physiology: Adaptation and Environment*, Cambridge University Press, 1975; from P.F. Scholander, *Biological Bulletin* 1950, 99: 234

is clearly highly modified hind feet, and seals, which do not have external ears but have a tail that is much harder to recognize (unless one sees the skeleton) as related to hind feet. All of these animals nevertheless breed and live on land, and are illustrated in Fig. 21.2.

What happens in the evolution of something like a hippopotamus that forages farther and farther into the ocean and returns as little as possible to the shore? The first clues were collected from the skeletons of large creatures similar to hippopotamus and horses that clearly were not very graceful on land. They had large, bulky bodies and quite stumpy legs (Fig. 21.3). No flight of imagination would make these animals anything other than clumsy, lumbering creatures on land. And yet some of them had skulls and teeth that defined them as carnivores (page 35). To be successful predators, they had to hunt in water, where their bulk would not be so cumbersome. In fact, they also had strong tails, rather like alligators and crocodiles, whose shape they generally matched. A strong tail could propel them through the water even though their legs were not strong. Their large jaws and powerful teeth would likewise compensate for legs not powerful enough to use claws as major weapons. Such skeletons were found in the mountains of Pakistan and, more recently, in China. (Why they are found in mountainous regions is addressed in Chapter 22.)

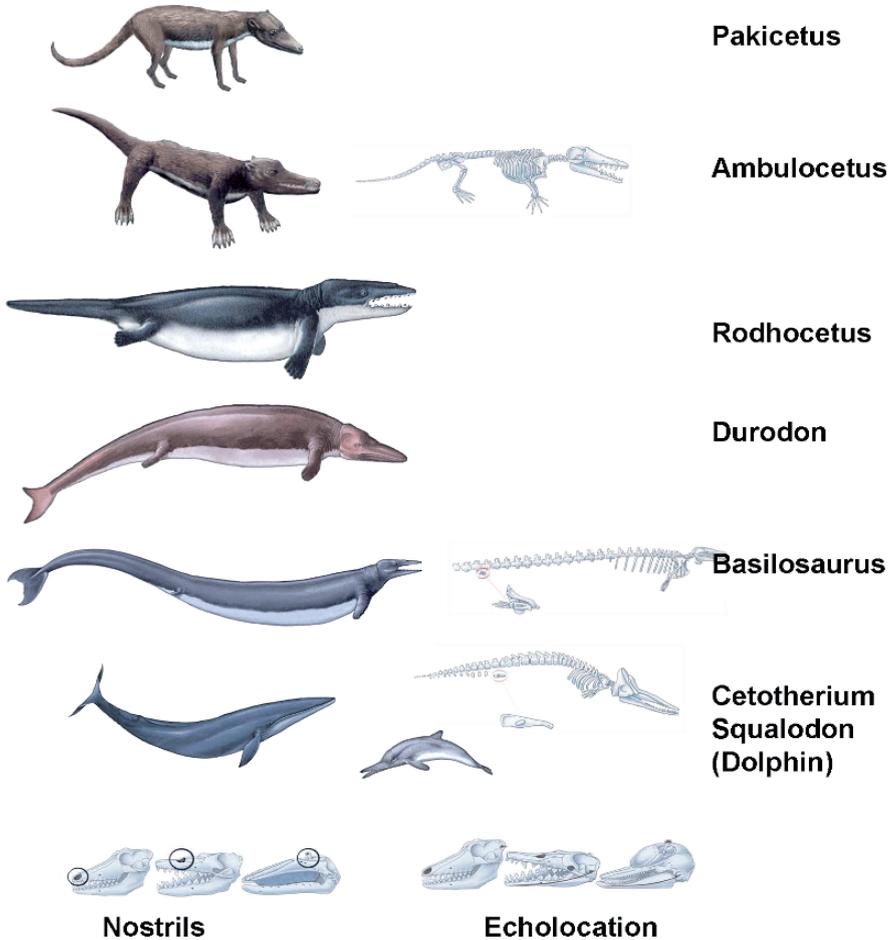
In the next series of skeletons the legs are clearly useless (Fig. 21.3). Such legs could never lift this creature off the ground, and would not have much function in the water, unless, like the forelimb, they were modified as paddles. We have no information about its reproduction, but this creature is similar enough to a whale to be recognizable as one. In the last of the fossil whales, as well as some modern ones, there is no sign of an external hindlimb, but there is a small and apparently useless pelvis. Such a situation is still encountered in today's anacondas and boa



*Figure 21.2.* Progressive adaptation to life in the water A. hippopotamus. The first adjective to come to your mind in looking at a hippo on land is unlikely to be “graceful,” meaning that you recognize that its small legs are not very effective in supporting its weight and making it agile. Its name translates to “river horse” and it is more comfortable grazing in water than on land. B. A hippo is an herbivore. To be a carnivore, one needs to be more quick and agile, as this sleek river otter is. Note that an otter is four-legged but that it has a strong tail to aid it to swim. C. Sea lions, also water-dwelling predators, have two flippers for front legs and their hind legs are fused into a tail flipper. However, they rest on land and breed on land. D. Manatees, which are slow-moving herbivores, have full tail fins and can no longer climb onto land. Credits: Manatee - © Photographer: Wayne Johnson | Agency: Dreamstime.com, Hippo - © Photographer: N joy Neish | Agency: Dreamstime.com, Otter - Image provided by Dreamstime.com” Sea lion - © Photographer: Ravter Bostjan | Agency: Dreamstime.com

constrictors, which have very small bones representing the vestiges of the pelvis of the legged reptiles from which they descended (Fig. 21.4). Today’s whales, porpoises, and manatees no longer have any signs of pelvises, but the line of descent is clear. The DNA trail confirms the story (Fig. 21.5). In fact, the evidence is overwhelming that whales derived from land animals. The types of evidence are numerous, and include the multiple, independent sources that we have emphasized before (page 114):

- Fetal whales have body hair, lost before birth, and fetal baleen whales (which have a hard, horny net to filter out small swimming animals, rather than teeth) also have teeth.
- In a study of 72 different mammals, Miyamoto and Goodman found that, in whales, several proteins common to all mammals were biochemically most closely related to those of the pig/hippo group.



*Figure 21.3.* Evolution of whales from 4-legged, swimming carnivores into completely aquatic mammals, according to the fossil record. The approximate ages of the fossils are Pakicetus, 50 million years; Ambulocetus, uncertain; Rodhocetus, 47 million years; Durodon and Basilosaurus, 38 million years; Cetotherium, approximately 20 million years; and Squalodon, 23 to 5 million years. In the lower panel is shown the gradual movement of the nostrils to the top of the head (blowhole) and the development of the bulbous structure that allows modern whales to hear and locate sound under water. Credits: Summary Adapted from National Geographic, November 2001, *The Evolution of Whales*, by Douglas H. Chadwick, Shawn Gould and Robert Clark Re-illustrated for public access distribution by Sharon Mooney ©2006, Wikipedia.org

- In many whale embryos external hind limb buds appear but, by ceasing to grow, disappear before the whale is born. They also have vestiges of external ears.
- In whale embryos, the nostrils start out at the front of the head but get pushed back to a blowhole by the growth of the nose beneath them.

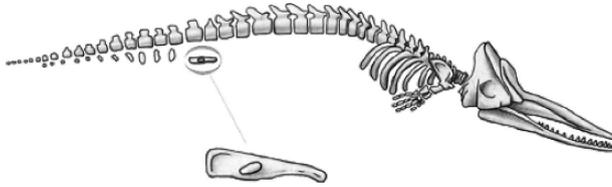


Figure 21.4. Rudiments of a hind limb and pelvis in a modern sperm whale. Credits: Summary Adapted from National Geographic, November 2001, The Evolution of Whales, by Douglas H. Chadwick, Shawn Gould and Robert Clark Re-illustrated for public access distribution by Sharon Mooney ©2006, Wikipedia.org

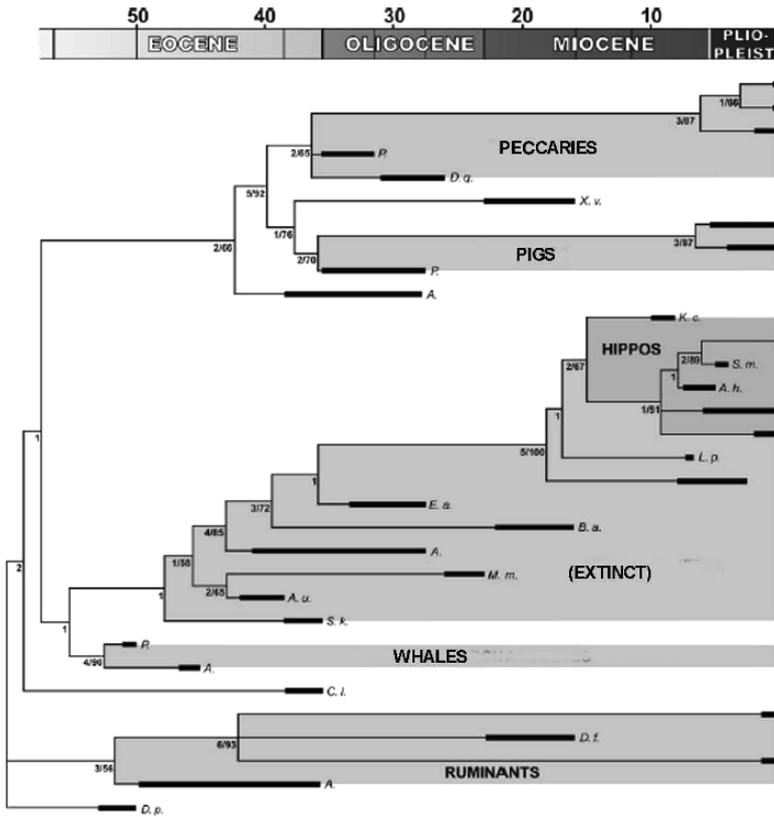


Figure 21.5. A modern interpretation of the evolution of whales. This sequence was derived primarily from interpretation of bone structures, but comparison of proteins of modern hippos, elephants, horses, and whales produces a similar sequence. Credits: The position of Hippopotamidae within Cetartiodactyla Jean-Renaud Boissarie, Fabrice Lihoreau, and Michel Brunet doi:10.1073/pnas.0409518102 2005;102;1537-1541; originally published online Jan 26, 2005; PNAS This information is current as of October 2006. Rights & Permissions To reproduce this article in part (figures, tables) or in entirety, see: [www.pnas.org/misc/rightperm.html](http://www.pnas.org/misc/rightperm.html)

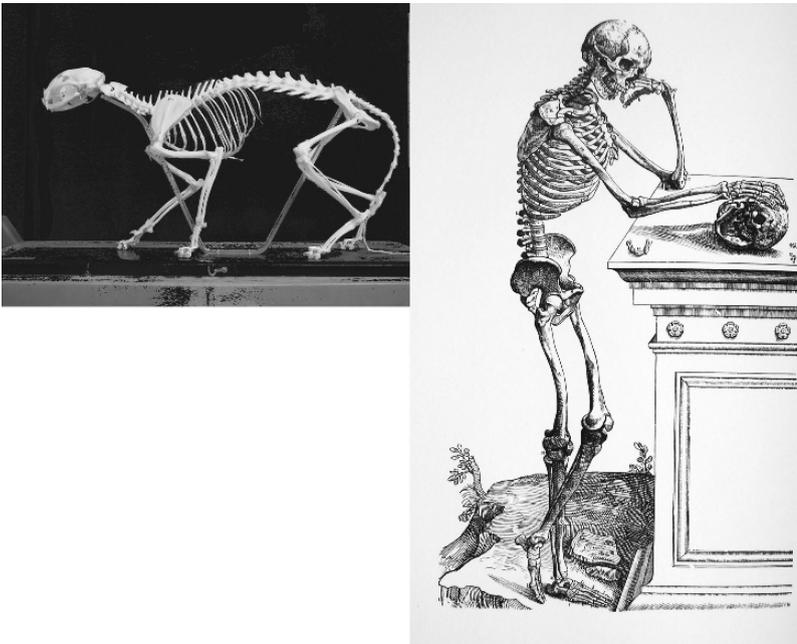
- The record of fossils confirms in many respects their history. The first whales, which had legs, are found in local regions; their bones have a composition that indicates that they drank fresh water; and the fossils are found in soils including washout characteristic of fresh-water lakes. Furthermore their skeletons have not developed the adaptations of the ear or thorax that are required for deep diving, and their nostrils are toward the front of their heads. All the indications are that these beasts (*Pakicetus*) lived on the shores of freshwater lakes and occasionally dived for food. *Amblocetus*, on the other hand, is found along with marine fossils, and *Rodhocetus* is found with deepwater soils.
- The localization of the fossils is confirmatory. *Pakicetus* has been found along the shores of presumptive lakebeds in Pakistan. The range expands until *Basilosaurus* is found worldwide, from Asia to lands bordering the Gulf of Mexico and the Canadian Pacific Coast.

The story of the whales also raises the question of the meaning of vestigial organs. Do they have any other functions? Why do they disappear, and why do they not disappear instead of gradually becoming less useful? All of these questions, when phrased properly, lead to interesting explorations and greater understanding of how evolution works.

The first interesting answer relates to the fact that young embryos of many species look far more alike than the older embryos (page 30). For instance, all vertebrate embryos have notochords, a firm gelatinous rod that serves as a structure against which muscles can pull in the most primitive chordates (page 66) but in the higher chordates the skeleton serves this purpose, and the notochord ceases to grow, becoming a small, inconspicuous structure in the adult. In the embryo, however, the notochord does serve a purpose. In all chordates, it is the structure that defines the axes of the embryo, particularly what is left, center, and right; and what is backside (dorsal) and bellysides (ventral). If one experimentally interferes with the formation of the notochord, the embryo cannot build its organs in the right places, and it will die as a disorganized or poorly organized mass of tissues. Even though in the adult the notochord apparently does not function, the first chordate embryos used the notochord as the basis of their organization, and this very important role has not been assumed by any other structure or mechanism.

The second principle is that evolution does not occur in the absence of selection. For a structure to be gained or lost, there must be some interaction favoring its construction or its loss. In other words, one can select for more and more powerful claws, but the most important factor favoring the loss of an already useless part would be that the resources used to build it can provide an advantage if diverted to other functions. Thus small legs that do not really help a permanently aquatic animal might be a problem if they were likely to scrape against something and be cut, or if smaller predatory animals could bite them off and cause an injury. Otherwise, the only way in which they might be lost is the following: There is always a possibility of an error in copying DNA, or a mutation. Organisms have many means of identifying and correcting errors in DNA, but occasionally an error gets through. If the error causes a severe problem, it will be selected against

(individuals bearing the error will not be as likely to leave progeny to the next generation), and therefore the gene will not change in the population. However, if the error has no particular impact, then there will be no selection against it. Thus it takes considerable biological energy to construct a hind limb. If the limb serves no purpose, then an error in its construction will not be selected against and will persist to the next generation. The laws of physics teach us that creating order requires energy, whereas decrease in order is spontaneous. It takes work to build a watch or a building, but the watch or the building can fail spontaneously and if there is no further use for the non-functioning watch or building, it will simply continue to disintegrate. As long as a limb or an eye serves a valuable function, individuals with poorly functioning limbs or eyes will be selected against. However, if for instance an animal that lives in caves learns to move and hunt using sounds or smells only, there is no further selection to preserve vision. A non-functional eye is only a source of potential injury, and there may be selection against it. Thus structures can gradually disappear, but will do so only gradually.



*Figure 21.6.* Backbones of tetrapods and humans. The backbone of a human is curved in an S-shape, the better to balance the torso. That of a tetrapod (cat) is arched to support the weight on four legs. Note also in the human skeleton how the weight is centered on the pelvis, the angle at which the spine joins the pelvis, the angle of the femurs (thigh bones) relative to the pelvis, and the angle and balance of the head on the spine. Note particularly the foramen magnum (the hole in the base of the skull on the table, where the spinal cord enters the skull)

Finally, evolution will always build on what is available and will not purposefully invent structures. The swimming motion of a whale or porpoise will be based on the abdomen-to-backside motion of the backbone of a running animal rather than the side-to-side motion of a fish. Likewise, the spine of an erect human has developed a few curves to help balance the body—the spine, upper body, and head are balanced on the pelvis much like balancing a broomstick on one’s hand—but is basically a rather crude means of converting the suspension bridge-type construction of the spine of a four-footed mammal into an entirely different support system. The construction is the origin of many problems ranging from fatigue in standing to backaches and spinal injuries (Fig. 21.6).

Although starting with the amphibia the story of the vertebrates has essentially been a story of finding better ways to survive on land, the search for new niches has led many animals to return to the water and to the air. We can recognize from evolutionary relationships and from the structures themselves whether the return represents a single evolutionary sequence or several. From the structure of the bones, the return to the air of flying (now extinct) reptiles, birds and bats were different sequences (Fig. 12.2) as were the return to water of plesiosaurs and swimming mammals; but whales and porpoises have a common ancestry.

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## STUDY QUESTIONS

1. What characteristics define a whale as a mammal? Could you argue that it is a fish?
2. Some sharks have a placenta-like structure and bear their young alive. Are they mammals? Why or why not?
3. Why does a seal need such a heavy layer of insulation?
4. What other explanations can you come up with to explain the existence of what we argue are vestigial pelvic bones?
5. What other explanations can you devise to explain the existence of small limbs on the embryos of porpoises and whales?
6. What other explanations can you give for a mechanism whereby unused structures are lost during evolution?