PART 3
Insider Deal;: the foundations of complexity

What exactly is it about the eukaryotic cell that seems to encourage the evolution of complexity?

  Mitochondria

  Once they existed, life was almost bound to become more complex

This seems to say the assignment of a forward-looking purpose

Monod in “Chance and Necessity”: biology is full of purpose and apparent trajectories

  Blind chance to a refined machines by purpose and natural selection

How to explain it?

Greater complexity demands more genes
Where do all these extra gene come from?
Large dramatic changes: non-Darwinian view (gradual evolution)

<u>The difference between bacteria and eukaryotes</u>
Bacteria: nearly unlimited biochemical diversity but no drive towards complexity
Eukaryotes: little biochemical diversity but a marvelous flowering in the realm of bodily design

Mitochondria are not simply an efficient means of generating energy

Fig. 9: 1905 Konstantine Merezhkovskii

an evolutionary tree of upside down variety

fused branches to generate a new domain of life

Cambrian explosion:

the great, and geologically sudden, proliferation of life around 560 million yrs ago

Later extinction of most of the major branches

Symbiosis: bicycle + engine = motorcycle (it is simply a Darwinian view)

Why there is no reason to evolve a motorcycle in the absence of symbiosis

Symbiosis made more profound evolutionary novelties

7. Why bacteria are simple: size & cell wall

How the eukaryotes were released from a selection pressure of genome size
that stifles even the most versatile bacteria?

What determines the bacterial genome size?

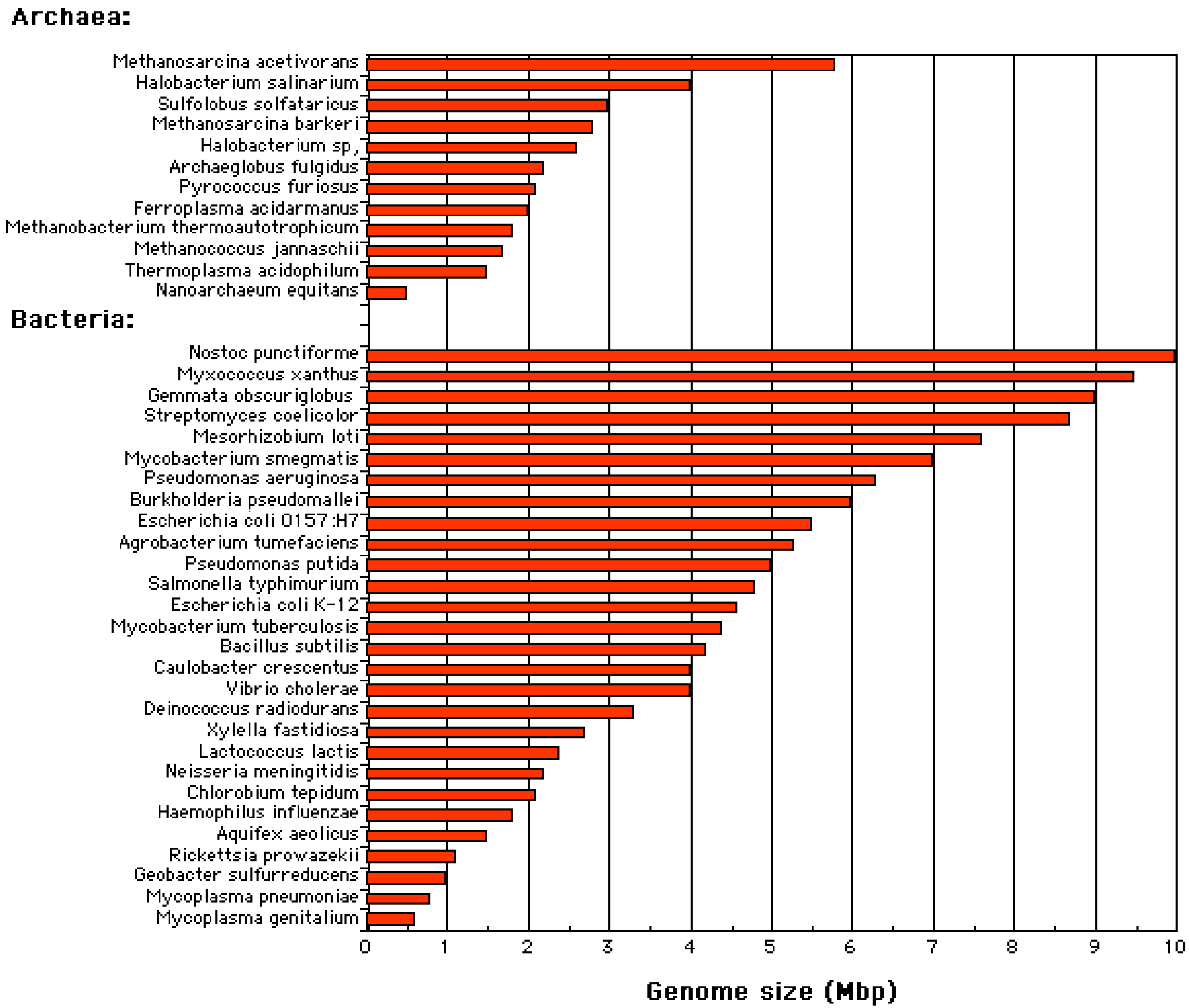
The bacteria replicate fastest dominate the population
The speed of cell division is determined by DNA replication
The speed of DNA replication depends on genome size
and effective energy production

Konstantino Konstantinidis & James Tiedje

when resources are scarce but diverse
where there is little penalty for slow growth
bacteria with the largest genomes provide more chance and therefore dominate

does it mean a possibility of larger bacterial genome size comparable to those of eukaryotes?

There seems to be a limit in bacterial genome size: selected against because of time and energy



http://www.sci.sdsu.edu/~smaloy/MicrobialGenetics/topics/chroms-genes-prots/genomes.html

organism	estimated size	estimated gene number	average gene density	chromosome number
Homo sapiens (human)	2900 million bases	~30,000	1 gene per 100,000 bases	46
Rattus norvegicus (rat)	2,750 million bases	~30,000	1 gene per 100,000 bases	42
Mus musculus (mouse)	2500 million bases	~30,000	1 gene per 100,000 bases	40
Drosophila melanogaster (fruit fly)	180 million bases	13,600	1 gene per 9,000 bases	8
Arabidopsis thaliana (plant)	125 million bases	25,500	1 gene per 4000 bases	10
Caenorhabditis elegans (roundworm)	97 million bases	19,100	1 gene per 5000 bases	12
Saccharomyces cerevisiae (yeast)	12 million bases	6300	1 gene per 2000 bases	32

http://www.ornl.gov/sci/techresources/Human_Genome/faq/compgen.shtml

Gene loss as an evolutionary trajectory

Gene loss is common in bacteria

Example: *Rickettsia prowazekii*

A tiny bacterium, almost as small as a virus

A parasite

834 protein coding genes, a quarter amount of usual bacteria

- what kinds of genes are left?
- ~1/4 of the total genome are junk DNA
- gene loss is continuing process occurring today

Balancing gene loss and gain in bacteria

Gene loss: “use it or lose it”

Free-living bacteria also face a similar pressure to lose superfluous genes

A related experiment by Tibor Vellai et al., 1998

- 3 plasmids of antibiotic marker deffering in non-coding DNA
- transformed *E. coli* cells were compared for growth
- after 12 hrs in culture
- + antibiotic: the smallest plasmids outgrew 10-fold
- - antibiotic: similar growth and plasmid loss

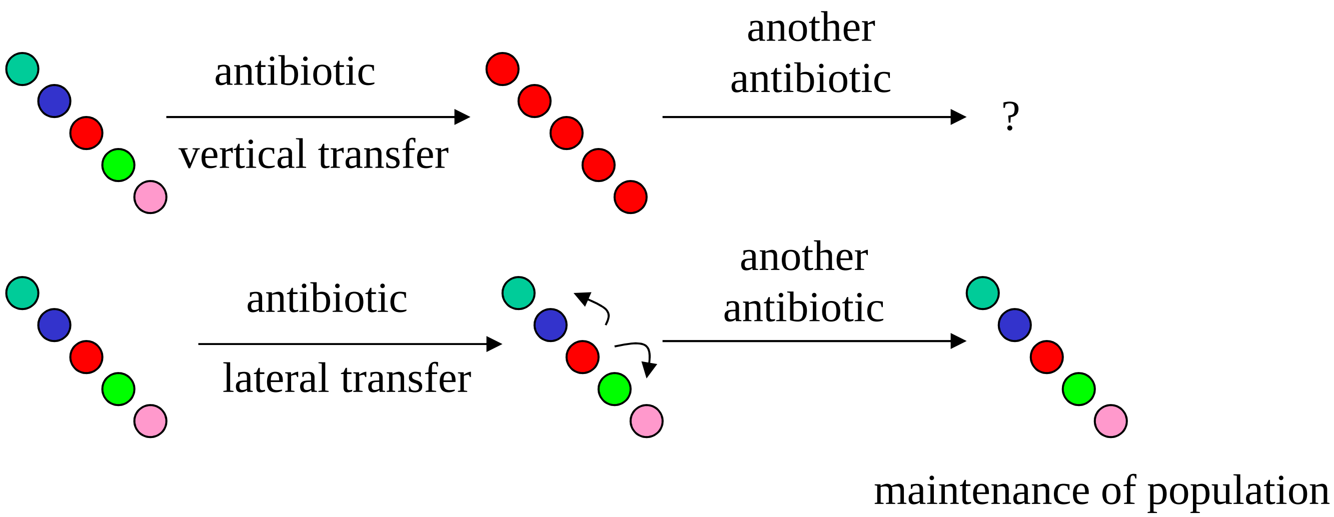
Gene gain: lateral gene transfer
Active gain of genes compensates for gene loss
In some bacterial sp. >90% of observed variation in a population comes from lateral gene transfer
Genes can be switched so quickly and so comprehensively, obliterating all traces of ancestry

example: *Neisseria gonorrhoeae*

E. coli

Why are bacteria so open-handed with their genes?

an evolutionarily stable strategy



Continuous switching of genes: loss and gain

in order to maintain their genome size (?)

On the hand gene expansion seems to pose no problem in eukaryotes

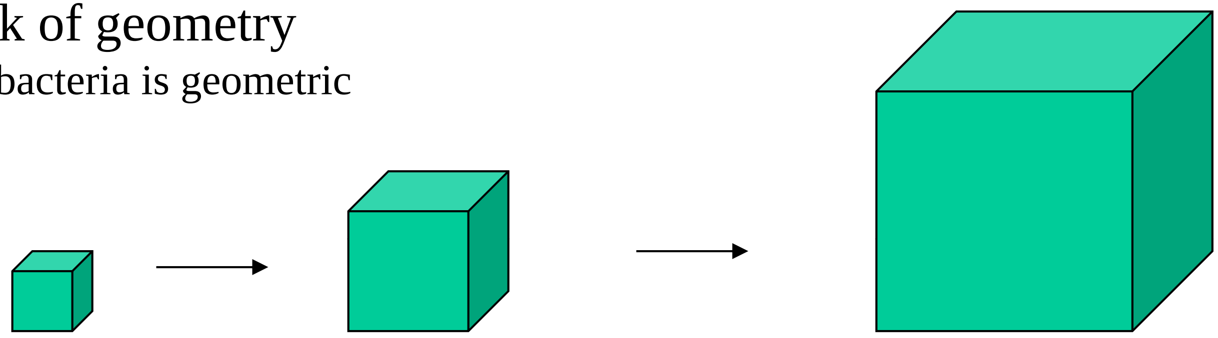
a single-celled Amoeba dubina has 670 billion bp genome

Tibor Vellai & Gabor Vida, 1999

bacteria are limited in their physical size, genome content, and complexity, because bacteria are forced to respire across their external cell membrane

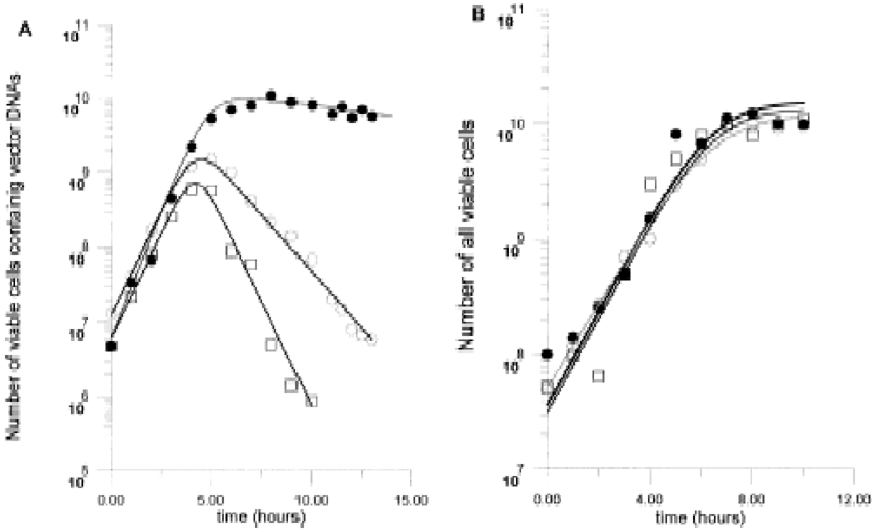
The stumbling block of geometry

The limitation for bacteria is geometric



Size	1 µm	2 µm	4 µm
Surface area	6 µm2	24 µm2	96 µm2
Volume	1 µm3	8 µm3	64 µm3
volume/surface area	6/1 = 6	24/3 = 3	96/64 = 1.5

Vellai T, Takács K, Vida G. A new aspect to the origin and evolution of eukaryotes. J Mol Evol. 1998 May;46(5):499-507.



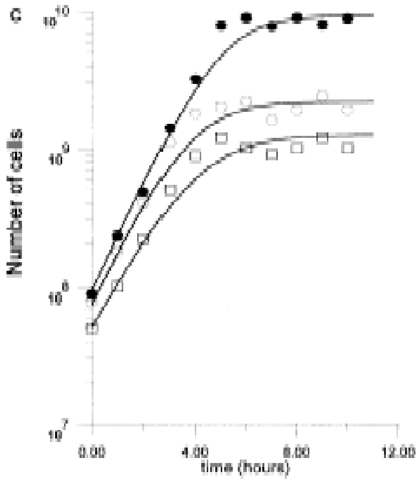


Fig. 1. The effect of genome size on the microbial growth. *Escherichia coli* XL1-Blue strain was transformed with a plasmid vector 6 kb in size (●) and two of its derivatives with different sizes. The sizes of these derivatives were as follows: The first construction was 11.8 kb (○), whereas the second one was 15.5 kb (□). **A** Cells containing vector DNAs, which have ampicillin resistance gene, were grown in nonselective LB medium in the absence of ampicillin under favorable conditions. The number and the growth curve of viable cells which could retain their vector DNA largely depend on the size of the carried vector DNA. **B** The total number of all viable cells in the previous experiment. Growth curves were similar in each case. **C** Cells containing vector DNAs were grown in selective LB^{Amp} medium supplemented with ampicillin. The number of cells in the stationary phase of typical growth curves depends on the DNA content of cells.

As bacteria become larger their respiratory efficiency declines hyperbolically

Surface area: the external membrane used for generating energy & absorbing nutrients

Volume: the mass of cell using up the available energy

The problem of decreasing volume/surface area

may be overcome by

changing cell shape to rod form (larger surface area to volume ratio)

folding the membrane into sheets or villi (Fig. 10)

there may be a limit because of complexity

Thiomargarita namibeienses: http://microbewiki.kenyon.edu/index.php/Thiomargarita

How to lose the cell wall without dying

Loss of cell wall means loss of proton gradient

examples

Mycoplasma: mostly parasites (M. genycoplasma has fewer than 500 genes)

No genes for oxidative respiration

Thermoplasma: extremophile archaea living in hot vinegar

Pumping out protons by respiration

Smallest non-parasitic genome encoding 1500 genes

The genome complexity is determined by their need to generate energy across the outer cell membrane

Why insider dealing pays

Mitochondria: internalization of energy generation

- Providing a chance to be free from cell wall
- Exposure of cell membrane provided other tasks such as signaling, movement, phagocytosis
- The most important: releasing from the geometric constraints
- Internal expansion of membranes by increasing the number of mitochondria
- 2 billion yrs ago sudden appearance of large eukaryotic cells in the fossil record

- Birth of a large energetic cell: overcoming the energy barrier to being larger
- Don't need to spend time replicating its DNA to stay ahead of the competition
- hunter-gatherers and settlers: which can maintain a large population?

- Eukaryotic life style: predator
- Predation tends to drive evolutionary arms races
- Bacteria can lose their cell wall but have never developed phagocytosis

Bacterial internalization of energy production

- folding the membrane into sheets or villi (Fig. 10)
- *Nitrosomonas* and *Nitrosococcus*
- Infolded large periplasmic compartments
- Why did they stop to form a full compartment

8. Why mitochondria make complexity possible

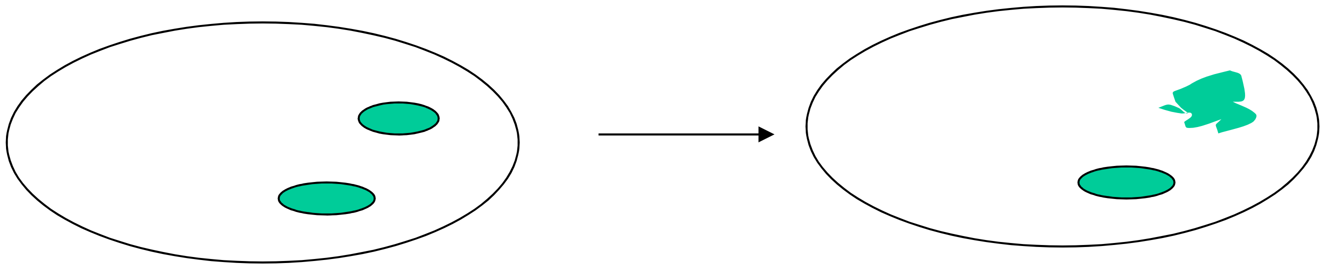
Bacteria: small size

- fast growing is important
- small genome size & fast replication
- large surface area to volume ratio: energetic efficiency
- some complex internal membrane but never approach eukaryotic complexity

Eukaryotic cells: large size (complexity)

- internal energy generation
- mitochondrial genome: mutual control?

Mitochondrial gene transfer to nucleus



primitive eukaryote　　　　　　mito death & DNA release

Jeremy Timmis: Nature 2003

chloroplast gene transfer to nucleus: ~1/16000 seeds in tobacco plant

a single plant produces as many as a million seeds

Nuclear-mitochondrial sequences (numts)

the same gene in both the mito and nucleus

duplication of chloroplast and mito genes in the nuclear genomes of many species

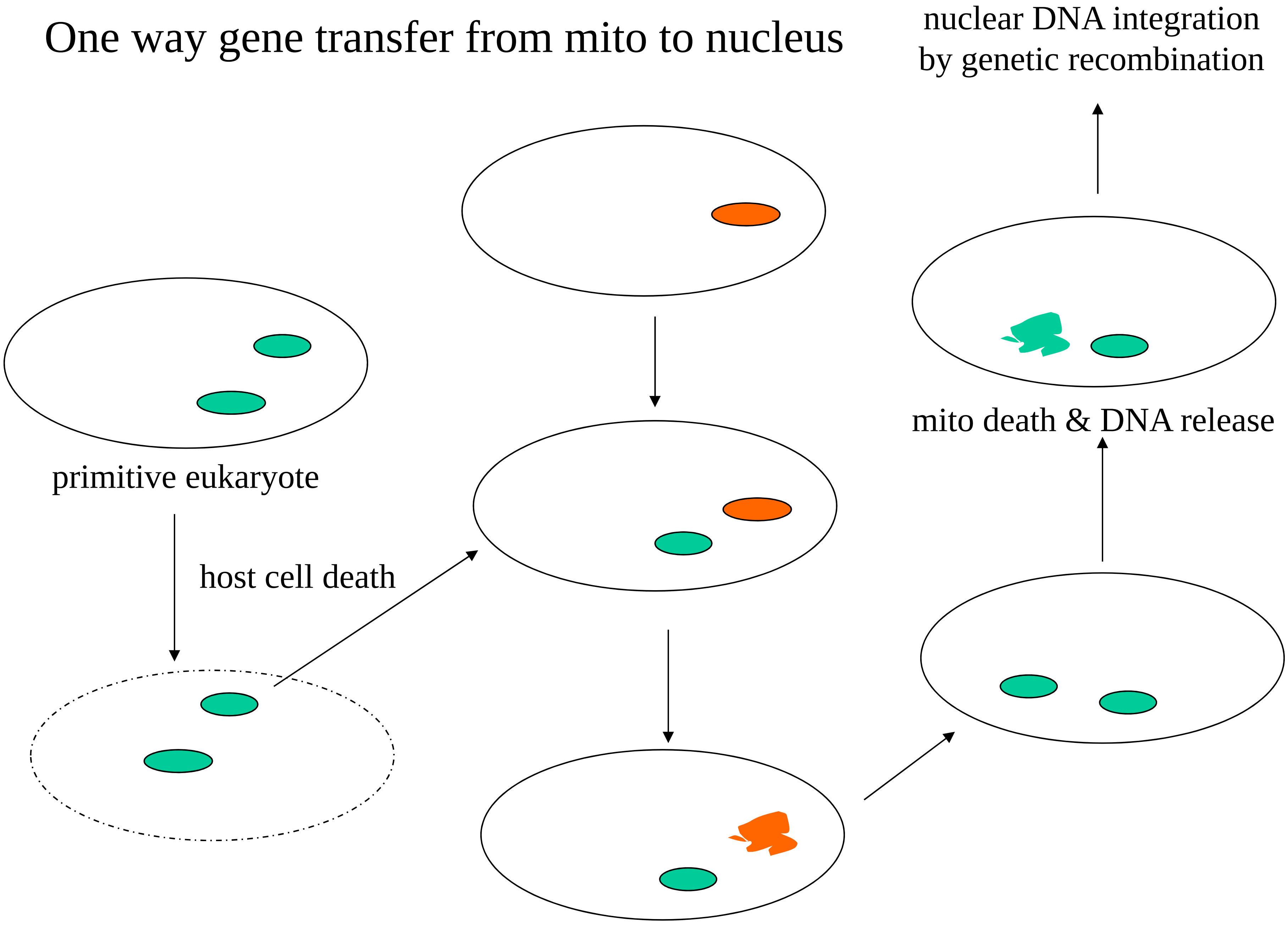
at least 354 separate independent transfers in humans

Clesson Turner, 2003: demonstration of gene transfer continuing today

a rare genetic disease Pallister-Hall syndrome

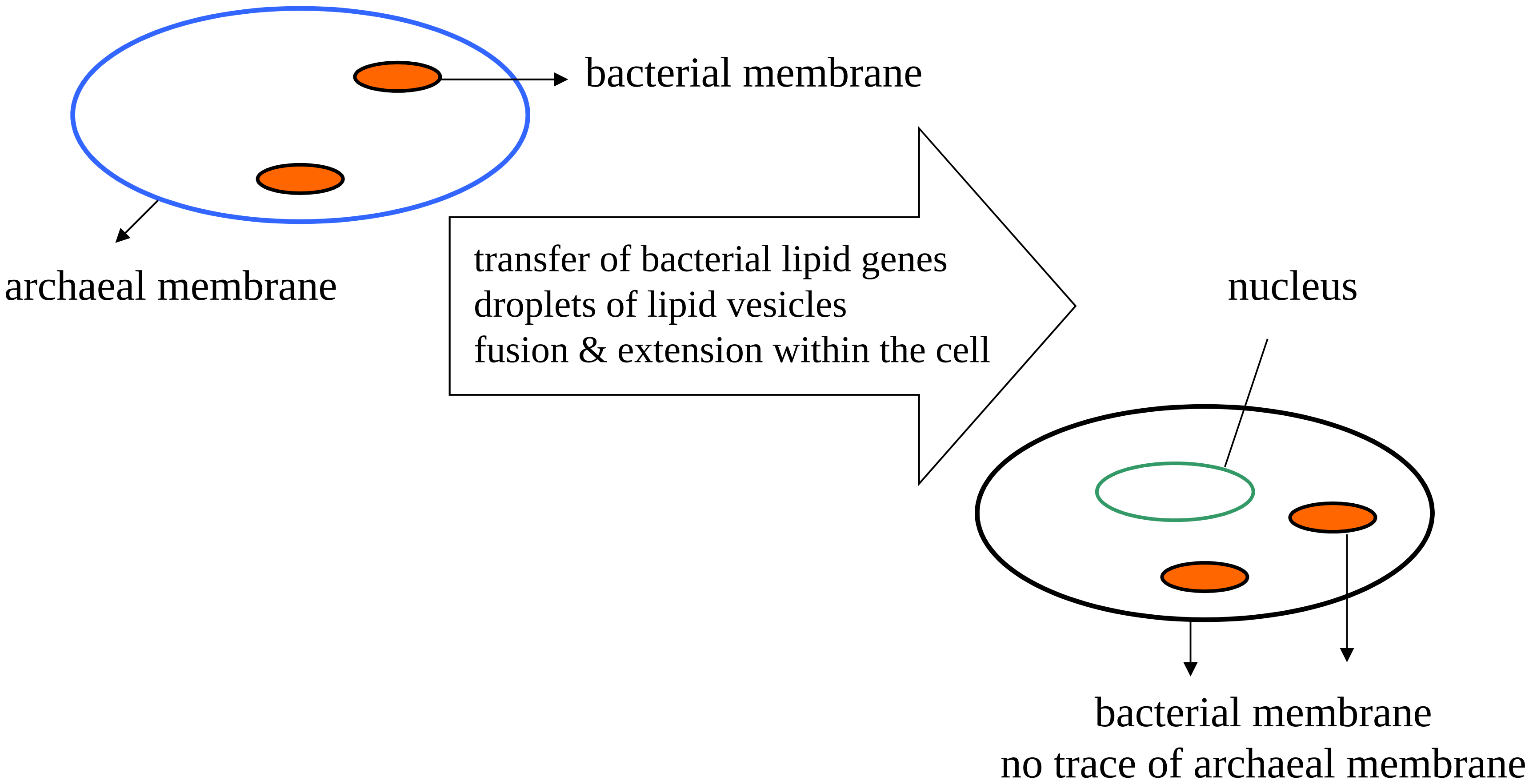
a spontaneous transfer of mito DNA to the nucleus

One way gene transfer from mito to nucleus



The origin of the nucleus

What happens to the genes that are transferred?

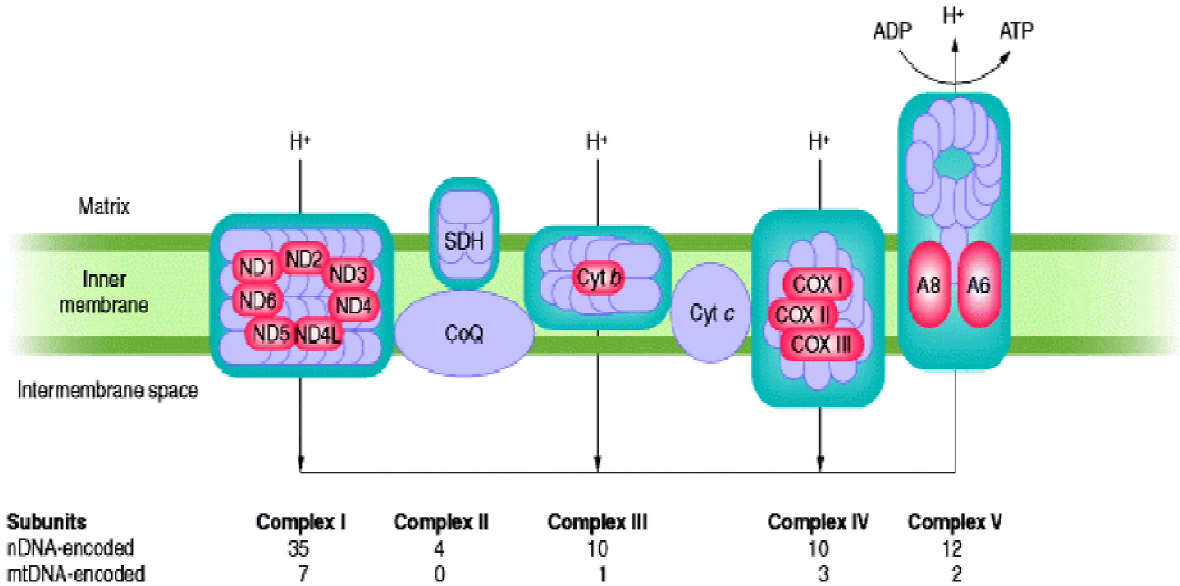


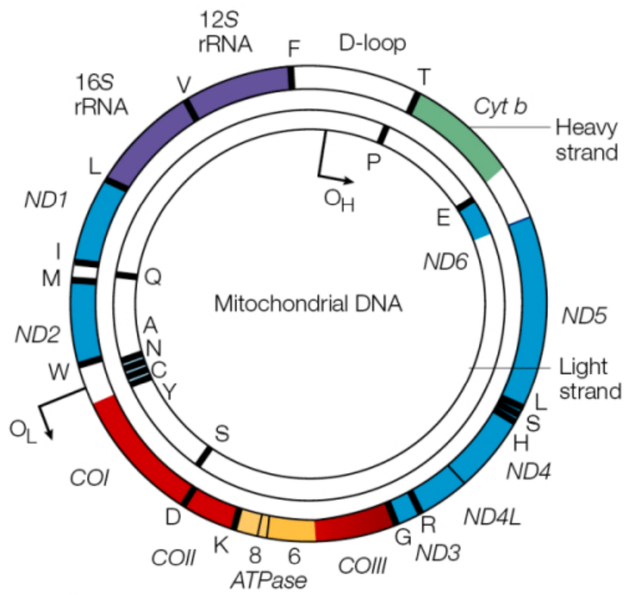
A probable evidence: fresh nuclear membrane in cell division
The replacement of membrane: natural selection for bacterial membrane
Terpenoids: the syntheses of isoprene units are vestiges of archaeal membrane

Why did mito retain any genes at all?

Big disadvantages

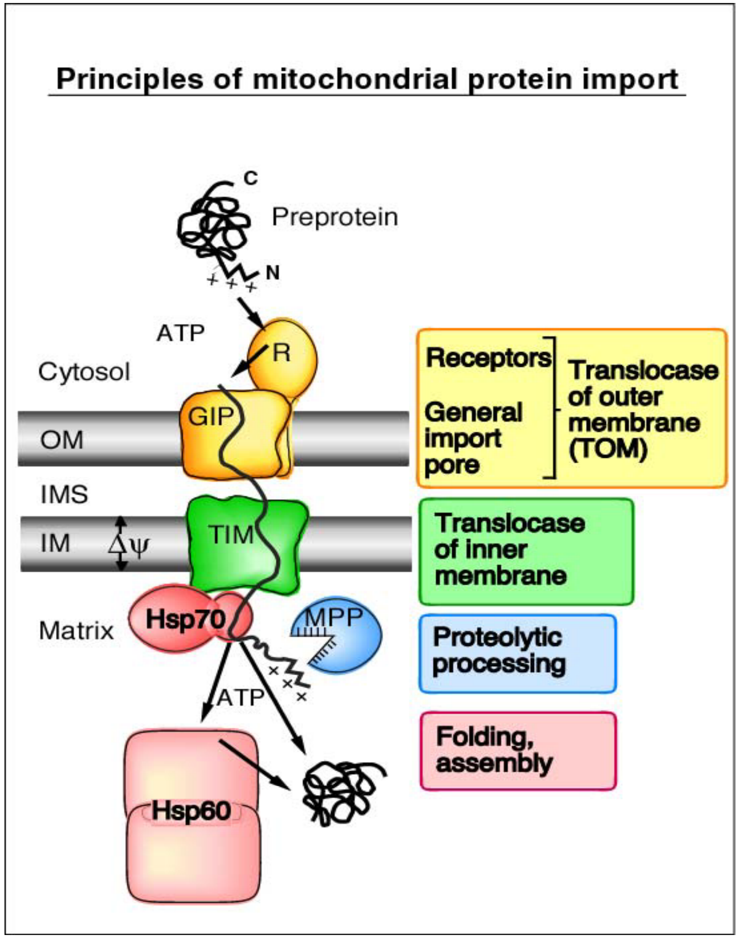
1. Thousands of copies in a cell: a costly process
2. Competition between different mito genomes within the same cell
3. Vulnerability to damage by free radicals

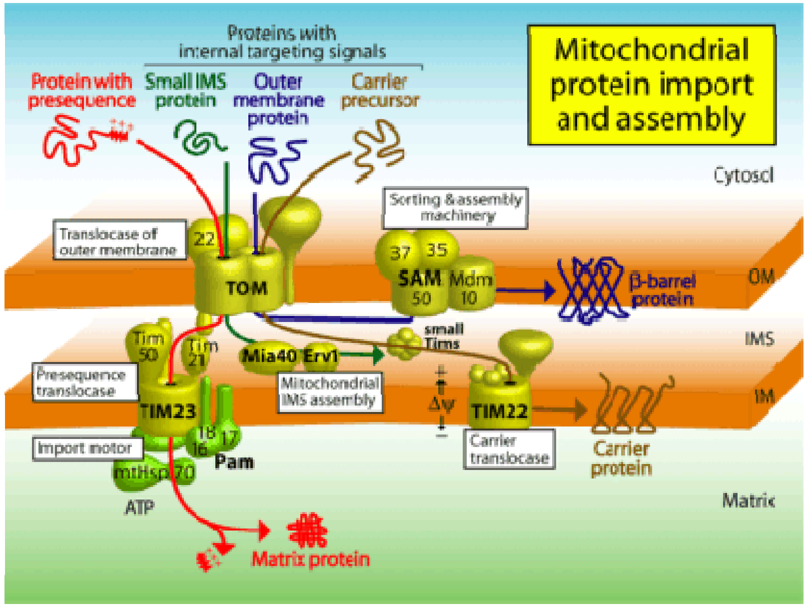




37 genes: 22 tRNA genes, 2 ribosomal RNA genes, 13 polypeptide-encoding gene

Protein import into mitochondria





Fungal Mitochondrial Genes

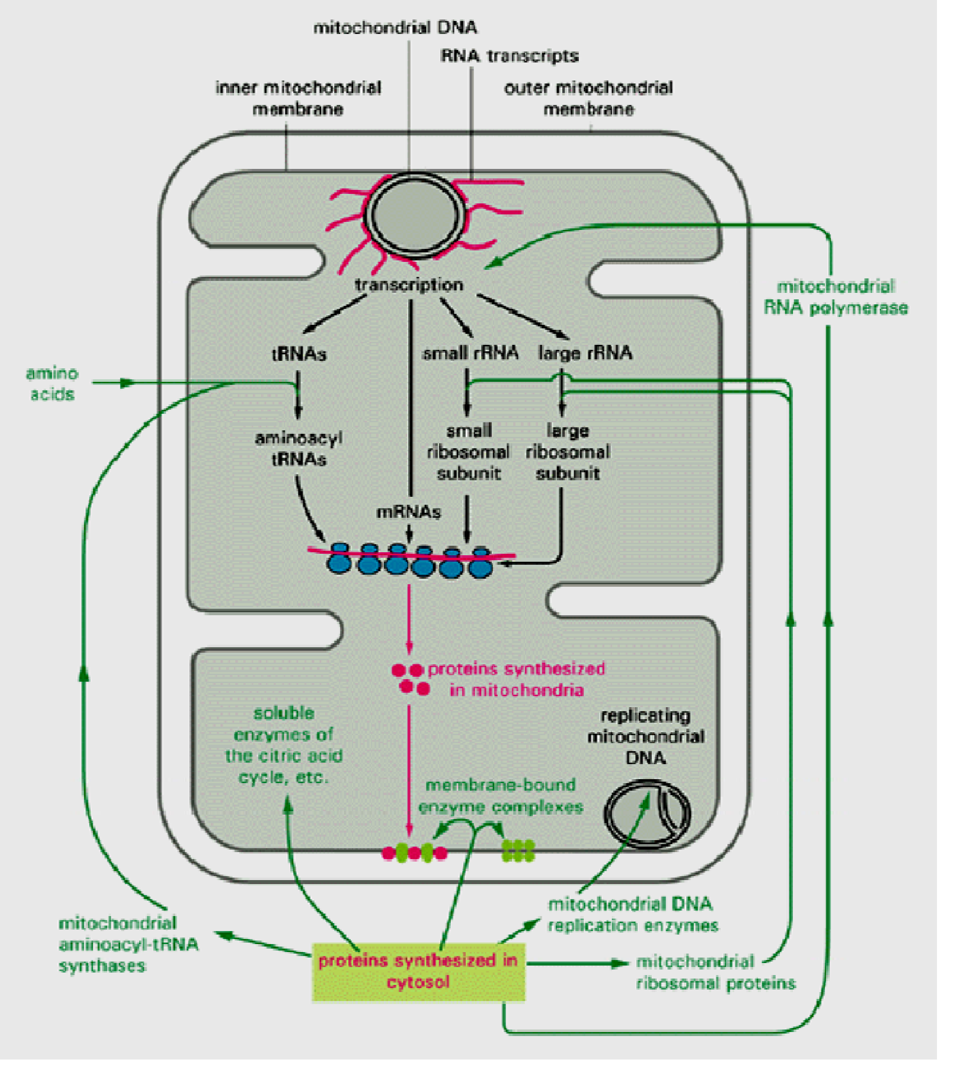
Organism	Class[a]	Genome Size /Structure[b]	Acc. # /Update[c]	Code [d]	Total ORFs[e]	Basic 14[f]	Other ORFs[g]	rRNAs /tRNAs[h]	Reference[i]
Allomyces macrogynus	Chy	57,473 C	NC001715 3/96	U	27	all	*rps3*	2 25	Paquin and Lang 1996
Aspergillus nidulans	Asc-F	33,300 [j] C	FMGP	S	~17	all	*rps3* *rnpB*	2 ~22	Brown et al. 1985
Candida albicans	Asc-Y	40,420 C	NC002653 1/01	Y	12	all		2 30	Anderson et al. 2001
Harpochytrium #94	Mon	19,473 C	FMGP	U	14	all		2* 8#	FMGP
Harpochytrium #105	Mon	24,570 C	FMGP	U	14	all		2* 8#	FMGP
Hyaloraphidium curvatum	Chy	29,593 L	NC003048 8/01	S	18	all		2* 7#	Forget et al. 2002
Hypocrea jeorina (Trichoderma reesei)	Asc-F	42,130 C	NC003388 2/02	S	19	all	*rps3*	2 26	Chambergo et al. 2002
Neurospora crassa	Asc-F	64,840 C	Whitehead Institute	S	~30	all	*rps3*	2 27	Griffiths et al.1995
Pichia canadensis (Hansenula wingei)	Asc-Y	27,694 C	NC001762 9/95	S	17	all	*rps3*	2 25	Sekito et al. 1995
Podospora anserina	Asc-F	100,300 C	NC001329 1/01	S	50	-atp9	*rps3*	2 27	Cummings et al. 1990
Rhizopus stolonifer	Zyg	54,178 C	FMGP	U	19	all	*rnpB*	2 24	FMGP
Rhizophydium sp. 136	Chy	68,834 C	NC003053 8/01	C	34	all		2 7	FMGP
Saccharomyces cerevisiae	Asc-Y	85,779 C	NC001224 8/99	Y	22	-nadx	*rps3* *rnpB*	2 24	Foury et al. 1998
Schizophyllum commune	Bas	49,704 C	NC003049 8/01	U	20	all	*rps3*	2 24	FMGP
Schizosaccharomyces pombe	Asc Y	19,431 C	NC001326 11/90	U	10	nadx	*rnpB*	2 25	Lang et al. 1983
Spizellomyces punctatus	Chy	58,830-C 1,381-C 1,136-C	NC003052, NC003061 NC003060 8/01	C	31	all		2 8#	FMGP
Yarrowia lipolytica	Asc-Y	47,916 C	NC002659 2/01	S	29	all		2 27	Kerscher et al. 2001

Retaining a handful of mito genes is a costly process

Tagged proteins, but not all, to be transferred to mito

Still on going process? One day no mito genes will be left?

Different species different numbers of genes: random nature?



The nucleus is not enough

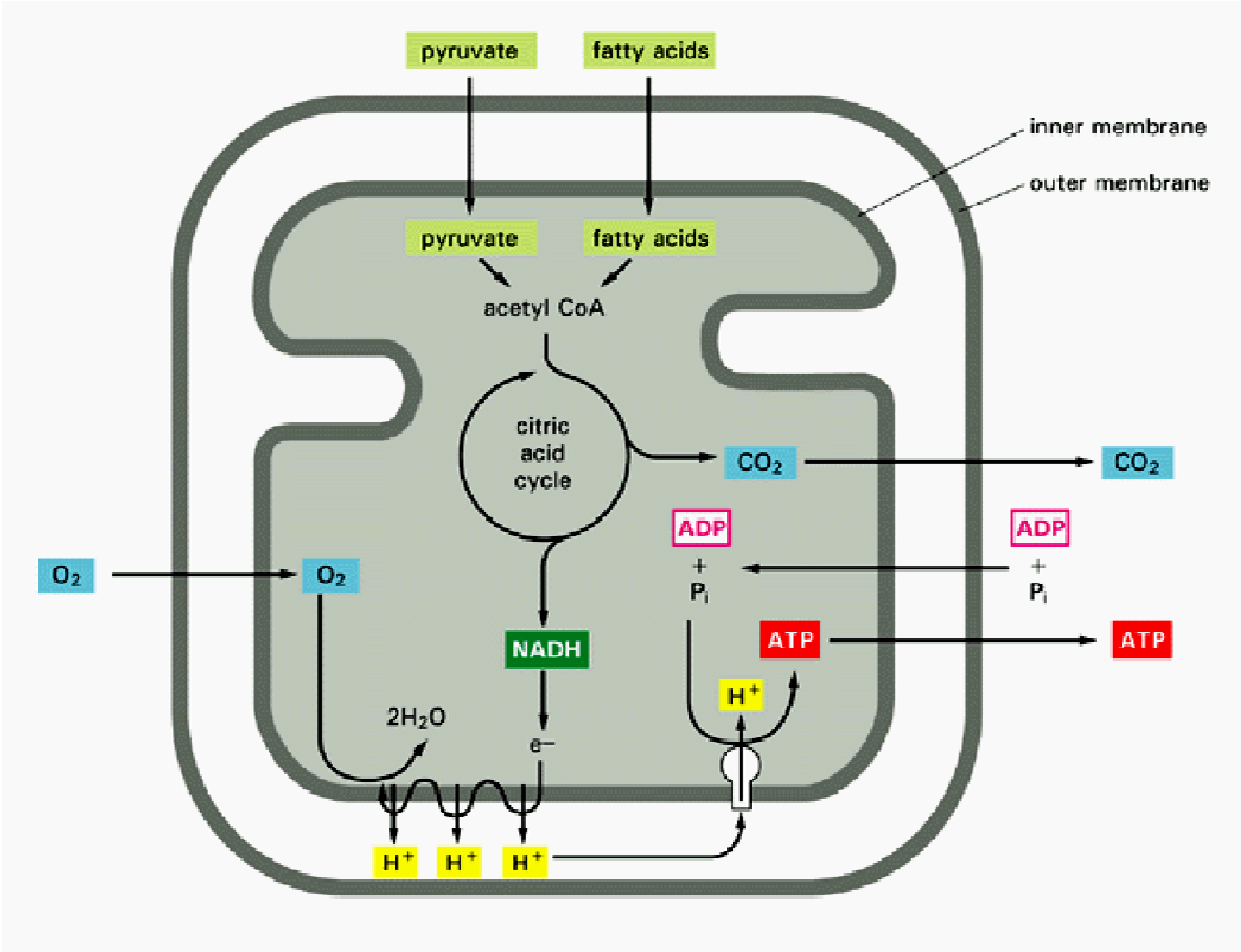
No species has lost them all: 95~99.9%, but not all
Gene loss has occurred in parallel
But kept essentially the same handful

Probable reasons:

- physical nature to be targeted to mito: disproved
- different genetic code in mito: many species have universal code
- **genetic outpost on site where respiration occur: 1993 John Allen**

The problem of poise

Speed & demand: respiration speed depends on demand
Balanced by the availability of glucose, ADP, Pi, oxygen

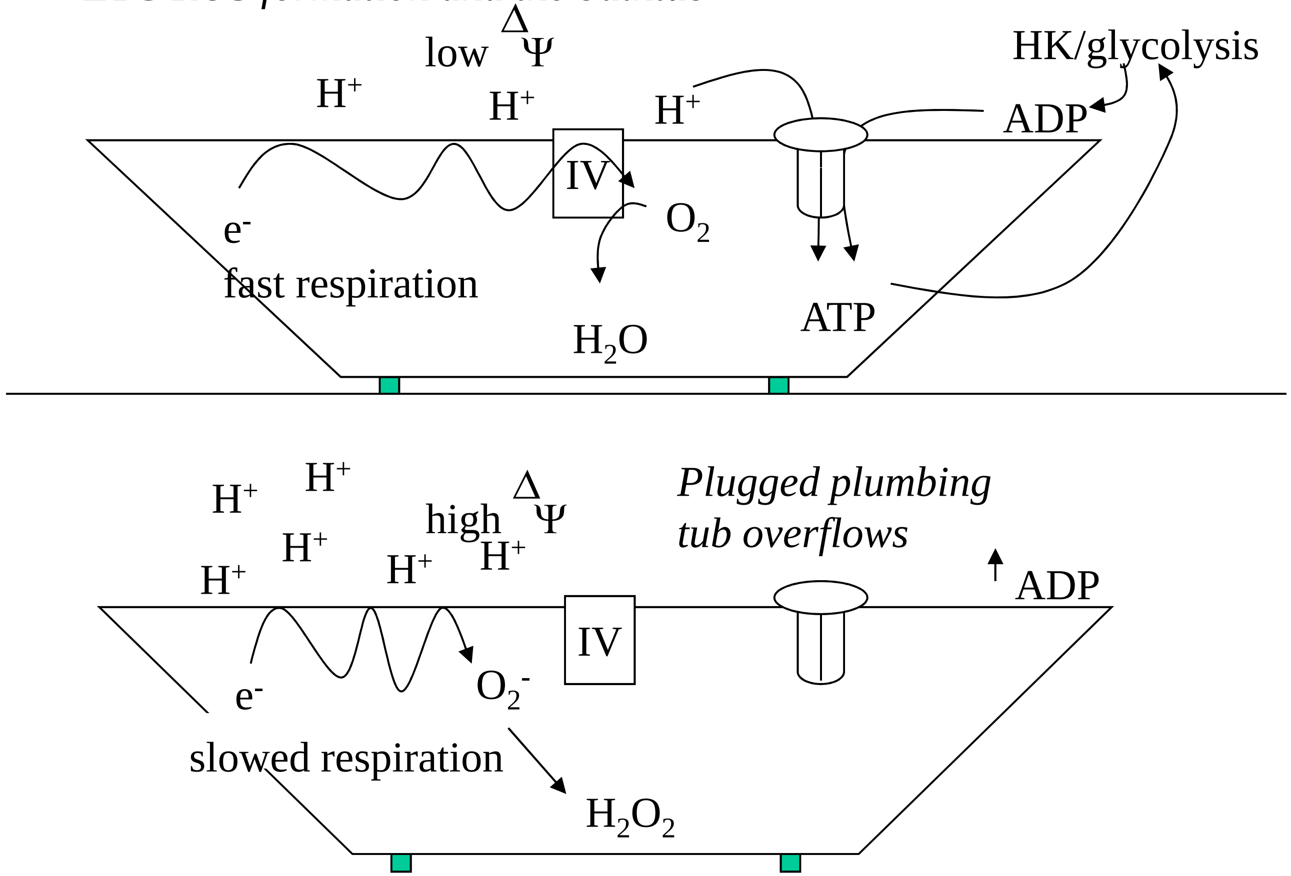


Two choices of ETC components: reduced or oxidized, never both
The dynamic equilibrium between ox and red determines the overall speed
To sustain poise

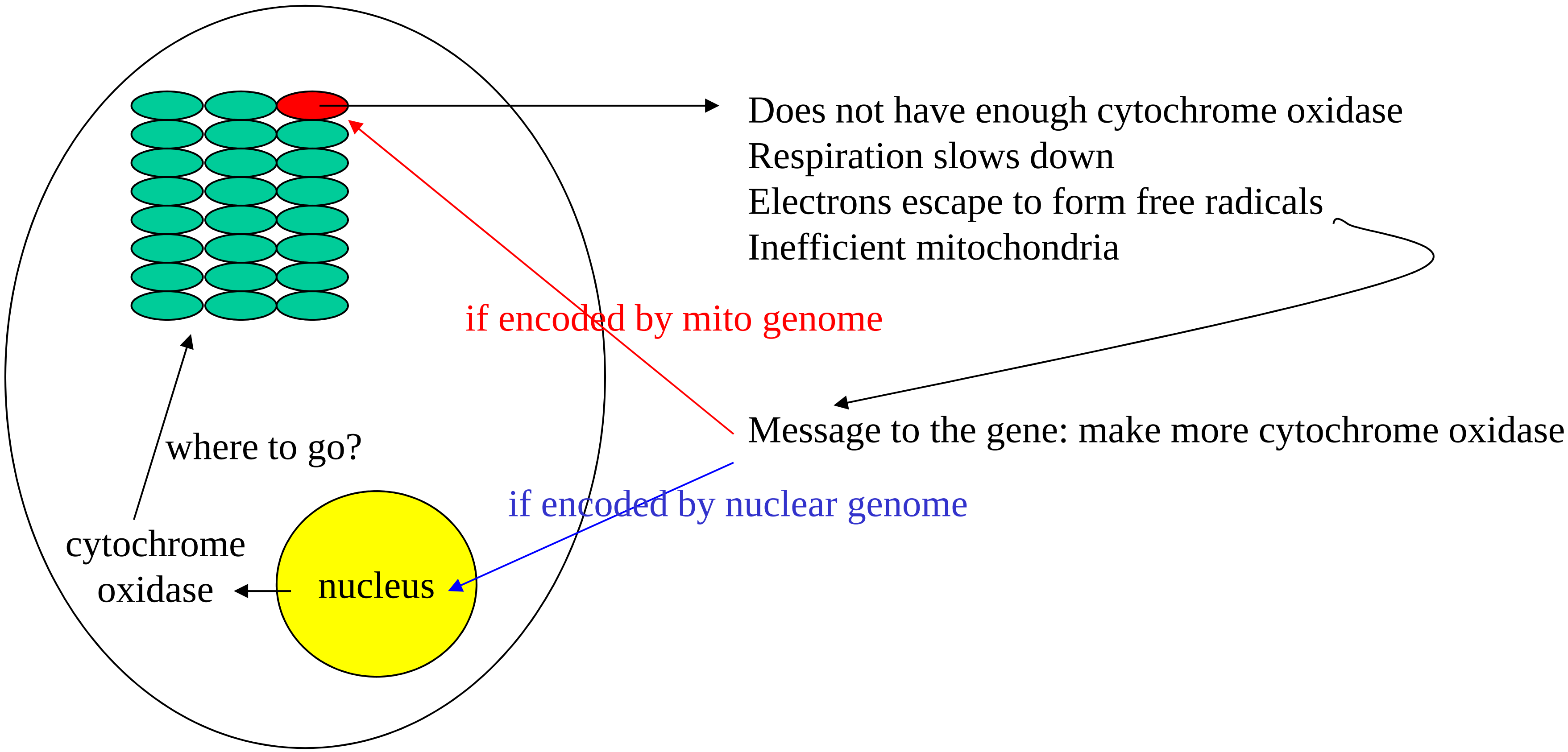
- Keep respiration as fast as possible
- Restrict the leak of reactive free radicals

Correct balance of electrons entering the ETC and the number of carriers

ETC ROS formation and the bathtub



Why mitochondria need genes (not proteins)



How could a few mito genes dominate?

A few core subunits (encoded by mito genes)
act as a flag, around which nuclear subunits assemble
The overall number of flags in the cell as a whole,
at any one time, might remain fairly constant
the rate of respiration in all the mitochondria in a cell at once
is tightly controlled

Both the mito and chloroplast genes of all species always encode
the critical electron-transport proteins

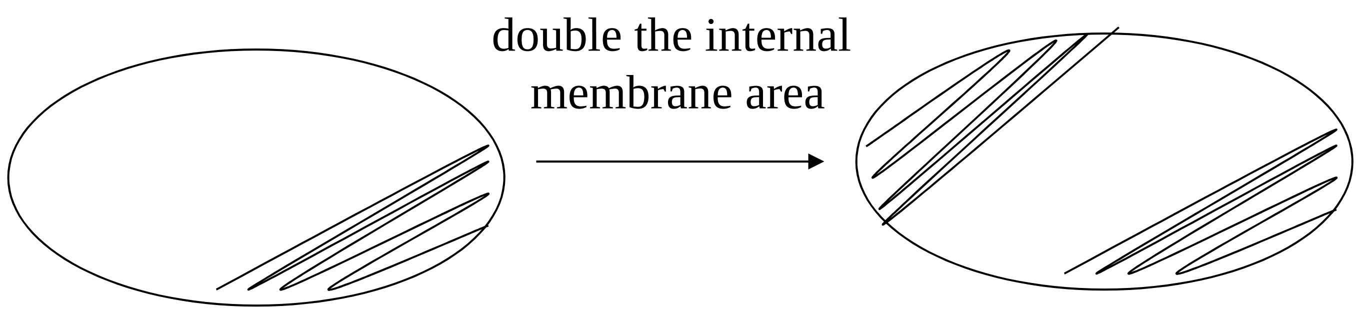
Plasmodium mitochondria
encode 3 proteins: cytochromes

Any organelles that do not need to conduct electrons will lose their genome
ex. hydrogenosomes

Barrier to complexity in bacteria

If mito need a core of genes to control the speed of respiration bacteria can’t evolve into eukaryotes by natural selection alone

Nitrosomonas and *Nitrosococcus*

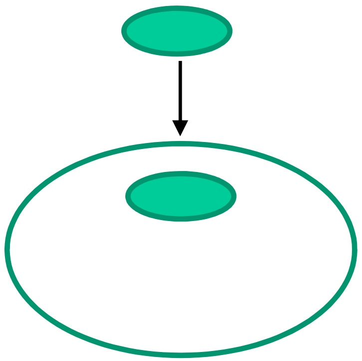


Control of respiration?

Origin of nucleus (2004, Science 305: 766-768)

1. Friendly merger: Lopez-Garcia & Moreira syntrophic model

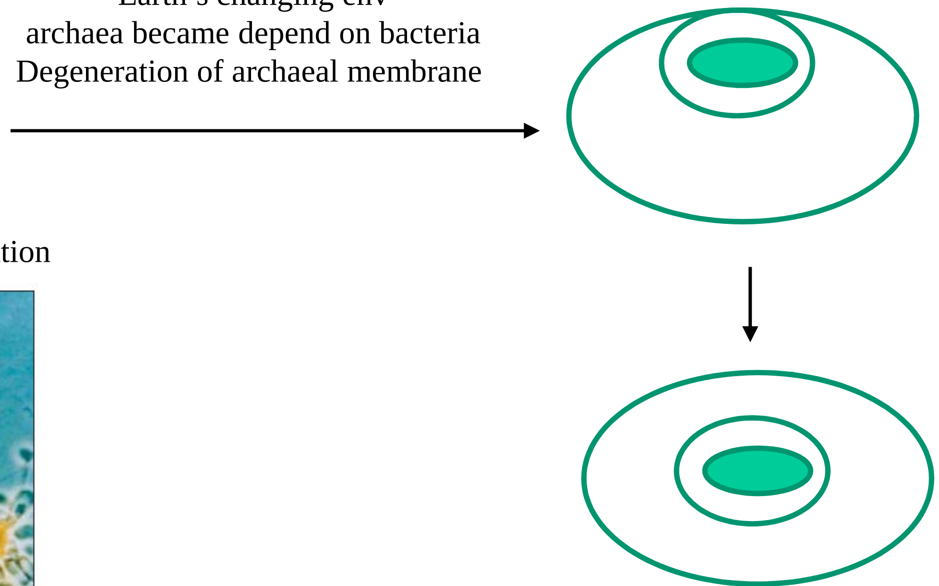
archaea making mechane from H_2

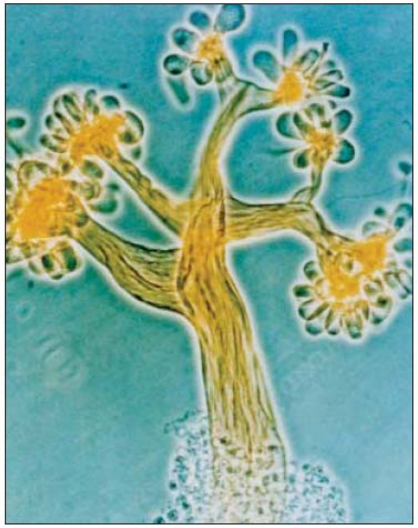


Eubacetria depending on fermentation

Earth's changing env
archaea became depend on bacteria
Degeneration of archaeal membrane

Invagination of membrane





Fruitful partnership. A bacterium akin to this myxobacterium may have paired off with an archaeum, eventually evolving a nucleus.

2. Self-starter: Fuerst

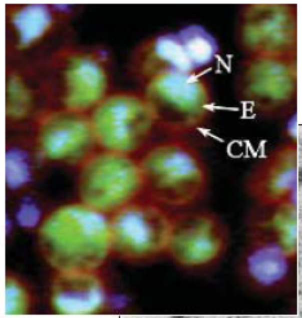
Eukaryote-like cells emerged earlier

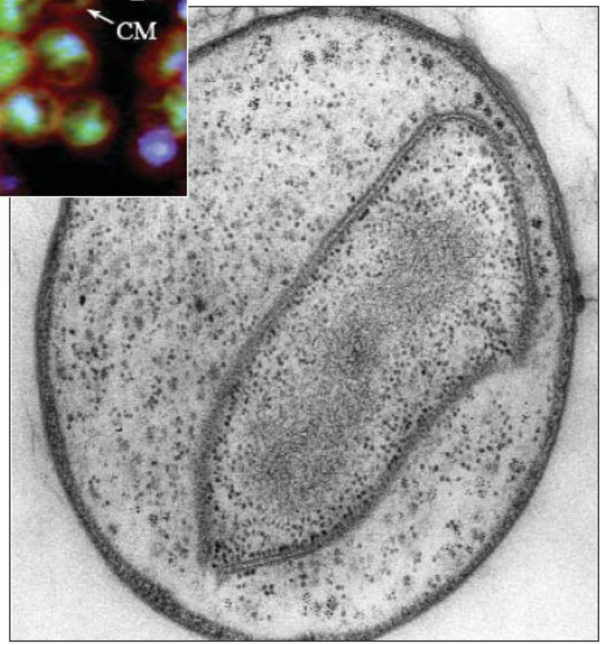
Planctomycetes: bacteria having membrane bound compartments

- where genetic material exists
- having double internal membrane
- pieces of folded membranes linked together indicating pores

More bacteria having nuclei

evolutionary novelty," says Eugene Koonin of the National Center for Biotechnology Information in Bethesda, Maryland.





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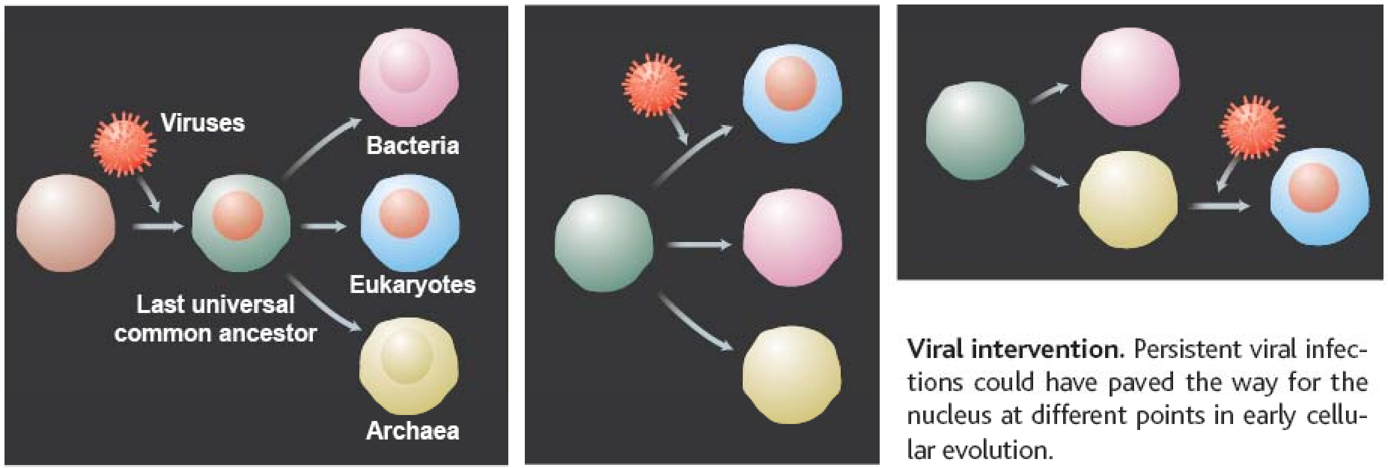
Precocious prokaryote. Bacteria aren't supposed to have nuclei, but *Gemmata obscuriglobus* does. A closer look shows DNA (N, blue) inside a proper nuclear envelope (E, green), as well as a cytoplasmic membrane (CM, red).

3. Hostile takeover: David Prangishvili

Presence of viral in the primordial soup
Persistence of virus in cells
Supplanted bacterial or archaeal genes

Similarity between nuclei and virus: protein or membrane bound
linear chromosomes
diassemble “membrane” during replication



Viral intervention. Persistent viral infections could have paved the way for the nucleus at different points in early cellular evolution.