The Origins of Life on Earth

The History of Life on Earth

• The record of life on Earth extends to about 3.85 Gya.
(Chemical indicators, δC^{13}, photosynthesis; fossils at ~ 3.5 Gya)

• The earliest "recognizable" life forms are single-celled prokaryotes.
(Fossil cellular microbial filaments, prokaryotic fossils at ~ 3.4 Gya)

• The subsequent historical record appears to be more-or-less continuous.
(Sequential, Consistent with vagaries of fossilization or preservation.)

• That record shows increasing complexity and diversity.
(Taxonomy & Cladistics; Speciation.)

• Subsequent forms are apparently descendants of these first life forms.
(Taxonomy & Cladistics. The independent temporal record.)
Three present-Day Domains: Archaea, Bacteria; Eukarya

How did the first simple life form(s) arise from non-living material?

Life is Chemistry

Evolution can explain the present-day diversity and complexity of life forms.

The basic ingredients of Darwinian evolutionary theory are:

- **Descent with Modification (Genetics)**
- **The Process of Natural Selection (Adaptation)**

Two other requirements are:

- **Time** (~ 3.8 Gyr)
- **A Last Universal Ancestor**

The first life form(s) ancestral to all present life forms.

The Problem

We need a primordial precursor capable of reproduction and evolution to something recognizable as life.

A clue to the probable nature of this initial form is provided by the molecular chemistry of the genetic code.

Question: When does a collection of chemicals become a creature?
Eukaryotes, Bacteria and Archaea are “alive” - but what about viruses?
Are reproducing molecules like DNA and RNA (or PNA)? “alive”?

The Origins of Life

An Operational Definition of Life

1. **An individual life form has identity; it occupies a bounded volume**
   ....bounded, perhaps, by a cell wall, shell, or skin, ...
2. **An individual life form reproduces, producing copies of itself**
   .... but not necessarily perfect copies
3. **A life form extracts energy (and matter) from its environment**
   .... which it uses for its own construction and function

Item #3 is required by Item #2 insofar as matter is concerned. It excludes some inorganic replication processes such as crystal growth and also implies:

4. **A life form responds to changes in its external environment**
   .... principally by changes in its level of activity

Present-day life forms exhibit other universal characteristics:

5. **Individuals are impermanent; they are born, live, and they die.**
6. **Populations arise from other populations (Speciation)**
7. **Populations (Species) can evolve and speciate, persist or vanish.**
8. **<u>All</u> known life forms are based on carbon chemistry.**

The Principle of Parsimony (a.k.a., Ockham's Razor) suggests that we adopt only the first three items above as providing our working definition of life:

" It's alive if it has identity, reproduces, and metabolizes."

The Mechanism of Evolution: The Genetic Code

Some Nomenclature

Deoxyribonucleic acid (DNA): A long molecule encoding genetic information.
(The DNA molecule is capable of self-replication and duplication.)

Ribonucleic acid (RNA) carries the genetic information for most viruses.
(It also acts as a template in translating DNA gene segments into proteins.)

Chromosomes: Collected stretches of DNA containing numerous genes.
(Ordered as paired identical chromatids in eukaryotes. Linear or rings in prokaryotes.)

Genes: The units of heredity. Physically, segments of DNA on chromosomes.
(The segments ultimately encode for amino acids and their ordering into proteins.)

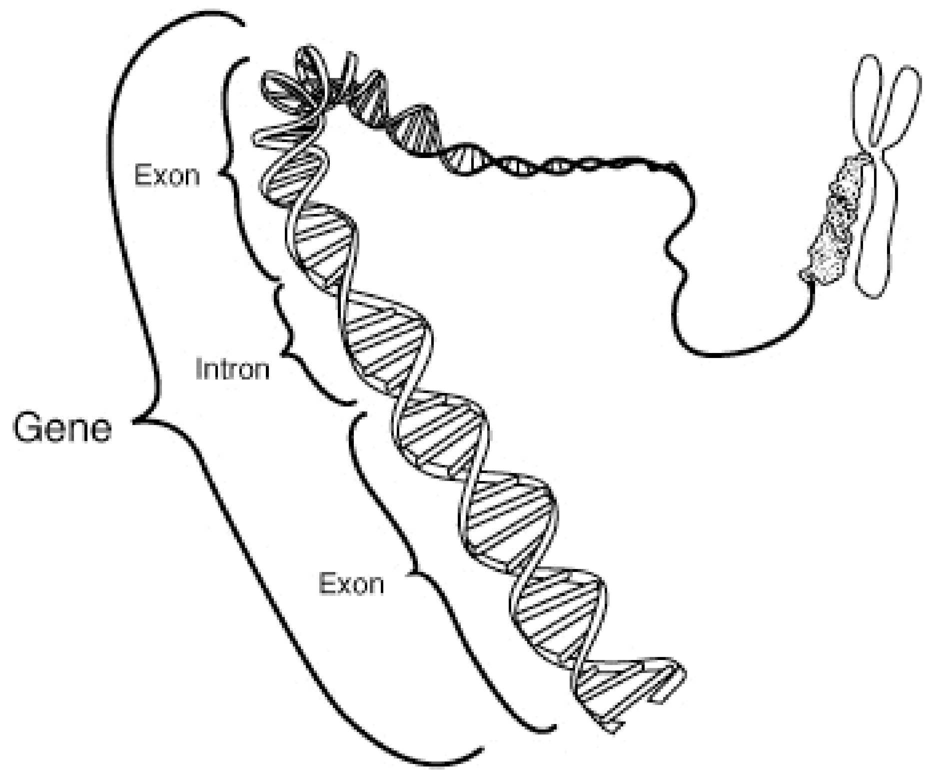
The Genetic Code: Base-Pair Coding in DNA

Guanine (G) - Cytosine (C)
Adenine (A)-Thymine (T)
but in RNA (and occasionally in DNA) the last is replaced by
Adenine (A) - Urasil (U)

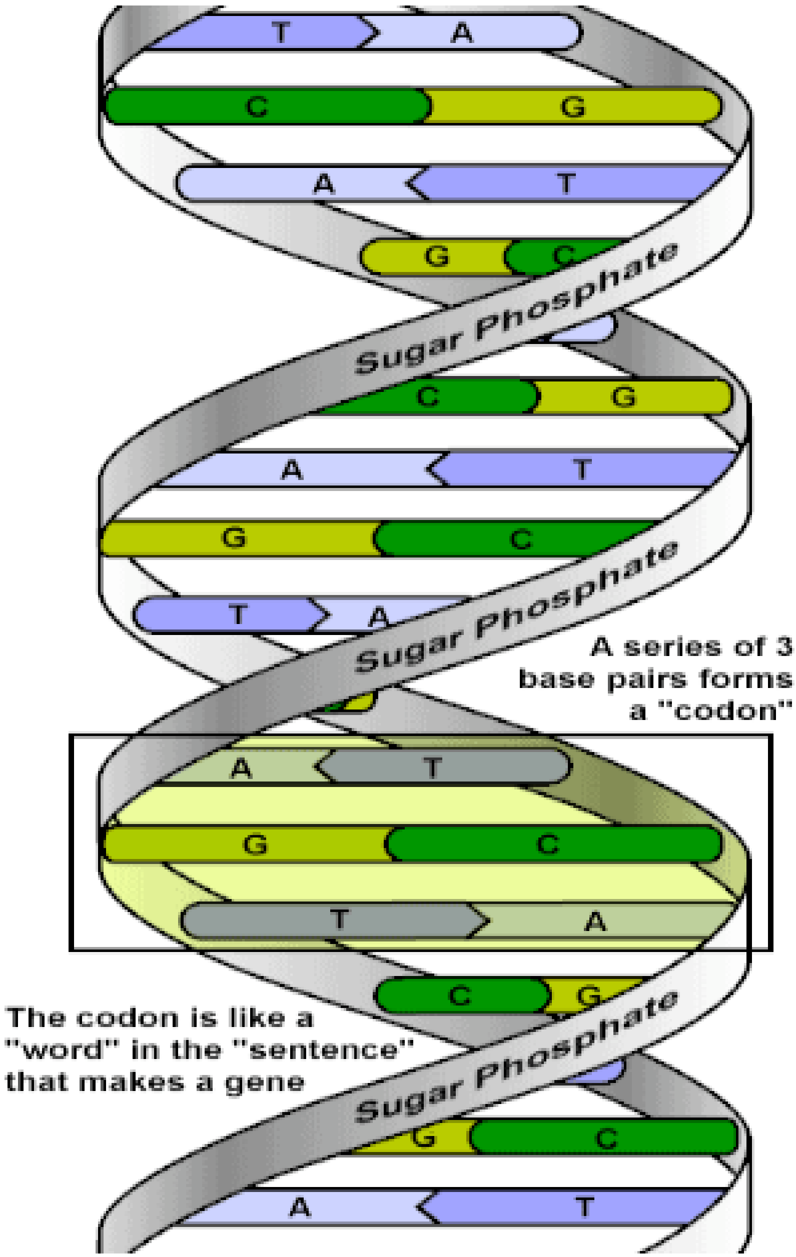
Codons: Three-base sequences (64 possibilities) that code for amino acids.
i.e., 6 bit “words”

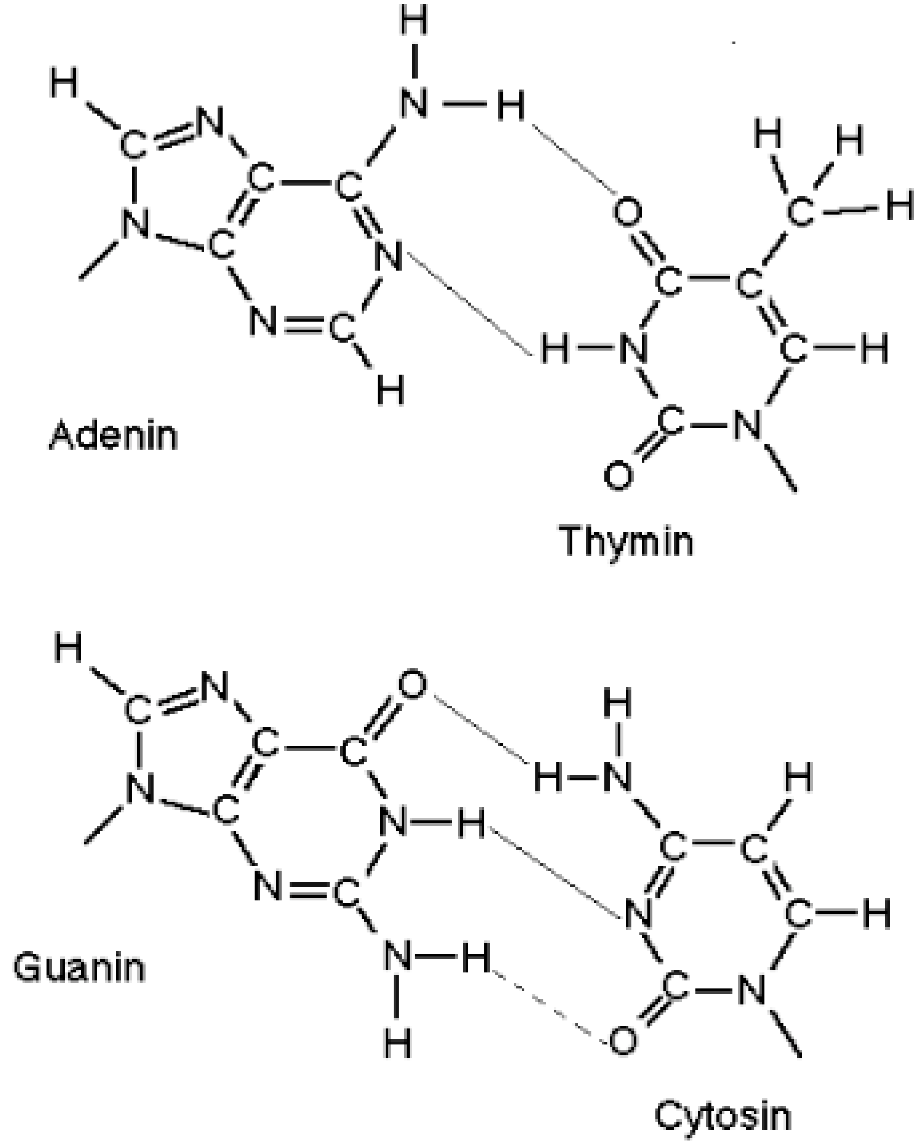
Chromosomes, Genes, and DNA

Diploid Chromosome (with 2 identical chromatids)



Exons are the information-carrying parts of the gene.
Introns are partswhich are spliced out after transcription from RNA to mRNA.
The Genome is the collection of chromosomes defining a life form.


Sugar Phosphate
Sugar Phosphate
Sugar Phosphate
A series of 3 base pairs forms a "codon"
The codon is like a "word" in the "sentence" that makes a gene


Adenin
Thymin
Guanin
Cytosin

The Genetic Code

The genetic code in DNA consists of a particular sequence of base pairs along the double-helix sugar phosphate backbone.

The genetic code of RNA consists of a particular sequence of bases along a single sugar phosphate backbone.

The “unit” of coding information is one of the four bases

Guanine (G)   Cytosine (C)
Adenine (A)   Thymine (T)

In RNA (and occasionally in DNA) Thymine is replaced by Urasil (U).

... so each base location represents 4 bits of information (i.e., 4 possible values)
... each 3 base codon represents 6 bits of information (i.e., 64 possible values)

The copying processs consists of exposing a string of bases, say

...AGGCTGAGT...

Which the then acquire the complementary bases from the enironment

...TCCGACTCA...

which, with its acquired backbone, separates as a piece of “Messenger RNA”.

This mRNA then provdes a template for making a copy of the original base string which (in the case of DNA) acquires a complementary base at each location and the second backbone to form a double-helix copy of the original.

The Genetic Code

Some Numbers for Reference and Perspective

Chromosomes (haploid and diploid)

Plants: Typically 10 - 50 (but ~1200 for ferns)
Animals: Typically 4 - 50 (but ~ 200 for butterflies)

Gene Numbers

Plants: Up to ~50,000
Animals: 10,000 - 30,000
Bacteria & Fungi: 500 - 6,000
DNA Viruses: 10 - 1,000
RNA Viruses: 1 - 25
Viroids: 0 or 1

Base Pairs

Plants: Up to ~10^{11}
Animals: ~1×10^{8} to ~ 3×10^{9}
Bacteria & Fungi: ~10^{5} to ~ 10^{7}
DNA Viruses: 5,000 to ~ 10^{6}
RNA Viruses: 1,000 to 23,000
Viroids: ~300

Scenario: The Appearance of Life

The initial step should be the "spontaneous" formation of a RNA-like molecule capable of replication.

Requirements:

- **A suitable solvent (e.g., Water)**
  ... in which certain molecules can form and move
- **A suitable mixture of bases (e.g., G,A,C,T, U, ...)**
  ... capable of forming base pairs of common length.
- **Molecules to form a suitable backbone chain.**
  ... and to which the ends of the base-pairs can bind.

The process of self-assembly can be an endothermic process. The rate (or likelihood) of the process will depend upon the concentration of the ingredients, the ambient physical conditions, and the absence of competing processes.