THE ORIGIN OF LIFE

Evolution and the Natural World

Lecture 12

14/11/2021

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Is that even a scientific question?

What do we want to know?

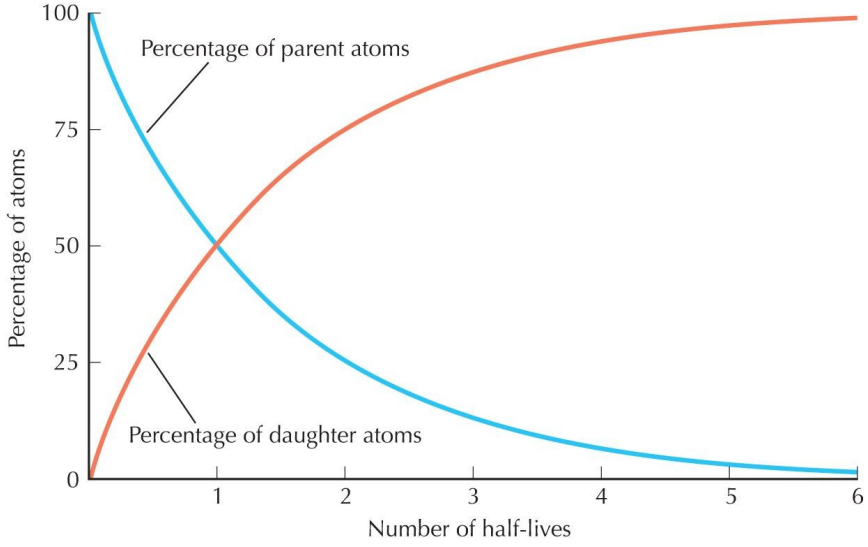
- How?
  - What were the first living organisms like?
  - What made the origin of such organisms possible?
  - How did they evolve into life as we know it now? How did universal traits like DNA, translation, cells and so on emerge?
- When?
- Where?

What are the sources of information?

- Rocks, meteorites and fossils
- Chemical/Biochemical experiments
- Comparison of extant species (but this gives information only about the Last Universal Common Ancestor – LUCA)
- Astrobiology (maybe in the future)

WHEN DID LIFE BEGIN?

How old is the Earth?



- Source of information – radiometric dating
- Age of the Earth is estimated to be ~4.5 bya
- Earth cooled down around 4.2-4.0 bya and that is when the hydrosphere formed

Earliest evidence of life

- Oldest undisputable indications of life – stromatolites 3.5 billion years old
- Some speculations of life being as old as or older than 4 bya

https://evolution.berkeley.edu/evolibrary/article/side_0_0/origsoflife_03
https://www.sharkbayvisit.com.au/stromatolites/stromatolites

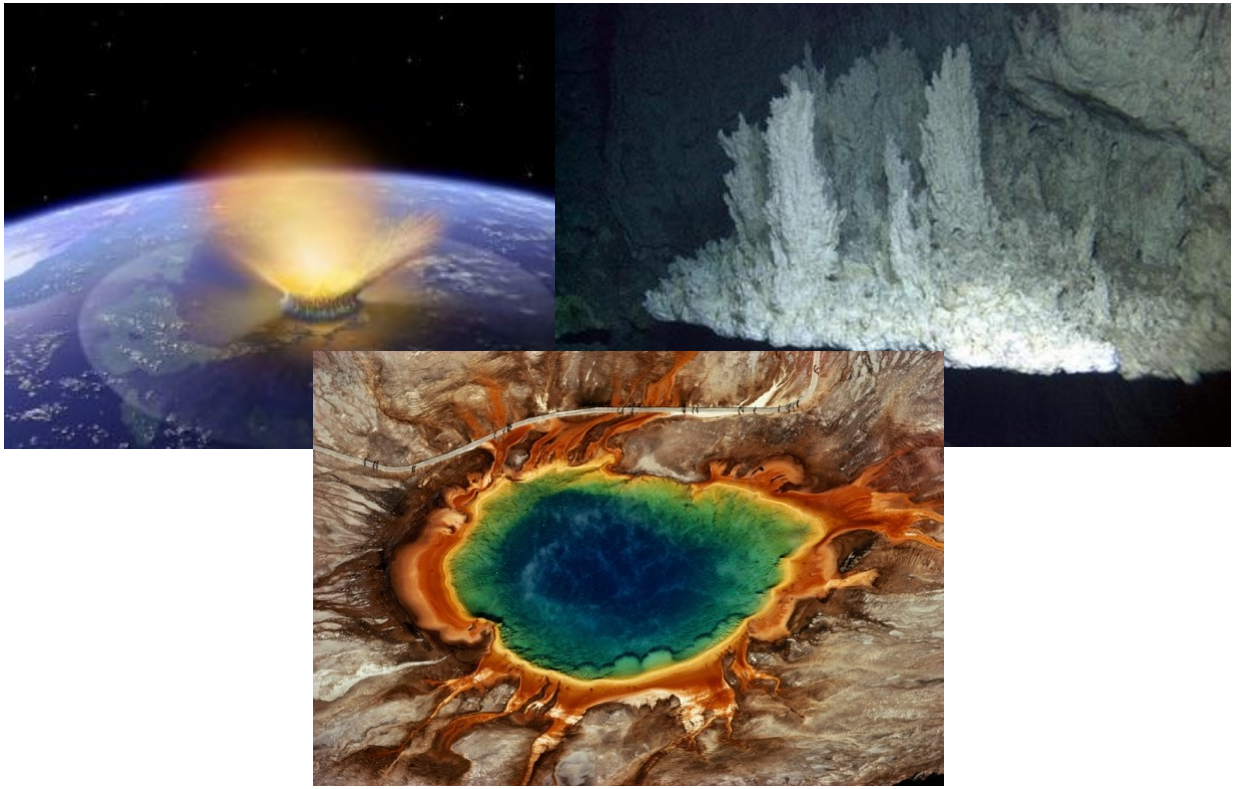
But these are already cells, so interesting stuff happened before that

WHERE DID LIFE BEGIN?

What and how can we know?

- Conditions should favor abiogenic synthesis of organic compounds
  - Inorganic precursors, energy source and catalysts are needed
  - Gradients of temperature, pH, etc. and non-equilibrium systems are believed to be “useful”
- Additional (disputed) criteria
  - Solution composition matching cytoplasm composition

Where did life begin?



- Panspermia
- Shallow ponds
- Hydrothermal vents
- Geothermal springs

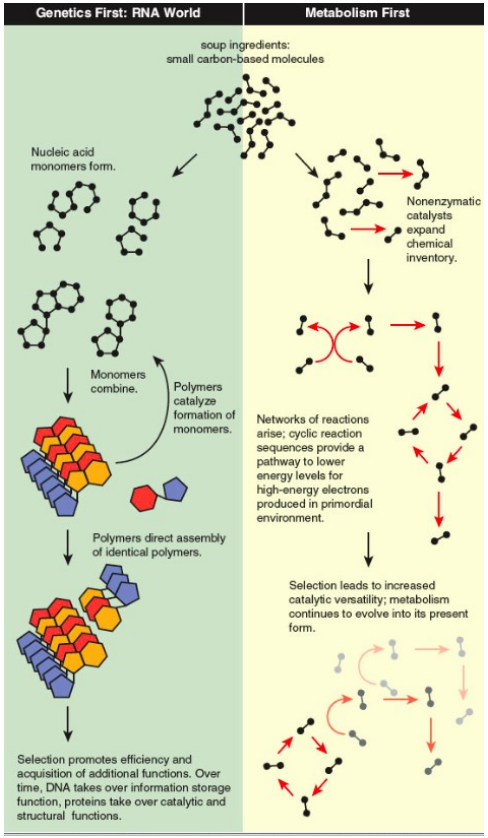
https://www.nature.com/news/debate-bubbles-over-the-origin-of-life-1.10024

WHAT WERE THE VERY FIRST LIFE FORMS LIKE?

What are we looking for?

- Living organisms are material objects capable of reproduction (with metabolism on the one hand and inheritance, variability and hence evolution on the other)

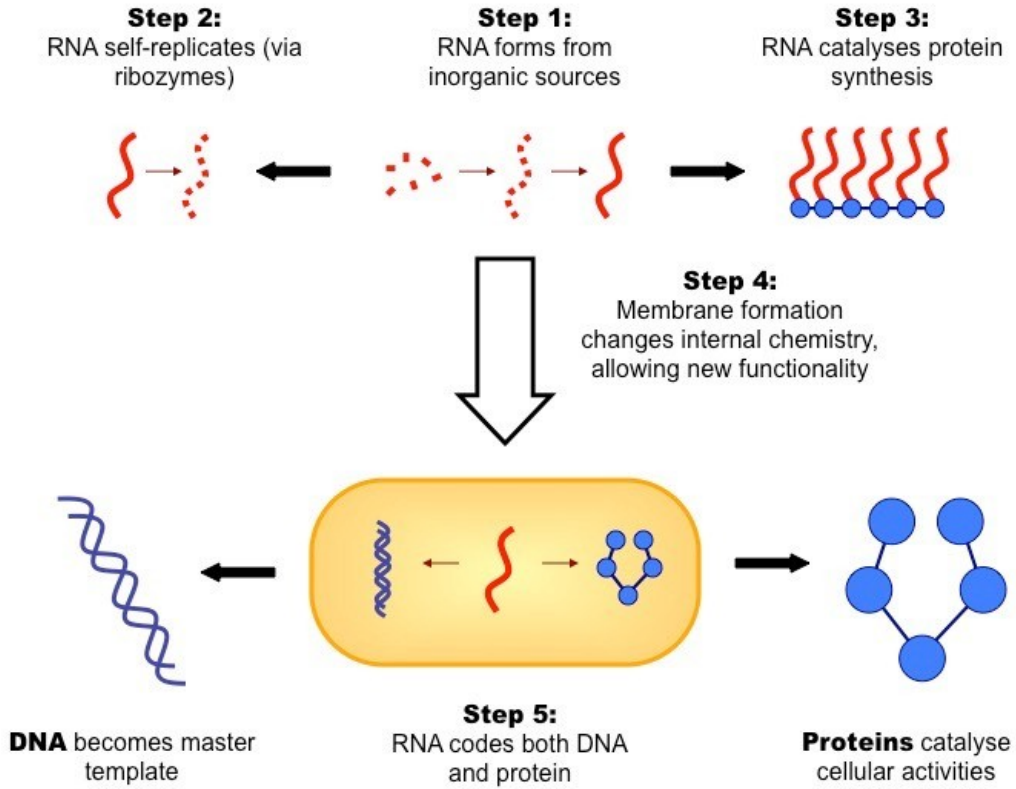
Different points of view



- **Metabolism first** – rather complex metabolism including cycles and networks of reactions was first. Sort of “chemical natural selection”
- **Replication first** – replicator molecules arose before advanced metabolism, which, in tern, emerged only when enzymes were around

https://gabrielledallman.wordpress.com/2016/10/15/metabolism-first-vs-replication-first/

Example: RNA-world hypothesis



- Prebiotic reactions lead to accumulation of ribonucleotides which assemble into random RNA sequences
- Some of these are replicated, so natural selection starts

RNA is special and ancient

- Carries genetic information (mRNA, some viral genomes)
- Is less stable, but more reactive than DNA + can have secondary and tertiary structure =>
- Ribozymes (enzymatic RNAs):
  - rRNA catalyze protein synthesis
  - RNA-cleavage activity, like self-splicing, self-cleavage of some viral RNA genomes
  - Artificial RNAs with ligase and polymerase activity

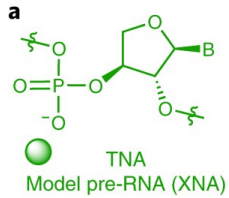
RNA is special and ancient

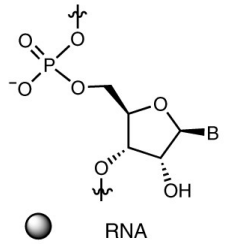
- RNA is involved in:
  - Translation (mRNA, tRNA, rRNA)
  - DNA-replication (primers)
  - Splicing, protein translocation, translation quality control, RNA interference
- Reverse transcription copies RNA to DNA
- Deoxyribonucleotides are synthesized from ribonucleotides

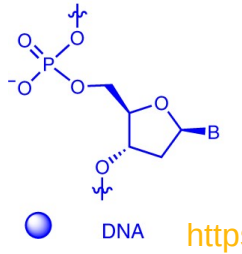
Problems of the “classic” RNA-world

- No “good” RNA-polymerase ribozymes were found so far
- Early replication systems are prone to parasitic infections
- The amount of free ribonucleotides in the solution needed doesn’t seem realistic

However…







- RNA might not be the first type of replicators, but it definitely has an important role in the early evolution of life
- A number of extensions to the RNA-world were proposed; one promising example is TNA (threose nucleic acid) and TRNA heteropolymers
- The parasitic problem can be solved by compartmentalization

https://www.nature.com/articles/s41557-019-0322-x

HOW DID ORGANIC MATTER APPEAR?

Prebiotic synthesis of organic matter

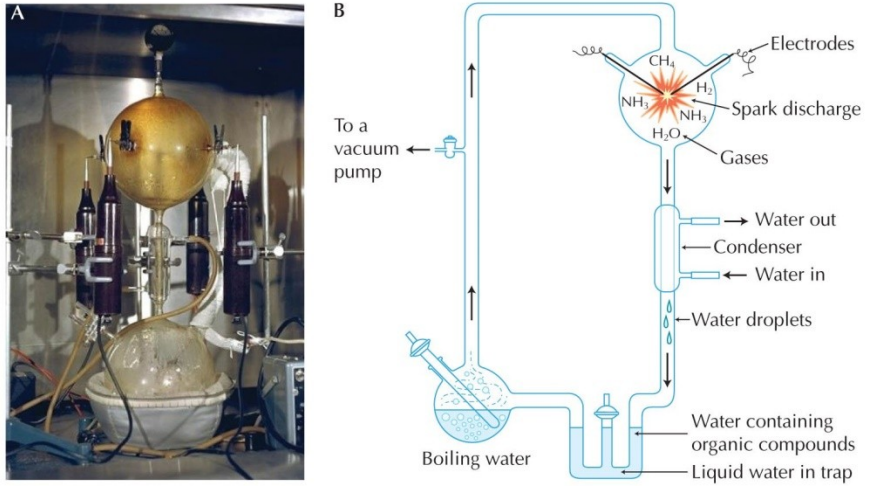


FIGURE 4.6. The apparatus used in the Miller–Urey experiments. (*A*) Recreation of the original apparatus. (*B*) Diagram of the apparatus.

4.6A, photo courtesy of NASA

- Vitalism was disproved in mid 19th century
- A number of experiments showed that organic molecules including amino acids and nitrogenous bases can be synthesized from inorganic ones (CH_4, H_2, NH_3, H_2O)

Problems

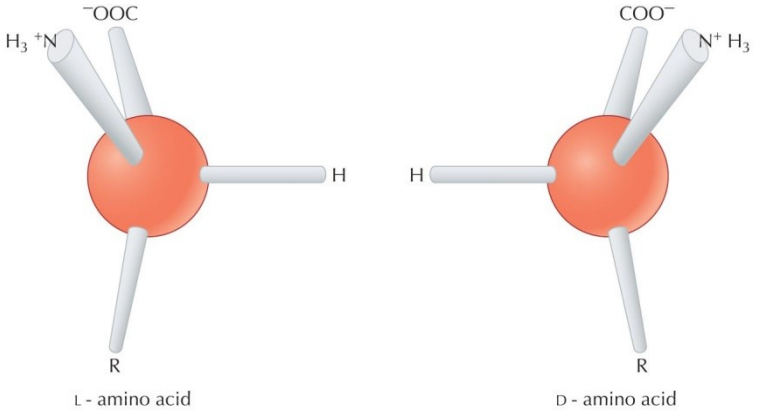


FIGURE 4.18. L and D amino acids. The L and D forms are stereoisomers (i.e., having the same chemical composition but with mirror images in bond positions). Building polymers (of amino acids or nucleotides) usually requires using only one form for the whole polymer.

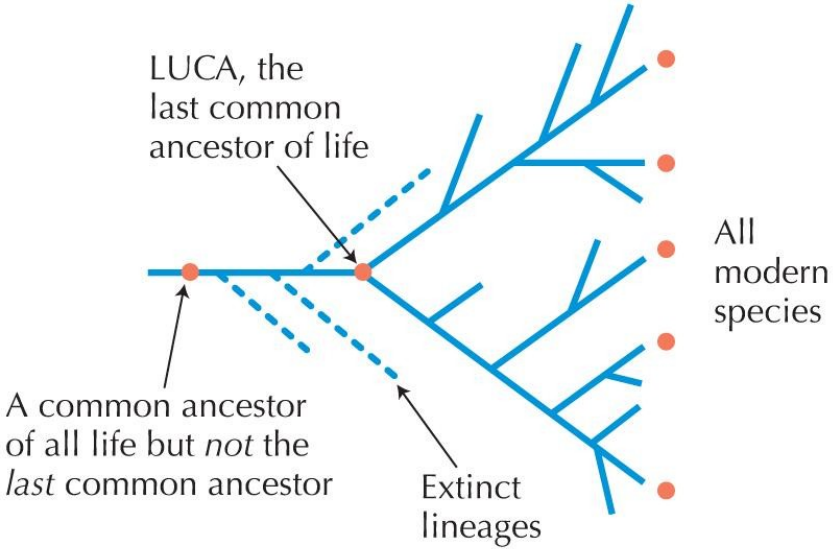
4.18, redrawn from http://www.lpi.usra.edu/publications/MSR/ Bada/Fig3.GIF

- Ribonucleotides are not efficiently synthesized
- Chirality

- **One solution to the chirality problem:** reactions on a mineral surface like FeS or ZnS

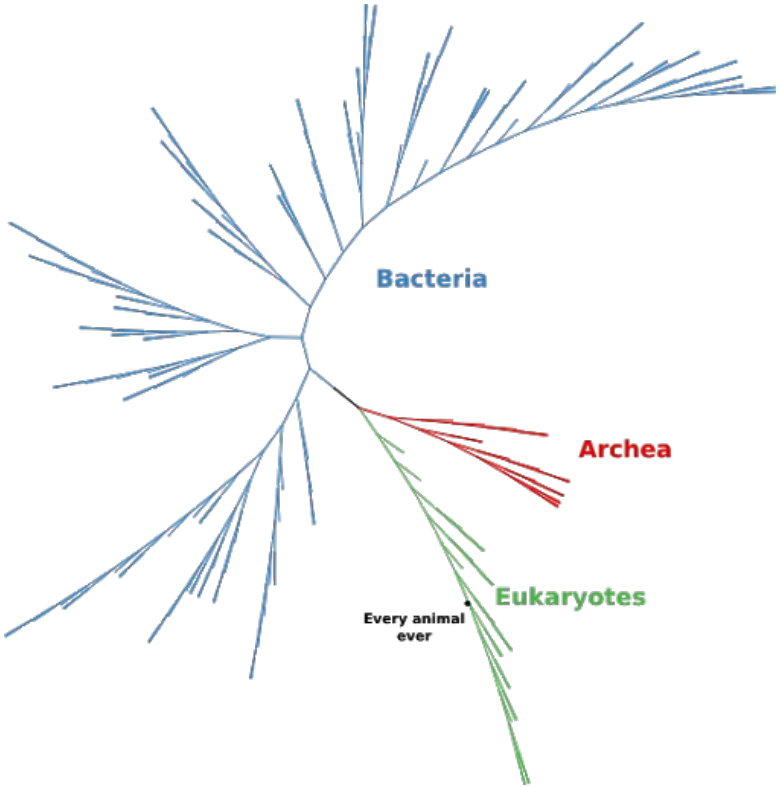
WHAT IS LUCA?

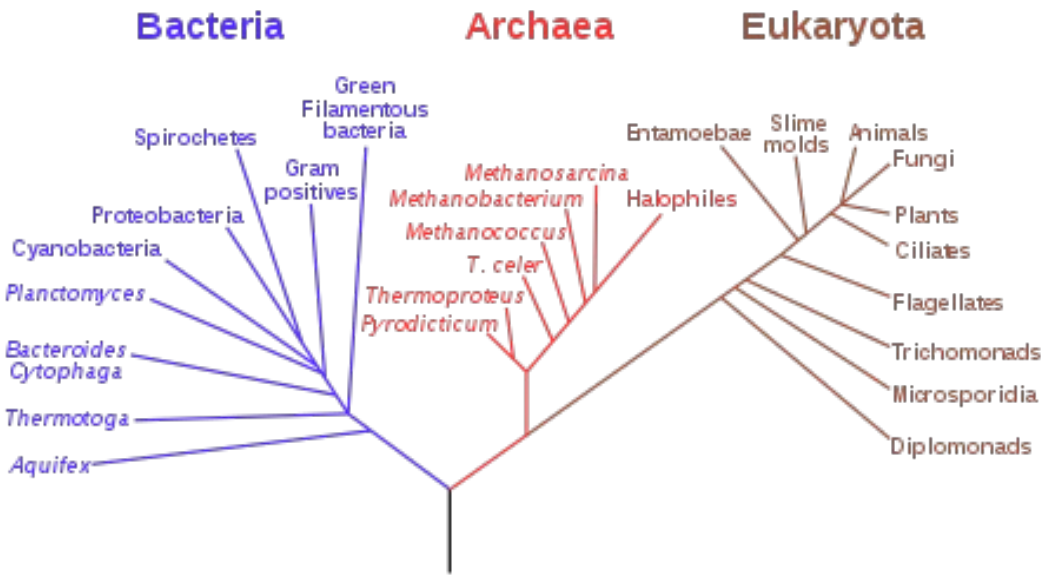
Last Universal Common Ancestor



- We can get insight into what LUCA was like through phylogenetic reconstruction

Rooting the tree of life





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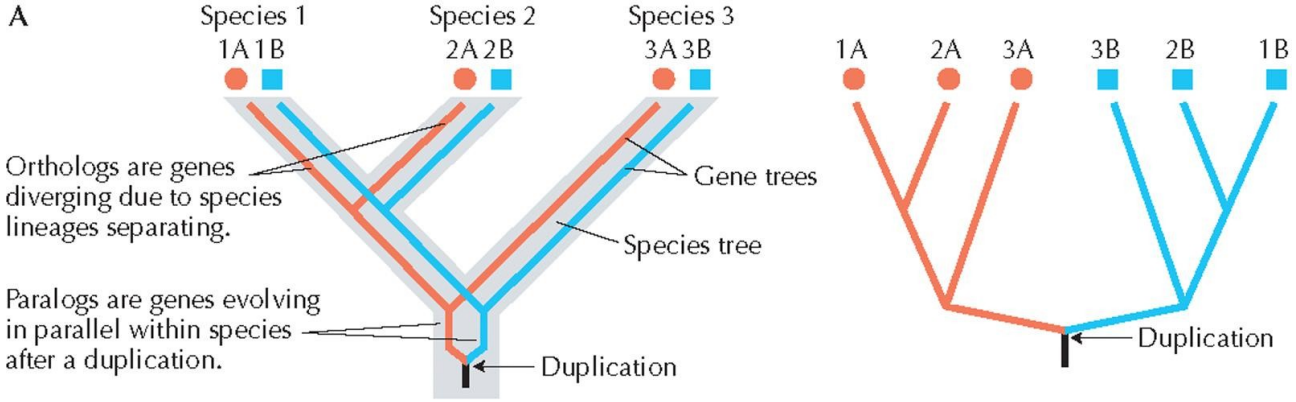
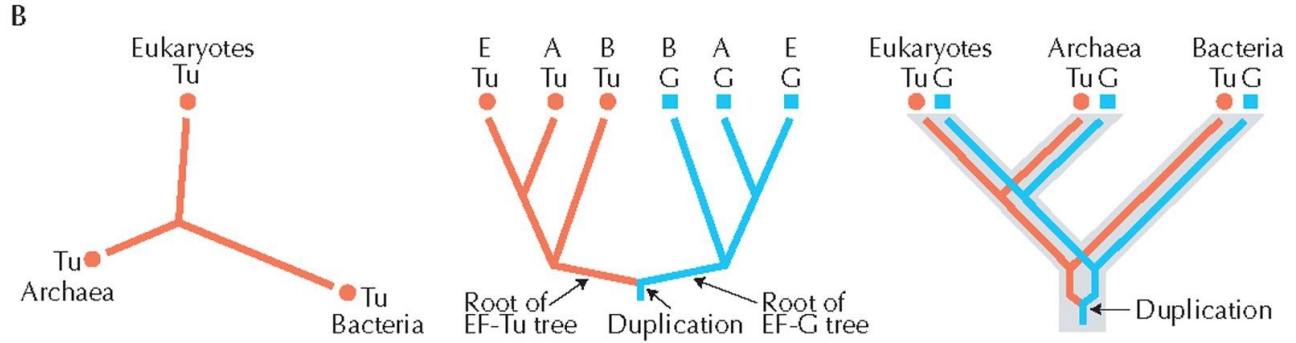


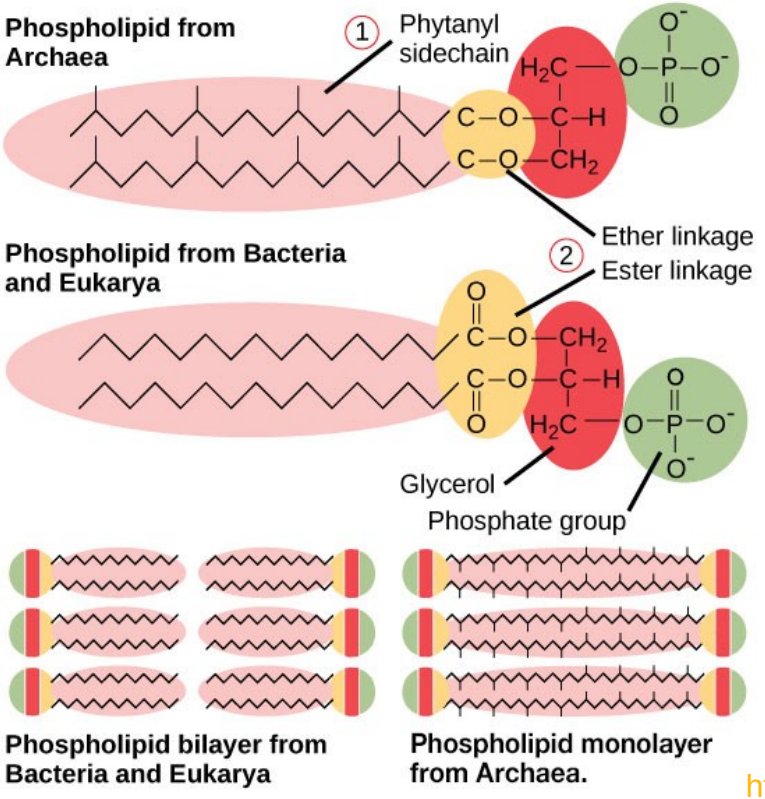


http://evolution-textbook.org/content/free/figures/05_EVOW_Art/20_EVOW_CH05.jpg

Universal homologies

- DNA>RNA>Proteins, almost universal genetic code
- Homology of RNA-polymerases
- Homology of translation machinery (ribosomal proteins and RNAs, tRNAs, aminoacyl-tRNA synthetases, some translation elongation factors)
- ATP-binding cassette (ABC) transmembrane transporters
- Some other transmembrane proteins
- ATP

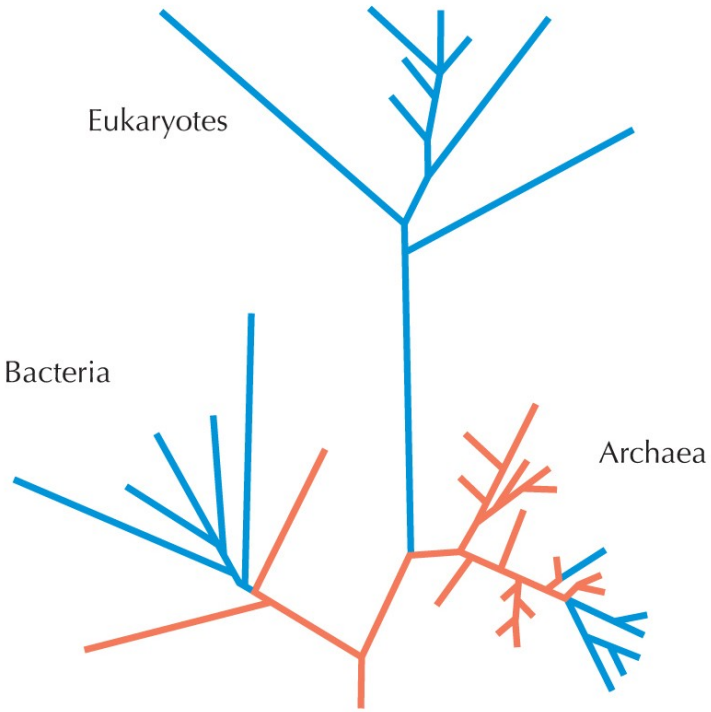
Was LUCA a cell?



- Maybe LUCA didn't have a cell membrane and wasn't cellular
- However, recall ABC transporters and other transmembrane proteins

http://library.open.oregonstate.edu/microbiology/chapter/archaea/

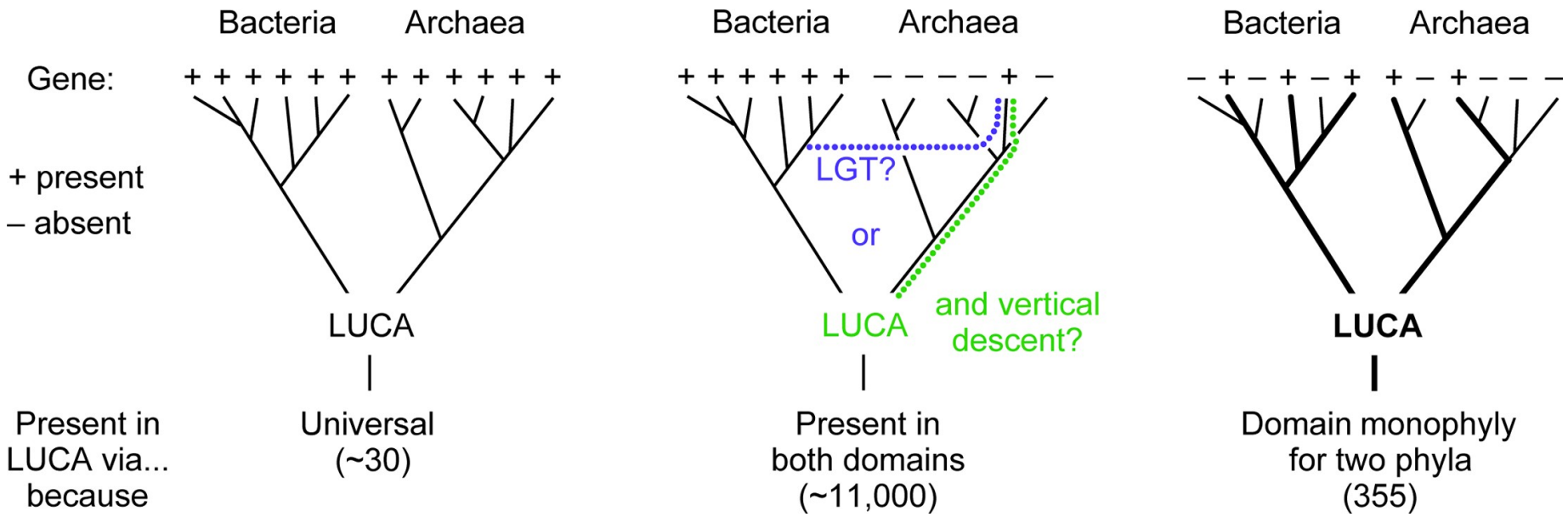
Hot LUCA?



- Some reconstructions indicate that early-branching groups of bacteria and archaea are thermophilic (shown in red) suggesting a “Hot LUCA”
- But the branching pattern close to the tree is poorly resolved

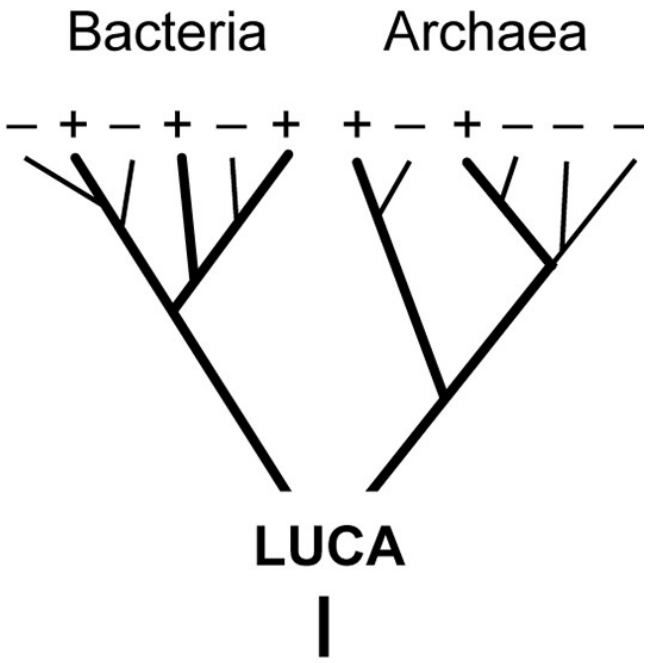
http://evolution-textbook.org/content/free/figures/06_EVOW_Art/17_EVOW_CH06.jpg

LUCA's gene content



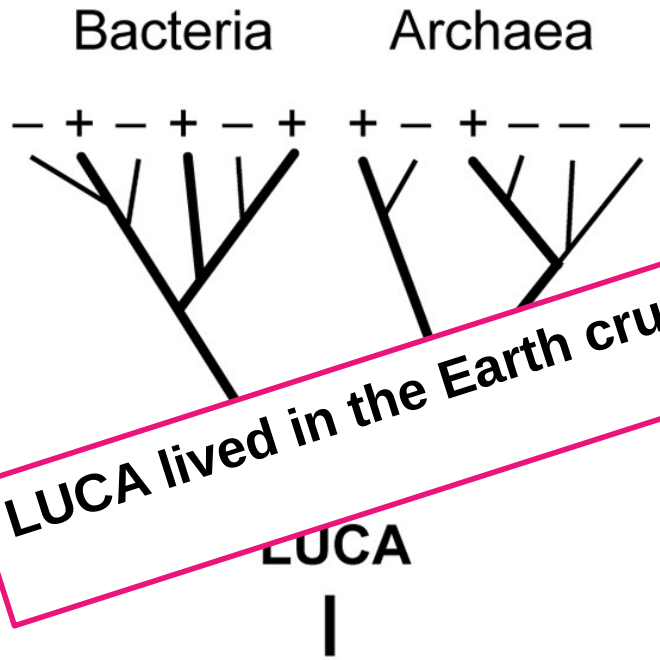
https://journals.plos.org/plosgenetics/article?id=10.1371/journal.pgen.1007518

LUCA's gene content



- Enzymes poisoned by O_2
- Enzymes involved in reducing CO_2 with H_2 and using this carbon to build organic molecules
- Some subunits of ATP-synthase
- Enzymes using FeS clusters
- Enzymes typical for thermophiles

LUCA's gene content



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  CO_2 with
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- Enzymes using FeS clusters
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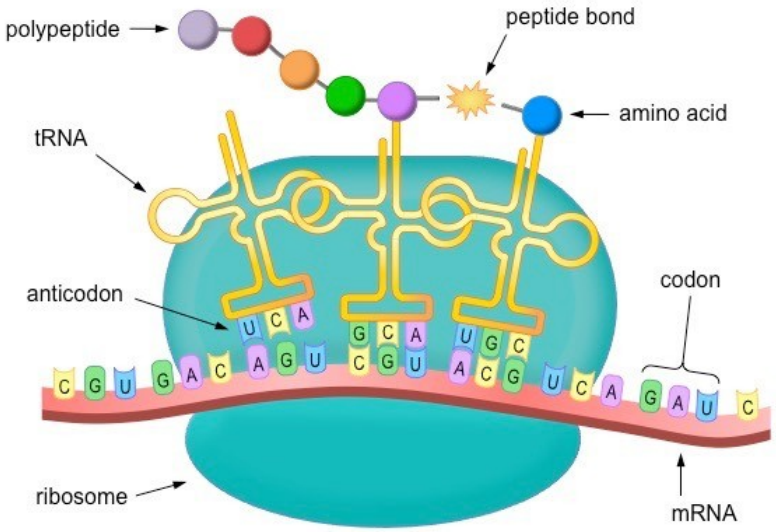
LUCA lived in the Earth crust in association with alkaline hydrothermal vents?

Conclusions about LUCA

- Simple transcription system
- Translation system almost as complex as the modern one
- DNA>RNA>Proteins; universal genetic code
- Cells and membranes – controversial
- Hot LUCA in the crust?

Origin of translation and the genetic code



- “Frozen accident” – match between codons and amino acids is random
- Stereochemistry theory – the genetic code table is not random + at least some AA specifically bind RNA at corresponding triplets

https://ib.bioninja.com.au/standard-level/topic-2-molecular-biology/27-dna-replication-transcri/translation.html

Origin of translation and the genetic code

First base position	Second base position: U		Second base position: C		Second base position: A		Second base position: G		Third base position
U	UUU	[1]P	UCU	S	UAU	Y	UGU	C	U
	UUC		UCC		UAC		UGC		C
	UUA	L	UCA		UAA	Stop	UGA	Stop	A
	UUG		UCG		UAG		UGG	W	G
C	CUU	L	CCU	P	CAU	H	CGU	R	U
	CUC		CCC		CAC		CGC		C
	CUA		CCA		CAA	Q	CGA		A
	CUG		CCG		CAG		CGG		G
A	AUU	I	ACU	T	AAU	N	AGU	S	U
	AUC		ACC		AAC		AGC		C
	AUA		ACA		AAA	K	AGA	R	A
	AUG	M	ACG		AAG		AGG		G
G	GUU	V	GCU	A	GAU	D	GGU	G	U
	GUC		GCC		GAC		GGC		C
	GUA		GCA		GAA	E	GGA		A
	GUG		GCG		GAG		GGG		G

[1]The one letter symbol of amino acids.

https://ib.bioninja.com.au/standard-level/topic-2-molecular-biology/27-dna-replication-transcri/translation.html

- "Frozen accident" – match between codons and amino acids is random
- Stereochemistry theory – the genetic code table is not random + at least some AA specifically bind RNA at corresponding triplets

Placing viruses on the tree of life

- Origin of viruses:
  - Vestigial cells
  - Escaped genes
  - Relicts of pre-cellular times
  - These are not mutually exclusive
- Lots of HGT transfer
- No genes present in all the viruses
- Homology between RNA and DNA viruses

Key points

- Life arose on Earth pretty early – no later then 3.5 bya and no more than 0.7 bya after it became possible
- Organic molecules (many types) can be synthesized abiotically, but proper conditions are needed (hydrothermal vents, land hot springs, outer space?)
- Accumulation of organic compounds could lead to metabolism and replicators

Key points

- One hypothesis – the RNA-world: RNA molecules were the first replicators, perhaps autoreplicators
- Phylogenetic reconstructions give some knowledge about LUCA
- One of the key events during the pre-LUCA evolution is the origin of translation and the genetic code