Whale Evolution Lab

Adapted from *http://www.indiana.edu/~ensiweb*

PRELAB (recommended)…

FROM LAND TO WATER: A Whale Evolution Internet Activity

http://www.indiana.edu/~ensiweb/lessons/whalekiosk.html

Click on "SCREEN" to "Find Out More"

A. Anatomy

B. Fossil record

C. Molecular evidence

A. WHALE ANATOMY

1. What does the Latin word "cetus" mean?
2. What three groups of organisms are considered cetaceans?
3. What are the two subgroups of cetaceans?
4. What characterizes the subgroup Odontoceti?
5. What characterizes the subgroup Mysticeti?
6. Follow the instructions given to compare anatomical parts. Click on the labels to ***compare the whale's anatomy*** with that of a fish and a cat. Fill out the chart below with your answers to each structure, by placing an "X" under the organism whose structure is more similar to the whale's.

Structure	FISH	CAT
Ears		
Eyes		
Lungs		

Structure	FISH	CAT
Forelimb		
Jaw		
Mammary gland		

7. According to the anatomical evidence, which organism is more closely related to a whale…fish or cat?
8. Draw and label the cladogram that you created for the whale, fish, and cat below.
9. What is the relationship between whales and cats?

B. FOSSIL RECORD

1. What is a fossil?
2. What are the most likely parts to become fossilized?
3. What are trace fossils? List some examples.
4. What is a coprolite?
5. What fossilized anatomical structure can be useful to anatomists?
6. Compare the fossil teeth of whales to the other organisms on the website. ***What sort of organism has fossil teeth most similar to whale teeth?***
7. What is a mesonychid? What is an ungulate? What is an ungal?
8. What are some modern-day ungulates?
9. To what group did the other skull belong?
10. ***Which are more closely related to whales…seals or horses?***
11. What other organisms belong in the Order Carnivora?
12. Check out the anklebones. List some examples of modern-day Artiodactyls.
13. Which anklebone looks more similar to the fossil whalebone?
14. What does this mean for whale's closest relatives?
15. Before we look at molecular evidence, check out more in the fossil record. ***What environmental shift was responsible for the process of natural selection that led to whales?***
16. How is the water different from the air? What does that really mean?
17. What doesn't light travel as straight or far in water as in air?

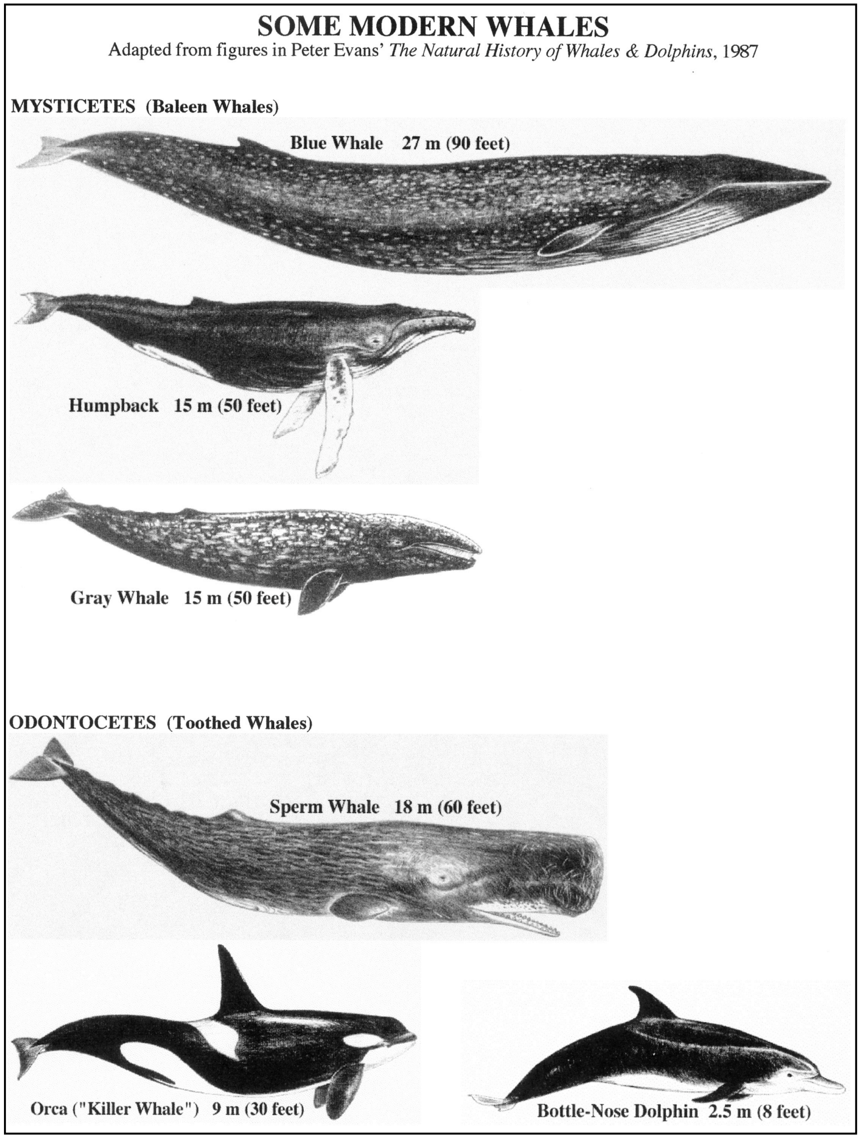
18. Why don't we have directional hearing under water (click on "HUH?")
19. What happens each time a molecule bounces into you?
20. What four parts of the whale have changed over time?
21. Click on the whale forelimb (arm). What is the earliest whale that investigators have found? What does it look like?
22. What were the forelimbs good for in the earliest whale?
23. Compare it to a human arm. How is your arm different from this whale's arm?
24. ***Which early whale could walk on land and swim in the water?*** What does it look like? How do its forelimbs compare to the whale's arm?
25. What was the first fully aquatic whale? How does its arm compare to *Ambulocetus* and a modern whale?
26. How are modern whale's arm bones different?
27. Click on "Games" and try "***Morph a Limb***". Click on a bone, then use the buttons to change its size or rotate it. How do you think the differences in bone shape relate to how the two animals moved in their environment?
28. Go back and try the game "Be a Paleontologist". How long did it take you to get the bones in their proper position?

C. THE MOLECULAR PICTURE

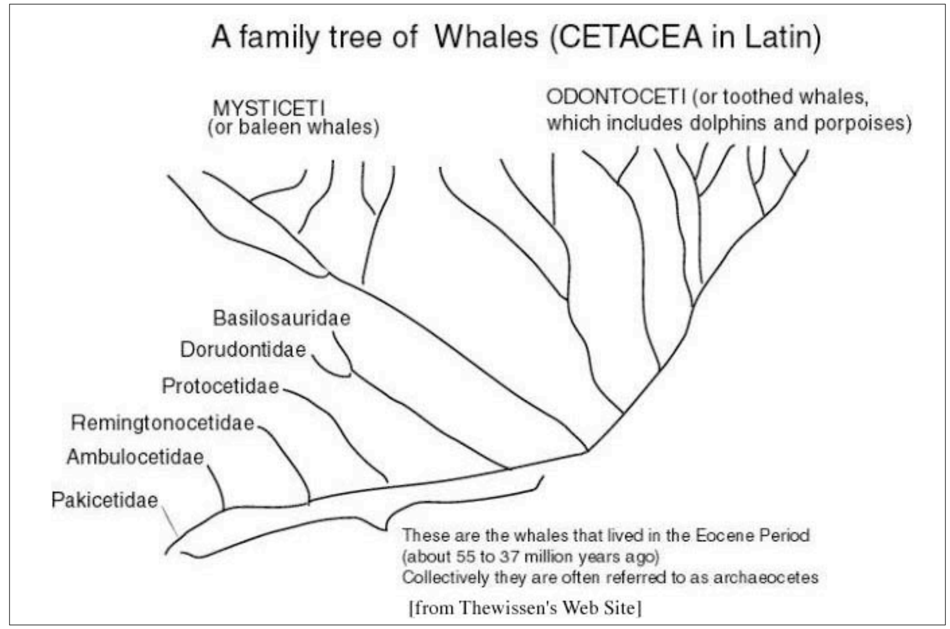
1. When finished, click the whale in the bottom left hand corner and return to "Molecules Home". ***Which molecules help to show how animals are related?***
2. What are chromosomes made of? What is DNA made of?
3. What are the steps of the DNA ladder made of?
4. What are the four flavors of nucleotide base pairs? What do they stand for? How do they pair together? What do they do?
5. Compare the patterns of a nucleotide sequence between a whale, a horse, a cow and a seal. Complete the chart:

	Number of differences **Horse**	Number of differences **Cow**	Number of differences **Seal**
Sequence #1			
Sequence #2			
Sequence #3			
Sequence #4			
Sequence #5			
Sequence #6			
Sequence #7			
Sequence #8			
Total Number of Matches			

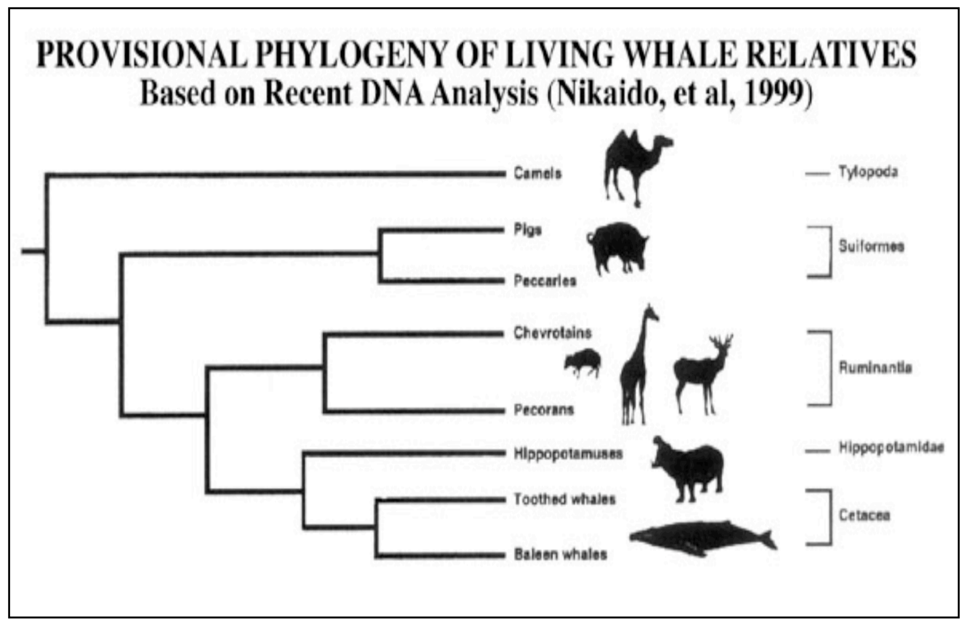
6. Draw your cladogram of the whale, horse, cow, and seal.
7. To which group does the molecular evidence suggest is most closely related to whales?
8. Click "Find out How DNA Changes". When was the common ancestor to cows and whales?
9. What is a part of the editing process of DNA?
10. What are mutations?
11. What is a point mutation? Record an example.
12. What is a neutral mutation?
13. What are the three other possible changes?
14. How can a change in meaning be helpful? What happens to that mutation in the population?
15. What if the mutation hurts the organism or its chance of having offspring?



SOME MODERN WHALES
Adapted from figures in Peter Evans' *The Natural History of Whales & Dolphins*, 1987
MYSTICETES (Baleen Whales)
Blue Whale 27 m (90 feet)
Humpback 15 m (50 feet)
Gray Whale 15 m (50 feet)
ODONTOCETES (Toothed Whales)
Sperm Whale 18 m (60 feet)
Orca ("Killer Whale") 9 m (30 feet)
Bottle-Nose Dolphin 2.5 m (8 feet)



A family tree of Whales (CETACEA in Latin)
MYSTICETI
(or baleen whales)
ODONTOCETI (or toothed whales, which includes dolphins and porpoises)
Basilosauridae
Dorudontidae
Protocetidae
Remingtonocetidae
Ambulocetidae
Pakicetidae
These are the whales that lived in the Eocene Period
(about 55 to 37 million years ago)
Collectively they are often referred to as archaeocetes
[from Thewissen's Web Site]



PROVISIONAL PHYLOGENY OF LIVING WHALE RELATIVES
Based on Recent DNA Analysis (Nikaido, et al, 1999)
Camels
Pigs
Peccaries
Chevrotains
Pecorans
Hippopotamuses
Toothed whales
Baleen whales
Tylopoda
Suiformes
Ruminantia
Hippopotamidae
Cetacea

Part A – WHALES IN TRANSITION

Preliminary Observations

1. Modern whales are typically found in two major groups: the **toothed whales** *(**Odontoceti**)* and the **baleen whales** *(**Mysticeti**)*.

2. Modern whales are clearly **mammals** which are totally ocean-adapted.

3. **Embryos** of several modern whales have well-developed **rear legs**, which then disappear. Sometimes these bones remain in the adult whales. Also, several species of baleen whales have **teeth** as embryos, which then disappear.

4. **Fossils** of modern whales appear less and less "modern-like" as we go backwards in time, so that by the Oligocene (24 million years ago [Mya]), we no longer find modern type whale fossils, but we do find primitive whale-like mammals (**archaeocetes**), with a number of whale traits, well into the Eocene (to about 40 Mya). Therefore, a good place to look for fossils of the earliest whales would be to search Eocene sediments (ranging from 55 to 34 Mya).

5. All evidence to date places the emergence of all mammals from a group of terrestrial pre-dinosaur tetrapods, called **synapsids**, about 200 Mya.

Question: **How did whales get here?**

Hypothesis: *Whales evolved from terrestrial mammals, gradually undergoing modifications of anatomy and physiology, producing the fully aquatic adaptations we see in whales today.*

Predictions: If whales evolved from terrestrial mammals, we should be able to find the fossil remains of early pre-whales, probably somewhat whale-like animals, but with legs of varying degrees of reduction, and certain other features varying in degrees of similarity to the ancestral and modern whales. Also, once fossils are found and dated, searching slightly earlier or later sediments should increase the chances of finding fossils of earlier or later whale-like creatures.

Some Important Constraints and Concepts about Whale Evolution

1. One of the little-known restrictions that evolution imposes on us is that, by far, most of the conceivable pathways by which any group of organisms might have evolved would be impossible. For example, since whales are clearly mammals (have mammary glands, hair, and several distinguishing skeletal characteristics of all mammals), it would be impossible to expect any direct ancestry of whales from early fishes or even the giant plesiosaurs (huge ocean swimming reptiles of the Mesozoic). If any fossils suggesting such an ancestry were found, it would seriously weaken a number of well-established perceptions about vertebrate evolution.

2. On the other hand, since whales clearly possess modified mammal traits, there must be an ancestral connection to earlier mammals, and we should expect to find, if we're lucky, and look in the right places, fossils of animals with traits intermediate between modern whales and their four-legged terrestrial mammal antecedents.

3. These "**intermediates**" (pre-whales and very early whales) would, in all likelihood, ***not*** be the direct lineal ancestors of modern whales (that's a "needle in a haystack" situation). Such fossils would much more likely be contemporary ***cousins*** of those direct ancestors, showing the existence of animals with a mosaic mix of pre-whale and modern whale traits, and probably related in a lateral way to the direct ancestors of that time.

Whale Hunt: Searching for Whale Fossils – *Use the fossil picture strips provided by your professor*

A) For many years, we have been finding a number of fossils of various primitive whales between 25 and 45 million years old (for which time frame no fossils of strictly modern type whales have been found). Examples of these early whales would include *Dorudon, Prozeuglodon*, and *Zygorhiza*. Place the **fossil picture strip #1** at about 36 Mya on your timeline (actual range about 40-36 Mya).

B) As more fossils have been discovered from the early Eocene epoch (55-33 Mya), scientists searched for a land mammal from which whales would have most likely evolved. The group of animals that had the most features common to the earliest primitive whales found was called the **mesonychids**. A typical example of these animals (e.g. *Pachyaena*, or *Sinonyx*) looked something like a wolf or hyena, with a large head, but with tiny hooves on all its toes! These are considered closely related to the even-toed hooved animals of today known as **artiodactyls**, with many branches evolving into modern deer, cattle, pigs, and hippos. Place the **mesonychid strip (#2)** at about the 55 Mya level on your timeline (mesonychids lived from 60-35 Mya). Whale specialists generally agreed that features such as teeth and various other skull features placed the now extinct mesonychids as the most likely group of land animals from which all whales of today evolved.

C) This picture of whale evolution was about all we had until 1983, when the first of a series of discoveries began to fill the empty gap between land animals and whales. That first discovery (reported by whale specialist Philip Gingerich and others) was *Pakicetus*. Place the ***Pakicetus* strip (#3)** on the timeline. It was a fragmented skull, with lots of teeth, found in Pakistan in sediments about 50 million years old. Some of its teeth were very similar to those in mesonychids, while other teeth resembled those found in the later archaeocetes. Some of its other skull features (including its shape) were also similar to late Eocene whales like *Dorudon*. It was found in river sediments near what was once a shallow sea.

D) In 1990, in Egypt, Gingerich and others reported the discovery of the fossilized hind limbs of a large, slender previously known primitive whale known as *Basilosaurus*, around 37 million years old (actually lived from 46 to 36 Mya). Its hind limbs were proportionally very tiny (about 35 cm of foot and lower leg), and clearly unable to support any movement on land, but they were better developed than those found embedded in the hip region of some modern whales today. Add ***Basilosaurus* (#4)** to your timeline.

E) In early 1994, Gingerich and others found the remains of *Rodhocetus*, with well-developed hip bones, and about 9 million years older than *Basilosaurus*. *Rodhocetus* is about 46 million years old. From what we have of its skeleton, we conclude that its hind legs were at least somewhat functional. However, its vertebrae suggest powerful tail muscles, suggesting typical whale-like swimming, possibly with tail flukes. Its skull possessed certain whale-like features, including placement of nostrils farther back on the head (toward the blowhole position), and enlarged ear capsule bones, typical of whales. Place ***Rodhocetus* (#5)** on the timeline.

F) At this point, notice the critical gap between 50 and 46 Mya. Although there are some apparently related fossils from those gaps, there are none showing clearly what the limbs or bodies were like for that period. Since *Rodhocetus* clearly had somewhat functional hind limbs (as indicated by the fairly robust pelvic bones), they were considerably reduced as compared with mesonychids. ***What traits you would expect to find*** (in the head, limbs, tail, and body) in a fossil from that period which would be an intermediate stage of an animal evolving from a mesonychid into an animal like *Rodhocetus*. ***Describe*** those traits, then ***illustrate*** your predictions by making a sketch on a piece of notebook paper, showing what you would expect. Also, ***predict*** what region of the world, and in rocks of what age, would you expect to find this intermediate stage?

G) **When you finish step F, show your professor what you predicted, and you will be given the next real discovery…**

H) In late 1994, Hans Thewissen (formerly one of Gingerich's students), and his team, reported the discovery in 48 million year old deposits in Pakistan of a nearly complete fossil with teeth similar to mesonychids and early whales. He called it *Ambulocetus*. Place the ***Ambulocetus* strip (#6)** on the timeline. It was about the size of a large sea lion. Its tail was long and slender, with no evidence of use for swimming. However, it had rather short, strong hind limbs, with huge feet (each toe with a tiny mesonychid-type hoof!). The head had a long snout with no blowhole. It probably walked on land like a sea lion, and swam with an undulating up and down motion of its hindquarters (like a sea otter), getting most of its propulsion force from its large feet. ***It was clearly a 4-legged cetacean.***

EPILOGUE: Recent studies of the **ankles** and **DNA** of cetaceans and supposed close relatives has resulted in some changes in our understanding of those relationships. They are the subjects of Parts B & C of this lab.

Part B – WHALE ANCESTRY: The Ankle Bone Connection

For many years now, we've known that the fossils of the most primitive whales (archaeocetes) and a particular group of extinct four-legged animals known as mesonychids shared several traits (especially their unique **tricuspid** teeth). Mesonychids also have hooves on their toes, suggesting they are probably related to the ancestors of today's animals with hooves (**ungulates**). All of this suggested, therefore, that the **cetaceans** (whales and porpoises) probably shared a close common ancestry with the mesonychids, and both of those groups apparently shared a common ancestry with all of today's hoofed animals (ungulates). But which ungulates are closest to the whales?

Modern ungulates (hoofed animals) are divided into two major sub-groups:

- **Perissodactyls** (ungulates with an *odd* number of toes (1, 3 or 5) on each foot
  - Examples: Horses, zebras, rhinos, and tapirs
- **Artiodactyls** (ungulates with an *even* number of toes (2, 4 or 6) on each foot
  - Examples: Cows, deer, giraffes, camels, pigs, hippos

As more primitive archaeocetes were found, some with leg bones (!), it was noticed that their *ankle* bones provided evidence pointing to a close relationship to one of those major sub-group of ungulates. Below are pictures of some of those ankle bones (**astragali**), and the corresponding bones of some other mammals thought to be related (due to other similarities). Compare the bones, and note how each bone is classified.

- ***Phenacodus*** = Early Eocene Perissodactyl (~63 Mya)
- ***Pachyaena*** = A Mesonychid (~55 Mya)
- ***Pakicetus*** = Early whale (Archaeocete) (~50 Mya)
- ***Diacodexis*** = Earliest Artiodactyl (~55 Mya)
- ***Sus*** = Domestic pig (a modern Artiodactyl)

Figures adapted from Christian de Muizon. 2001. "Walking with whales." Nature, vol. 413, 20 September 2001

Part C – WHALE ANCESTRY: DNA Activity

The plot thickens. We have narrowed the search for the origin of whales to a close connection with Artiodactyls. The next question is: ***Which one*** of the diverse members of that group are whales *most* closely aligned?

DNA to the rescue! As we learn the DNA sequences of more and more organisms, we can compare corresponding sequences to see which living species have DNA that is most alike.

As the DNA for a particular gene is inherited by new descendent species, and time passes, **mutations** can occur (replacements of former DNA bases by different bases), many without any significant effect. The more time that has passed (the more distant the ancestry), the more mutations will have occurred, and the more differences we will find.

You will be provided with eleven DNA segments from the gene for **beta-casein**, a milk protein found in all mammals. The segment is 60 base pairs (bp) long, from bp 141 to bp 200 in the gene. That same corresponding segment is presented for 11 species, including:

- **3 Cetaceans:** Right Whale, Sperm Whale, and a Porpoise
- **7 Artiodactyls:** A Giraffe, a Hippo, a Cow, a Camel, a Deer, Domestic Pig, and a Peccary
- **1 Perissodactyl:** The Indian Rhino (serves as a basis for comparison as an "outgroup")

PART A Questions to Answer

Based on your fossil timeline from the PART A background information…

1. Which typical whale traits were the earliest to appear?

2. Which whale traits evolved much later?

3. What age sediments, and in what region of the world, would you search now to get the fossils which would shed more light on whale origins, and what specific traits would you expect to find?

4. How closely did your "predicted traits" (expected for an intermediate between mesonychids and *Rodhocetus*) match the *Ambulocetus* fossil found? Does *Ambulocetus* seem to fit fairly well into the sequence between mesonychids and *Rodhocetus*?

5. Notice the reconstruction of *Pakicetus*, showing it as a four-legged animal. What evidence, if any, would suggest such a reconstruction? How confident are you of that reconstruction? What additional evidence would give you greater confidence in that reconstruction?

6. As each new "intermediate fossil" was found, filling a "gap", how many new gaps were formed?

7. Can we make predictions about past events? Why?

8. Explain why the absence of transitional (intermediate) fossils is ***not*** a fair argument against evolution.

9. Why is it very UNlikely that these fossils of early whale evolution are the ***direct*** ancestors of whales? How are they probably related to those direct ancestors? What is wrong with the popular "missing link" concept (misconception) of evolution?

10. Several species of modern whales have well-developed rear limbs while embryos. As the embryo continues to mature, these limbs atrophy (shrink) and become nonfunctional. Why do you suppose this happens? (Why do the limbs form, and then why do they atrophy?)

11. Summarize what you have learned about the process of evolution in this lesson.

PART B Questions to Answer

Based on your generalizations from the PART B background information…

1. Are Mesonychid ankles more like the ankles of Perissodactyls, or of Artiodactyls? *(circle one)*
2. Are early whale ankles (*Pakicetus*) more like those of Perissodactyls, Mesonychids, or Artiodactyls?
3. Therefore, which do whales most likely share their most recent common ancestry with: Perissodactyls, Mesonychids, or Artiodactyls?
4. So what does this change in our ideas about ancestry tell us about the nature of science?

PART C Questions to Answer

Using the DNA strips described in the PART C background information…

1. Align the DNA segments from two species, and count the number of loci where the bases ***differ***. For each pair of species compared, place the number of differences in the proper space on the grid below. **You are allowed to pair up with a classmate to divide up the work on this question (Q#1 only)…It's picky work!** You will find that the numbers sort into two groups: Pairs with 2-4 differences, then pairs with 7-18 differences.

RESULTS:

S.Whale										
Porpoise										
Giraffe										
Hippo										
Cow										
Camel										
Deer										
Pig										
Peccary										
Rhino										
	R.Whale	S.Whale	Porpoise	Giraffe	Hippo	Cow	Camel	Deer	Pig	Peccary

2. In the table below, list the pairs of species with ***only 2-4 differences*** in their DNA. Show the number of differences for each pair:

2 – Porpoise – Sperm Whale	3 –	3 –
3 –	3 –	4 –
3 –	3 –	4 –

3. a. Notice in that set of 9 pairings in the second table above, there are **4 species** that are found in ***all possible combinations*** with each other. What are those 4 species? (Give common names, as used on the strips.) We will call them "Group A".

   b. What does this suggest about how closely those 4 species in Group A are related to each other (or how relatively recently they branched from a common ancestry?

4. a. Then there are **3 species** that are found in their own 3 possible combinations. What are those 3 species? We will call them "Group B".

   b. What does this suggest about how closely those 3 species in Group B are related to each other (or how relatively recently they branched from a common ancestry?

5. a. Notice that there is a gap in the number of differences between pairs of DNA segments: There are none with 5 or 6 differences, and only one pair with 7 differences. What pair of **2 species** show 7 differences from each other? We will call them "Group C".

   b. What might that suggest about the relationship of those 2 species in Group C to each other, relative to the other 2 groups (Groups A & B)?

6. The remaining pairings all range between 8 and 18 differences in this segment of DNA. What are the **2 remaining species** that were ***not listed already*** (in questions 3, 4, 5)? We will call them "Group D".

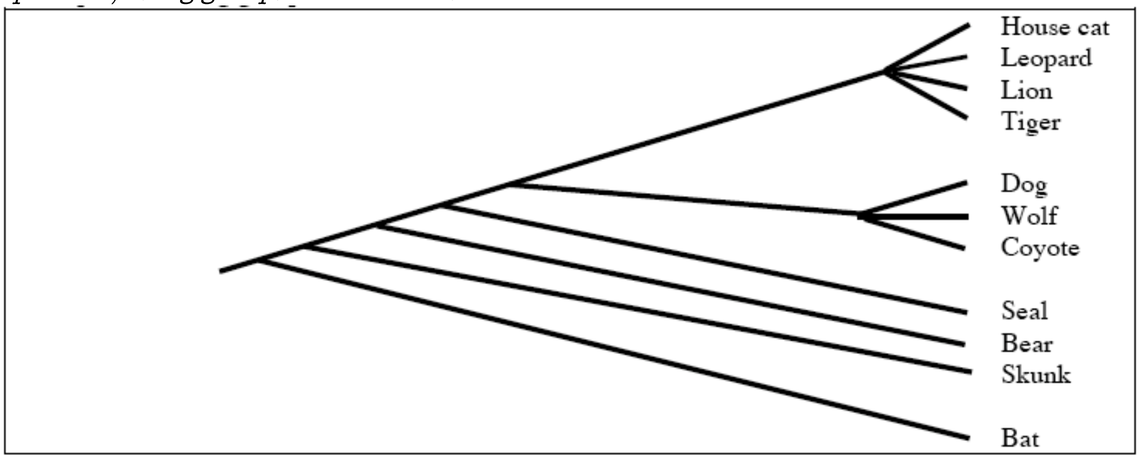
7. What does this suggest regarding the relative time when each group of these species shared a common ancestor with the other groups?

8. As for our original question, to which species are cetaceans (whales and porpoises) most closely related?

Comparing the specific numbers of differences between these last 4 species and those previous 7 species can be a little tricky, mainly because differences of 1-3 don't seem very significant, and the range is fairly wide (from 8 to 18, with no real gaps in the continuum). However, for our purposes, this isn't important.

9. Using the analysis you've made above, try drawing a "**family tree**" with all the species we've looked at here. Show short branches for closely related (recently branching) species, and longer branches for the more distantly related species. Label the common name for each species at the end of each branch. Most people find it easier to draw the tree as if it's lying on its side, with the "trunk" end to the left, and the shorter branches on the right. You might want to practice before drawing it in neatly in lower box.

Here's a sample tree, using groups of carnivores:



Your family tree for cetaceans and artiodactyls (use only your data above):

*Fortunately for the scientists who do this kind of work, there are sophisticated computer programs, with online access by anyone, that can compare very large DNA segments (even entire genes) between many different species, and can also draw branching "family trees" based on those differences, showing which groups are most closely related (most recently branched from a common ancestor) and which are more distantly related (longer branches from common ancestry at an earlier time). Different genes may give slightly different results, but overall, looking at many genes and many representatives of each group, a fair amount of consensus has emerged, generally consistent with the small sampling that you've looked at here. In fact, cetaceans and artiodactyls are now tentatively combined in the single order "**Certiodactyla**".*

If you would like to use those online tools to compare and draw trees for any particular group of animals, try the tutorial lesson "Investigating Evolutionary Questions: Using online Molecular Databases" at:

http://www.indiana.edu/~ensiweb/lessons/p.tut.db.html