Phylogeny and the history of life

Phylogeny

The history of life

Processes of diversification

Outline

Phylogeny
- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life
- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification
- Adaptive radiations
- Mass extinctions

Phylogeny

- Phylogeny is the evolutionary history of a group of organisms

Phylogeny

- Phylogeny is the evolutionary history of a group of organisms
- Based on the idea that organisms are related by evolution

Phylogeny

- Phylogeny is the evolutionary history of a group of organisms
- Based on the idea that organisms are related by evolution
- Understanding these relationships is critical to our understanding of both evolution, and how biological processes work

Phylogeny

- Phylogeny is the evolutionary history of a group of organisms
- Based on the idea that organisms are related by evolution
- Understanding these relationships is critical to our understanding of both evolution, and how biological processes work

Outline

Phylogeny

- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life

- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification

- Adaptive radiations
- Mass extinctions

Interpreting phylogenetic trees

- A **phylogenetic tree** is a model of how a group of organisms descended from a common ancestor

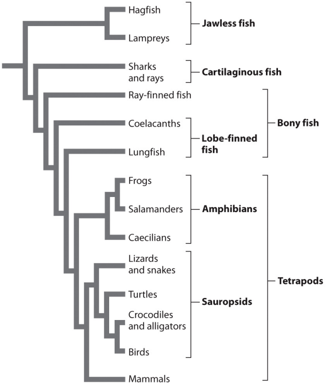


Figure 22.2
Biology: How Life Works

Interpreting phylogenetic trees

- A **phylogenetic tree** is a model of how a group of organisms descended from a common ancestor

- The model consists of **nodes**, where groups split, **branches** where evolution occurs, and **tips** representing observed **taxa** which are the endpoints of the process we are trying to model.

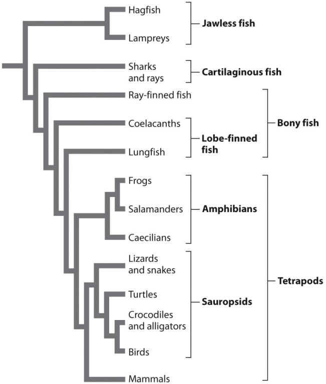


Figure 22.2
Biology: How Life Works

Interpreting phylogenetic trees

- A **phylogenetic tree** is a model of how a group of organisms descended from a common ancestor
- The model consists of **nodes**, where groups split, **branches** where evolution occurs, and **tips** representing observed **taxa** which are the endpoints of the process we are trying to model.

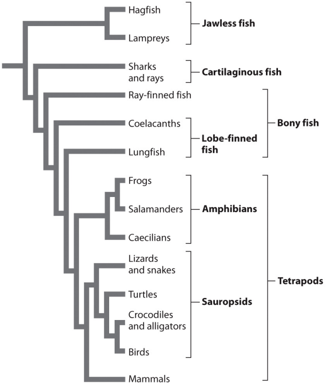


Figure 22.2
Biology: How Life Works

Monophyletic group

- A **monophyletic group** is a group *defined by* a single common ancestor

Monophyletic group

- A **monophyletic group** is a group *defined by* a single common ancestor
  - All descendants of the ancestor must be in the group

Monophyletic group

- A **monophyletic group** is a group *defined by* a single common ancestor
  - All descendants of the ancestor must be in the group
- Monophyletic groups can also be called **clades** or **taxa**.

Monophyletic group

- A **monophyletic group** is a group *defined by* a single common ancestor
  - All descendants of the ancestor must be in the group
- Monophyletic groups can also be called **clades** or **taxa**.
- As biologists, we should try to think in terms of clades

Monophyletic group

- A **monophyletic group** is a group *defined by* a single common ancestor
  - All descendants of the ancestor must be in the group
- Monophyletic groups can also be called **clades** or **taxa**.
- As biologists, we should try to think in terms of clades
  - Are winged tetrapods a clade?

Monophyletic group

- A **monophyletic group** is a group *defined by* a single common ancestor
  - All descendants of the ancestor must be in the group
- Monophyletic groups can also be called **clades** or **taxa**.
- As biologists, we should try to think in terms of clades
  - Are winged tetrapods a clade?
  - What are some prominent groups that are not clades?

Monophyletic group

- A **monophyletic group** is a group *defined by* a single common ancestor
  - All descendants of the ancestor must be in the group
- Monophyletic groups can also be called **clades** or **taxa**.
- As biologists, we should try to think in terms of clades
  - Are winged tetrapods a clade?
  - What are some prominent groups that are not clades?
    - *

Monophyletic group

- A **monophyletic group** is a group *defined by* a single common ancestor
  - All descendants of the ancestor must be in the group
- Monophyletic groups can also be called **clades** or **taxa**.
- As biologists, we should try to think in terms of clades
  - Are winged tetrapods a clade?
  - What are some prominent groups that are not clades?
    - * apes, reptiles, trees

Monophyletic group

- A **monophyletic group** is a group *defined by* a single common ancestor
  - All descendants of the ancestor must be in the group
- Monophyletic groups can also be called **clades** or **taxa**.
- As biologists, we should try to think in terms of clades
  - Are winged tetrapods a clade?
  - What are some prominent groups that are not clades?
    - * apes, reptiles, trees

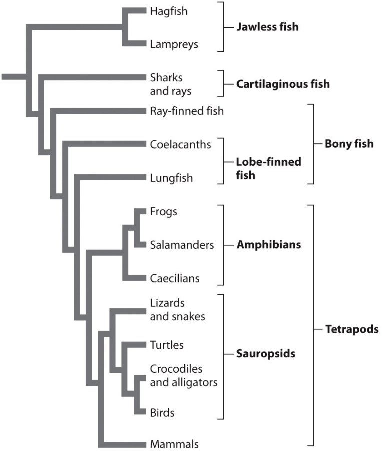


Figure 22.2
Biology: How Life Works

Sister taxa

- Sister taxa can be a useful way of thinking about trees

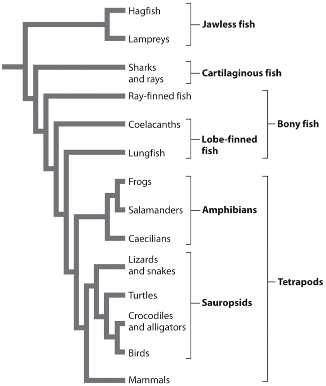


Figure 22.2
Biology: How Life Works

Sister taxa

- Sister taxa can be a useful way of thinking about trees
  - two taxa that share a common node

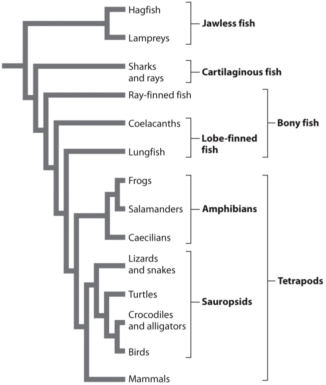


Figure 22.2
Biology: How Life Works

Sister taxa

- Sister taxa can be a useful way of thinking about trees
  - two taxa that share a common node
  - at any scale

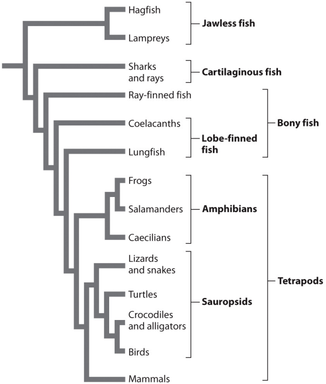


Figure 22.2
Biology: How Life Works

Sister taxa

- Sister taxa can be a useful way of thinking about trees
  - two taxa that share a common node
  - at any scale
  - You need to take the whole taxon

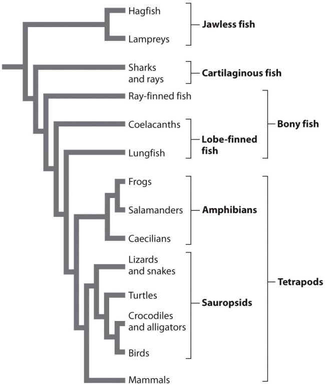


Figure 22.2
Biology: How Life Works

Sister taxa

- Sister taxa can be a useful way of thinking about trees
  - two taxa that share a common node
  - at any scale
  - You need to take the whole taxon

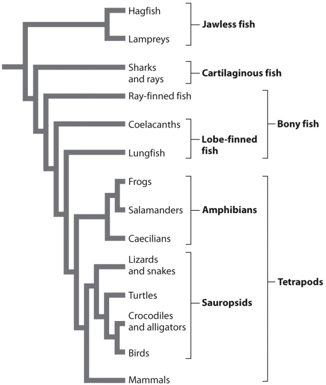


Figure 22.2
Biology: How Life Works

Interpreting phylogenetic trees

- The tree indicates the pattern of branching of **lineages** (evolving lines)

Interpreting phylogenetic trees

- The tree indicates the pattern of branching of **lineages** (evolving lines)
- Tips are *assumed* by the model to be monophyletic

Interpreting phylogenetic trees

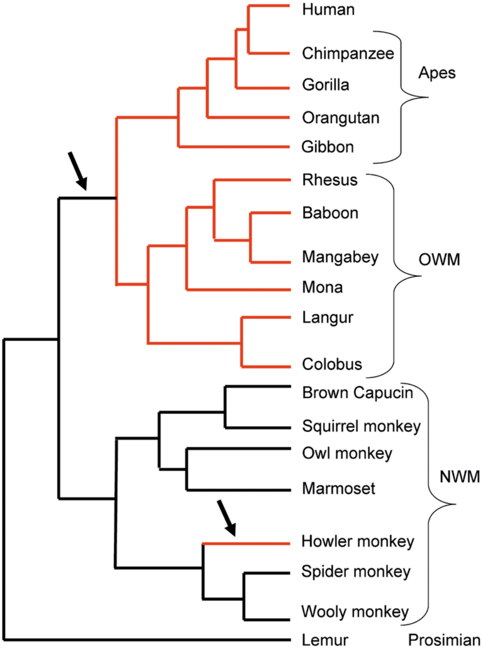
- The tree indicates the pattern of branching of **lineages** (evolving lines)
- Tips are *assumed* by the model to be monophyletic
- A tree is a model of how evolution occurred

Interpreting phylogenetic trees

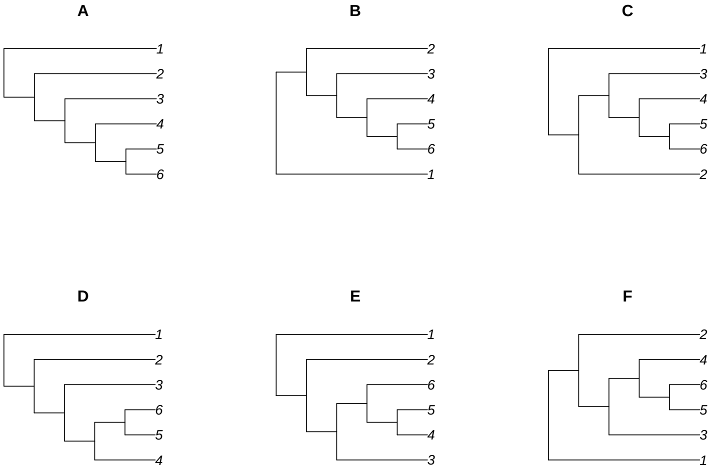
- The tree indicates the pattern of branching of **lineages** (evolving lines)
- Tips are *assumed* by the model to be monophyletic
- A tree is a model of how evolution occurred
  - Trees that correspond to the same model are considered equivalent

Interpreting phylogenetic trees

- The tree indicates the pattern of branching of **lineages** (evolving lines)
- Tips are *assumed* by the model to be monophyletic
- A tree is a model of how evolution occurred
  - Trees that correspond to the same model are considered equivalent


Human
Chimpanzee
Gorilla
Orangutan
Gibbon
Apes
Rhesus
Baboon
Mangabey
Mona
Langur
Colobus
OWM
Brown Capucin
Squirrel monkey
Owl monkey
Marmoset
Howler monkey
Spider monkey
Wooly monkey
NWM
Lemur
Prosimian

Activity: which of these things is not like the others?



Order of species

- Except for the branching pattern, we don't interpret anything about the order of a tree

Order of species

- Except for the branching pattern, we don't interpret anything about the order of a tree
  - No species are higher or lower than others, according to the tree

Order of species

- Except for the branching pattern, we don't interpret anything about the order of a tree
  - No species are higher or lower than others, according to the tree
  - We've all been evolving for the same amount of time

Order of species

- Except for the branching pattern, we don't interpret anything about the order of a tree
  - No species are higher or lower than others, according to the tree
  - We've all been evolving for the same amount of time
- How do we judge how closely related two organisms are, according to a tree?

Order of species

- Except for the branching pattern, we don't interpret anything about the order of a tree
  - No species are higher or lower than others, according to the tree
  - We've all been evolving for the same amount of time
- How do we judge how closely related two organisms are, according to a tree?
  - *

Order of species

- Except for the branching pattern, we don't interpret anything about the order of a tree
  - No species are higher or lower than others, according to the tree
  - We've all been evolving for the same amount of time
- How do we judge how closely related two organisms are, according to a tree?
  - * By looking for their common ancestor

Order of species

- Except for the branching pattern, we don't interpret anything about the order of a tree
  - No species are higher or lower than others, according to the tree
  - We've all been evolving for the same amount of time
- How do we judge how closely related two organisms are, according to a tree?
  - * By looking for their common ancestor

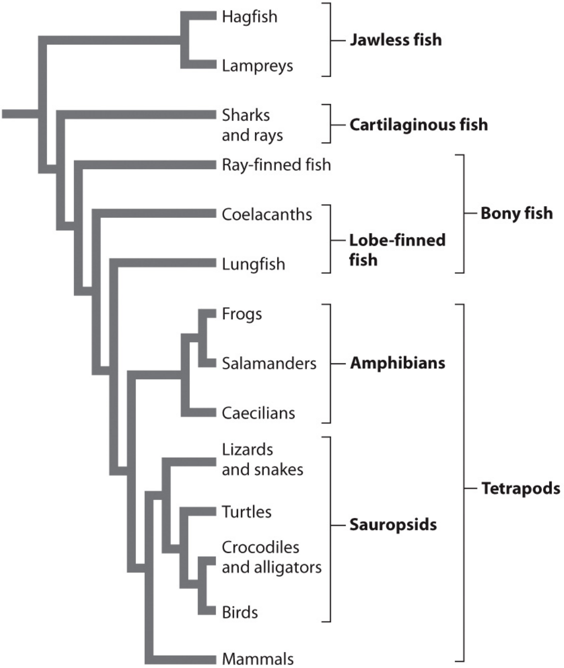
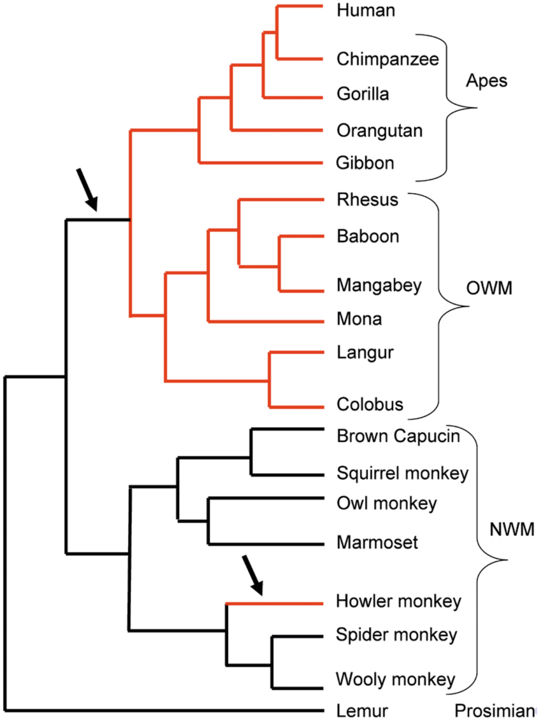


Figure 22.2
Biology: How Life Works


Human
Chimpanzee
Gorilla
Orangutan
Gibbon
Apes
Rhesus
Baboon
Mangabey
Mona
Langur
Colobus
OWM
Brown Capucin
Squirrel monkey
Owl monkey
Marmoset
NWM
Howler monkey
Spider monkey
Wooly monkey
Lemur
Prosimian

Outline

Phylogeny
- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life
- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification
- Adaptive radiations
- Mass extinctions

Constructing phylogenetic trees

- First, measure **characteristics** (or **characters**) of the taxa of interest – i.e., anything that seems useful to measure

Constructing phylogenetic trees

- First, measure **characteristics** (or **characters**) of the taxa of interest – i.e., anything that seems useful to measure
  - Can be **morphological** (i.e., physical) or genetic

Constructing phylogenetic trees

- First, measure **characteristics** (or **characters**) of the taxa of interest – i.e., anything that seems useful to measure
  - Can be **morphological** (i.e., physical) or genetic
- Then infer (make an educated guess about) the phylogenetic relationships.

Constructing phylogenetic trees

- First, measure **characteristics** (or **characters**) of the taxa of interest – i.e., anything that seems useful to measure
  - Can be **morphological** (i.e., physical) or genetic
- Then infer (make an educated guess about) the phylogenetic relationships.
  - **Phenetic** approaches use measures of distance between organisms

Constructing phylogenetic trees

- First, measure **characteristics** (or **characters**) of the taxa of interest – i.e., anything that seems useful to measure
  - Can be **morphological** (i.e., physical) or genetic
- Then infer (make an educated guess about) the phylogenetic relationships.
  - **Phenetic** approaches use measures of distance between organisms
  - **Cladistic** approaches are based on modeling how evolution occurs on the tree

Constructing phylogenetic trees

- First, measure **characteristics** (or **characters**) of the taxa of interest – i.e., anything that seems useful to measure
  - Can be **morphological** (i.e., physical) or genetic
- Then infer (make an educated guess about) the phylogenetic relationships.
  - **Phenetic** approaches use measures of distance between organisms
  - **Cladistic** approaches are based on modeling how evolution occurs on the tree

Morphological vs. genetic characteristics

- Should we use morphological or genetic characteristics to infer phylogenies?

Morphological vs. genetic characteristics

- Should we use morphological or genetic characteristics to infer phylogenies?
  - We usually have more information from genetic characteristics, and this information is easier to measure precisely

Morphological vs. genetic characteristics

- Should we use morphological or genetic characteristics to infer phylogenies?
  - We usually have more information from genetic characteristics, and this information is easier to measure precisely
- When should we use morphological characteristics?

Morphological vs. genetic characteristics

- Should we use morphological or genetic characteristics to infer phylogenies?
  - We usually have more information from genetic characteristics, and this information is easier to measure precisely
- When should we use morphological characteristics?
  - *

Morphological vs. genetic characteristics

- Should we use morphological or genetic characteristics to infer phylogenies?
  - We usually have more information from genetic characteristics, and this information is easier to measure precisely
- When should we use morphological characteristics?
  - * When genetic information is not available

Morphological vs. genetic characteristics

- Should we use morphological or genetic characteristics to infer phylogenies?
  - We usually have more information from genetic characteristics, and this information is easier to measure precisely

- When should we use morphological characteristics?
  - * When genetic information is not available
    - *

Morphological vs. genetic characteristics

- Should we use morphological or genetic characteristics to infer phylogenies?
  - We usually have more information from genetic characteristics, and this information is easier to measure precisely
- When should we use morphological characteristics?
  - * When genetic information is not available
    - * Most fossil organisms

Morphological vs. genetic characteristics

- Should we use morphological or genetic characteristics to infer phylogenies?
  - We usually have more information from genetic characteristics, and this information is easier to measure precisely
- When should we use morphological characteristics?
  - * When genetic information is not available
    - * Most fossil organisms
  - *Some viruses evolve so fast that morphological characteristics can be more stable than genetic characteristics*

Morphological vs. genetic characteristics

- Should we use morphological or genetic characteristics to infer phylogenies?
  - We usually have more information from genetic characteristics, and this information is easier to measure precisely
- When should we use morphological characteristics?
  - * When genetic information is not available
    - * Most fossil organisms
  - *Some viruses evolve so fast that morphological characteristics can be more stable than genetic characteristics*

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies
- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies
- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies
- Which is better?

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies
- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies
- Which is better?
  - *

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies
- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies
- Which is better?
  - * Cladistic analysis

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies
- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies
- Which is better?
  - * Cladistic analysis
- When should we use the other one?

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies

- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies

- Which is better?
  - * Cladistic analysis

- When should we use the other one?
  - *

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies

- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies

- Which is better?
  - * Cladistic analysis

- When should we use the other one?
  - * When our data are only distances, with no characters available – e.g., certain molecular techniques

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies
- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies
- Which is better?
  - * Cladistic analysis
- When should we use the other one?
  - * When our data are only distances, with no characters available – e.g., certain molecular techniques
  - *

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies
- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies
- Which is better?
  - * Cladistic analysis
- When should we use the other one?
  - * When our data are only distances, with no characters available – e.g., certain molecular techniques
  - * When we don't have enough baseline information

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies

- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies

- Which is better?
  - * Cladistic analysis

- When should we use the other one?
  - * When our data are only distances, with no characters available – e.g., certain molecular techniques
  - * When we don't have enough baseline information
  - *The book talks about trusting the molecular clock, but this is complicated and there are still no* advantages

Phenetic vs. cladistic analysis

- Cladistic analysis makes use of the phylogenetic model of organisms evolving from each other to infer phylogenies

- Phenetic analysis ignores the phylogenetic model of organisms evolving from each other while inferring phylogenies

- Which is better?
  - * Cladistic analysis

- When should we use the other one?
  - * When our data are only distances, with no characters available – e.g., certain molecular techniques
  - * When we don't have enough baseline information
  - *The book talks about trusting the molecular clock, but this is complicated and there are still no* advantages


Reptiles in a box
A tortoise's shell is made of two
bony parts – the plastron on the underside

Synapomorphies

- Classical cladistic analysis is based on **synapomorphies** – shared, **derived** characters – as evidence that two taxa are related

Synapomorphies

- Classical cladistic analysis is based on **synapomorphies** – shared, **derived** characters – as evidence that two taxa are related
- Why do we focus on derived characters?

Synapomorphies

- Classical cladistic analysis is based on **synapomorphies** – shared, **derived** characters – as evidence that two taxa are related
- Why do we focus on derived characters?
  - *

Synapomorphies

- Classical cladistic analysis is based on **synapomorphies** – shared, **derived** characters – as evidence that two taxa are related
- Why do we focus on derived characters?
  - * These are things that evolved in the relevant context

Synapomorphies

- Classical cladistic analysis is based on **synapomorphies** – shared, **derived** characters – as evidence that two taxa are related
- Why do we focus on derived characters?
  - * These are things that evolved in the relevant context
  - *

Synapomorphies

- Classical cladistic analysis is based on **synapomorphies** – shared, **derived** characters – as evidence that two taxa are related
- Why do we focus on derived characters?
  - * These are things that evolved in the relevant context
  - * So they are the things our model (the phylogenies) must explain

Synapomorphies

- Classical cladistic analysis is based on **synapomorphies** – shared, **derived** characters – as evidence that two taxa are related
- Why do we focus on derived characters?
  - * These are things that evolved in the relevant context
  - * So they are the things our model (the phylogenies) must explain

Flight as evidence

- Oaks and fish don't fly, but birds do

Flight as evidence

- Oaks and fish don't fly, but birds do
  - *

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - *

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - *

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - * Flight evolved once in either case

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - * Flight evolved once in either case
- Mosquitoes and birds fly, but fish don't

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - * Flight evolved once in either case
- Mosquitoes and birds fly, but fish don't
  - *

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - * Flight evolved once in either case
- Mosquitoes and birds fly, but fish don't
  - * Evidence (flight might have evolved once or twice on this tree)

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - * Flight evolved once in either case
- Mosquitoes and birds fly, but fish don't
  - * Evidence (flight might have evolved once or twice on this tree)
  - *

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - * Flight evolved once in either case
- Mosquitoes and birds fly, but fish don't
  - * Evidence (flight might have evolved once or twice on this tree)
  - * But this evidence points in the wrong direction

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - * Flight evolved once in either case
- Mosquitoes and birds fly, but fish don't
  - * Evidence (flight might have evolved once or twice on this tree)
  - * But this evidence points in the wrong direction
    - *

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - * Flight evolved once in either case
- Mosquitoes and birds fly, but fish don't
  - * Evidence (flight might have evolved once or twice on this tree)
  - * But this evidence points in the wrong direction
    - * This is why we combine evidence from different sources

Flight as evidence

- Oaks and fish don't fly, but birds do
  - * We're pretty sure that the common ancestor didn't fly
  - * No evidence (any model will have flight evolve once)
  - * Flight evolved once in either case
- Mosquitoes and birds fly, but fish don't
  - * Evidence (flight might have evolved once or twice on this tree)
  - * But this evidence points in the wrong direction
    - * This is why we combine evidence from different sources

What characters are derived?

- Derived compared to what?

What characters are derived?

- Derived compared to what?
  - The common ancestor (characteristics of the common ancestor are called **basal** or **ancestral** characters).

What characters are derived?

- Derived compared to what?
  - The common ancestor (characteristics of the common ancestor are called **basal** or **ancestral** characters).
    - What if our flight example was ostriches, hawks, and sparrows?

What characters are derived?

- Derived compared to what?
  - The common ancestor (characteristics of the common ancestor are called **basal** or **ancestral** characters).
    - What if our flight example was ostriches, hawks, and sparrows?
    - *

What characters are derived?

- Derived compared to what?
  - The common ancestor (characteristics of the common ancestor are called **basal** or **ancestral** characters).
    - What if our flight example was ostriches, hawks, and sparrows?
    - * No evidence for similarity between hawks and sparrows

What characters are derived?

- Derived compared to what?
  - The common ancestor (characteristics of the common ancestor are called **basal** or **ancestral** characters).
    - What if our flight example was ostriches, hawks, and sparrows?
    - * No evidence for similarity between hawks and sparrows
    - *

What characters are derived?

- Derived compared to what?
  - The common ancestor (characteristics of the common ancestor are called **basal** or **ancestral** characters).
    - What if our flight example was ostriches, hawks, and sparrows?
    - * No evidence for similarity between hawks and sparrows
    - * We believe the common ancestor could fly, so there is no shared, derived characteristic

What characters are derived?

- Derived compared to what?
  - The common ancestor (characteristics of the common ancestor are called **basal** or **ancestral** characters).
    - What if our flight example was ostriches, hawks, and sparrows?
    - * No evidence for similarity between hawks and sparrows
    - * We believe the common ancestor could fly, so there is no shared, derived characteristic
  - A **derived** character is a character not shared by the common ancestor of the group that we are currently thinking about

What characters are derived?

- Derived compared to what?
  - The common ancestor (characteristics of the common ancestor are called **basal** or **ancestral** characters).
    - What if our flight example was ostriches, hawks, and sparrows?
    - * No evidence for similarity between hawks and sparrows
    - * We believe the common ancestor could fly, so there is no shared, derived characteristic
  - A **derived** character is a character not shared by the common ancestor of the group that we are currently thinking about
  - One way to think about cladistic vs. phenetic analysis is that phenetic analysis treats derived and basal characters equally

What characters are derived?

- Derived compared to what?
  - The common ancestor (characteristics of the common ancestor are called **basal** or **ancestral** characters).
    - What if our flight example was ostriches, hawks, and sparrows?
    - * No evidence for similarity between hawks and sparrows
    - * We believe the common ancestor could fly, so there is no shared, derived characteristic
  - A **derived** character is a character not shared by the common ancestor of the group that we are currently thinking about
  - One way to think about cladistic vs. phenetic analysis is that phenetic analysis treats derived and basal characters equally

Inferring the common ancestor

- We want to know what the common ancestor was like, so we can tell which characters are derived (as opposed to basal)

Inferring the common ancestor

- We want to know what the common ancestor was like, so we can tell which characters are derived (as opposed to basal)
- This can be done sometimes by common sense

Inferring the common ancestor

- We want to know what the common ancestor was like, so we can tell which characters are derived (as opposed to basal)
- This can be done sometimes by common sense
- Inferring the common ancestor statistically is difficult, for technical reasons

Inferring the common ancestor

- We want to know what the common ancestor was like, so we can tell which characters are derived (as opposed to basal)
- This can be done sometimes by common sense
- Inferring the common ancestor statistically is difficult, for technical reasons
  - We can make use of an **outgroup** to study a group. An outgroup is an organism closely related to, but outside, the group being studied.

Inferring the common ancestor

- We want to know what the common ancestor was like, so we can tell which characters are derived (as opposed to basal)
- This can be done sometimes by common sense
- Inferring the common ancestor statistically is difficult, for technical reasons
  - We can make use of an **outgroup** to study a group. An outgroup is an organism closely related to, but outside, the group being studied.
  - We assume that the the **root**, or beginning, of the tree is where the outgroup branches from the group

Inferring the common ancestor

- We want to know what the common ancestor was like, so we can tell which characters are derived (as opposed to basal)
- This can be done sometimes by common sense
- Inferring the common ancestor statistically is difficult, for technical reasons
  - We can make use of an **outgroup** to study a group. An outgroup is an organism closely related to, but outside, the group being studied.
  - We assume that the the **root**, or beginning, of the tree is where the outgroup branches from the group

Confusing the phylogeny

- Two species may have the same trait because the trait evolved twice independently – **convergent evolution**

Confusing the phylogeny

- Two species may have the same trait because the trait evolved twice independently – **convergent evolution**
  - *

Confusing the phylogeny

- Two species may have the same trait because the trait evolved twice independently – **convergent evolution**
  - * Flight, trees, dolphins and icthyosaurs

Confusing the phylogeny

- Two species may have the same trait because the trait evolved twice independently – **convergent evolution**
  - * Flight, trees, dolphins and icthyosaurs
- An organism may lack a character that its ancestors had – **secondary loss**

Confusing the phylogeny

- Two species may have the same trait because the trait evolved twice independently – **convergent evolution**
  - * Flight, trees, dolphins and icthyosaurs
- An organism may lack a character that its ancestors had – **secondary loss**
  - This can be even more confusing

Confusing the phylogeny

- Two species may have the same trait because the trait evolved twice independently – **convergent evolution**
  - * Flight, trees, dolphins and icthyosaurs
- An organism may lack a character that its ancestors had – **secondary loss**
  - This can be even more confusing
- Similarities that are not homologies (ie., not due to common ancestry) are called **analogies**

Confusing the phylogeny

- Two species may have the same trait because the trait evolved twice independently – **convergent evolution**
  - * Flight, trees, dolphins and icthyosaurs
- An organism may lack a character that its ancestors had – **secondary loss**
  - This can be even more confusing
- Similarities that are not homologies (ie., not due to common ancestry) are called **analogies**

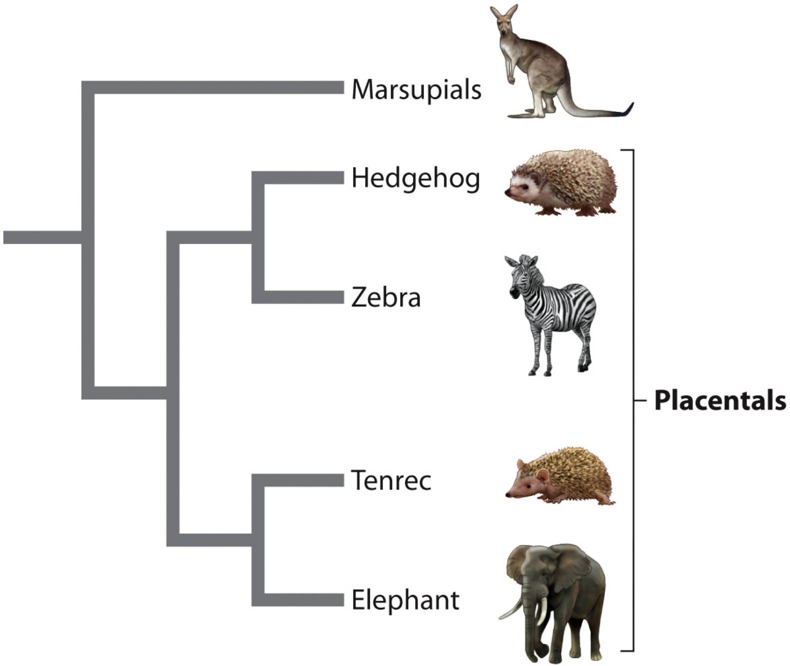


Figure 22.7
Biology: How Life Works

Parsimony

- Classical cladistic analysis is based on searching for the tree that can explain the observed data most **parsimoniously** – with the fewest number of changes necessary.

Parsimony

- Classical cladistic analysis is based on searching for the tree that can explain the observed data most **parsimoniously** – with the fewest number of changes necessary.

- How do we address the problem of convergent evolution and analogy?

Parsimony

- Classical cladistic analysis is based on searching for the tree that can explain the observed data most **parsimoniously** – with the fewest number of changes necessary.
- How do we address the problem of convergent evolution and analogy?
    - *

Parsimony

- Classical cladistic analysis is based on searching for the tree that can explain the observed data most **parsimoniously** – with the fewest number of changes necessary.
- How do we address the problem of convergent evolution and analogy?
  - * Make use of many different characteristics, when possible

Parsimony

- Classical cladistic analysis is based on searching for the tree that can explain the observed data most **parsimoniously** – with the fewest number of changes necessary.
- How do we address the problem of convergent evolution and analogy?
  - * Make use of many different characteristics, when possible
  - *

Parsimony

- Classical cladistic analysis is based on searching for the tree that can explain the observed data most **parsimoniously** – with the fewest number of changes necessary.
- How do we address the problem of convergent evolution and analogy?
  - * Make use of many different characteristics, when possible
  - * It may also help to use many different taxa

Parsimony

- Classical cladistic analysis is based on searching for the tree that can explain the observed data most **parsimoniously** – with the fewest number of changes necessary.
- How do we address the problem of convergent evolution and analogy?
  - * Make use of many different characteristics, when possible
  - * It may also help to use many different taxa
- *Modern approaches that use genetic data may use more sophisticated approaches, rather than simple parsimony*

Parsimony

- Classical cladistic analysis is based on searching for the tree that can explain the observed data most **parsimoniously** – with the fewest number of changes necessary.
- How do we address the problem of convergent evolution and analogy?
  - * Make use of many different characteristics, when possible
  - * It may also help to use many different taxa
- *Modern approaches that use genetic data may use more sophisticated approaches, rather than simple parsimony*

Outline

Phylogeny

- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life

- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification

- Adaptive radiations
- Mass extinctions

Example: the evolution of whales

- Whales seem, on the surface, to be pretty different from other mammals, including the closest group, the artiodactyls

Example: the evolution of whales

- Whales seem, on the surface, to be pretty different from other mammals, including the closest group, the artiodactyls
- Early phenetic analyses showed whales in their own group (sisters to artiodactyls)

Example: the evolution of whales

- Whales seem, on the surface, to be pretty different from other mammals, including the closest group, the artiodactyls
- Early phenetic analyses showed whales in their own group (sisters to artiodactyls)
  - Whales lack the distinctive artiodactyl ankle structure (surprise!)

Example: the evolution of whales

- Whales seem, on the surface, to be pretty different from other mammals, including the closest group, the artiodactyls
- Early phenetic analyses showed whales in their own group (sisters to artiodactyls)
  - Whales lack the distinctive artiodactyl ankle structure (surprise!)
- What about cladistic analysis?

Example: the evolution of whales

- Whales seem, on the surface, to be pretty different from other mammals, including the closest group, the artiodactyls
- Early phenetic analyses showed whales in their own group (sisters to artiodactyls)
  - Whales lack the distinctive artiodactyl ankle structure (surprise!)
- What about cladistic analysis?

Biology is crazy!

- Which of these doesn't belong?

Biology is crazy!

- Which of these doesn't belong?
  - Whale

Biology is crazy!

- Which of these doesn't belong?
  - Whale
  - Rhinocerous

Biology is crazy!

- Which of these doesn't belong?
  - Whale
  - Rhinocerous
  - Hippopotamus

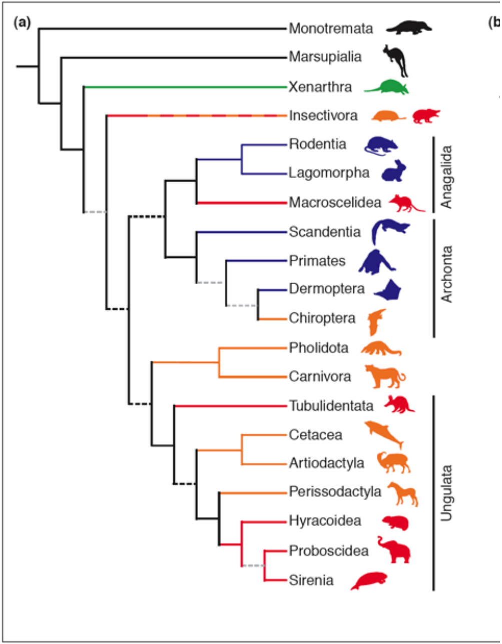
Biology is crazy!

- Which of these doesn't belong?
  - Whale
  - Rhinocerous
  - Hippopotamus
  - Elephant

Biology is crazy!

- Which of these doesn't belong?
  - Whale
  - Rhinocerous
  - Hippopotamus
  - Elephant

Morphological tree



Activity: Tree-construction analysis

- Hippos have derived characters A, B, C, D, Z

Activity: Tree-construction analysis

- Hippos have derived characters A, B, C, D, Z
- Cows have derived character A, Z

Activity: Tree-construction analysis

- Hippos have derived characters A, B, C, D, Z
- Cows have derived character A, Z
- Whales have derived characters B, C, D, E, F, G, H, I, Z

Activity: Tree-construction analysis

- Hippos have derived characters A, B, C, D, Z
- Cows have derived character A, Z
- Whales have derived characters B, C, D, E, F, G, H, I, Z
- Calculate distances, and make a phenetic tree

Activity: Tree-construction analysis

- Hippos have derived characters A, B, C, D, Z
- Cows have derived character A, Z
- Whales have derived characters B, C, D, E, F, G, H, I, Z
- Calculate distances, and make a phenetic tree
- List synapomorphies, and make a cladistic tree

Activity: Tree-construction analysis

- Hippos have derived characters A, B, C, D, Z
- Cows have derived character A, Z
- Whales have derived characters B, C, D, E, F, G, H, I, Z
- Calculate distances, and make a phenetic tree
- List synapomorphies, and make a cladistic tree

Tree discussion

- What is the effect of universal characteristics (like Z, above)?

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - *

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None
- What is the effect of unique characteristics (like E, F, G, H, I)

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None
- What is the effect of unique characteristics (like E, F, G, H, I)
  - *

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None
- What is the effect of unique characteristics (like E, F, G, H, I)
  - * They affect phenetic trees, but not cladistic trees

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None
- What is the effect of unique characteristics (like E, F, G, H, I)
  - * They affect phenetic trees, but not cladistic trees
  - *

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None
- What is the effect of unique characteristics (like E, F, G, H, I)
  - * They affect phenetic trees, but not cladistic trees
  - * As long as we are sure that they are derived!

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None
- What is the effect of unique characteristics (like E, F, G, H, I)
  - * They affect phenetic trees, but not cladistic trees
  - * As long as we are sure that they are derived!
- Why might whales have more derived characters than the other species?

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None
- What is the effect of unique characteristics (like E, F, G, H, I)
  - * They affect phenetic trees, but not cladistic trees
  - * As long as we are sure that they are derived!
- Why might whales have more derived characters than the other species?
  - *

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None
- What is the effect of unique characteristics (like E, F, G, H, I)
  - * They affect phenetic trees, but not cladistic trees
  - * As long as we are sure that they are derived!
- Why might whales have more derived characters than the other species?
  - * Because they have had to adapt more since moving to the water

Tree discussion

- What is the effect of universal characteristics (like Z, above)?
  - * None
- What is the effect of unique characteristics (like E, F, G, H, I)
  - * They affect phenetic trees, but not cladistic trees
  - * As long as we are sure that they are derived!
- Why might whales have more derived characters than the other species?
  - * Because they have had to adapt more since moving to the water

Similarities vs. differences

- Conceptually, we expect the pair with the fewest differences to match the pair with most similarities

Similarities vs. differences

- Conceptually, we expect the pair with the fewest differences to match the pair with most similarities
- We count differences for phenetic trees and similarities for cladistic trees because it's easier

Similarities vs. differences

- Conceptually, we expect the pair with the fewest differences to match the pair with most similarities
- We count differences for phenetic trees and similarities for cladistic trees because it's easier
- The conceptual difference between phenetic and cladistic is:

Similarities vs. differences

- Conceptually, we expect the pair with the fewest differences to match the pair with most similarities
- We count differences for phenetic trees and similarities for cladistic trees because it's easier
- The conceptual difference between phenetic and cladistic is:
  - *

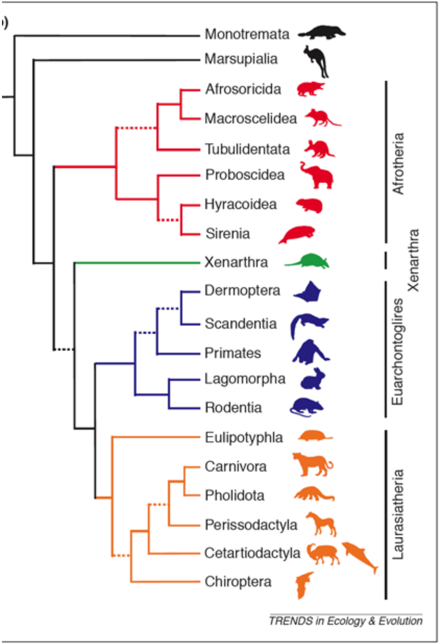
Similarities vs. differences

- Conceptually, we expect the pair with the fewest differences to match the pair with most similarities
- We count differences for phenetic trees and similarities for cladistic trees because it's easier
- The conceptual difference between phenetic and cladistic is:
  - * cladistic focuses specifically on *derived* similarities

Similarities vs. differences

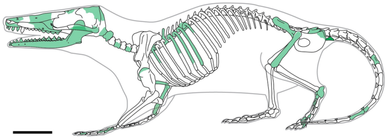
- Conceptually, we expect the pair with the fewest differences to match the pair with most similarities
- We count differences for phenetic trees and similarities for cladistic trees because it's easier
- The conceptual difference between phenetic and cladistic is:
  - * cladistic focuses specifically on *derived* similarities

Modern tree



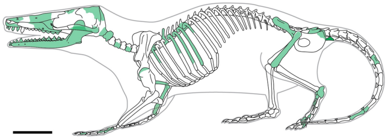
Monotremata
Marsupialia
Afrosoricida
Macroscelidea
Tubulidentata
Proboscidea
Hyracoidea
Sirenia
Xenarthra
Dermoptera
Scandentia
Primates
Lagomorpha
Rodentia
Eulipotyphla
Carnivora
Pholidota
Perissodactyla
Cetartiodactyla
Chiroptera
Afrotheria
Xenarthra
Euarchontoglires
Laurasiatheria
TRENDS in Ecology & Evolution

Confirmation



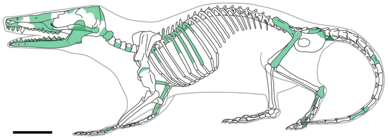
- Intermediate forms between hippo-like animals and whales

Confirmation

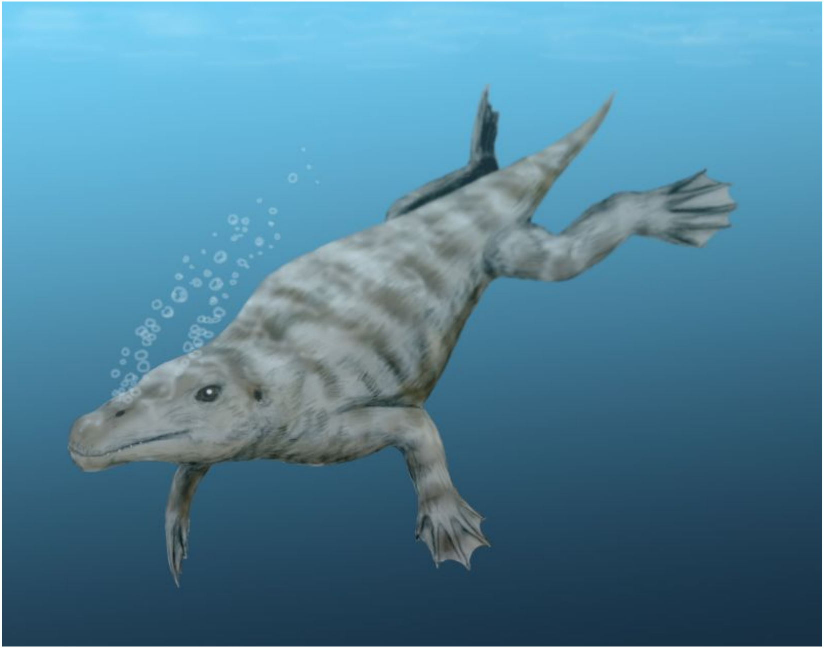


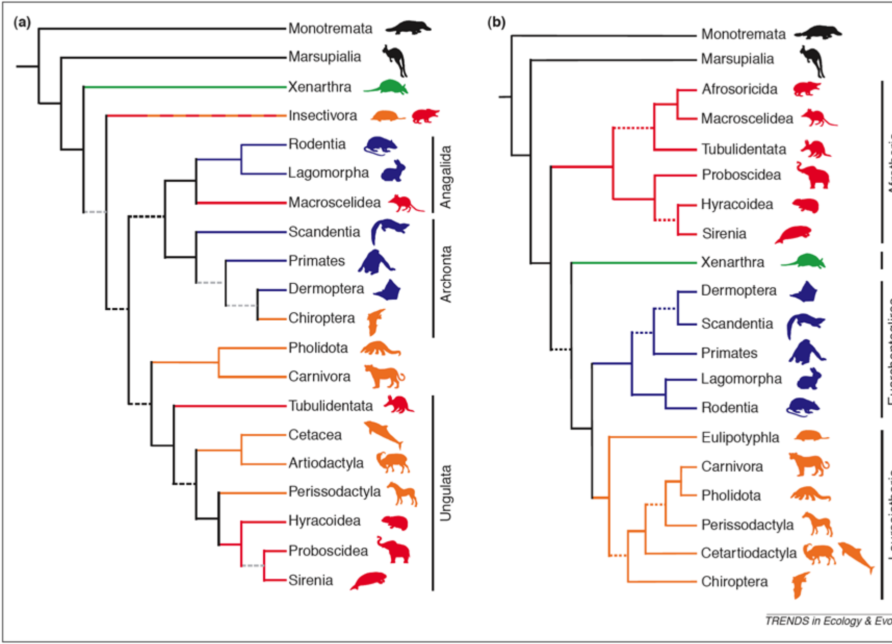
- Intermediate forms between hippo-like animals and whales
- Discovered *after* they were predicted from DNA evidence!

Confirmation



- Intermediate forms between hippo-like animals and whales
- Discovered *after* they were predicted from DNA evidence!





(a)
Monotremata
Marsupialia
Xenarthra
Insectivora
Rodentia
Lagomorpha
Macroscelidea
Scandentia
Primates
Dermoptera
Chiroptera
Pholidota
Carnivora
Tubulidentata
Cetacea
Artiodactyla
Perissodactyla
Hyracoidea
Proboscidea
Sirenia
Anagalida
Archonta
Ungulata
(b)
Monotremata
Marsupialia
Afrosoricida
Macroscelidea
Tubulidentata
Proboscidea
Hyracoidea
Sirenia
Xenarthra
Dermoptera
Scandentia
Primates
Lagomorpha
Rodentia
Eulipotyphla
Carnivora
Pholidota
Perissodactyla
Cetartiodactyla
Chiroptera

How to make a phenetic tree

- 1. Join the two open nodes that are closest to each other

How to make a phenetic tree

- 1. Join the two open nodes that are closest to each other
  - Shortest distance

How to make a phenetic tree

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- 2. They are no longer active. Make a new node halfway between them

How to make a phenetic tree

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- 2. They are no longer active. Make a new node halfway between them
  - Average the traits

How to make a phenetic tree

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- 2. They are no longer active. Make a new node halfway between them
  - Average the traits
  - This step is conceptually simple and practically tricky

How to make a phenetic tree

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- 2. They are no longer active. Make a new node halfway between them
  - Average the traits
  - This step is conceptually simple and practically tricky
  - *This is why we have computers*

How to make a phenetic tree

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- 2. They are no longer active. Make a new node halfway between them
  - Average the traits
  - This step is conceptually simple and practically tricky
  - *This is why we have computers*
- 3. Go back to step 1

How to make a phenetic tree

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- 2. They are no longer active. Make a new node halfway between them
  - Average the traits
  - This step is conceptually simple and practically tricky
  - *This is why we have computers*
- 3. Go back to step 1

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other
    - Shortest distance

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- *

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- * 2. *Stop!* You're done.

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- * 2. *Stop!* You're done.
  - *

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- * 2. *Stop!* You're done.
  - * I will only give you three species

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- * 2. *Stop!* You're done.
  - * I will only give you three species
  - *

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- * 2. *Stop!* You're done.
  - * I will only give you three species
  - * Seriously.

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- * 2. *Stop!* You're done.
  - * I will only give you three species
  - * Seriously.
- *I'm here to teach you concepts, not how to be a really bad computer.*

How to make a phenetic tree in this course

- 1. Join the two open nodes that are closest to each other
  - Shortest distance
- * 2. *Stop!* You're done.
  - * I will only give you three species
  - * Seriously.
- *I'm here to teach you concepts, not how to be a really bad computer.*

Lessons

- Phenetic analysis uses less information

Lessons

- Phenetic analysis uses less information
- To do a cladistic analysis, inferences about the common ancestor can be crucial

Lessons

- Phenetic analysis uses less information
- To do a cladistic analysis, inferences about the common ancestor can be crucial
  - What if we thought the artiodactyl ancestor was aquatic?

Lessons

- Phenetic analysis uses less information
- To do a cladistic analysis, inferences about the common ancestor can be crucial
  - What if we thought the artiodactyl ancestor was aquatic?
    - E, F, G, H and I could all be basal characters

Lessons

- Phenetic analysis uses less information
- To do a cladistic analysis, inferences about the common ancestor can be crucial
  - What if we thought the artiodactyl ancestor was aquatic?
    - E, F, G, H and I could all be basal characters
    - *

Lessons

- Phenetic analysis uses less information
- To do a cladistic analysis, inferences about the common ancestor can be crucial
  - What if we thought the artiodactyl ancestor was aquatic?
    - E, F, G, H and I could all be basal characters
    - * We would conclude that cows are closely related to hippos

Lessons

- Phenetic analysis uses less information
- To do a cladistic analysis, inferences about the common ancestor can be crucial
  - What if we thought the artiodactyl ancestor was aquatic?
    - E, F, G, H and I could all be basal characters
    - * We would conclude that cows are closely related to hippos

Genetic vs. morphological

- Why was the genetic analysis more effective than the morphological?

Genetic vs. morphological

- Why was the genetic analysis more effective than the morphological?
  - *

Genetic vs. morphological

- Why was the genetic analysis more effective than the morphological?
  - * It can be hard to tell which traits are derived

Genetic vs. morphological

- Why was the genetic analysis more effective than the morphological?
  - * It can be hard to tell which traits are derived
    - *

Genetic vs. morphological

- Why was the genetic analysis more effective than the morphological?
  - * It can be hard to tell which traits are derived
    - * This can also be a problem with the genetic analysis

Genetic vs. morphological

- Why was the genetic analysis more effective than the morphological?
  - * It can be hard to tell which traits are derived
    - * This can also be a problem with the genetic analysis

  - *

Genetic vs. morphological

- Why was the genetic analysis more effective than the morphological?
  - * It can be hard to tell which traits are derived
    - * This can also be a problem with the genetic analysis
  - * Genetic analyses typically allow us to analyze more traits

Genetic vs. morphological

- Why was the genetic analysis more effective than the morphological?
  - * It can be hard to tell which traits are derived
    - * This can also be a problem with the genetic analysis
  - * Genetic analyses typically allow us to analyze more traits

Phylogenetic trees are approximations!

- Phylogenetic trees are tremendously useful and powerful tools for organizing, understanding and analyzing biological data

Phylogenetic trees are approximations!

- Phylogenetic trees are tremendously useful and powerful tools for organizing, understanding and analyzing biological data
- But they have limitations:

Phylogenetic trees are approximations!

- Phylogenetic trees are tremendously useful and powerful tools for organizing, understanding and analyzing biological data
- But they have limitations:
  - The true history of life cannot really be summarized by a tree

Phylogenetic trees are approximations!

- Phylogenetic trees are tremendously useful and powerful tools for organizing, understanding and analyzing biological data
- But they have limitations:
    - The true history of life cannot really be summarized by a tree
        - Sex, other forms of combination or gene transfer

Phylogenetic trees are approximations!

- Phylogenetic trees are tremendously useful and powerful tools for organizing, understanding and analyzing biological data
- But they have limitations:
  - The true history of life cannot really be summarized by a tree
    - Sex, other forms of combination or gene transfer
  - Trees constructed by humans are not necessarily even the best approximations to the true history of life

Phylogenetic trees are approximations!

- Phylogenetic trees are tremendously useful and powerful tools for organizing, understanding and analyzing biological data
- But they have limitations:
  - The true history of life cannot really be summarized by a tree
    - Sex, other forms of combination or gene transfer
  - Trees constructed by humans are not necessarily even the best approximations to the true history of life
  - Our guesses often change over time

Phylogenetic trees are approximations!

- Phylogenetic trees are tremendously useful and powerful tools for organizing, understanding and analyzing biological data
- But they have limitations:
  - The true history of life cannot really be summarized by a tree
    - Sex, other forms of combination or gene transfer
  - Trees constructed by humans are not necessarily even the best approximations to the true history of life
  - Our guesses often change over time

Outline

Phylogeny
- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life
- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification
- Adaptive radiations
- Mass extinctions

Outline

Phylogeny
- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life
- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification
- Adaptive radiations
- Mass extinctions

The shape of the tree

- Big recent innovations have told us a lot about the history of life

The shape of the tree

- Big recent innovations have told us a lot about the history of life
  - Detailed genetic information

The shape of the tree

- Big recent innovations have told us a lot about the history of life
  - Detailed genetic information
  - Sophisticated analysis techniques

The shape of the tree

- Big recent innovations have told us a lot about the history of life
  - Detailed genetic information
  - Sophisticated analysis techniques
  - Electronic computers

The shape of the tree

- Big recent innovations have told us a lot about the history of life
  - Detailed genetic information
  - Sophisticated analysis techniques
  - Electronic computers

Three domains

- Bacteria

Three domains

- Bacteria
  - no nuclei; mostly small

Three domains

- Bacteria
  - no nuclei; mostly small
  - most of the micro-organisms you see

Three domains

- Bacteria
  - no nuclei; mostly small
  - most of the micro-organisms you see
- Archaea

Three domains

- Bacteria
  - no nuclei; mostly small
  - most of the micro-organisms you see
- Archaea
  - no nuclei; mostly small

Three domains

- Bacteria
  - no nuclei; mostly small
  - most of the micro-organisms you see
- Archaea
  - no nuclei; mostly small
  - rarer, or live in more extreme environments

Three domains

- Bacteria
  - no nuclei; mostly small
  - most of the micro-organisms you see
- Archaea
  - no nuclei; mostly small
  - rarer, or live in more extreme environments
- Eukarya

Three domains

- Bacteria
  - no nuclei; mostly small
  - most of the micro-organisms you see
- Archaea
  - no nuclei; mostly small
  - rarer, or live in more extreme environments
- Eukarya
  - large, nucleated cells

Three domains

- Bacteria
  - no nuclei; mostly small
  - most of the micro-organisms you see
- Archaea
  - no nuclei; mostly small
  - rarer, or live in more extreme environments
- Eukarya
  - large, nucleated cells

Eukaryotes

- Seem to be sisters with archaea, according to most of our key genes

Eukaryotes

- Seem to be sisters with archaea, according to most of our key genes
- Characterized by **nuclei** and **mitochondria**

Eukaryotes

- Seem to be sisters with archaea, according to most of our key genes
- Characterized by **nuclei** and **mitochondria**
- Mitochondria came later, and are captured bacteria!

Eukaryotes

- Seem to be sisters with archaea, according to most of our key genes
- Characterized by **nuclei** and **mitochondria**
- Mitochondria came later, and are captured bacteria!
- Where did the nucleus come from?

Eukaryotes

- Seem to be sisters with archaea, according to most of our key genes
- Characterized by **nuclei** and **mitochondria**
- Mitochondria came later, and are captured bacteria!
- Where did the nucleus come from?
  - Nobody knows

Eukaryotes

- Seem to be sisters with archaea, according to most of our key genes
- Characterized by **nuclei** and **mitochondria**
- Mitochondria came later, and are captured bacteria!
- Where did the nucleus come from?
  - Nobody knows

The web of life

- The tree is only part of the story!

The web of life

- The tree is only part of the story!
  - If genes (or even whole bacteria) can be transferred, life is not really a tree

The web of life

- The tree is only part of the story!
  - If genes (or even whole bacteria) can be transferred, life is not really a tree
- Reuniting can create new species

The web of life

- The tree is only part of the story!
  - If genes (or even whole bacteria) can be transferred, life is not really a tree
- Reuniting can create new species
  - Hybridization

The web of life

- The tree is only part of the story!
  - If genes (or even whole bacteria) can be transferred, life is not really a tree
- Reuniting can create new species
  - Hybridization
  - Allopolyploidy

The web of life

- The tree is only part of the story!
  - If genes (or even whole bacteria) can be transferred, life is not really a tree
- Reuniting can create new species
  - Hybridization
  - Allopolyploidy
    - *

The web of life

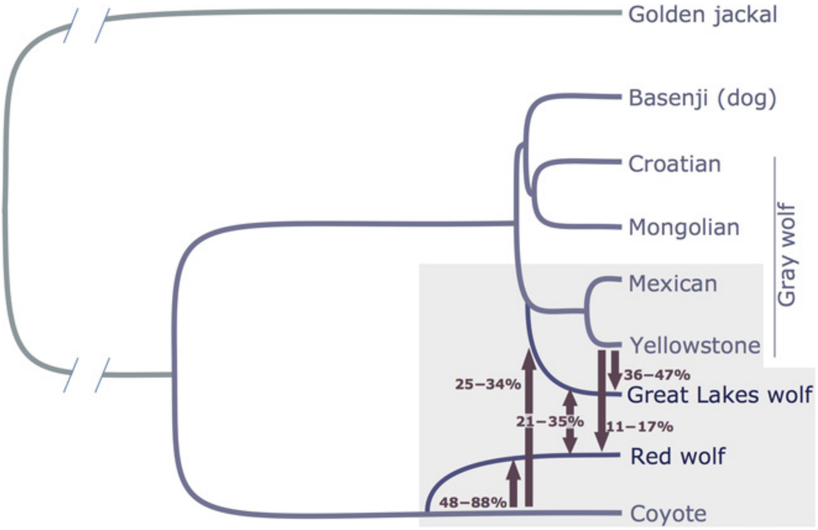
- The tree is only part of the story!
  - If genes (or even whole bacteria) can be transferred, life is not really a tree
- Reuniting can create new species
  - Hybridization
  - Allopolyploidy
    - * Polyploids arising from different (allo-) species

The web of life

- The tree is only part of the story!
  - If genes (or even whole bacteria) can be transferred, life is not really a tree
- Reuniting can create new species
  - Hybridization
  - Allopolyploidy
    - * Polyploids arising from different (allo-) species
- Wolf-coyote example

The web of life

- The tree is only part of the story!
  - If genes (or even whole bacteria) can be transferred, life is not really a tree
- Reuniting can create new species
  - Hybridization
  - Allopolyploidy
    - * Polyploids arising from different (allo-) species
- Wolf-coyote example



Golden jackal
Basenji (dog)
Croatian
Mongolian
Mexican
Yellowstone
Gray wolf
36–47%
Great Lakes wolf
25–34%
21–35%
11–17%
Red wolf
48–88%
Coyote

Five kingdoms

- *

Five kingdoms

- *

Five kingdoms

- *
- Not really a good way to describe the evolution of life

Five kingdoms

- *
- Not really a good way to describe the evolution of life
- So why has this idea persisted for so long?

Five kingdoms

- *
- Not really a good way to describe the evolution of life
- So why has this idea persisted for so long?
  - *

Five kingdoms

- *

- Not really a good way to describe the evolution of life

- So why has this idea persisted for so long?
  - * It matches the way the world *looks* – animals, plants and fungi dominate *visible* life

Five kingdoms

- *
- Not really a good way to describe the evolution of life
- So why has this idea persisted for so long?
  - * It matches the way the world *looks* – animals, plants and fungi dominate *visible* life
    - *

Five kingdoms

- *
- Not really a good way to describe the evolution of life
- So why has this idea persisted for so long?
  - * It matches the way the world *looks* – animals, plants and fungi dominate *visible* life
    - * Some branches are have organisms that are much smaller, or just have much fewer organisms

Five kingdoms

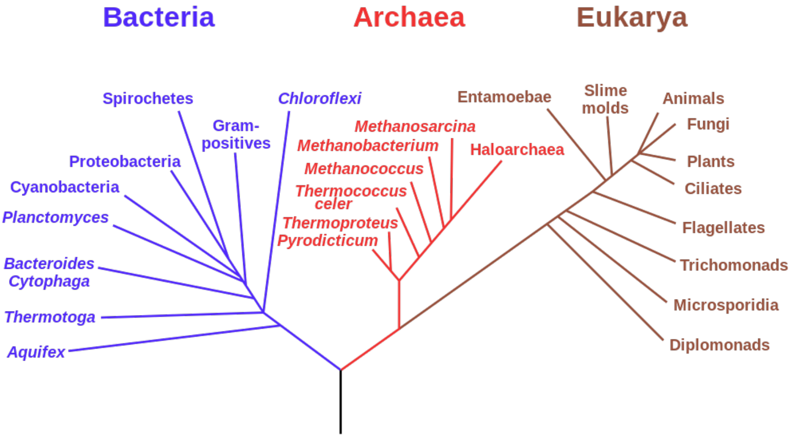
- *
- Not really a good way to describe the evolution of life
- So why has this idea persisted for so long?
  - * It matches the way the world *looks* – animals, plants and fungi dominate *visible* life
    - * Some branches are have organisms that are much smaller, or just have much fewer organisms
  - *

Five kingdoms

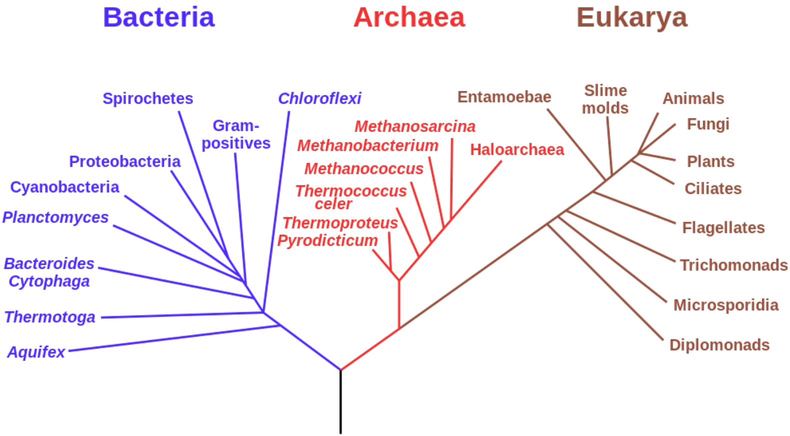
- *
- Not really a good way to describe the evolution of life
- So why has this idea persisted for so long?
  - * It matches the way the world *looks* – animals, plants and fungi dominate *visible* life
    - * Some branches are have organisms that are much smaller, or just have much fewer organisms
  - * Archaea and bacteria are difficult to tell apart even with a microscope

Five kingdoms

- *
- Not really a good way to describe the evolution of life
- So why has this idea persisted for so long?
  - * It matches the way the world *looks* – animals, plants and fungi dominate *visible* life
    - * Some branches are have organisms that are much smaller, or just have much fewer organisms
  - * Archaea and bacteria are difficult to tell apart even with a microscope

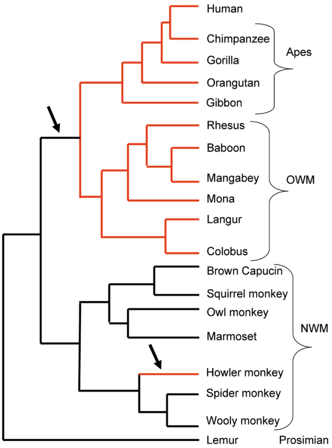


Bacteria
Archaea
Eukarya
Spirochetes
Chloroflexi
Gram-positives
Proteobacteria
Cyanobacteria
Planctomyces
Bacteroides Cytophaga
Thermotoga
Aquifex
Methanosarcina
Methanobacterium
Haloarchaea
Methanococcus
Thermococcus celer
Thermoproteus
Pyrodicticum
Entamoebae
Slime molds
Animals
Fungi
Plants
Ciliates
Flagellates
Trichomonads
Microsporidia
Diplomonads


Bacteria
Archaea
Eukarya
Spirochetes
Chloroflexi
Gram-positives
Proteobacteria
Cyanobacteria
Planctomyces
Bacteroides Cytophaga
Thermotoga
Aquifex
Methanosarcina
Methanobacterium
Haloarchaea
Methanococcus
Thermococcus celer
Thermoproteus
Pyrodicticum
Entamoebae
Slime molds
Animals
Fungi
Plants
Ciliates
Flagellates
Trichomonads
Microsporidia
Diplomonads

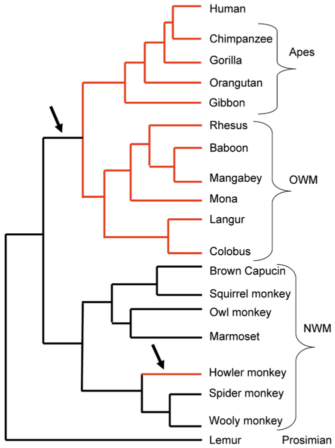
When are trees a good approximation?

- *



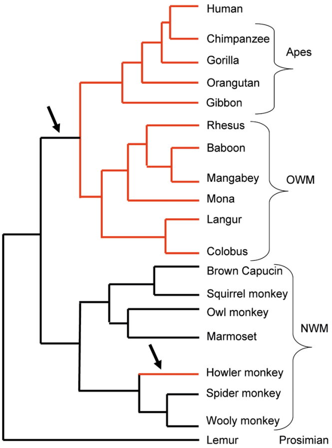
When are trees a good approximation?

- * When populations are not mixing



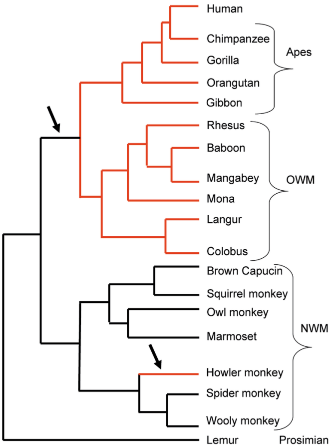
When are trees a good approximation?

- * When populations are not mixing
  - *



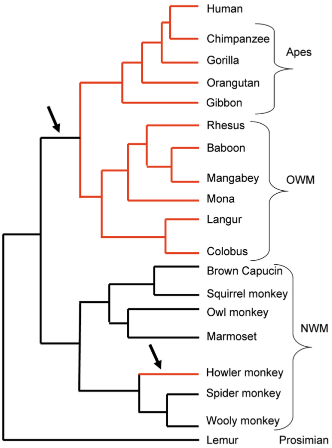
When are trees a good approximation?

- * When populations are not mixing
  - * Genetic exchange must be structured via sex



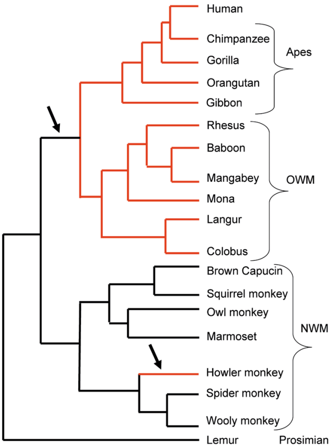
When are trees a good approximation?

- * When populations are not mixing
    - * Genetic exchange must be structured via sex
    - *



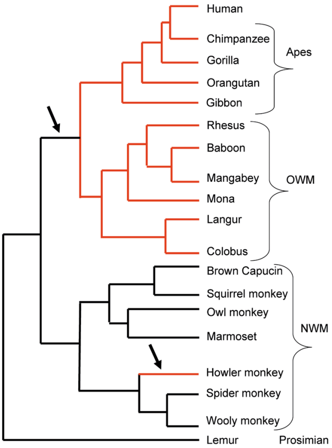
When are trees a good approximation?

- * When populations are not mixing
  - * Genetic exchange must be structured via sex
  - * populations have diverged enough to not have sex with each other



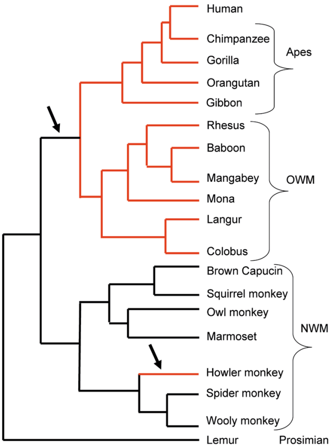
When are trees a good approximation?

- * When populations are not mixing
  - * Genetic exchange must be structured via sex
  - * populations have diverged enough to not have sex with each other
- Otherwise?



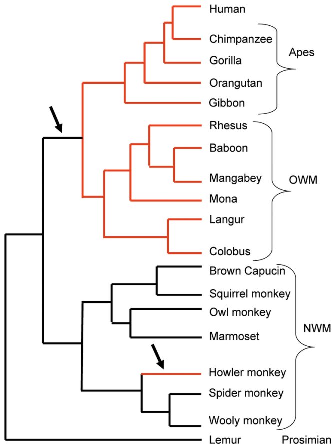
When are trees a good approximation?

- * When populations are not mixing
  - * Genetic exchange must be structured via sex
  - * populations have diverged enough to not have sex with each other
- Otherwise?
  - *



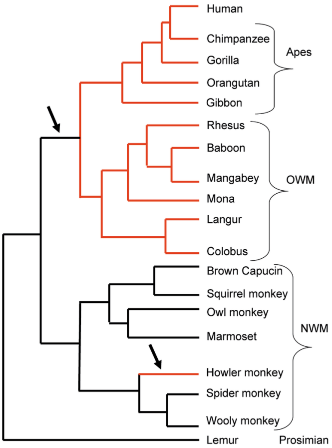
When are trees a good approximation?

- * When populations are not mixing
  - * Genetic exchange must be structured via sex
  - * populations have diverged enough to not have sex with each other
- Otherwise?
  - * We may need to make trees of genes or genetic components, instead of organisms



When are trees a good approximation?

- * When populations are not mixing
  - * Genetic exchange must be structured via sex
  - * populations have diverged enough to not have sex with each other
- Otherwise?
  - * We may need to make trees of genes or genetic components, instead of organisms



Outline

Phylogeny
- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life
- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification
- Adaptive radiations
- Mass extinctions

The fossil record

- A **fossil** is a physical trace of an organism from the past

The fossil record

- A **fossil** is a physical trace of an organism from the past
  - Intact fossils retain their form and substance

The fossil record

- A **fossil** is a physical trace of an organism from the past
  - Intact fossils retain their form and substance
  - Compression fossils are squashed into a thin film

The fossil record

- A **fossil** is a physical trace of an organism from the past
  - Intact fossils retain their form and substance
  - Compression fossils are squashed into a thin film
  - Cast fossils occur when the decomposing piece is replaced by minerals different from the surrounding ones

The fossil record

- A **fossil** is a physical trace of an organism from the past
  - Intact fossils retain their form and substance
  - Compression fossils are squashed into a thin film
  - Cast fossils occur when the decomposing piece is replaced by minerals different from the surrounding ones
  - Permineralized fossils occur if minerals infiltrate cells as they are decomposing

The fossil record

- A **fossil** is a physical trace of an organism from the past
  - Intact fossils retain their form and substance
  - Compression fossils are squashed into a thin film
  - Cast fossils occur when the decomposing piece is replaced by minerals different from the surrounding ones
  - Permineralized fossils occur if minerals infiltrate cells as they are decomposing
- *Does any of this seem likely?*

The fossil record

- A **fossil** is a physical trace of an organism from the past
  - Intact fossils retain their form and substance
  - Compression fossils are squashed into a thin film
  - Cast fossils occur when the decomposing piece is replaced by minerals different from the surrounding ones
  - Permineralized fossils occur if minerals infiltrate cells as they are decomposing
- *Does any of this seem likely?*

Biases in the fossil record

- Scientists have learned a lot from studying fossils, but care is needed. Very few things fossilize, and some things are much more likely to fossilize than others, for example:

Biases in the fossil record

- Scientists have learned a lot from studying fossils, but care is needed. Very few things fossilize, and some things are much more likely to fossilize than others, for example:
  - Things that live in swampy areas, or underground (**Habitat bias**)

Biases in the fossil record

- Scientists have learned a lot from studying fossils, but care is needed. Very few things fossilize, and some things are much more likely to fossilize than others, for example:
  - Things that live in swampy areas, or underground (**Habitat bias**)
  - Hard things, or hard parts of things (**Taxonomic bias**)

Biases in the fossil record

- Scientists have learned a lot from studying fossils, but care is needed. Very few things fossilize, and some things are much more likely to fossilize than others, for example:
  - Things that live in swampy areas, or underground (**Habitat bias**)
  - Hard things, or hard parts of things (**Taxonomic bias**)
  - Things that lived more recently have had less time to be destroyed, or to be buried too deep for recovery (**Temporal bias**)

Biases in the fossil record

- Scientists have learned a lot from studying fossils, but care is needed. Very few things fossilize, and some things are much more likely to fossilize than others, for example:
  - Things that live in swampy areas, or underground (**Habitat bias**)
  - Hard things, or hard parts of things (**Taxonomic bias**)
  - Things that lived more recently have had less time to be destroyed, or to be buried too deep for recovery (**Temporal bias**)
  - Things that are more abundant have more chances to be preserved (**Abundance bias**)

Biases in the fossil record

- Scientists have learned a lot from studying fossils, but care is needed. Very few things fossilize, and some things are much more likely to fossilize than others, for example:
  - Things that live in swampy areas, or underground (**Habitat bias**)
  - Hard things, or hard parts of things (**Taxonomic bias**)
  - Things that lived more recently have had less time to be destroyed, or to be buried too deep for recovery (**Temporal bias**)
  - Things that are more abundant have more chances to be preserved (**Abundance bias**)

Accounting for biases

- Because the fossil record is biased, scientists must be very careful about making inferences from what they see

Accounting for biases

- Because the fossil record is biased, scientists must be very careful about making inferences from what they see
  - Just because you don't see it, doesn't mean that it wasn't there

Accounting for biases

- Because the fossil record is biased, scientists must be very careful about making inferences from what they see
  - Just because you don't see it, doesn't mean that it wasn't there
  - Just because you see a lot, doesn't mean that there were a lot (relatively speaking)

Accounting for biases

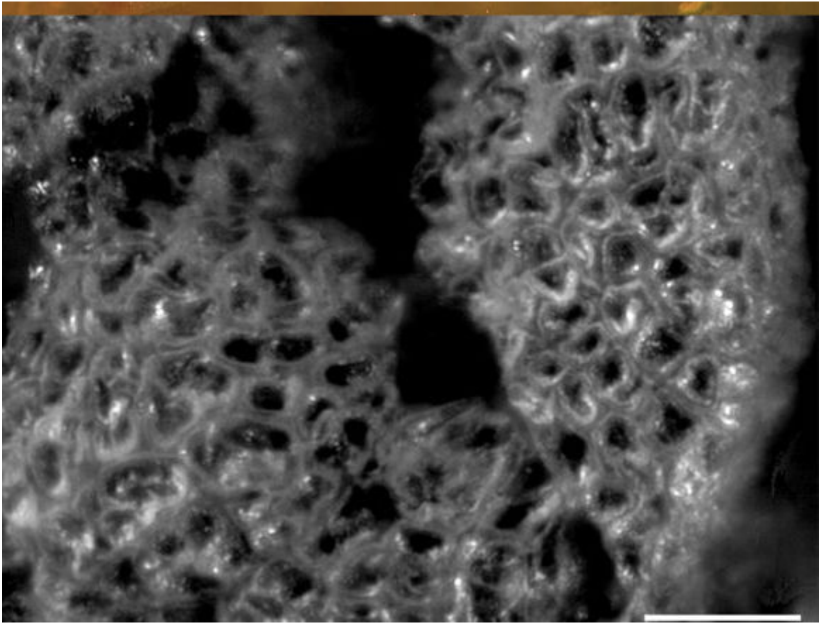
- Because the fossil record is biased, scientists must be very careful about making inferences from what they see
    - Just because you don't see it, doesn't mean that it wasn't there
    - Just because you see a lot, doesn't mean that there were a lot (relatively speaking)
- Trying to figure out what happened based on what kind of fossils we happen to find is tricky

Accounting for biases

- Because the fossil record is biased, scientists must be very careful about making inferences from what they see
  - Just because you don't see it, doesn't mean that it wasn't there
  - Just because you see a lot, doesn't mean that there were a lot (relatively speaking)
- Trying to figure out what happened based on what kind of fossils we happen to find is tricky
- Orchid phylogeny

Accounting for biases

- Because the fossil record is biased, scientists must be very careful about making inferences from what they see
  - Just because you don't see it, doesn't mean that it wasn't there
  - Just because you see a lot, doesn't mean that there were a lot (relatively speaking)
- Trying to figure out what happened based on what kind of fossils we happen to find is tricky
- Orchid phylogeny



Outline

Phylogeny
- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life
- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification
- Adaptive radiations
- Mass extinctions

Putting the timeline together

- Dates of specimens can be inferred using radioactive isotopes (harder than it sounds)

Putting the timeline together

- Dates of specimens can be inferred using radioactive isotopes (harder than it sounds)

- Geologic inferences can be made about the relative age of different things (for example, if one was deposited on top of another).

Putting the timeline together

- Dates of specimens can be inferred using radioactive isotopes (harder than it sounds)
- Geologic inferences can be made about the relative age of different things (for example, if one was deposited on top of another).
- Molecular clocks are based on inferences about how fast things are evolving

Putting the timeline together

- Dates of specimens can be inferred using radioactive isotopes (harder than it sounds)
- Geologic inferences can be made about the relative age of different things (for example, if one was deposited on top of another).
- Molecular clocks are based on inferences about how fast things are evolving
- These techniques are complicated, and making the timeline is a difficult and exciting puzzle

Putting the timeline together

- Dates of specimens can be inferred using radioactive isotopes (harder than it sounds)
- Geologic inferences can be made about the relative age of different things (for example, if one was deposited on top of another).
- Molecular clocks are based on inferences about how fast things are evolving
- These techniques are complicated, and making the timeline is a difficult and exciting puzzle

Outline

Phylogeny
- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life
- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification
- Adaptive radiations
- Mass extinctions

Processes of diversification

- Diversity sometimes arises gradually, and sometimes dramatically (**radiation** events)

Processes of diversification

- Diversity sometimes arises gradually, and sometimes dramatically (**radiation** events)
- Species (and families, and bigger groups) sometimes disappear gradually, and sometimes dramatically (**mass extinction** events)

Processes of diversification

- Diversity sometimes arises gradually, and sometimes dramatically (**radiation** events)
- Species (and families, and bigger groups) sometimes disappear gradually, and sometimes dramatically (**mass extinction** events)

Outline

Phylogeny
- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life
- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification
- Adaptive radiations
- Mass extinctions

Adaptive radiations

- An **adaptive radiation** occurs when a single lineage produces many descendant species, in a short period of time, that make their living in a variety of different ways

Adaptive radiations

- An **adaptive radiation** occurs when a single lineage produces many descendant species, in a short period of time, that make their living in a variety of different ways
- Triggered by opportunity, either in the environment, or because of the evolution of the organisms themselves

Adaptive radiations

- An **adaptive radiation** occurs when a single lineage produces many descendant species, in a short period of time, that make their living in a variety of different ways
- Triggered by opportunity, either in the environment, or because of the evolution of the organisms themselves

Triggers for adaptive radiation

- Ecological opportunity

Triggers for adaptive radiation

- Ecological opportunity
  - An organism arrives in an area with no similar organisms

Triggers for adaptive radiation

- Ecological opportunity
  - An organism arrives in an area with no similar organisms
  - A group of competing species is driven extinct (or nearly extinct) by some other cause

Triggers for adaptive radiation

- Ecological opportunity
  - An organism arrives in an area with no similar organisms
  - A group of competing species is driven extinct (or nearly extinct) by some other cause
- Morphological innovation: an organism comes up with a good, new idea

Triggers for adaptive radiation

- Ecological opportunity
  - An organism arrives in an area with no similar organisms
  - A group of competing species is driven extinct (or nearly extinct) by some other cause
- Morphological innovation: an organism comes up with a good, new idea
  - Legs in tetrapods

Triggers for adaptive radiation

- Ecological opportunity
  - An organism arrives in an area with no similar organisms
  - A group of competing species is driven extinct (or nearly extinct) by some other cause
- Morphological innovation: an organism comes up with a good, new idea
  - Legs in tetrapods
  - New body plans in the Cambrian explosion

Triggers for adaptive radiation

- Ecological opportunity
  - An organism arrives in an area with no similar organisms
  - A group of competing species is driven extinct (or nearly extinct) by some other cause
- Morphological innovation: an organism comes up with a good, new idea
  - Legs in tetrapods
  - New body plans in the Cambrian explosion
  - Multi-cellularity

Triggers for adaptive radiation

- Ecological opportunity
  - An organism arrives in an area with no similar organisms
  - A group of competing species is driven extinct (or nearly extinct) by some other cause
- Morphological innovation: an organism comes up with a good, new idea
  - Legs in tetrapods
  - New body plans in the Cambrian explosion
  - Multi-cellularity
- Co-evolution: the evolution of one group creates new niches for another group, and vice versa

Triggers for adaptive radiation

- Ecological opportunity
  - An organism arrives in an area with no similar organisms
  - A group of competing species is driven extinct (or nearly extinct) by some other cause
- Morphological innovation: an organism comes up with a good, new idea
  - Legs in tetrapods
  - New body plans in the Cambrian explosion
  - Multi-cellularity
- Co-evolution: the evolution of one group creates new niches for another group, and vice versa
  - The insects and the flowering plants

Triggers for adaptive radiation

- Ecological opportunity
  - An organism arrives in an area with no similar organisms
  - A group of competing species is driven extinct (or nearly extinct) by some other cause
- Morphological innovation: an organism comes up with a good, new idea
  - Legs in tetrapods
  - New body plans in the Cambrian explosion
  - Multi-cellularity
- Co-evolution: the evolution of one group creates new niches for another group, and vice versa
  - The insects and the flowering plants

Competition

- Mammals did very well after the dinosaurs went extinct

Competition

- Mammals did very well after the dinosaurs went extinct
- We have seen major tree species driven near extinction by introduced diseases in the last century

Competition

- Mammals did very well after the dinosaurs went extinct
- We have seen major tree species driven near extinction by introduced diseases in the last century
  - *

Competition

- Mammals did very well after the dinosaurs went extinct
- We have seen major tree species driven near extinction by introduced diseases in the last century
  - * This opens up ecological niches

Competition

- Mammals did very well after the dinosaurs went extinct
- We have seen major tree species driven near extinction by introduced diseases in the last century
  - * This opens up ecological niches
  - *

Competition

- Mammals did very well after the dinosaurs went extinct
- We have seen major tree species driven near extinction by introduced diseases in the last century
  - * This opens up ecological niches
  - * Species may diverge to fill these niches

Competition

- Mammals did very well after the dinosaurs went extinct
- We have seen major tree species driven near extinction by introduced diseases in the last century
  - * This opens up ecological niches
  - * Species may diverge to fill these niches
  - *

Competition

- Mammals did very well after the dinosaurs went extinct
- We have seen major tree species driven near extinction by introduced diseases in the last century
  - * This opens up ecological niches
  - * Species may diverge to fill these niches
  - * Or spread around the world to fill them

Competition

- Mammals did very well after the dinosaurs went extinct
- We have seen major tree species driven near extinction by introduced diseases in the last century
  - * This opens up ecological niches
  - * Species may diverge to fill these niches
  - * Or spread around the world to fill them

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans ...

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans ...
  - The tetrapod body plan

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans . . .
  - The tetrapod body plan
    - reptiles, mammals . . .

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans . . .
  - The tetrapod body plan
    - reptiles, mammals . . .
  - Flowering plants

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans . . .
  - The tetrapod body plan
    - reptiles, mammals . . .
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans ...
  - The tetrapod body plan
    - reptiles, mammals ...
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators
    - *

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans . . .
  - The tetrapod body plan
    - reptiles, mammals . . .
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators
    - * Animals evolved to exploit the flowering plants

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans . . .
  - The tetrapod body plan
    - reptiles, mammals . . .
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators
    - * Animals evolved to exploit the flowering plants
    - *

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans . . .
  - The tetrapod body plan
    - reptiles, mammals . . .
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators
    - * Animals evolved to exploit the flowering plants
    - * Flowering plants and animals *co-evolved*

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans . . .
  - The tetrapod body plan
    - reptiles, mammals . . .
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators
    - * Animals evolved to exploit the flowering plants
    - * Flowering plants and animals *co-evolved*
    - *

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans ...
  - The tetrapod body plan
    - reptiles, mammals ...
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators
    - * Animals evolved to exploit the flowering plants
    - * Flowering plants and animals *co-evolved*
    - * Natural defenses and exploits

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans . . .
  - The tetrapod body plan
    - reptiles, mammals . . .
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators
    - * Animals evolved to exploit the flowering plants
    - * Flowering plants and animals *co-evolved*
    - * Natural defenses and exploits
    - *

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans . . .
  - The tetrapod body plan
    - reptiles, mammals . . .
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators
    - * Animals evolved to exploit the flowering plants
    - * Flowering plants and animals *co-evolved*
    - * Natural defenses and exploits
    - * Pollination and dispersal

Morphological innovation

- A new adaptive mutation can open up further possibilities for adaptation
  - The arthropod body plan
    - insects, arachnids, crustaceans ...
  - The tetrapod body plan
    - reptiles, mammals ...
  - Flowering plants
    - This opened many new opportunities for *everyone* (insects, mammals, birds), not just the innovators
    - * Animals evolved to exploit the flowering plants
    - * Flowering plants and animals *co-evolved*
    - * Natural defenses and exploits
    - * Pollination and dispersal

Gene duplication

- One or more genes may be accidentally duplicated so that the genome has two copies of each gene

Gene duplication

- One or more genes may be accidentally duplicated so that the genome has two copies of each gene
  - Chromosomal duplication by polyploidy is one way this can happen

Gene duplication

- One or more genes may be accidentally duplicated so that the genome has two copies of each gene
  - Chromosomal duplication by polyploidy is one way this can happen
- This may make the organism less efficient, and thus be selected against

Gene duplication

- One or more genes may be accidentally duplicated so that the genome has two copies of each gene
  - Chromosomal duplication by polyploidy is one way this can happen
- This may make the organism less efficient, and thus be selected against
- It may also allow for innovation. Why?

Gene duplication

- One or more genes may be accidentally duplicated so that the genome has two copies of each gene
  - Chromosomal duplication by polyploidy is one way this can happen
- This may make the organism less efficient, and thus be selected against
- It may also allow for innovation. Why?
  - *

Gene duplication

- One or more genes may be accidentally duplicated so that the genome has two copies of each gene
  - Chromosomal duplication by polyploidy is one way this can happen
- This may make the organism less efficient, and thus be selected against
- It may also allow for innovation. Why?
  - * Because one copy can continue to do the old function, while the other evolves a new function

Gene duplication

- One or more genes may be accidentally duplicated so that the genome has two copies of each gene
  - Chromosomal duplication by polyploidy is one way this can happen
- This may make the organism less efficient, and thus be selected against
- It may also allow for innovation. Why?
  - * Because one copy can continue to do the old function, while the other evolves a new function

Outline

Phylogeny
- Interpreting phylogenetic trees
- Constructing phylogenetic trees
- Example: the evolution of whales

The history of life
- The shape of the tree
- The fossil record
- Putting the timeline together

Processes of diversification
- Adaptive radiations
- Mass extinctions

Mass extinctions

- Five major mass extinctions so far

Mass extinctions

- Five major mass extinctions so far
- The last one (and maybe others) was caused by a cosmic impact

Mass extinctions

- Five major mass extinctions so far
- The last one (and maybe others) was caused by a cosmic impact
  - It could happen again

Mass extinctions

- Five major mass extinctions so far
- The last one (and maybe others) was caused by a cosmic impact
  - It could happen again
- Are we in the middle of a mass extinction now?

Mass extinctions

- Five major mass extinctions so far
- The last one (and maybe others) was caused by a cosmic impact
  - It could happen again
- Are we in the middle of a mass extinction now?
  - Extinction rate very high over the last 400 years

Mass extinctions

- Five major mass extinctions so far
- The last one (and maybe others) was caused by a cosmic impact
  - It could happen again
- Are we in the middle of a mass extinction now?
  - Extinction rate very high over the last 400 years
  - Many scientists believe that we are likely to cause a geologically significant mass extinction

Mass extinctions

- Five major mass extinctions so far
- The last one (and maybe others) was caused by a cosmic impact
  - It could happen again
- Are we in the middle of a mass extinction now?
  - Extinction rate very high over the last 400 years
  - Many scientists believe that we are likely to cause a geologically significant mass extinction

Activity: how are people causing extinctions?

- *

Activity: how are people causing extinctions?

- *

Activity: how are people causing extinctions?

- *
- *

Activity: how are people causing extinctions?

- *
- *

Activity: how are people causing extinctions?

- *
- *
- *

Activity: how are people causing extinctions?

- *
- *
- *

Activity: how are people causing extinctions?

- *
- *
- *
- *

Activity: how are people causing extinctions?

- *
- *
- *
- *

Activity: how are people causing extinctions?

- *
- *
- *
- *

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred
  - Molecular information, and computer modeling has changed our view of the tree of life

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred
  - Molecular information, and computer modeling has changed our view of the tree of life
  - life is not really a tree

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred
  - Molecular information, and computer modeling has changed our view of the tree of life
  - life is not really a tree
    - genetic information can be transferred

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred
  - Molecular information, and computer modeling has changed our view of the tree of life
  - life is not really a tree
    - genetic information can be transferred
    - sexual mixing occurs at different scales

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred
  - Molecular information, and computer modeling has changed our view of the tree of life
  - life is not really a tree
    - genetic information can be transferred
    - sexual mixing occurs at different scales
- Scientists use many clues to figure out the history of life on earth

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred
  - Molecular information, and computer modeling has changed our view of the tree of life
  - life is not really a tree
    - genetic information can be transferred
    - sexual mixing occurs at different scales
- Scientists use many clues to figure out the history of life on earth
  - Fossils, geology, phylogeny

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred
  - Molecular information, and computer modeling has changed our view of the tree of life
  - life is not really a tree
    - genetic information can be transferred
    - sexual mixing occurs at different scales
- Scientists use many clues to figure out the history of life on earth
  - Fossils, geology, phylogeny
- Life has diversified both gradually, and with dramatic episodes

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred
  - Molecular information, and computer modeling has changed our view of the tree of life
  - life is not really a tree
    - genetic information can be transferred
    - sexual mixing occurs at different scales
- Scientists use many clues to figure out the history of life on earth
  - Fossils, geology, phylogeny
- Life has diversified both gradually, and with dramatic episodes
  - Adaptive radiations, mass extinctions

Conclusion

- The best way to reconstruct evolution is with a *model* of how it occurred
  - Molecular information, and computer modeling has changed our view of the tree of life
  - life is not really a tree
    - genetic information can be transferred
    - sexual mixing occurs at different scales
- Scientists use many clues to figure out the history of life on earth
  - Fossils, geology, phylogeny
- Life has diversified both gradually, and with dramatic episodes
  - Adaptive radiations, mass extinctions