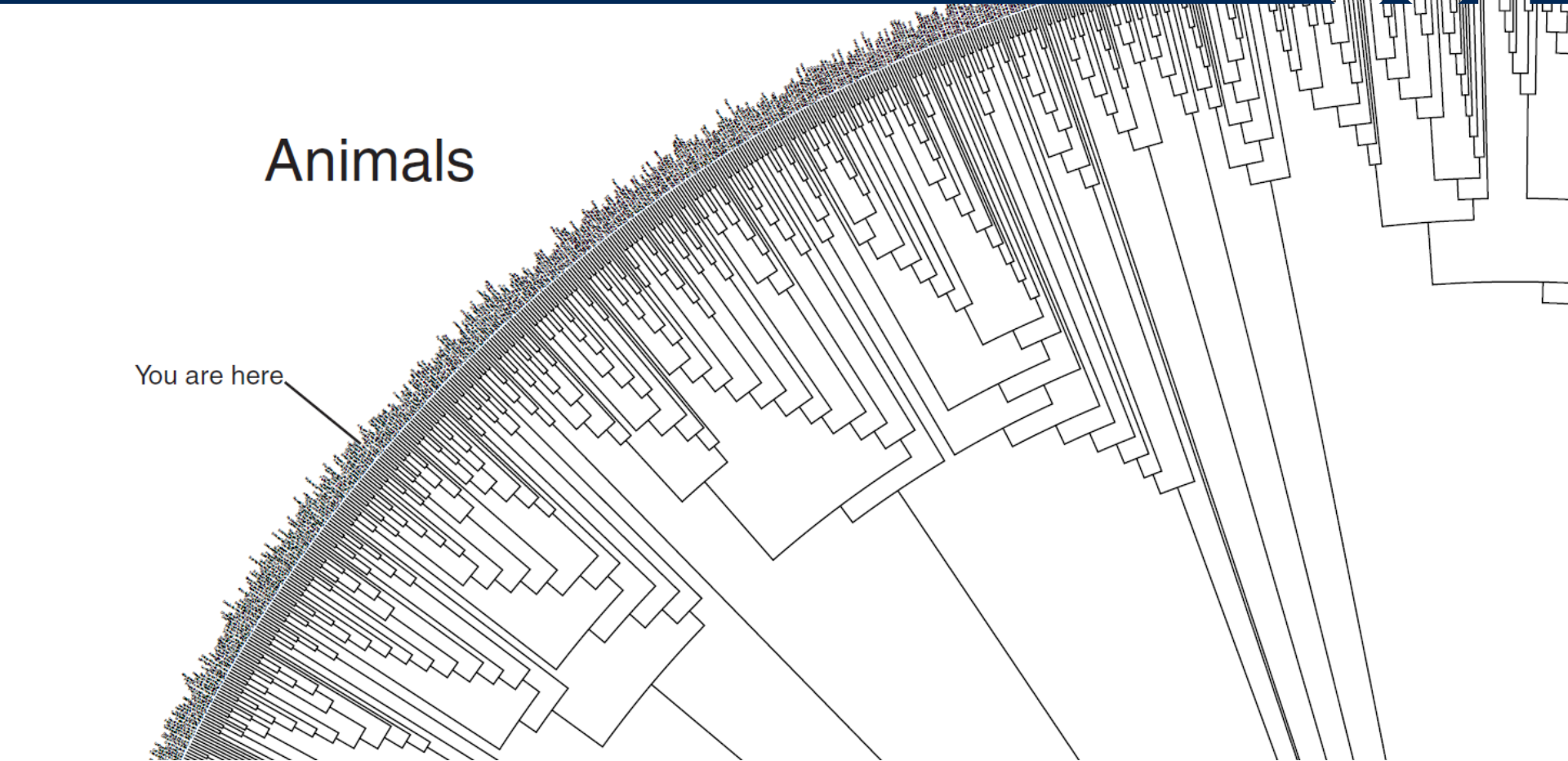
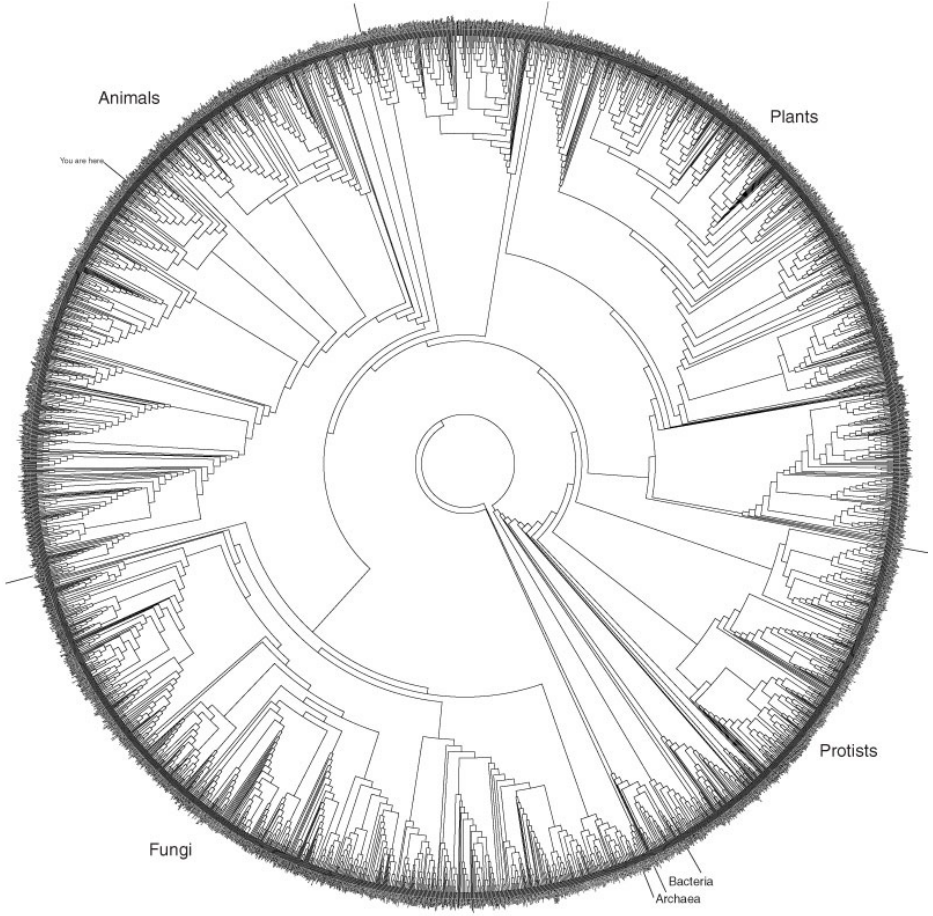
How energy flow shapes the evolution of life

Nick Lane

Professor of Evolutionary Biochemistry
University College London

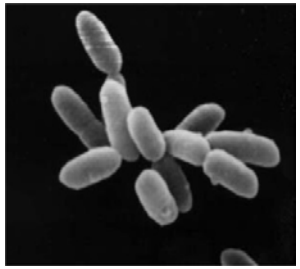
Life on Earth – anything goes


Animals
You are here

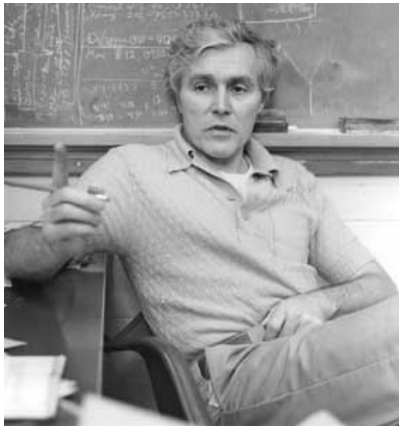

Animals
You are here
Plants
Protists
Fungi
Bacteria
Archaea

The three domains ‘tree of life’

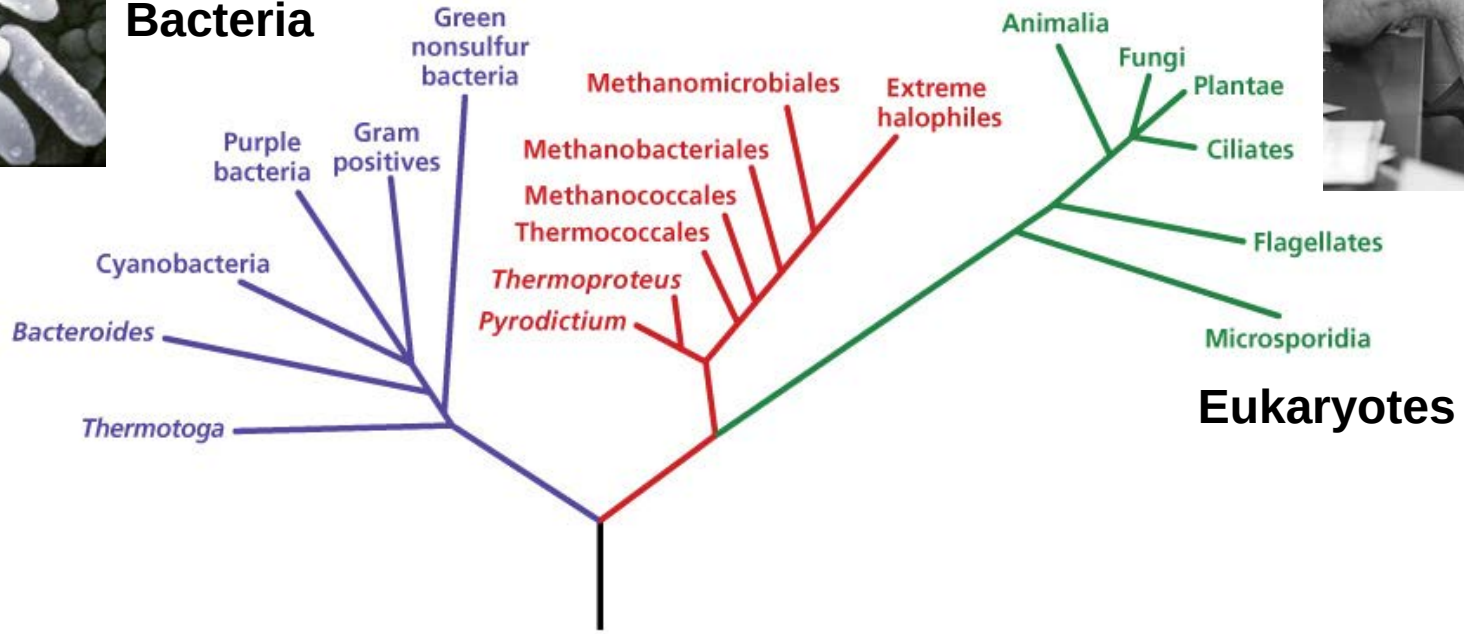
Bacteria



Archaea

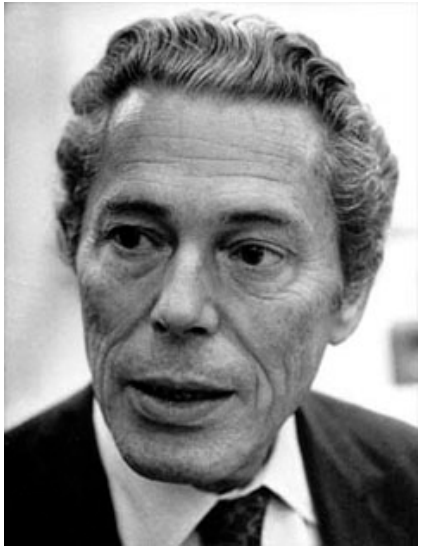


Carl Woese



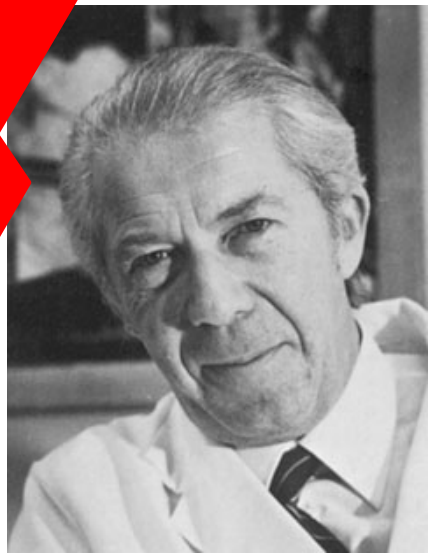
Eukaryotes

Chance or Necessity?



Jacques Monod

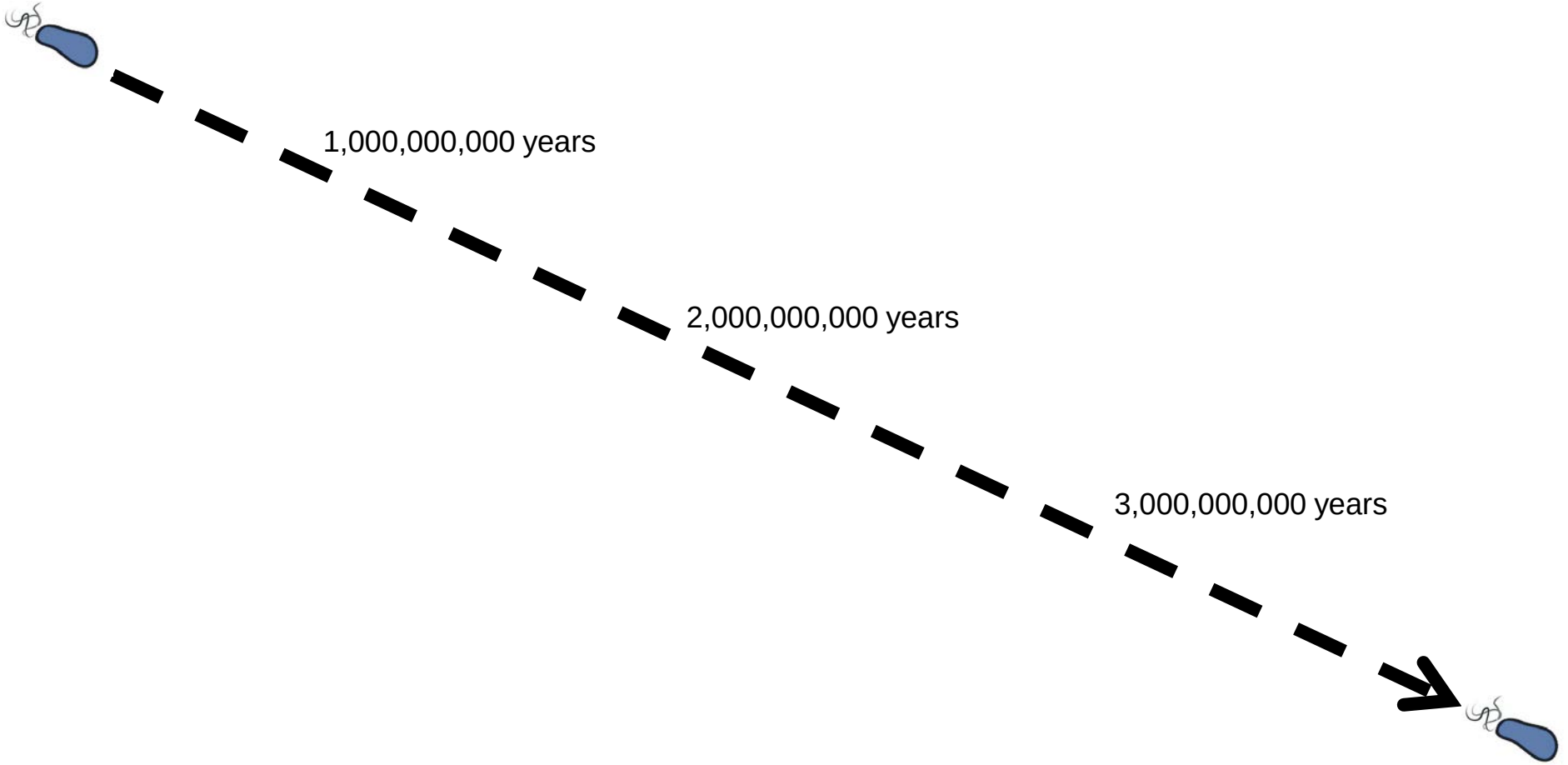
Steven Jay Gould

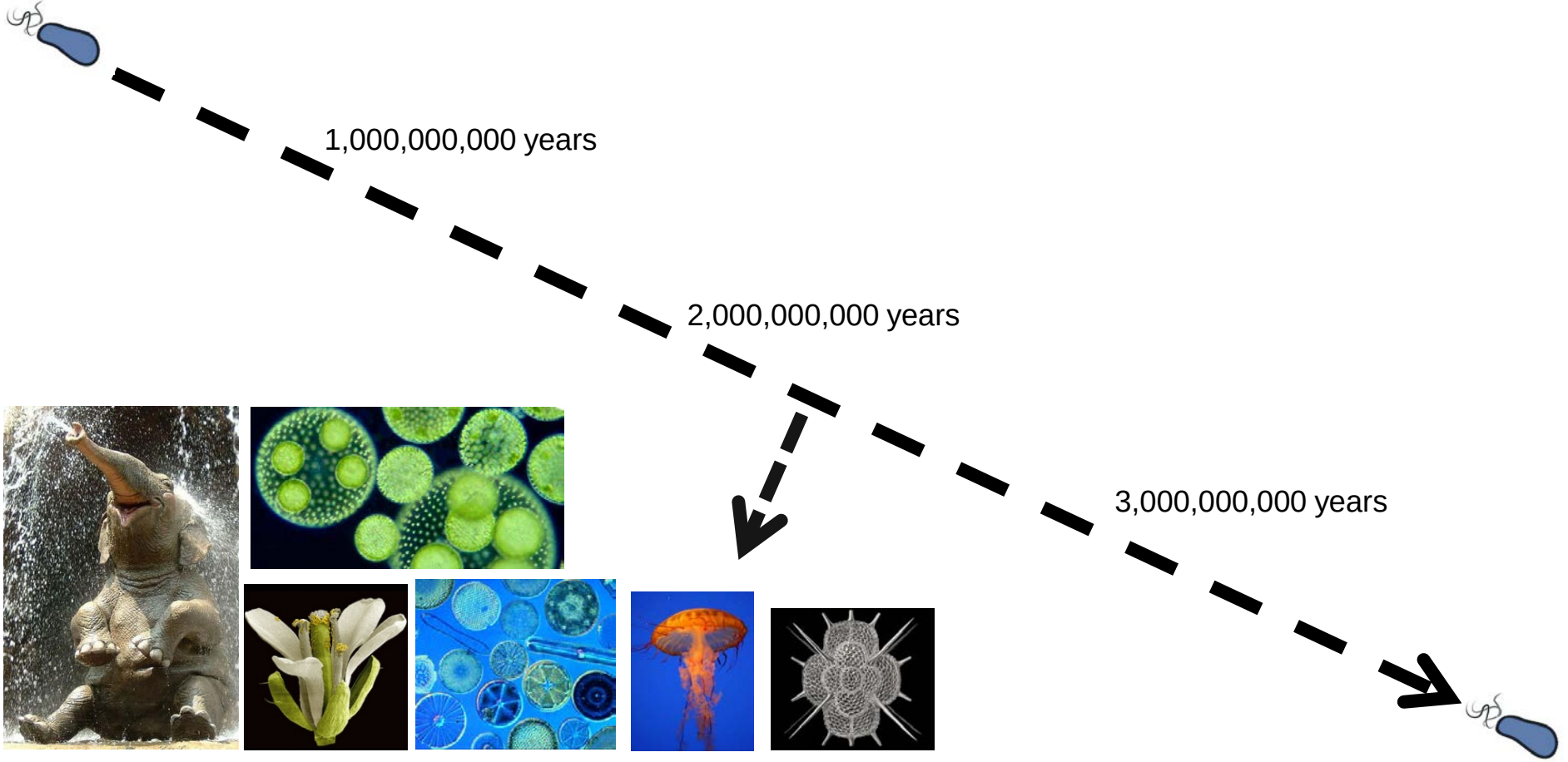


Christian de Duve

Simon Conway-Morris

Is complex life the inevitable outcome of natural selection or more unlikely contingent processes?


1,000,000,000 years
2,000,000,000 years
3,000,000,000 years


1,000,000,000 years
2,000,000,000 years
3,000,000,000 years

What forces constrain the evolution of bacteria?

How did complex cells escape?

Would these forces be similar on other planets?

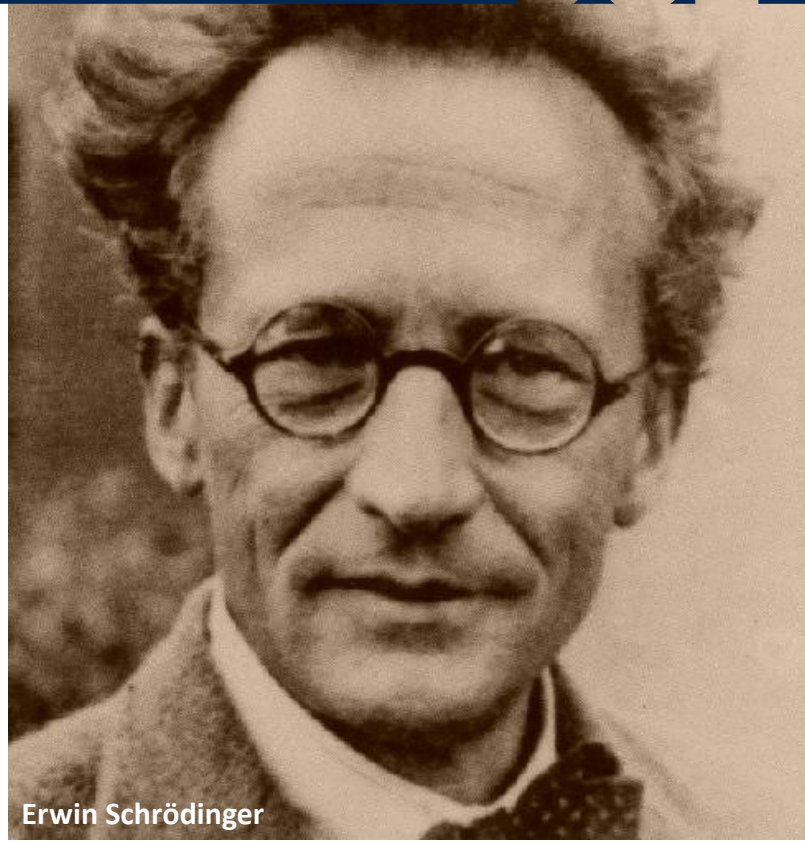
What is life?

Genes

“Chromosomes … contain in some kind of **code-script** the entire pattern of the individual's future development and of its functioning in the mature state”

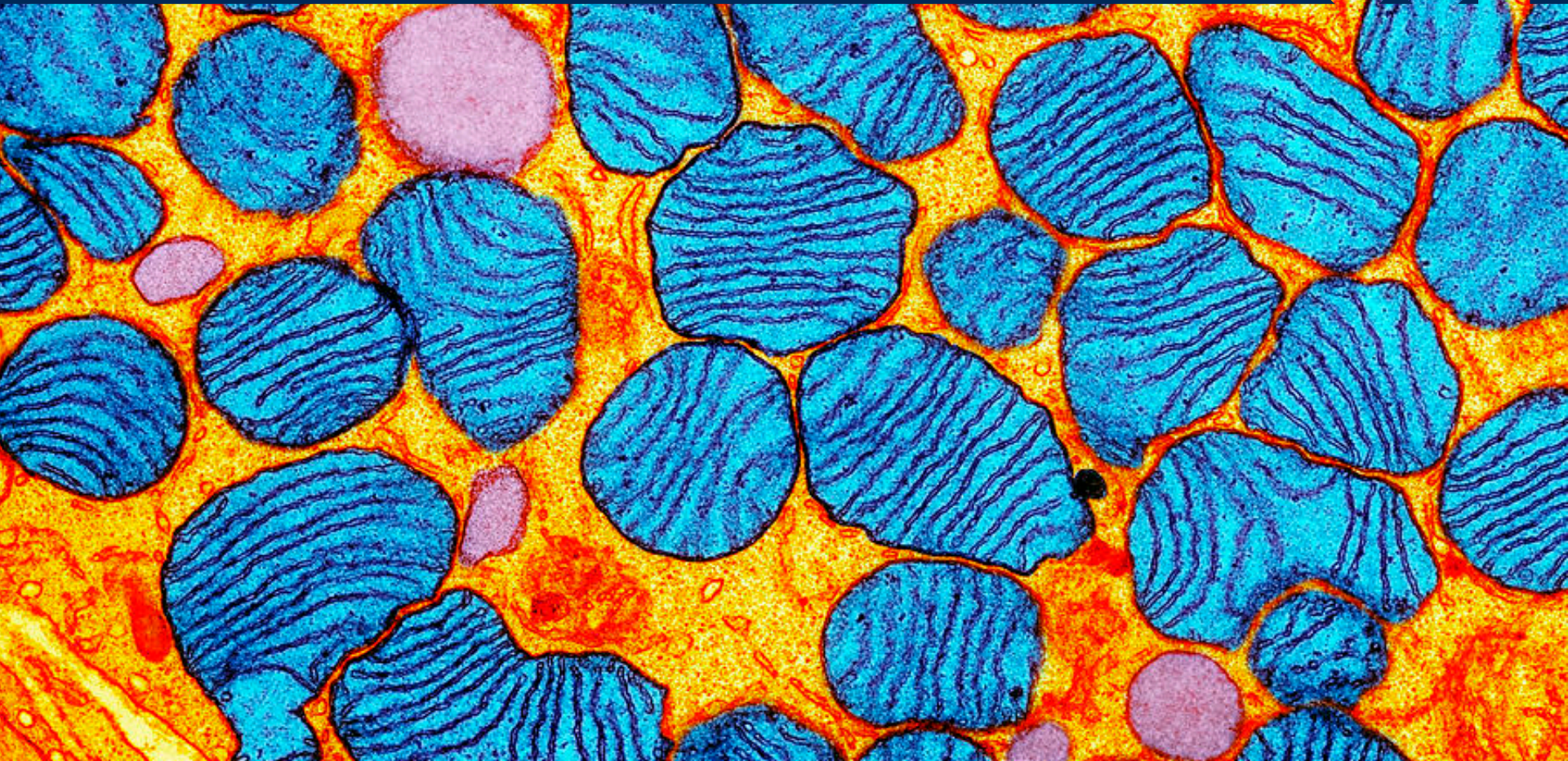
Energy

“Life feeds on negative entropy…The device by which an organism maintains itself stationary at a fairly high level of orderliness really consists in **continually sucking orderliness from its environment**”

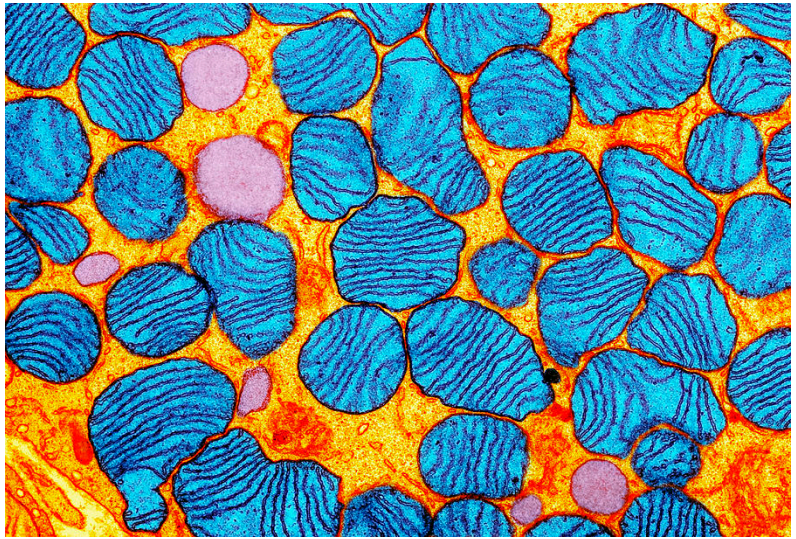

Erwin Schrödinger

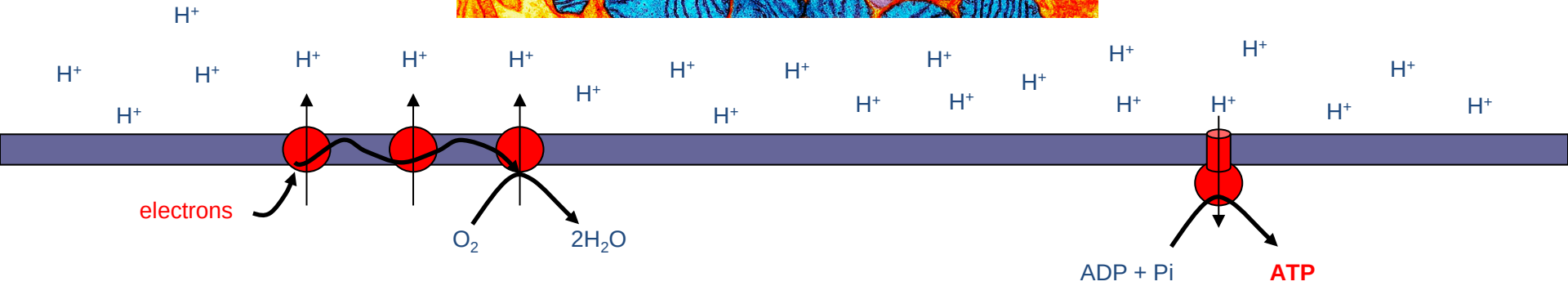
“If I had been catering for physicists alone I should have let the discussion turn on free energy instead”

Mitochondria – powerhouses of the cell



What's happening in you right now





ATP synthase is an amazing rotary motor set in the membrane – a turbine

Sir John Walker

Proton gradients – as universal as the code

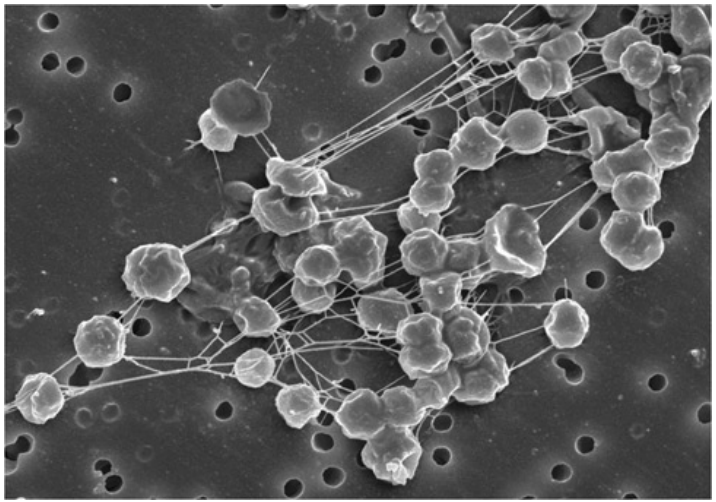
“Not since Darwin has biology come up with an idea as counterintuitive as those of, say, Einstein, Heisenberg or Schrödinger…” Leslie Orgel


Jennifer Moyle and Peter Mitchell

“I cannot consider the organism without its environment… from a formal point of view the two may be regarded as equivalent phases between which dynamic contact is maintained by the membranes that separate and link them.”

Peter Mitchell, 1957

How did the first cells make their living?

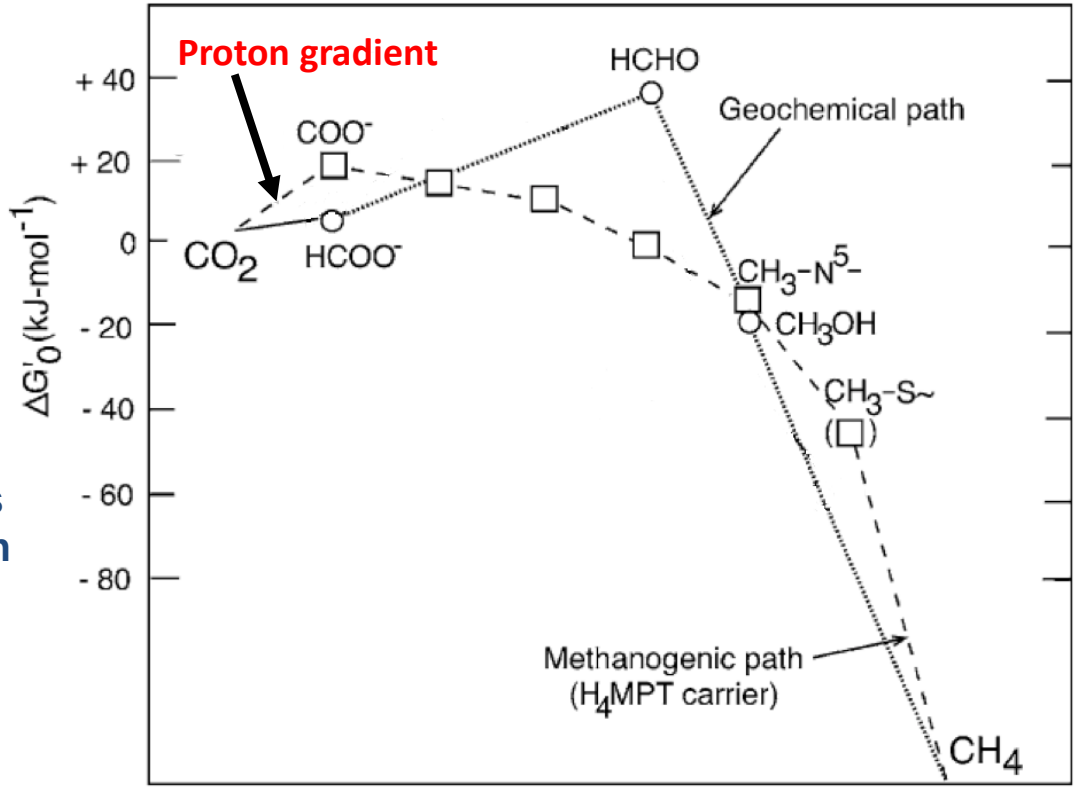


Methanogens – archaea

$CO_2 + 4H_2 \longrightarrow \mathbf{CH_4} + 2H_2O$ **+ ENERGY**

But to drive the reaction between H_2 and CO_2 they need a proton gradient

Proton gradients drive the reaction of CO_2 with H_2



The first steps of this reaction are difficult – try making synthetic gasoline

This mechanism points to an environment where life might have started

Alkaline hydrothermal vents


Deborah Kelley

Lost City vent field

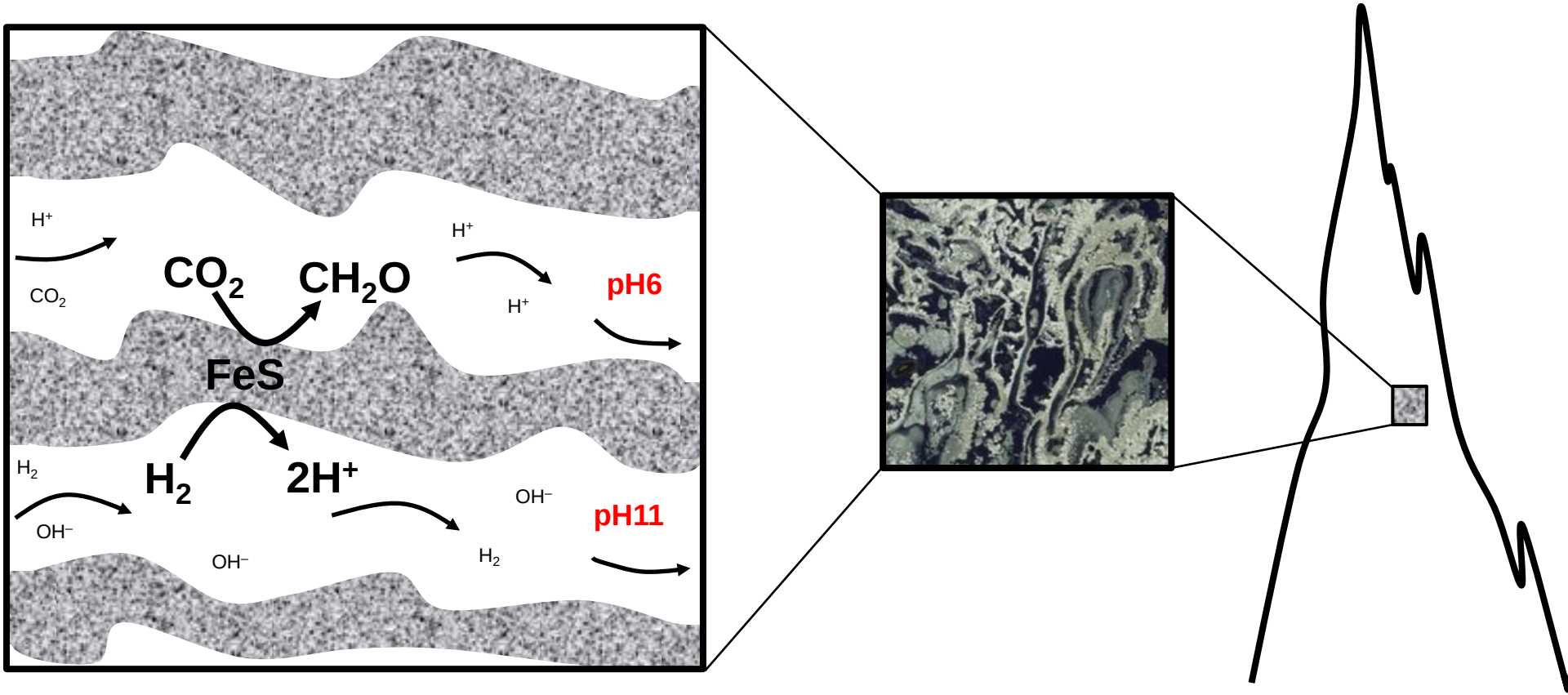
Electrochemical flow reactors

Mike Russell, Nascence Man

High concentrations of H_2 and CO_2

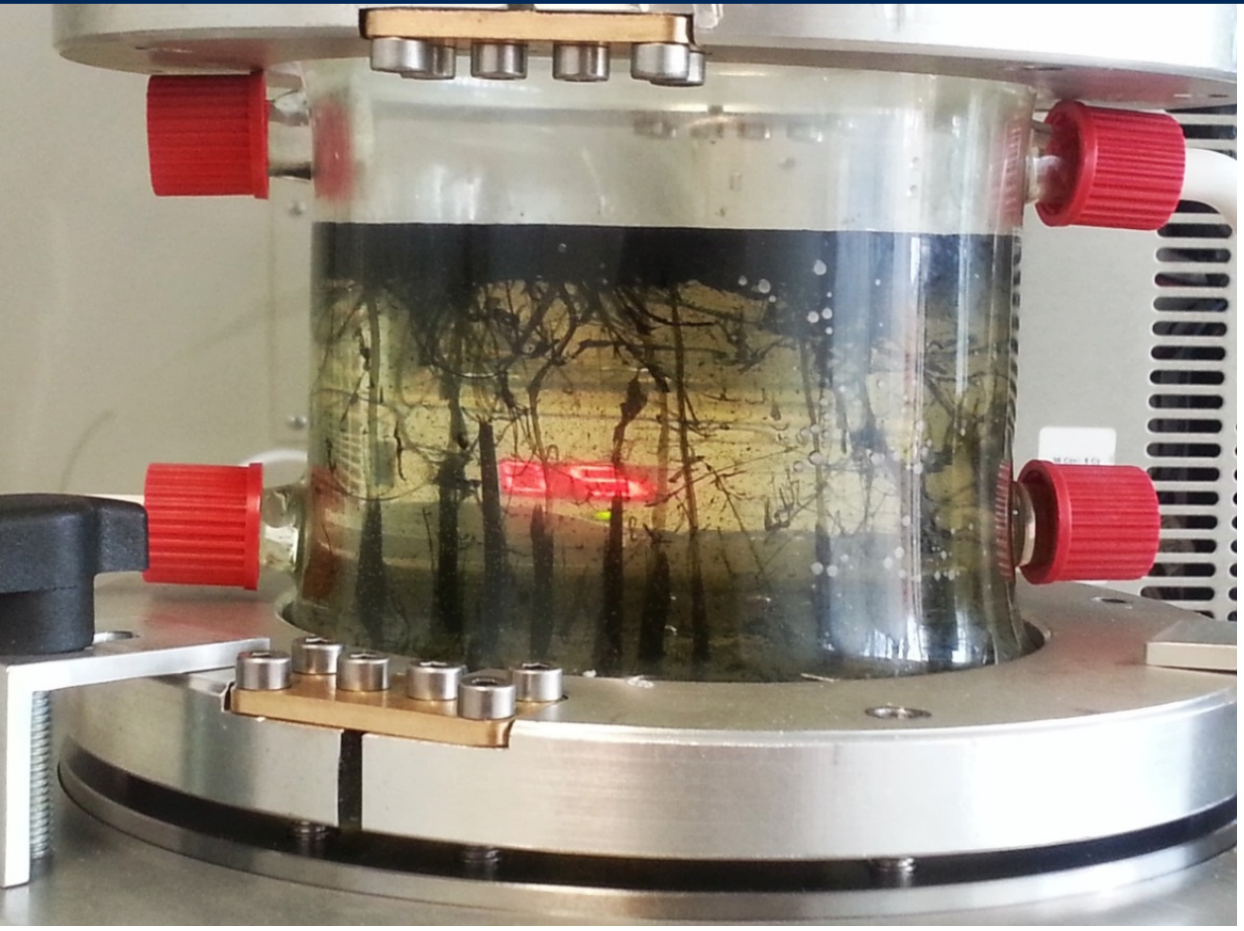
Proton gradients across catalytic walls

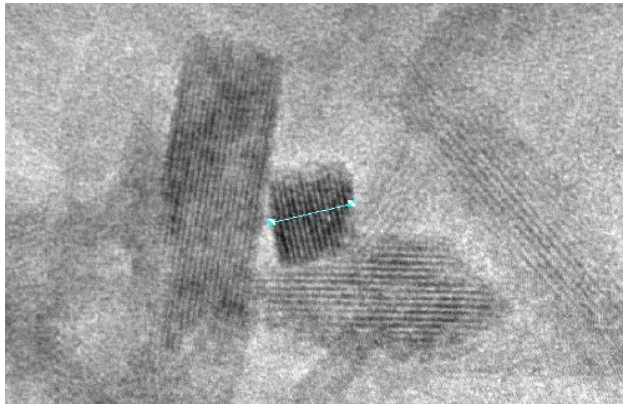
Making organic molecules?

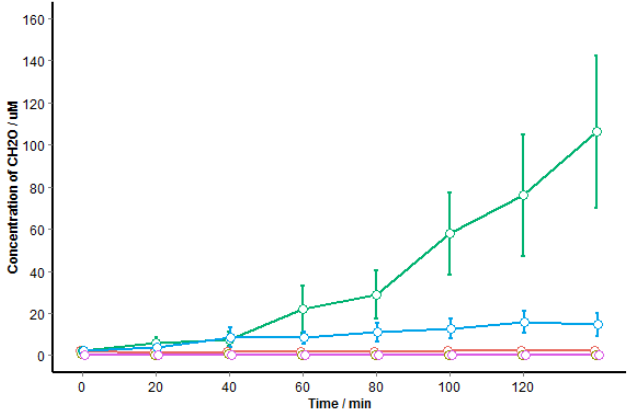


H_2 should reduce CO_2 across a semiconducting barrier to form CH_2O

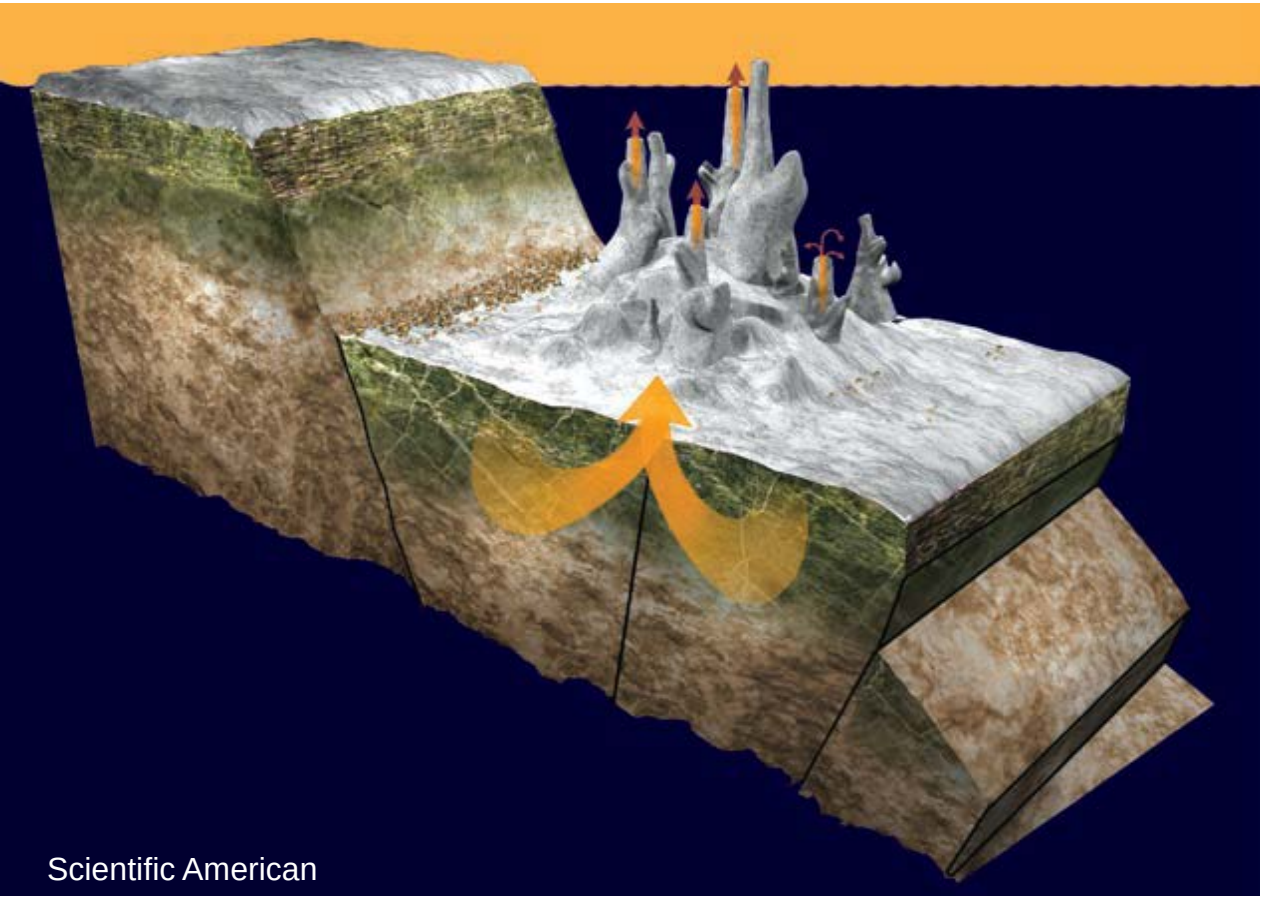
An origin-of-life reactor







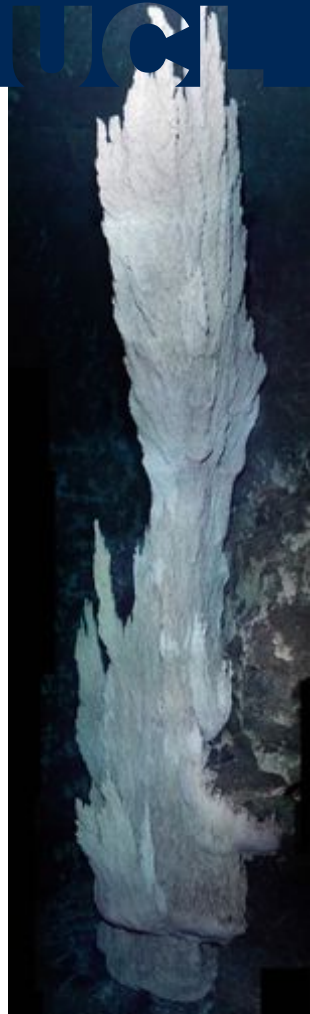
How Lost City was formed



Scientific American

Alkaline vents are formed by a spontaneous chemical reaction between water and rock (olivine)

They should form on any wet rocky planet or moon



Alkaline vents in the solar system?

Enceladus – alkaline ocean, pH 11 plumes

Methane on Mars? (Curiosity Rover)

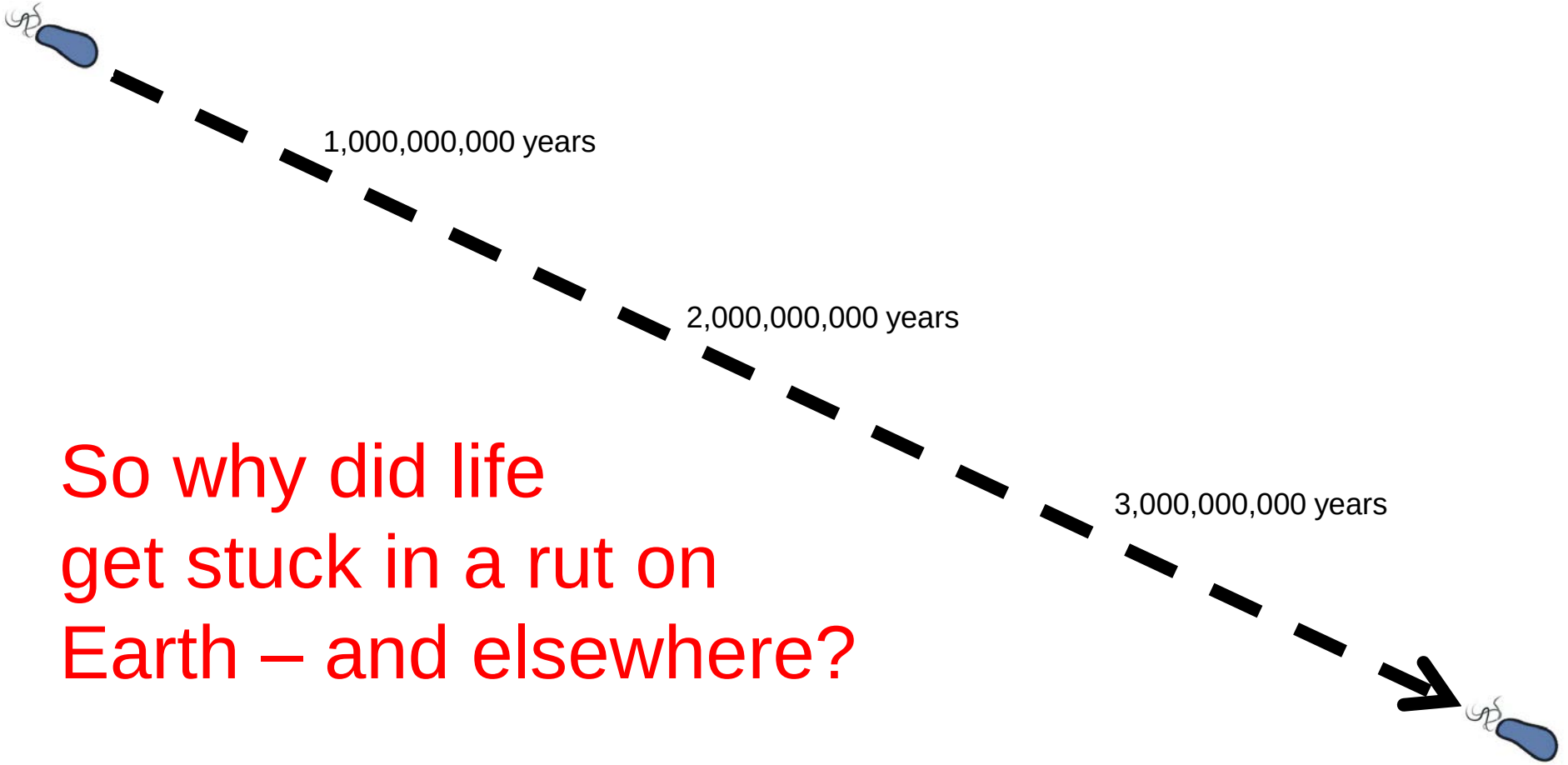
Europa's oceans may be larger than Earth's

Wet, rocky planets will form alkaline vents bubbling with H_2 gas

Alkaline vents should have natural proton gradients

Proton gradients drive the difficult reaction between H_2 and CO_2

Life elsewhere should face the same constraints



So why did life get stuck in a rut on Earth – and elsewhere?

An ‘evolutionary scandal’

All complex life is made of eukaryotic cells

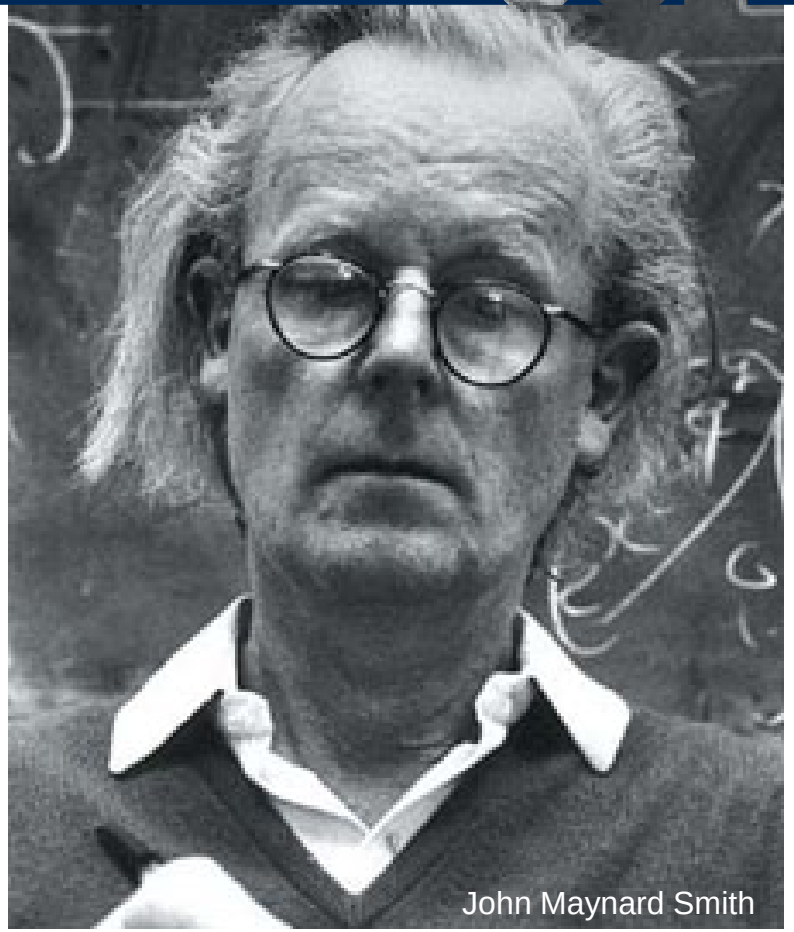
Eukaryotes only arose once in 4 billion years

All eukaryotes share universal traits like **sex**

Bacteria don’t evolve these complex traits

The scandal:

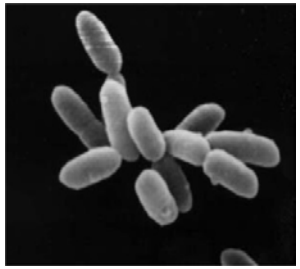
If these traits evolved step by step and each step has an advantage why did none evolve in bacteria?



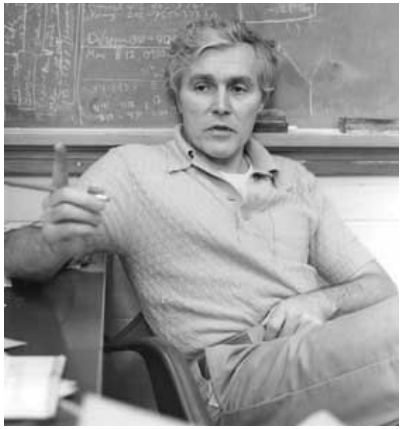
John Maynard Smith

Half an eye is easy

The three domains ‘tree of life’

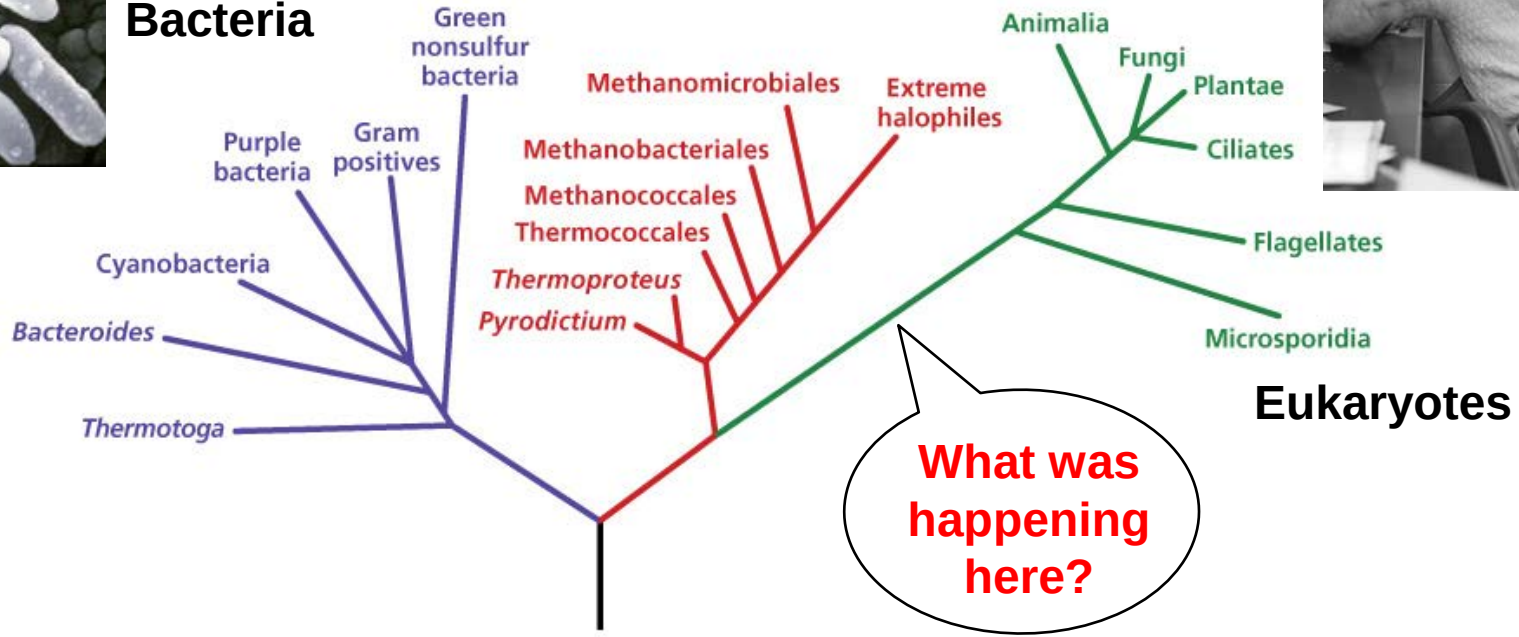


Archaea



Carl Woese

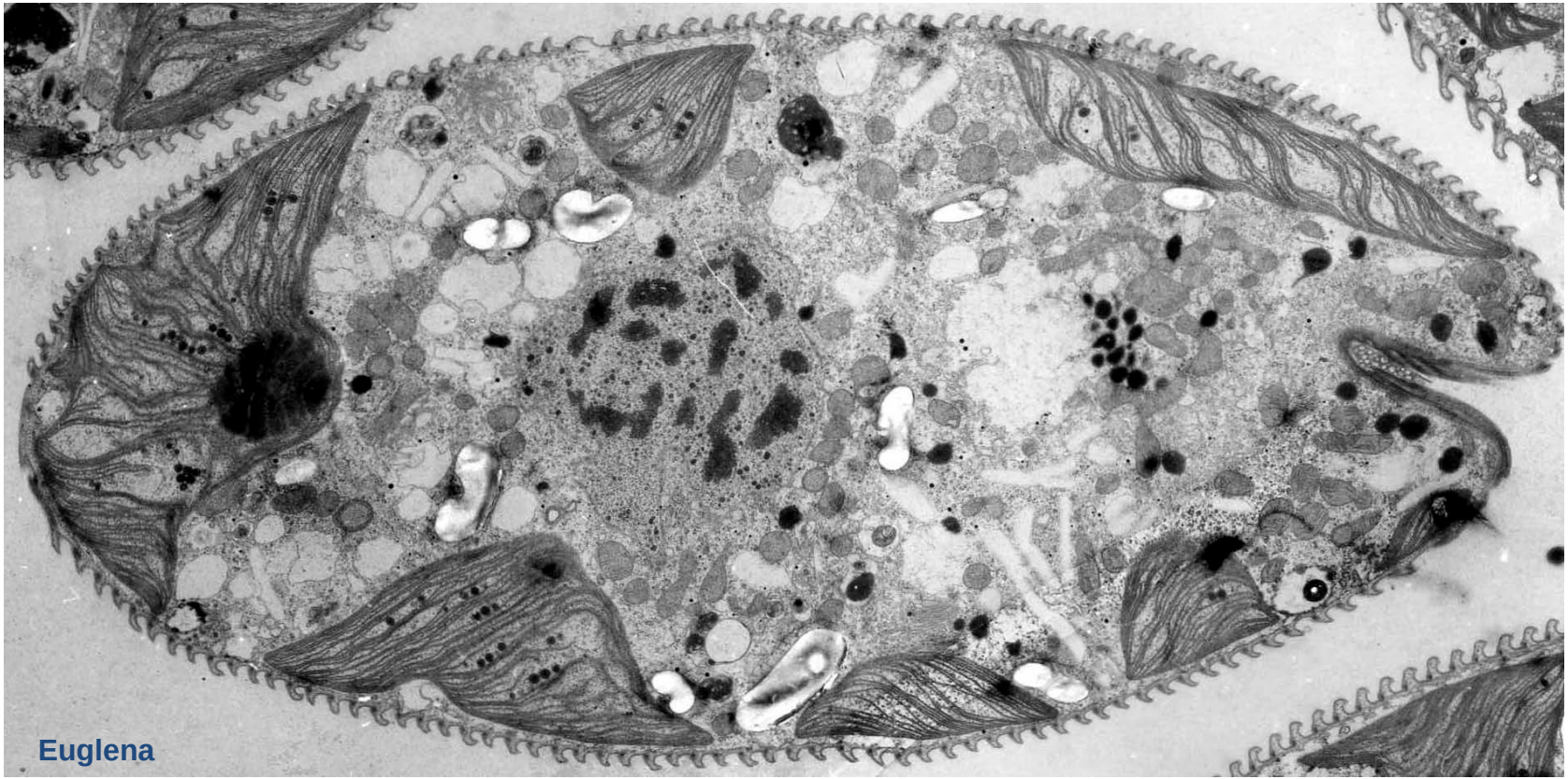
Bacteria



Eukaryotes

What was happening here?

The black hole at the heart of biology

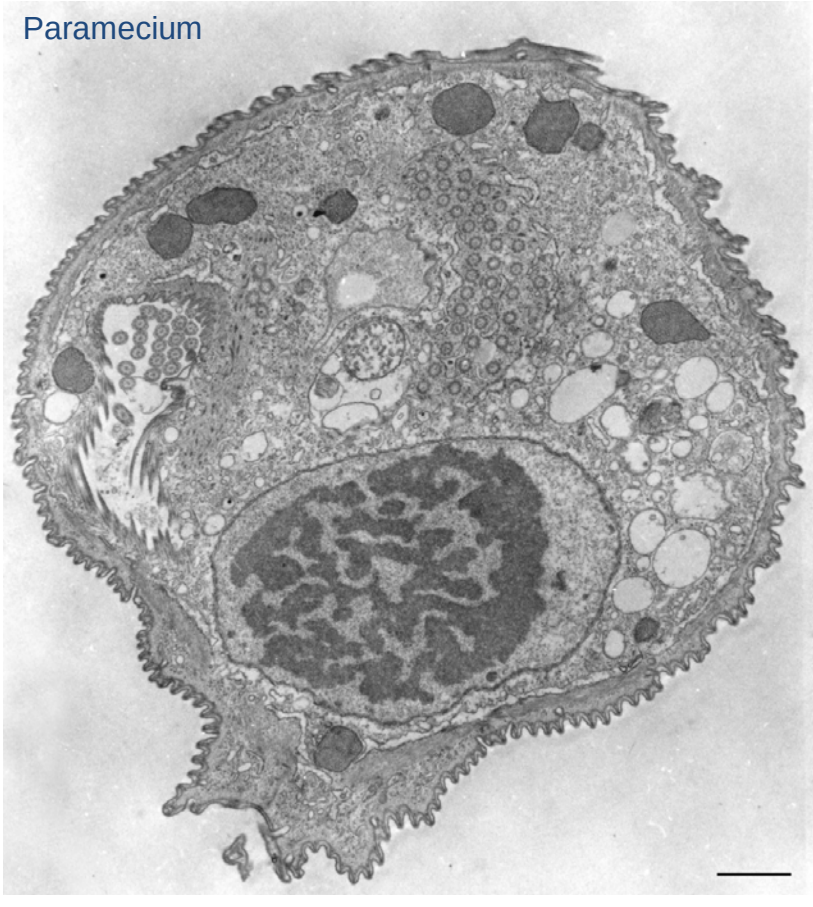


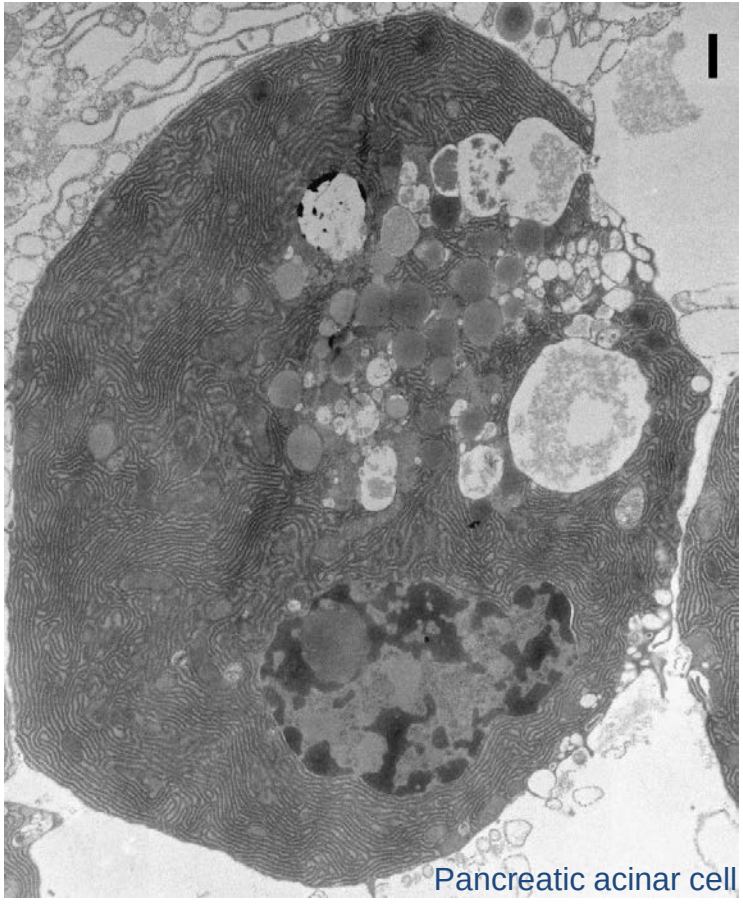
Euglena

Planctomycete

The Last Eukaryotic Common Ancestor was a complex cell with many compartments and 3000 new gene families

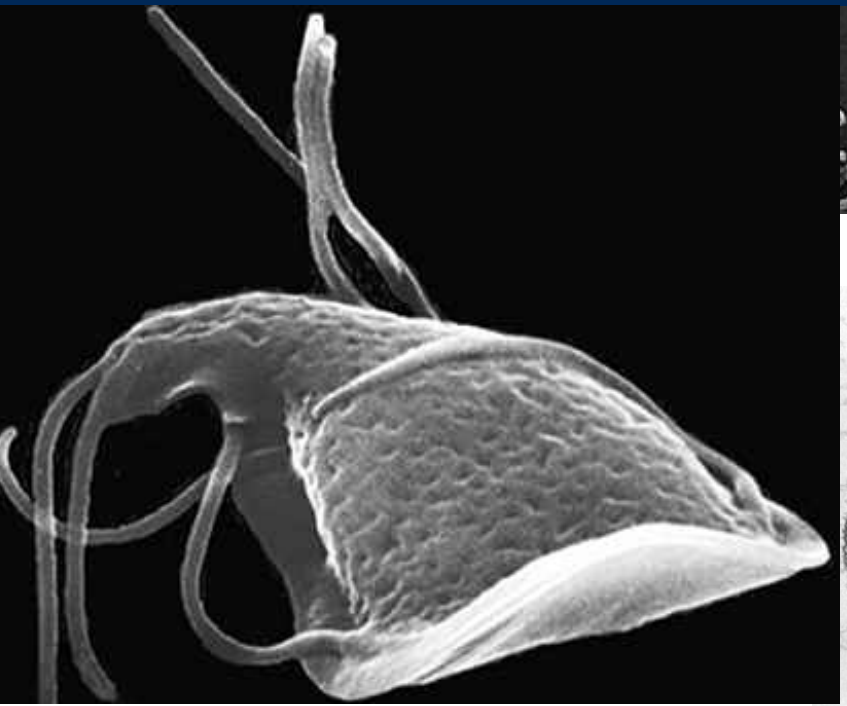
Similar complexity of eukaryotic cells



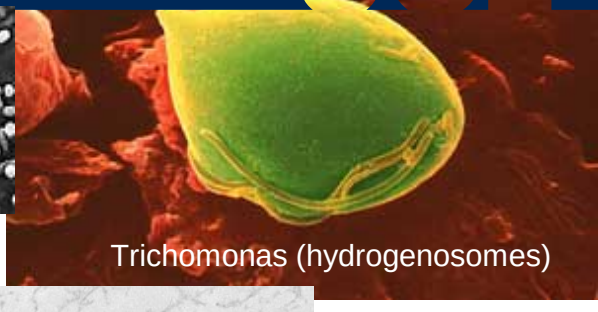


Why are eukaryotes so similar in cell structure despite fundamental differences in lifestyle?

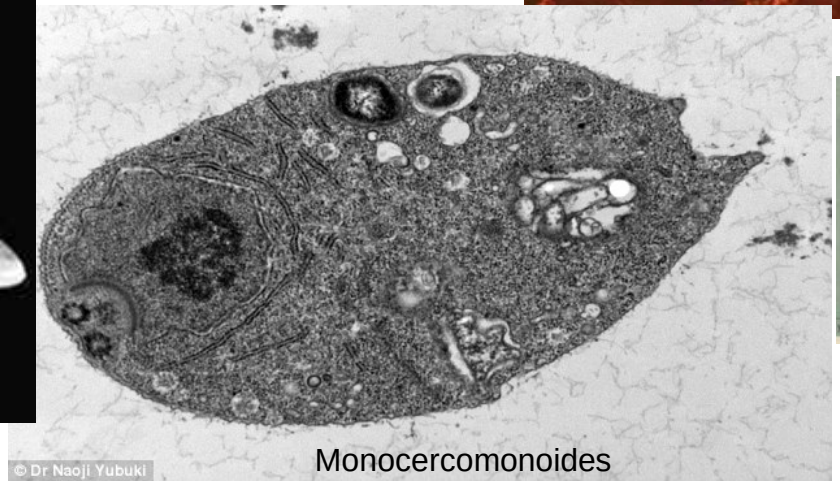
All eukaryotes have or had mitochondria



Microsporidia (derived fungi)



Trichomonas (hydrogenosomes)



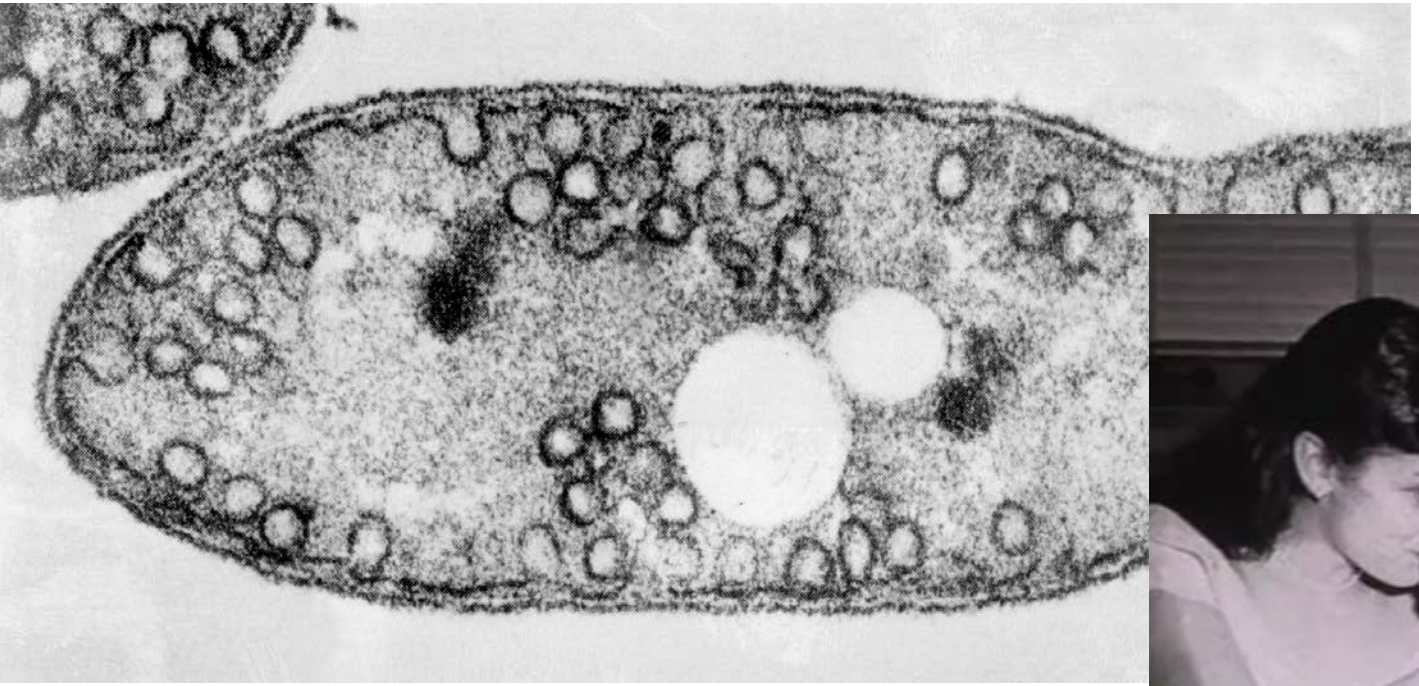
Monocercomonoides
lost its mitochondria completely

Entamoeba
(mitosomes)

All these cells once had mitochondria and lost them by reductive evolution

The Last Eukaryotic Common Ancestor therefore had mitochondria

Mitochondria were once bacteria



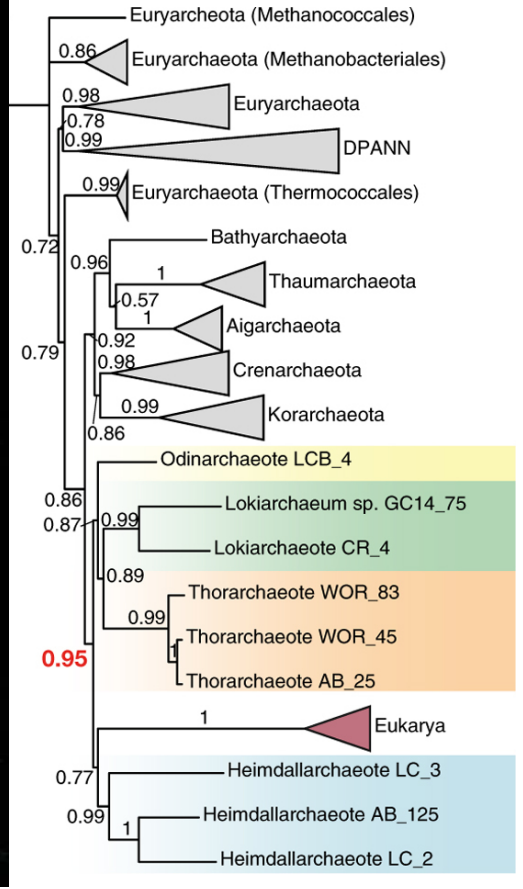
Rhodobacter sphaeroides

Lynn Margulis and Carl Sagan

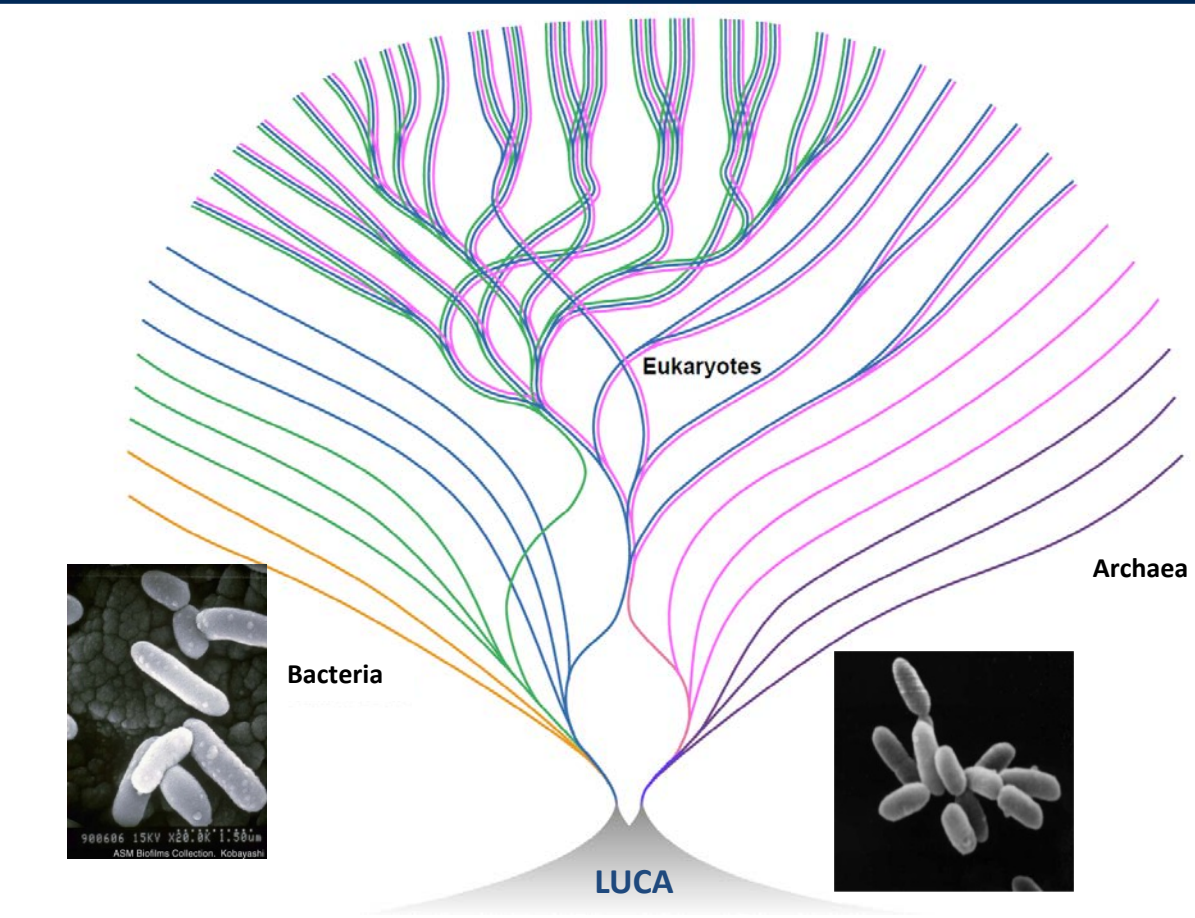
On the origin of mitosing cells – Lynn Sagan, Journal of Theoretical Biology, 1967 – **semicentennial year!**

The host cell was an archaeon

Lokiarchaeota: discovered near Loki's Castle – we only have a genome sequence



A singular chimeric origin of complex life



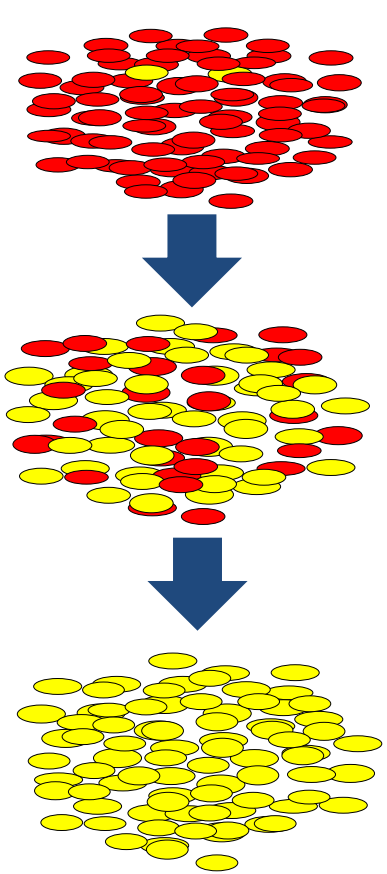
Bill Martin

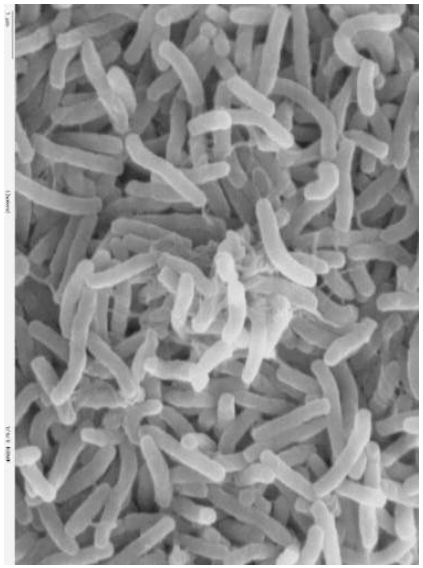
A cell within a cell

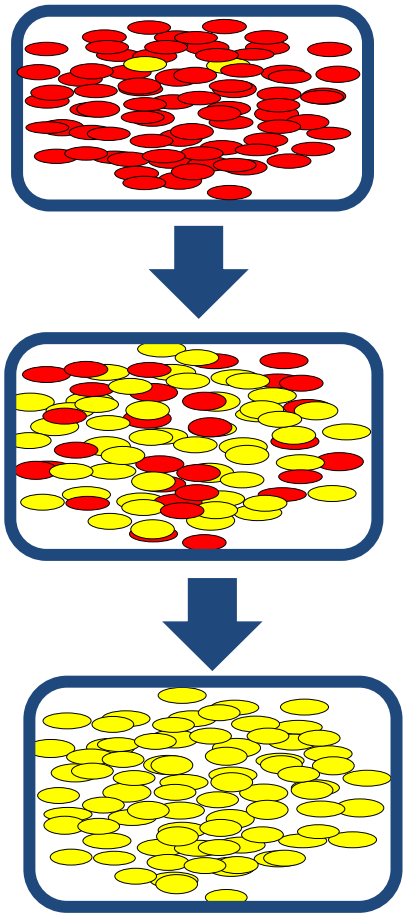
A rare change in structure

A cell within a cell – has it's own cell division machinery enabling it to divide independently within the host cell

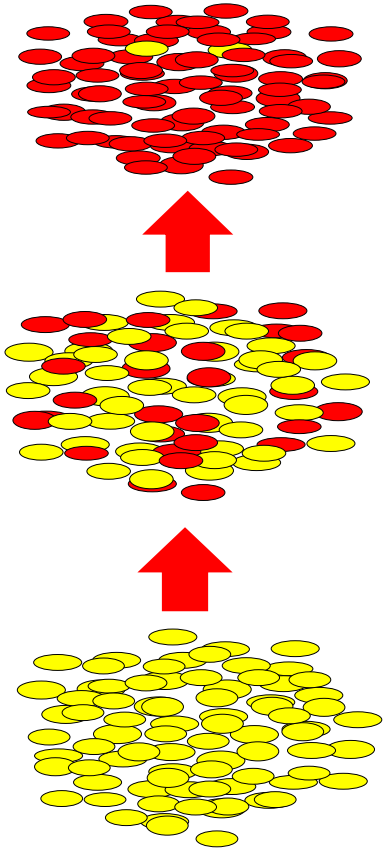
Competition for inheritance

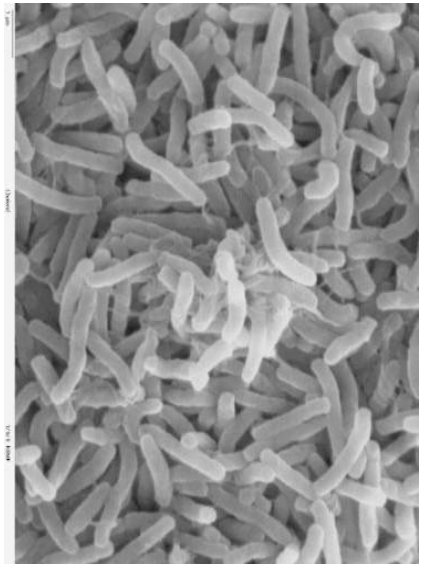


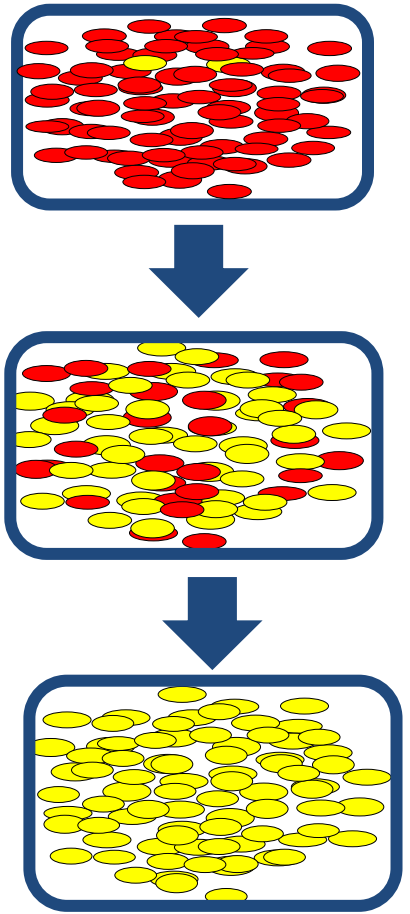




Competition for inheritance





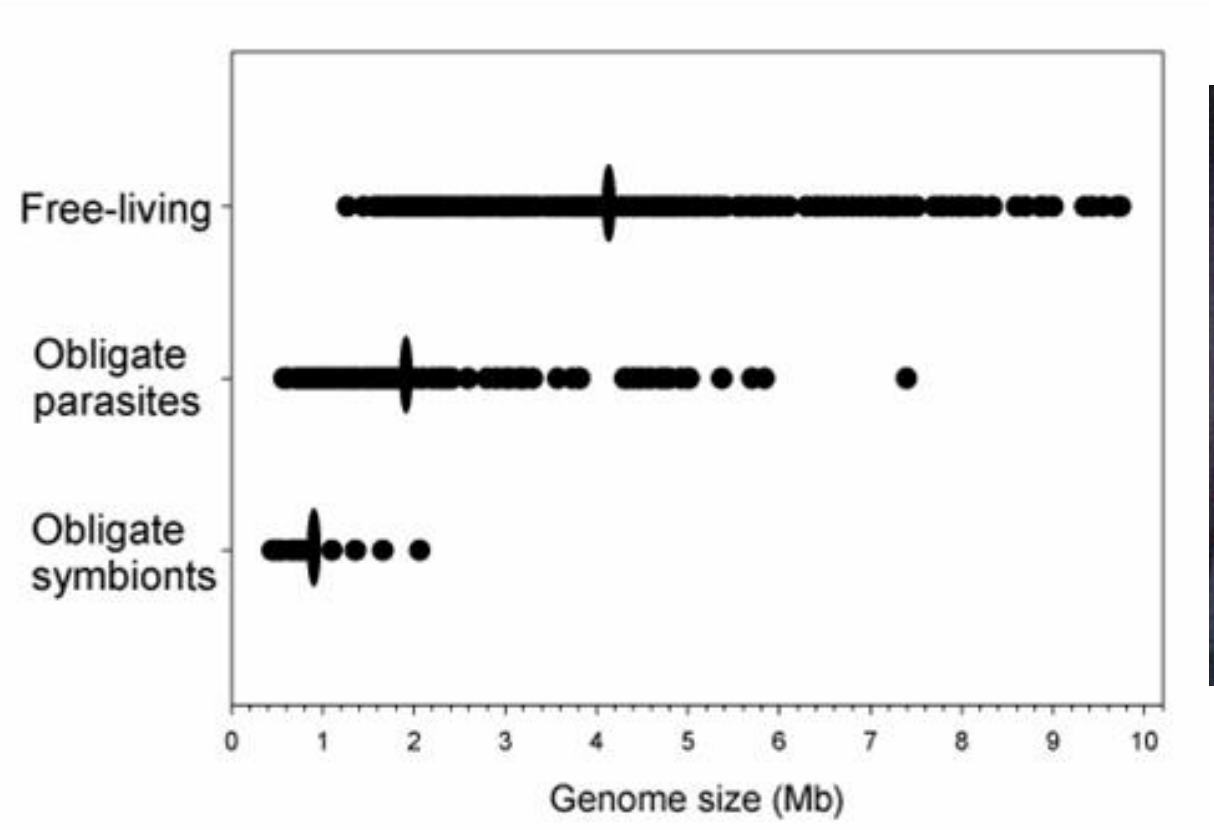


The horror of typhus – intracellular bacteria

Adolph Northen
Napoleon's retreat
from Moscow

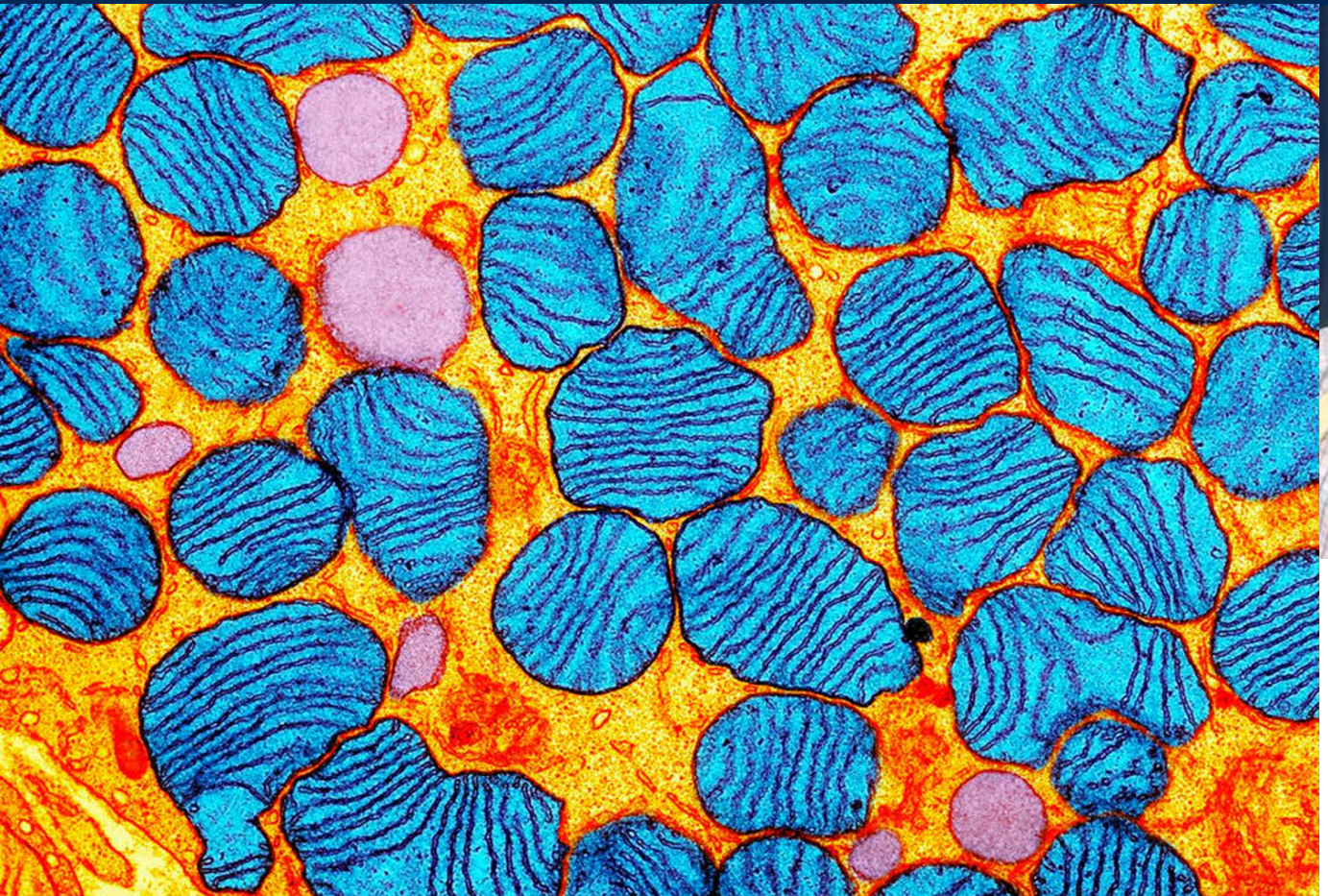
The cause of typhus – *Rickettsia* – is an intracellular bacteria that has lost most of its genes

Genome size shrinks in intracellular bacteria



T Ryan Gregory

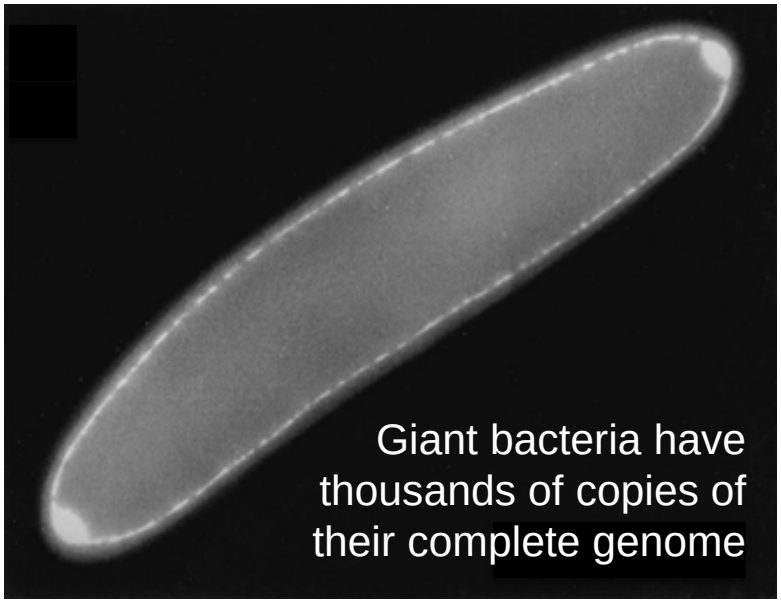
Multi-bacterial power without overheads

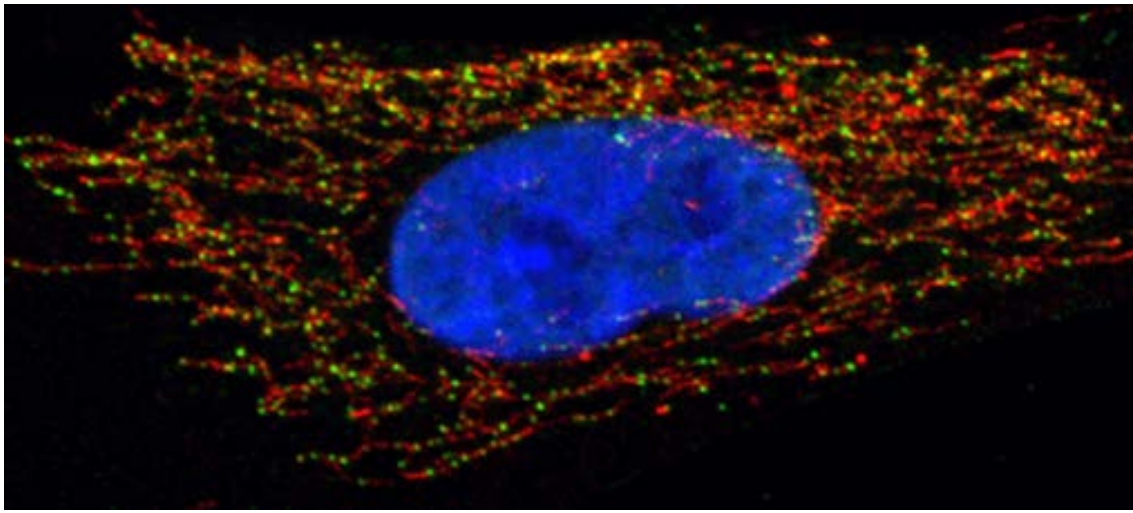


John Allen

Mitochondria retain only the genes they need to control respiration

How eukaryotic cells got super-charged

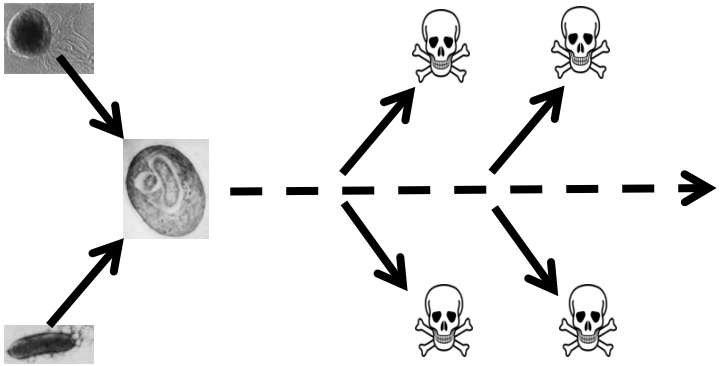




Eukaryotic cells have thousands of tiny mitochondrial genomes supporting a massive nuclear genome

Eukaryotes have ~100,000 times more energy per gene than bacteria, which allows them to support far larger and more complex genomes and make far more proteins from each gene

Why complex life only evolved once



Endosymbioses between bacteria is rare – only one known example

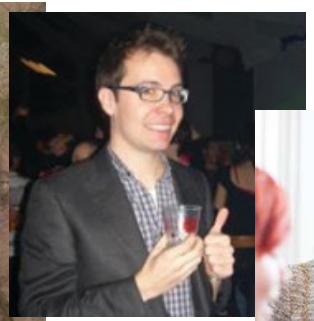
Problem of living together – synchronizing life cycles, conflict resolution, coadaptation

Thank you!

Dr Victor Sojo

Dr Alex Whicher

Dr Barry Herschy



Eloi Camprubi

Silvana Pinna

Sylvia Lim

Dr Sean Jordan

Dr Rafaela Vasiliadou

Dr Flo Camus

Dr Zena Hadjivasiliou

Dr Arunas Radzvilavicius

Dr Will Kotiadis

Marco Colnaghi

Tim West

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