MCB 3421
Class 6 2024

The tangled tree of life

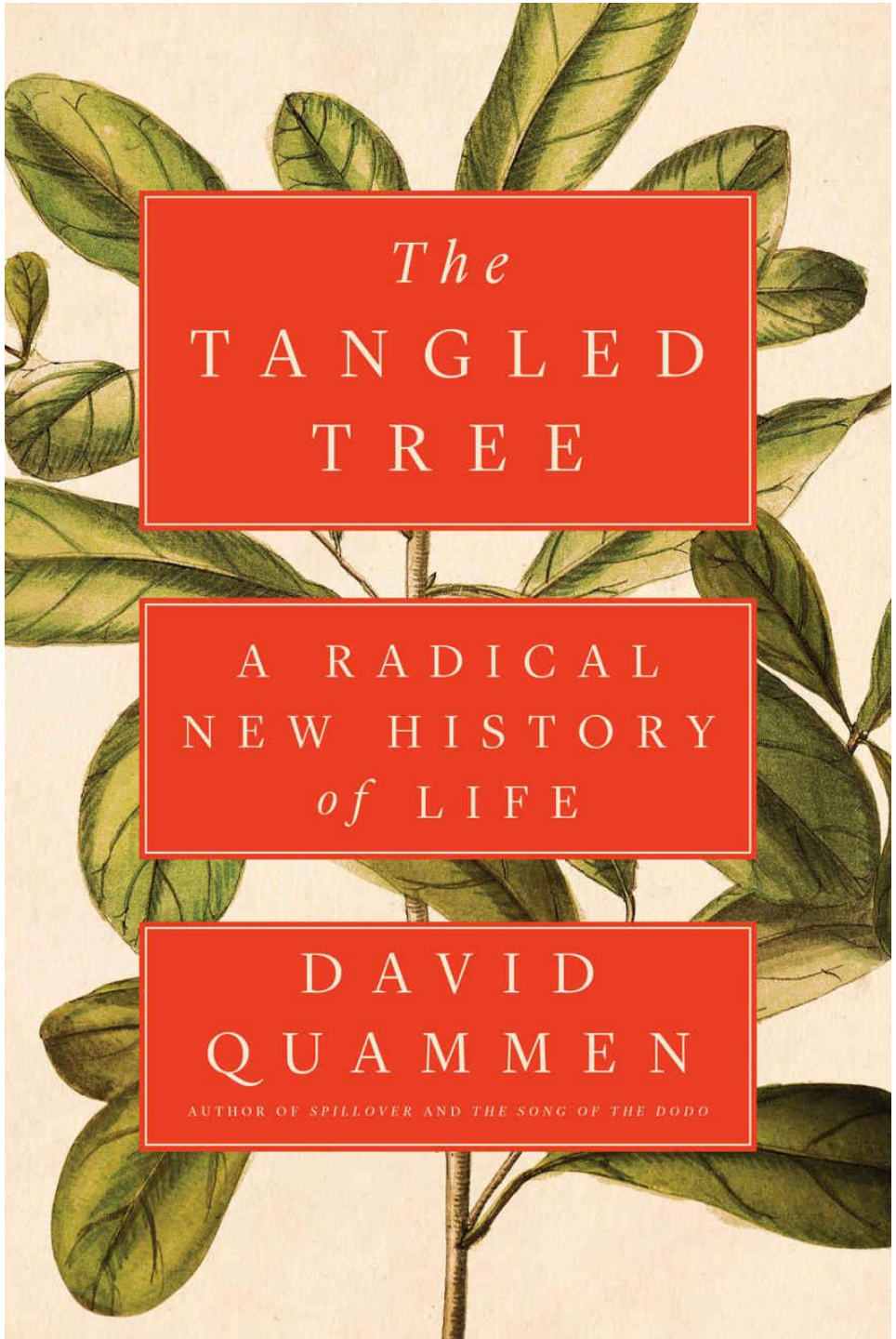
or

How to depict evolutionary history?

If you want to learn more about
the recent upheaval of tree thinking with respect
to evolution see the book by David Quamann:
The Tangled Tree,
A Radical New History of Life

and

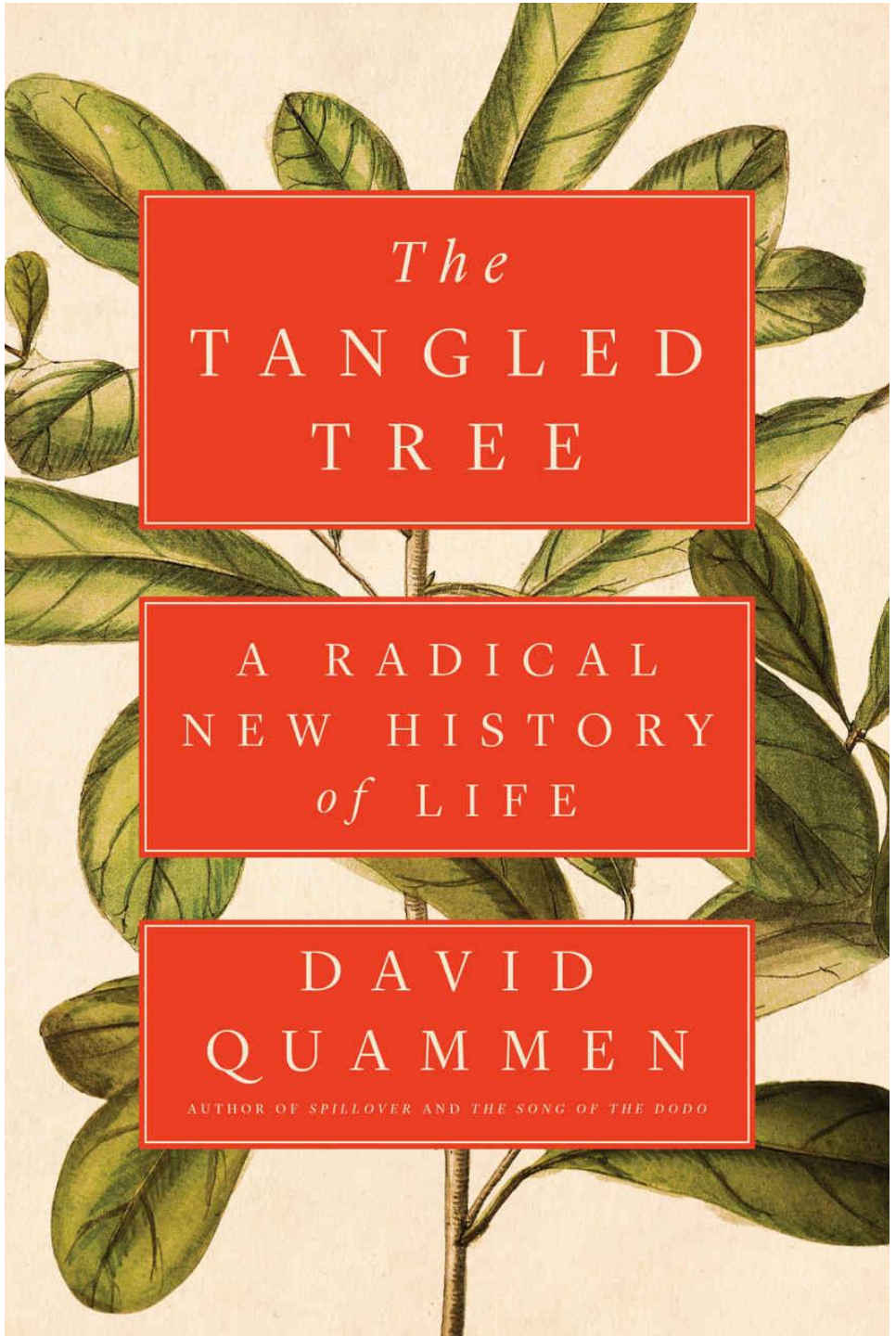
Soucy SM, Huang J, Gogarten JP (2015)
Horizontal gene transfer: building the web of life.
Nature Reviews in Genetics 16, 472–482. doi:
10.1038/nrg3962



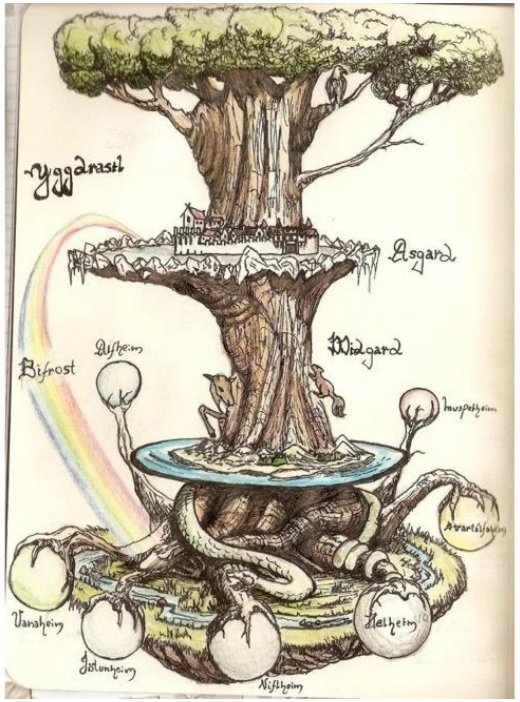
"the four horsemen" of the gene-transfer apocalypse: William Martin, Jeffrey Lawrence, Peter Gogarten and Ford Doolittle.

The debate is ongoing as to who is Pestilence, War, Famine, and Death.

Painting by Viktor Vasnetsov
1887, *via* Wikipedia



Trees have a long history in depicting evolutionary history, but also for depicting the diversity of life.
(Note, many Trees of Life depict the latter, and do not imply an evolutionary history)

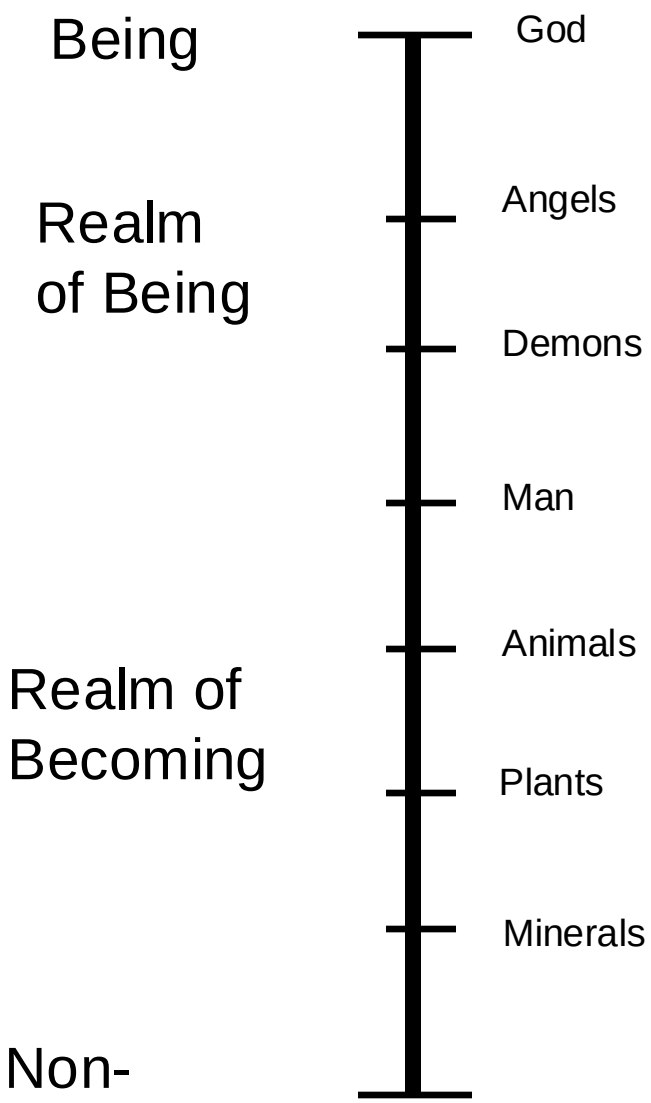


Yggdrasil
(North Mythology)

The biblical tree of life

Mexican tree of life

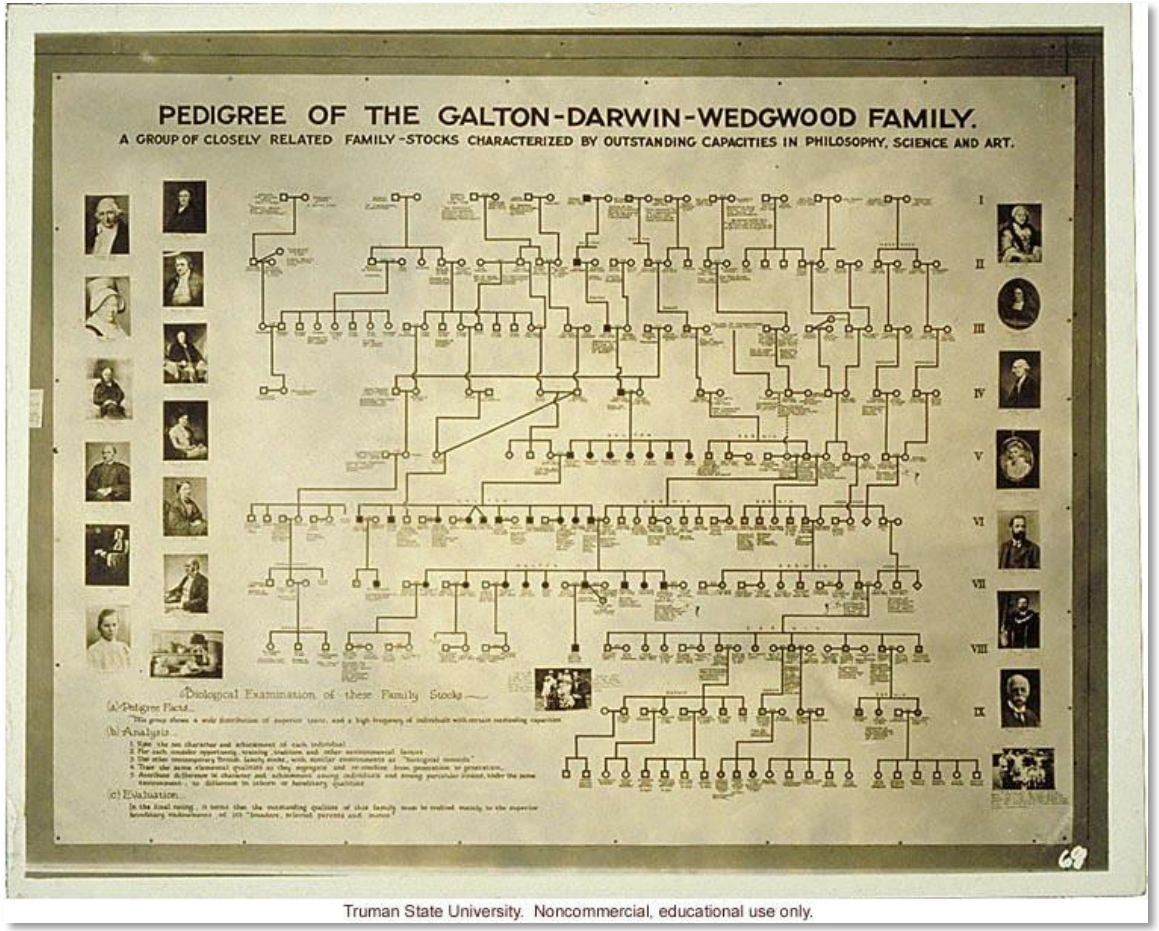
Scala Naturae



1579 drawing of the Great Chain of Being from Didacus Valades, Rhetorica Christiana. Source Wikipedia

Family Trees, Genealogies, Pedigrees

Genealogy
(Church Ceiling,
Santo Domingo,
Oaxaca)

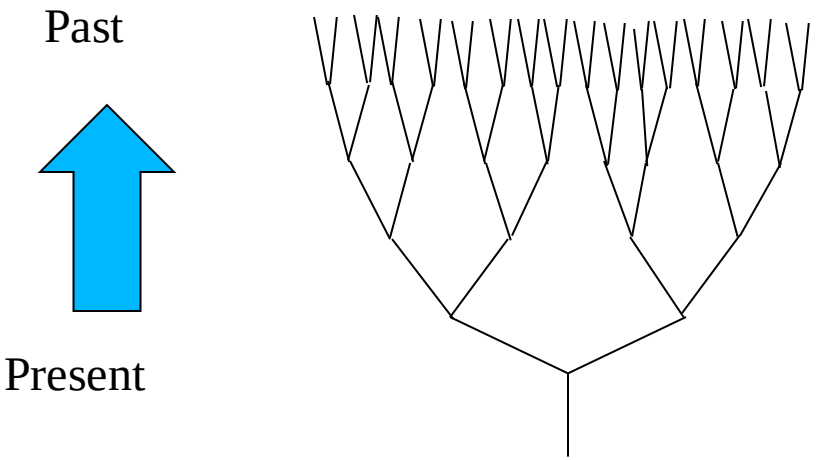


Charles Darwin's Family "Tree"

Family Tree

Each individual has two parents.

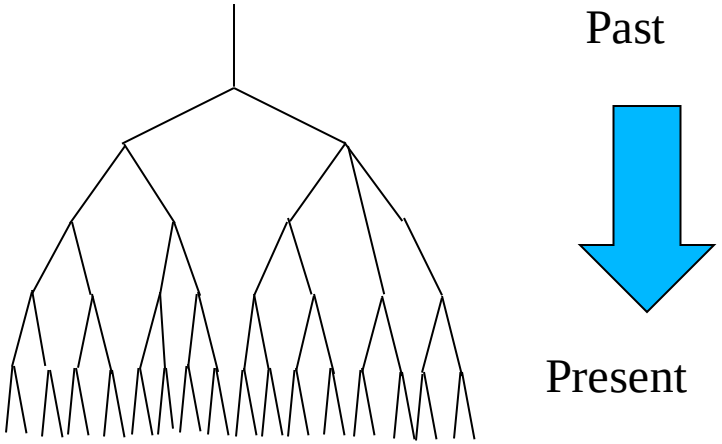
Tree branches, as one goes back in time



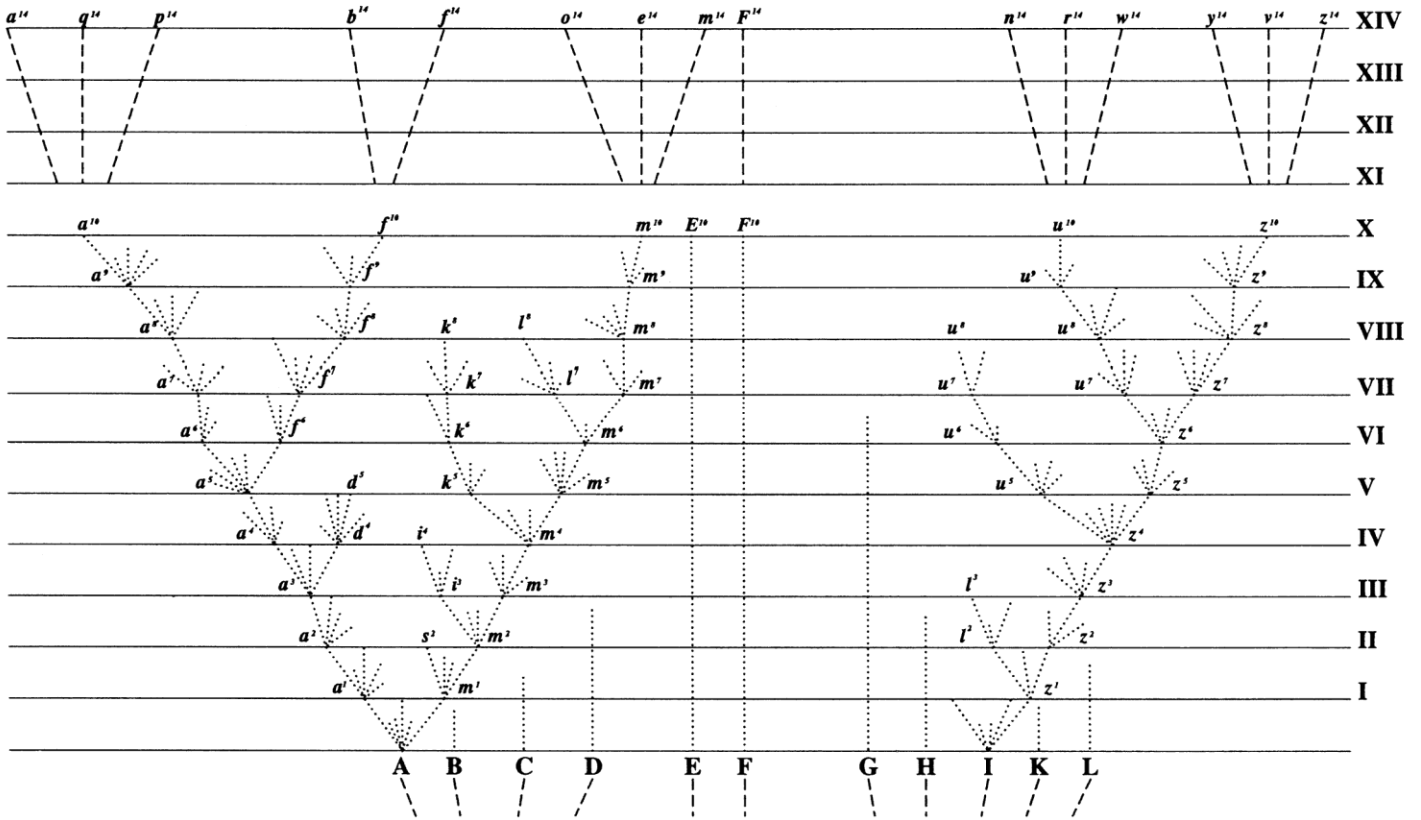
Species tree

Species split at time moves forward

Tree branches as one moves forward in time



Following Darwin most biologist draw phylogenetic trees to that the present time is on top and the past at the bottom



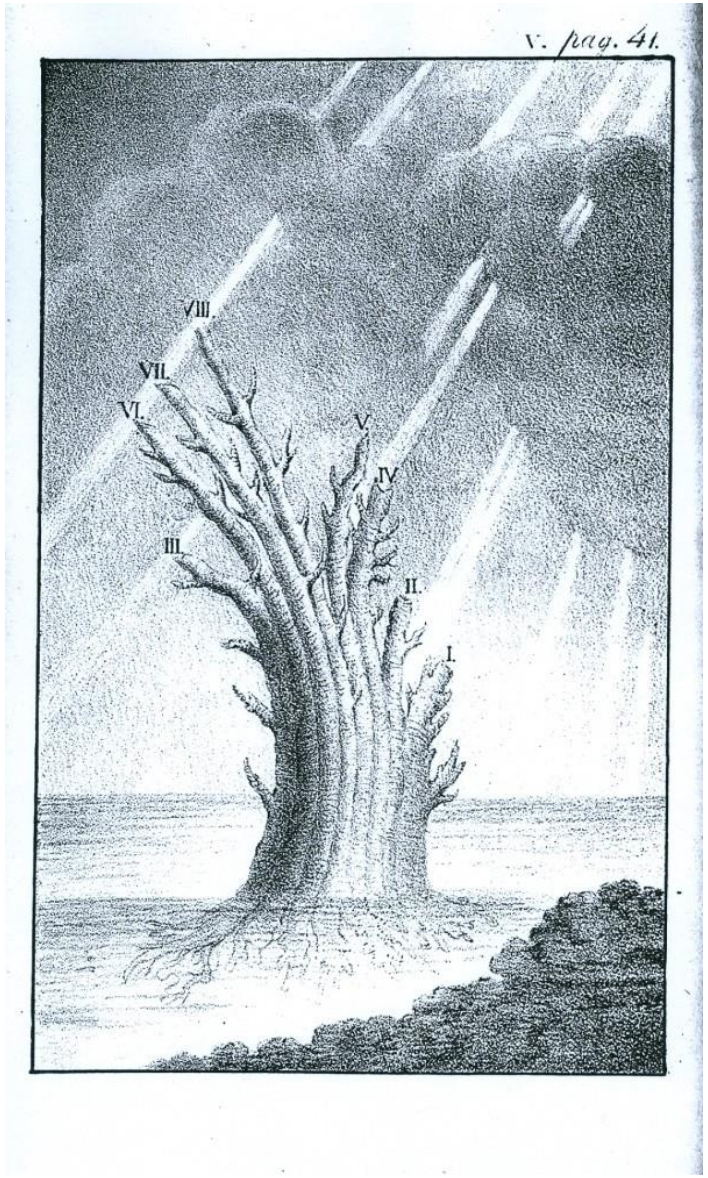
Present

Past

Mathematicians often do it the other way around

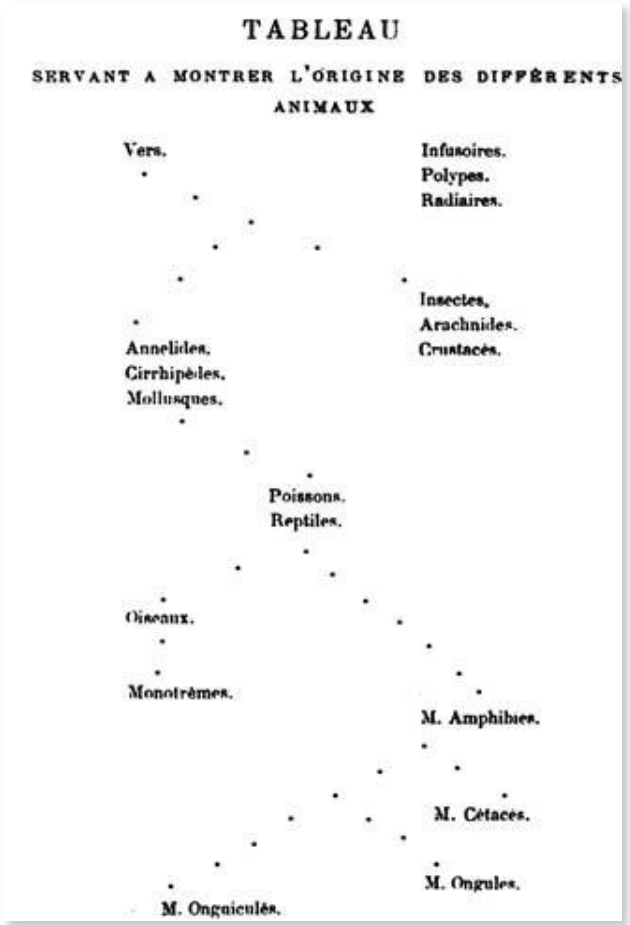
Russian naturalist **Peter Simon Pallas (**1766): "But the system of organic bodies is best of all represented by an image of a tree which immediately from the root would lead forth out of the most simple plants and animals a double, variously contiguous animal and vegetable trunk; the first of which **would proceed** from mollusks to fishes, with a large side branch of insects sent out between these, hence to amphibians and at the farthest tip it would sustain the quadrupeds, but below the quadrupeds it would put forth birds as an equally large side branch."

(translation from Latin by E. N. Genovese, from *J. David Archibald: "Edward Hitchcock's Pre-Darwinian (1840) 'Tree of Life'" Journal of the History of Biology (2009) 42:561–592*)

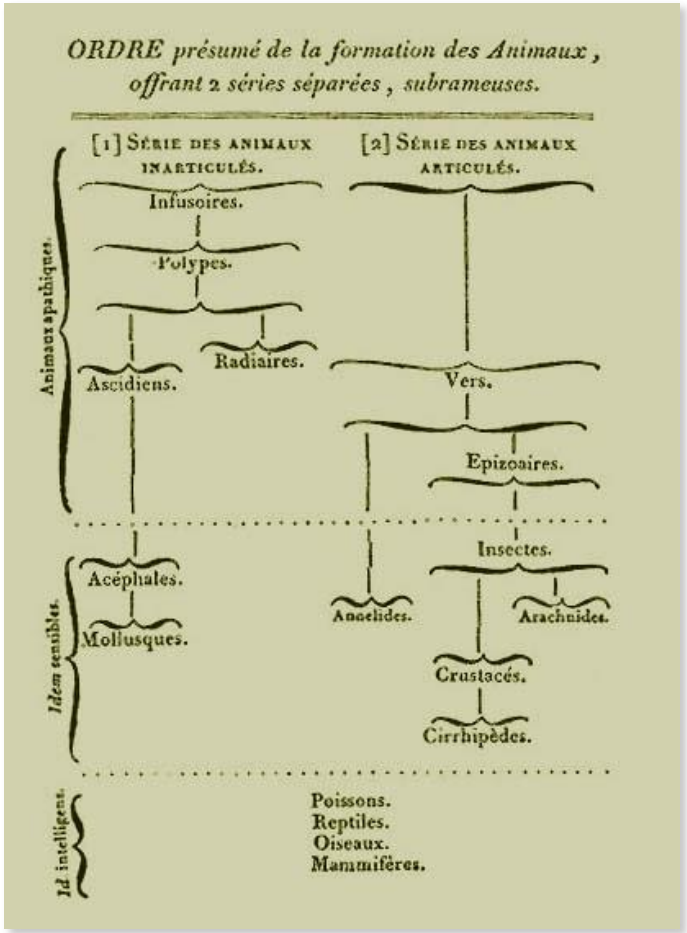


Tree of animal life, Depiction of the tree proposed by Peter Simon Pallas, from Carl Edward von Eichwald's ***Zoologia specialis* (1829)**. (From: *Mark A. Ragan: "Trees and networks before and after Darwin", Biol Direct. 2009 Nov 16;4:43.*)

Jean-Baptiste Lamarck

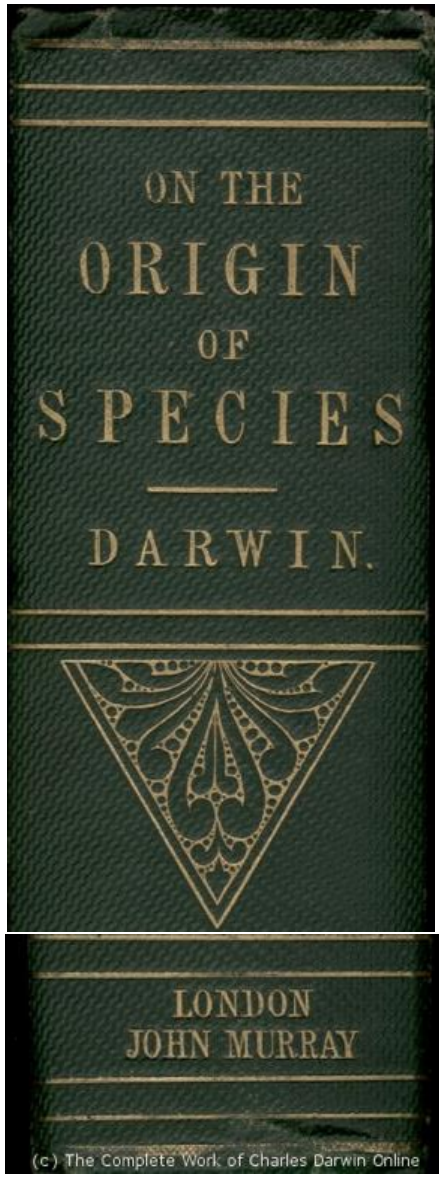


Tree from 1809



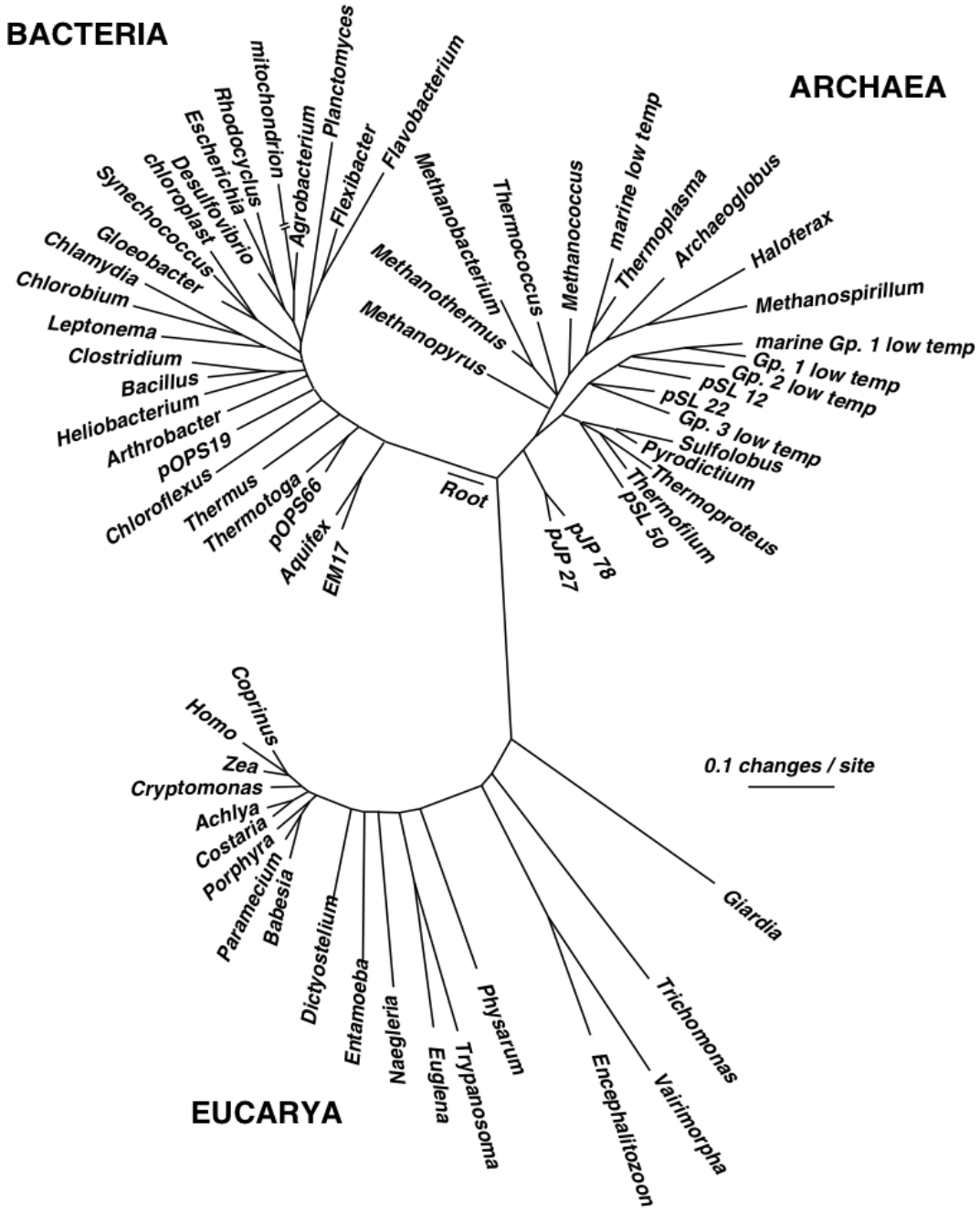
Tree-like classification from 1815

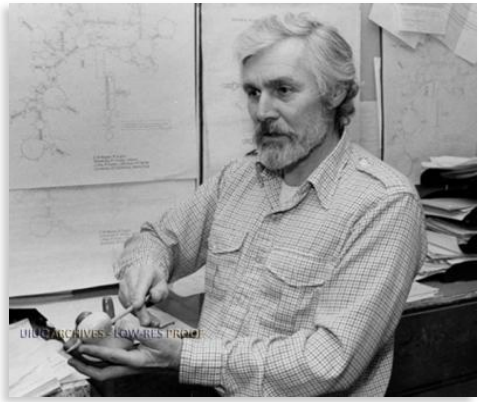
“As buds give rise by growth to fresh buds, and these, if vigorous, branch out and overtop on all sides many a feebler branch, so by generation I believe it has been with the great Tree of Life, which fills with its dead and broken branches the crust of the earth, and covers the surface with its ever-branching and beautiful ramifications.”



Charles Darwin in
“On the **Origin of Species** by **Means of Natural Selection** or the **Preservation of Favoured Races in the Struggle for Life**”,
p 162 ff, London, John Murray, 1859

Small Subunit Ribosomal RNA based Tree of Life.





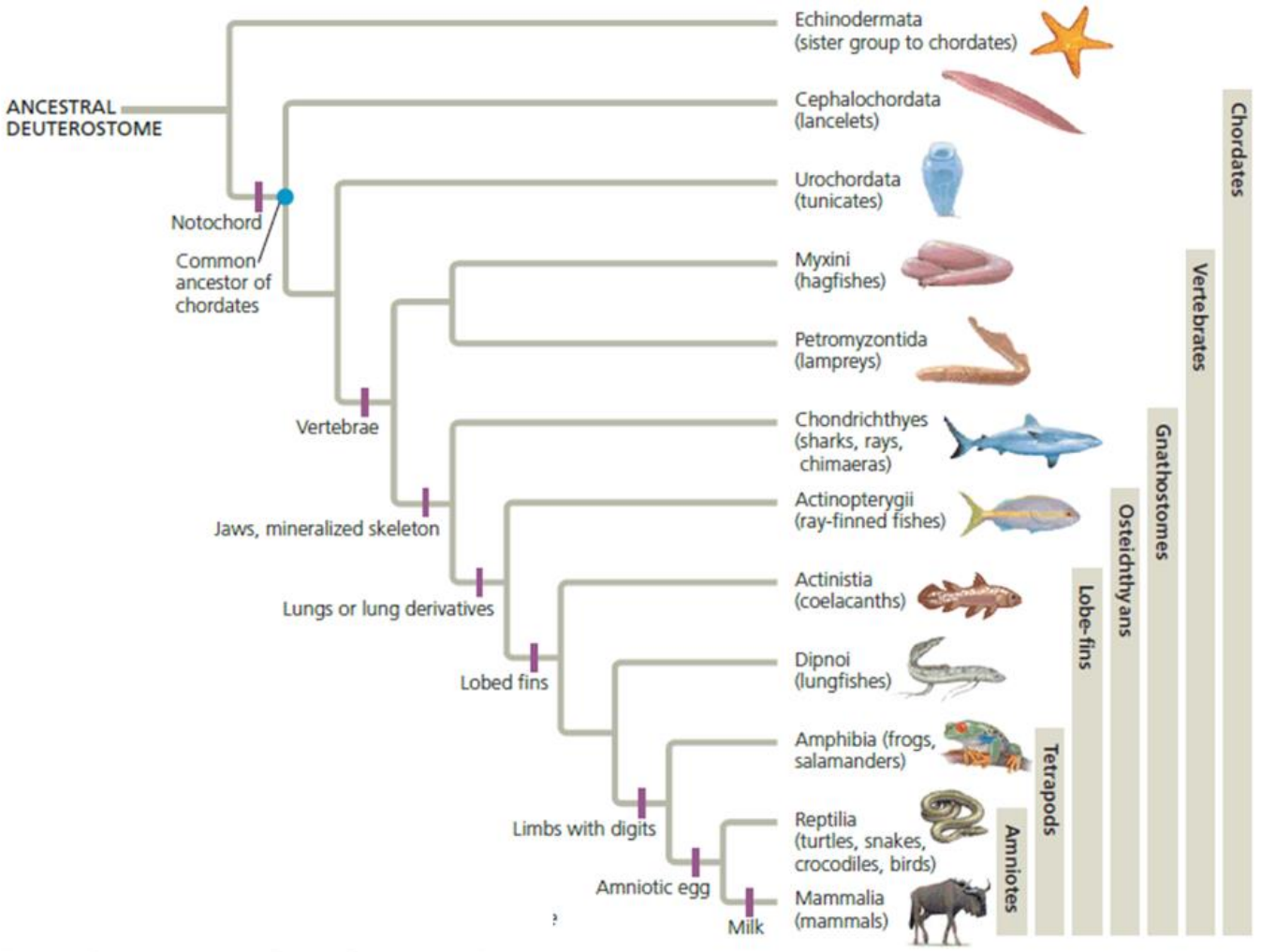
Carl Woese

George Fox

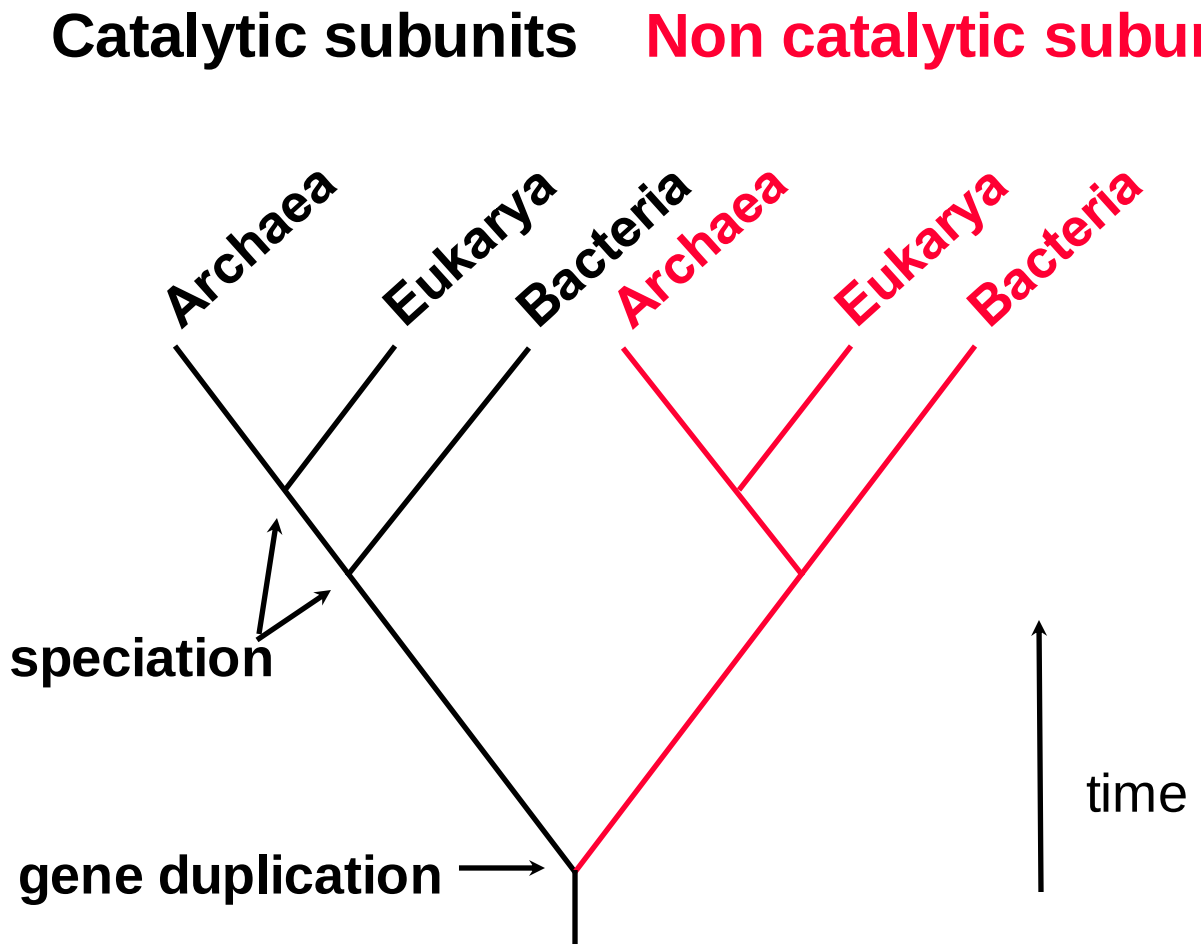
How to root a tree?

- Using polarized characters (i.e., derived and primitive characters). For many characters, especially molecular characters (e.g., a nucleotide position in a gene) this is not possible.

- Using an Outgroup: Include one or more organisms that are related but outside of the group one wants to study. E.g., for a tree of birds, one could use crocodiles as outgroup.



From: https://www.chegg.com/homework-help/questions-and-answers/outgroup-tree--echinodermata-b-mammalia-c-ancestral-deuterostomes-d-urochordata-q85102920

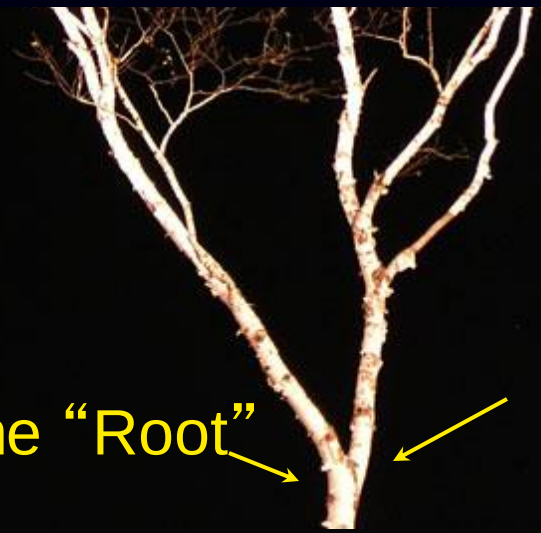


Gogarten et al, 1989, PNAS 86, 17, 6661–6665
http://www.pnas.org/content/113/32/E4654.full.pdf?with-ds=yes

The Tree of Life according to SSU ribosomal RNA (+)

- strictly bifurcating
- no reticulation
- only extant lineages
- based on a single molecular phylogeny
- branch length is not proportional to time

PHYLOGENY: from Greek phylon, race or class, and -geneia, born.
"*the origin and evolution of a set of organisms, usually of a species*" (Wikipedia);



The "Root"

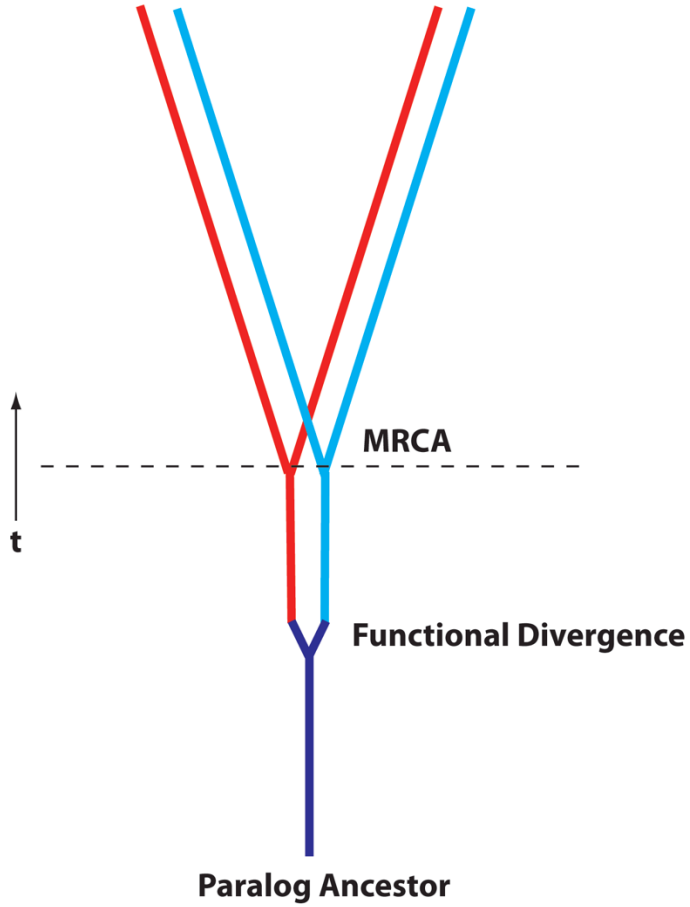
Cenancestor
(aka MRCA or LUCA)
as placed by ancient duplicated genes (ATPases, Signal recognition particles, EF)

What could one use to root the tree of life that contains all living organisms?

Deep Paralogs

(Paralog: homologs that evolved through a gene duplication)

- Gene families evolve by **duplication**, **gene transfer** and **divergence**
- For ancient proteins, some of these divergences occurred before the divergence of the three domains of life (MRCA, aka Last Universal Common Ancestor LUCA);
- Determining function of paralog ancestors could elucidate primordial physiology… however, lack of time machine prevents direct experimental observation.
- In some special cases, can be inferred using amino acid composition…



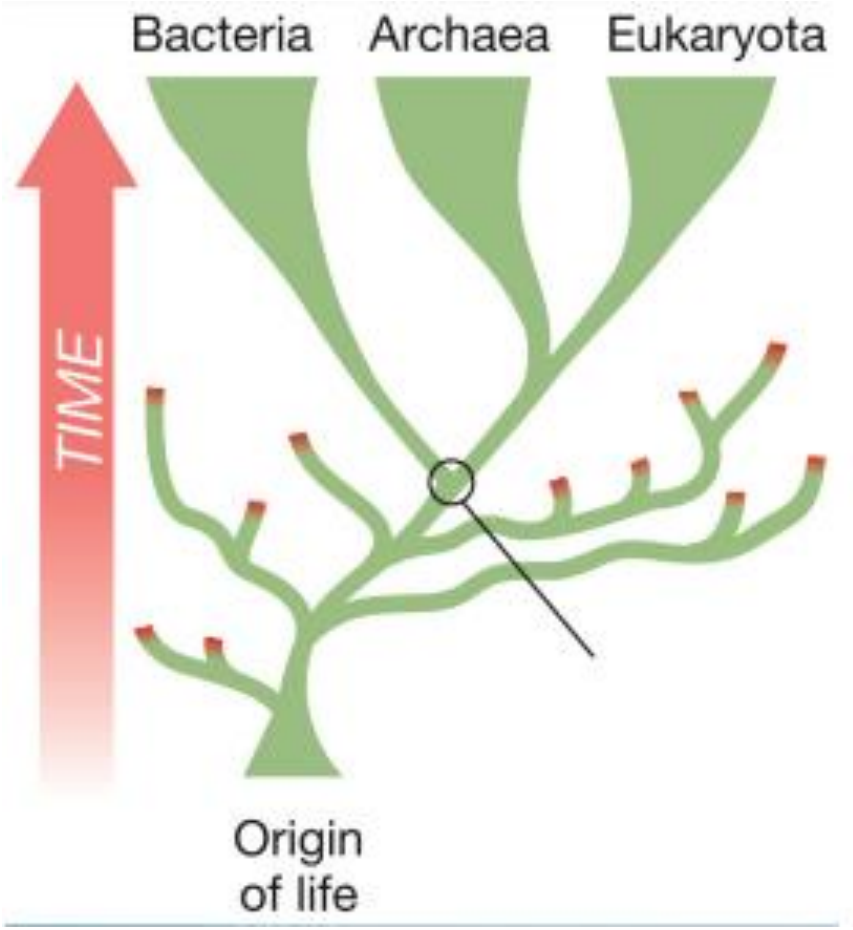
Other ancient duplicated genes used to root the tree of life:

- Elongation factors (play a role in ribosomal protein synthesis)
- Signal recognitions factors (bind to membrane proteins during their synthesis at the ribosome and direct them to the membrane)
- Aminoacyl tRNA synthetases (they charge the tRNAs with the correct amino acid). These enzymes fall into two groups of homologs.
- Lactic and malic acid dehydrogenase.

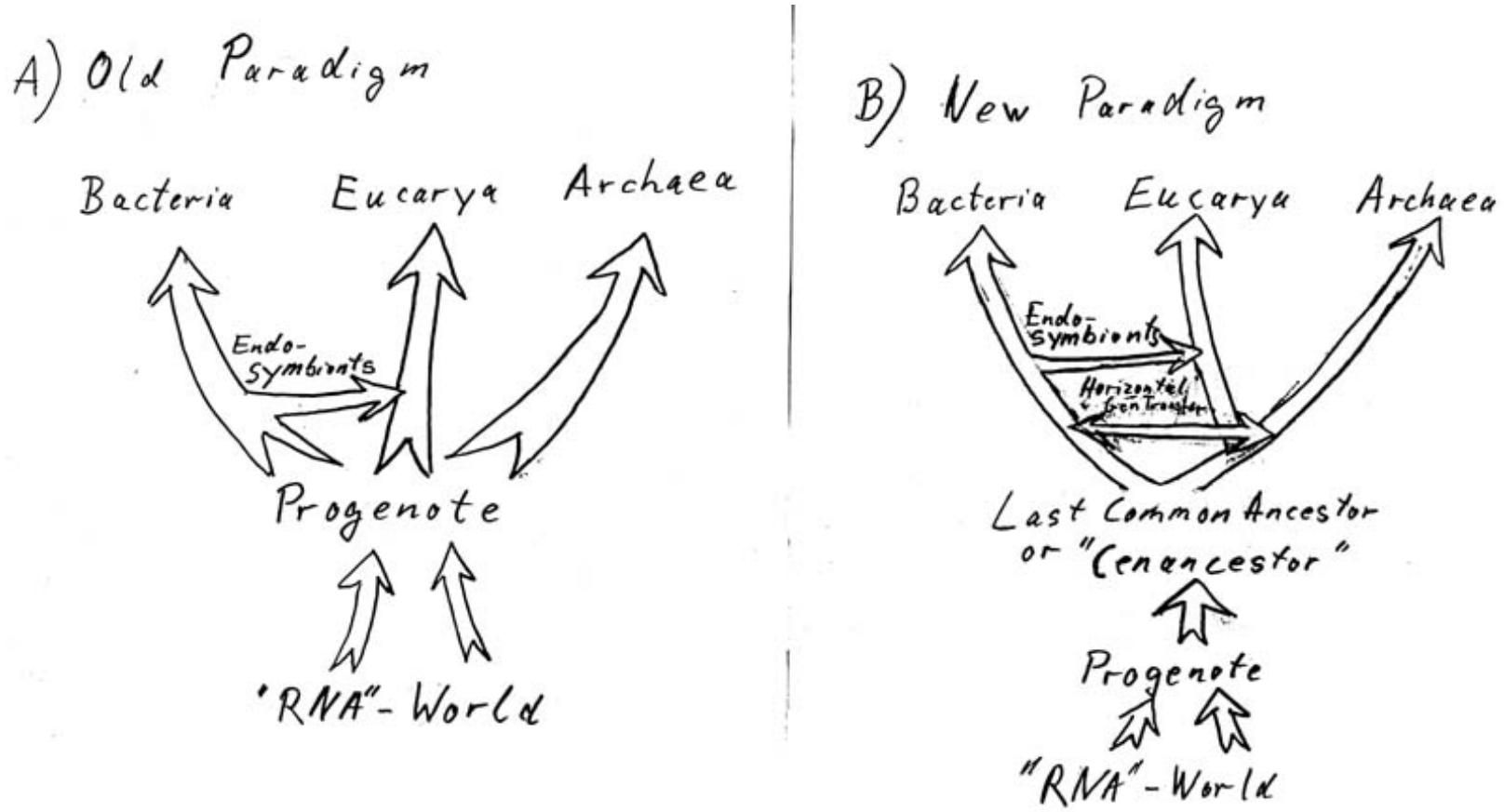
Based on the ancient duplicated genes,
The **Last Universal Common Ancestor** (aka **LUCA** or cenancestor) had

- energized membranes
- ribosomal template directed protein biosynthesis
- used 20 different amino acids

This is very different from
the first living thing.

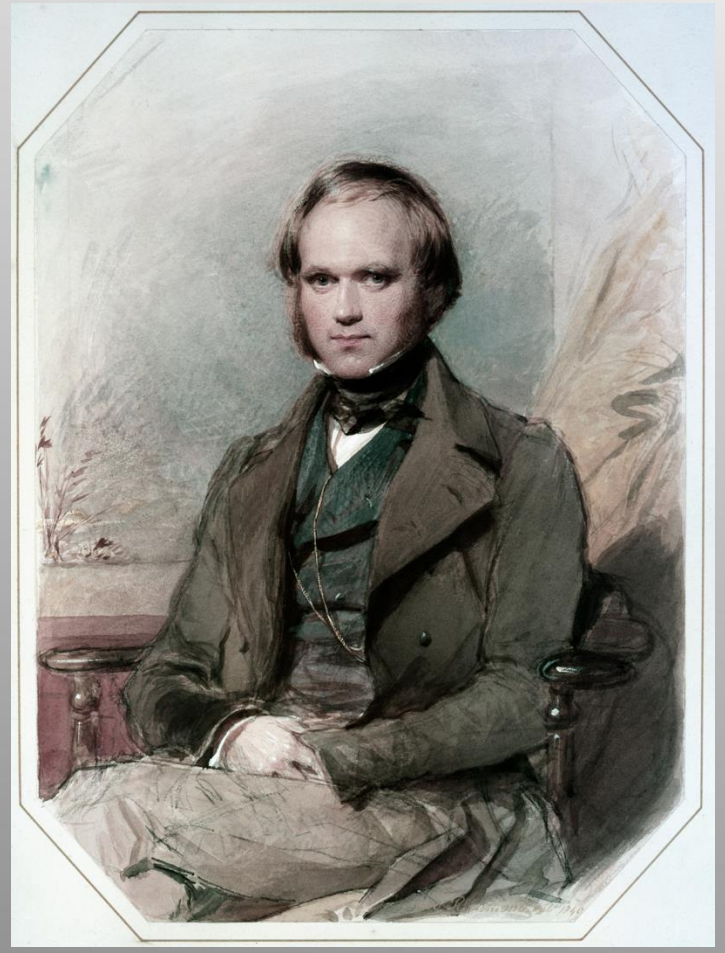


The early evolution of life:



Why is the RNA-world assumed to be an early stage in Life's history?
What problem is solved by assuming a progenote phase of life?
(progenote: organisms existing before a strict linkage between geno- and phenotype – genes frequently transferred between entities)

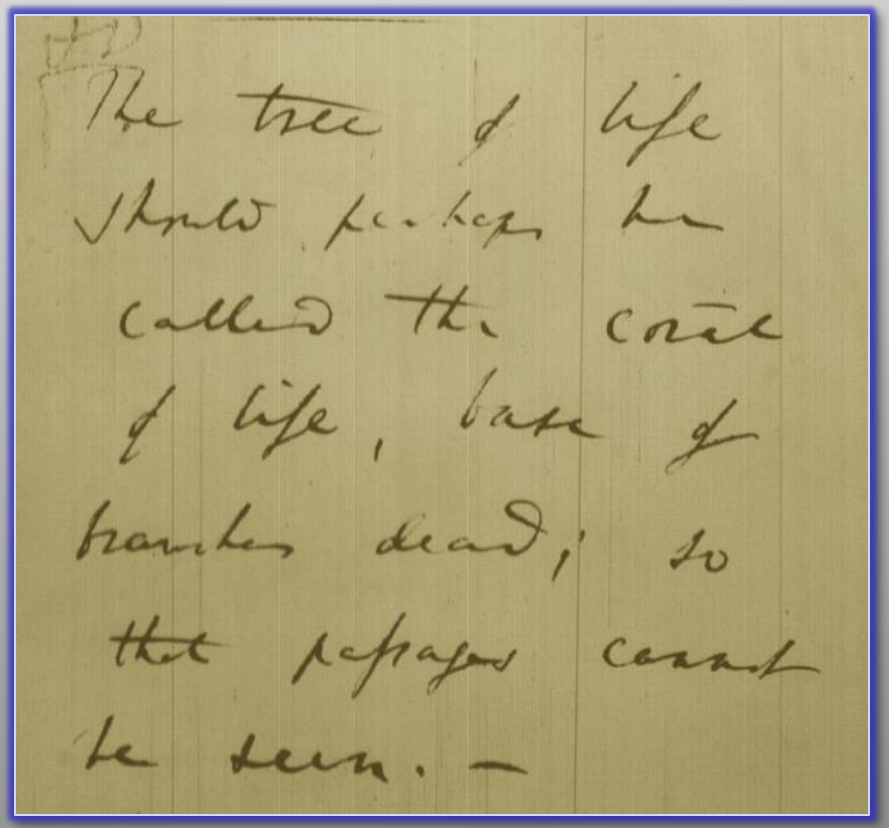
Tree, Web, or Coral of Life?



Charles Darwin

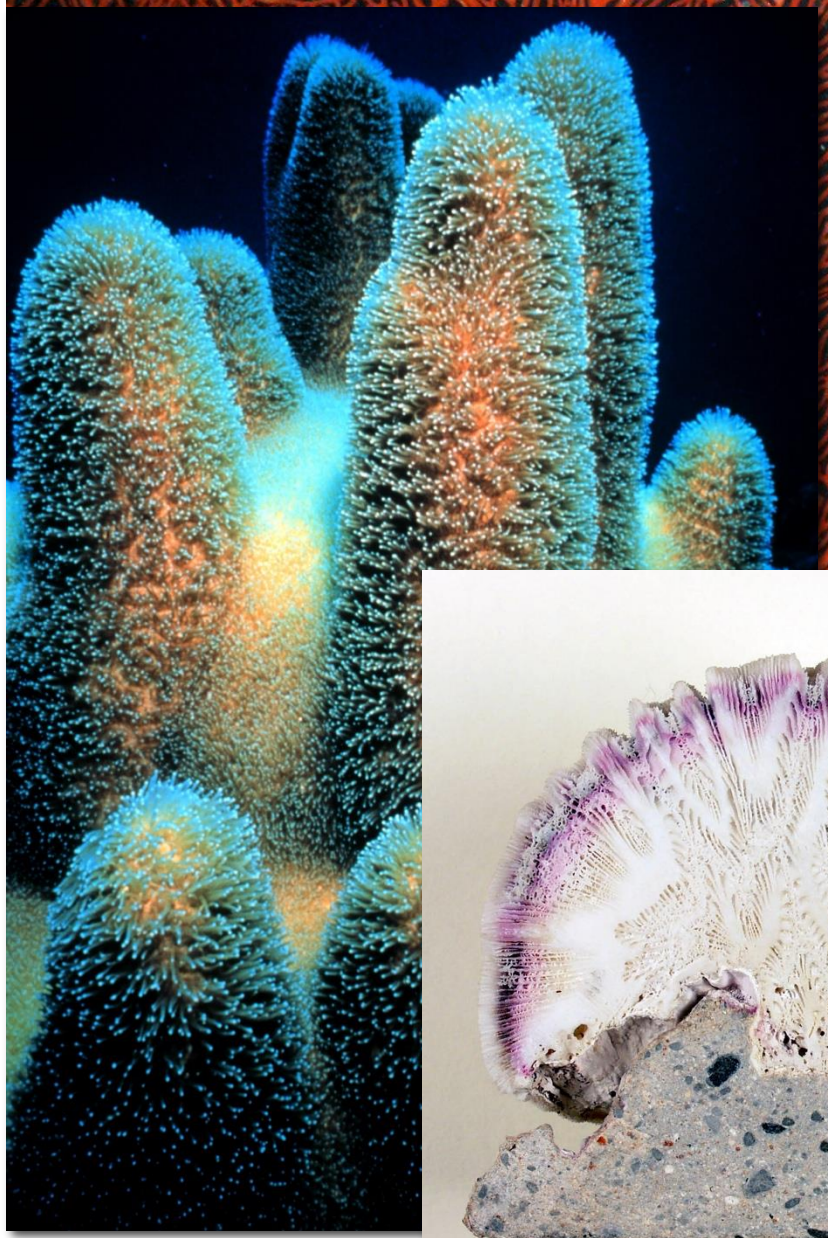
painted by George Richmond in the late 1830

"The tree of life should perhaps be called the coral of life, base of branches dead"

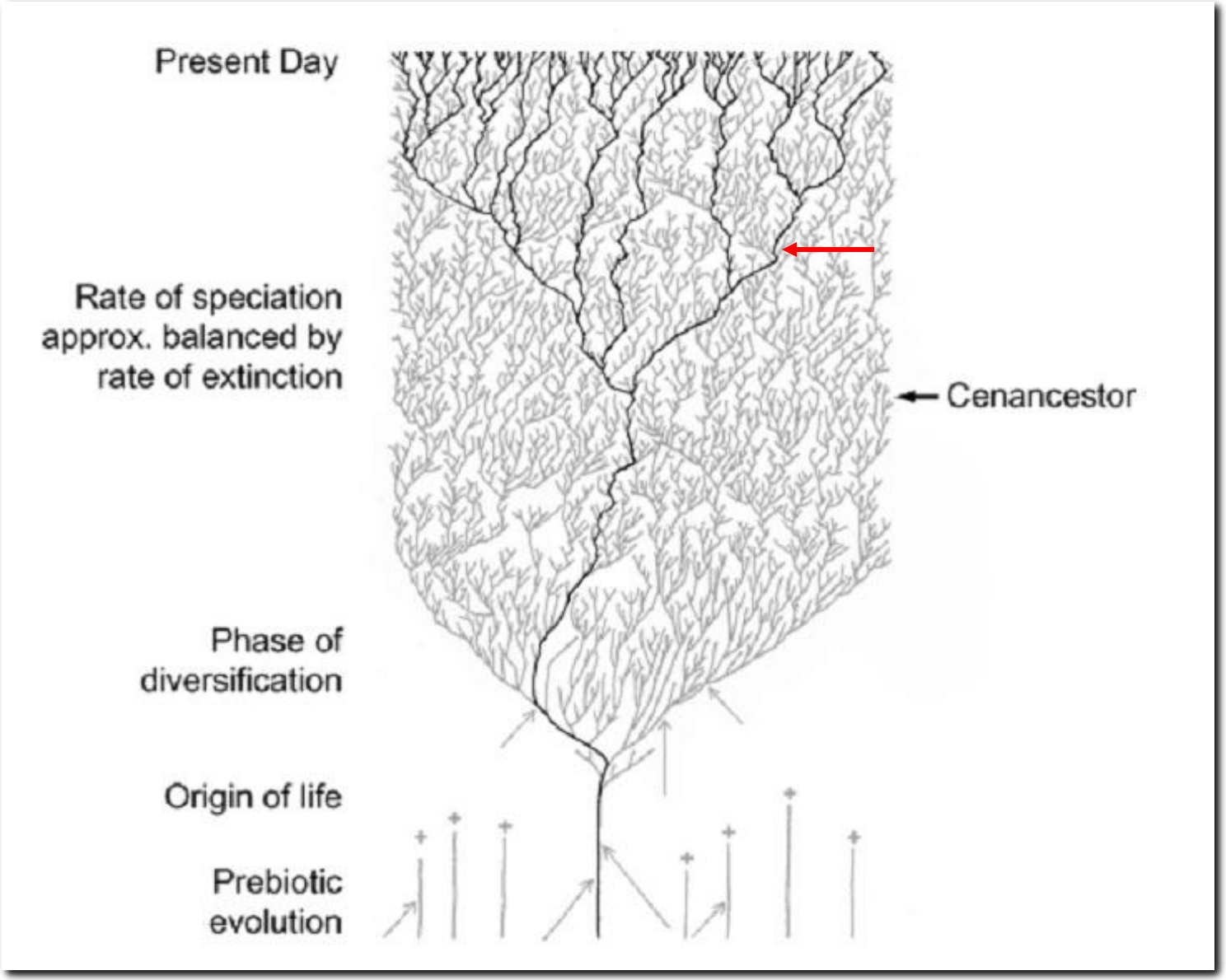


Page B26 from Charles Darwin's (1809-1882) notebook (1837/38)

Which Type of Coral?



The Coral of Life (Darwin)



Y chromosome Adam

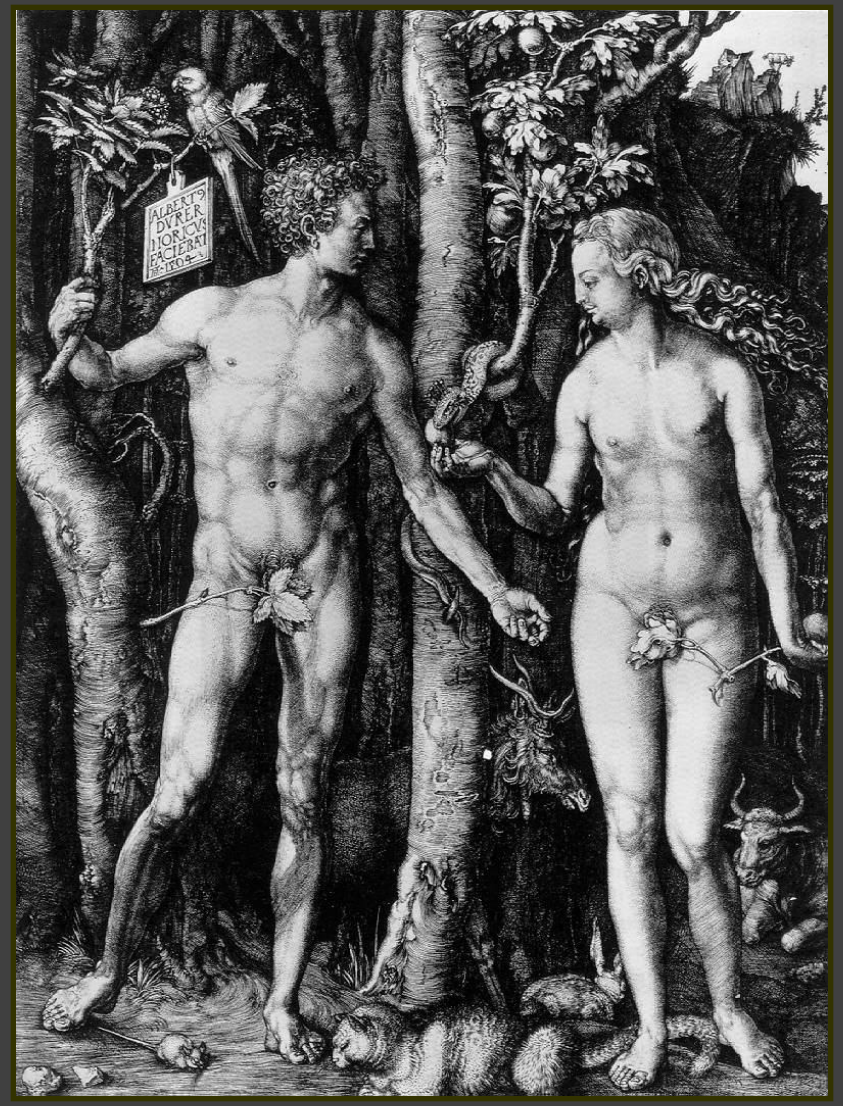
Lived approximately ~~40,000~~ years ago

>250,000

Thomson, R. *et al.* (2000) *Proc Natl Acad Sci* U S A 97, 7360-5

Underhill, P.A. *et al.* (2000) *Nat Genet* 26, 358-61

Mendez et al. (2013) American Journal of Human Genetics 92 (3): 454.



Albrecht Dürer, The Fall of Man, 1504

Mitochondrial Eve

Lived 166,000-249,000 years ago

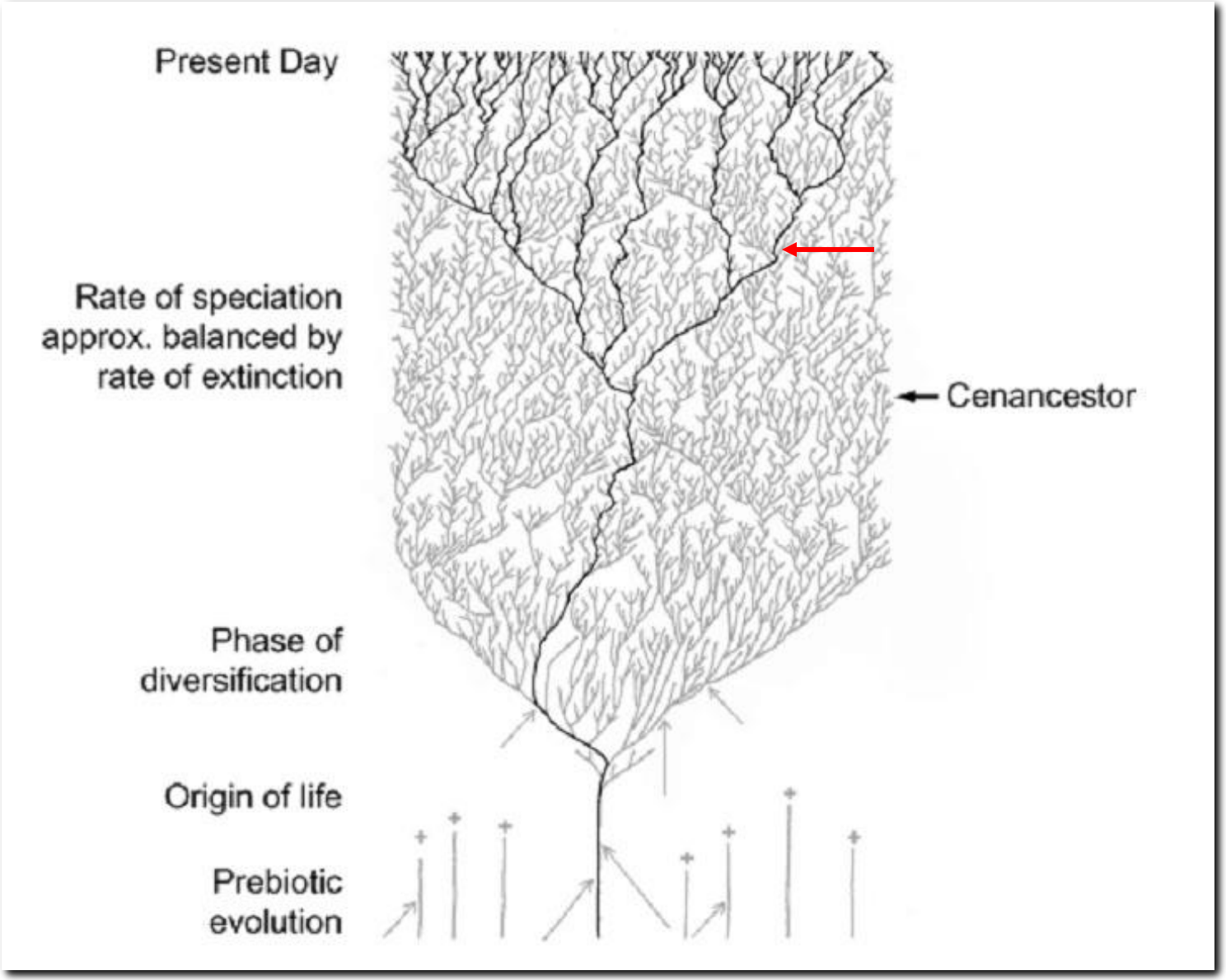
Cann, R.L. *et al.* (1987) *Nature* 325, 31-6

Vigilant, L. *et al.* (1991) *Science* 253, 1503-7

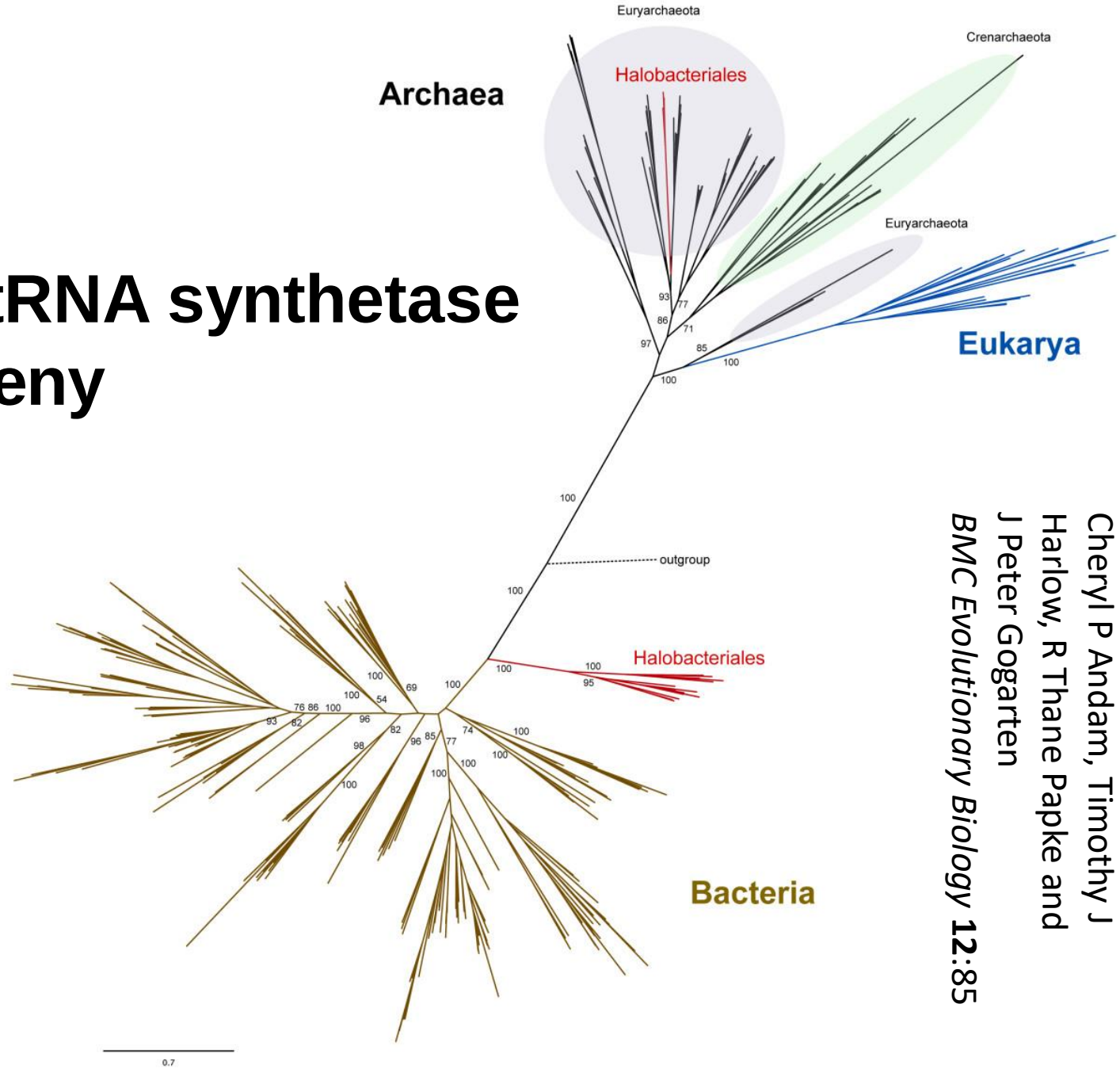
Adam and Eve never met ☹

The same is true for ancestral rRNAs, EF, ATPases!

The Coral of Life (Darwin)

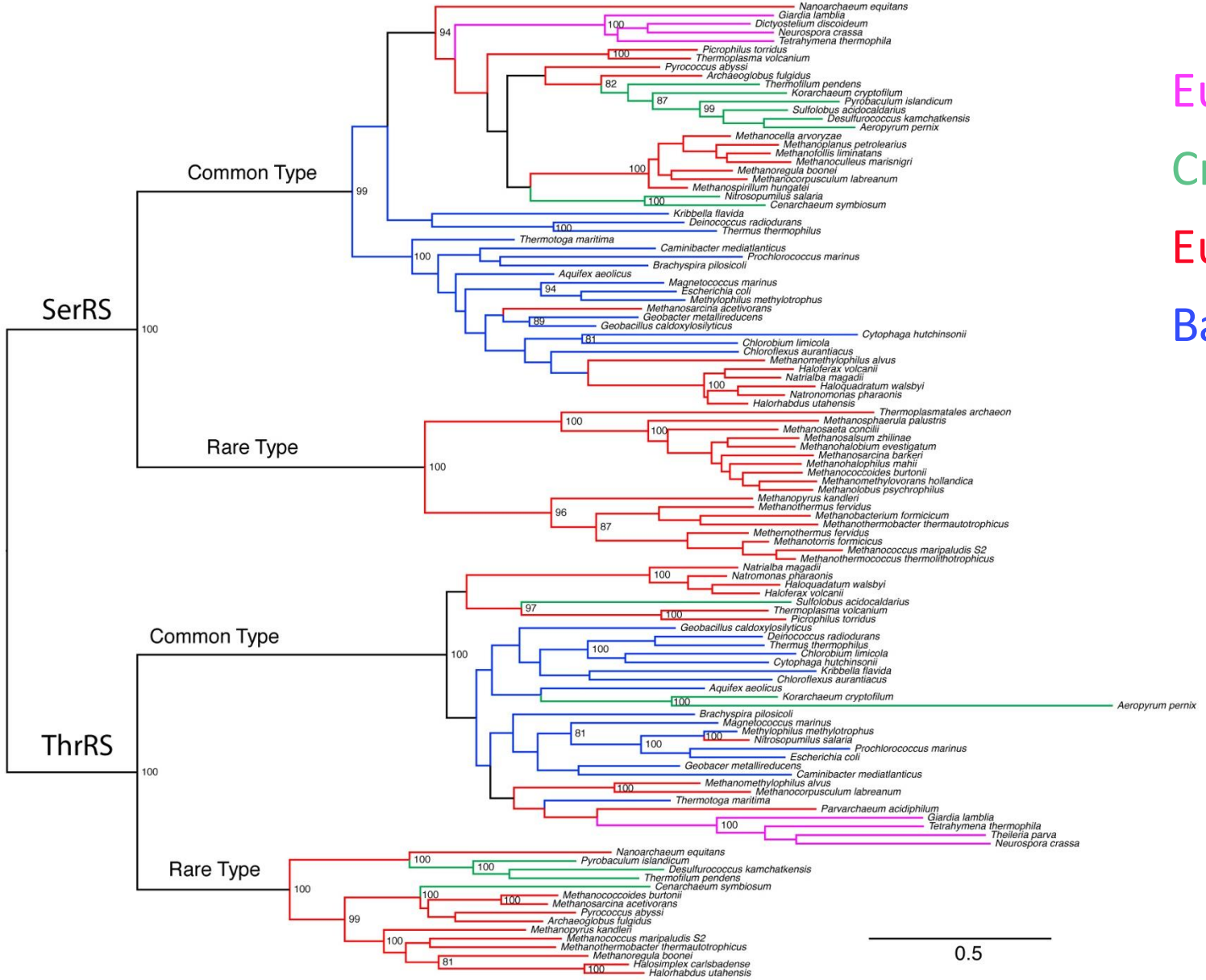


leucyl-tRNA synthetase phylogeny



Ancient origin of the divergent forms of leucyl-tRNA synthetases in the Halobacteriales
Cheryl P Andam, Timothy J Harlow, R Thane Papke and J Peter Gogarten
BMC Evolutionary Biology **12**:85

thrRS and serRS phylogeny



Eukaryotes

Crenarchaeota

Euryachaeota

Bacteria

Alignment with PRANK and SATé, tree with phyml (WAG, gamma +I)

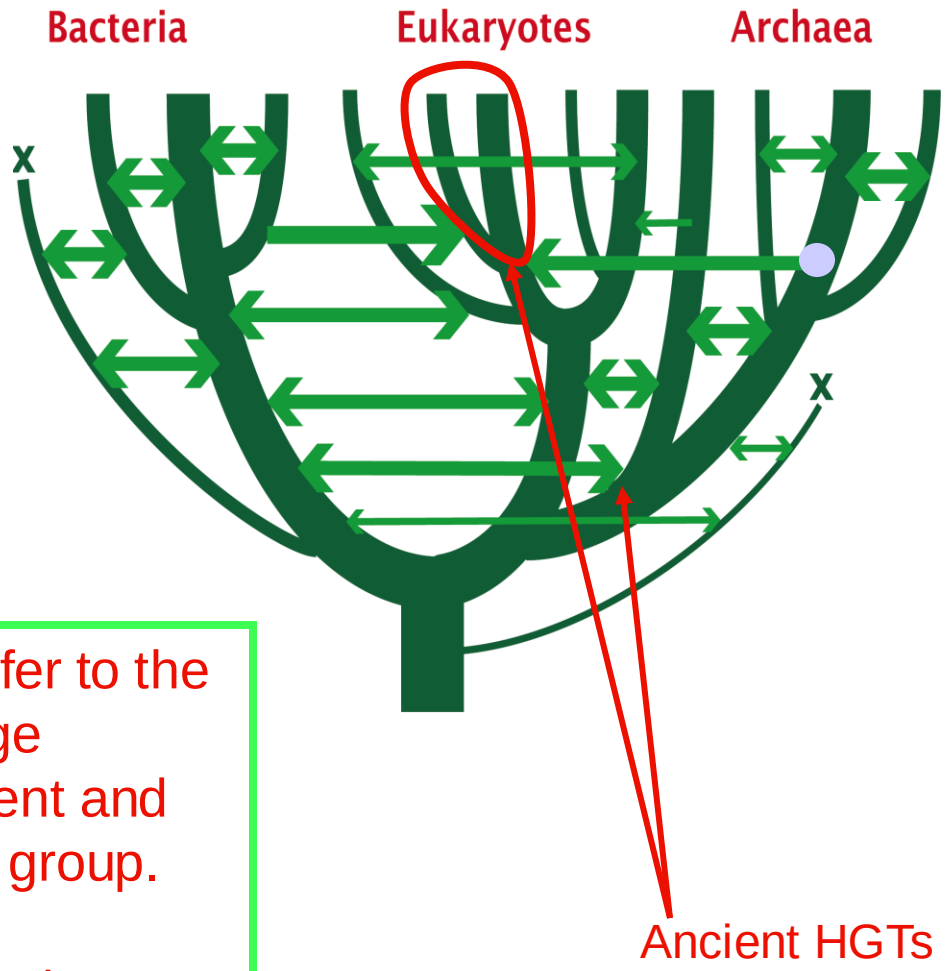
Gene Transfer and Phylogenetic Reconstruction: Friends or Foes?

Popular view

Gene transfer is a disruptive force in phylogenetic reconstruction.

New view

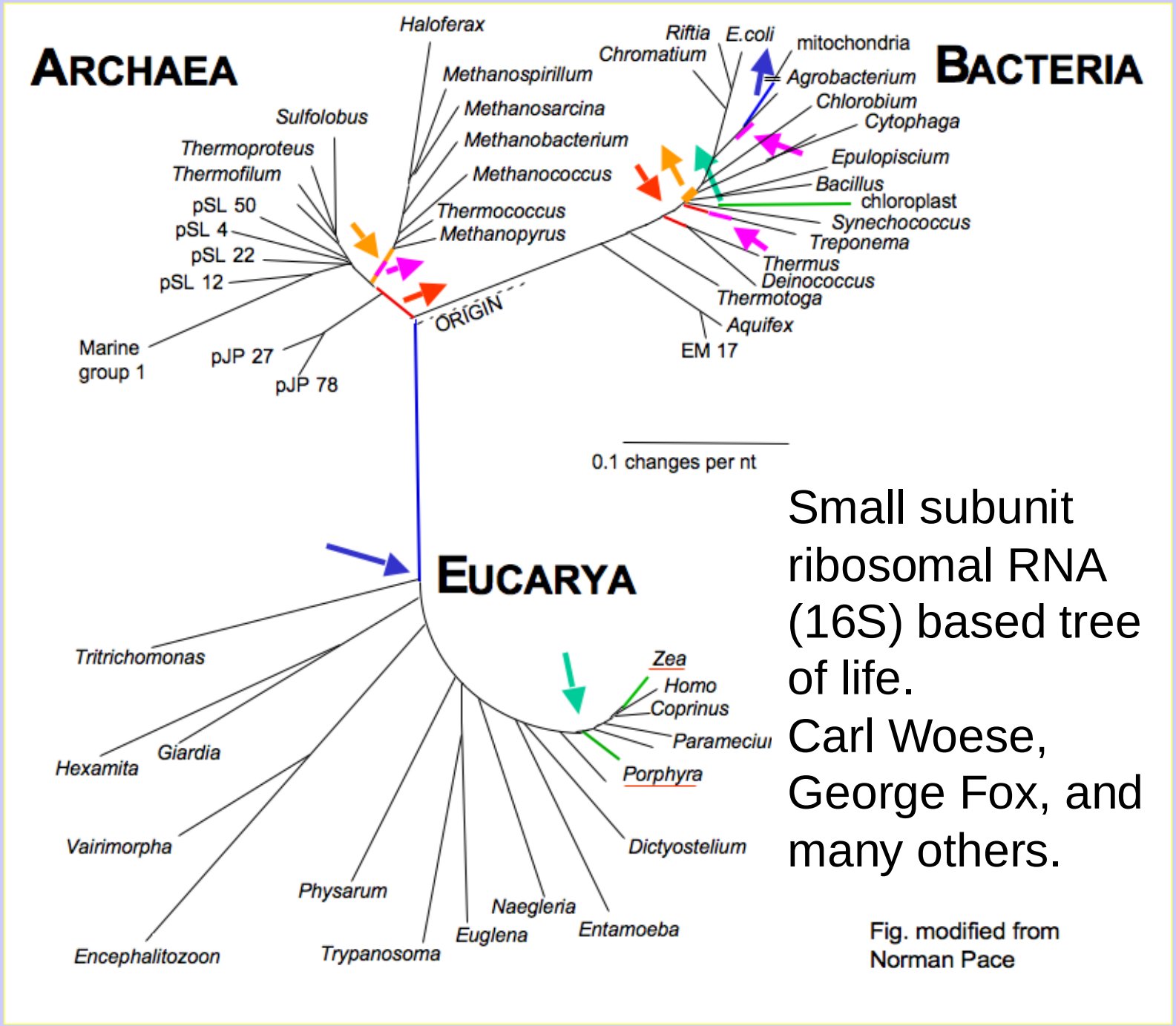
Events of ancient gene transfer are valuable tools for reconstructing organismal phylogeny.



1. Any ancient gene transfer to the ancestor of a major lineage implicitly marks the recipient and descendents as a natural group.

2. The donor must exist at the same time or earlier than the recipient.

SSU-rRNA Tree of Life

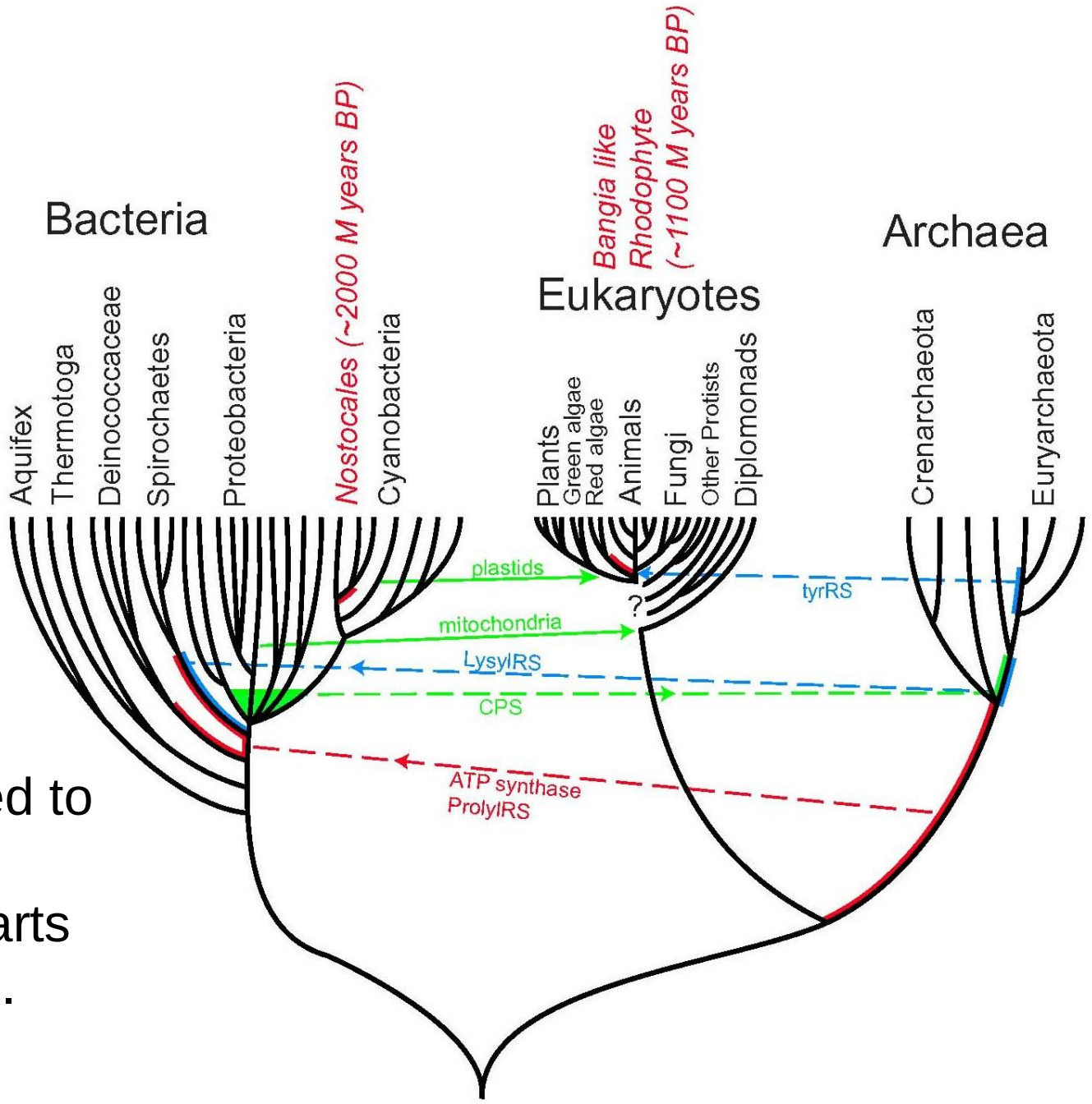


Small subunit ribosomal RNA (16S) based tree of life.
Carl Woese, George Fox, and many others.

Fig. modified from Norman Pace

Presence of a transferred gene is a shared derived character that can be useful in systematics.

Gene “ping-pong” between different lineages can be used to build correlations between different parts of the tree/net of life.

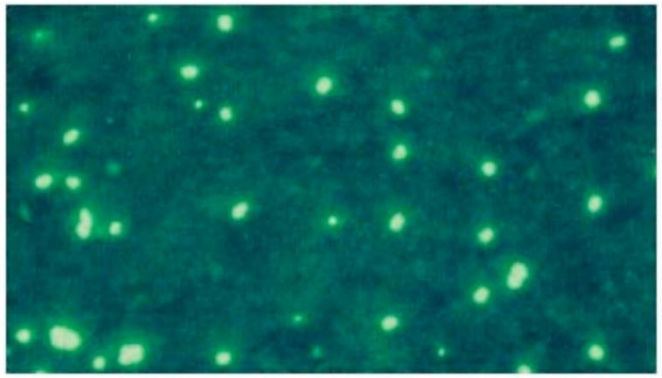


Gene transfer as a tool to correlate evolutionary events and define clades

Bacterial and archaeal groups had already diverged into different families and genera, before the major eukaryotic kingdoms diverged:

- Animals – Fungi diverge after split of Haloarchaea into lineages that contain *Halobacterium* and *Haloarcula,* respectively.

- Archaeplastida (glaucocystophytes, red-, and green algae) diverge after Chlamydiae split into lineages containing *Chlamydia* and *Parachlamydia*, respectively.



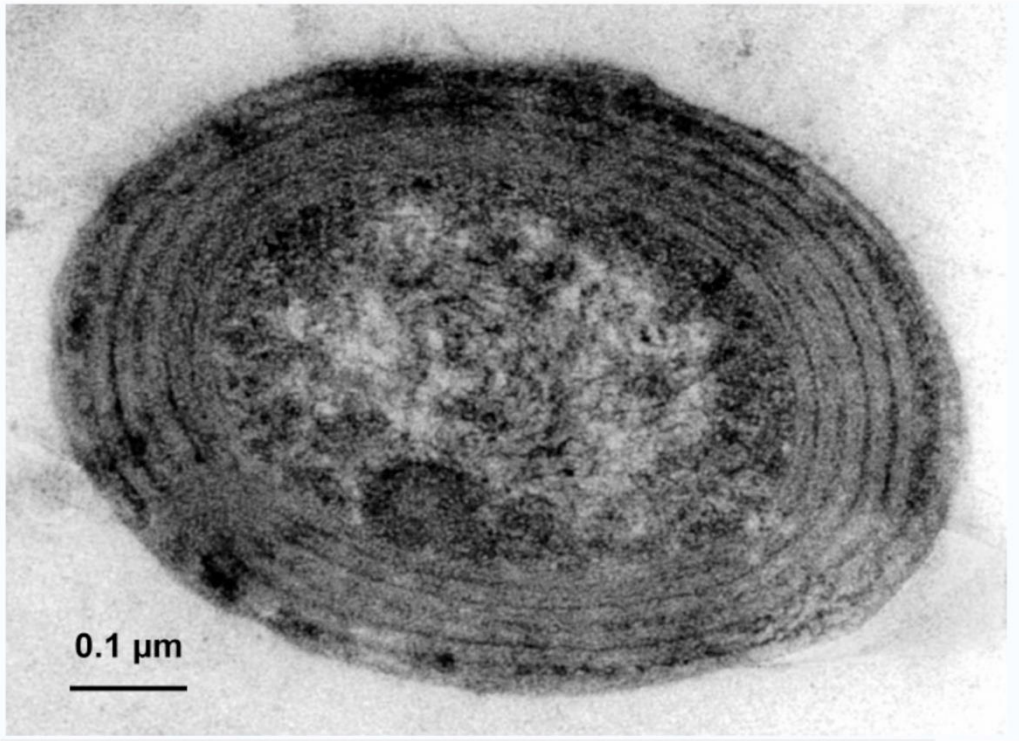
Alexandra Z. Worden and Mya E. Breitbart

(a)

Penny Chisholm

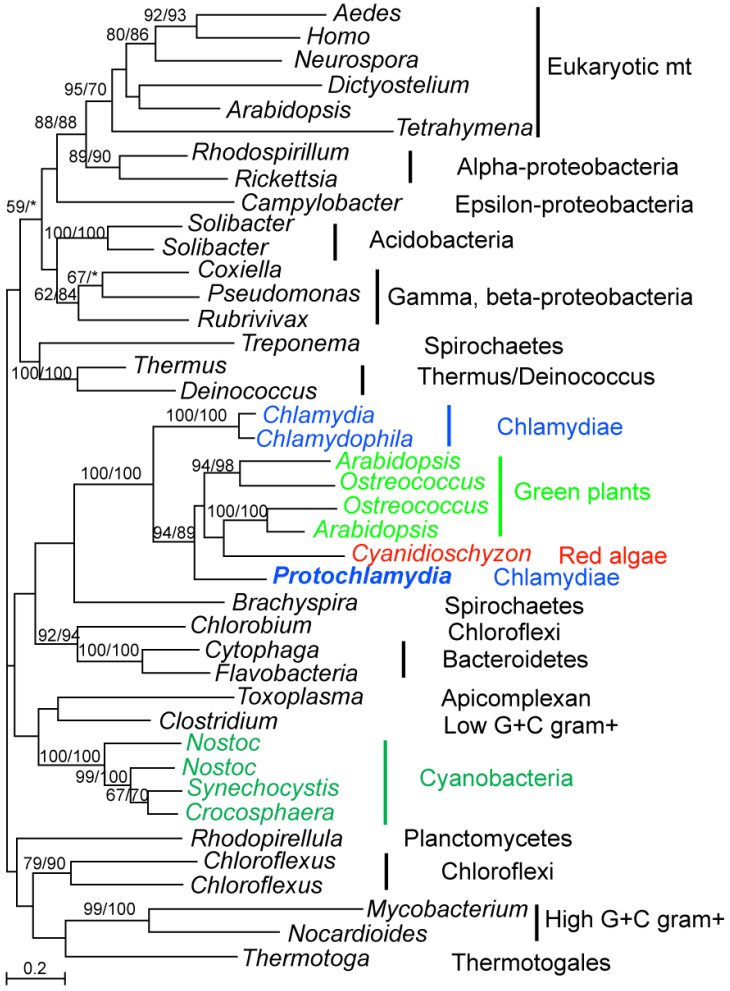
(b)

Figure 23.15 ***Prochlorococcus*, the most abundant oxygenic phototroph in the oceans.** *(a)* FISH-stained cells of *Prochlorococcus* in a marine water sample. *(b)* A cell suspension of *Prochlorococcus* showing the olive green color of the chlorophyll *a*- and *b*-containing cells.

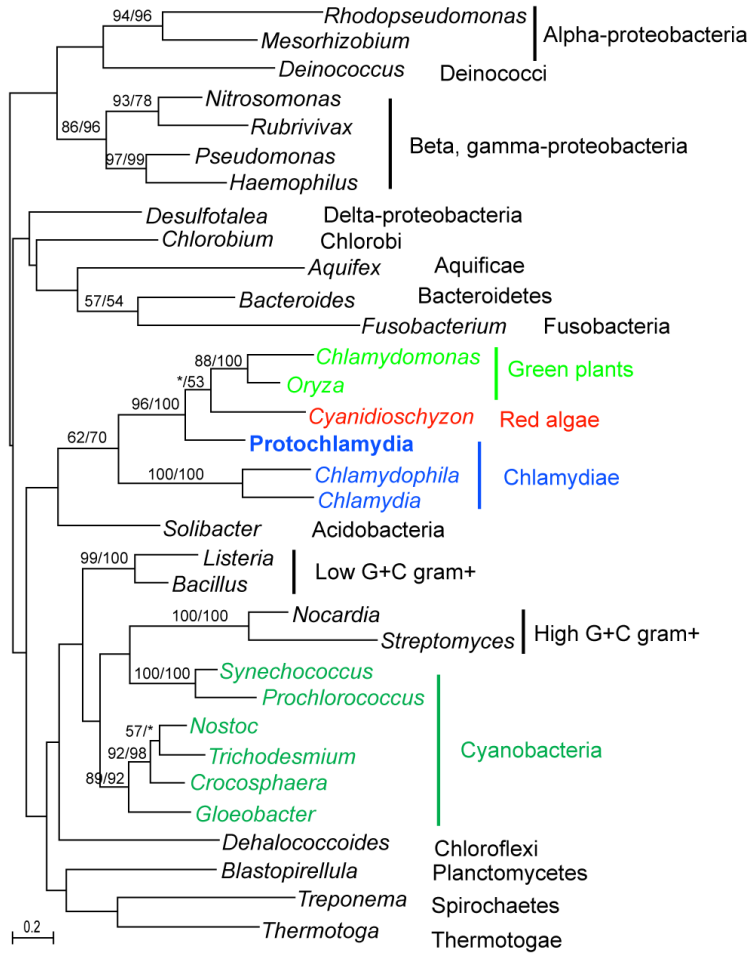


From http://en.wikipedia.org/wiki/Prochlorococcus

Chlamydial-type genes in red algae and plants are often specifically associated with *Protochlamydia (Parachlamydia)*



Beta-ketoacyl-ACP synthase (*fabF*)



4-diphosphocytidyl-2-C-methyl-D-erythritol kinase (*ispE*)

Huang and Gogarten 2007, Genome Biol 8:R99

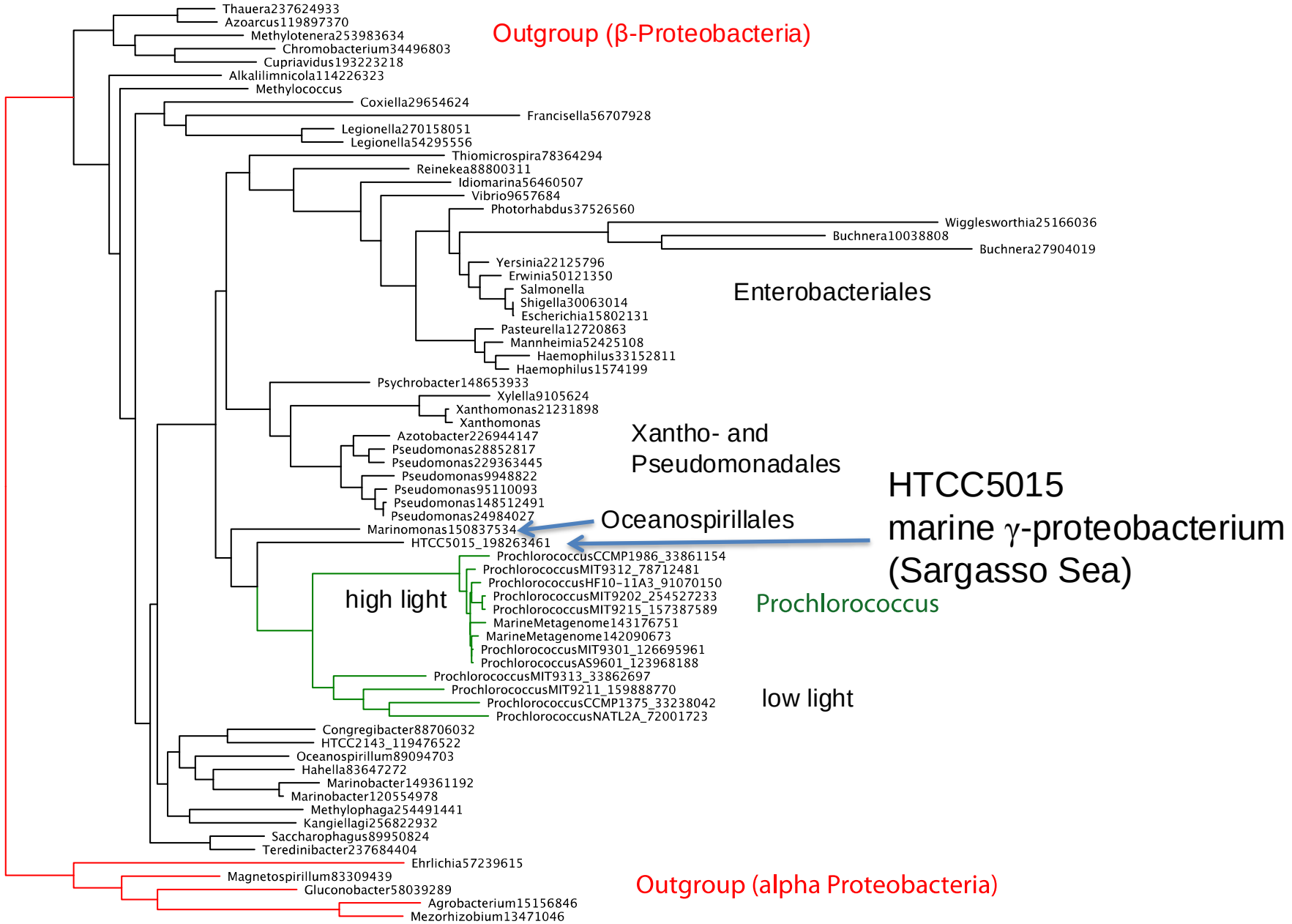
Red Algal and Green Plant Genes of Chlamydial Origin

Gene Name or Gene Product	Presence	Putative Function
ADT/ATP translocase	R and G	ATP/ADP transport
Phosphate transporter	G	Phosphate transport
Sodium:hydrogen antiporter	R and G	Ion transport
Cu-ATPase	R and G	Ion transport
4-hydroxy-3-methylbut-2-en-1-yl diphosphate synthase (*gcpE*)	R and G	Isoprenoid biosynthesis
4-diphosphocytidyl-2-C-methyl-D-erythritol kinase (*ispE*)	R and G	Isoprenoid biosynthesis
2-C-methyl-D-erythritol 4-phosphate cytidylyltransferase (*ispD*)	R and G	Isoprenoid biosynthesis
Enoyl-ACP reductase (*fabI*)	R and G	Fatty acid biosynthesis
Beta-ketoacyl-ACP synthase (*fabF*)	R and G	Fatty acid biosynthesis
Glycerol-3-phosphate acyltransferase	R and G	Phospholipid
Polynucleotide phosphorylase	R and G	RNA degradation
Phosphoglycerate mutase	G	Glycolysis
Oligoendopeptidase F	R	Amino acid biosynthesis
Aspartate transaminase	R and G	Amino acid metabolism
Malate dehydrogenase	G	Energy conversion
Tyrosyl-tRNA synthetase	R and G	Translation
23S rRNA (Uracil-5-)-methyltransferase	R and G	RNA modification
Isoamylase	R and G	Starch biosynthesis
Hypothetical protein	R	Unknown
Sugar phosphate isomerase	G	Sugar interconversion
CMP-KDO synthetase	G	Cell envelope formation

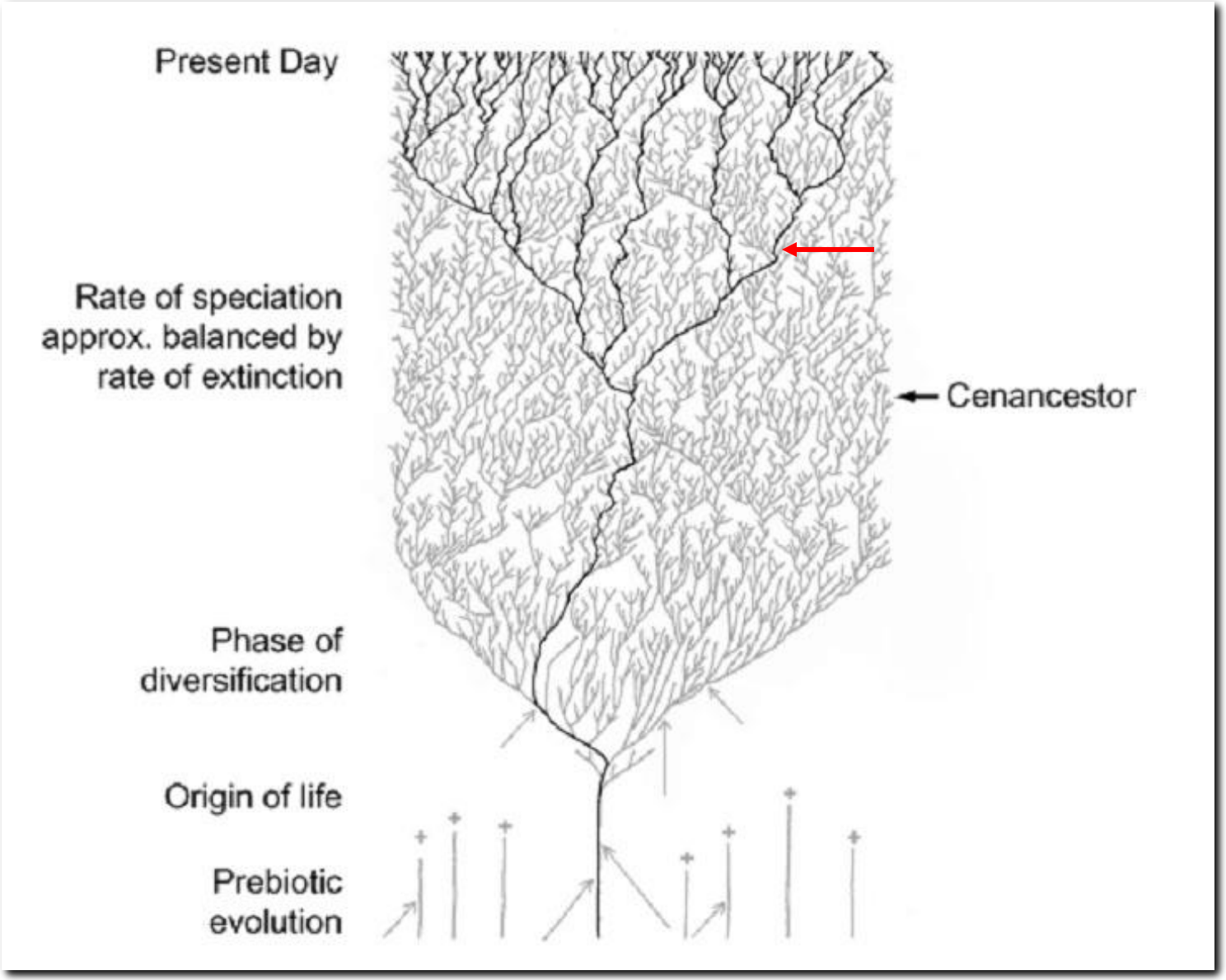
Consistent phylogenetic signal links Chlamydiae, red algae and green plants.

modified from
Huang and Gogarten 2007, Genome Biol 8:R99
Additional genes reported in
Becker B, Hoef-Emden K, Melkonian M.
BMC Evol Biol. 2008 Jul 15;8:203.
Moustafa A, Reyes-Prieto A, Bhattacharya D..
PLoS ONE. 2008 May 21;3(5):e2205.

ThrRS Phylogeny – γ-Proteobacteria



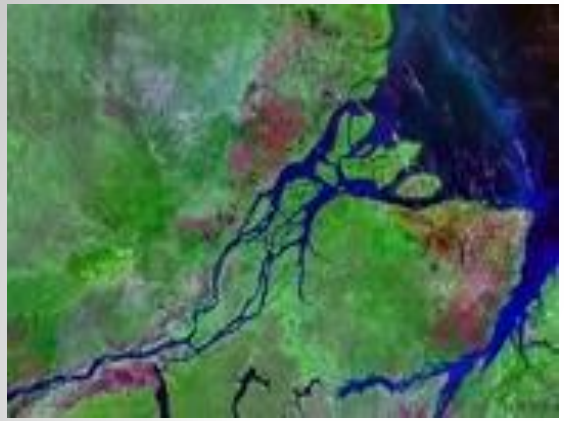
The Coral of Life (Darwin)



The Watershed of Life

Jonathan Eisen in his Tree of Life Blog on
"Top Five Metaphors Charles Darwin Considered"

http://phylogenomics.blogspot.com/2008/06/top-five-metaphors-darwin-considered.html



http://www.southcom.mil/appssc/files/Blogs/633600980055909252.jpg

Meeting of the meeting of Solimões and Negro rivers at Origin of the Amazon

THE POTATO OF LIFE

Successive independent crystallization of the three domains of life from a population of pre-cells

Glansdorff N, Xu Y, Labedan B: *The Last Universal Common Ancestor: emergence, constitution and genetic legacy of an elusive forerunner.* *Biol Direct* 2008, **3**:29.

Kandler O (1994) *The early diversification of life*. In *Early Life on Earth, Nobel Symposium*, vol. 84, pp. 152-509: Columbia Univ. Press.

Woese CR (2002) *On the evolution of cells*. *PNAS* 99: 8742-7

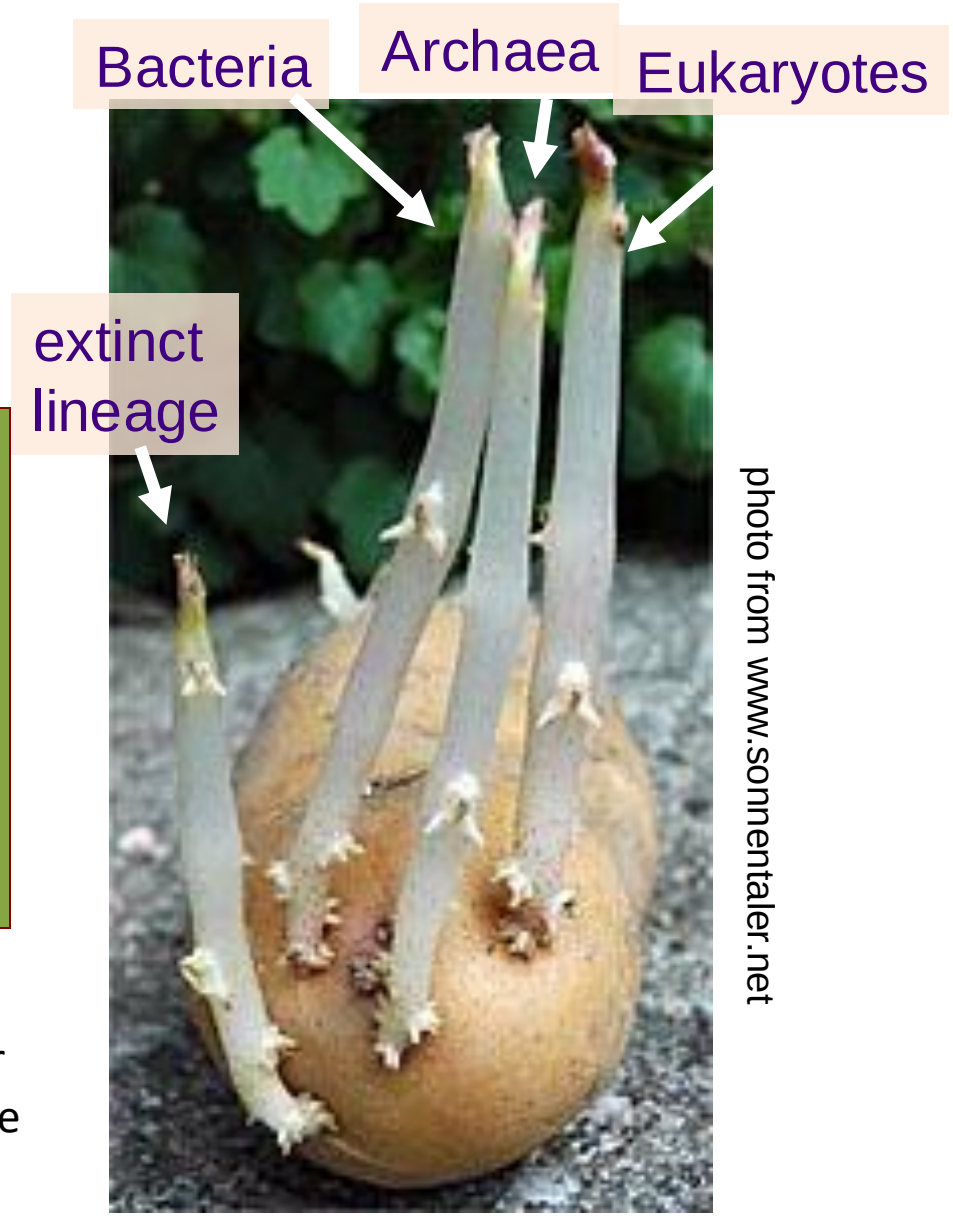
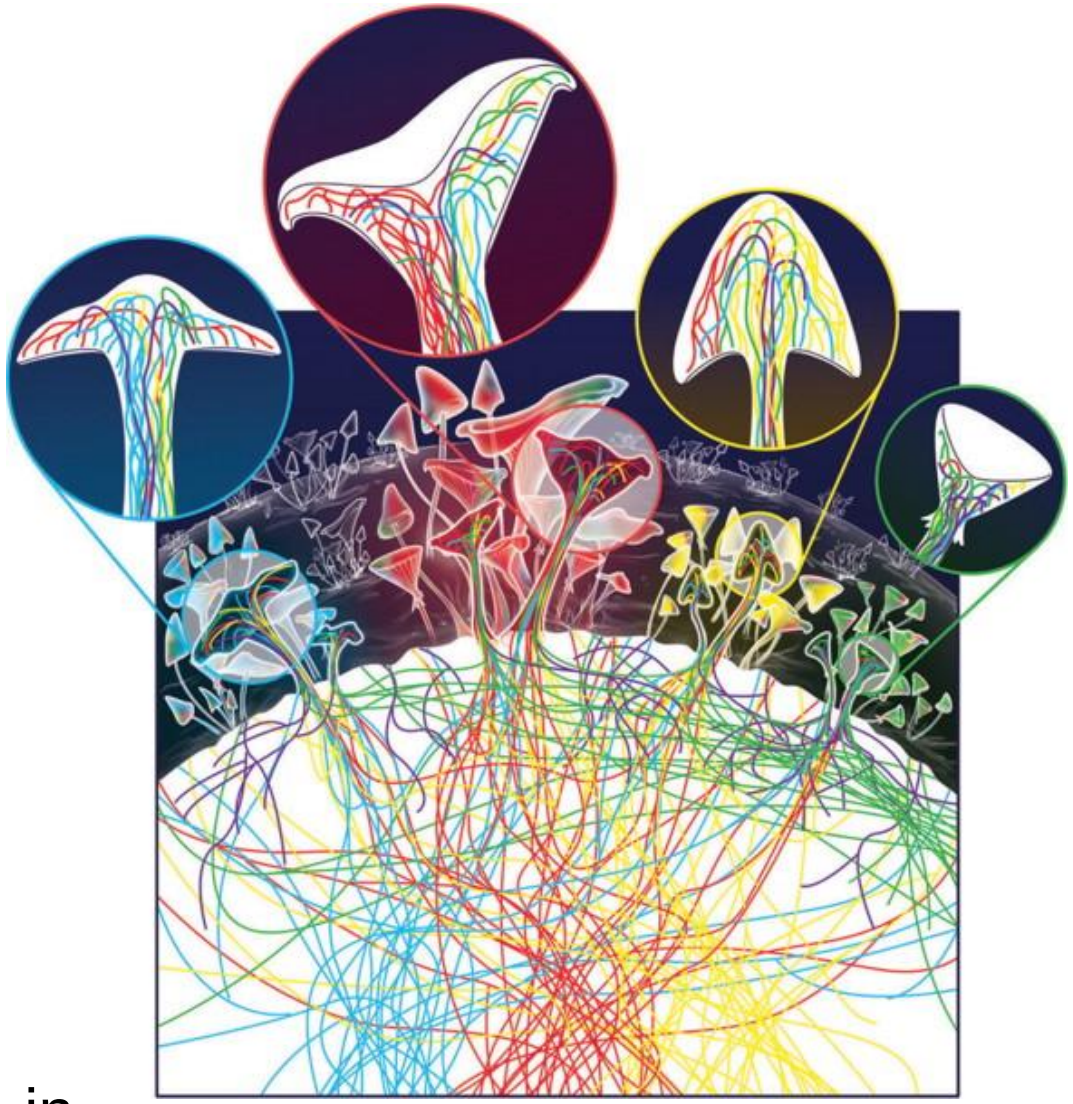


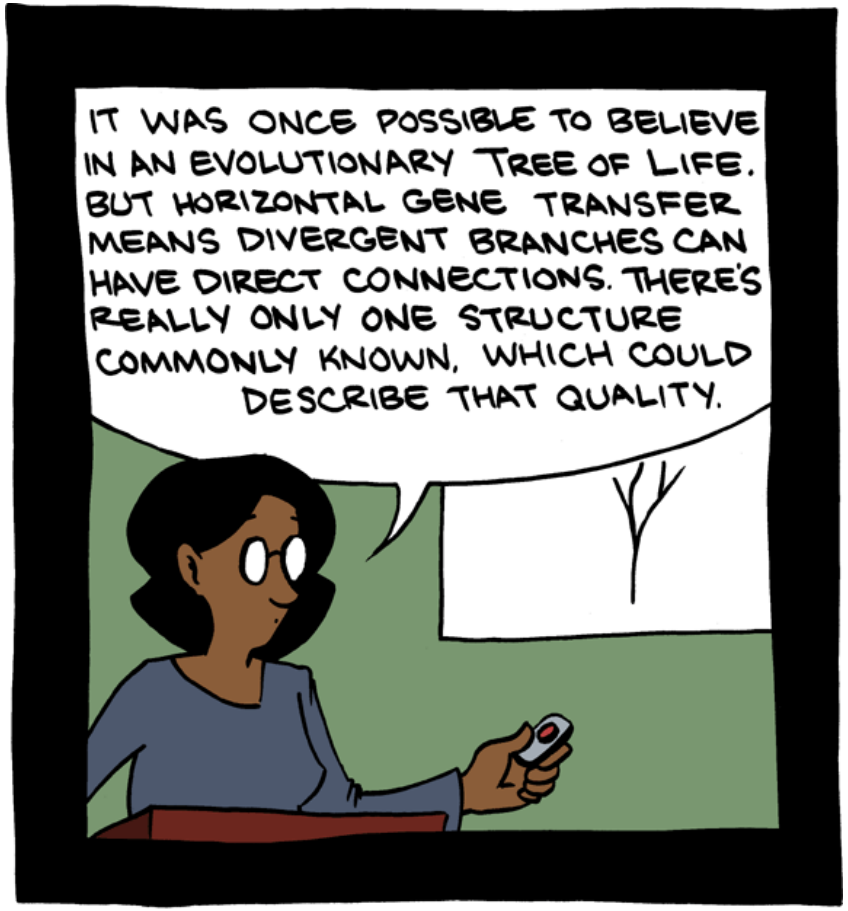
photo from www.sonnentaler.net

This is just included, because it is cute. The three cellular lineage almost certainly did not separate in the progenote stage symbolized here as the potato.

The Rhizome of Life (Didier Raoult)



See opinion piece in
https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(09)61958-9/fulltext



Nobody appreciated my "Ewok Village of Life" concept.

See https://phylogenomics.blogspot.com/2008/06/top-five-metaphors-darwin-considered.html for more