Whale Evolution
Activity Facilitation Guide
Table Activity

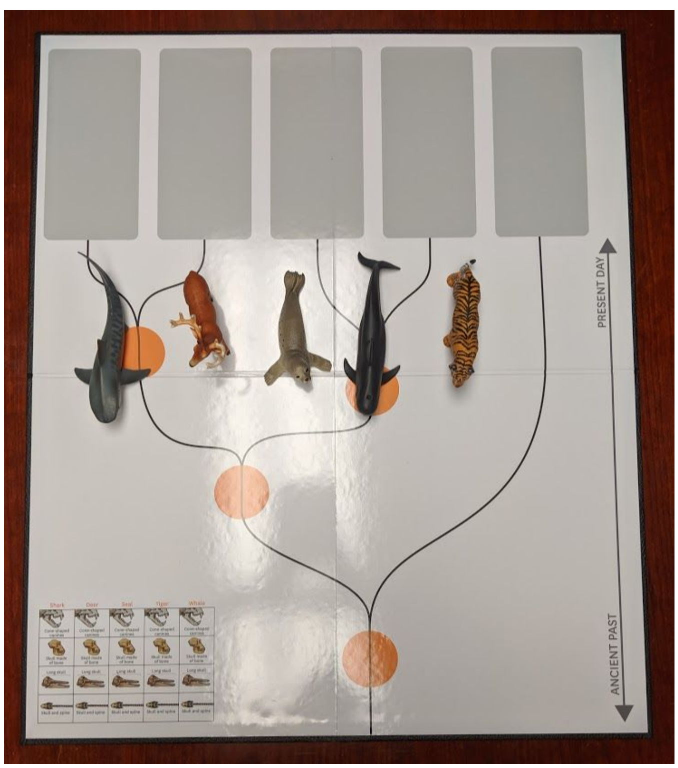
NATIONAL MUSEUM *of* NATURAL HISTORY

Materials and Set-Up

MATERIALS:

5 animal toys (shark, deer, seal, tiger, and pilot whale)
5 photographs of animal skulls (shark, deer, seal, tiger, and pilot whale)
2 game boards: each has an evolutionary tree featuring empty boxes for players to place animals and traits
One hypothesis board
Cards depicting traits (illustrated)
Colored tokens to make hypotheses
5 sets of fossil evidence (skull, mandible and forelimb of ***Maiacetus*, *Pakicetus*, *Dorudon*, Pilot Whale, and White-Tailed Deer**)
Cards depicting 5 animals (skeleton on one side, animal with covering on other side)

SET-UP:
Requires 1 five-foot or six-foot table. Activity begins with the first board and the five toys on the table. The other materials are close at hand.

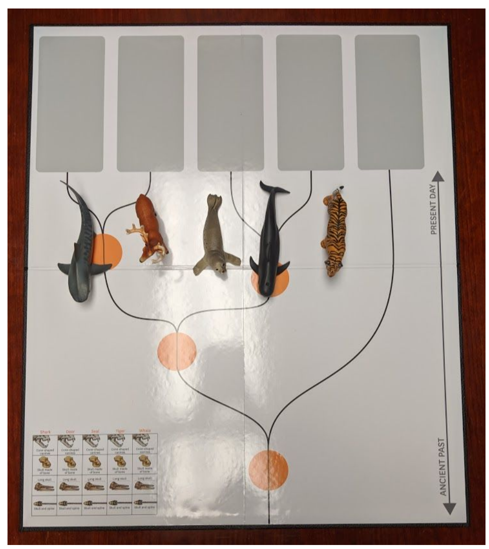


Whale Evolution Activity Facilitation Guide

Activity Goal	Visitors find the closest living relatives among a set of animals using shared characteristics. Then they use fossils to investigate the whale lineage from the last common ancestor of whales and deer to today.
Activity Summary	In this two-part activity, visitors explore the idea of common ancestry by making hypotheses about relatedness among whales, deer, tigers, seals and sharks. They use an evolutionary tree to keep track of their hypotheses and observations about these animals. Upon learning that whales and deer are closely related, they move to Part 2, in which they compare traits visible in modern and fossil skeletons to understand more about whale ancestry. Visitors split into two paleontology roles - the lead researcher and the field paleontologists. They work together to build a whale evolutionary tree that tracks their observations and hypotheses about when and how shared derived traits evolved. Then they use the tree to pose and answer questions about the nature of change over time, looking particularly at how terrestrial mammals evolved to live in marine habitats.
Learning Objectives (what visitors think, feel and do during the activity)	In the course of doing this activity, visitors will: -Make observations of, describe and compare the traits of extinct and extant whale relatives -Use an evolutionary tree to make hypotheses about evolutionary relationships -Use specific characteristics of skulls and skeletons to work out how closely the animals are related -Use the tree to answer questions about when different traits emerged along the whale/artiodactyl lineage -Discuss, explain, and debate with family members to make hypotheses, and make decisions while building the tree -Feel like they are doing science
Learning Outcomes (new understandings or changes in perspective that result from activity)	We anticipate that visitors who participate in the activity are more likely to: -Begin to understand more about how scientists use shared derived characters to work out relatedness. -Better understand how to make and read evolutionary trees and why and how scientists use them to represent hypotheses about relatedness, to explore and generate questions about evolution of traits, and to represent shared features among living things. -Understand that certain skeletal features are more useful than external features for investigating relatedness between living things.

	-Think more critically about how much living things can change if given large enough spans of time--from mammals that walked on land to ocean creatures that could not survive outside of the water. -Feel more comfortable and confident engaging with science, independently and as a group or family.
Target Audience	Families with children 8-12, but adaptable for all.

Activity Flow

What to say	What to do
HOOK [INSERT YOUR OWN HERE]	Differentiate according to audience; make sure to invite all family members to participate.
INTRODUCTION Every living thing, every species on earth is related. We all share a common ancestor. And one thing that biologists and paleonotologists want to understand is how different groups of animals evolved over time, to make the huge biodiversity that we see today, and how different species evolved or branched off from one another, from early common ancestors. And today you are going to be a research team with me to investigate the evolution of one of those groups of animals.	
GUIDED PARTICIPATION Here are models of 5 animals that are alive today. We have a tiger, a shark, a deer, a whale and a seal. We want to figure out which ones are most closely related to each other. Can you look at them, and based on what you see, make a hypothesis	

about which ones are most closely related?

Form 3 groups, based on which ones you think are most similar. Form pairs that appear to be the closest. You'll have one animal that stands alone.

This will be your first hypothesis. You'll have a chance to change it later.

Ok great. Does everyone agree? Why did you group them the way you did?
How confident do you feel about your groups?

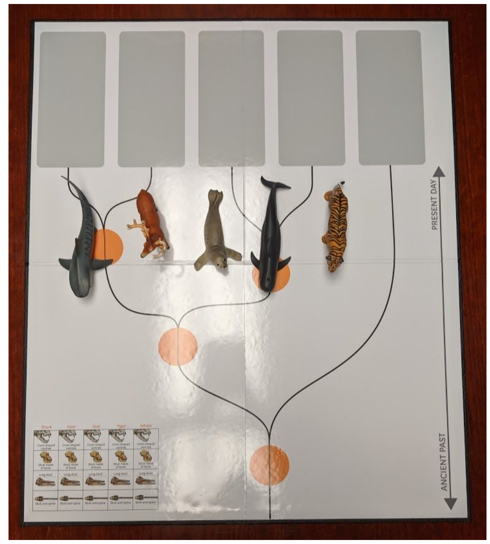
So this is just your starting hypothesis.

It would be hard to be that confident--you don't have much to go on. It's common to make assumptions based on exactly the same things you did. But science shows us that you can't judge a book by its cover.

This tree is a diagram that scientists use to show evolutionary relationships, relationships of living things through time.

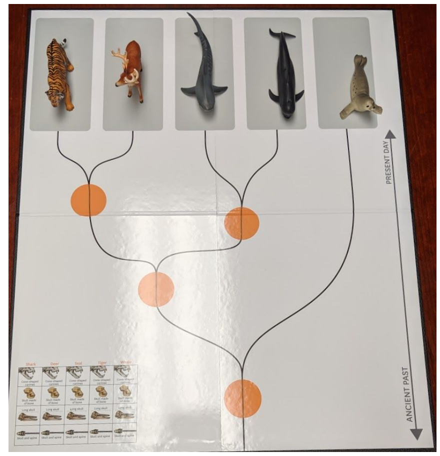
If you start back here, this is the ancient past, and as you go up here, we are going forward in time. And these lines represent the passage of time as living things evolve, so as you go up the tree, something branches off and there's a new species that shares some characteristics with its ancestors but is different too. Each of these circles represents a feature that is shared by everything that comes after.

Emphasize that things that have similar features are often closely related.



I'm going to take your hypothesis and put it on the tree.

Something like: "You chose two pairs of close relatives. You put the tiger and the deer. We put these together because there is a recent branching point, which means it's a close relative. This branch is far in the past. So the most distantly related animal goes at the end of that branch." Now, if we place your groupings at the ends of branches of an evolutionary tree, they may look something like this. Where these are grouped together because they share this trait and branched off here from a common ancestor. And these the same, and this point show where these two groups may have split from one another.



[Place the toys on the ends of the branches and talk about why you are placing them where you are.]

Give Skull photos

[Give photos of skulls to visitors.]

Now, one thing paleontologists have learned is that we have to look closer than the surface. What happens when we look at the bones of these animals? In particular, let's look at the skulls. What do you notice?

Do you see two that look really similar? What about these others?

Let's see if you want to update your hypothesis.

[Give them a chance to make their own observations; you can prompt them to look at the shape of the skull--is it long or short, presence of cone-shaped canine teeth, and a skull made of bone, not cartilage.]

Now we'll look at the tree again. Remember how we said that we can use the traits that these animals have in common to place them on the tree and show how they are related. We'll use this chart to keep track.

So let's start with skull and spine. How many of these creatures have a skull and a spine? That's right. All of them do. So you can mark that on the chart. Where would you place this trait? So many millions of years ago all these things shared this characteristic in common. From there, things started branching.

How would you place these other three traits and the animals on the tree based on your new observations?

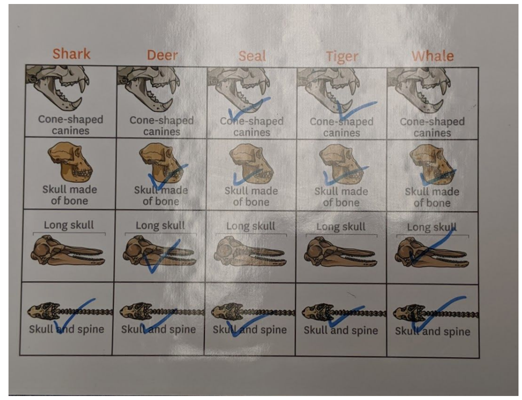
So, these are the evolutionary relationships for all these.

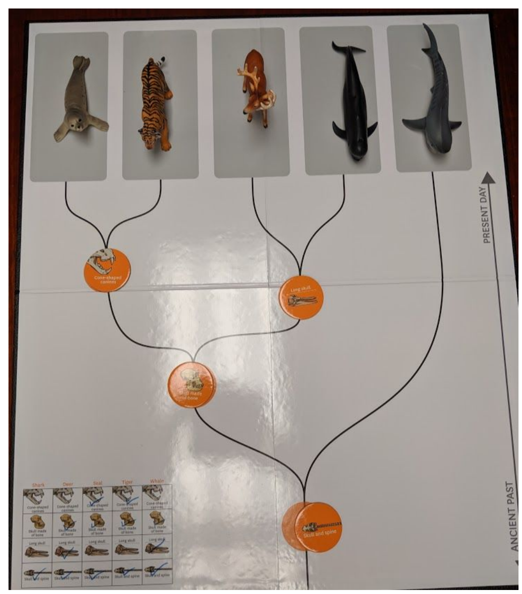
Is it surprising to you that whales and deer are so closely related? How are these giants of the ocean, which can't live on land, close relatives of animals that live exclusively on land? Did deerlike animals evolve to become whales? Did whale-like animals evolve to become deer? What do you think? Do you think the most recent common ancestor of whales lived ON LAND? Or IN THE OCEAN?

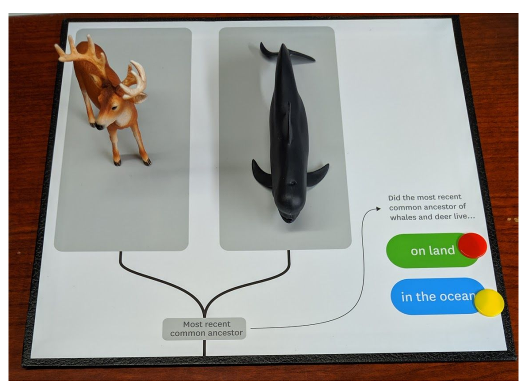
If you think about their most recent common ancestor, this place where they split, do you think that ancestor would have lived in the ocean or on land? [Have them use tokens to make a hypothesis]

Why do you think that? How can we find out the answer?

*In this round, it's quicker to mark the chart for them and then let them place the traits and rearrange the animals. They'll have a chance to work through the chart themselves in the next round.





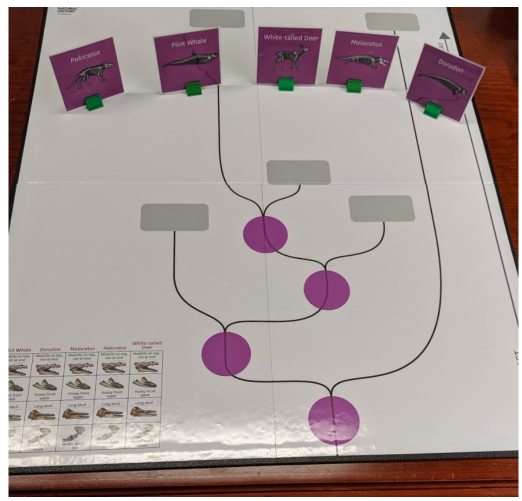


Now that you've made your hypotheses, I'm going to ask you to apply what you've learned about using observations and making trees to try to answer this question. And you get to use fossils!

One thing we can do with these trees is use them to answer questions. And I have a tree that you can use together to solve a question.

You can make a hypothesis and you'll get a chance to revise your hypothesis.

Part 2

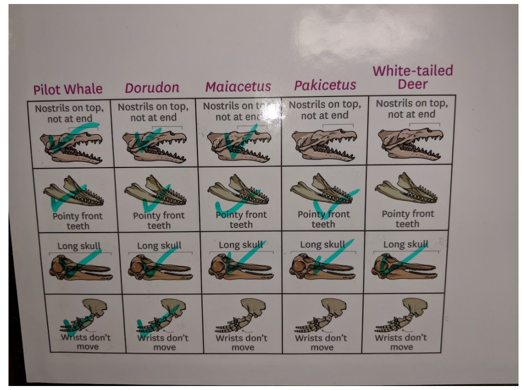


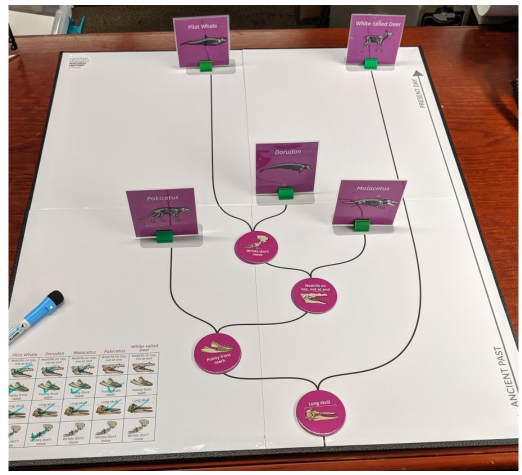
[Bring out the second tree game board.] This part of the activity works more like a game. We're going to assign one of you to be in charge of building the tree - you will be the lead researcher. Your colleagues are going into the field to collect data on these different relatives of whales and deer. You will ask them to make observations that you can use to put these animals where they belong on the tree.

Lead researcher, these are the animals that your colleagues will have skeletal remains or bones for, and these are the traits you will need them to look for and describe to you. Again, you have a chart to help you keep track as they give you their information.

[Visitors work together to put the traits and whale relatives on the tree.]

Can you point to the branch of the most recent common ancestor? So, if you go back to your hypothesis, what do you think?





If they get STUCK seeing that the earliest relatives lived on land, you can have them look at the individual animals and say something like:

Let's look at these traits and start back at the earliest point after the most recent common ancestor. Then we'll

<table>
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<td>move up through time to today. Do you think these are useful for living in the water? If you had to point to a place on this tree for when animals started to live only in the water and not on land, where would you point? What about living near the water and water some of the time? Now what do you think about your hypothesis?


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<td>WRAP UP/RELEASE

Doing what you did, but with loads more fossils and traits, scientists have figured out that the ancestors of modern whales lived on land around 50 million years ago. Different early whales evolved traits that made it easier to spend time in the water, and as new species continued to evolve, some of them had traits that made it possible to live in the ocean full time.

Scientists only worked this out recently so this represents current research.

[INSERT YOUR OWN HERE]</td>
<td>

Identify the science skills the visitor used in the activity.

Direct them to other parts of the museum or elsewhere for related content.</td>
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Background Information

Basic whale evolution: groups, timing, migration, diversity

When people think of whales (cetaceans), the first thing that comes to mind is often their massive size, and with good reason! The blue whale is known to reach lengths of over 90 feet and can weigh in at over 300,000 pounds! This makes the blue whale not only the largest living animal, but the largest animal known in Earth's history! But this is not the only thing that is impressive about these mysterious aquatic creatures. You may already know that despite being similar in appearance to fish, whales are mammals like us. They produce milk, give birth to live young, use their lungs to breathe air, and are warm-blooded. Whales belong to a group of mammals called artiodactyls which includes animals such as pigs, deer, cows, sheep, hippos, and even giraffes! You may wonder how whales could possibly be closely related to all these animals when they look so different from each other. To understand this, we will have to delve into the fascinating ancestry of whales that began around 50 million years ago. As we explore this history of whales, keep in mind that evolution is not a straight path. All the animals discussed here share similarities that tell us they are closely related, but that does not mean they each directly led from one to the other. Rather, they all shared a common ancestor.

It may surprise you to find out that the earliest whales bared little resemblance to the whales we know of today, and actually looked much more similar to deer and pigs! *Pakicetus* is an animal from Pakistan that lived 50 million years ago and is thought to be the earliest animal we consider a whale 4. This animal was a predator that had teeth adapted for eating fish and other small animals. It had four fully developed legs with a long snout and tail, and it was around the size of a large dog. *Indohyus* was a similar animal that lived 48 million years ago in what is now India, though it was somewhat smaller than *Pakicetus* and adapted for eating plants. 3, 6

Both animals seem to have lived primarily on land, although some features of their skeletons indicate that they were partially aquatic as well. *Pakicetus* and *Indohyus* both have a dense bone structure that would have aided them in staying submerged underwater. *Pakicetus* also had upward oriented eyes that would have allowed it to view its surroundings above the surface while in the water. 10

While *Pakicetus* and *Indohyus* seem to have spent at least a portion of their life wading in shallow freshwater, a group of whales known as ambulocetids are the first to be fully aquatic. 1 They were also able to tolerate varying degrees of salt content in the water, indicating that this group displays a point in cetacean evolution during the transition from freshwater to saltwater habitats. 8 The ambulocetids likely swam by using their large back feet to push and steer themselves through the water, along with smooth, up and down movements of the spine (undulations) to generate more force.7 These undulations of the spine are key in how whales swim, even today, so this development is a very important milestone in cetacean evolution.

The remingtonocetids are another group of early whales that lived 49 to 43 million years ago in southern Asia. The remingtonocetids had small limbs that likely wouldn't have been able to generate much force in the water. Instead, they largely depended on their long, powerful tails to swim. 2,9 This family is one of the first groups in Cetacea to be fully adapted to marine environments. 8

Up until this point, whale ancestors had remained largely concentrated in southern Asia. A very diverse group of cetaceans called the protocetids were the first group to spread more globally across not just Asia, but North and South America, Europe, and Africa as well. Through the course of cetacean evolution, major modifications occurred that allowed increased mobility of the spine for movement in the water, and many of these changes can be seen across the protocetids. We saw the beginnings of the use of spinal undulations for swimming in the ambulocetids, but the protocetids are the first to display significant adaptations to the pelvis (hip bones) and spine that helped make these undulations easier and more effective. In land mammals, the pelvis is attached to a series of fused vertebrae in the spine called the sacrum. This structure provides much needed stability to this region to support the animal while walking and running. As whales adapted to life in the water, they no longer required so much stability in this area. Through a reduction of the pelvis, loosening of vertebrae in the sacrum, and eventually the detachment of the pelvis from these vertebrae entirely, whales' spines became much more flexible, allowing them to move through the water more efficiently. 5

With this shift toward using undulations of the spine to swim instead of paddling with their limbs, it's no surprise that over time, whales' limbs became modified as well. Basilosaurids, which evolved around 40 million years ago, are the first group of whales to truly look similar to modern day whales. Their hindlimbs were significantly reduced in size, likely making them unusable, and their forelimbs were modified into flippers used largely to steer through the water. Basilosaurids also had the iconic tail flukes that we see in modern cetaceans that help to propel them through the water. 9

Although today's whales no longer have external hindlimbs, when we look at their skeletons we can still see small remnants of the bones of the hindlimbs and pelvis that once played such an important role in the lives of their ancestors. These little bones serve as reminders to us of their incredible transition from land to water. Though whales have certainly come a long way through the course of their evolution, their story is far from over. As our climate changes, it will be interesting to see how whale populations continue to evolve in response to these shifting environments.

Modern Whales

Modern whales are broken down into two main groups: the toothed whales (Odontoceti) and the baleen whales (Mysticeti). Odontoceti includes groups that have relatively smaller body sizes such as belugas, dolphins, and porpoises. As their name suggests, members of Odontoceti have teeth that they use to grab onto larger prey such as fish and squid.

Mysticeti features many of the larger groups, such as blue whales and humpback whales. Members of Mysticeti are very distinct in their feeding behavior. Instead of teeth, their mouths are filled with bristles of baleen that allow them to filter-feed. These whales will open their mouths to take in large amounts of water, including any small organisms that were swimming in that water. Their thick baleen then allows them to push the water out of their mouth while entrapping any animals between the hairs. While these whales feed on very small animals such as krill and plankton, they consume incredible quantities of them to sustain their large body size. A blue whale, for example, can eat up to 8,000 pounds of krill in a day! Paleontologists believe that the incredible size we see in Mysticeti whales today is likely linked to their food sources. It seems that around three million years ago there may have been a spike in the abundance of nutrients and small organisms in the oceans, providing whales with plentiful food sources that may have led to their rapidly increasing size.

Resource:
https://ocean.si.edu/ocean-life/marine-mammals/when-did-todays-whales-get-so-big

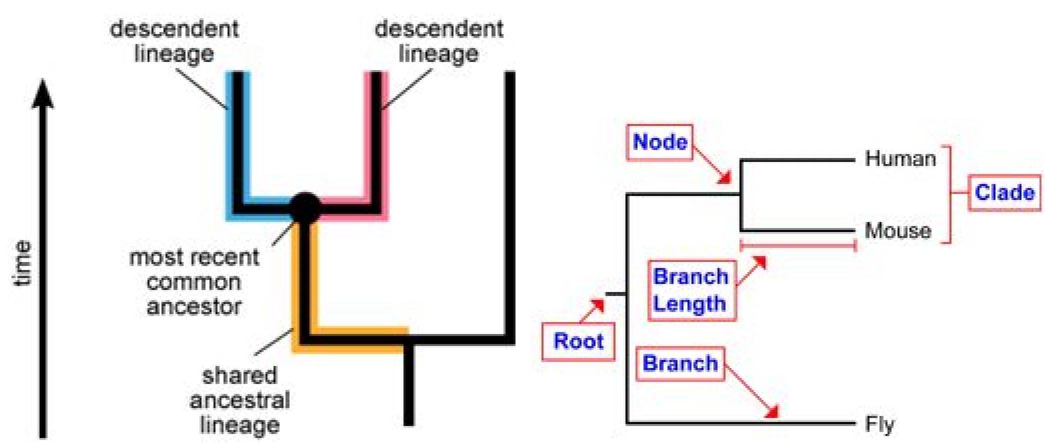
Convergent Evolution - Back to the Water

While whales and fish may appear very similar at first glance, once we start to examine them more closely, it’s easy to see how different they truly are! Both whales and fish spend their lives swimming in the water, but this is not an adaptation that they gained from a common ancestor. Whales and fish adapted to aquatic environments independently from one another through what is known as convergent evolution. Convergent evolution is when groups evolve similar traits independently from each other, rather than sharing the trait due to it being passed down from a common ancestor. Often this is due to these organisms adapting to a similar environment.
In the case of whales and fish, they both developed a similar streamlined body shape to reduce resistance in the water and allow them to swim through the water more smoothly and

efficiently. We also see that whales evolved fin-like structures (flippers) similar to what we encounter in fish, however the internal structure of these appendages gives us evidence of their distinct ancestry. Whale flippers have the same bones of the wrist and fingers that we see in other mammals, once again indicating their land-based origins, whereas the pectoral fins of fish lack these bones. Whales and fish also both evolved a tail fin, however their usage of this structure is very distinct. While fish have a vertical tail fin that helps them swim by moving side-to-side, whales have a horizontal tail fin that they move up and down to help propel them through the water.
Resource:
https://evolution.berkeley.edu/evolibrary/article/similarity_ms_08

Evolutionary Tree Primer

One of the biggest challenges that paleontologists face is trying to understand the complex relationships between all organisms, whether living or extinct. One way we try to accomplish this is by constructing **evolutionary (phylogenetic) trees** that act as visual representations of our hypotheses of these interconnected relationships. Each **branch** represents a particular lineage and each branching point of a tree (**node**) indicates the point where an ancestral lineage diverged into two distinct lineages. Therefore, each node represents the most recent common ancestor that is shared between all the groups following that node.



Source: **https://www.ncbi.nlm.nih.gov/Class/NAWBIS/Modules/Phylogenetics/phylo7.html**

To construct an evolutionary tree, we first need to determine the evolutionary relationships between each of our organisms by examining their shared heritable characteristics/traits. Organisms that share a greater number of traits with each other are likely more closely related. By making a checklist of which traits are present or absent in each of our organisms, we can determine which features likely evolved early in their ancestry and became passed down to each subsequent lineage, versus traits that evolved more recently and help to distinguish a separate lineage. Traits that evolved that differentiate new lineages from their ancestral groups are known as **derived** traits, whereas **ancestral** traits are those that are inherited from more distant ancestors.

https://www.khanacademy.org/science/biology/her/tree-of-life/a/phylogenetic-trees
https://www.khanacademy.org/science/biology/her/tree-of-life/a/building-an-evolutionary-tree

https://evolution.berkeley.edu/evolibrary/article/0_0_0/evotrees_intro