Reconstructing the evolution of living things

- Systematists study evolutionary relationships
- Look for shared derived (=different from ancestor) traits to group organisms
- Evidence used: morphology, development, and molecular data (especially DNA sequences)
Why can’t we figure it out perfectly?

• More distant history is obscured by more changes

• Among oldest lineages of Bacteria and Archaea in particular, lots of “lateral gene transfer.” Makes it difficult to infer relationships from phylogeny of single genes.
Diversity of Prokaryotes
Bacteria & Archaea

Early prokaryote fossil
What are microbes?

- Only a minority make us sick
- Robert Koch, *Germ Theory of Disease*
- In ordinary English, might be anything small
  - bacteria
  - yeast
  - protists
  - viruses
- In science, classify by evolutionary relationships...

Life can be divided into 3 domains

- **Prokaryotes** = bacteria + archaea
- Prokaryote was ancestral and only form for billions of years
Eukarya

are Prokaryotes monophyletic, paraphyletic, polyphyletic?

Scheme has been revised before:

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Three kingdoms</td>
<td>Five kingdoms</td>
<td>Six kingdoms</td>
<td>Three domains</td>
</tr>
<tr>
<td>Protista</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monera (prokaryotes)</td>
<td></td>
<td>Eubacteria</td>
<td>Bacteria</td>
<td></td>
</tr>
<tr>
<td>Archaebacteria</td>
<td></td>
<td>Archaebacteria</td>
<td>Archaea</td>
<td></td>
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<tr>
<td>Protista</td>
<td></td>
<td>Protista</td>
<td></td>
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</tr>
<tr>
<td>Plantae</td>
<td>Fungi</td>
<td>Fungi</td>
<td>Eukarya</td>
<td></td>
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<tr>
<td>Plantae</td>
<td></td>
<td>Plantae</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Animalia</td>
<td>Animalia</td>
<td>Animalia</td>
<td></td>
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</tr>
</tbody>
</table>

modified from Wikipedia
Shared by all 3 domains

- **Glycolysis** (use glucose to get ATP)
- **Semi-conservative DNA replication**: (2 strands in double helix, during replication each daughter cell gets one strand from parent, other is new)
- DNA encodes polypeptides
- Polypeptides produced by transcription and translation according to genetic code
- Plasma membranes and ribosomes

Unique to Prokaryotes

- **Circular chromosome**
- **Genes organized into operons**
- **NO**
  - nucleus: translation of mRNA into protein begins before transcription of DNA into mRNA is complete
  - organelles
  - cytoskeleton
  - **meiosis** [Genes can still get moved around in other ways, both within and between species. The latter is horizontal gene transfer. Antibiotic resistance can spread in this way.]
Divide by fission

(26-02)

Salmonella enteritidis
360x real speed:
replicate in 30 min.
http://life8eiml.sinauer.com/Videos/Video-26-02.mpg

Prokaryotes are everywhere

- All around us and in us, too:
- Way more bacteria + archaea on your skin & in your intestinal tract than “you” cells
  - WE ARE HABITAT
- > 3x10^{28} in ocean (vs. visible stars in universe)
- Some survive extreme heat, alkalinity, saltiness
- Bottom of the sea
- Rocks more than 2km into Earth’s solid crust
What do they look like?

Predominantly unicellular

may be found singly or in 2D/3D chains/plates/blocks ≠ multicellular: each cell is viable independently

Biofilms

• Many prokaryotes (and some other microbes) lay down a gel-like substance on a surface. This matrix traps others, forming a biofilm.

• Biofilms can make bacteria difficult to kill. Pathogenic bacteria may form a film that is impermeable to antibiotics, for example.

• Dental plaque is a biofilm
Bioluminescence

- Some bacteria make light
- Useful for getting into a new fish gut!

Most common bacterial motion is via flagella

Fibril of flagellin protein, plus a hook and basal body

Rotates about its base

Different from eukaryotic flagellum, which beats
Cell wall differences seen by Gram stain

Gram-positive bacteria: dense peptidoglycan cell wall

Gram-negative bacteria: thin peptidoglycan layer, behind outer membrane

Exploiting unique bacterial features

- **Peptidoglycan** cell walls unique to bacteria: not found in eukaryotes or archaea
- Many **antibiotics** disrupt cell-wall synthesis
- This affects only bacteria, and has little or no effect on eukaryotic cells
Morphology gives only limited view of bacterial diversity

Huge diversity in **metabolic pathways**
- oxygen tolerance
- energy source
- carbon source
- nitrogen and sulfur metabolism

**Bioresumption?**
**Hydrogen Production?**

- Clean up oil spills, toxins
- Produce chemicals we find useful

**Enrichment Cultures**
grow microbes under variable conditions and see which thrive
6 nutritional categories \(\text{(energy, carbon)}\)

1. Photoautotrophs
   energy from \textbf{light}, \underline{carbon from CO}_2

2. Photoheterotrophs
   energy from \textbf{light}, \underline{C from other organisms}

3. Chemolithotrophs
   energy from oxidizing \textbf{inorganic} substances
   \underline{carbon from CO}_2
   some bacteria, many archaea

4. Chemolithotrophic heterotrophs
   energy from oxidizing \textbf{inorganic} substances
   \underline{carbon from other organisms}

5. Chemoorganooautotrophs
   energy from other organisms, \underline{carbon from CO}_2

6. Chemoorganoheterotrophs
   energy and \underline{carbon from other organisms}
   - most known prokaryotes, all animals, fungi,
     many protists

\[\text{3 ways to get energy} \times \text{2 ways to get carbon} = \text{6 nutritional (metabolic) categories}\]
Prokaryotic Metabolic Variety

<table>
<thead>
<tr>
<th>6 Metabolic Categories</th>
<th>Energy Source</th>
<th>Carbon Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoautotrophs</td>
<td>light</td>
<td>CO₂</td>
</tr>
<tr>
<td>Photoheterotrophs</td>
<td>light</td>
<td>other organisms</td>
</tr>
<tr>
<td>Chemolithotrophs</td>
<td>oxidizing inorganic substances</td>
<td>CO₂</td>
</tr>
<tr>
<td>Chemolithotrophic heterotrophs</td>
<td>oxidizing inorganic substances</td>
<td>other organisms</td>
</tr>
<tr>
<td>Chemoorganoheterotrophs</td>
<td>other organisms</td>
<td>other organisms</td>
</tr>
<tr>
<td>Chemoorganoheterotrophs</td>
<td>other organisms</td>
<td>other organisms</td>
</tr>
</tbody>
</table>

Evolution of Photosynthesis in Cyanobacteria
OXYGEN

None in atmosphere for first 2.3 billion years

Cyanobacteria evolved photosynthesis (oxygenic):
(ATP + water + oxygen)

Aerobic more efficient than anaerobic
Oxygen

• Early earth had little free oxygen ($O_2$)

• 2.5 bya prokaryotes evolved ability to split $2H_2O \rightarrow 4H^+ + O_2 + 4e^-$

• Electrons used to reduce $CO_2$ and make organic compounds.

• $O_2$ was a waste product.
Then make glucose (and other sugars) ...
Oxygen-generating cyanobacteria form rocklike structures called stromatolites

Oxygen

- Oxygen was poison when it first appeared
- Organisms evolved not just to tolerate oxygen, but to thrive
- Aerobic metabolism faster and more efficient
Increasing oxygen in atmosphere
Aerobic vs anaerobic metabolism

1. Oxygen is toxic to obligate anaerobes
2. Facultative anaerobes can shift between anaerobic metabolism (such as fermentation) and the aerobic mode (cellular respiration).
3. Aerotolerant anaerobes don’t use oxygen, but aren’t damaged by it
4. Obligate aerobes cannot survive without oxygen

Nitrogen and sulfur metabolism

Some bacteria use oxidized inorganic ions, such as nitrate, nitrite or sulfate
  - Denitrifiers
  - Nitrogen fixers
  - Nitrifiers
  - Sulfur-based metabolism
Prokaryotes are important in element cycling

- Plants depend on prokaryotic nitrogen-fixers
- Denitrifiers prevent accumulation of toxic levels of nitrogen in lakes and oceans
Nitrogen fixers

- Convert atmospheric $N_2$ gas into **ammonia** by means of the following reaction:

$$N_2 + 6 \, H \rightarrow 2 \, NH_3$$

- All organisms require fixed nitrogen (not $N_2$) for their proteins, nucleic acids, and other nitrogen-containing compounds

- Only archaea and bacteria, including some cyanobacteria, can fix nitrogen

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**TABLE 28.5 Some Electron Donors and Acceptors Used by Bacteria and Archaea**

<table>
<thead>
<tr>
<th>Electron Donor</th>
<th>Electron Acceptor</th>
<th>By-Products From Electron Donor</th>
<th>By-Products From Electron Acceptor</th>
<th>Category*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugars</td>
<td>$SO_4^{2-}$</td>
<td>$CO_2$</td>
<td>$H_2O$</td>
<td>Organotrophs</td>
</tr>
<tr>
<td>H$_2$, or organic compounds</td>
<td>$CD_3$</td>
<td>$H_2$</td>
<td>$CH_4$</td>
<td>Methanogens</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>$O_2$</td>
<td>$SO_4^{2-}$</td>
<td>$H_2O$</td>
<td>Methanotrophs</td>
</tr>
<tr>
<td>$S^{2-}$ or $H_2S$</td>
<td>$Fe^{3+}$</td>
<td>$CO_2$</td>
<td>$Fe^{2+}$</td>
<td>Sulfur bacteria</td>
</tr>
<tr>
<td>Organic compounds</td>
<td>$NO_3^-$</td>
<td>$CO_2$</td>
<td>$N_2$</td>
<td>Nitrifiers (or nitrate reducers)</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>$O_2$</td>
<td>$NO_3^-$</td>
<td>$H_2O$</td>
<td>Nitrifiers</td>
</tr>
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<td>$NO_3^-$</td>
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<td>$N_2$</td>
<td>Nitrifiers</td>
</tr>
</tbody>
</table>

*The same biologists use to identify species that use a particular metabolic strategy.*

We use **sugars** as electron donor and **oxygen** as electron acceptor when making energy (**Cellular Respiration**) for **Prokaryotes Variable!**
Sulfur-based metabolism

Some photoautotrophic bacteria and chemolithotrophic archaea use H$_2$S as an electron donor instead of H$_2$O.

Archaea stave off global warming

- 10 trillion tons of methane lying deep under the ocean floor
- Archaea at the bottom of the seas metabolize this methane as it rises
- Otherwise global warming would be extreme
Prokaryotes live on and in other organisms

- Mitochondria and chloroplasts are descendents of free-living bacteria
- Plants and bacteria form cooperative nitrogen-fixing nodules on plant roots
- Ruminants depend on prokaryotes to digest cellulose
- Humans use vitamins produced by our intestinal bacteria

A very few bacteria are pathogens

- Endotoxins
  - e.g. Salmonella and Escherichia
  - released when bacteria die or lyse (burst)
  - lipopolysaccharides from the outer membrane of Gram-negative bacteria
  - usually cause fever, vomiting, diarrhea
- Exotoxins
  - e.g. tetanus, botulism, cholera, plague, anthrax
  - released by living, multiplying bacteria
  - can be highly toxic, even fatal without fever
Diversity of prokaryotes

- We will discuss 6 clades of bacteria and 2 of archaea
- More are known
- More still are uncharacterized: can be hard to culture in lab
- PCR allows sequencing of unculturable organisms
- Phylogeny based primarily on DNA sequence: other traits can evolve rapidly
1. Proteobacteria

- “purple bacteria”
- ancestor of mitochondria
- Some fix nitrogen (Rhizobium)
- E. coli
- Some cycle nitrogen and sulfur

2. Cyanobacteria

- “blue-green” bacteria
- photoautotrophs
- transformed Earth with $O_2$
- many fix nitrogen
- ancestor of chloroplasts
3. Spirochetes

- Gram-negative
- motile
- chemoheterotrophic
- some are human parasites
- cause syphilis and Lyme disease

**Axial filaments produce corkscrew-like motion**
4. Chlamydias

- extremely small: 0.2-1.5 µm diameter
- Gram-negative cocci
- can only live as parasites
- cause
  - sexually transmitted disease
  - eye infections (especially trachoma)
  - some forms pneumonia

5. Firmicutes

- mostly Gram-positive
- some produce dormant endospores to wait out bad times e.g. heat, cold, drought
  - replicate DNA and encapsulate one copy in a tough cell wall
  - parent cell breaks down, releasing endospore
  - some endospores can be reactivated after more than a thousand years of dormancy
Firmicutes

Staphylococcus is a firmicute
Mycoplasmas are firmicutes

- no cell walls
- smallest known cellular organisms
- very little DNA

6. Actinobacteria
often w/ branching filaments

Mycobacterium tuberculosis is an actinomycete

Most of our antibiotics come from actinomycetes e.g. Streptomyces
Archaea

• We don’t know much
• None are human pathogens
• Most live in extreme environments: temperature, salinity, oxygen concentration, or pH
• Have distinctive lipids in their membranes
• Look at 2 groups
  – Crenarchaeota
  – Euryarchaeota

1. Crenarchaeota

- Most are thermophilic and acidophilic
- *Sulfolobus* live in hot sulfur springs, die of cold at 131°F
2. Euryarchaeota

- Some are **methanogens**, producing $\text{CH}_4$ from $\text{CO}_2$

- Responsible for 80-90% atmospheric methane, often from **belching cows**

- $\text{CH}_4$ is potent **greenhouse gas**

Some Euryarchaeota are **halophiles**

- very salty environments
- most organisms "dry" to death
- contain pink carotenoids
- live in commercial evaporating ponds