Earth is about 4.5 billion years old

Fossils of the first organisms (bacteria) are about 3.5 billion years old

Until less than 1 billion years ago, the only kinds of life on Earth were prokaryotes

What happened on Earth that led to the appearance of the first living things?

What happened during the 2.5 billion years between the time that the first life forms appeared, and the time less than 1 billion years ago when eukaryotes began to appear?

Organisms are:

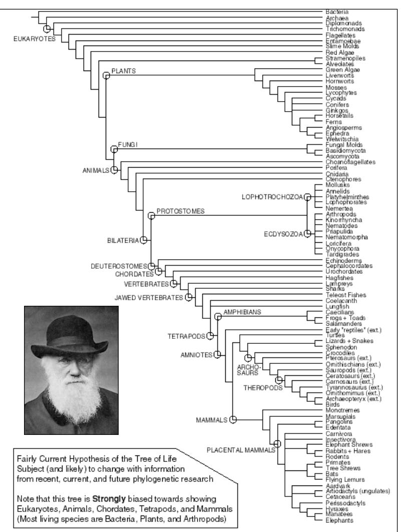
- Chemically complex
- Highly organized
- Capable of processing energy (metabolism)
- Capable of development and growth
- Capable of self-replication
- Constantly evolving through time
- In possession of a heritable code that regulates all of these

*But what is "life"?*

The Biological Decentralization recognized that the natural order of life is a tree-like history of shared ancestry between organisms.

Therefore, "life" is also that single common history that all organisms share.

Life is the all-inclusive clade of organisms on earth; all of the descendants from shared, extinct ancestors.




History of the Earth: First, Fire…

- Early Earth had no atmosphere
- Early Earth had no oceans
- Early Earth had no free Oxygen (but did have $H_2O$ and $CO_2$)
- Outgassing from volcanic activity resulted in an atmosphere rich in water vapor

… Then Rain

Torrential "great rains" dissolved soluble compounds on the Earth and collected in low regions, forming seas

*Still no free Oxygen*

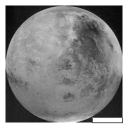
• Living things require complex carbon-based (organic) compounds (e.g. carbohydrates, lipids, proteins, nucleic acids)

• But organic compounds do not form easily or spontaneously without the input of free energy

• Compounds in the early seas were mainly stable and non-reactive

• Where did the first organic compounds come from?


Earth?


Mars?


Somewhere else?

1. Terrestrial Origin of Organic Compounds


Earth

External energy from ultraviolet (UV) radiation, lightning, or heat from the Earth may have caused complex organic compounds to form from simpler chemicals that were already abundant in the seas of ancient Earth.

Water ($H_2O$)

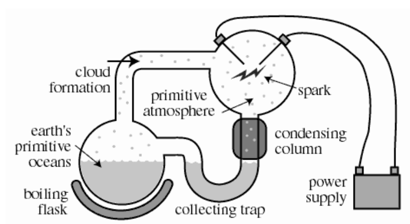
Ammonia ($NH_3$)

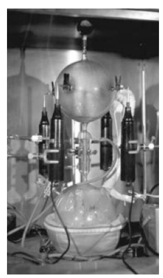
Methane ($CH_4$)

Hydrogen ($H_2$)

• This has been demonstrated experimentally!

The Miller and Urey Experiment (1953)
(has also been replicated many times)



• Closed system of water, ammonia, methane, and hydrogen, when given an electrical charge, spontaneously formed many organic compounds including amino acids, particularly the ones most abundant in proteins today.

• Such a process could have caused organic compounds to accumulate in early oceans, especially if there were no organisms to use them up

2. Extraterrestrial Origin of Organic Compounds

• Comets, asteroids, and meteors are rich in organic compounds formed at the time of the Big Bang

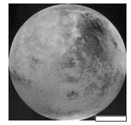
• Extraterrestrial objects falling to Earth could have deposited enough organic material over hundreds of millions of years to accumulate in large amounts


Comet Hale-Bopp

• Panspermia: one step further

The hypothesis that simple bacteria-like organisms exist throughout the universe, and can survive the void of space to travel long distances on comets, asteroids, and meteors. When they land on worlds with suitable characteristics, they may thrive, evolve, and diversify.

## Are we all from Mars… or somewhere else?



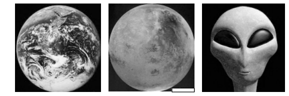
Mars

Martian dust and meteors occasionally hit the Earth, ejected from Mars by asteroid impacts. To date, 26 Martian meteorites have been found.

In 1996, NASA scientists reported that a known Martian meteorite, known as ALH84001, contains magnetite crystals consistent with biodeposition, and tiny globs of carbonate that appear to be microfossils of bacteria-like organisms. Later studies both supported and refuted this.

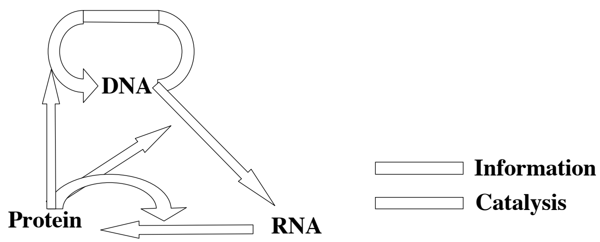
At least two other known Martian meteorites contain structures hypothesized to be possible microfossils

## The next problem:



*Whether life (as we know it) originated on Earth, Mars, or Somewhere Else, there is still the question of how organisms came to exist from pre-existing organic compounds.*

## Evolving the Information Circle
(A Chicken-or-the-Egg-Type Puzzle)

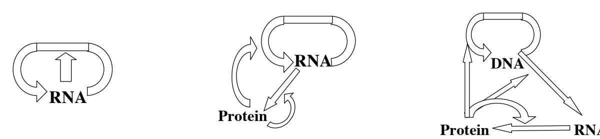



Catalyst: An agent that accelerates the rate of a chemical reaction, without getting used up or incorporated into the products. Protein catalysts are made by and required by the I.C.

How could self-replication and translation begin?

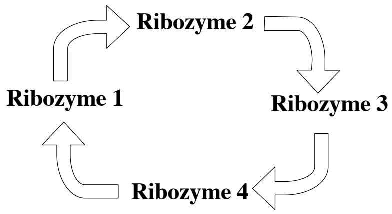
## The evolution of self-replication

- RNA can sometimes act as a catalyst
- Ribozymes are RNA molecules that can catalyze their own replication, although slowly and inefficiently
- The first self-replicating molecules were probably RNA-based ribozymes that could act as their own catalysts
- This is the basis of the "RNA World" model




**1. RNA only** **2. Protein added** **3. DNA added**

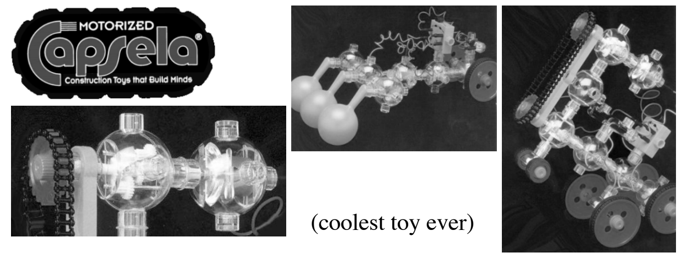
Because ribozymes are inefficient in self-replication, their efficiency could be improved by cooperative hypercycles. Mutations that increase efficiency would be perpetuated by natural selection.




The hypercycle illustrates that life is unlikely to have begun from a single kind of self-replicating molecule, but instead, would have required multiple different molecules that cooperated in a self-sustaining way. These molecules and cooperative relationships were initially formed by chance.

*Life-like phenomena began with chance encounters between different organic molecules. The results of most of these encounters were unremarkable; however, some of them resulted in self-sustaining cooperative interactions.*

Thus, life began with a "kit" of modular organic components. Some "worked well" together -- others didn't.




(coolest toy ever)

**The Origin of Translation:**

The genetic code could not utilize 2-position codons due to the existence of 20 amino acids and only 16 ways that 4 bases can combine

Therefore, there is degeneracy

The genetic code is nearly universal. Only mitochondria and some microbes vary slightly from it.

2nd base in codon

| 1st base in codon | U | C | A | G | 3rd base in codon |
|---|---|---|---|---|---|
| U | Phe | Ser | Tyr | Cys | U |
| | Phe | Ser | Tyr | Cys | C |
| | Leu | Ser | STOP | STOP | A |
| | Leu | Ser | STOP | Trp | G |
| C | Leu | Pro | His | Arg | U |
| | Leu | Pro | His | Arg | C |
| | Leu | Pro | Gln | Arg | A |
| | Leu | Pro | Gln | Arg | G |
| A | Ile | Thr | Asn | Ser | U |
| | Ile | Thr | Asn | Ser | C |
| | Ile | Thr | Lys | Arg | A |
| | Met | Thr | Lys | Arg | G |
| G | Val | Ala | Asp | Gly | U |
| | Val | Ala | Asp | Gly | C |
| | Val | Ala | Glu | Gly | A |
| | Val | Ala | Glu | Gly | G |

Life may have evolved multiple times in the early history of Earth, or on other planets, but life on Earth as we know it now all stemmed from a common ancestor.

- Phylogenetic evidence (homology of DNA/RNA sequences)

- All life shares universal characteristics that are chemically arbitrary -- for example, the codons in the genetic code

- Another chemically arbitrary fact: only L-optical isomers of amino acids are synthesized and used by living things. D-optical isomers are equally likely to be formed in abiotic synthesis, and could have worked just as well. But, you can only build functional proteins using one set of isomers, or the other. Thus the fact that only L optical isomers are used in life is a result of early contingency.

Contingency: "One damn thing leads to another"

Example 1: The tiny Hawaiian Islands contain over 200 different species of crickets, while other insect groups -- such as termites and cockroaches -- are completely absent from Hawaii. Why crickets?

Example 2: Until relatively recently (less than 1 million years ago), the dominant predators in South America were giant, flightless birds (now extinct). Why aren't they still the dominant predators there?

Example 3: When large, bird-like "reptiles" (dinosaurs) were the dominant vertebrates on land, mammals were small, non-diverse, and not tremendously important. Why isn't the world still like this?

Contingency: "One damn thing leads to another"

Example 1: The tiny Hawaiian Islands contain over 200 different species of crickets, while other insect groups -- such as termites and cockroaches -- are completely absent from Hawaii. Why crickets?
*They were among the first insects to reach the Hawaiian islands, and thus had more time to diversify with little competition, until they became a dominant part of the insect fauna*

Example 2: Until relatively recently (less than 1 million years ago), the dominant predators in South America were giant, flightless birds (now extinct). Why aren't they still the dominant predators there?
*When the land bridge to North America was formed, carnivorous mammals from North America entered South America and outcompeted the giant predator birds.*

Example 3: When large, bird-like "reptiles" (dinosaurs) were the dominant vertebrates on land, mammals were small, non-diverse, and not tremendously important. Why isn't the world still like this?
*About 65 million years ago, a large asteroid impacted the Earth near the Yucatan peninsula, causing a mass extinction and opening up new opportunities for mammals to diversify.*

**Where did the first cells come from?**

- In the modular RNA world, different kinds of molecules cooperated in an "open" environment
- Cells provide a means of isolating and protecting cooperative relationships from the external environment
- Although cells are self-contained, they still permit the entrance of molecules from the external environment, but this can be largely controlled by the cell.
- The first cell membranes could have formed spontaneously from certain molecules; coacervate droplets and proteinoid microspheres are natural, cell-like (but nonliving) molecular constructs that can keep out the external environment, contain chemical reactions, and even "grow" and "divide" like living cells.

Coacervate droplets: macromolecules surrounded by a shell of water molecules which are rigidly oriented relative to the macromolecule forming a "membrane". Coacervate droplets adsorb and absorb chemicals from the surrounding medium and can be highly selective like a cell membrane.

Proteinoid microspheres form when hot aqueous solutions of polypeptides are cooled. They are much more stable than coacervate droplets and have the following characteristics: swell in a high salt solution, shrink in a low salt solution, have a double-layered outer boundary which is very similar to a cell membrane, show internal movement similar to cytoplasmic streaming "grow" in size and complexity, "bud" in a manner superficially similar to yeast cell reproduction, have electrical potential differences across the outer boundary which is necessary for cell membranes to generate ATP, and aggregate into clusters.

Both of these "prebionts" are structurally complex and sharply separated from their environment, creating a situation in which chemical reactions can take place inside the prebionts that would not happen in the surrounding medium.

Early cells

- The first cells were bacteria or bacteria-like heterotrophs that acquired organic compounds and energy from the surrounding environment
- Eventually, the organic "soup" must have gotten depleted, and some bacteria became predators or parasites of others
- When nutrient supplies were greatly depleted, bacteria-like organisms evolved autotrophy, the ability to make organic compounds and acquire energy from inorganic molecules (e.g. Sulfur, CO2, Ammonia)
- The first of these were chemoautotrophs, which still exist today, often in extreme environments such as deep-sea thermal vents, volcanoes, oxygen-poor bogs and marshes, or environments of high salinity (salt content.) Note that these habitats resemble the early environment of Earth!

Photoautotrophy: Big News for Earth

Used Solar radiation for energy for making organic molecules

The first photoautotrophs were probably cyanobacteria (blue-green "algae"; still extant today)

The oldest fossils we know of, stromatolites, are formed from layers of ancient cyanobacteria mixed with sediment

Cyanobacteria do not require free oxygen,
*but they release it as a product of photosynthesis!*

- Fossil Stromatolites: Over 3.5 billion years old
- Formed by layers of cyanobacteria mixed with sediment
- The process continues even today

**The Oxygen Revolution**

- The evolution of photoautotrophy (and photosynthesis) was the key event that filled Earth's atmosphere with its product, free oxygen.

**Results of the oxygen revolution:**

1.) Oxidizing reactions made possible, allowing more chemical interactions and more efficient use of energy;

2.) An ozone layer ($O_3$) formed above the Earth, which screened out UV radiation from the sun

3.) Therefore, the primitive conditions on Earth that allowed life to begin in the first place were destroyed forever

Another Revolution: The Eukaryotic Cell

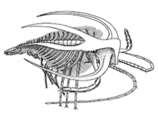
- Up to this time, all organisms on Earth were prokaryotic: no cell nucleus, no specialized organelles, circular genome
- Eukaryotes -- including all plants, animals, and fungi -- have a membrane-bound cell nucleus, specialized organelles such as chloroplasts or mitochondria, and a linear genome. They did not exist on Earth until about 1 billion years ago.
- The Eukaryotic cell evolved through endosymbiosis of prokaryotes. The chloroplast is derived from cyanobacteria; the mitochondrion is derived from oxygen-using bacteria
- Evidence: Chloroplasts and mitochondria have their own genomes which are more similar to the genomes of cyanobacteria and aerobic bacteria (respectively) than they are to the genomes of the eukaryotes they live in.

Then, about 550 Million Years Ago...

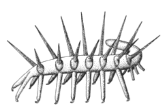
**The Cambrian "Explosion"**

During the Cambrian explosion, all of the animal phyla present today appeared within a very short period of time.

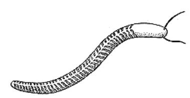
(Phyla: Arthropods, Mollusks, Chordates, "Worms", etc.,)
Each phylum has its own characteristic bauplan (body plan)



*Marrella* (arthropod)



*Hallucigenia* (onycophoran)



*Pikaia* (chordate)

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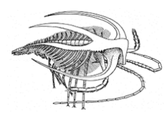
(Phyla: Arthropods, Mollusks, Chordates, "Worms", etc.,)
Each phylum has its own characteristic bauplan (body plan)

But the Cambrian explosion also produced a lot of bizarre body plans that are now extinct; those animals cannot be assigned to any phyla that exist today. They were unique "kinds" of animals.



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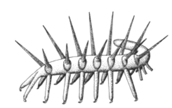

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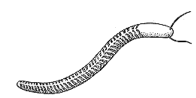

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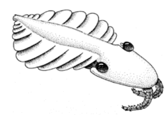
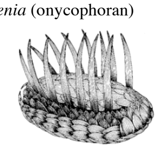


*Anomalocaris*

*Amiskwia*



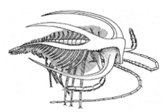
*Wiwaxia*

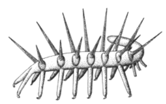
*Opabinia*

A Lesson from the Cambrian Explosion: contingency (again)

Like modular molecules in the early RNA World, Cambrian animals were random experiments in animal design.  Why some phyla survived and others went extinct is unknown. The phyla that survived were probably just lucky.

Why should arthropods and onycophorans have survived to the present day, but not the phyla represented by *Anomalocaris* and *Wiwaxia*?





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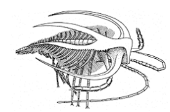
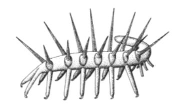
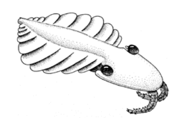




If we could “rewind” and “play” the history of life again, it would be a completely different world today -- perhaps with animals like *Anomalocaris* and *Wiwaxia*.



The Incomplete Nature of the Fossil Record

The fossil record has been likened to a book in which 90% of the pages are missing.  On the remaining 10% of pages, 90% of the words have been erased.  And within the remaining 10% of words, only 1 out of every 10 letters is still legible

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Consider:  for every fossil organism, the physical and chemical conditions of its immediate environment at the time of its death had to be just right for fossilization to occur.

- Then, the fossil had to resist erosion for tens of millions or hundreds of millions of years.
- After all of this, you still have to find it!

Despite the incompleteness of the fossil record, the history of life can still be reconstructed using phylogeny, without actually having specific knowledge of all of life's ancestors.

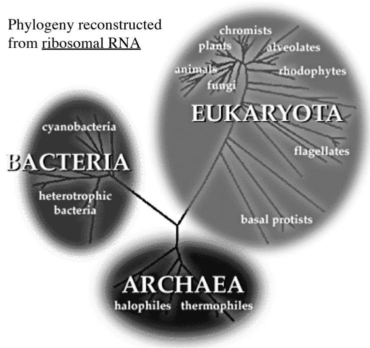
We now know that the natural organization of all life is into three domains:

Bacteria

Archaea

Eukaryota

Phylogeny reconstructed from ribosomal RNA




While we go through the history of life, remember that all this evolution was occurring concurrently in different lineages. Plants, animals, fungi, and other dominant groups have all been around for over 540 million years

Multicellular organisms have been around for over 650 million years, and basic eukaryotes, about 1 billion years

Bacteria and Archaea:
Much longer

**GEOLOGIC TIME SCALE**

| Time Units of the Geologic Time Scale | | | | | Development of Plants and Animals |
|---|---|---|---|---|---|
| Eon | Era | Period | Epoch | | |
| Phanerozoic | Cenozoic | Quaternary | Holocene | 0.01 | Earliest *Homo sapiens* |
| | | | Pleistocene | 1.6 | |
| | | Tertiary | Pliocene | 5.3 | Earliest hominids |
| | | | Miocene | 23.8 | |
| | | | Oligocene | 33.7 | "Age of Mammals" |
| | | | Eocene | 55 | |
| | | | Palaeocene | 65 | Extinction of dinosaurs and many other species |
| | Mesozoic | Cretaceous | "Age of Reptiles" | 145 | First flowering plants |
| | | Jurassic | | 208 | First birds<br>Dinosaurs dominant |
| | | Triassic | | 248 | First mammals |
| | Palaeozoic | Permian | "Age of Amphibians" | 286 | Extinction of trilobites and many other marine animals |
| | | Carboniferous: Pennsylvanian | | 320 | First reptiles<br>Large coal swamps |
| | | Carboniferous: Mississippian | | 360 | Amphibians abundant |
| | | Devonian | "Age of Fishes" | 410 | First amphibians<br>First insect fossils |
| | | Silurian | | 438 | Fishes dominant |
| | | Ordovician | "Age of Invertebrates" | 505 | First land plants<br>First fishes |
| | | Cambrian | | 545 | Trilobites dominant<br>First organisms with shells |
| | | Vendian | "Soft-bodied faunas" | 650 | Abundant Ediacaran faunas |
| Proterozoic | Collectively called Precambrian<br>comprises about 87% of the geological time scale | | | 2500 | First multicelled organisms |
| Archean | | | | 3800 | First one-celled organisms<br>Age of oldest rocks |
| Hadean | | | | 4600 Ma | Origin of the earth |