

Exam 2: Ch 26, 27, 28

Phylogeny · prokaryotes · protists

Genus names are italicized and underlined. Blue = big idea · yellow = what she stressed · green = memory hooks · pink = be able to draw/explain and traps.

1. 26.1 Phylogenies show evolutionary relationships
2. 26.2 Phylogenies are inferred from morphological and molecular data
3. 26.3 Shared characters are used to construct phylogenetic trees
4. 26.4 An organism's evolutionary history is documented in its genome
5. 26.5 Molecular clocks help track evolutionary time
6. 26.6 Our understanding of the tree of life continues to change based on new data
7. 27.1 Structural and functional adaptations contribute to prokaryotic success
8. 27.2 Rapid reproduction, mutation, and genetic recombination promote genetic diversity in prokaryotes
9. 27.3 Diverse nutritional and metabolic adaptations have evolved in prokaryotes
10. 27.4 Prokaryotes have radiated into a diverse set of lineages
11. 27.5 Prokaryotes play crucial roles in the biosphere
12. 27.6 Prokaryotes have both beneficial and harmful impacts on humans
13. PV Phylogenetics videos: taxonomy, homology vs analogy, and the anole lizards
14. 28.1 Most eukaryotes are single-celled organisms
15. 28.2 Excavates include protists with modified mitochondria and protists with unique flagella
16. 28.3 The "SAR" clade is a highly diverse group of protists defined by DNA similarities
17. 28.4 Red algae and green algae are the closest relatives of plants
18. 28.5 Unikonts include protists that are closely related to fungi and animals
19. 28.6 Protists play key roles in ecological communities

Phylogenies show evolutionary relationships

[Lecture video 26.1 \(opens online\)](#)

Big idea

Phylogeny is the evolutionary history of a species or group of related species, and systematics is the discipline that classifies organisms and determines their evolutionary relationships. Linnaeus (18th century) gave us binomial nomenclature and hierarchical classification, both still used. A phylogenetic tree is a hypothesis about evolutionary relationships: branch points are common ancestors, and the branching pattern (not the order of the tips) shows the order in which lineages diverged. Trees show patterns of descent, not phenotypic similarity, and do not show when species evolved or how much change occurred.

Must know

- Phylogeny: evolutionary history of a species or group of related species.
- Systematics: discipline focused on classifying organisms and determining their evolutionary relationships.
- Carl Linnaeus, 18th century, based his taxonomy on morphology (resemblance). Two features still used: two-part species names (binomial nomenclature) and hierarchical classification.
- Binomial = genus + specific epithet. Genus is capitalized, specific epithet is not; the whole name is italicized when typed and underlined when handwritten.
- Example binomial: *Panthera pardus* (leopard/panther). *Panthera* is the genus, *pardus* is the specific epithet.
- Hierarchy from broad to narrow: domain, kingdom, phylum, class, order, family, genus, species. Memorize the order.
- A group at any level is a taxon (plural taxa). Broader taxa are not comparable between lineages (an order of snails does not have the same diversity as an order of mammals).
- Linnaean placements do not always reflect evolutionary relationships because the system was built on morphology. Systematists want only groups that include a common ancestor and all its descendants to be named.
- Branch point (node): divergence of two lineages from a common ancestor.
- Evolutionary lineage: sequence of ancestral organisms leading to a particular descendant taxon.
- Sister taxa: groups that share an immediate common ancestor not shared by any other group (chimps and humans in the lecture figure).
- Branches can be rotated around a branch point without changing relationships. Trees can be drawn horizontally, vertically, or diagonally.
- Rooted tree: includes a branch representing the most recent common ancestor of all taxa in the tree.
- Basal taxon: a lineage that diverges from all other members of the group early in the group's history (fishes in the lecture figure).
- You cannot assume a taxon evolved from the taxon next to it on the tree.

Terms

phylogeny

The evolutionary history of a species or group of related species.

systematics

The discipline that classifies organisms and determines their evolutionary relationships.

binomial nomenclature

Linnaeus's two-part scientific name for a species: genus plus specific epithet.

genus

First part of the binomial; always capitalized.

specific epithet

Second part of the binomial; unique for each species within the genus; not capitalized.

hierarchical classification

Grouping species in increasingly inclusive categories, from species up to domain.

taxon (taxa)

A named group at any level of the hierarchy.

phylogenetic tree

A branching diagram that represents a hypothesis about the evolutionary history of a group.

branch point (node)

The point where two lineages diverge from a common ancestor.

evolutionary lineage

A sequence of ancestral organisms leading to a particular descendant taxon.

sister taxa

Groups that share an immediate common ancestor that is not shared by any other group.

rooted tree

A tree that includes a branch for the most recent common ancestor of all taxa in the tree.

basal taxon

A lineage that diverges early in the history of the group, off on its own branch near the root.

polytomy

A branch point from which more than two lineages emerge; it means the order of divergence is not yet resolved. (Term assigned by the study guide request; not stated in the lecture audio.)

Examples

- Lizard tree: geckos kept limbs; snakes lost limbs (hash mark); glass lizards also lost limbs independently. Glass lizards resemble snakes but are not closely related to them.
- Panthera pardus: genus Panthera, family Felidae, order Carnivora, class Mammalia, phylum Chordata, kingdom Animalia, domain Eukarya.
- Order Carnivora tree: Felidae (Panthera pardus), Mustelidae (Taxidea taxus American badger, Lutra lutra European otter), Canidae (Canis latrans coyote, Canis lupus gray wolf).
- Snakes lost limbs, so a morphology-only system would not group them with other reptiles; DNA evidence supports reclassification.
- Chimps and humans are sister taxa; switching their positions changes nothing.

What she stressed in lecture

- Know the order of the hierarchy: domain, kingdom, phylum, class, order, family, genus, species.
- Know how to write a binomial: capitalize genus, lowercase epithet, italicize if typed, underline if handwritten.
- 'The branching pattern is what signifies the order in which the lineages diverge from common ancestors. So where it branches is the important place to look.'
- 'Phylogenetic trees do not indicate when species evolved, and they do not show how much change has occurred within the lineage.'
- 'You can't assume that a taxon evolved from the taxon next to it.'

Memory hooks

Dear King Philip Came Over For Great Soup

Domain, Kingdom, Phylum, Class, Order, Family, Genus, Species (broad to narrow).

Genus is the Grown-up, species is the small kid

Genus starts with a capital letter, specific epithet is all lowercase: *Panthera pardus*.

*Type it **tilted**, write it with a **line***

Typed binomials are italic; handwritten ones are underlined.

*Basal = at the **base***

A basal taxon branches off first, near the root (fishes in the lecture tree).

Sister taxa share the same parent and no one else

Sister taxa share an immediate common ancestor that no other group shares.

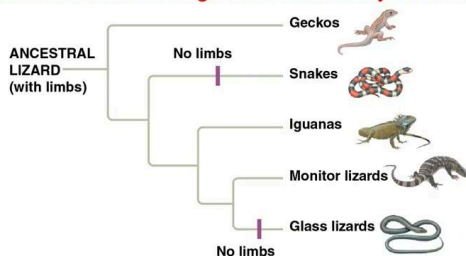
Spin the branches, same family

Rotating branches around a node does not change relationships.

Slides

CONCEPT 26.1 Phylogenies show evolutionary relationships

- Phylogeny** is the evolutionary history of a species or group of related species
- Systematics** is a discipline focused on classifying organisms and determining their evolutionary relationships



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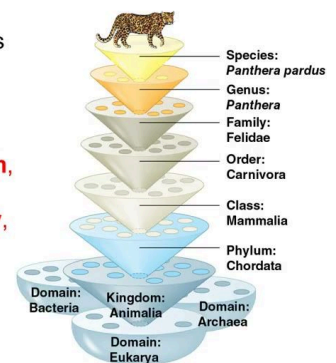
Slide 1. Limb loss in lizards: snakes vs glass lizards

No limbs evolved twice: once in snakes and once in glass lizards. Glass lizards look like snakes but are more closely related to monitor lizards, so a phylogeny shows descent, not resemblance. ▶ **Play from 0:07**

Lecture 26.1, slide 002

Hierarchical Classification

- Linnaeus introduced a system for grouping species in increasingly inclusive categories
- The taxonomic groups from broad to narrow are **domain, kingdom, phylum** (plural, **phyla**), **class, order, family, genus, and species**
- A group at any level of hierarchy is called a **taxon**



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Slide 2. Hierarchical classification of the leopard

Linnaeus grouped species in increasingly inclusive categories, shown here for *Panthera pardus*. Know the order from broad to narrow: domain, kingdom, phylum, class, order, family, genus, species; a group at any level is a taxon.

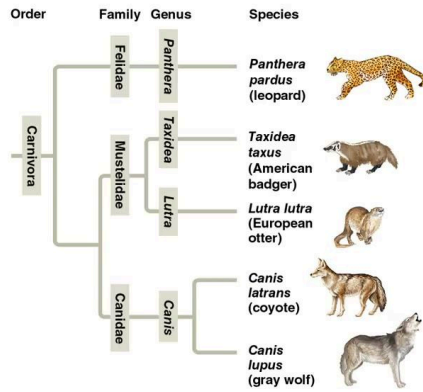
How to draw it: Draw the nested levels for the leopard and label each: Domain Eukarya, Kingdom Animalia, Phylum Chordata, Class Mammalia, Order Carnivora, Family Felidae, Genus *Panthera*, Species *Panthera pardus*.

▶ **Play from 5:40**

Lecture 26.1, slide 005

Linking Classification and Phylogeny

- The evolutionary history of a group of organisms can be represented in a branching diagram called a **phylogenetic tree**



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Slide 3. Linking classification and phylogeny: order Carnivora

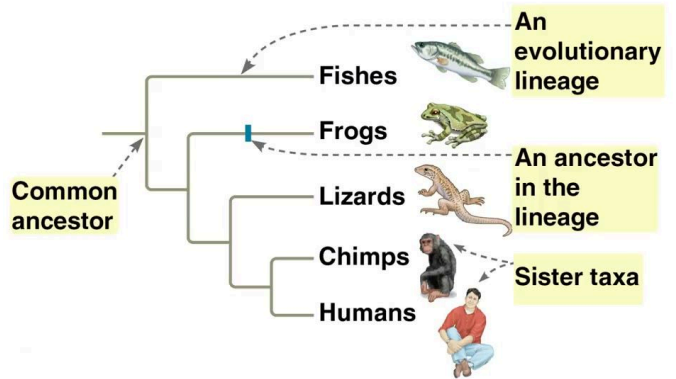
A phylogenetic tree of Carnivora with the families Felidae, Mustelidae and Canidae and their genera. The branching matches the Linnaean groups, so *Canis latrans* and *Canis lupus* share the most recent common ancestor.

► Play from 8:46

Lecture 26.1, slide 007

Figure 26.5 Visualizing phylogenetic relationships

Parts of a Phylogenetic Tree



Slide 4. Parts of a phylogenetic tree

Each branch point is the divergence of two lineages from a common ancestor, and sister taxa (chimps and humans) share an ancestor not shared by any other group. The branch at the base marks the common ancestor of all taxa, which makes the tree rooted.

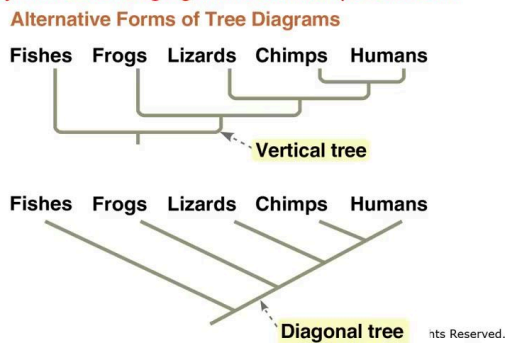
How to draw it: Draw a rooted tree of fishes, frogs, lizards, chimps and humans; label the common ancestor, one branch point, an evolutionary lineage, an ancestor in the lineage, and the sister taxa (chimps and humans).

► Play from 14:25

Lecture 26.1, slide 011

What We Can and Cannot Learn from Phylogenetic Trees

- Phylogenetic trees can be drawn horizontally, vertically, or diagonally without changing the relationships between groups



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Slide 5. Vertical and diagonal forms of the same tree

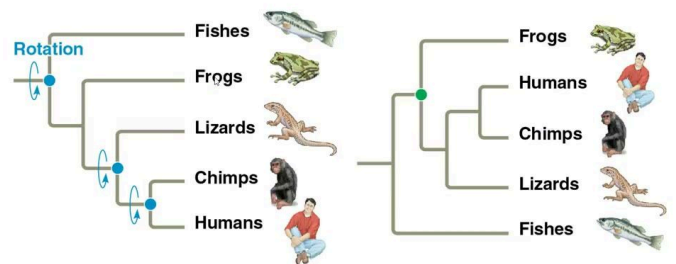
The same five taxa drawn as a vertical tree and a diagonal tree. Tree orientation does not change the relationships; only the branching pattern matters.

► Play from 16:32

Lecture 26.1, slide 012

Figure 26.5 Visualizing phylogenetic relationships

Rotating Around Branch Points



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Slide 6. Rotating around branch points

Branches rotate around a branch point without changing relationships, so both trees say the same thing. The order of taxa at the tips is not significant, and a taxon did not evolve from the taxon next to it.

► Play from 18:07

Lecture 26.1, slide 016

Be able to draw / explain

- Posted concept figure: tree of fishes, frogs, humans, chimps, geckos, snakes, iguanas, glass lizards. The blue dot at the root is the common ancestor of all groups. A hash mark 'Four limbs' sits on the branch leading to everything except fishes; a hash mark 'Hair' sits on the branch leading to humans and chimps. Humans and chimps are bracketed as a sister group. A blue dot marks the common ancestor of the lizards and snakes, which had limbs; separate 'No limbs' hash marks sit on the snake branch and on the glass lizard branch (limbs lost twice). Iguanas are the sister group of glass lizards. Fishes are the basal taxon. Rule from the figure: a hash mark is a character shared by all groups to the right of the mark.
- Three layouts of the same tree (horizontal, vertical, diagonal) show identical relationships.
- Rotation figure: rotating around three nodes changes tip order but not relationships.

My notes

Phylogenies are inferred from morphological and molecular data

[Lecture video 26.2 \(opens online\)](#)

Big idea

Systematists use morphology, genes (DNA and protein sequences), and biochemistry to infer phylogeny. Only features that result from common ancestry (homologies) are useful. Analogy is similarity due to convergent evolution, and it must be sorted out from homology before building a tree. The more complex the shared similarity, the more likely it reflects common ancestry.

Must know

- Common ancestry is a MUST: only features resulting from common ancestry are useful for building trees.
- Homology: phenotypic and genetic similarity due to shared ancestry.
- Analogy: similarity due to convergent evolution, not common ancestry.
- Convergent evolution: unrelated species evolve superficially similar features because natural selection acts in similar environments.
- Organisms with similar morphology or DNA sequence are likely more closely related than those very different in structure and sequence.
- Morphology and genetics do not always match: species can look very different but be genetically similar (Hawaiian silverswords), or vice versa.
- More complex similarity (for example, many shared portions of nucleotide sequence) means homology is more likely.
- Coincidental sequence matches happen; statistical tools and databases score molecular homology and separate distant homology from coincidence.

Terms

homology

Similarity (phenotypic or genetic) due to shared ancestry.

analogy

Similarity due to convergent evolution rather than shared ancestry.

convergent evolution

Independent evolution of similar features in unrelated species exposed to similar selection pressures.

homologous structures

Structures similar because they were inherited from a common ancestor, even if they now serve different functions.

analogous structures

Structures with similar function or appearance that arose by convergent evolution, not common ancestry.

Examples

- Hawaiian silverswords: look very different (tall twiggy trees to dense ground-hugging shrubs) depending on the island, but are genetically very similar.
- Australian mole and African golden mole: look alike and both dig tunnels, but similarity is analogy from similar lifestyles, not shared ancestry.

- Video: forelimbs of human, bat, and whale are homologous (four limbs in a shared ancestor).
- Video: grasshopper and butterfly mouthparts and antennae are homologous.
- Video: North American cactus (*Astrophytum*) and African *Euphorbia* look alike (spherical, eight symmetrical sectors, store water) by convergent evolution.
- Video: bird wings and insect wings are analogous; bird wings contain bones homologous to human arm bones, insect wings have no bones.

What she stressed in lecture

- 'Analogy is similarity due to convergent evolution. Homology is similarity due to shared ancestry.'
- 'The more similarity between complex structures, the more likely they evolved from a common ancestor.'
- Video: the first step in building a tree is to distinguish homologous from analogous structures.

Memory hooks

*HOM*ology = same *HOM*e

Homology means similar because of a shared ancestor.

*ANA*logy = *AN*other *A*ncessor

Analogy means similar because of convergent evolution, not common ancestry.

Look alike, live alike, not kin

The Australian mole and the African golden mole look alike only because they live alike (analogy).

The more complex the match, the more likely it's family

Complex shared similarities, like long stretches of matching DNA, are more likely to be homology.

Slides

Sorting Homology from Analogy

- Superficial similarities evolve in unrelated species through convergent evolution in response to natural selection to similar environmental conditions
 - For example, similarities between the Australian "mole" and the African golden mole result from adaptation to similar lifestyles, not shared ancestry



Australian "mole"



African golden mole

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Slide 7. Analogy: Australian mole and African golden mole

The Australian "mole" and the African golden mole look alike because of convergent evolution to similar burrowing lifestyles, not shared ancestry. Their similarity is analogy, not homology, so it cannot be used to build a phylogeny.

▶ Play from 4:04

Lecture 26.2, slide 006

Be able to draw / explain

- Australian mole (top) and African golden mole (bottom): nearly identical burrowing body forms produced by convergent evolution.

My notes



Shared characters are used to construct phylogenetic trees

[Lecture video 26.3 \(opens online\)](#)

Big idea

Cladistics groups organisms by common ancestry into clades, which are monophyletic (ancestor plus all descendants). Paraphyletic groups leave out some descendants, and polyphyletic groups leave out the most recent common ancestor. Trees are built from shared derived characters, identified by comparing an ingroup with an outgroup. Maximum parsimony picks the tree with the fewest evolutionary events, and maximum likelihood picks the tree most probable under rules of DNA change.

Must know

- Cladistics: organisms grouped primarily by common ancestry.
- Clade: an ancestral species and ALL of its descendants. Clades can be nested within larger clades.
- Monophyletic group: ancestor and all its descendants; only monophyletic groups are clades.
- Paraphyletic group: ancestral species and some, but not all, of its descendants. The common ancestor IS in the group.
- Polyphyletic group: includes distantly related species but not their most recent common ancestor.
- Know Figure 26.10 and be able to give and explain an example of each group type.
- Shared ancestral character: originated in an ancestor of the taxon.
- Shared derived character: an evolutionary novelty unique to a particular clade. Losses count too (limb loss in snakes or whales).
- Ancestral vs derived is relative: a backbone is ancestral within vertebrates but derived when separating vertebrates from other animals.
- Outgroup: closely related to, but not part of, the group being studied. Ingroup: the group being studied.
- Characters shared by outgroup and ingroup are assumed ancestral. Each derived character is assumed to arise only once in the ingroup.
- Branch lengths can be proportional to genetic change, or proportional to time (calibrated with fossil data).
- Maximum parsimony: the most likely tree requires the fewest evolutionary events; for DNA, the fewest base changes.
- Maximum likelihood: the tree most likely to have produced the DNA data, based on probability rules about how DNA changes (for example, assuming all substitutions equally likely).
- Computer programs search for trees that are both parsimonious and likely. The goal is the most likely tree, not a perfect tree.

Terms

cladistics

An approach that classifies organisms by common ancestry.

clade

A group made of an ancestral species and all of its descendants.

monophyletic

A group containing an ancestor and all of its descendants.

paraphyletic

A group containing an ancestor and some, but not all, of its descendants.

polyphyletic

A group of distantly related species that does not include their most recent common ancestor.

shared ancestral character

A character that originated in an ancestor of the taxon being studied.

shared derived character

An evolutionary novelty unique to a particular clade.

outgroup

A species or group closely related to, but not part of, the group being studied.

ingroup

The group of species being studied.

maximum parsimony

The principle that the best tree needs the fewest evolutionary events (fewest base changes for DNA).

maximum likelihood

The principle that the best tree is the one most likely to produce the data, given probability rules for DNA change.

Examples

- Paraphyletic: even-toed ungulates plus hippopotamuses, leaving out cetaceans (which share their ancestor). Adding cetaceans makes it monophyletic.
- Polyphyletic: cetaceans plus seals grouped because they look alike; their most recent common ancestor is left out.
- Character table (lancelet outgroup; lamprey, bass, frog, turtle, leopard ingroup): characters are vertebral column, hinged jaws, four limbs, amnion, hair. 0 = absent, 1 = present. Lancelet has none. Vertebral column: lamprey onward. Hinged jaws: bass onward. Four limbs: frog, turtle, leopard. Amnion: turtle and leopard. Hair: leopard only.
- Branch lengths proportional to genetic change: *Drosophila* (fruit fly) has the longest branch; lancelet, zebrafish, frog, chicken, human, mouse follow.
- Lost features as shared derived characters: loss of limbs in snakes or whales.

What she stressed in lecture

- 'I do want you to know Figure 26.10' (monophyletic, paraphyletic, polyphyletic). 'Make sure that you can give an example of each of these groups and be able to explain.'
- Shared ancestral vs shared derived: 'You should know those definitions.'
- 'Only monophyletic groupings are going to be included as a clade.'
- Polyphyletic is 'the weird one'.
- Lab will use derived characters to infer phylogeny from a 0/1 character table.

Memory hooks

MONO = the **ONE** whole family

Monophyletic: the ancestor and ALL of its descendants. Only these groups are clades.

PARA = **PAR**tial family

Paraphyletic: the ancestor plus only SOME of its descendants.

POLY = **POL**ice line-up of strangers

Polyphyletic: distant relatives grouped together WITHOUT their most recent common ancestor.

Parsimony = penny-pincher

Maximum parsimony picks the tree with the fewest evolutionary changes.

Likelihood = likely odds

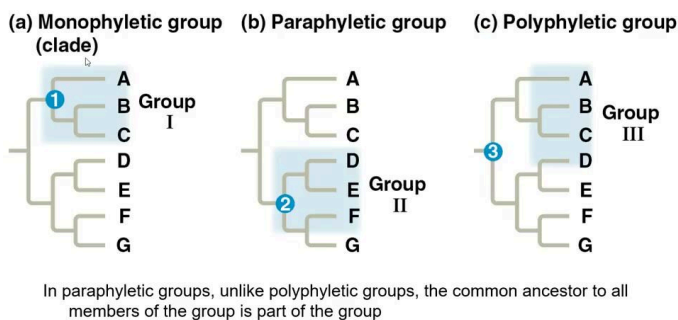
Maximum likelihood picks the tree most likely to produce the DNA data, using probability rules for how DNA changes.

The **OUT**group is the **OUT**sider you compare against

Traits shared by the outgroup and the ingroup are ancestral; traits only in the ingroup are derived.

Slides

Figure 26.10 Monophyletic, paraphyletic, and polyphyletic groups



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Slide 8. Monophyletic, paraphyletic and polyphyletic groups

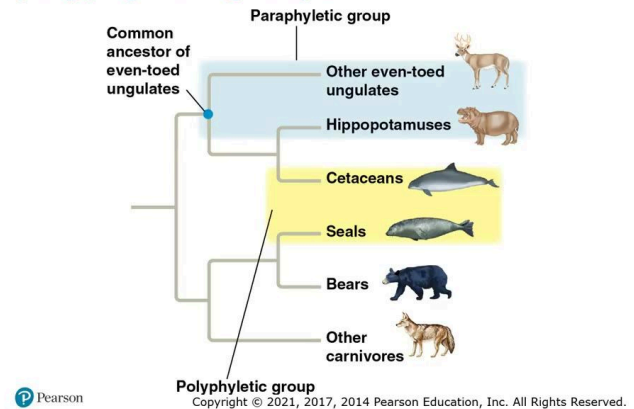
A monophyletic group (clade) holds an ancestor and all its descendants; a paraphyletic group holds an ancestor and only some descendants; a polyphyletic group holds taxa with different ancestors. In a paraphyletic group, unlike a polyphyletic group, the common ancestor of all members is part of the group.

How to draw it: Draw three copies of a tree with tips A through G and shade Group I as a clade (ancestor 1 plus A, B, C), Group II as paraphyletic (ancestor 2 plus D, E, F, leaving out G), and Group III as polyphyletic (A, B, C, D without their shared ancestor 3); label each type.

▶ Play from 2:46

Lecture 26.3, slide 006

Figure 26.11 Paraphyletic versus polyphyletic groups



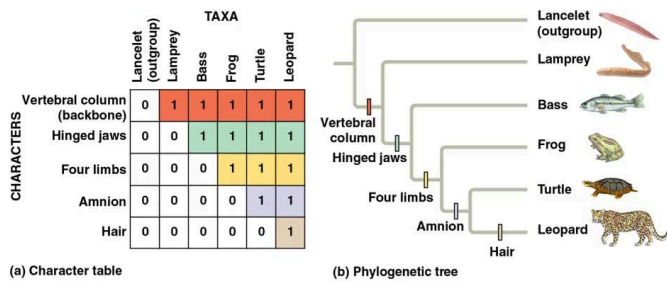
Slide 9. Even-toed ungulates and marine mammals

Grouping other even-toed ungulates with hippopotamuses but leaving out cetaceans makes a paraphyletic group. Grouping cetaceans with seals makes a polyphyletic group, because their similar body forms come from convergent evolution.

▶ Play from 6:06

Lecture 26.3, slide 007

Figure 26.12 Using derived characters to infer phylogeny



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Slide 10. Character table and tree from shared derived characters

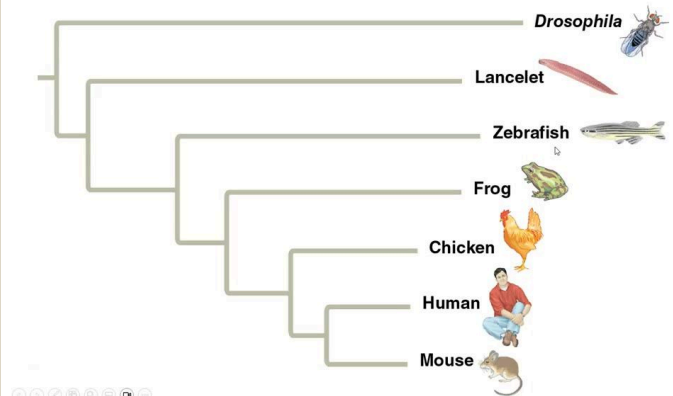
A 0/1 character table uses the lancelet as the outgroup to sort shared ancestral from shared derived characters. Each derived character (vertebral column, hinged jaws, four limbs, amnion, hair) appears once on the tree and marks the clade that has it.

How to draw it: Draw the character table (taxa lancelet, lamprey, bass, frog, turtle, leopard; characters vertebral column, hinged jaws, four limbs, amnion, hair) and the matching tree with a hash mark for each derived character on the branch where it first appears; label the lancelet as the outgroup.

► Play from 12:40

Lecture 26.3, slide 013

Figure 26.13 Branch lengths can represent genetic change



Slide 11. Branch lengths represent genetic change

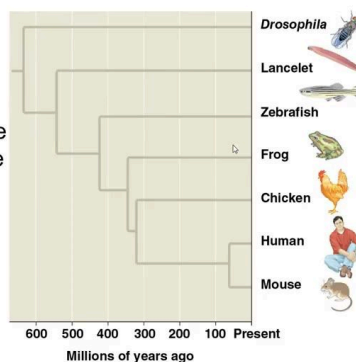
In this tree, branch length shows the amount of genetic change in each lineage. The mouse branch is longer than the human branch, so the mouse lineage has changed more even though both have had the same time since their common ancestor.

► Play from 16:56

Lecture 26.3, slide 018

Phylogenetic Trees with Proportional Branch Lengths

- In some trees, branch length is proportional to time
- Fossil data is used to place branch points in the context of geological time



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Slide 12. Branch lengths proportional to time

Here branch lengths are drawn to a time scale in millions of years ago, so all tips end at the present. Fossil data places the branch points in geological time. ► Play from 16:56

Lecture 26.3, slide 019

Be able to draw / explain

- Figure 26.10 (letters A to G): shading A, B, C with their common ancestor = monophyletic. Shading a group with its ancestor but leaving out one descendant (G) = paraphyletic. Shading A, B, C, D without their common ancestor = polyphyletic.
- Character table to tree: draw a ladder tree with the lancelet on the first branch, then hash marks in order: vertebral column, hinged jaws, four limbs, amnion, hair. Each taxon branches off before the next hash mark it lacks.
- Trees with branch lengths proportional to genetic change, and with branch lengths proportional to time (millions of years ago).

My notes

An organism's evolutionary history is documented in its genome

[Lecture video 26.4 \(opens online\)](#)

Big idea

Molecular comparisons reveal relatedness among groups that are morphologically dissimilar or poorly represented in the fossil record. Different genes evolve at different rates: rRNA genes change slowly (ancient relationships) and mitochondrial DNA changes fast (recent events). Gene duplication creates gene families, and homologous genes are either orthologous (from speciation) or paralogous (from duplication within a species).

Must know

- Molecular data help with groups that are morphologically dissimilar or poorly represented in the fossil record.
- DNA coding for ribosomal RNA (rRNA) changes very slowly: used for ancient relationships.
- Mitochondrial DNA evolves relatively rapidly: used for more recent evolutionary events.
- Gene duplication increases the number of genes and gives more opportunity for evolutionary change. Repeated duplications produce gene families.
- Orthologous genes: homology from a speciation event; found in different species. Used to infer phylogeny because they reflect the history of speciation.
- Paralogous genes: homology from gene duplication; found as copies within one species; can diverge within that species.
- Lineages that diverged long ago still share many orthologous genes. Humans and mice diverged about 65 million years ago, and 99% of their genes are orthologous.

Terms

gene duplication

Copying of a gene that increases the number of genes in a genome.

gene family

A group of related genes within a genome produced by repeated gene duplications.

orthologous genes

Homologous genes in different species whose homology results from speciation.

paralogous genes

Homologous genes within one species whose homology results from gene duplication.

Examples

- Cytochrome c genes (orthologous): same function in humans and dogs, but sequences have diverged since their last common ancestor.
- Human olfactory receptor gene family (paralogous): copies diverged to make proteins that respond to many different molecules.
- Humans and mice: diverged about 65 million years ago; 99% of genes orthologous.

What she stressed in lecture

- Both orthologous and paralogous genes are types of homologous genes.
- 'Orthologous genes are what is ultimately used for inferring phylogeny, because they actually reflect the history of speciation events.'
- Choice of rRNA vs mitochondrial DNA depends on which point in evolutionary time you want to look at.

Memory hooks

ORTHO = *Other species*; **PARA** = *PAIR in one genome*

Ribosomal = *Remote past*;
Mitochondrial = *More recent*

Copy, then change

Orthologous genes come from speciation and are found in different species. Paralogous genes come from duplication and are copies within one species.

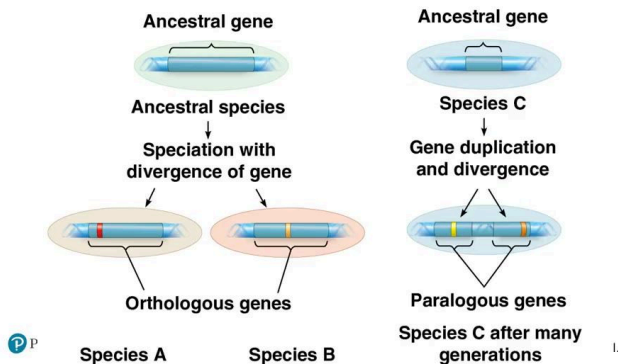
rRNA genes change very slowly, so they show ancient splits. mtDNA changes fast, so it shows recent events.

Gene duplication makes extra copies, which are free to evolve into gene families.

Slides

Figure 26.18 Two types of homologous genes

(a) Formation of orthologous genes: a product of speciation (b) Formation of paralogous genes: within a species



Slide 13. Orthologous vs paralogous genes

Orthologous genes form when speciation splits an ancestral gene between species A and species B. Paralogous genes form when a gene duplicates and the copies diverge within one species; orthologs are the ones used to infer phylogeny.

How to draw it: Draw (a) an ancestral gene in an ancestral species splitting by speciation into species A and species B, labeled orthologous genes; and (b) an ancestral gene in species C duplicating into two diverged copies in the same genome, labeled paralogous genes.

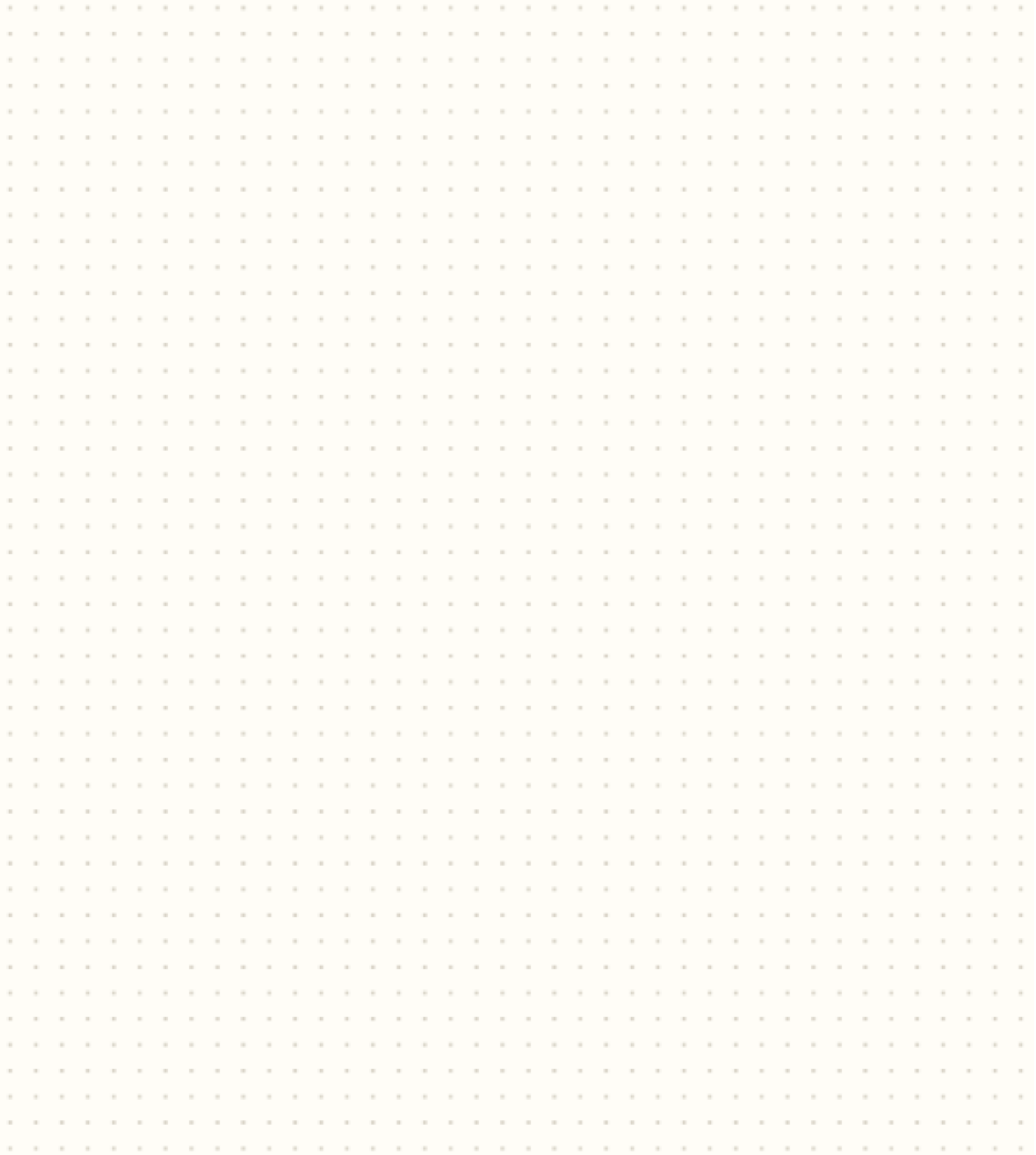
▶ Play from 3:25

Lecture 26.4, slide 008

Be able to draw / explain

- Orthologous genes: ancestral gene, then speciation, then the gene in species A and in species B diverge. Paralogous genes: ancestral gene duplicates within one species, then the two copies diverge.

My notes



Molecular clocks help track evolutionary time

[Lecture video 26.5 \(opens online\)](#)

Big idea

A molecular clock estimates the absolute time of evolutionary change, based on the observation that some genes evolve at a constant rate. It assumes the number of nucleotide substitutions is proportional to time since the split from a common ancestor (orthologs) or since gene duplication (paralogs). Clocks are calibrated against branch-point dates from the fossil record, and they have limits because some genes change in bursts and rates differ among genes and taxa.

Must know

- Molecular clock: approach to estimate the absolute time of evolutionary change, based on genes that appear to evolve at a constant rate.
- Assumption: number of nucleotide substitutions is proportional to the time since the split from a common ancestor (orthologous genes) or since gene duplication (paralogous genes).
- Calibration: graph the number of genetic differences against dates of branch points known from the fossil record; the inferred rate estimates dates not visible in the fossil record.
- Limits: some genes evolve in irregular bursts; rate deviates from the average periodically; the same gene may evolve at different rates in different taxa; some clocklike genes evolve at very different rates from each other.
- Neutral mutations are neither beneficial nor harmful. If most mutations are neutral, molecular change should be regular like a clock.
- If an amino acid sequence is critical to survival, mutations are harmful and change is slow. If it is less critical, more mutations are neutral and change is faster.
- Irregularities come from natural selection favoring some mutations over others.
- Estimates older than the fossil record have a high degree of uncertainty. Using multiple genes may improve estimates.

Terms

molecular clock

A method that uses constant rates of molecular change to estimate the absolute time of evolutionary events.

neutral mutation

A mutation that is neither beneficial nor detrimental.

calibration

Setting the clock rate by graphing genetic differences against fossil-dated branch points.

Examples

- Irregular bursts of change compared to punctuated equilibrium from the first exam.

What she stressed in lecture

- 'Concept 26.5 is a little bit difficult to fathom... make sure you read about this in the textbook.'
- Estimates older than the fossil record 'cannot be relied upon. They have a very high degree of uncertainty.'

Memory hooks

Neutral mutations tick like a clock

If most mutations are neutral, they pile up at a steady rate, and that is the molecular clock.

Vital genes barely tick

Sequences critical to survival change slowly, because most mutations in them are harmful.

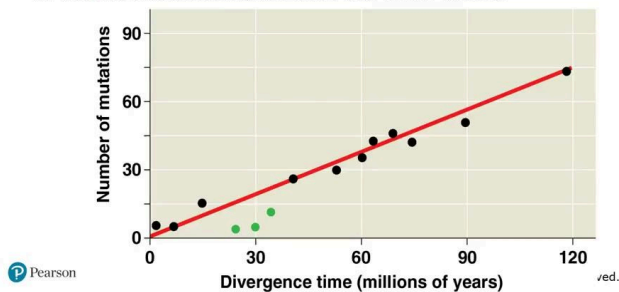
Set the clock with fossils

Calibration: plot genetic differences against fossil-dated branch points, then use that rate to date splits that have no fossils.

Slides

Molecular Clocks

- A molecular clock is calibrated by graphing the number of genetic differences in a gene against dates of branch points known from the fossil record
- The inferred rate of change is used to estimate the dates of events not discernable from the fossil record



Slide 14. Calibrating a molecular clock

The graph plots number of mutations in a gene against divergence time known from fossils; the straight line gives the rate of change. That rate estimates dates of branch points not found in the fossil record.

How to draw it: Draw a graph with number of mutations on the y axis and divergence time (millions of years) on the x axis, points from fossil-dated branch points, and a best-fit straight line; label the line as the molecular clock rate.

► Play from 2:27

Lecture 26.5, slide 004

Be able to draw / explain

- Calibration graph: number of mutations (y axis) vs divergence time in millions of years (x axis); points fall along a straight line.

My notes

Our understanding of the tree of life continues to change based on new data

Lecture video 26.6 (opens online)

Big idea

Classification moved from two kingdoms (plants and animals) to five kingdoms by the 1960s (Monera, Protista, Plantae, Fungi, Animalia) to the current three domains (Bacteria, Archaea, Eukarya). Prokaryotes form two domains because some differ from each other as much as from eukaryotes, and Archaea are more closely related to Eukarya than to Bacteria. Horizontal gene transfer moved genes between genomes and even between domains, so the early tree of life looks more like a tangled web than a clean branching tree.

Must know

- Two kingdoms: plants and animals. Fungi and prokaryotes were placed with plants (fungi are sedentary; prokaryotes have cell walls).
- Five kingdoms (by the 1960s): Monera (prokaryotes), Protista, Plantae, Fungi, Animalia.
- Three domains: Bacteria, Archaea, Eukarya. Domain is a level above kingdom.
- Bacteria: most known prokaryotes. Archaea: diverse prokaryotes in a wide variety of environments. Eukarya: single-celled and multicellular organisms with true nuclei.
- Eukarya includes kingdoms Plantae, Fungi, Animalia. Protista is no longer a kingdom because some protists are more closely related to plants, fungi, or animals than to other protists.
- Domain Archaea is more closely related to domain Eukarya than to domain Bacteria.
- Lokiarchaeota (recently discovered archaea) may be the sister group of eukaryotes.
- Horizontal gene transfer: movement of genes from one genome to another, between species or even between domains. Mechanisms: exchange of transposable elements, plasmids, viral infection, possibly fusion of organisms.
- Disparities between trees built from different genes result from horizontal gene transfer.
- Horizontal gene transfer played a key role in the evolution of both prokaryotes and eukaryotes and was probably common from the very beginning.

Terms

domain

The broadest taxonomic category, above kingdom: Bacteria, Archaea, Eukarya.

Monera

Former kingdom that held all prokaryotes in the five-kingdom system.

horizontal gene transfer

Movement of genes from one genome to another, between species or even domains.

Examples

- The red alga *Galdieria sulphuraria* acquired about 5% of its genes from bacteria and archaea.
- rRNA gene tree: eukaryotes and archaea are more closely related to each other than to bacteria.
- Tangled 'highway' diagram of ancestral cell populations exchanging genes, instead of a clean dichotomous tree.

What she stressed in lecture

- 'There is a concept that I do want you to know called horizontal gene transfer.'
- 'Domain archaea is actually more closely related to domain eukarya than it is to domain bacteria.'
- 'Our classification system is manmade', and it will keep changing as molecular data grow.
- 'Just because two things might look the same... it doesn't mean that they're closely related.'

Memory hooks

2 → 5 → 3

Classification went from 2 kingdoms, to 5 kingdoms (1960s), to 3 domains.

My Pretty Purple Fat Ant

The five kingdoms: Monera, Protista, Plantae, Fungi, Animalia.

B-A-E: Archaea stand next to Eukarya

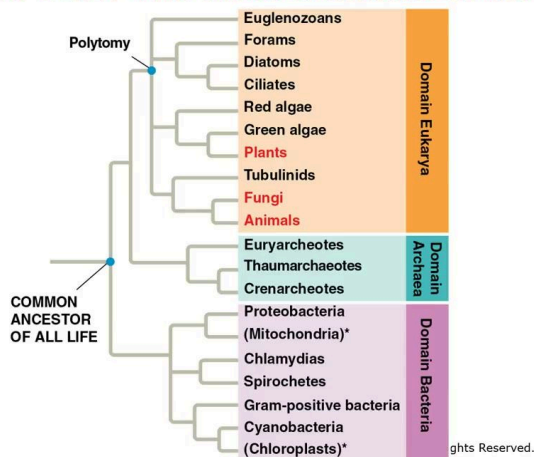
Three domains: Bacteria, Archaea, Eukarya. Archaea are more closely related to Eukarya than to Bacteria.

Horizontal = handed sideways

Horizontal gene transfer passes genes sideways between species (even between domains), not down from parent to offspring.

Slides

Figure 26.21 The three domains of life



Slide 15. The three domains of life

The rRNA-based tree splits life into Bacteria, Archaea and Eukarya, with Archaea and Eukarya more closely related to each other than either is to Bacteria. Mitochondria came from proteobacteria and chloroplasts from cyanobacteria; the polytomy marks unresolved branching.

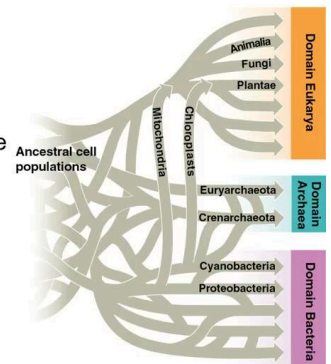
How to draw it: Draw a tree from the common ancestor of all life with three branches labeled Domain Bacteria, Domain Archaea and Domain Eukarya, with Archaea and Eukarya as sister groups; mark plants, fungi and animals inside Eukarya.

▶ Play from 3:25

Lecture 26.6, slide 006

The Important Role of Horizontal Gene Transfer

- Some biologists argue that horizontal gene transfer was commonplace in the early history of life
- They suggest representing the base of the tree of life as a tangled network of connected branches rather than a dichotomously branching tree



Slide 16. Tangled base of the tree of life

Horizontal gene transfer was common early in the history of life, so some biologists draw the base of the tree as a tangled network rather than a dichotomously branching tree. The mitochondria and chloroplasts arrows show genes moving from bacteria into eukaryotes. ▶ Play from 8:01

Lecture 26.6, slide 011

Be able to draw / explain

- Three-domain tree: common ancestor of all life at the root; Bacteria branches off first; Archaea and Eukarya share a more recent common ancestor.
- Web-like tree of life showing horizontal gene transfer among early lineages.

My notes

Structural and functional adaptations contribute to prokaryotic success

[Lecture video 27.1 \(opens online\)](#)

Big idea

Prokaryotes (domains Bacteria and Archaea) were the first organisms on Earth and are the most abundant. They are small, mostly unicellular, and come as cocci, bacilli, and spirals. Surface structures (cell wall, capsule, fimbriae, pili, endospores) and flagella help them survive; they lack membrane-bound organelles and carry one circular chromosome in a nucleoid, plus plasmids. They reproduce by binary fission with short generation times.

Must know

- Size: about 0.5 to 5 micrometers, vs 10 to 100 micrometers for eukaryotic cells.
- Shapes: cocci (spheres), bacilli (rods), spirals (corkscrew or S shape).
- Cell wall maintains shape, protects the cell, and prevents bursting in a hypotonic environment.
- Salt preserves food because water loss (plasmolysis) slows the growth of food-spoiling prokaryotes.
- Eukaryotic walls: cellulose (plants) or chitin (fungi). Bacterial walls contain peptidoglycan: sugars cross-linked by polypeptides.
- Archaeal walls contain polysaccharides and proteins but lack peptidoglycan.
- Gram stain classifies bacteria by cell wall composition. Gram-positive: thick peptidoglycan layer, stains purple. Gram-negative: thin peptidoglycan between membranes plus an outer lipopolysaccharide layer, stains pink/red.
- Gram-negative bacteria are more resistant to antibiotics because the outer membrane blocks drugs from reaching the peptidoglycan.
- Many antibiotics target peptidoglycan. Human cells have no peptidoglycan, so these antibiotics do not harm our cells.
- Capsule: dense, well-defined sticky layer of polysaccharide or protein outside the wall (a slime layer if less organized). Functions: adherence to substrate, prevents dehydration, protects from the host immune system.
- Endospores: metabolically inactive, resistant cells formed when water or nutrients are lacking; the cell copies its chromosome and surrounds it with a multilayer structure. Can stay viable for centuries.
- Fimbriae: short hairlike projections that stick cells to a substrate or to each other ('Velcro').
- Pili (sex pili): longer than fimbriae; connect two cells for DNA exchange.
- Taxis: movement toward or away from a stimulus (chemotaxis = toward/away from chemicals; light can also trigger it). About half of prokaryotes are motile.
- Prokaryotic flagella have the same function as eukaryotic flagella but differ in structure, propulsion mechanism, and molecular composition. Do not memorize the structure.
- No complex compartmentalization (no membrane-bound organelles), but infolded specialized membranes carry out respiration (aerobic prokaryote) or photosynthesis (photosynthetic prokaryote).
- One circular chromosome in the nucleoid (region with no membrane). Eukaryotes have multiple linear chromosomes. Prokaryotes have less DNA and fewer proteins.
- Plasmids: smaller rings of independently replicating DNA; exchanged through pili.
- Differences in ribosomes and in DNA replication, transcription, translation let some antibiotics kill bacteria without harming human cells.
- Binary fission every 1 to 3 hours under optimal conditions; fastest about every 20 minutes.
- Three key features: small size, binary fission, short generation times.

Terms

prokaryote

Single-celled organism without a nucleus or membrane-bound organelles; domains Bacteria and Archaea.

peptidoglycan

Bacterial cell wall material made of sugars cross-linked by polypeptides.

Gram-positive

Bacteria with a thick peptidoglycan wall; stain purple.

capsule

A dense, sticky polysaccharide or protein layer around the cell wall.

fimbriae

Short hairlike projections for attaching to surfaces or other cells.

taxis

Movement toward or away from a stimulus.

plasmid

Small ring of DNA that replicates independently of the chromosome.

cocci / bacilli / spirals

Sphere-shaped / rod-shaped / spiral-shaped prokaryotes.

Gram stain

A stain that classifies bacteria as Gram-positive or Gram-negative by cell wall composition.

Gram-negative

Bacteria with a thin peptidoglycan layer and an outer lipopolysaccharide membrane; stain pink/red; more antibiotic resistant.

endospore

A dormant, resistant cell formed inside a bacterium to survive harsh conditions.

pili (sex pili)

Longer appendages that connect two cells for DNA transfer.

nucleoid

Region of a prokaryotic cell that holds the circular chromosome, with no membrane around it.

binary fission

Asexual division of a prokaryotic cell into two identical cells.

Examples

- 'Curse of the pyramids': people entering Egyptian pyramids got sick and died from bacterial endospores.
- Oreo analogy: Gram-negative wall is like an Oreo (outer lipopolysaccharide membrane and inner membrane with thin peptidoglycan between). Gram-positive is an Oreo with one cookie removed (thick peptidoglycan, no outer membrane).
- Salted food resists spoilage because prokaryotes lose water.

What she stressed in lecture

- 'I want you guys to be aware of a stain called the gram stain.' Know Gram-positive vs Gram-negative and why Gram-negative resists antibiotics.
- 'I don't want you guys to know the structure' of the prokaryotic flagellum, but know it differs from the eukaryotic flagellum.
- Three key features: 'They're small. They reproduce by binary fission, and they have short generation times. And we're going to talk about these key features over and over.'

Memory hooks

Cocci = *Cheerios*, **Bacilli** = *bars*,
Spirals = *springs*

Positive = *Purple*; **Negative** = *pink*

Negative has an extra raincoat

Fimbriae = *Fasteners*; **Pili** = *Pass DNA*

Endospore = *emergency bunker*

Small, Split, Speedy

Prokaryote shapes: spheres, rods, and corkscrews.

Gram-positive cells have a thick peptidoglycan wall and stain purple.
Gram-negative cells have a thin wall plus an outer membrane and stain pink/red.

The outer lipopolysaccharide membrane of Gram-negative bacteria blocks antibiotics, so they are more resistant.

Fimbriae are short Velcro-like hairs. Pili are longer and join two cells to exchange DNA.

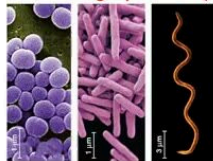
An endospore is a dormant, tough cell that survives drought or starvation for centuries.

Three keys to success: small size, binary fission, short generation times.

Slides

CONCEPT 27.1: Structural and functional adaptations contribute to prokaryotic success

- Prokaryotes were the first organisms to inhabit Earth
- Most are unicellular, but some species form colonies
- Most prokaryotic cells are $0.5\text{--}5\text{ }\mu\text{m}$, much smaller than the $10\text{--}100\text{ }\mu\text{m}$ of many eukaryotic cells
- They have a variety of shapes including spheres (cocci), rods (bacilli), and spirals



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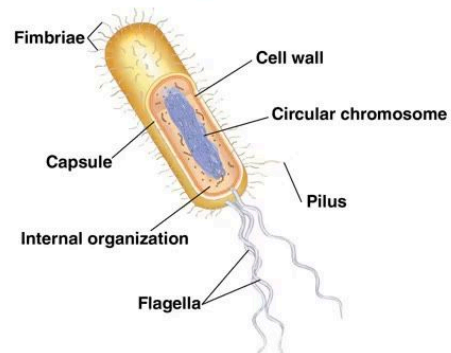
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Slide 17. Prokaryote shapes: cocci, bacilli, spirals

Prokaryotes come in three common shapes: spheres (cocci), rods (bacilli) and spirals. Most prokaryotic cells are 0.5 to 5 micrometers, much smaller than the 10 to 100 micrometers of many eukaryotic cells. [▶ Play from 0:19](#)

Lecture 27.1, slide 002

Figure 27.UN04 Summary of key concepts: prokaryote adaptations



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Slide 18. Prokaryote adaptations summary

A labeled bacterium shows the structures behind prokaryotic success: fimbriae, capsule, cell wall, circular chromosome, pilus, internal organization and flagella. Know the function of each part.

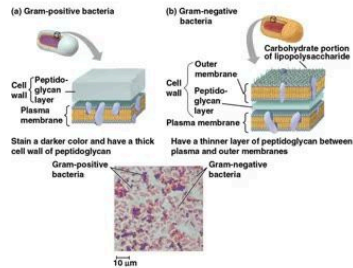
How to draw it: Draw a rod-shaped bacterium and label the capsule, cell wall, circular chromosome, internal organization, fimbriae, pilus and flagella.

[▶ Play from 1:55](#)

Lecture 27.1, slide 003

Cell-Surface Structures

- Scientists use the **Gram stain** to classify bacteria by cell wall composition
- Gram-positive** bacteria have simpler walls with a **large amount of peptidoglycan**
- The walls of **Gram-negative** bacteria have **less peptidoglycan** and are more complex with an outer membrane that contains **lipopolysaccharides**



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Slide 19. Gram-positive vs gram-negative cell walls

Gram-positive walls have a thick peptidoglycan layer and stain darker. Gram-negative walls have a thin peptidoglycan layer between the plasma membrane and an outer membrane with lipopolysaccharides, and they resist antibiotics more.

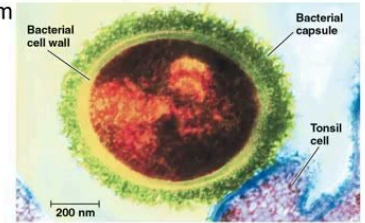
How to draw it: Draw both walls in cross section. Gram-positive: plasma membrane under a thick peptidoglycan layer. Gram-negative: plasma membrane, thin peptidoglycan layer, then outer membrane with lipopolysaccharide; label each layer.

► Play from 5:12

Lecture 27.1, slide 006

Cell-Surface Structures

- Many prokaryotes have a sticky layer of polysaccharide or protein surrounding the cell wall
- It is called a **capsule** if it is dense and well-defined, or a **slime layer** if it is not well organized
- Both types enable adherence to the substrate or other individuals, prevent dehydration, and protect the cell from the host's immune system



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Slide 20. Bacterial capsule

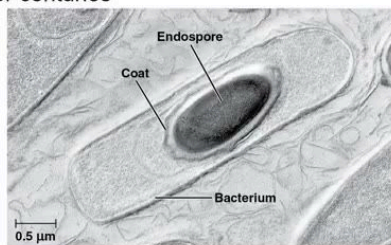
A dense, well-defined sticky layer of polysaccharide or protein outside the cell wall is a capsule (a loose one is a slime layer). It lets the cell stick to surfaces such as this tonsil cell, prevents dehydration and protects against the host immune system.

► Play from 8:25

Lecture 27.1, slide 008

Cell-Surface Structures

- Some bacteria form metabolically inactive **endospores** when water or nutrients are lacking
- The cell copies its chromosome and surrounds it with a multilayered structure
- Endospores can withstand extreme conditions and remain viable for centuries



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Slide 21. Endospore

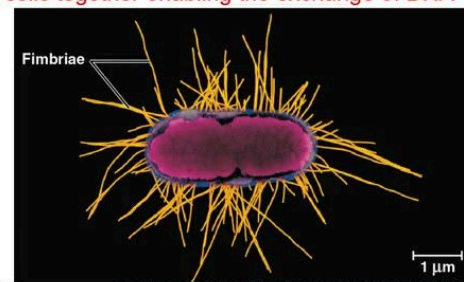
When water or nutrients run out, some bacteria copy the chromosome and wrap it in a multilayered coat to form a metabolically inactive endospore. Endospores withstand extreme conditions and stay viable for centuries.

► Play from 9:51

Lecture 27.1, slide 009

Cell-Surface Structures

- Some prokaryotes have hairlike appendages called **fimbriae** that allow them to **stick to their substrate or other individuals in a colony**
- Pili** (or sex *pili*) are longer than fimbriae and **function to pull cells together enabling the exchange of DNA**



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Slide 22. Fimbriae

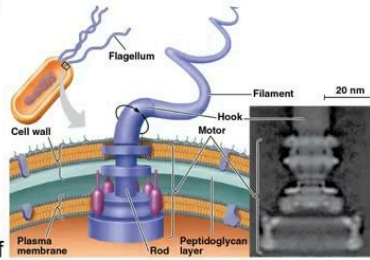
Fimbriae are short hairlike appendages that let prokaryotes stick to a substrate or to each other in a colony. Pili (sex pili) are longer and pull cells together to exchange DNA.

► Play from 11:33

Lecture 27.1, slide 010

Motility

- **Flagella** are the most common structures used by prokaryotes for movement
- They may be scattered over the entire surface or concentrated at the ends of the cell
- Flagella of prokaryotes and eukaryotes differ in structure, mechanism of propulsion, and molecular composition



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Slide 23. Prokaryotic flagellum

The bacterial flagellum has a filament, a hook and a motor anchored in the cell wall and plasma membrane by a rod. Prokaryotic and eukaryotic flagella differ in structure, mechanism of propulsion and molecular composition.

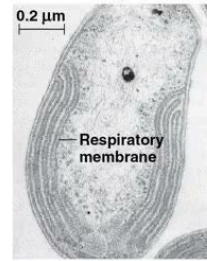
How to draw it: Draw the flagellum crossing the cell wall, peptidoglycan layer and plasma membrane; label the filament, hook, motor and rod.

▶ Play from 13:08

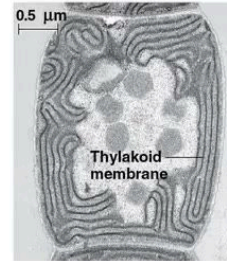
Lecture 27.1, slide 012

Internal Organization and DNA

- **Prokaryotic cells lack complex compartmentalization**
- Some prokaryotes have specialized membranes that perform metabolic functions
- These are usually infoldings of the cell membrane



(a) Aerobic prokaryote



(b) Photosynthetic prokaryote

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Slide 24. Specialized internal membranes

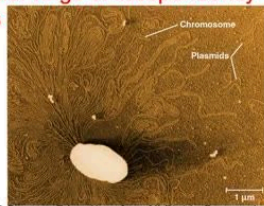
Prokaryotes lack complex compartments, but some have infoldings of the cell membrane that do metabolic work. An aerobic prokaryote has respiratory membranes and a photosynthetic prokaryote has thylakoid membranes.

▶ Play from 14:09

Lecture 27.1, slide 013

Internal Organization and DNA

- Prokaryotes have less DNA and produce fewer proteins than the eukaryotes
- **Prokaryotes have one circular chromosome; eukaryotes have multiple linear chromosomes**
- **Prokaryotes lack a nucleus; the chromosome is in the nucleoid, a region with no membrane**
- Prokaryotes may also have **smaller rings of independently replicating DNA called plasmids**



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Slide 25. Chromosome and plasmids

A burst cell spills one long circular chromosome and several small rings of independently replicating DNA called plasmids. The chromosome sits in the nucleoid, a region with no membrane.

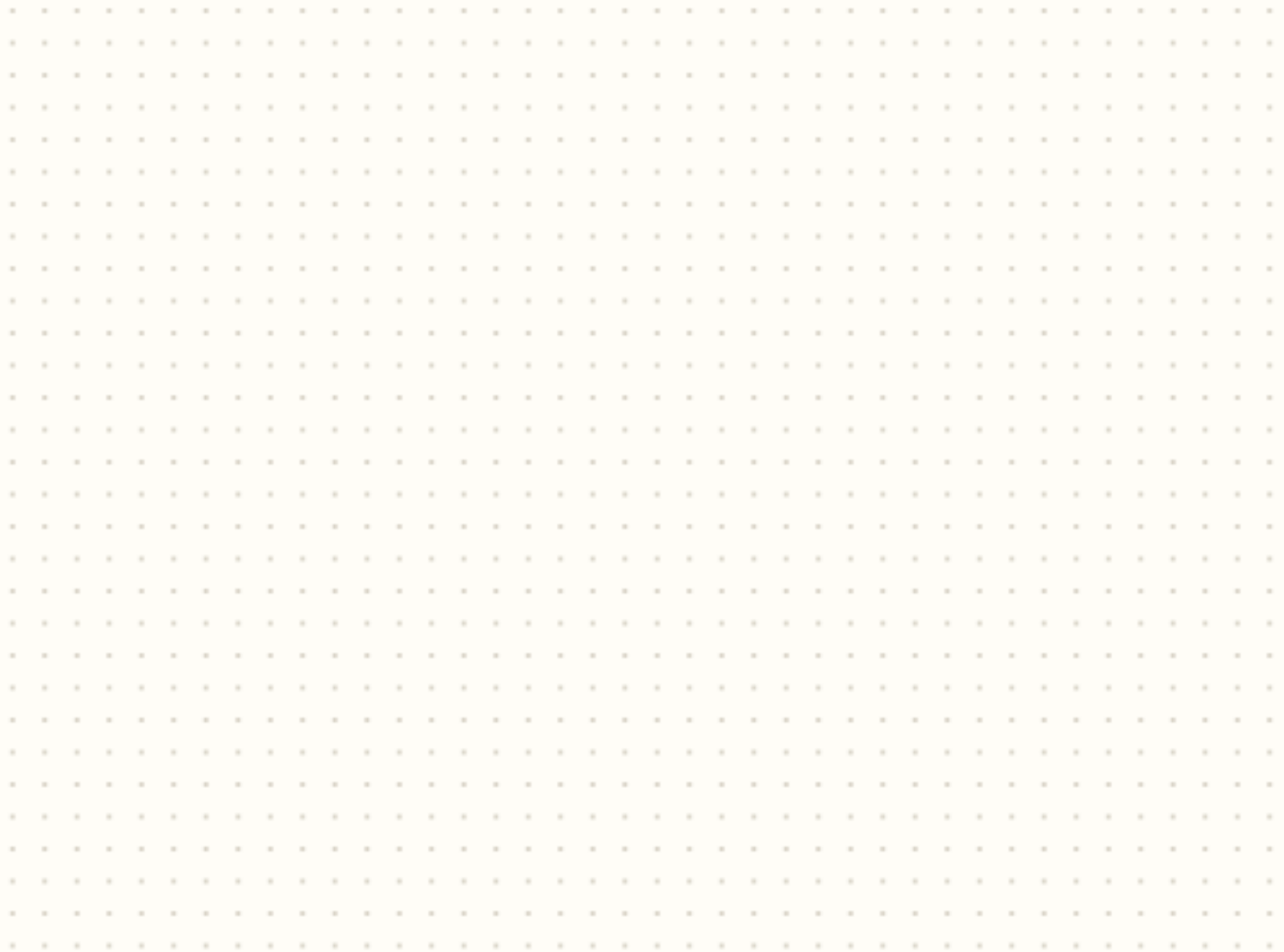
▶ Play from 15:41

Lecture 27.1, slide 014

Be able to draw / explain

- Posted concept figure: 'What characteristics enable prokaryotes to reach huge population sizes and thrive in diverse environments?' Four panels: small size and rapid reproduction (J-shaped population growth curve), mutations (colonies with altered chromosomes), diverse adaptations (hot spring), rapid evolution/endospore (a protective coat around the endospore, 'resistant cell that can enable bacterium to survive harsh conditions'). Center: rod-shaped bacterium with fimbriae and flagella.
- Draw a prokaryote: label cell wall, plasma membrane, capsule, fimbriae, pili, flagella, nucleoid with circular chromosome, ribosomes, plasmid.
- Draw Gram walls: Gram-positive = plasma membrane plus thick peptidoglycan. Gram-negative = plasma membrane, thin peptidoglycan, outer membrane with lipopolysaccharide. Color: purple (positive), pink/red (negative).
- Internal membranes: respiratory membranes in an aerobic prokaryote; photosynthetic membranes in a photosynthetic prokaryote.

My notes



Rapid reproduction, mutation, and genetic recombination promote genetic diversity in prokaryotes

[Lecture video 27.2 \(opens online\)](#)

Big idea

Three factors produce the high genetic diversity of prokaryotes: rapid reproduction, mutation, and genetic recombination. Binary fission makes identical cells, but mutations accumulate quickly because generations are short and populations are huge. Recombination combines DNA from two sources by transformation (DNA from the surroundings), transduction (phages carry genes), and conjugation (one-way DNA transfer between cells through a pilus).

Must know

- Three factors for genetic diversity: rapid reproduction, mutation, genetic recombination.
- Binary fission cells are generally identical; differences arise by mutation.
- Mutation rates are low, but mutations accumulate rapidly because of short generation times and very large populations.
- Genetic recombination: combining DNA from two sources, by transformation, transduction, or conjugation.
- Movement of genes between individual prokaryotes of different species = horizontal gene transfer.
- Transformation: a cell takes up foreign DNA from its surroundings. A nonpathogenic cell can take up an allele for pathogenicity and become pathogenic.
- Transduction: bacteriophages (viruses that infect bacteria) carry prokaryotic genes from one host to another; usually an unintended result of the phage replicative cycle.
- Conjugation: DNA transfer between two prokaryotic cells joined by a pilus; transfer is always one direction (donor to recipient). Plasmids can be transferred.
- R plasmids carry antibiotic resistance genes; the instructor will not test on R plasmids.

Terms

genetic recombination

Combining DNA from two sources.

transformation

Uptake of foreign DNA from the surroundings.

transduction

Transfer of prokaryotic genes between cells by bacteriophages.

bacteriophage (phage)

A virus that infects bacteria.

conjugation

One-way transfer of DNA between two prokaryotic cells that are temporarily joined.

Examples

- Transformation: nonpathogenic cell takes up a pathogenicity allele and becomes a pathogenic recombinant cell.

What she stressed in lecture

- 'Three factors that I want you guys to know': rapid reproduction, mutation, genetic recombination.
- Conjugation: 'the DNA transfer is always in one direction... I want you guys to be aware of that.'
- 'I'm not going to ask you about R plasmids and antibiotic resistance on the test.'

Memory hooks

Take, Taxi, Touch

Transformation: take up DNA from the surroundings. Transduction: a phage carries DNA like a taxi. Conjugation: cells touch through a pilus.

Reproduce, Mutate, Recombine

The three sources of genetic diversity in prokaryotes.

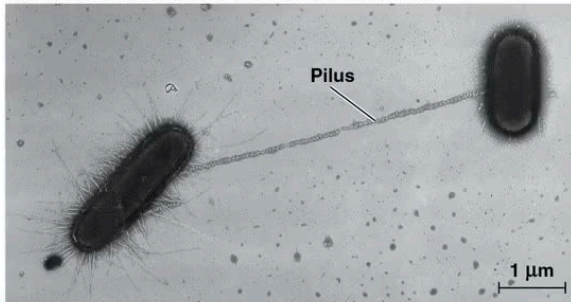
ConJUGation is a one-way pour

In conjugation, DNA flows one way only, from donor to recipient.

Slides

Conjugation and Plasmids

- **Conjugation** is the process through which DNA is transferred between two prokaryotic cells
- In bacteria, the DNA transfer is always one way: One cell donates the DNA and the other receives it



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Slide 26. Conjugation through a pilus

In conjugation, a pilus pulls two cells together and DNA passes one way from the donor cell to the recipient. R plasmids move this way and spread antibiotic resistance genes. ▶ **Play from 4:33**

Lecture 27.2, slide 007

Be able to draw / explain

- Conjugation: two cells connected by a pilus; plasmid DNA moves from donor to recipient.

My notes

Diverse nutritional and metabolic adaptations have evolved in prokaryotes

[Lecture video 27.3 \(opens online\)](#)

Big idea

Prokaryotes are classified by energy source (phototrophs use light, chemotrophs use chemicals) and carbon source (autotrophs use CO₂, heterotrophs need organic nutrients), giving four nutritional modes. They differ in oxygen use (obligate aerobes, obligate anaerobes, facultative anaerobes). Some fix atmospheric nitrogen into ammonia, as in the heterocysts of *Anabaena*, and many cooperate in biofilms.

Must know

- Energy source: phototrophs (light) vs chemotrophs (chemicals).
- Carbon source: autotrophs (CO₂ or related compounds) vs heterotrophs (organic nutrients).
- Four modes: photoautotroph (light, CO₂), chemoautotroph (inorganic chemicals, CO₂), photoheterotroph (light, organic compounds), chemoheterotroph (organic compounds for both energy and carbon).
- Obligate aerobes: require oxygen for cellular respiration.
- Obligate anaerobes: cannot use oxygen; oxygen is poisonous to them; use anaerobic respiration (less efficient).
- Facultative anaerobes: use oxygen if present; if not, carry out fermentation or anaerobic respiration.
- Nitrogen is needed for amino acids and nucleic acids in all organisms.
- Nitrogen fixation: conversion of atmospheric N₂ to ammonia (NH₃). Humans cannot use atmospheric nitrogen and must get it from diet.
- *Anabaena* (cyanobacterium): photosynthetic vegetative cells plus occasional heterocysts that fix nitrogen and share it with the other cells.
- Biofilm: one or more prokaryotic species cooperate to form a surface-coating colony; edge cells release signaling molecules to recruit cells; channels bring nutrients in and wastes out.
- Biofilm problems: corrosion of industrial structures and products, contamination of medical devices, tooth decay, chronic antibiotic-resistant infections.

Terms

phototroph

Organism that obtains energy from light.

chemotroph

Organism that obtains energy from chemicals.

autotroph

Organism that uses CO₂ or related compounds as its carbon source.

heterotroph

Organism that needs an organic nutrient as its carbon source.

photoautotroph

Uses light for energy and CO₂ for carbon.

chemoautotroph

Uses inorganic chemicals for energy and CO₂ for carbon.

photoheterotroph

Uses light for energy and organic compounds for carbon.

chemoheterotroph

Uses organic compounds for both energy and carbon.

obligate aerobe

Requires oxygen for cellular respiration.

obligate anaerobe

Cannot use oxygen and is poisoned by it.

facultative anaerobe

Uses oxygen when present, switches to fermentation or anaerobic respiration when it is absent.

nitrogen fixation

Conversion of atmospheric nitrogen (N_2) to ammonia (NH_3).

heterocyst

Specialized cyanobacterial cell that fixes nitrogen.

biofilm

A surface-coating colony formed by cooperating prokaryotes.

Examples

- Anabaena: green vegetative (photosynthetic) cells and heterocysts that fix nitrogen.
- Tooth decay from biofilm on teeth.

What she stressed in lecture

- Nutrition table: 'Make sure you spend some time with this table and that you understand completely what these terms mean... make sure you know this particular table.'
- 'I do want you guys to know about biofilms.'
- Photo/chemo refers to energy; auto/hetero refers to carbon.

Memory hooks

Energy first, carbon second

Read the name in order: photo/chemo is the energy source (light or chemicals), auto/hetero is the carbon source (CO_2 or organic).

'Auto makes its own; hetero eats others'

Autotrophs build from CO_2 ; heterotrophs take organic carbon.

*Obligate = Obligated, no choice;
Facultative = Flexible*

Obligate aerobes need O_2 ; obligate anaerobes are poisoned by it; facultative anaerobes use O_2 if it is there and ferment if not.

Heterocyst = helper cell

Anabaena heterocysts fix nitrogen and share it with the photosynthetic cells.

Table 27.1 Major Nutritional Modes

Mode	Energy Source	Carbon Source	Types of Organisms
AUTOTROPH			
Photoautotroph	Light	CO ₂ , HCO ₃ ⁻ , or related compound	Photosynthetic prokaryotes (for example, cyanobacteria); plants; certain protists (for example, algae)
Chemoautotroph	Inorganic chemicals (such as H ₂ S, NH ₃ , or Fe ²⁺)	CO ₂ , HCO ₃ ⁻ , or related compound	Unique to certain prokaryotes (for example, <i>Sulfolobus</i>)
HETEROTROPH			
Photoheterotroph	Light	Organic compounds	Unique to certain aquatic and salt-loving prokaryotes (for example, <i>Rhodospirillum rubrum</i> , <i>Chloroflexus</i>)
Chemoheterotroph	Organic compounds	Organic compounds	Many prokaryotes (for example, <i>Clostridium</i>) and protists; fungi; animals; some plants

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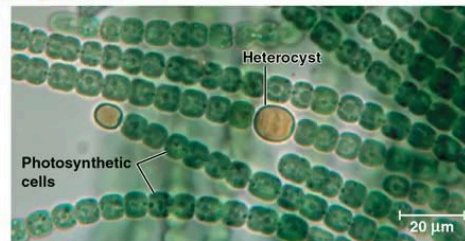
Slide 27. Table 27.1 Major nutritional modes

Energy source (light or chemicals) plus carbon source (CO₂ or organic compounds) gives four modes: photoautotroph, chemoautotroph, photoheterotroph and chemoheterotroph. Chemoautotrophs (for example *Sulfolobus*) and photoheterotrophs are found only in certain prokaryotes; animals are chemoheterotrophs. ▶ Play from 2:03

Lecture 27.3, slide 004

Nitrogen Metabolism

- Nitrogen is essential for the production of amino acids and nucleic acids in all organisms
- Prokaryotes metabolize nitrogen in many forms
 - For example, some prokaryotes convert atmospheric nitrogen (N₂) to ammonia (NH₃) in a process called **nitrogen fixation**



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Slide 28. Nitrogen fixation in *Anabaena* heterocysts

In the cyanobacterium *Anabaena*, most cells in the filament photosynthesize while heterocysts carry out nitrogen fixation, converting N₂ to NH₃. The heterocyst shares fixed nitrogen with the other cells, an example of metabolic cooperation.

▶ Play from 4:40

Lecture 27.3, slide 006

Metabolic Cooperation

- Biofilms are common in nature, but can cause many problems for humans including
 - Corrosion of industrial structures and products
 - Contamination of medical devices
 - Tooth decay
 - Chronic, antibiotic-resistant infections



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Slide 29. Biofilm

A biofilm is a surface-coating colony of cooperating prokaryotes, with channels that bring in nutrients and remove wastes. Biofilms cause corrosion, contaminate medical devices, cause tooth decay and cause chronic antibiotic-resistant infections. ▶ Play from 7:36

Lecture 27.3, slide 008

Be able to draw / explain

- Table of nutritional modes: rows photoautotroph, chemoautotroph, photoheterotroph, chemoheterotroph; columns energy source, carbon source, types of organisms.
- Anabaena* filament: chain of vegetative cells with a larger heterocyst.

My notes



Prokaryotes have radiated into a diverse set of lineages

[Lecture video 27.4 \(opens online\)](#)

Big idea

Prokaryotes date to about 3.5 billion years ago and inhabit every environment that supports life. Genetic analysis in the 1970s split them into Bacteria and Archaea. Bacteria include Proteobacteria, Chlamydias, Spirochetes, Cyanobacteria (all Gram-negative) and Gram-positive bacteria. Archaea share traits with both bacteria and eukaryotes and include extremophiles (extreme halophiles, extreme thermophiles) and methanogens, organized into Euryarchaeota, the TACK supergroup, and Lokiarchaeotes.

Must know

- Prokaryotes date back about 3.5 billion years; first organisms on Earth.
- Genetic analysis in the 1970s divided prokaryotes into Bacteria and Archaea.
- About 16,000 prokaryotic species named; 700,000 to 1.4 million bacterial species estimated. A handful of soil may hold about 10,000 species. Metagenomics samples all genomes in an environment.
- Every major mode of nutrition and metabolism is found among bacteria.
- Proteobacteria: Gram-negative; include photoautotrophs, chemoautotrophs, heterotrophs. Pathogens: *Neisseria gonorrhoeae* (gonorrhea), *Vibrio cholerae* (cholera), *Helicobacter pylori* (stomach ulcers).
- Chlamydias: all parasitize animal cells; Gram-negative but walls lack peptidoglycan. *Chlamydia trachomatis* causes nongonococcal urethritis, one of the most common STDs in the US.
- Spirochetes: helical, Gram-negative heterotrophs; move by rotating internal filaments; many free-living, some pathogens. *Treponema* (syphilis), *Borrelia* (Lyme disease, carried by ticks). Know genus only.
- Cyanobacteria: Gram-negative photoautotrophs; solitary or filamentous; freshwater and marine.
- Gram-positive bacteria: very diverse. Actinomycetes form colonies; include pathogens and soil decomposers. *Streptomyces* are cultured as a source of antibiotics. Pathogens: *Staphylococcus aureus*, *Bacillus anthracis* (anthrax), *Clostridium botulinum* (botulism, paralysis, source of Botox).
- Only the Gram-positive group is Gram-positive; the other four bacterial groups covered are Gram-negative.
- Archaea share some traits with bacteria, some with eukaryotes, and have unique traits.
- Three-domain comparison: nuclear envelope and membrane-enclosed organelles only in Eukarya; peptidoglycan only in Bacteria; branched hydrocarbons in membrane lipids only in Archaea; one kind of RNA polymerase in Bacteria vs several kinds in Archaea and Eukarya; initiator amino acid formyl-methionine in Bacteria vs methionine in Archaea and Eukarya.
- Extreme halophiles: tolerate or require very salty environments.
- Extreme thermophiles: tolerate very high temperatures (even over 100 degrees C), such as hot springs.
- Methanogens: obligate anaerobes that produce methane as a by-product; found under ice in Greenland, in swamps and marshes, and in guts of cattle, termites, and other herbivores.
- Euryarchaeota: extreme halophiles, most methanogens, some extreme thermophiles.
- TACK supergroup: Thaumarchaeota, Aigarchaeota, Crenarchaeota, Korarchaeota. Crenarchaeota includes the rest of the extreme thermophiles.
- Lokiarchaeotes: closely related to TACK archaea; may be the sister group of eukaryotes.

Terms

metagenomics

Studying all the prokaryotic genomes in an environmental sample to identify which species are present.

Chlamydias

Gram-negative animal-cell parasites whose walls lack peptidoglycan.

Cyanobacteria

Gram-negative photoautotrophic bacteria.

extremophiles

Archaea that live in extreme environments uninhabitable for most organisms.

extreme thermophiles

Archaea adapted to very high temperatures.

TACK supergroup

Group of closely related archaeal clades: Thaumarchaeota, Aigarchaeota, Crenarchaeota, Korarchaeota.

Proteobacteria

Large Gram-negative bacterial clade with photoautotrophs, chemoautotrophs, and heterotrophs.

Spirochetes

Helical Gram-negative heterotrophs that move by rotating internal filaments.

Actinomycetes

Colony-forming Gram-positive bacteria that include pathogens and soil decomposers.

extreme halophiles

Archaea that tolerate or require very salty environments.

methanogens

Obligately anaerobic archaea that produce methane.

Examples

- Sulfur bacterium *Thiomargarita namibiensis* (Proteobacteria): autotroph that gets energy by oxidizing hydrogen sulfide and produces sulfur as waste.
- *Neisseria gonorrhoeae*, *Vibrio cholerae*, *Helicobacter pylori*: pathogenic Proteobacteria.
- *Chlamydia trachomatis*: nongonococcal urethritis.
- *Treponema* (syphilis) and *Borrelia* (Lyme disease): spirochetes.
- *Streptomyces*: soil actinomycete, fungus-like appearance ('myces' means fungus-like), source of antibiotics; the instructor named tetracycline.
- *Staphylococcus aureus*, *Bacillus anthracis* (anthrax), *Clostridium botulinum* (botulism, Botox, lockjaw-type paralysis): Gram-positive pathogens.
- Hot spring with steam: extreme thermophile habitat.
- Swamp smell comes from methanogen methane.

What she stressed in lecture

- Proteobacteria pathogens: 'Make sure you know these different species. You might see these again on the exam.'
- Spirochetes: 'I just want you to know the genus... Don't worry about the specific epithet.'
- Three-domain chart: 'focus on what is different, not what's the same... you might see this on the exam.'
- TACK: 'I want you to learn it just like this.' Euryarchaeota: 'that's all I want you to know about this particular clade.'

Memory hooks

Only the positives are positive

Of the five bacterial groups, only Gram-positive bacteria are Gram-positive. Proteobacteria, chlamydias, spirochetes, and cyanobacteria are Gram-negative.

*Halo = salt, Thermo = heat,
Methano = methane*

Extreme halophiles love salt, extreme thermophiles love heat (over 100 °C), and methanogens make methane (cattle guts, swamps).

TACK it down

TACK supergroup: Thaumarchaeota, Aigarchaeota, Crenarchaeota, Korarchaeota.

Spirochetes spiral

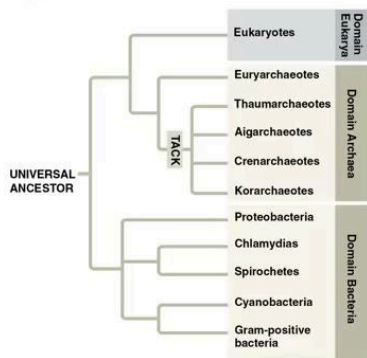
Spirochetes are helical: Treponema causes syphilis, Borrelia causes Lyme disease.

*Streptomyces = stream of
antibiotics*

Streptomyces (actinomycetes) are cultured to make antibiotics.

Slides

Figure 27.16 A simplified phylogeny of prokaryotes



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Slide 30. Simplified phylogeny of prokaryotes

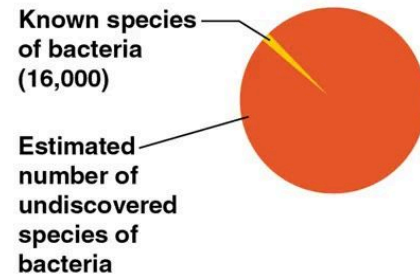
From the universal ancestor, Domain Bacteria splits from the line leading to Archaea and Eukarya. Archaea includes the Euryarchaeotes and the TACK supergroup (Thaumarchaeotes, Aigarchaeotes, Crenarchaeotes, Korarchaeotes).

▶ Play from 3:08

Lecture 27.4, slide 004

Figure 27.17 Exploring bacterial diversity

- There are about **16,000 known species of bacteria**
- The actual number is estimated to be **700,000–1.4 million species**



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Slide 31. Known vs undiscovered bacterial species

About 16,000 bacterial species are named, a thin slice of the estimated 700,000 to 1.4 million species. Metagenomics now reveals much of this unseen diversity.

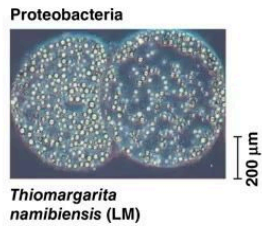
▶ Play from 6:03

Lecture 27.4, slide 008

Figure 27.17 Exploring bacterial diversity

Proteobacteria Gram-negative bacteria including photoautotrophs, chemoautotrophs, and heterotrophs

- For example, the sulfur bacterium *Thiomargarita namibiensis*, is an autotroph that obtains energy by oxidizing H_2S and producing sulfur as a waste product



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Slide 32. Proteobacteria: *Thiomargarita namibiensis*

Proteobacteria are gram-negative and include photoautotrophs, chemoautotrophs and heterotrophs. *Thiomargarita namibiensis* is a sulfur bacterium that gets energy by oxidizing H_2S and releases sulfur as waste.

▶ Play from 6:39

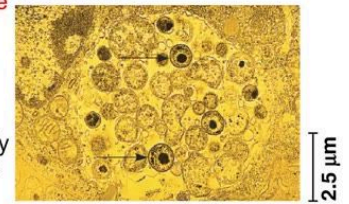
Lecture 27.4, slide 011

Figure 27.17 Exploring bacterial diversity

Chlamydias

- All species parasitize animal cells and have gram-negative walls lacking peptidoglycan
 - For example, *Chlamydia trachomatis* causes nongonococcal urethritis, the most common sexually transmitted disease in the United States

Chlamydias



Chlamydia
(inside an animal cell; TEM)

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Slide 33. Chlamydias: *Chlamydia* inside an animal cell

All chlamydias parasitize animal cells and have gram-negative walls lacking peptidoglycan. *Chlamydia trachomatis* causes nongonococcal urethritis, the most common sexually transmitted disease in the United States.

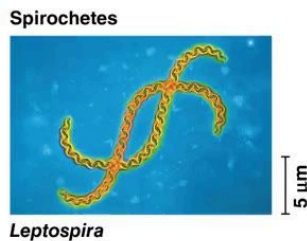
▶ Play from 8:23

Lecture 27.4, slide 013

Figure 27.17 Exploring bacterial diversity

Spirochetes

- These bacteria are **helical gram-negative heterotrophs** that spiral through the environment by rotating internal filaments
- Many are free-living, but others are pathogens
 - For example, *Treponema pallidum*, causes syphilis, and *Borrelia burgdorferi*, causes Lyme disease



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Slide 34. Spirochetes: *Leptospira*

Spirochetes are helical gram-negative heterotrophs that spiral by rotating internal filaments. Pathogens include *Treponema pallidum* (syphilis) and *Borrelia burgdorferi* (Lyme disease).

▶ Play from 9:03

Lecture 27.4, slide 014

Figure 27.17 Exploring bacterial diversity

Cyanobacteria

- These bacteria are **gram-negative photoautotrophs**
- Solitary and filamentous cyanobacteria are abundant components of freshwater and marine phytoplankton

Cyanobacteria



Cylindrospermum

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Slide 35. Cyanobacteria: *Cylindrospermum*

Cyanobacteria are gram-negative photoautotrophs that make up much of freshwater and marine phytoplankton, as solitary cells or filaments. Chloroplasts descend from cyanobacteria.

▶ Play from 10:19

Lecture 27.4, slide 015

Figure 27.17 Exploring bacterial diversity

Gram-Positive Bacteria

- Gram-positive bacteria are a diverse group
 - Actinomycetes** are colony-forming bacteria including pathogens and soil decomposers
 - Soil-dwelling species of ***Streptomyces*** are cultured as a source of antibiotics, including tetracycline
 - Other subgroups include pathogens such as ***Staphylococcus aureus***; ***Bacillus anthracis***, the cause of anthrax; and ***Clostridium botulinum***, the cause of botulism



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Slide 36. Gram-positive bacteria: ***Streptomyces***

Gram-positive bacteria include colony-forming actinomycetes; soil-dwelling ***Streptomyces*** is the source of antibiotics such as tetracycline. Gram-positive pathogens include ***Staphylococcus aureus***, ***Bacillus anthracis*** (anthrax) and ***Clostridium botulinum*** (botulism).

▶ Play from 11:01

Lecture 27.4, slide 016

Table 27.2 A Comparison of the three domains of life

CHARACTERISTIC	DOMAIN		
	Bacteria	Archaea	Eukarya
Nuclear envelope	Absent	Absent	Present
Membrane-enclosed organelles	Absent	Absent	Present
Peptidoglycan in cell wall	Present	Absent	Absent
Membrane lipids	Unbranched hydrocarbons	Some branched hydrocarbons	Unbranched hydrocarbons
RNA polymerase	One kind	Several kinds	Several kinds
Initiator amino acid for protein synthesis	Formyl-methionine	Methionine	Methionine

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Slide 37. Table 27.2 Comparison of the three domains

Bacteria and Archaea both lack a nuclear envelope and membrane-enclosed organelles; only Bacteria have peptidoglycan. Archaea match Eukarya in having several kinds of RNA polymerase and methionine as the initiator amino acid, while Bacteria use formyl-methionine.

▶ Play from 13:44

Lecture 27.4, slide 019

Archaea

- Extremophiles** are archaea that live in extreme environments, uninhabitable for most organisms
 - Extreme halophiles** either tolerate or require highly saline environments
 - Extreme thermophiles** have adaptations that make their DNA and proteins stable at high temperatures (even above 100°C)



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Slide 38. Extreme thermophiles: hot spring

Extremophile archaea live where most organisms cannot: extreme halophiles need very salty water, and extreme thermophiles like those in this hot spring have DNA and proteins stable above 100 degrees C. Most extreme thermophiles belong to the Crenarchaeota in the TACK supergroup.

▶ Play from 16:33

Lecture 27.4, slide 024

Be able to draw / explain

- Simplified prokaryote phylogeny: universal ancestor at the root; Bacteria on its own branch; Archaea and Eukarya branch from a more recent ancestor. Bacterial clades shown: Proteobacteria, Chlamydias, Spirochetes, Cyanobacteria, Gram-positive bacteria. Archaeal groups: Euryarchaeota, TACK, Lokiarchaeotes.
- Pie/bar comparison: about 16,000 known bacterial species vs 700,000 to 1.4 million estimated.
- Table comparing Bacteria, Archaea, Eukarya (see compare table).

My notes



Prokaryotes play crucial roles in the biosphere

[Lecture video 27.5 \(opens online\)](#)

Big idea

Without prokaryotes, the prospects for other life on Earth would be dim. They recycle chemical elements between living and nonliving parts of the environment, act as decomposers, fix CO₂ and nitrogen into forms other organisms use, and can also immobilize nutrients. They form symbioses (mutualism, commensalism, parasitism) with larger hosts, and some ecosystems such as hydrothermal vents depend on them.

Must know

- Prokaryotes recycle chemical elements between living and nonliving components.
- Chemoheterotrophic prokaryotes act as decomposers, breaking down dead organisms and wastes and releasing carbon and other elements to the soil.
- Autotrophic prokaryotes use CO₂ to make sugars and release oxygen used by other organisms.
- Nitrogen-fixing bacteria make atmospheric nitrogen available to other organisms.
- Prokaryotes can increase soil nutrients for plants, or immobilize (decrease) nutrients by using them in their own cells.
- Symbiosis: two species live in close contact; usually a larger host and a smaller symbiont.
- Mutualism: both benefit. Commensalism: one benefits, the other is neither helped nor harmed. Parasitism: parasite harms but usually does not kill its host.
- Pathogens: parasites that cause disease.
- Hydrothermal vents: deep-ocean ecosystems that depend on chemoautotrophic bacteria using vent gases; these bacteria form symbioses with vent animals.

Terms

decomposer

Organism that breaks down dead organisms and wastes and returns elements to the environment.

symbiosis

An ecological relationship in which two species live in close contact.

host

The larger organism in a symbiosis.

symbiont

The smaller organism in a symbiosis.

mutualism

Symbiosis in which both organisms benefit.

commensalism

Symbiosis in which one organism benefits and the other is neither helped nor harmed.

parasitism

Symbiosis in which the parasite harms, but usually does not kill, the host.

pathogen

A parasite that causes disease.

Examples

- Hydrothermal vents: chemoautotrophic bacteria use gases from Earth's interior and support vent animals.

What she stressed in lecture

- 'If prokaryotes were to disappear, the prospects for any other life surviving on Earth would be dim.'
- 'The existence of some ecosystems actually depend upon prokaryotes. I want you guys to be aware of this': hydrothermal vents.

Memory hooks

+/+ mutual, +/- comfortable, +/- pest

Mutualism: both benefit. Commensalism: one benefits, the other is unaffected. Parasitism: one benefits, the host is harmed.

Dead to dirt

Chemoheterotrophic decomposers break down dead matter and return its elements to the soil.

Vents run on chemistry, not sunlight

Hydrothermal vent ecosystems depend on chemoautotrophic bacteria that use vent gases.

My notes

Prokaryotes have both beneficial and harmful impacts on humans

[Lecture video 27.6 \(opens online\)](#)

Big idea

The best-known prokaryotes are pathogens, but they are a small fraction of all prokaryotes. Mutualistic gut bacteria make nutrients, and prokaryotes are used in food production, DNA technology, plastics, biofuels, and bioremediation. All known pathogenic prokaryotes are bacteria; they cause disease through exotoxins or endotoxins, and antibiotic resistance has evolved rapidly since antibiotics were introduced in the 1940s.

Must know

- Human intestines hold about 500 to 1,000 species of bacteria; intestinal bacterial cells outnumber human cells by a factor of ten.
- Mutualistic gut bacteria make carbohydrates, vitamins, and other nutrients and signal human genes for absorption and antimicrobial production.
- All known pathogenic prokaryotes are bacteria. Bacteria cause about half of all human diseases.
- Tuberculosis: lung disease caused by *Mycobacterium tuberculosis*; about 1.5 million deaths per year worldwide.
- Lyme disease: *Borrelia*, transmitted by ticks; bullseye rash; arthritis, heart disease, nervous disorders, death; about 300,000 US infections per year; treated with about a 30-day antibiotic course.
- Exotoxins: proteins secreted by bacteria; cause disease even if the bacteria are no longer present. Example: cholera from *Vibrio cholerae*.
- Endotoxins: lipopolysaccharide components of the outer membrane of Gram-negative bacteria; released only when bacteria die and their walls break down. Example: *Salmonella* food poisoning.
- Horizontal gene transfer spreads virulence genes: pathogenic strains of *E. coli* came from phage-mediated gene transfer.
- Antibiotics introduced in the 1940s; for every antibiotic in use, at least one bacterial species has evolved resistance. Rapid reproduction spreads resistance quickly, and horizontal gene transfer spreads it between species.
- 2018: virus-like particles developed that target and kill specific multidrug-resistant bacteria.
- Foods: cheese and yogurt from milk, beer, wine, pepperoni, fermented cabbage (sauerkraut), soy sauce.
- DNA technology: *E. coli* in gene cloning; DNA polymerase from *Pyrococcus furiosus* used in PCR (heat tolerant); CRISPR-Cas9 (a prokaryotic defense against viruses) used for gene editing, including HIV research.
- Bacteria make natural biodegradable plastics from an energy-storage polymer, and ethanol biofuel from agricultural waste, switchgrass, or corn.
- Bioremediation: using organisms to remove pollutants from soil, air, or water, such as bacteria that break down spilled oil.

Terms

exotoxin

A protein secreted by bacteria that causes disease even after the bacteria are gone.

endotoxin

Lipopolysaccharide from the outer membrane of Gram-negative bacteria, released when the bacteria die.

antibiotic resistance

Evolved ability of bacteria to survive an antibiotic.

CRISPR-Cas9

A prokaryotic defense system against viruses, now used as a gene-editing tool.

bioremediation

Use of organisms to remove pollutants from soil, air, or water.

Examples

- Mycobacterium tuberculosis: tuberculosis, about 1.5 million deaths per year.
- Borrelia via ticks: Lyme disease, about 300,000 US cases per year, bullseye rash.
- Vibrio cholerae: cholera by exotoxin.
- Salmonella: food poisoning by endotoxin; can be on fruits and vegetables; warning about food from dented cans.
- E. coli: pathogenic strains from phage-mediated gene transfer; used in gene cloning.
- Pyrococcus furiosus: heat-stable DNA polymerase for PCR.
- Gut bacterium Bacteroides thetaiotaomicron makes nutrients (instructor: you do not need to know this name).
- Oil spill cleanup by oil-metabolizing bacteria.

What she stressed in lecture

- Tuberculosis: 'a good example that's here that I do want you guys to know about.'
- Exotoxins and endotoxins: 'I do want you to know what those are.' Cholera: 'I do want you to know that, so you can get cholera even if the bacterium isn't there any longer.'
- 'I do want you to know a little bit about antibiotic resistance, because this is important in today's world.'

Memory hooks

EXO = EXported; **ENDO = END** of the cell

Exotoxins are secreted proteins that work even after the bacteria are gone (cholera). Endotoxins are outer-membrane lipopolysaccharides released only when Gram-negative cells die (Salmonella).

Pyrococcus: **pyro** = fire-proof

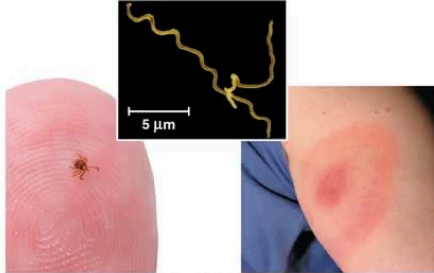
Pyrococcus furiosus DNA polymerase is heat tolerant, so it is used in PCR.

Every drug gets a dodger

For every antibiotic in use, at least one bacterial species has evolved resistance.

Pathogenic Bacteria

- Some bacterial diseases are transmitted by other species
 - For example, **Lyme disease**, which can cause arthritis, heart disease, nervous disorders, and death, infects about 300,000 people per year in the United States
 - It is caused by a bacterium that is **carried by ticks**



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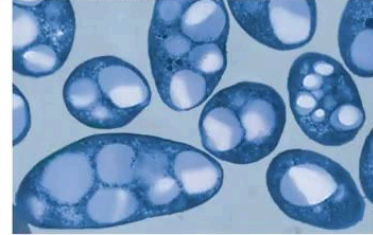
Slide 39. Lyme disease: tick, spirochete and rash

Lyme disease is caused by the spirochete *Borrelia burgdorferi*, carried to humans by ticks, and often shows a red rash at the bite. It can cause arthritis, heart disease, nervous disorders and death. ▶ **Play from 2:42**

Lecture 27.6, slide 006

Prokaryotes in Research and Technology

- Bacteria can be used to produce natural plastics
 - For example, some bacteria synthesize PHA, a polymer used to store chemical energy
 - PHA can be extracted, formed into pellets, and used to make durable, biodegradable plastics



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Slide 40. Bacteria making PHA plastic

Some bacteria store chemical energy as the polymer PHA, seen as the pale granules inside these cells. PHA is extracted, formed into pellets and made into durable, biodegradable plastics. ▶ **Play from 11:05**

Lecture 27.6, slide 015

Prokaryotes in Research and Technology

- Prokaryotes can also be used in **bioremediation**, the use of organisms to remove pollutants from soil, air, or water
 - For example, bacteria that metabolize oil can be used to increase the breakdown of oil following a spill



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Slide 41. Bioremediation of an oil spill

Bioremediation uses organisms to remove pollutants from soil, air or water. After an oil spill, oil-metabolizing bacteria speed the breakdown of the oil. ▶ **Play from 11:55**

Lecture 27.6, slide 017

Be able to draw / explain

- Lyme disease: tiny tick on a fingertip; bullseye rash spreading from the bite.

My notes



Phylogenetics videos: taxonomy, homology vs analogy, and the anole lizards

Big idea

Crash Course 'Taxonomy' covers Linnaeus and the hierarchy, using the cat (*Felis catus*) as a walk-through. A short video shows that homologous structures come from common ancestry while analogous structures come from convergent evolution. The anole lizard video (Jonathan Losos with Sean Carroll) shows adaptation, rapid evolution, reproductive isolation, and DNA-based tree building that revealed the same body types evolved independently on each Caribbean island.

Must know

- Carl Linnaeus: Swede born 1707; professor at Uppsala University; classified by morphology; catalogued about 7,700 plants and 4,400 animals in *Systema Naturae*; motto 'God created, Linnaeus organized.'
- Before Linnaeus, a tomato plant's name was a long phrase (*Solanum caule inerme herbaceo...*).
- Linnaeus picked homologous traits (such as plant reproductive structures and milk production in mammals) even though he did not know about evolution.
- About 2 million known species; estimates range from 5 million to 100 million.
- Archaea are more closely related to eukaryotes; they have different cell membranes, and their RNA polymerase is more like ours.
- Cat classification: Animalia, Chordata, Mammalia, Carnivora, Felidae, *Felis*, *Felis catus*.
- Phylogenetic tree reading (video): humans are more closely related to mice than to fish, and more closely related to fish than to fruit flies.
- Anoles in Puerto Rico partition habitat: grass-bush anole (slender, long tail), trunk-ground anole (long legs, stocky, sprinter), twig anole (short legs, grips thin branches), canopy anole (large, big toe pads).
- Long legs = speed on broad surfaces; short legs = stability on twigs. Large toe pads with tiny hairs hold canopy lizards on slick leaves.
- Experiment: tree-dwelling anoles placed on seven hurricane-cleared islands with only small bushes; average leg length shortened within two generations, and kept shortening over four years. Evolution can be rapid when selection is strong.
- Dewlap: throat flap males display to attract females; each species in an area has a different dewlap. A dewlap color change can cause reproductive isolation and speciation.
- DNA showed lizards on each island (Puerto Rico, Jamaica, Cuba, Hispaniola) are more closely related to each other than to look-alikes on other islands, so the same body types evolved independently on each island (convergent evolution).
- Tree building from DNA: species with fewest sequence differences are joined at a node (common ancestor), then joined to the next most closely related.

Terms

taxonomy

The science of classifying living things.

dewlap

A flap of throat skin that male anoles display to attract females.

reproductive isolation

Something that prevents members of one population from breeding with a closely related population.

Examples

- *Felis catus* walk-through of the hierarchy.
- Anole lizards: grass-bush, trunk-ground, twig, canopy body types on four large Caribbean islands.
- Serengeti grazers (zebras tall grass, wildebeest medium, Thomson's gazelles shortest) and Galapagos finches: many habitats support many species.

What she stressed in lecture

- The instructor posted these videos 'to help with your understanding of phylogenetics.'

Memory hooks

Dear King Philip... meets the cat Animalia, Chordata, Mammalia, Carnivora, Felidae, *Felis*, *Felis catus*.

Long legs for lanes, short legs for sticks Long-legged anoles sprint on broad trunks; short-legged anoles grip thin twigs; big toe pads hold canopy anoles on leaves.

Same island, same family Anoles on each island are each other's closest relatives; similar body types on different islands are convergent (analogy).

My notes

Most eukaryotes are single-celled organisms

[Lecture video 28.1 \(opens online\)](#)

Big idea

"Protist" is an informal term for all eukaryotes that are not plants, animals or fungi. Kingdom Protista no longer exists because some protists are more closely related to plants, fungi or animals than to other protists. Protists are the most structurally, functionally and nutritionally diverse eukaryotes. All eukaryotes, protists included, are sorted into four supergroups: Excavata, SAR, Archaeplastida and Unikonta (Figure 28.5).

Must know

- Protist = informal term: any eukaryote that is not a plant, animal or fungus. Kingdom Protista was abandoned.
- Protists show more structural and functional diversity than any other eukaryotes.
- Most are unicellular; some are colonial; some are multicellular.
- Unicellular protists are the most complex of all cells: one cell must carry out every function of life.
- Most nutritionally diverse eukaryotes: photoautotrophs (have chloroplasts), heterotrophs (absorb organic molecules or ingest food), and MIXOTROPHS (combine photosynthesis and heterotrophic nutrition).
- Reproduction: some only asexual; some asexual and sexual. All three basic sexual life cycles occur in protists (life cycles are not the focus of this chapter, except *Plasmodium*).
- FOUR SUPERGROUPS of eukaryotes: Excavata, SAR, Archaeplastida, Unikonta. "Make sure you know these."
- Figure 28.5 is needed for BOTH lecture and lab. Yellow = clades; gray = major groups (also clades).
- SAR is an acronym for its three major groups: Stramenopiles, Alveolates, Rhizarians.
- Archaeplastida: red algae, green algae (major group: chlorophytes + charophytes) and plants.
- Unikonta major groups: Amoebozoans (amoeba-like) and Opisthokonts (animals, fungi and their protist relatives).
- Examples by supergroup: *Giardia* (Excavata); diatoms and *Globigerina*, a foram with thread-like pseudopodia through a porous test (SAR); *Volvox* (Archaeplastida, multicellular/colonial green alga, seen in lab); *Amoeba proteus*, a tubulinid (Unikonta).
- *Amoeba* movement: pseudopodia (extensions of cytoplasm) move it and engulf food by phagocytosis. Clear leading edge = ectoplasm (rich in actin); the rest = endoplasm, which flows forward into the extending pseudopod.
- The root of the eukaryotic tree is not known. Some newly found groups (haptophytes, cryptophytes) are not yet placed in a supergroup; expect changes.

Terms

protist

Informal name for any eukaryote that is not a plant, animal or fungus.

mixotroph

An organism that combines photosynthesis with heterotrophic nutrition.

supergroup

One of the four largest groupings of eukaryotes: Excavata, SAR, Archaeplastida, Unikonta.

major group

A large clade inside a supergroup (gray in Fig. 28.5), e.g. stramenopiles, green algae, amoebozoans.

pseudopodium (pl. pseudopodia)

Extension of the cell surface used to move and to engulf food.

phagocytosis

Engulfing food particles by surrounding them with the cell membrane.

ectoplasm / endoplasm

Clear, actin-rich outer cytoplasm at the amoeba's leading edge / the inner, granular cytoplasm that flows forward.

Examples

- Giardia intestinalis: never drink untreated stream water; boil it first.
- Volvox: called multicellular or colonial green alga; both terms show up.

What she stressed in lecture

- "There are four super groups of eukaryotes... Make sure you know these."
- "Figure 28.5 is a figure that you're going to need for both lecture and lab."
- Learn the yellow groups as clades and the gray groups as major groups.

Memory hooks

Every Smart Ant Understands

The four supergroups: Excavata, SAR, Archaeplastida, Unikonta.

SAR spells its members

SAR = Stramenopiles, Alveolates, Rhizarians.

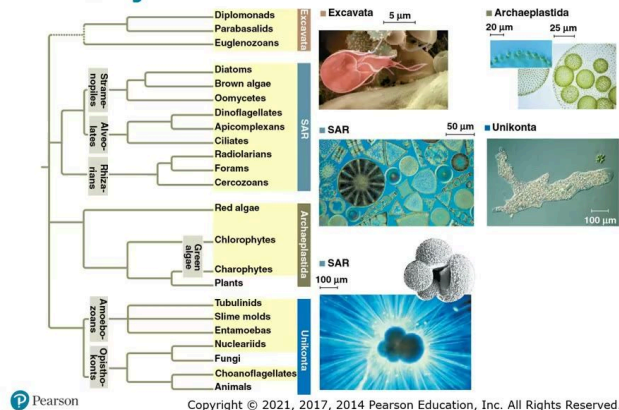
Mixotroph = mix of both

Mixotrophs combine photosynthesis with heterotrophic nutrition.

Ecto = exterior edge, Endo = inside flow

In Amoeba, the clear leading edge is ectoplasm and the flowing interior is endoplasm.

Figure 28.5 Exploring protistan diversity



Slide 42. Figure 28.5 Exploring protistan diversity (full tree)

The four supergroups from the common ancestor of eukaryotes: Excavata, SAR, Archaeplastida, Unikonta, with every clade and major group. Needed for lecture AND lab.

How to draw it: Draw a root with four branches; list the clades under each supergroup from memory.

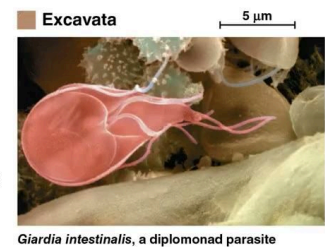
► Play from 4:22

Lecture 28.1, slide 007

Figure 28.5 Exploring protistan diversity

Excavata

- This supergroup includes three clades:
 - Parabasalids
 - Diplomonads
 - Euglenozoans
- For example, *Giardia intestinalis* is a diplomonad parasite that causes intestinal infections in mammals



Slide 43. Excavata: *Giardia intestinalis*

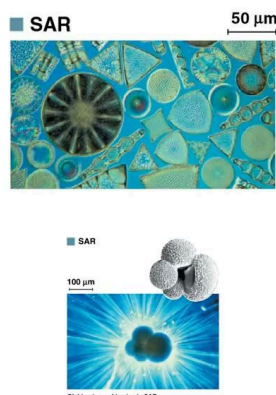
Excavata has three clades (parabasalids, diplomonads, euglenozoans). *Giardia* is a diplomonad parasite causing intestinal infection in mammals. ► Play from 7:31

Lecture 28.1, slide 008

Figure 28.5 Exploring protistan diversity

SAR

- This supergroup includes three large clades (major groups):
 - Stramenopila
 - Alveolata
 - Rhizaria
- For example, diatoms are important photosynthetic stramenopiles
- For example, many rhizarians are amoebas with threadlike pseudopodia, such as *Globigerina*



Slide 44. SAR: diatoms and the foram *Globigerina*

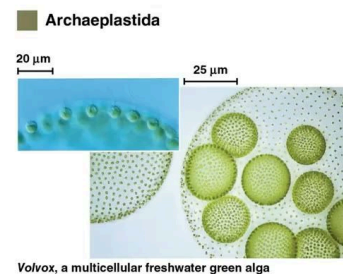
SAR has three major groups: stramenopiles, alveolates, rhizarians. Diatoms are important photosynthetic stramenopiles; *Globigerina* is a rhizarian with thread-like pseudopodia. ► Play from 8:35

Lecture 28.1, slide 009

Figure 28.5 Exploring protistan diversity

Archaeplastida

- red algae
- green algae
- plants



- Red and green algae include unicellular, colonial, and multicellular species
 - For example, *Volvox* is a multicellular green algae

Slide 45. Archaeplastida: *Volvox*

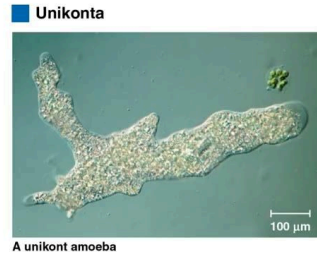
Red algae, green algae, plants. Red and green algae include unicellular, colonial and multicellular species; *Volvox* is a multicellular freshwater green alga. ► Play from 9:41

Lecture 28.1, slide 010

Figure 28.5 Exploring protistan diversity

Unikonta

- amoebas with lobe- or tube-shaped pseudopodia
- Animals
- Fungi
- non-amoeba protists closely related to animals or fungi
 - For example, *Amoeba proteus* is a tubulinid amoeba



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Slide 46. Unikonta: *Amoeba proteus*

Amoebas with lobe- or tube-shaped pseudopodia, animals, fungi and protists close to them. *Amoeba proteus* is a tubulinid.

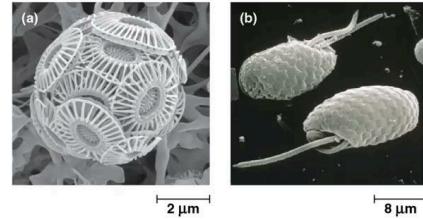
How to draw it: *Amoeba* outline with blunt lobe-shaped pseudopodia; label pseudopodium, ectoplasm, endoplasm.

▶ Play from 10:33

Lecture 28.1, slide 013

Four Supergroups of Eukaryotes

- The root of the eukaryotic tree is not known
- Some major new groups of protists have been recently discovered, but their relationship to the supergroups is unresolved
 - For example, haptophytes, cryptophytes, and hemimastigophores are unresolved groups



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Slide 47. Unresolved groups

The root of the eukaryotic tree is not known; haptophytes, cryptophytes and hemimastigophores are not yet placed in a supergroup. ▶ Play from 12:28

Lecture 28.1, slide 020

Be able to draw / explain

- Figure 28.5: four supergroups branching from the common ancestor of eukaryotes. Be able to place each clade and major group under its supergroup.

My notes

Excavates include protists with modified mitochondria and protists with unique flagella

[Lecture video 28.2 \(opens online\)](#)

Big idea

Excavata is defined by its cytoskeleton; some members have an excavated feeding groove on one side of the body. It has three monophyletic groups (clades): diplomonads, parabasalids and euglenozoans. Diplomonads and parabasalids lack plastids, have reduced mitochondria and mostly live in anaerobic environments. Euglenozoans have a spiral or crystalline rod inside each flagellum and split into kinetoplastids and euglenids.

Must know

- Excavata: characterized by its CYTOSKELETON; some have an excavated FEEDING GROOVE (a trench along one side of the body); not all members have it.
- Three clades "I do want you to know": DIPLOMONADS, PARABASALIDS, EUGLENOZOANS.
- Diplomonads and parabasalids: no plastids, reduced mitochondria, mostly anaerobic environments (no oxygen).
- Diplomonads: reduced mitochondria called MITOSOMES that lack electron transport chains, so energy comes from anaerobic pathways. Two equal-sized nuclei and multiple flagella. Many are parasites: *Giardia intestinalis* (intestinal infections in mammals).
- Parabasalids: reduced mitochondria called HYDROGENOSOMES that make some energy anaerobically and release HYDROGEN GAS as a by-product.
- *Trichomonas vaginalis*: parabasalid, sexually transmitted parasite with an UNDULATING MEMBRANE; travels the reproductive and urinary tracts and feeds on the vaginal lining; about 140 million people per year (lecture figure).
- Euglenozoans: very diverse (predatory heterotrophs, photosynthetic autotrophs, mixotrophs, parasites). Distinguishing feature: a SPIRAL or CRYSTALLINE ROD inside each flagellum.
- Euglenozoa is a MAJOR GROUP with two clades: KINETOPLASTIDS and EUGLENIDS.
- Kinetoplastids: a single mitochondrion with an organized mass of DNA called a KINETOPLAST. Free-living ones eat prokaryotes in freshwater, marine and moist land habitats; some are parasites.
- *Trypanosoma* (kinetoplastid, seen in lab): causes SLEEPING SICKNESS; Chagas disease (also *Trypanosoma*) can lead to congestive heart failure and is on the rise. Sleeping sickness infects about 10,000 people a year.
- Euglenids: 1 or 2 flagella emerge from a POCKET at one end of the cell; some are mixotrophs that switch between autotrophic and heterotrophic modes. *Euglena*: flexible PELLICLE and a red EYESPOT (light detector).

Terms

Excavata

Supergroup defined by its cytoskeleton; some have a feeding groove.

hydrogenosome

Reduced mitochondrion of parabasalids; makes some ATP anaerobically, releasing H₂.

mitosome

Reduced mitochondrion of diplomonads; lacks an electron transport chain.

undulating membrane

Wavy membrane along the side of *Trichomonas* (and *Trypanosoma*) used in movement.

kinetoplast

Organized mass of DNA in the single large mitochondrion of a kinetoplastid.

pellicle

Flexible protein layer under the membrane of Euglena that lets it change shape.

eyespot

Red light-detecting spot near the flagellum base of Euglena.

Examples

- Diplomonad: Giardia intestinalis
- Parabasalid: Trichomonas vaginalis
- Kinetoplastid: Trypanosoma
- Euglenid: Euglena

What she stressed in lecture

- "I do want you to know these three clades."
- "The term Euglenozoa is always a major group" with two clades, kinetoplastids and euglenids.
- Mitosome vs hydrogenosome: which clade has which, and what each lacks or releases.

Memory hooks

Dirty Parasites Everywhere

The three Excavata clades: Diplomonads, Parabasalids, Euglenozoans.

Diplo = double

Diplomonads have two equal-sized nuclei (Giardia).

Mitosome = missing ETC;

Hydrogenosome = makes hydrogen

Diplomonad mitosomes lack electron transport chains. Parabasalid hydrogenosomes release hydrogen gas.

Kinetoplast = kinetoplastid DNA ball

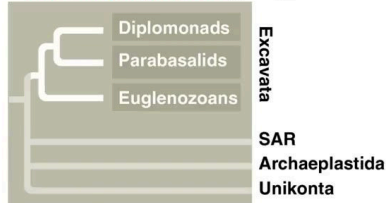
Kinetoplastids have one mitochondrion with an organized mass of DNA (Trypanosoma, sleeping sickness).

Eye-glena

Euglena has a red eyespot that detects light, plus a flexible pellicle.

CONCEPT 28.2: Excavates include protists with modified mitochondria and protists with unique flagella

- **Excavata** is characterized by its **cytoskeleton**
- Some members have an “excavated” feeding groove on one side of the body
- The excavates include **three monophyletic** groups:
 - Diplomonads
 - Parabasalids
 - Euglenozoans



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Slide 48. Excavata: three monophyletic groups

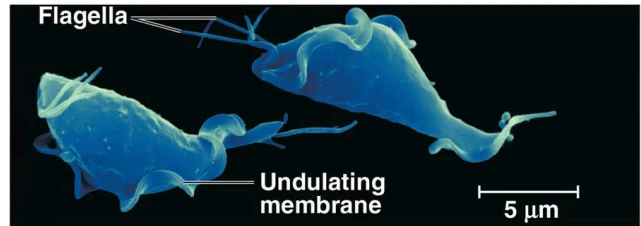
Diplomonads, parabasalids and euglenozoans. Excavata is defined by its cytoskeleton; some have an excavated feeding

groove. ▶ Play from 0:09

Lecture 28.2, slide 002

Diplomonads and Parabasalids

- The best known parabasalid is *Trichomonas vaginalis*, a **sexually transmitted parasite**
- It travels along the human reproductive and urinary tracts and feeds on the vaginal lining in females
- *T. vaginalis* infects about 140 million people per year worldwide



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Slide 49. *Trichomonas vaginalis* (parabasalid)

Sexually transmitted parasite; flagella and the undulating membrane; about 140 million infections a year.

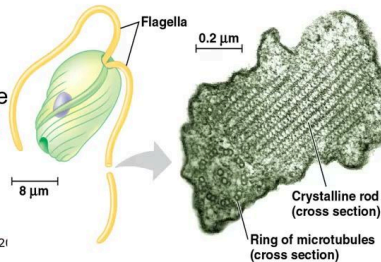
How to draw it: Teardrop cell, flagella at the front, a wavy undulating membrane down one side.

▶ Play from 3:30

Lecture 28.2, slide 006

Euglenozoans

- **Euglenozoa** is a diverse clade including
 - predatory heterotrophs
 - photosynthetic autotrophs
 - mixotrophs
 - parasites
- This clade includes the **kinetoplastids and euglenids**
- The main feature distinguishing the clade is the **spiral or crystalline rod inside each flagella**



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Slide 50. Euglenozoans: crystalline rod in the flagellum

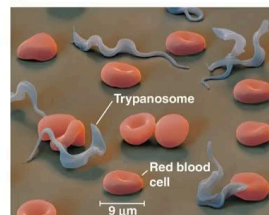
Diverse clade (predatory heterotrophs, autotrophs, mixotrophs, parasites) with kinetoplastids and euglenids; defined by a spiral or crystalline rod inside each flagellum (ring of

microtubules around it). ▶ Play from 4:33

Lecture 28.2, slide 007

Kinetoplastids

- Some species parasitize animals, plants, and other protists
 - For example, members of the genus *Trypanosoma* infect humans, causing **sleeping sickness** in about 10,000 people per year
 - Trypanosomes also cause Chagas' disease which can lead to congestive heart failure



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Slide 51. *Trypanosoma* among red blood cells

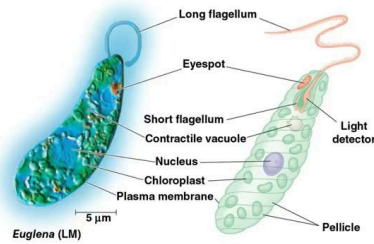
Kinetoplastid parasite: sleeping sickness (about 10,000 people a year) and Chagas disease (can cause congestive heart

failure). ▶ Play from 6:30

Lecture 28.2, slide 009

Euglenids

- **Euglenids** have one or two flagella that emerge from a pocket at one end of the cell
- Some species are **mixotrophs** that **switch between autotrophic and heterotrophic modes**, depending on the environmental conditions



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Slide 52. *Euglena*, labeled

Euglenid: long and short flagella from a pocket at one end, eyespot and light detector, contractile vacuole, nucleus, chloroplasts, pellicle. Some are mixotrophs.

How to draw it: Spindle-shaped cell; long flagellum from the front pocket; red eyespot; chloroplast ovals; label pellicle.

► Play from 7:37

Lecture 28.2, slide 010

Be able to draw / explain

- Excavata branch of Fig. 28.5: diplomonads, parabasalids, euglenozoans (kinetoplastids + euglenids).
- *Euglena*: long flagellum, short flagellum, eyespot, pellicle, chloroplasts.

My notes

The "SAR" clade is a highly diverse group of protists defined by DNA similarities

[Lecture video 28.3 \(opens online\)](#)

Big idea

SAR is grouped by DNA similarity and has three major groups. Stramenopiles (hairy + smooth flagellum) include diatoms, brown algae and oomycetes. Alveolates (alveoli, sacs under the plasma membrane) include dinoflagellates, apicomplexans and ciliates. Rhizarians are mostly amoebas with thread-like pseudopodia: radiolarians, forams and cercozoans. The *Plasmodium* (malaria) life cycle is the one life cycle to know.

Must know

- SAR: grouped by DNA similarities. Three MAJOR GROUPS: Stramenopiles, Alveolates, Rhizarians.
- STRAMENOPILES: some of the most important photosynthetic organisms on Earth; most have a HAIRY flagellum paired with a SMOOTH flagellum. Clades: diatoms, oomycetes, brown algae.
- DIATOMS: unicellular algae with a unique two-part wall of SILICON DIOXIDE (glass-like). Walls resist high pressure, protecting against predators. Diatomaceous earth (pool filters). About 100,000 species; marine and freshwater PHYTOPLANKTON; so abundant their photosynthesis affects global CO₂.
- BROWN ALGAE: largest and most complex multicellular algae; ALL multicellular; brown color from CAROTENOIDS; mostly marine; the seaweeds.
- Brown alga body: HOLDFAST (root-like, anchors to rock), STIPE (stem-like), BLADES (leaf-like), gas-filled FLOATS (keep blades near the surface). Plant-like but NO true tissues or organs.
- Brown algae as food: *Laminaria* is eaten; ALGINATE (gel in the cell wall) thickens processed foods.
- OOMYCETES: water molds, white rusts, downy mildews. Once classified as fungi (multinucleate filaments look like hyphae), but cell walls are CELLULOSE, not chitin, and DNA shows they are not closely related to fungi. No plastids, no photosynthesis; parasites or decomposers.
- *Phytophthora infestans*: oomycete causing POTATO LATE BLIGHT.
- ALVEOLATES: named for ALVEOLI, membrane-enclosed sacs just under the plasma membrane. Clades: dinoflagellates, apicomplexans, ciliates.
- DINOFLAGELLATES: marine and freshwater phytoplankton; TWO FLAGELLA in grooves of CELLULOSE PLATES; the beating makes them SPIN.
- RED TIDE = dinoflagellate bloom; water looks red, pink or brownish from carotenoids; toxic, kills invertebrates and fish and can poison people who eat contaminated seafood; becoming more common, ocean warming is thought to be a factor.
- APICOMPLEXANS: nearly all are animal PARASITES; spread as SPOROZOITES; the APEX holds a complex of organelles for penetrating host cells; life cycles have sexual and asexual stages and need TWO OR MORE HOSTS.
- *Plasmodium* (apicomplexan) causes MALARIA; hosts are mosquitoes and humans; about 220 million infected and up to 450,000 deaths per year; the first licensed malaria vaccine began routine use in Africa in 2019.
- PLASMODIUM LIFE CYCLE (know it; extra-credit question): mosquito bite injects SPOROZOITES (n) → human LIVER cells → MEROZOITES (n) released → infect RED BLOOD CELLS → GAMETOCYTES (n, male and female) → taken up by another mosquito → GAMETES → fertilization → ZYGOTE (2n, the only diploid stage) → MEIOSIS → OOCYST → sporozoites. Sexual stages in the MOSQUITO; asexual stages in the HUMAN.
- CILIATES: use CILIA to move and feed; cilia cover the whole surface (*Paramecium*, oral groove) or are clustered in rows or tufts (*Stentor*).

- Ciliates have two kinds of nuclei: tiny MICRONUCLEI and large MACRONUCLEI. CONJUGATION exchanges micronuclei = genetic variation WITHOUT reproduction. Asexual reproduction = BINARY FISSION (know this; skip the nuclear details).
- RHIZARIANS: many are amoebas with THREAD-LIKE pseudopodia. Clades: radiolarians, forams, cercozoans.
- RADIOLARIANS: symmetrical internal skeletons usually of SILICA (glass); mostly marine.
- FORAMS (foraminiferans): porous CALCIUM CARBONATE shells called TESTS; pseudopodia through the pores for swimming, test formation and feeding; some host photosynthetic algae; marine and freshwater; their fossils form much of the marine sediment.
- CERCOZOANS: amoeboid and flagellated, thread-like pseudopodia; marine, freshwater and soil; mostly heterotrophic parasites or predators.

Terms

SAR

Supergroup named for its major groups: Stramenopiles, Alveolates, Rhizarians.

phytoplankton

Photosynthetic plankton (e.g. diatoms, dinoflagellates).

holdfast / stipe / blade

Root-like anchor / stem-like stalk / leaf-like photosynthetic surface of a brown alga.

alginate

Gel-forming substance in brown algal cell walls; food thickener.

alveoli

Membrane-enclosed sacs just under the plasma membrane of alveolates.

sporozoite

Infectious cell of an apicomplexan.

merozoite

Plasmodium stage released from liver cells that infects red blood cells.

gametocyte

Plasmodium stage in red blood cells that becomes gametes inside the mosquito.

micronucleus / macronucleus

Small nuclei exchanged in conjugation / large nucleus that runs the cell (ciliates).

conjugation

Exchange of micronuclei between two ciliates; genetic variation without reproduction.

test

Porous shell of a foram (calcium carbonate).

Examples

- Diatoms: two-part silica walls
- Brown alga: kelp, Laminaria
- Oomycete: Phytophthora infestans, water mold on a goldfish
- Dinoflagellate: red tide
- Apicomplexan: Plasmodium
- Ciliates: Paramecium, Stentor
- Rhizarians: radiolarian, foram, cercozoan

What she stressed in lecture

- "There is one life cycle I want you to know. And this is the life cycle of Plasmodium... Make sure that you know this for the upcoming exam. This will be an extra credit question."
- Learn stramenopiles, alveolates and rhizarians as MAJOR GROUPS.
- Ciliates: "I want you to know the binary fission, but not necessarily what happens with the nuclei."
- Oomycete cell walls are cellulose, not chitin: not fungi.

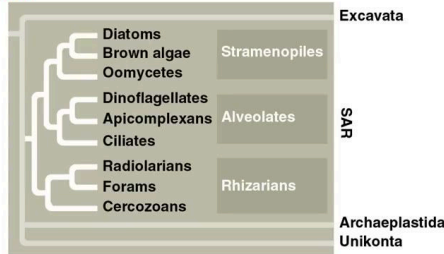
Memory hooks

<i>Diatoms On Boats</i>	Stramenopile clades: Diatoms, Oomycetes, Brown algae.
<i>Dinos Attack Cilia</i>	Alveolate clades: Dinoflagellates, Apicomplexans, Ciliates.
<i>Really Fine Cords</i>	Rhizarian clades: Radiolarians, Forams, Cercozoans, all with thread-like pseudopodia.
<i>Stramenopile = straw-hair</i>	Most stramenopiles have a hairy flagellum paired with a smooth one.
<i>Hold Still, Big Float</i>	Brown alga body from bottom to top: Holdfast, Stipe, Blades, Floats.
<i>Silly Little Mosquitoes Really Gross</i>	<u>Plasmodium</u> cycle in the human: Sporozoites → Liver cells → Merozoites → Red blood cells → Gametocytes (back to the mosquito).
<i>Diatoms live in glass houses; forams live in chalk houses</i>	Diatom walls are silicon dioxide (radiolarian skeletons are silica too); foram tests are calcium carbonate.
<i>Oomycetes: no chitin, so not fungi</i>	Oomycete walls are cellulose; DNA shows they are not fungi. <u>Phytophthora</u> causes potato late blight.
<i>Dinos spin and paint the tide red</i>	Dinoflagellates spin with two flagella in grooves; their blooms cause red tide.
<i>Micronuclei mingle</i>	Ciliate conjugation exchanges micronuclei: genetic variation without reproduction.

CONCEPT 28.3: SAR is a highly diverse group of protists defined by DNA similarities

- SAR** is a monophyletic supergroup named for the first letters of its three major clades:

- **Stramenopiles**
- **Alveolates**
- **Rhizarians**



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Slide 53. SAR tree

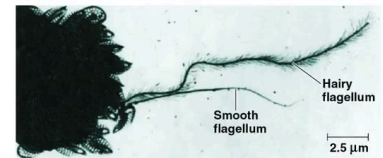
Stramenopiles (diatoms, brown algae, oomycetes), alveolates (dinoflagellates, apicomplexans, ciliates), rhizarians

(radiolarians, forams, cercozoans). [▶ Play from 0:08](#)

Lecture 28.3, slide 002

Stramenopiles

- Stramenopiles** include some of the most important photosynthetic organisms on Earth
- Most have a “hairy” flagellum paired with a “smooth” flagellum



- Three important groups:
 - **Diatoms**
 - **Oomycetes**
 - **Brown algae**



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Slide 54. Stramenopile flagella

Most stramenopiles have a hairy flagellum paired with a smooth flagellum. [▶ Play from 0:50](#)

Lecture 28.3, slide 003

Diatoms

- Diatoms** are unicellular algae with a unique two-part, glass-like wall of silicon dioxide
- The wall withstands pressure up to 1.4 million kg/m², protecting diatoms from the crushing jaws of predators



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Slide 55. Diatom

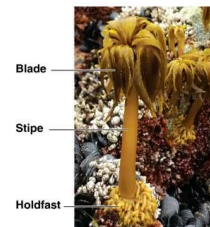
Unicellular alga with a two-part glass-like wall of silicon dioxide that withstands up to 1.4 million kg/m².

[▶ Play from 1:35](#)

Lecture 28.3, slide 004

Brown Algae

- Brown algal seaweeds** have plantlike structures: the rootlike **holdfast**, which anchors the alga, and a stemlike **stipe**, which supports the leaflike **blades**
- Some have gas-filled, bubble-shaped floats to keep photosynthetic structures near the water surface
- Brown algae lack the true tissues and organs found in plants**



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Slide 56. Brown alga body plan

Root-like holdfast anchors; stem-like stipe supports leaf-like blades; some have gas-filled floats. No true tissues or organs.

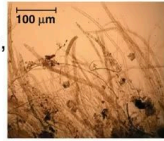
How to draw it: Kelp: holdfast at the bottom, stipe, blades, a float; label all four.

[▶ Play from 4:30](#)

Lecture 28.3, slide 008

Oomycetes (Water Molds and Their Relatives)

- **Oomycetes** include **water molds, white rusts, and downy mildews**
- They were misidentified as fungi due to their multinucleate filaments that resemble fungal hyphae
- One key difference is that **oomycetes cell walls are composed of cellulose, rather than chitin**
- Based on molecular analysis, oomycetes and fungi are not closely related



(a) Closeup of oomycete hyphae (LM)



(b) Water mold hyphae growing on a goldfish

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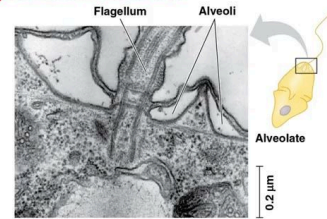
Slide 57. Oomycetes (water molds)

Water molds, white rusts, downy mildews. Filaments look like fungal hyphae, but walls are cellulose; not close relatives of fungi. Water mold growing on a goldfish. ▶ **Play from 6:37**

Lecture 28.3, slide 010

Alveolates

- **Alveolates** have **membrane-enclosed sacs (alveoli)** just under the **plasma membrane**



- Three clades included in the alveolates:
 - **Dinoflagellates**
 - **Apicomplexans**
 - **Ciliates**

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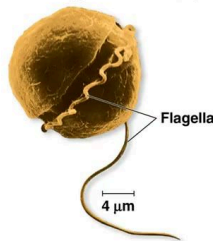
Slide 58. Alveoli

Alveolates have membrane-enclosed sacs (alveoli) just under the plasma membrane. Three clades: dinoflagellates, apicomplexans, ciliates. ▶ **Play from 8:58**

Lecture 28.3, slide 012

Phy

- **Dinoflagellates** are abundant components of **marine and freshwater phytoplankton**
- They **have two flagella housed in the grooves of armor-like cellulose plates that surround the cell**
- Beating of the spiral flagella causes dinoflagellates to spin as they move through the water



(a) Dinoflagellate flagella

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Slide 59. Dinoflagellate

Two flagella in grooves of armor-like cellulose plates; the spiral flagellum makes the cell spin.

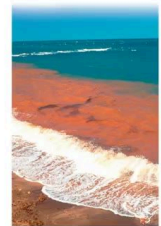
How to draw it: Round cell with a groove around the middle and a second groove down; one flagellum in each.

▶ **Play from 9:55**

Lecture 28.3, slide 013

Dinoflagellates

- **Dinoflagellate blooms cause "red tides"** where the water appears brownish red or pink due to the carotenoids present in their plastids
- **Red tides are toxic and can cause massive kills of invertebrates and fishes**
- Ocean warming caused by climate change is facilitating more frequent red tides



(b) Red tide in the Gulf of Carpentaria in northern Australia

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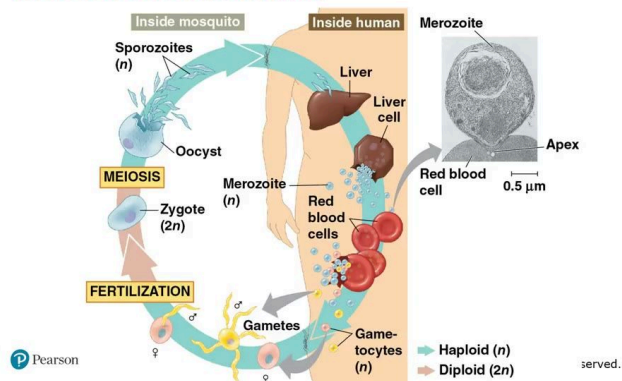
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Slide 60. Red tide

Dinoflagellate bloom colors the water brownish red or pink (carotenoids); toxic; kills invertebrates and fish; becoming more frequent with ocean warming. ▶ **Play from 11:09**

Lecture 28.3, slide 016

Figure 28.18 The two-host life cycle of *Plasmodium*, the apicomplexan that causes malaria



Slide 61. Figure 28.18 *Plasmodium* two-host life cycle
 KNOW THIS (extra credit). Inside human: sporozoites (n) → liver cells → merozoites (n) → red blood cells → gametocytes (n). Inside mosquito: gametes → fertilization → zygote ($2n$) → meiosis → oocyst → sporozoites.

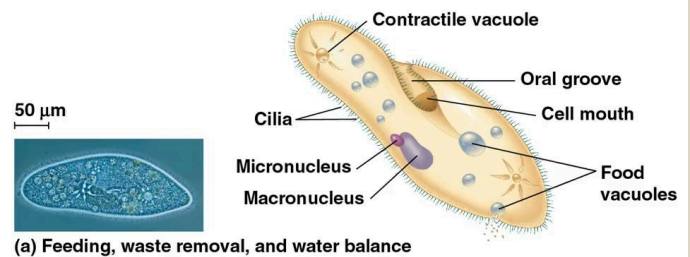
How to draw it: Two halves: mosquito (sexual) and human (asexual); label every stage with n or $2n$; box MEIOSIS and FERTILIZATION.

▶ Play from 14:49

Lecture 28.3, slide 019

Ciliates

- Ciliates** are named for their use of **cilia** to move around and feed on bacteria or other protists
- The cilia may completely cover the cell surface or be clustered in a few rows or tufts



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Slide 62. *Paramecium*, labeled

Ciliate: cilia over the whole surface, oral groove, cell mouth, food vacuoles, contractile vacuole, micronucleus and macronucleus.

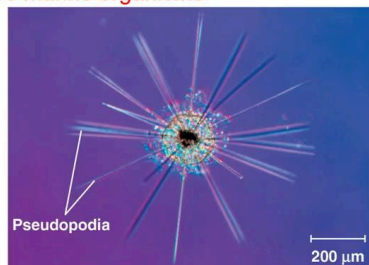
How to draw it: Slipper-shaped cell fringed with cilia; oral groove on one side; large macronucleus, small micronucleus; label all.

▶ Play from 17:34

Lecture 28.3, slide 020

Radiolarians

- Radiolarians** have delicate, **symmetrical internal skeletons typically made of silica**
- Pseudopodia reinforced by microtubules radiate from the central body
- Most radiolarians are marine organisms**



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Slide 63. Radiolarian

Symmetrical internal skeleton usually of silica; thread-like pseudopodia reinforced by microtubules radiate out; mostly marine.

▶ Play from 21:53

Lecture 28.3, slide 030

Forams

- Forams live in the **ocean and fresh water**, and their fossils make up part of the marine sediments



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Slide 64. Forams

Porous calcium carbonate tests; ocean and fresh water; fossils form part of the marine sediments.

▶ Play from 23:28

Lecture 28.3, slide 032

Cercozoans

- **Cercozoans** are amoeboid and flagellated protists that feed using threadlike pseudopodia
- They are common in **marine, fresh water, and soil ecosystems**
- Most cercozoans are **heterotrophic parasites or predators**



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Slide 65. Cercozoan

Amoeboid and flagellated, thread-like pseudopodia; marine, freshwater and soil; heterotrophic parasites or predators.

► Play from 24:22

Lecture 28.3, slide 033

Be able to draw / explain

- Plasmodium life cycle: draw the two-host cycle; human side (liver, red blood cells) asexual; mosquito side (gametes, zygote $2n$, oocyst) sexual; label sporozoites, merozoites, gametocytes, $n/2n$.
- Brown alga: label holdfast, stipe, blades, floats.
- Dinoflagellate: cellulose plates, two flagella in grooves.

My notes

Red algae and green algae are the closest relatives of plants

[Lecture video 28.4 \(opens online\)](#)

Big idea

Archaeplastida contains red algae (a clade), green algae (a major group of chlorophytes and charophytes) and plants. Plastids arose when a heterotrophic protist took in a cyanobacterial endosymbiont; its photosynthetic descendants became the red and green algae, and plants descended from green algae. Red algae get their color from phycoerythrin; green algae have plant-like green chloroplasts.

Must know

- Archaeplastida = red algae (clade) + green algae (major group: CHLOROPHYTES and CHAROPHYTES) + plants.
- Red and green algae are the closest relatives of plants; plants descended from green algae.
- Plastids arose by ENDOSYMBIOSIS: a heterotrophic protist acquired a CYANOBACTERIUM; its descendants evolved into the red and green algal lineages.
- RED ALGAE: accessory pigment PHYCOERYTHRIN masks chlorophyll's green; color varies with depth (greenish red in shallow water, dark red to almost black in deep water).
- Most red algae are multicellular; the largest are seaweeds. Reproduction is SEXUAL; life cycles show ALTERNATION OF GENERATIONS.
- Red algae live in WARM coastal waters of tropical oceans; some are eaten: *Porphyra* (nori) wraps sushi.
- GREEN ALGAE: green chloroplasts structurally and chemically like plants'.
- Green algae are a PARAPHYLETIC group (charophytes + chlorophytes); not monophyletic.
- CHAROPHYTES are the algae most closely related to plants.
- CHLOROPHYTES: mostly freshwater, also marine and some terrestrial; some unicellular and free-living, some symbiotic; often in high visible and UV light.
- Three ways green algae got larger and more complex: (1) COLONIES of individual cells (*Pediastrum*), (2) true MULTICELLULAR bodies by cell division and differentiation (*Volvox* and *Ulva*, sea lettuce), (3) repeated nuclear division with NO cytoplasmic division, one huge multinucleate cell (*Caulerpa*, invasive).
- Most chlorophytes have complex life cycles with both sexual and asexual stages.

Terms

Archaeplastida

Supergroup of red algae, green algae and plants.

phycoerythrin

Red accessory pigment of red algae that masks chlorophyll.

chlorophytes

Green algae clade, mostly freshwater (e.g. *Volvox*, *Ulva*, *Caulerpa*).

charophytes

Green algae clade most closely related to land plants.

paraphyletic

Includes an ancestor and some, but not all, of its descendants (green algae leave out plants).

Examples

- Red alga: nori
- Colonial: Pediastrum
- Multicellular: Volvox, Ulva
- Multinucleate single cell: Caulerpa

What she stressed in lecture

- Green algae = major group; red algae = clade; chlorophytes and charophytes = clades.
- Red algae are the group found in warm water.
- Red algae: know that reproduction is sexual (alternation of generations comes with plants).

Memory hooks

Erythro = red

Red algae get their color from phycoerythrin, which masks chlorophyll and is darker in deep water.

Charophytes are plants' **charming** cousins

Charophytes are the algae most closely related to plants.

Porphyra = purple paper

Porphyra (nori) is the red alga that wraps sushi.

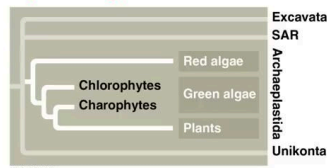
Green algae are **PARA**-green

Green algae (chlorophytes + charophytes) are paraphyletic, because plants are left out.

Slides

CONCEPT 28.4: Red algae and green algae are the closest relatives of plants

- Plastids arose when a heterotrophic protist acquired a cyanobacterial endosymbiont
- The photosynthetic descendants of this ancient protist evolved into red algae and green algae
- **Plants are descended from the green algae**
- **Archaeplastida** is the supergroup that includes:
 - red algae
 - green algae
 - plants



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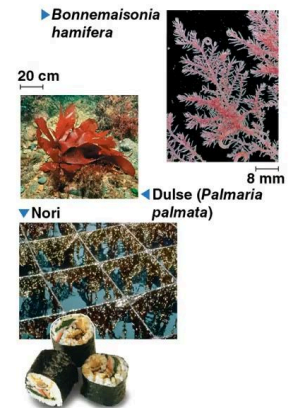
Slide 66. Archaeplastida tree

Plastids came from a cyanobacterial endosymbiont. Red algae, green algae (chlorophytes, charophytes) and plants; plants descended from green algae. ▶ **Play from 0:11**

Lecture 28.4, slide 002

Red Algae

- **Reproduction is sexual** in red algae and life cycles often include alternation of generations
- Red algae are common in **coastal waters of tropical oceans**
- Some species are **consumed by humans**, such as Porphyra ("nori") that is used to wrap sushi



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Slide 67. Red algae

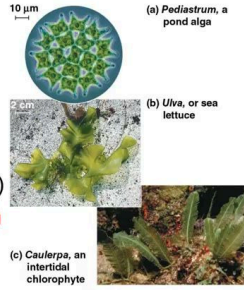
Sexual reproduction, often alternation of generations; common in warm coastal tropical waters; Porphyra (nori) wraps sushi; dulse. ▶ **Play from 2:55**

Lecture 28.4, slide 004

Green Algae

Larger size and greater complexity evolved in green algae by three different mechanisms:

1. Formation of colonies from individual cells (*Pediastrum*)
2. Formation of true multicellular bodies by cell division and differentiation (*Volvox* and *Ulva*)
3. Repeated division of nuclei with no cytoplasmic division (*Caulerpa*)



Most chlorophytes have complex life cycles with both sexual and asexual reproductive stages

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Slide 68. Green algae: three ways to get bigger

(1) Colonies of individual cells (*Pediastrum*); (2) true multicellular bodies (*Volvox*, *Ulva*); (3) repeated nuclear division with no cytoplasmic division (*Caulerpa*).

► Play from 5:49

Lecture 28.4, slide 007

Be able to draw / explain

- Archaeplastida branch: red algae, chlorophytes, charophytes, plants (green algae bracket is paraphyletic).

My notes

Unikonts include protists that are closely related to fungi and animals

[Lecture video 28.5 \(opens online\)](#)

Big idea

Unikonta contains animals, fungi and related protists in two major groups: Amoebozoans (amoebas with lobe- or tube-shaped pseudopodia: tubulinids, slime molds, entamoebas) and Opisthokonts (animals, fungi, choanoflagellates, nucleariids). One controversial hypothesis puts unikonts as the first eukaryotes to diverge.

Must know

- Unikonta: two MAJOR GROUPS: AMOEBOZOANS and OPISTHOKONTS.
- Amoebozoans: amoebas with LOBE- or TUBE-shaped pseudopodia (rhizarians have THREAD-like ones). Clades: TUBULINIDS, SLIME MOLDS, ENTAMOEBAS.
- Opisthokonts: ANIMALS, FUNGI and related protists (choanoflagellates, nucleariids).
- Root of the eukaryotic tree is uncertain; one controversial hypothesis: unikonts diverged first, so they may be most like the common ancestor of eukaryotes.
- TUBULINIDS: diverse amoebozoans (e.g. *Amoeba proteus*); soil, freshwater and marine; predators or detritus feeders (detritus = dead material on the bottom).
- SLIME MOLDS (mycetozoans): once thought to be fungi because they make spores; the resemblance is CONVERGENT EVOLUTION, not homology.
- PLASMODIAL slime molds: bright yellow or orange; feeding mass = PLASMODIUM, ONE huge cell with many DIPLOID nuclei and no membranes dividing it; when conditions worsen it forms FRUITING BODIES for sexual reproduction.
- CELLULAR slime molds: feeding stage = solitary cells; when conditions worsen they aggregate into a slug-like mass (cells stay separated by membranes) → fruiting body → spores → amoebas. Not in lab.
- ENTAMOEBAS: parasites of vertebrates and some invertebrates; humans host at least 6 species but only *Entamoeba histolytica* is pathogenic: AMOEBIC DYSENTERY, the 3rd leading cause of death from eukaryotic parasites.

Terms

Unikonta

Supergroup of amoebozoans and opisthokonts (animals, fungi and related protists).

Amoebozoa

Major group of amoebas with lobe- or tube-shaped pseudopodia.

Opisthokonta

Major group of animals, fungi and their protist relatives.

plasmodium (slime mold)

Single huge multinucleate (diploid) feeding mass of a plasmodial slime mold. Not the same as the malaria genus *Plasmodium*.

fruiting body

Stalked spore-producing structure slime molds form when conditions get bad.

detritus

Dead organic material, usually on the bottom of a lake or ocean.

Examples

- Tubulinid: *Amoeba proteus*

- Plasmodial slime mold: bright yellow mass
- *Entamoeba*: *Entamoeba histolytica* (amoebic dysentery)

What she stressed in lecture

- "I want you to know that it causes amoebic dysentery."
- Two major groups of unikonts: amoebozoans and opisthokonts.
- Slime molds look like fungi by convergent evolution.

Memory hooks

*Amoebas and Opisthokonts =
Animals' Origin*

Unikonta has two major groups: Amoebozoans and Opisthokonts (animals, fungi and their protist relatives).

Tubes, Slime, Entails

Amoebozoan clades: Tubulinids, Slime molds, Entamoebas (*Entamoeba histolytica* causes amoebic dysentery).

Lobes vs threads

Amoebozoans have lobe- or tube-shaped pseudopodia; rhizarians have thread-like ones.

*Plasmodial = one big blob;
cellular = separate cells*

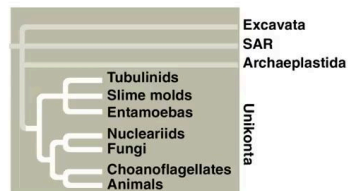
A plasmodial slime mold is one huge cell with many diploid nuclei. Cellular slime molds stay separate cells that clump together.

Slides

CONCEPT 28.5: Unikonts include protists that are closely related to fungi and animals

- The supergroup **Unikonta** includes:

- Animals
- Fungi
- some protists



- The **two major clades** of unikonts:
 - amoebozoans (tubulinids and relatives)
 - opisthokonts (animals, fungi, and related protists)



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Slide 69. Unikonta tree

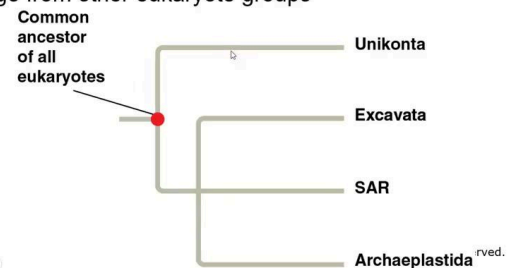
Two major groups: amoebozoans (tubulinids, slime molds, entamoebas) and opisthokonts (nucleariids, fungi, choanoflagellates, animals).

[▶ Play from 0:32](#)

Lecture 28.5, slide 004

CONCEPT 28.5: Unikonts include protists that are closely related to fungi and animals

- The root of the eukaryotic tree is uncertain
- One controversial hypothesis is that unikonts were the first to diverge from other eukaryote groups



Slide 70. Hypothesis: unikonts diverged first

The root of the eukaryotic tree is uncertain; one controversial hypothesis puts unikonts as the first group to branch from the common ancestor of all eukaryotes.

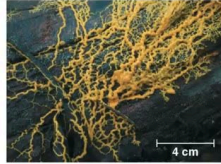
[▶ Play from 1:35](#)

Lecture 28.5, slide 005

Slime Molds

Plasmodial Slime Molds

- Many plasmodial slime molds are brightly colored, often yellow or orange
- They form a large feeding mass called a plasmodium (single "supercell" that contains many diploid nuclei undivided by plasma membranes)
- The plasmodium forms a fruiting body for sexual reproduction in unfavorable environmental conditions



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Slide 71. Plasmodial slime mold

Bright yellow or orange plasmodium: one supercell with many diploid nuclei, undivided by membranes; forms fruiting bodies

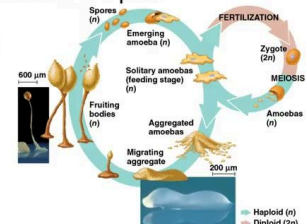
when conditions are poor. ▶ Play from 4:53

Lecture 28.5, slide 009

Slime Molds

Cellular Slime Molds

- Cellular slime molds form multicellular aggregates in which cells are separated by plasma membranes
- The feeding stage consists of solitary cells
- Solitary cells unite to form a slug-like aggregate for migration when habitat conditions are poor
- Ultimately, the aggregated cells form a fruiting body



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Slide 72. Cellular slime mold life cycle

Solitary feeding cells aggregate into a slug-like mass (cells keep their membranes) that forms a fruiting body.

▶ Play from 5:59

Lecture 28.5, slide 010

Be able to draw / explain

- Unikonta branch: amoebozoans (tubulinids, slime molds, entamoebas) and opisthokonts (nucleariids, fungi, choanoflagellates, animals).

My notes

Protists play key roles in ecological communities

[Lecture video 28.6 \(opens online\)](#)

Big idea

Protists live in aquatic and moist terrestrial habitats and act as symbionts (mutualists or parasites) or as producers. Photosynthetic protists and prokaryotes are the main producers in aquatic communities. Warming sea surfaces reduce the growth of photosynthetic protists, which can affect fisheries and the carbon cycle.

Must know

- Two key ecological roles: SYMBIONTS and PRODUCERS.
- Mutualists: dinoflagellates inside coral polyps nourish reef-building corals (the coral gives them a home); protists in TERMITE guts digest wood (termites can't alone).
- Parasites: *Plasmodium* (malaria); *Pfiesteria*, a dinoflagellate that attacks fish skin; *Phytophthora* (sudden oak death).
- Producers: use light (or inorganic compounds) to turn CO₂ into organic compounds; photosynthetic protists + prokaryotes are the MAIN PRODUCERS in aquatic communities.
- All other organisms are consumers that feed on producers directly (herbivorous plankton) or indirectly (carnivorous plankton, animals).
- Warmer sea surface → less growth of photosynthetic protists and prokaryotes, because warm surface water keeps cold, nutrient-rich water from rising. Effects: fishery yields and the global carbon cycle.
- End-of-chapter summary figure: suggested study sheet for Exam 2.

Terms

symbiont

An organism living in close association with another (mutualist or parasite).

producer

Organism that makes organic compounds from CO₂ (photosynthesis).

consumer

Organism that eats producers directly or indirectly.

Examples

- Coral + dinoflagellates
- Termite gut protists
- Sudden oak death (*Phytophthora*)
- *Pfiesteria* on fish

What she stressed in lecture

- "This might be something that you want to print out from your textbook and add some notes to it to make it a really nice study sheet to get ready for exam number two" (chapter summary figure).

Memory hooks

Share and Produce

Coral's roommates, termite's chefs

A warm lid starves the sea

The two ecological roles of protists: Symbionts and Producers.

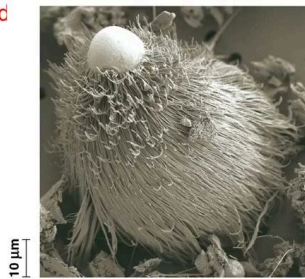
Dinoflagellates feed reef-building corals; gut protists digest wood for termites.

Warm surface water keeps cold, nutrient-rich water from rising, so producers grow less.

Slides

Symbiotic Protists

- Some protist symbionts benefit their hosts
 - Some dinoflagellates live within the polyps and nourish reef-building corals
 - Some protists inhabit the guts of termites and aid with the digestion of wood



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Slide 73. Termite gut protist

Mutualist that digests wood inside termites; dinoflagellates nourish reef-building corals. [▶ Play from 0:50](#)

Lecture 28.6, slide 003

Symbiotic Protists

- Some protist symbionts are parasites
 - Plasmodium* causes malaria in humans
 - A species of *Pfiesteria* is a dinoflagellate that attaches and feeds on the skin of fish
 - There is a species of *Phytophthora* that causes sudden oak death



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Slide 74. Sudden oak death

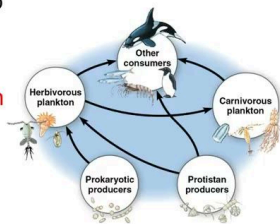
A species of *Phytophthora* kills oaks; *Pfiesteria* (dinoflagellate) feeds on fish skin; *Plasmodium* causes malaria.

[▶ Play from 1:50](#)

Lecture 28.6, slide 004

Photosynthetic Protists

- Many protists are **producers**, organisms that use energy from light (or inorganic compounds) to convert CO₂ to organic compounds
- In **aquatic communities**, the **main producers are photosynthetic protists** and prokaryotes
- All other organisms are **consumers** that directly or indirectly depend on producers for food



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Slide 75. Producers in an aquatic food web

Photosynthetic protists and prokaryotes are the main producers; all other organisms are consumers.

[▶ Play from 2:55](#)

Lecture 28.6, slide 005

Figure 28.UN06 Summary of key concepts: eukaryote supergroups

Eukaryote Supergroup	Major Groups	Key Morphological Characteristics	Specific Examples
Excavata	Diplomonads and parabasalids Euglenozoans Kinetoplastids Euglenids	Modified mitochondria Spiral or crystalline rod inside flagella	Giant, Trichomonas Trypanosoma, Euglena
"SAR" Clade	Stramenopiles Diatoms Oomycetes Brown algae Alveolates Dinoflagellates Apicomplexans Ciliates Rhizaria Radiolarians Forams Cercariae	Hairy and smooth flagella Membrane-enclosed sacs (alveoli) beneath plasma membrane Amoebae with threadlike pseudopodia	Phytophthora, Laminaria Pfiesteria, Plasmodium, Paramecium Globigerina
Archaeplastida	Red algae Green algae Plants	Phycocyanin (photosynthetic pigment) Plant-type chloroplasts (See Chapters 29 and 30.)	Porphyridium, Palmaria Chlamydomonas, Ulva Mosses, ferns, conifers, flowering plants
Unikonta	Amoebozoans Tubulinids Slime molds Entamoebas Opisthokonts	Amoebae with lobe-shaped or tube-shaped pseudopodia (Highly variable; see Chapters 31–34.)	Amoeba, Dictyostelium Choanoflagellates, nucleariids, animals, fungi

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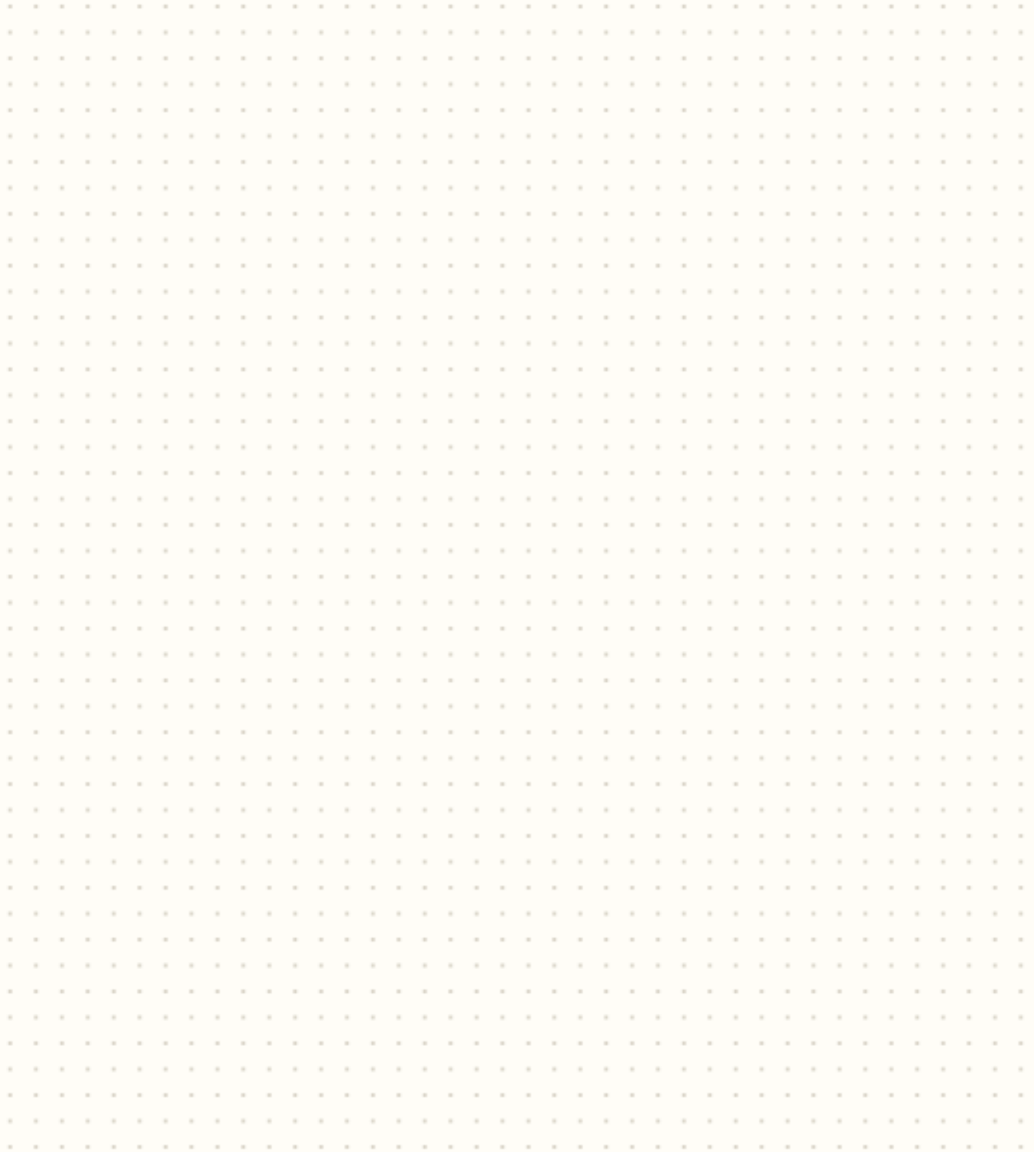
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Slide 76. Figure 28.UN06 Summary of key concepts

Chapter summary table: supergroup, major groups, key morphological characteristics, specific examples. Suggested study sheet for Exam 2. [▶ Play from 6:02](#)

Lecture 28.6, slide 007

My notes



Compare tables, traps, essays

Bacteria vs Archaea vs Eukarya (focus on the differences)

Characteristic	Bacteria	Archaea	Eukarya
Cell type	Prokaryote	Prokaryote	Eukaryote
Nuclear envelope	Absent	Absent	Present
Membrane-enclosed organelles	Absent	Absent	Present
Chromosome	One circular chromosome in nucleoid	One circular chromosome in nucleoid	Multiple linear chromosomes in nucleus
Peptidoglycan in cell wall	Present	Absent (polysaccharides and proteins)	Absent (cellulose in plants, chitin in fungi)
Membrane lipids	Unbranched hydrocarbons	Some branched hydrocarbons	Unbranched hydrocarbons
RNA polymerase	One kind	Several kinds	Several kinds
Initiator amino acid for protein synthesis	Formyl-methionine	Methionine	Methionine
Pathogens	All known pathogenic prokaryotes	None known	Some
Examples from lecture	Proteobacteria, Chlamydias, Spirochetes, Cyanobacteria, Gram-positive bacteria	Extreme halophiles, extreme thermophiles, methanogens (Euryarchaeota, TACK, Lokiarchaeotes)	Plants, fungi, animals, protists
Closest relative	Branched off first	Eukarya	Archaea

Four nutritional modes

Mode	Energy source	Carbon source	Examples from lecture
Photoautotroph	Light	CO ₂	Cyanobacteria (<i>Anabaena</i>), some Proteobacteria, plants
Chemoautotroph	Inorganic chemicals (such as hydrogen sulfide)	CO ₂	Sulfur bacterium <i>Thiomargarita</i> , hydrothermal vent bacteria
Photoheterotroph	Light	Organic compounds	Certain prokaryotes only
Chemoheterotroph	Organic compounds	Organic compounds	Decomposer prokaryotes, pathogens, spirochetes, fungi, animals

Gram-positive vs Gram-negative

Feature	Gram-positive	Gram-negative
Peptidoglycan	Thick layer	Thin layer
Outer membrane	None	Outer lipopolysaccharide membrane
Stain color	Purple	Pink/red
Antibiotic resistance	Less resistant (drugs reach peptidoglycan)	More resistant (outer membrane blocks drugs)
Endotoxins	No outer membrane lipopolysaccharide	Lipopolysaccharide released as endotoxin when cells die
Lecture groups	Actinomycetes, <u>Streptomyces</u> , <u>Staphylococcus</u> , <u>Bacillus</u> , <u>Clostridium</u>	Proteobacteria, Chlamydias, Spirochetes, Cyanobacteria
Oreo analogy	Oreo with one cookie removed	Whole Oreo

Monophyletic vs paraphyletic vs polyphyletic

Group	Includes most recent common ancestor	Includes all descendants	Lecture example
Monophyletic (clade)	Yes	Yes	Even-toed ungulates plus hippos plus cetaceans
Paraphyletic	Yes	No	Even-toed ungulates plus hippos, leaving out cetaceans
Polyphyletic	No	Not applicable (distantly related members)	Cetaceans plus seals grouped by appearance

Transformation vs transduction vs conjugation

Process	How DNA moves	Key detail
Transformation	Cell takes up foreign DNA from surroundings	Can turn a nonpathogenic cell pathogenic
Transduction	Bacteriophage carries genes between hosts	Unintended result of phage replication
Conjugation	Direct transfer between two joined cells via pilus	One direction only, donor to recipient; plasmids transferred

Orthologous vs paralogous genes

Feature	Orthologous	Paralogous
Origin of homology	Speciation event	Gene duplication
Where found	In different species	Copies within one species
Use	Inferring phylogeny	Show divergence within a genome (gene families)
Example	Cytochrome c in humans and dogs	Human olfactory receptor genes

Exotoxins vs endotoxins

Feature	Exotoxin	Endotoxin
What it is	Protein secreted by bacteria	Lipopolysaccharide of Gram-negative outer membrane
When released	Secreted by living bacteria	Only when bacteria die and walls break down
Needs bacteria present	No, causes disease even after bacteria are gone	Released from bacterial cells
Example	<u>Vibrio cholerae</u> , cholera	<u>Salmonella</u> , food poisoning

Oxygen relations

Type	Oxygen use
Obligate aerobe	Requires oxygen for cellular respiration
Obligate anaerobe	Cannot use oxygen; poisoned by it; anaerobic respiration
Facultative anaerobe	Uses oxygen if present; otherwise fermentation or anaerobic respiration

Major bacterial groups

Group	Gram	Key traits	Named examples
Proteobacteria	Negative	Photoautotrophs, chemoautotrophs, heterotrophs	<u>Neisseria gonorrhoeae</u> (gonorrhea), <u>Vibrio cholerae</u> (cholera), <u>Helicobacter pylori</u> (ulcers), <u>Thiomargarita</u>
Chlamydias	Negative	Parasites of animal cells; walls lack peptidoglycan	<u>Chlamydia trachomatis</u> (nongonococcal urethritis)
Spirochetes	Negative	Helical heterotrophs; internal filaments; free-living or pathogenic	<u>Treponema</u> (syphilis), <u>Borrelia</u> (Lyme disease)
Cyanobacteria	Negative	Photoautotrophs; solitary or filamentous	<u>Anabaena</u> (heterocysts)
Gram-positive bacteria	Positive	Very diverse; actinomycetes form colonies, soil decomposers, pathogens	<u>Streptomyces</u> (antibiotics), <u>Staphylococcus aureus</u> , <u>Bacillus anthracis</u> (anthrax), <u>Clostridium botulinum</u> (botulism)

Archaeal groups

Group	Members / habitat
Extreme halophiles	Very salty environments
Extreme thermophiles	Very hot environments, over 100 degrees C
Methanogens	Obligate anaerobes making methane; under Greenland ice, swamps, marshes, guts of cattle, termites, herbivores
Euryarchaeota	Extreme halophiles, most methanogens, some extreme thermophiles
TACK supergroup	Thaumarchaeota, Aigarchaeota, Crenarchaeota (rest of extreme thermophiles), Korarchaeota
Lokiarchaeotes	Close to TACK; possible sister group of eukaryotes

History of classification schemes

System	Groups
Two kingdoms	Plants, animals (fungi and prokaryotes with plants)
Five kingdoms (by 1960s)	Monera, Protista, Plantae, Fungi, Animalia
Three domains (current)	Bacteria, Archaea, Eukarya (Plantae, Fungi, Animalia; Protista no longer a kingdom)

Traps (ch26-27)

- Homology (shared ancestry) vs analogy (convergent evolution). Similar looks do not mean close relationship: glass lizards look like snakes but are not their close relatives; Australian and African golden moles look alike by convergence.
- Paraphyletic INCLUDES the common ancestor but leaves out some descendants. Polyphyletic LEAVES OUT the most recent common ancestor. Only monophyletic groups are clades.
- Order of tip labels means nothing: rotating branches does not change relationships. Read branch points, not neighbors. A taxon did not evolve from the taxon next to it.
- Trees show pattern of descent, not phenotypic similarity, and (unless branch lengths are proportional) not when species evolved or how much change happened.
- Basal taxon diverged early; it is not 'primitive' or the ancestor of the others.
- Shared ancestral vs shared derived is relative: a backbone is ancestral within vertebrates but derived relative to other animals.
- Outgroup is closely related but not part of the ingroup. Characters shared by outgroup and ingroup are ancestral.
- Character table: in the lecture audio the instructor said the amnion is in 'frog and leopard.' The nested tree she drew (four limbs: frog, turtle, leopard; then amnion) requires the amnion group to be turtle and leopard; the frog branches off before the amnion hash mark.
- Lizard tree: in the lecture audio the instructor paired glass lizards with monitor lizards; the posted concept figure shows iguanas as the sister of glass lizards. Either way, glass lizards and snakes lost limbs independently.
- Orthologous (speciation, between species, used for phylogeny) vs paralogous (duplication, within one species).
- rRNA genes change slowly (ancient relationships); mitochondrial DNA changes fast (recent events).
- Molecular clock: critical sequences change SLOWLY (mutations harmful); less critical sequences change FASTER (more neutral mutations).
- Archaea are more closely related to Eukarya than to Bacteria, even though Archaea and Bacteria are both prokaryotes.
- Crash Course video lists Protista as a kingdom and calls Monera a 'domain.' The instructor says Protista is no longer a kingdom, and Monera was a kingdom in the five-kingdom system. Follow the instructor.
- Peptidoglycan is in Bacteria only. Archaea lack it. Chlamydias are bacteria that also lack peptidoglycan.
- Gram-NEGATIVE bacteria (thin peptidoglycan plus outer membrane) are MORE resistant to antibiotics. Gram-positive has the thick peptidoglycan layer.
- Gram-positive stains purple; Gram-negative stains pink/red.
- Capsule vs fimbriae vs pili: capsule is a sticky layer around the wall; fimbriae are short hairs for sticking; pili are longer and join cells for DNA transfer.
- Endospores are for survival (dormancy), not reproduction. Prokaryotes reproduce by binary fission.
- Nucleoid is a region with no membrane, not a nucleus.
- Salt preserves food because prokaryotes lose water (plasmolysis) in a salty (hypertonic) environment. In the audio the instructor said 'hypotonic' here; the cell wall is what prevents bursting in hypotonic environments.
- Generation time: 27.1 audio says binary fission every 1 to 3 hours (fastest about 20 minutes); 27.2 audio says every 1 to 2 hours.
- Photo/chemo = ENERGY source. Auto/hetero = CARBON source.
- Obligate anaerobes are poisoned by oxygen; facultative anaerobes use oxygen when present but can live without it.
- Nitrogen fixation converts N₂ to ammonia (NH₃); in *Anabaena* it happens in heterocysts, not in vegetative cells.

- Transformation (DNA from surroundings) vs transduction (virus carries DNA) vs conjugation (direct one-way transfer through a pilus).
- Exotoxin (secreted protein, works even when bacteria are gone, cholera) vs endotoxin (Gram-negative outer membrane lipopolysaccharide, released when bacteria die, *Salmonella*).
- All known pathogenic prokaryotes are bacteria, not archaea.
- Parasites usually do not kill their host.
- *Streptomyces* is a Gram-positive bacterium (actinomycete) that produces antibiotics; 'myces' refers to its fungus-like look, but it is not a fungus.
- Spirochetes: *Treponema* causes syphilis; *Borrelia* causes Lyme disease. Do not swap them.
- Euryarchaeota contains MOST methanogens and SOME extreme thermophiles; the rest of the extreme thermophiles are in Crenarchaeota (TACK).
- Humans and mice: about 65 million years since divergence and 99% of genes orthologous; the audio says 'give or take a few years.'

Essay / short-answer prompts

Use this character table to build a phylogenetic tree and explain your reasoning. Taxa: lancelet, lamprey, bass, frog, turtle, leopard. Characters: vertebral column, hinged jaws, four limbs, amnion, hair (lancelet has none; lamprey has vertebral column only; bass adds hinged jaws; frog adds four limbs; turtle adds amnion; leopard adds hair). Identify the outgroup, the shared ancestral and shared derived characters, and the sister taxa.

- Lancelet is the outgroup: closely related but not part of the ingroup; lacks all characters.
- Characters shared by outgroup and ingroup are ancestral; characters present in only some ingroup members are shared derived characters.
- Each derived character is assumed to arise only once; place hash marks in order: vertebral column, hinged jaws, four limbs, amnion, hair.
- Branch order: lancelet, then lamprey, bass, frog, turtle, leopard.
- Turtle and leopard are sister taxa (share amnion, the most recent shared derived character).
- Tree is rooted at the common ancestor; hair is unique to leopard.
- Mention maximum parsimony: this tree needs the fewest evolutionary changes.

Define monophyletic, paraphyletic, and polyphyletic groups. Draw one tree and circle an example of each. Give a real example of a paraphyletic and a polyphyletic group from lecture.

- Monophyletic: ancestor and all descendants; the only kind of group that is a clade.
- Paraphyletic: ancestor and some, but not all, descendants.
- Polyphyletic: distantly related species without their most recent common ancestor.
- Paraphyletic example: even-toed ungulates plus hippos without cetaceans.
- Polyphyletic example: cetaceans plus seals grouped by appearance.
- Cladistics names only monophyletic groups.

Distinguish homology from analogy. Explain why systematists must separate them before building a tree, how they tell them apart, and give examples of each from lecture and the videos.

- Homology: similarity due to shared ancestry (phenotypic or genetic).
- Analogy: similarity due to convergent evolution in unrelated species facing similar selection pressures.
- Only features resulting from common ancestry are useful for inferring phylogeny.
- More complex similarity makes homology more likely; statistical tools separate molecular homology from coincidental matches.
- Homology examples: human, bat, whale forelimbs; insect mouthparts and antennae.
- Analogy examples: Australian mole and African golden mole; bird and insect wings; *Astrophytum* and *Euphorbia*; anole body types on different islands.
- Morphology and genes can disagree (Hawaiian silverswords).

Compare the cell walls of Gram-positive and Gram-negative bacteria. Explain how the Gram stain distinguishes them, why Gram-negative bacteria are more resistant to antibiotics, why peptidoglycan-targeting antibiotics do not harm humans, and how the Gram-negative wall relates to endotoxins.

- Bacterial walls contain peptidoglycan (sugars cross-linked by polypeptides); archaeal walls lack it.
- Gram-positive: thick peptidoglycan, no outer membrane, stains purple.
- Gram-negative: thin peptidoglycan plus outer lipopolysaccharide membrane, stains pink/red.
- Outer membrane blocks antibiotics from reaching peptidoglycan, so Gram-negative cells are more resistant.
- Human cells lack peptidoglycan, so these antibiotics target bacteria only.
- Endotoxins are the lipopolysaccharide of the Gram-negative outer membrane, released when the cells die (*Salmonella*).
- Cell wall functions: maintain shape, protect, prevent bursting in hypotonic environments.

Prokaryotes reproduce asexually by binary fission, yet their populations are highly diverse. Explain the three factors that produce this diversity and describe the three mechanisms of genetic recombination.

- Binary fission yields identical cells; generation times of 1 to 3 hours (as fast as 20 minutes).
- Rapid reproduction: huge populations quickly.
- Mutation: low rates but rapid accumulation due to short generations and large populations.
- Genetic recombination combines DNA from two sources; between species it is horizontal gene transfer.
- Transformation: uptake of foreign DNA from surroundings (nonpathogenic cell becomes pathogenic).
- Transduction: bacteriophages carry genes between hosts.
- Conjugation: one-way DNA transfer from donor to recipient through a pilus; plasmids can transfer.

Describe the four nutritional modes of prokaryotes and give an example of each type of organism from lecture. Then explain oxygen relations and nitrogen fixation, including the role of heterocysts.

- Photo vs chemo = energy source (light vs chemicals); auto vs hetero = carbon source (CO₂ vs organic).
- Photoautotroph: light + CO₂ (cyanobacteria).
- Chemoautotroph: inorganic chemicals + CO₂ (sulfur bacteria, hydrothermal vent bacteria).
- Photoheterotroph: light + organic carbon.
- Chemoheterotroph: organic compounds for both (decomposers, pathogens).
- Obligate aerobes need oxygen; obligate anaerobes are poisoned by it; facultative anaerobes use it if present or ferment.
- Nitrogen fixation: N₂ to NH₃; needed for amino acids and nucleic acids; *Anabaena* heterocysts fix nitrogen for the filament.

The four supergroups (Fig. 28.5)

Supergroup	Major groups / clades	Defining feature	Examples
Excavata	Diplomonads, parabasalids, euglenozoans (kinetoplastids + euglenids)	Cytoskeleton; some have an excavated feeding groove; modified mitochondria or unique flagella	<i>Giardia</i> , <i>Trichomonas</i> , <i>Trypanosoma</i> , <i>Euglena</i>
SAR	Stramenopiles (diatoms, brown algae, oomycetes); Alveolates (dinoflagellates, apicomplexans, ciliates); Rhizarians (radiolarians, forams, cercozoans)	Grouped by DNA similarity	Diatoms, kelp, <i>Phytophthora</i> , red tide, <i>Plasmodium</i> , <i>Paramecium</i> , forams
Archaeplastida	Red algae; green algae (chlorophytes, charophytes); plants	Plastids from a cyanobacterial endosymbiont	Nori (<i>Porphyra</i>), <i>Pediastrum</i> , <i>Volvox</i> , <i>Ulva</i> , <i>Caulerpa</i>
Unikonta	Amoebozoans (tubulinids, slime molds, entamoebas); Opisthokonts (animals, fungi, choanoflagellates, nucleariids)	Lobe/tube pseudopodia (amoebozoans); closest to fungi and animals	<i>Amoeba proteus</i> , slime molds, <i>Entamoeba histolytica</i>

Diseases and the protist that causes them

Disease / effect	Organism	Group
Intestinal infection (giardiasis)	<i>Giardia intestinalis</i>	Excavata: diplomonad
Sexually transmitted infection	<i>Trichomonas vaginalis</i>	Excavata: parabasalid
Sleeping sickness; Chagas disease	<i>Trypanosoma</i>	Excavata: kinetoplastid
Potato late blight	<i>Phytophthora infestans</i>	SAR: oomycete
Sudden oak death	<i>Phytophthora</i>	SAR: oomycete
Red tide (toxic bloom)	Dinoflagellates	SAR: alveolate
Fish skin attacks	<i>Pfiesteria</i>	SAR: dinoflagellate
Malaria	<i>Plasmodium</i>	SAR: apicomplexan
Amoebic dysentery	<i>Entamoeba histolytica</i>	Unikonta: entamoeba

Reduced mitochondria and special structures

Structure	Who has it	What it is
Mitosome	Diplomonads	Reduced mitochondrion, no electron transport chain
Hydrogenosome	Parabasalids	Reduced mitochondrion, releases H_2
Kinetoplast	Kinetoplastids	Organized DNA mass in the single mitochondrion
Crystalline/spiral rod in flagellum	Euglenozoans	Defining feature of the major group
Alveoli	Alveolates	Sacs under the plasma membrane
Apex	Apicomplexans	Organelle complex to penetrate host cells
Silica wall (2 parts)	Diatoms	Glass-like protective wall
Silica skeleton	Radiolarians	Symmetrical internal skeleton
Calcium carbonate test	Forams	Porous shell

Traps (ch28)

- Plasmodium (malaria genus, apicomplexan) vs plasmodium (feeding mass of a plasmodial slime mold, amoebozoan). Different things.
- Pseudopodia: THREAD-like = rhizarians (SAR). LOBE- or TUBE-shaped = amoebozoans (Unikonta).
- Oomycetes are not fungi: cellulose walls, not chitin.
- Slime molds are not fungi: spores are convergent evolution.
- Mitosomes = diplomonads (no ETC). Hydrogenosomes = parabasalids (release H_2).
- Green algae are PARAPHYLETIC; charophytes, not chlorophytes, are the closest relatives of plants.
- Red algae: phycoerythrin, warm tropical coastal water. Brown algae: carotenoids, the largest/most complex multicellular algae.
- Diatoms: silicon dioxide (silica) walls. Forams: calcium carbonate tests. Radiolarians: silica skeletons.
- Plasmodium: the zygote in the mosquito is the ONLY diploid stage; sexual = mosquito, asexual = human.
- Ciliate conjugation gives genetic variation but is not reproduction; reproduction is binary fission.
- Euglenozoa is a MAJOR GROUP (two clades: kinetoplastids, euglenids); stramenopiles, alveolates, rhizarians are major groups of SAR.

Essay / short-answer prompts

Describe the life cycle of Plasmodium. Name each stage, its host and ploidy, and say which part is sexual and which is asexual.

- Infected mosquito bites a human and injects sporozoites (n).
- Sporozoites enter liver cells; liver cells release merozoites (n).
- Merozoites infect red blood cells and multiply (asexual); some become male and female gametocytes (n).
- Another mosquito takes up gametocytes with a blood meal; they become gametes in the mosquito.
- Fertilization makes the zygote ($2n$), the only diploid stage; meiosis → oocyst → sporozoites that move to the salivary glands.
- Sexual stages in the mosquito; asexual stages in the human; two-host (complex) life cycle; apicomplexan.

Name the four supergroups of eukaryotes and give the major groups or clades and one example in each.

- Excavata: diplomonads (*Giardia*), parabasalids (*Trichomonas*), euglenozoans (kinetoplastids: *Trypanosoma*; euglenids: *Euglena*).
- SAR: stramenopiles (diatoms, brown algae, oomycetes), alveolates (dinoflagellates, apicomplexans like *Plasmodium*, ciliates like *Paramecium*), rhizarians (radiolarians, forams, cercozoans).
- Archaeplastida: red algae, green algae (chlorophytes, charophytes), plants.
- Unikonta: amoebozoans (tubulinids, slime molds, entamoebas) and opisthokonts (animals, fungi, choanoflagellates, nucleariids).

Compare oomycetes and slime molds with true fungi. Why were they once classified as fungi, and why are they not fungi?

- Oomycetes: filaments resemble hyphae, but cellulose walls (not chitin); DNA places them in stramenopiles (SAR).
- Slime molds: make spores and fruiting bodies like fungi, but this is convergent evolution; they are amoebozoans (Unikonta).
- Fungi are opisthokonts with chitin walls.