First Cells and the Universal Tree of Life

In lecture 2 we discussed Earth’s early environment (hot, rocky!), gave a very basic definition of what life is (not all agreed), and described how the first polymers (long-chained molecules) of nucleotides and polypeptides probably came into being from the most basic and common elements (CHON-PS) available on earliest Earth. There is still controversy over what the early atmosphere was like, whether it was a reducing atmosphere (CHN, NH$_3$) or whether it was oxidizing (CO$_2$, O$_2$). We are left to consider question 3.: What were the first cells like?

1. **What was the Earth’s environment like when life arose?**
2. **How is life defined, and how did life arise from inorganic forms?**
3. **What were the characteristics of the very first cells?**

Research methods that have led to knowledge of what first cells might have been like:

Because there is no direct evidence in the form of fossils of the earliest cells, evidence must be gathered from several disciplines to infer what earliest cells were like.

1. **PALEONTOLOGY** provides us with fossil evidence of early cells, which date back to about 3.5 billion years. Obviously, this means that the first cells came into being much earlier than this. These earliest fossil cells found in the Apex chert rock formation in Western Australia are thus far not definitively identified, but William Schopf (Cradle of Life), renowned paleontologist of early life fossils, believes they are cyanobacteria (photosynthesizing bacteria). However, because there are no fossils of the very first single cells, paleontology can only take us near the answer of the first cells.

2. **PHYLOGENETICS** provides insights using a different approach. Using the methods of DNA sequencing and phylogenetic analysis (via parsimony and maximum likelihood) to obtain the “tree of life”, it is possible to use the tree to map traits onto the “tree of life” to see how they might have evolved. One can use the tree to infer what the earliest common ancestor of all cells must have looked like.

The universal tree of life was first inferred by **Carl Woese** in the 1970’s using sequences of the nuclear rRNA gene known as 18S. The research led to a completely new view of the relationships of the earliest life. He discovered that Bacteria in the older sense was in fact not a monophyletic group. One group of bacteria, the extremophiles, were more closely related to the eucaryotes than they were to the other bacteria. So he and his colleagues named 3 new domains of life: **Bacteria, Archaea and Eucarya.** Relationships of these 3 groups related like this:

\[(\text{Bacteria} \ (\text{Archaea}+\text{Eucarya}))\]
Rooting the tree of life
This is difficult because there are no outgroups! Why?

However, it is possible to infer the root by using information from multi-gene families and the knowledge that gene families evolved by ancient gene duplication events. Therefore, one can use one of the early gene copies as an outgroup.

Example: aminoacyl-tRNA synthetase gene family—IleRS (Isoleucine tRNA synthetase) gene, ValRS (ValineRS) gene and LeuRS (LeucineRS) gene, three members of the family. Sequencing each of these genes from organisms from all three Domains (Bacteria, Archaea and Eucarya) will give insights into how the three Domains are related by revealing the rooting of the tree of their relationships. If the branching pattern of taxa for each gene shows the same (Bacteria + (Archaea + Eucarya)) pattern of relationships—the same rooting of the three Domains for each gene—it is possible to conclude that the entire gene family consistently shows the same relationships. In that case, the rooting is probably the correct one. [Note: the example in the book is confusing so please use this modified version.]

Lateral Gene Transfer
From DNA sequences of many organisms, the Universal Tree of Life shows that there was a lot of movement of genes from one taxon to another (lateral gene transfer). An infamous example of this sharing of genes is that of the mitochondrial and chloroplast cells. These are now organelles within all eukaryotic cells, but they were at one time free-living single-celled forms of Bacteria: Purple Bacteria ⇒ Mitochondria; Cyanobacteria ⇒ Chloroplasts.
Fossils as estimates of divergence times of the branches on the Universal Tree

The Apex fossils put a minimum age of the first cells at 3.5 billion years ago, but they are too advanced to be close to life’s beginnings. “Living systems arose during the first billion years of Earth’s existence, but just when is an open question.” (Schopf, 1999, p. 166).

No life could have evolved and lasted during the first 500-600 Ma of Earth’s history (between 4.5-3.9 billion years ago) due to the catastrophic collisions by falling meteors. These collisions resulted in complete sterilization of the planet, the vaporization of the oceans.

But after the last of the major impacts, relatively complex cells arose within only about 400 Ma—between 3.9 and 3.5 billion years ago.

The oldest known fossil eukaryotes are 1.85-2.1 billion years old, collected in Michigan and thought to be algae.

Earth’s environment had only trace quantities of oxygen until about 2.0 billion years ago, when cyanobacterial oxygen from photosynthesis was allowed to accumulate in the atmosphere. Before that it reacted chemically in the oceans with ferrous iron from the earth’s hot interior to produce ferric iron oxides which precipitated out of solution to form the banded-iron formations. These rocks contain evidence of photosynthesizing cyanobacteria. Stromatolites (microbial mats, rich in cyanobacteria) also provide evidence of early phytosynthetic life—the oldest stromatolites are found in Western Australia (3.45 billion years old). Today’s living stromatolitic beds look similar to the ancient fossilized beds—i.e., they have not changed much. Thus, they can tell us what the early environment was like but not much about the evolution of cells.

First Cells

Several lines of evidence suggest that the first-celled organisms looked like or even were bacterial in form.

- The Universal Tree of Life based on many phylogenetic analyses of different DNA sequences and application of the parsimony criterion suggest that the common ancestor of the tree was a single-celled organism, likely to have been bacterial-like; it probably contained DNA and/or RNA. It also suggests that some of its genes came from lateral transfer of other cells or other genes.
- Geology and Paleontology provide evidence that the first cells were bacterial-like, if not actually cyanobacteria. Evidence from Iron-band formations and stromatolites indicate the origin (first divergence on the tree) of cellular life was probably between 3.9 and 3.5 billion years ago. The time estimates are not accepted by all scientists in the field.
- Bacteria and Archaea have not changed much since their early evolution, and any change has been slow and gradual.
- Eukarya, however, underwent major change and radiation of diversity.

References