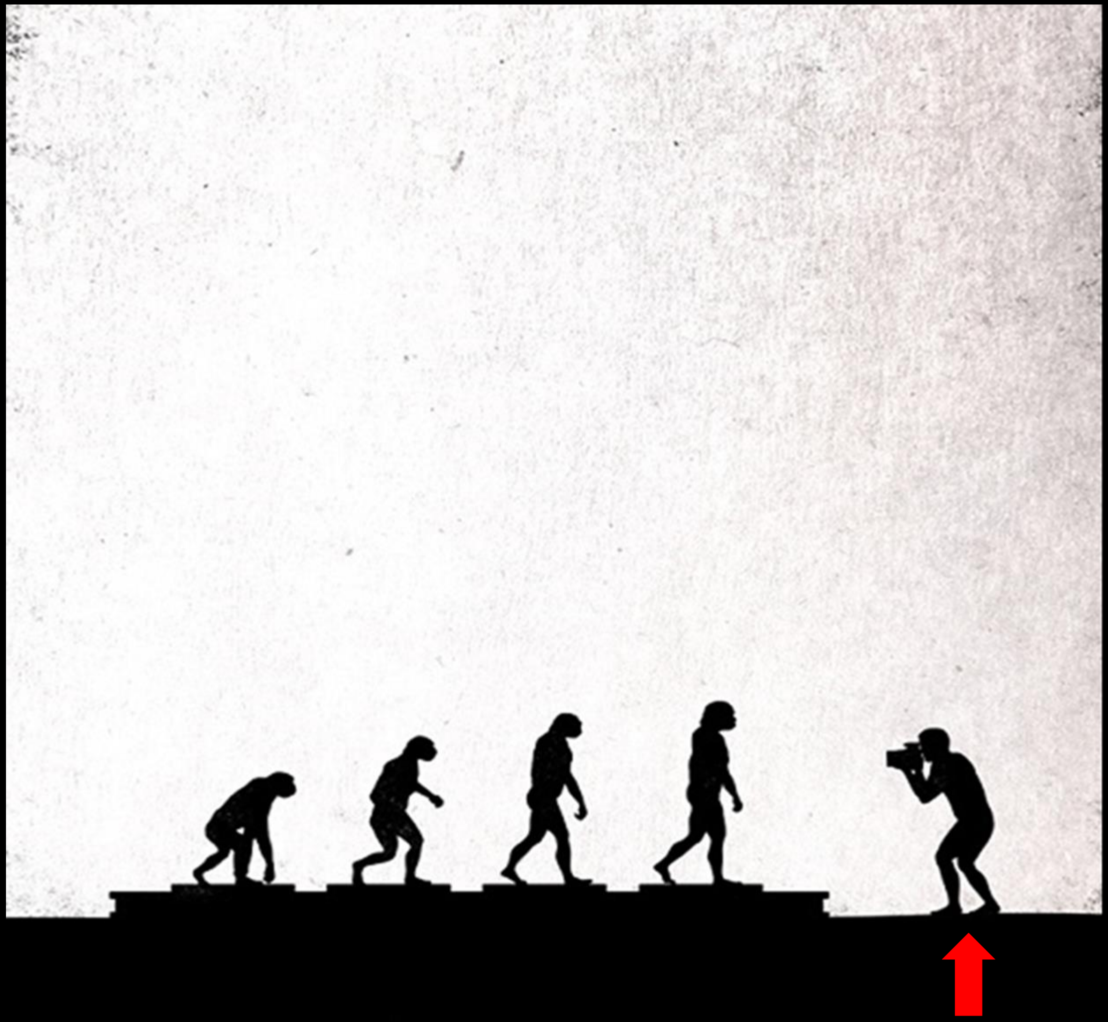
(Inter)dependency and resilience in the living world:
An evolutionary biology perspective

Dr. Eric Bapteste

I am an evolutionary biologist.



An evolutionary biologist

Evolutionary biology tries to explain the history and diversity of life.

What processes produced and sustained the diversity of life froms, over time?

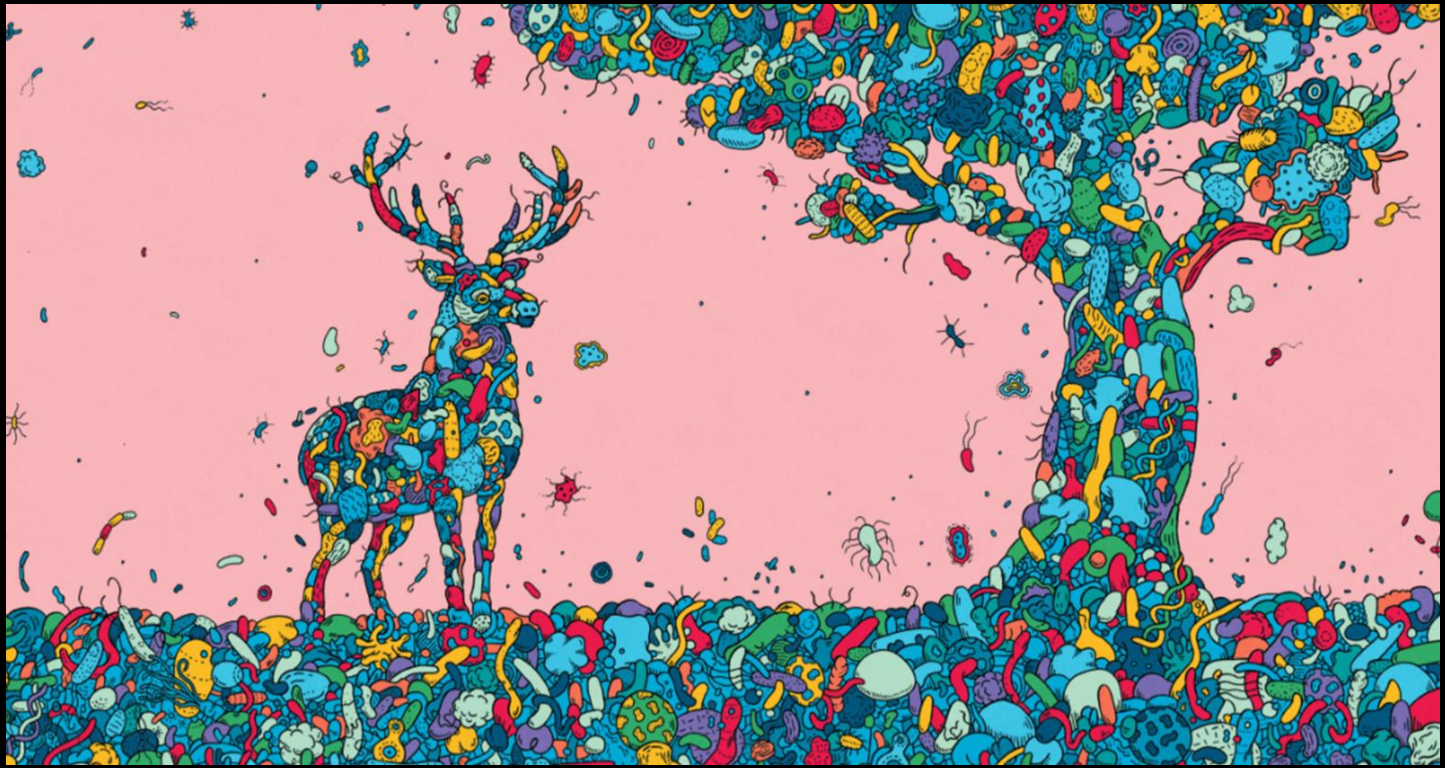
I investigate these issues using networks, focusing on interactions.

Aim of this talk

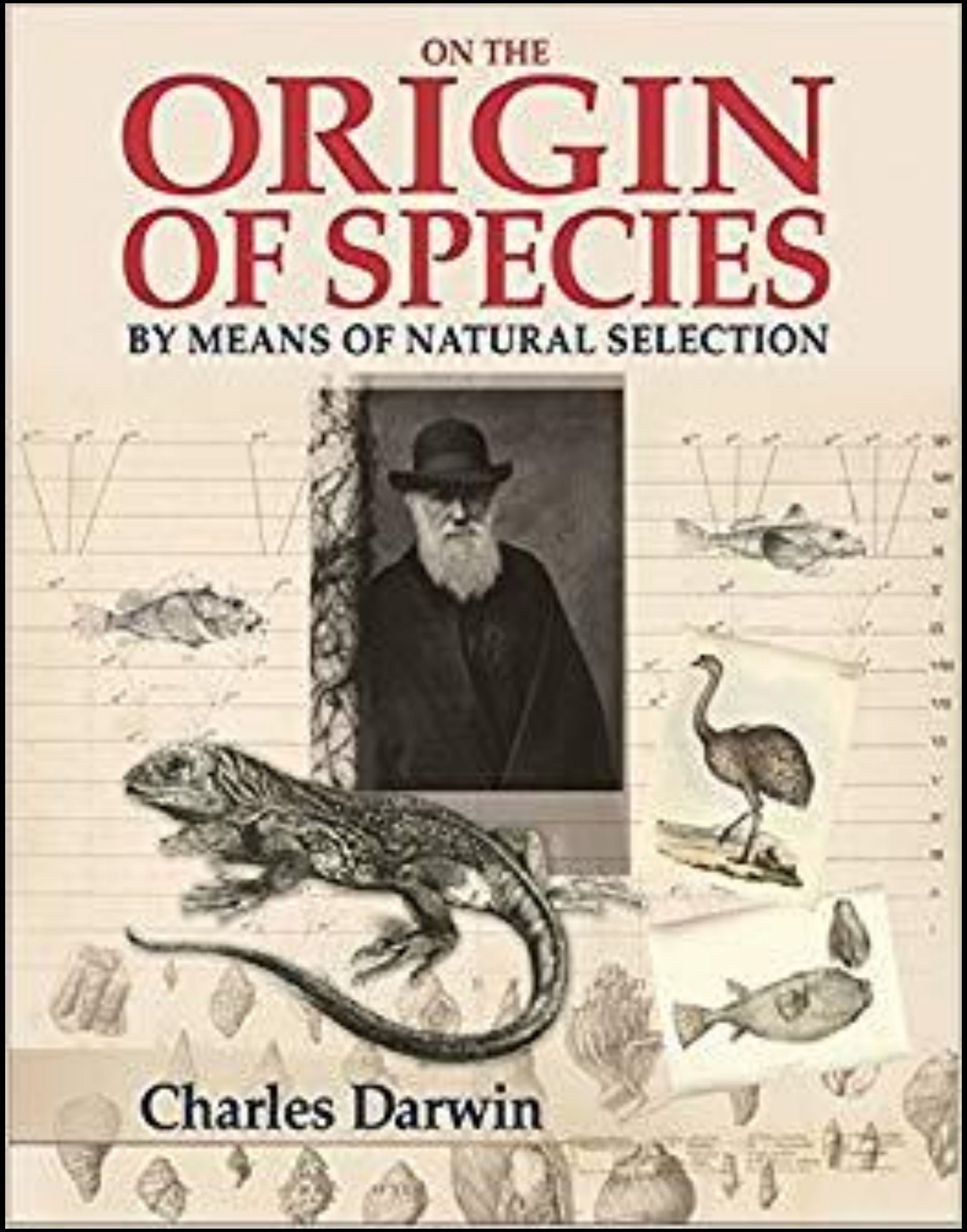
A (long but) simple argument to show that evolutionary biology may have something relevant and new to say about dependencies and interdepencies in the biological world.

Rough plan of the talk

- Traditionally, evolutionary biology focuses on lineages
- However, a different focus - on interactions- appears very relevant
- A focus on interactions expands evolutionary explanations
- with potential to better track dependencies/interdependencies in the living world



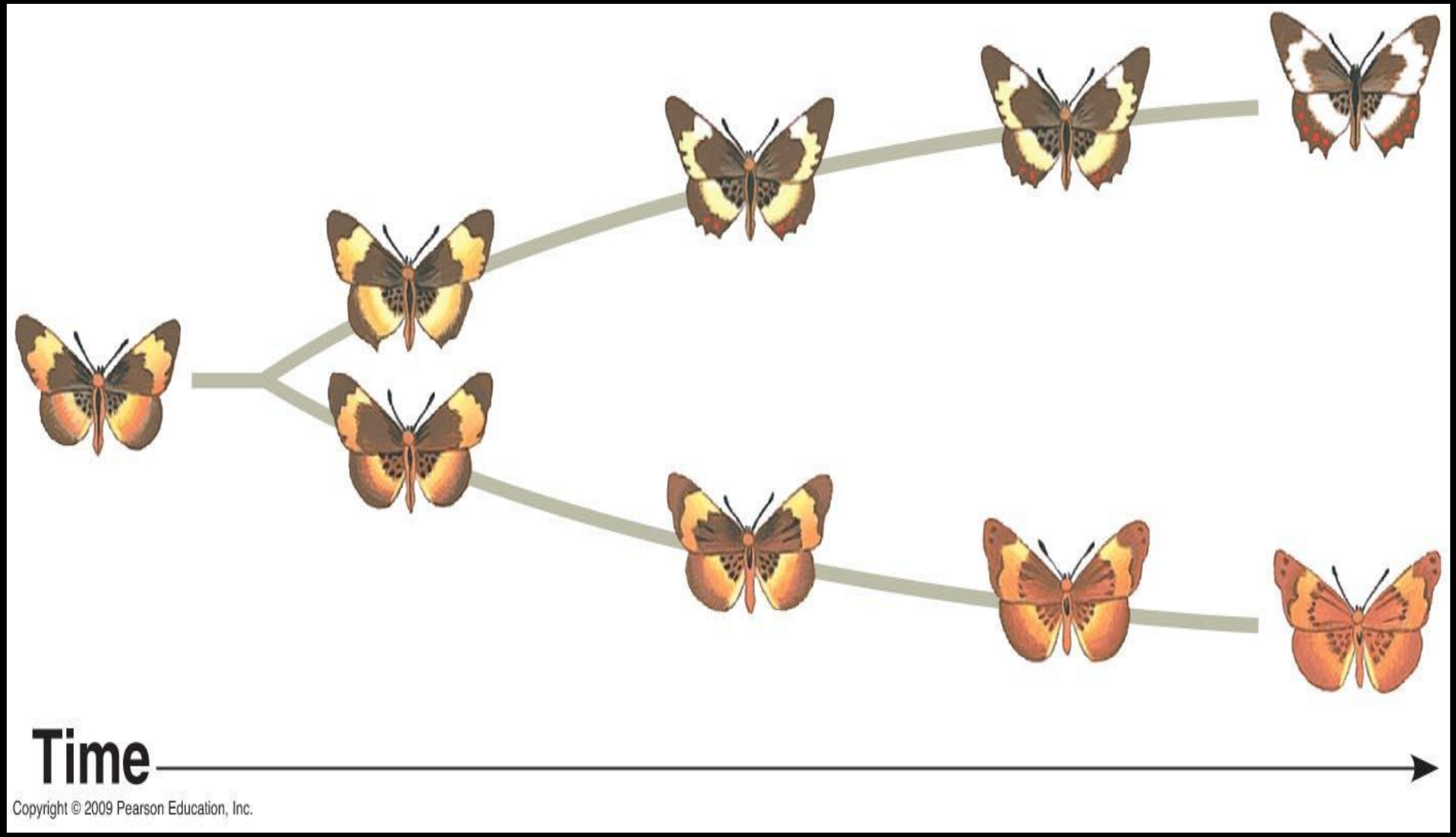
Evolutionary biology traditionally describes the history of **lineages**.

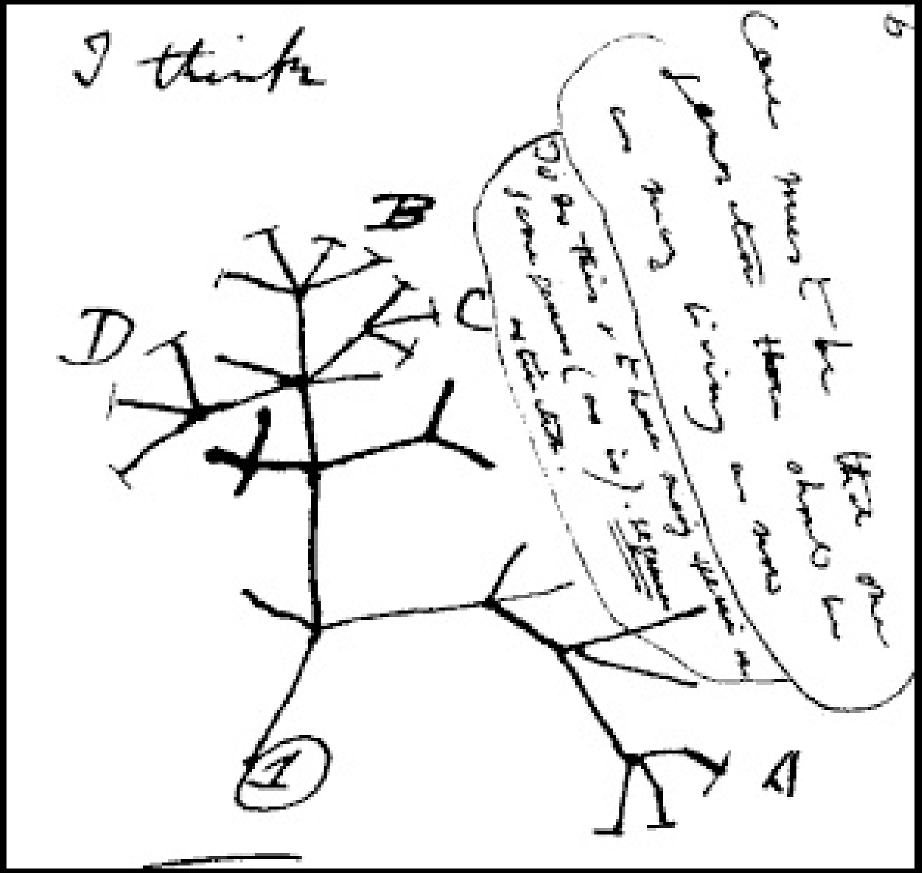

ON THE
ORIGIN
OF SPECIES
BY MEANS OF NATURAL SELECTION
Charles Darwin

1859

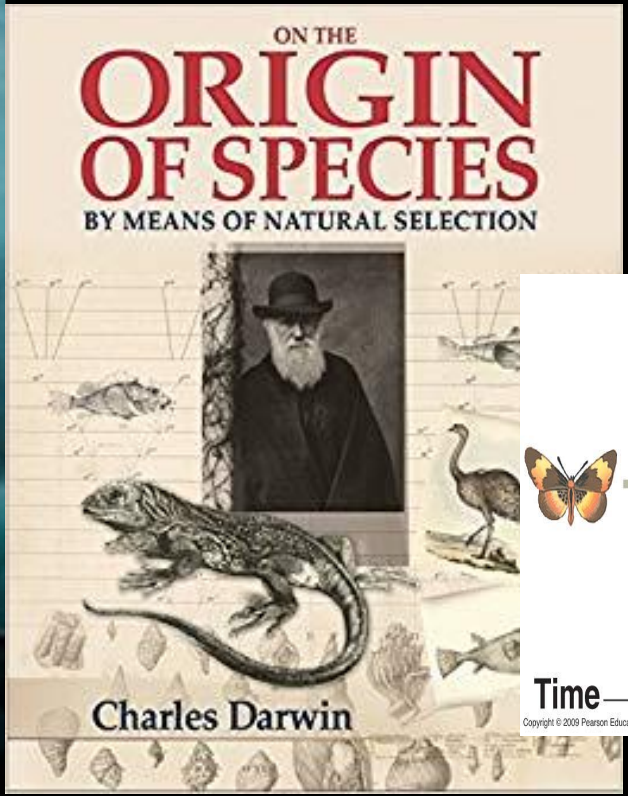
This book presented:

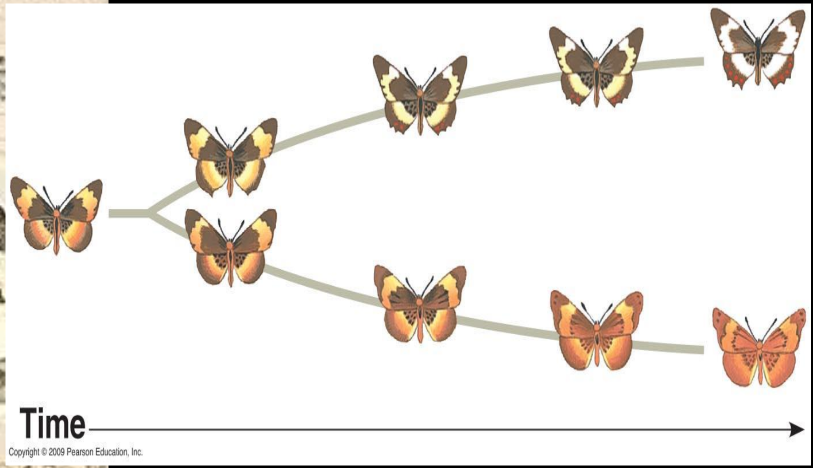
- **1 process**: descent with modification
- **3 conditions** for its realization (variation, inheritance, differential fitness)
- **2 bold hypotheses**: ***natural selection*** + ***tree of life***





Therefore, classic evolutionary biology is centered on natural selection, to explain the survival of the fittest



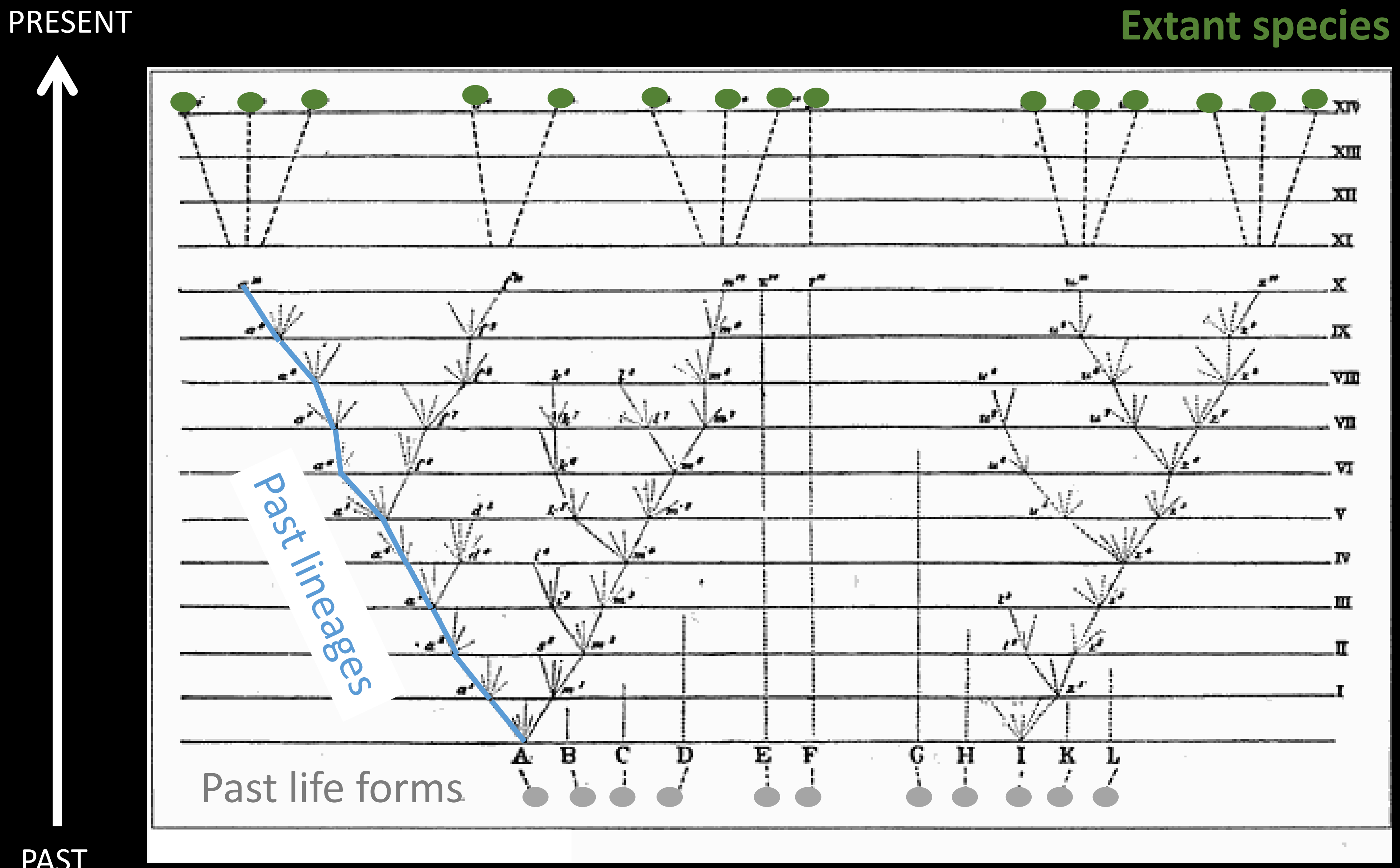


- the **production of (advantageous) variation**
- the **transmission of that (advantageous) variation to offsprings**
- An **increased ability of organisms with advantageous variations to produce more offsprings,**

So that, over generations, **the frequency of more fit organisms would increase in a population.**

The bottom line is that
« genes mutate, organism change and population or species evolve».

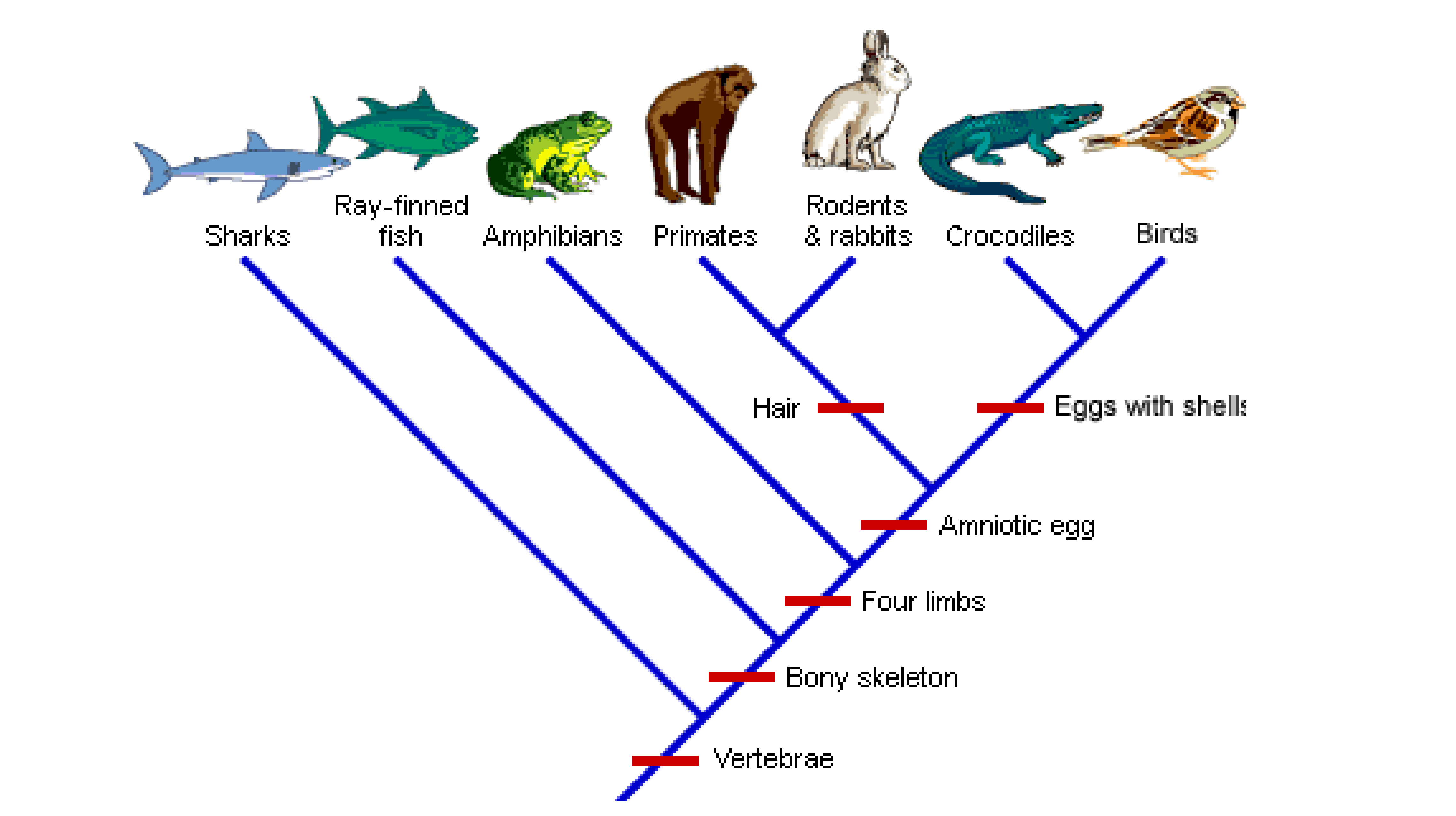
Furthermore, Darwin extrapolated this logic to explain the evolution of all **organismal** lineages on Earth.



C. Darwin 1859

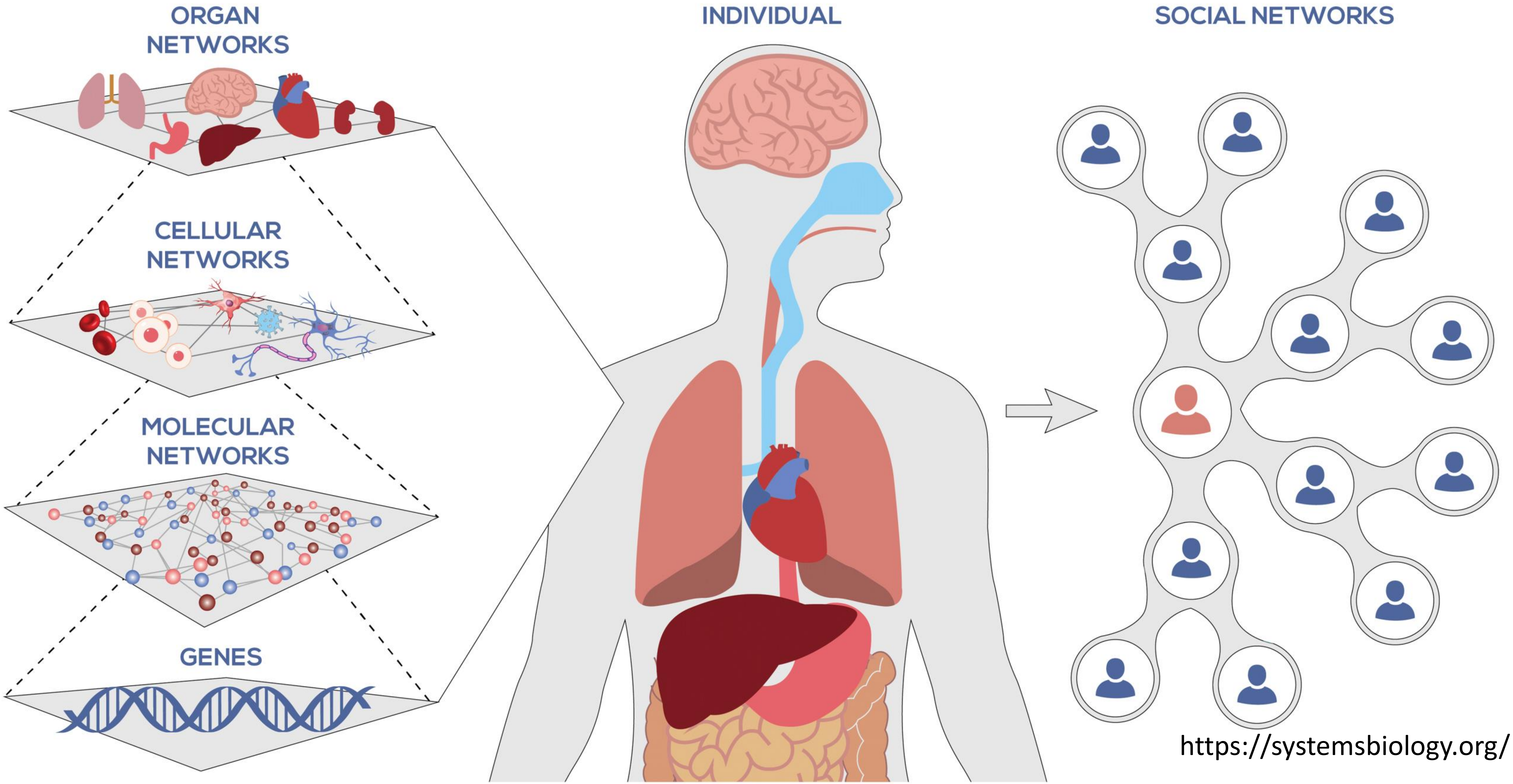
There are indeed **many good reasons to use a tree model** to study the biological world and its evolution.

It offers a popular way to classify living beingss and to infer shared derived traits inherited from an ancestor.



But this tree-based picture **should not hide another biological observation**: there are **interactions everywhere in the biological world**.

We are composed of networks and part of networks.



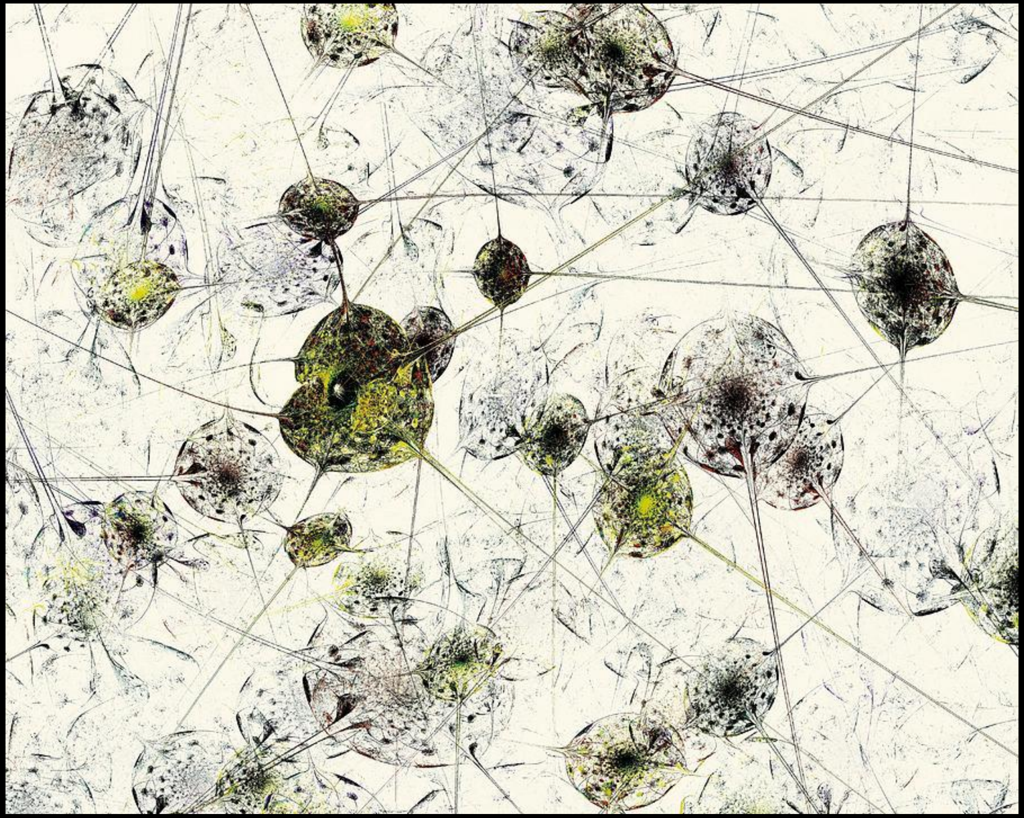
https://systemsbiology.org/

Importantly, these networks **introduce dependences/interdependences**

and their structure and evolvability **may explain the stability of Life on Earth**.

Let’s now consider the biology in a bit more details.
What are these interaction networks?

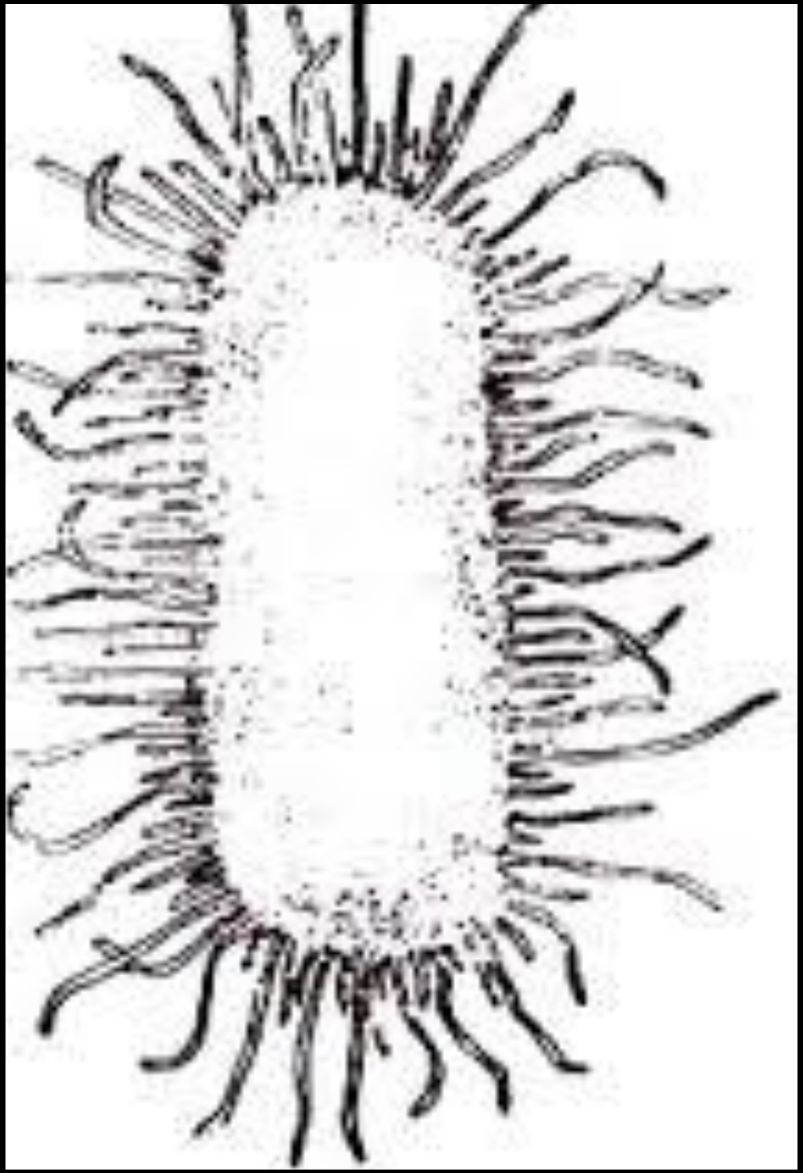
There are **interactions everywhere in organisms**, even in simple cells.

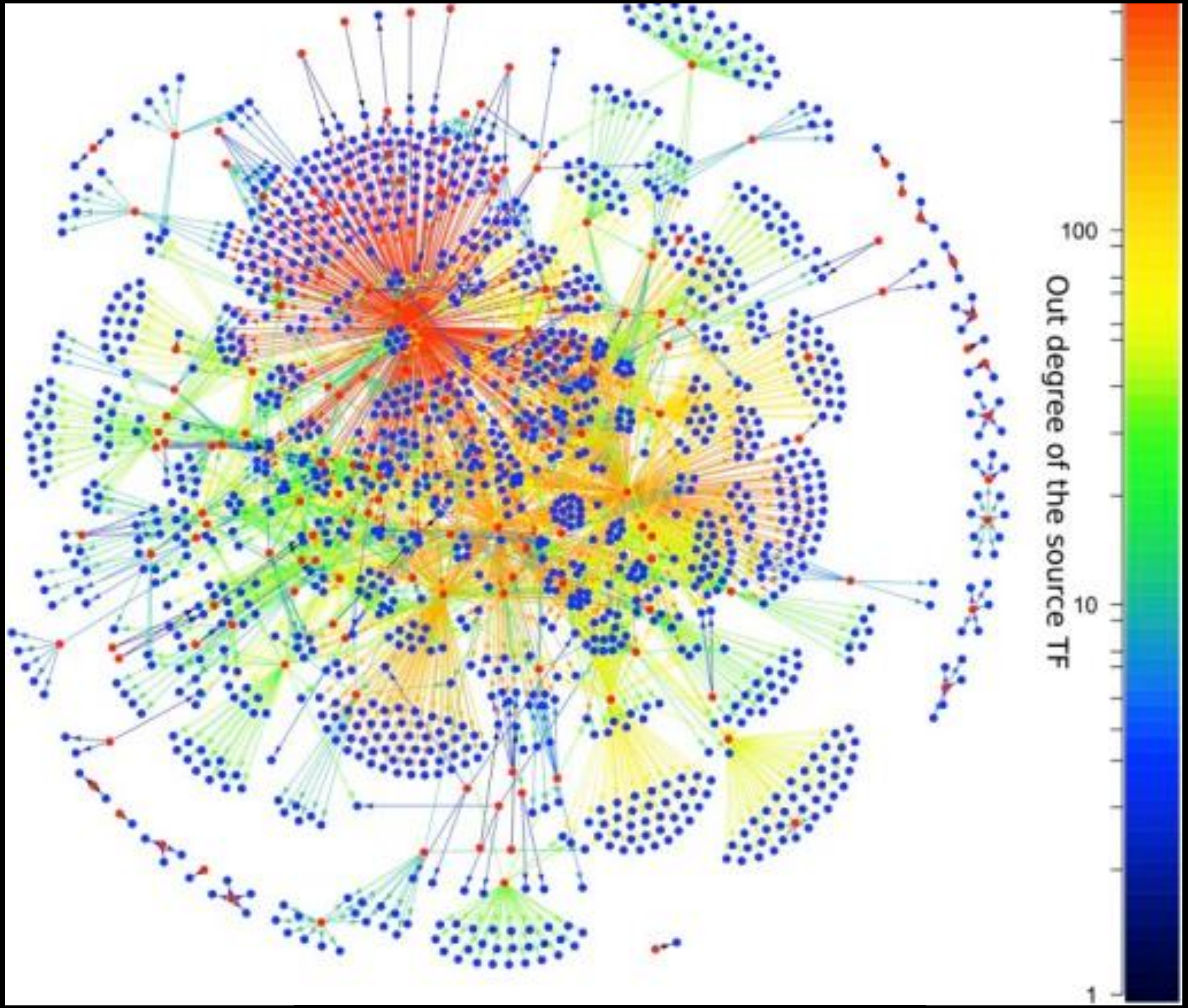


A. Malakhova

For instance, 2 representations of *E. coli*

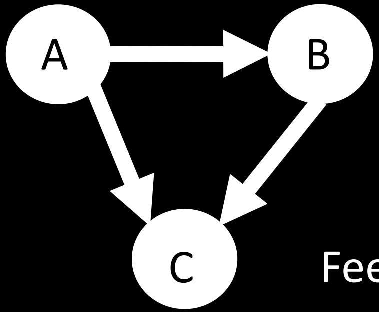
left morphological; right: emerging from gene regulatory networks





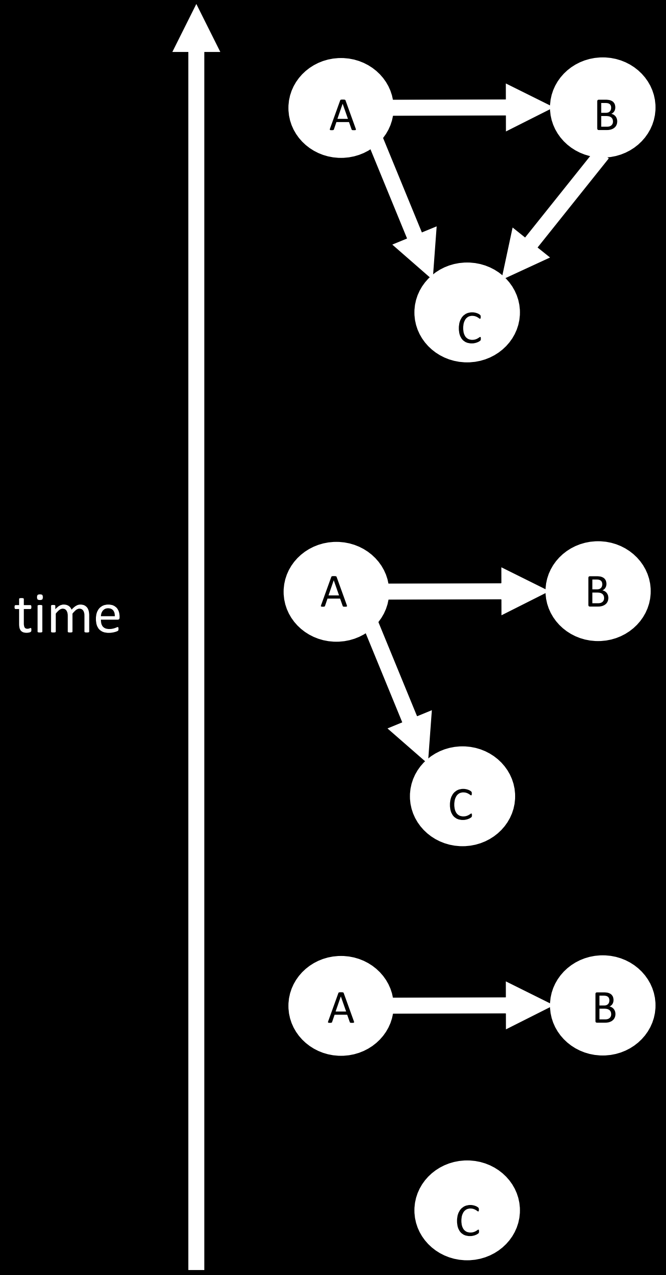
Regulators Other genes

The architecture of these networks is informative.



Feed-forward loop

This introduces new biological questions: how did the architecture of such networks evolve?

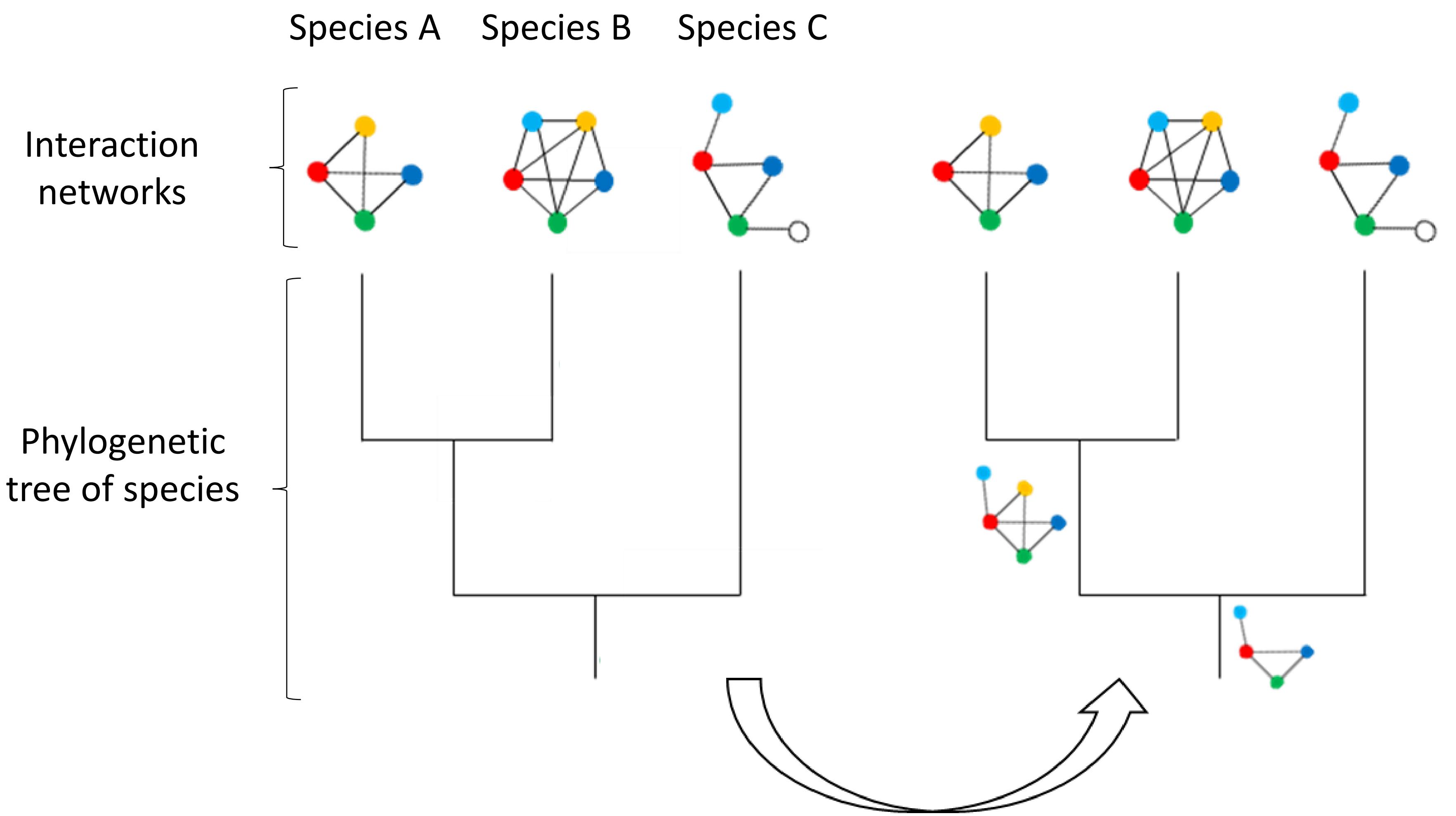


Networks support **different explanations** than a tree:

➡ **Are there organizing principles for biological networks?**

We are developing « phylosystemic » methods dedicated to **infer interaction network evolution**.

Principle of a 'phylosystemic'/'evosystemic' study.



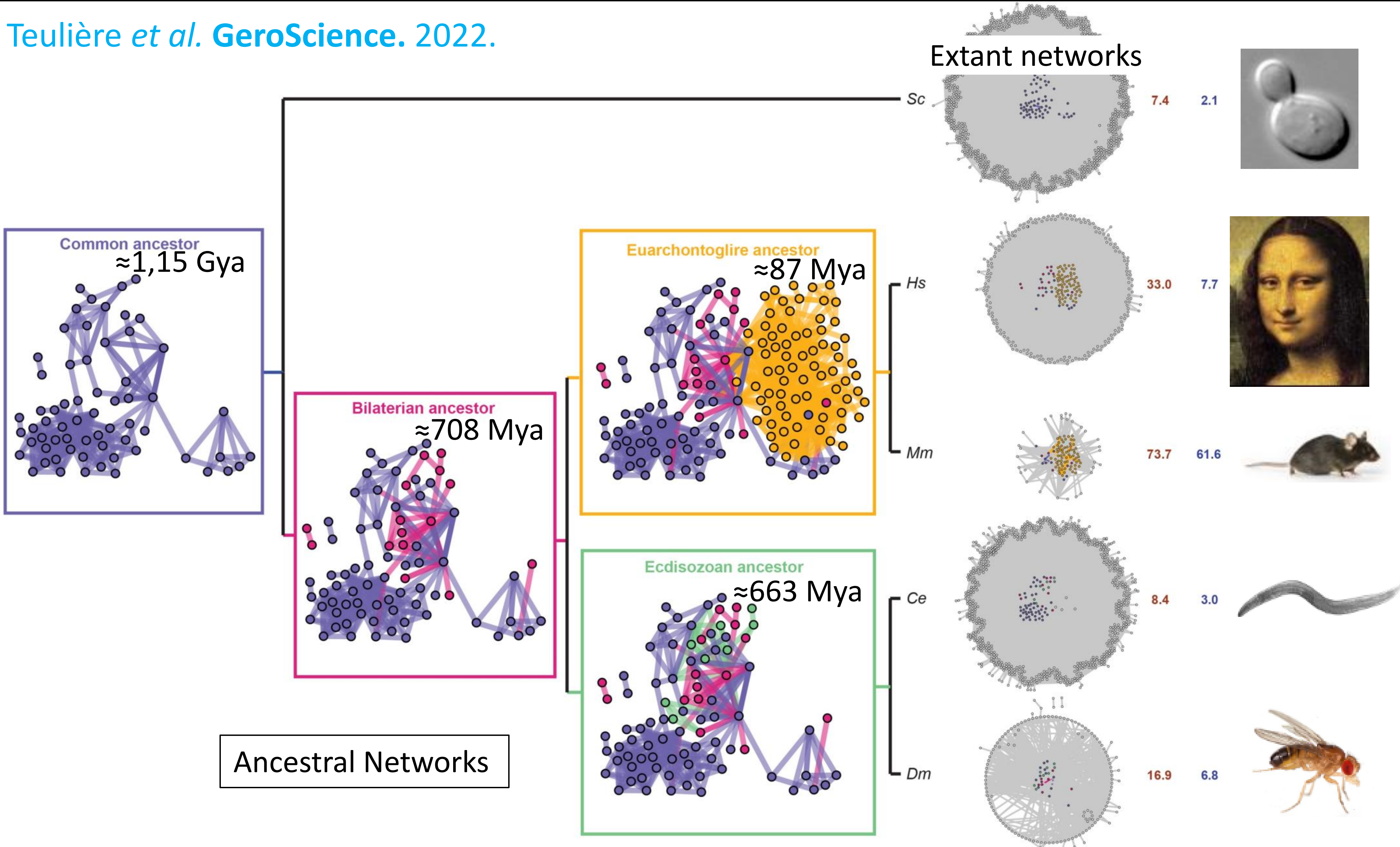
Inputs:
- Interaction networks
- A reference phylogeny
- Orthology relationships between nodes in networks.

Outputs:
- Hypothetical ancestral networks

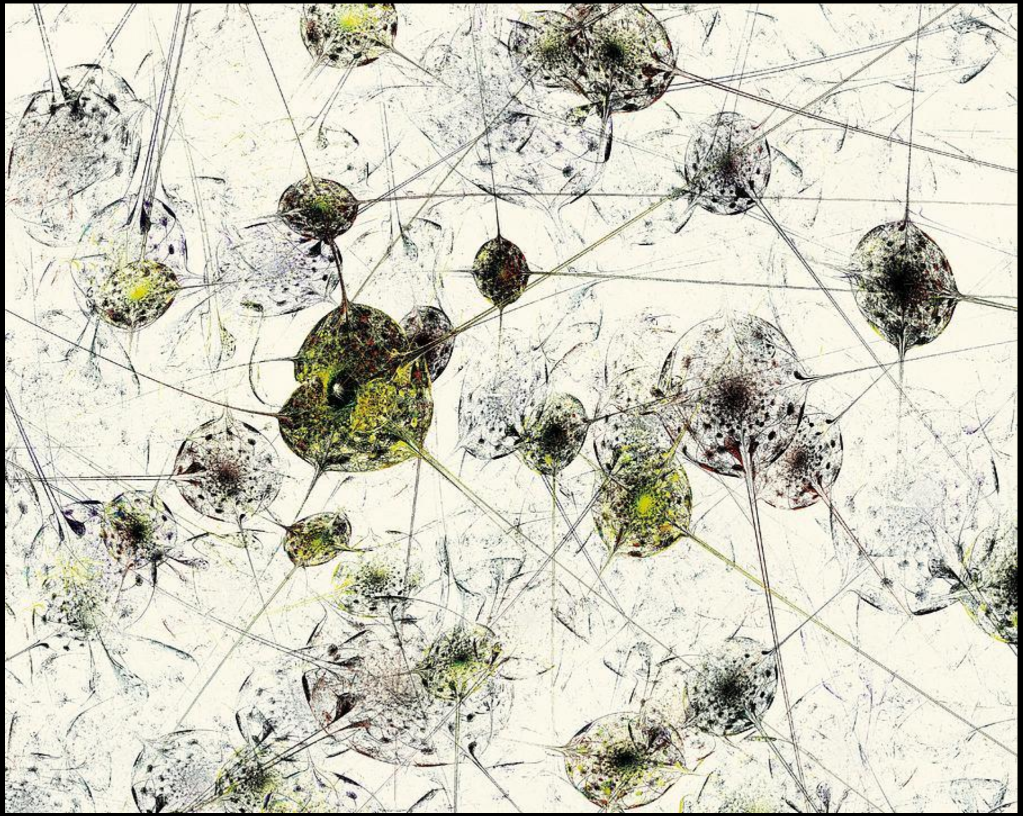
Watson, A.K., Habib, M., Bapteste, E., 2020. Phylosystemics: Merging Phylogenomics, Systems Biology, and Ecology to Study Evolution. Trends Microbiol. 28, 176–190

For instance, we inferred the evolution of protein interactions associated with ageing

Teulière *et al.* **GeroScience.** 2022.



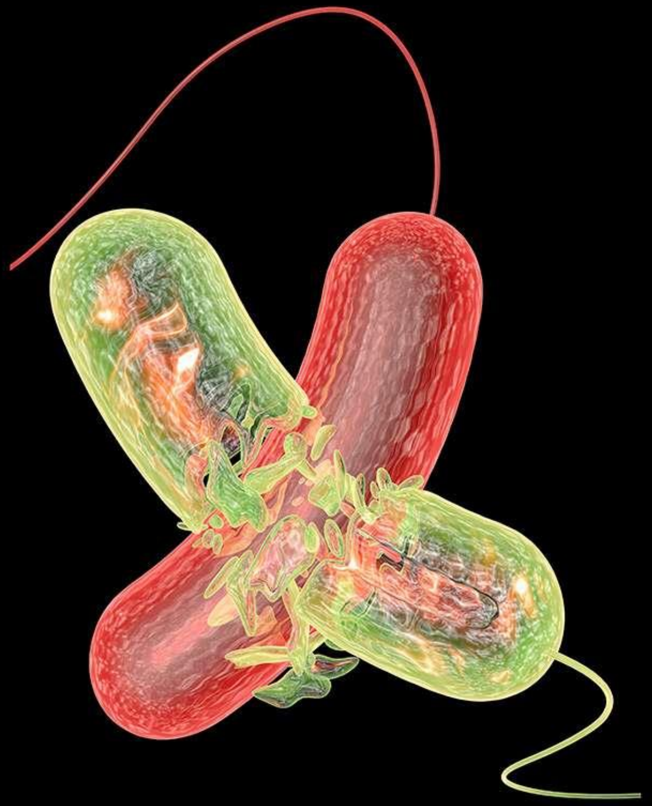
- **Organisms**, even simple cells, **belong to networks**.



A. Malakhova

Microbes interact in many ways.

- **Competition**

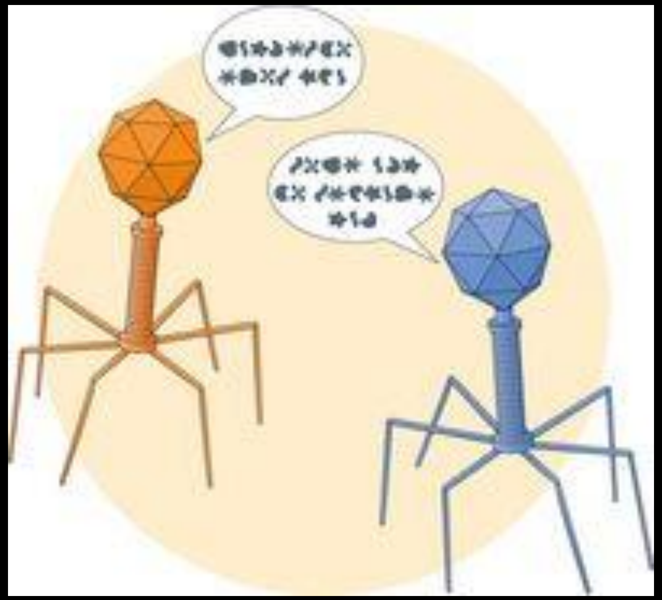


Alfred Pasieka/SPL

- **Cooperation**

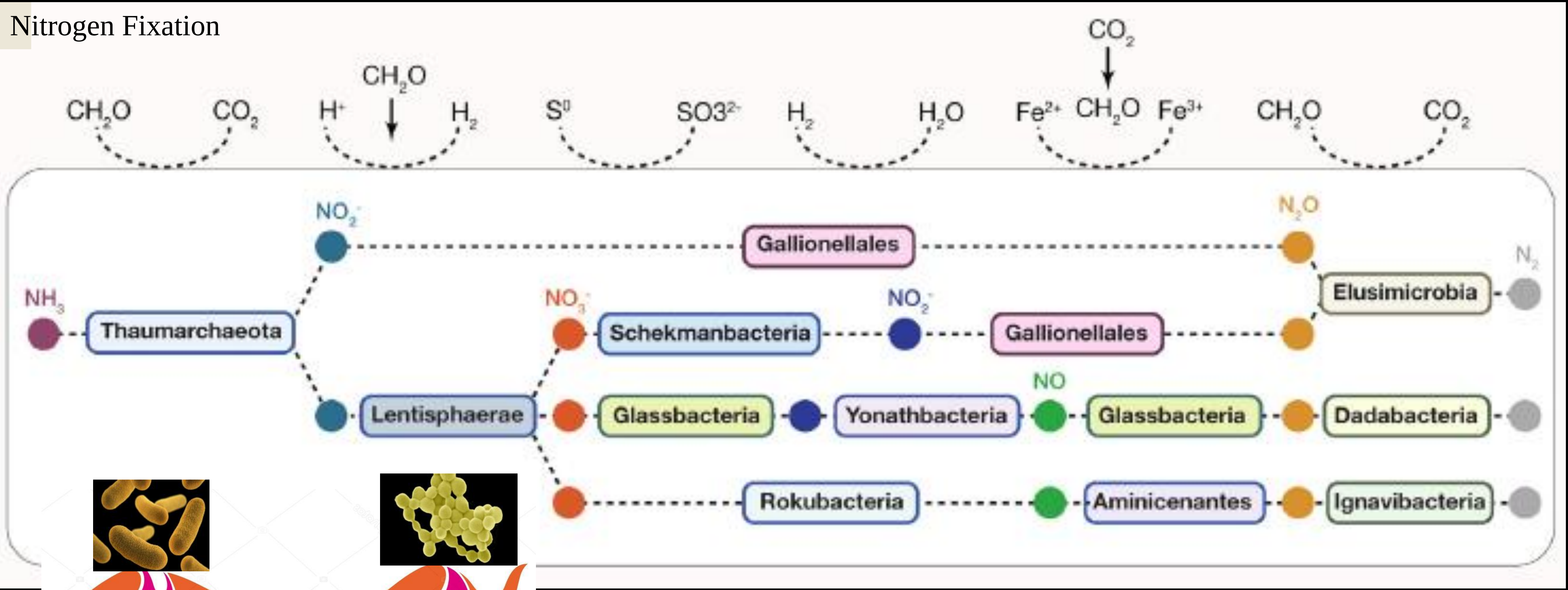
Wanner *et al.*, J. Bact.(2008)

- **Communication**



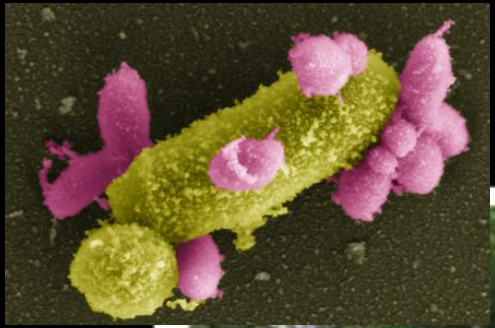
Erez *et al.*, Nature

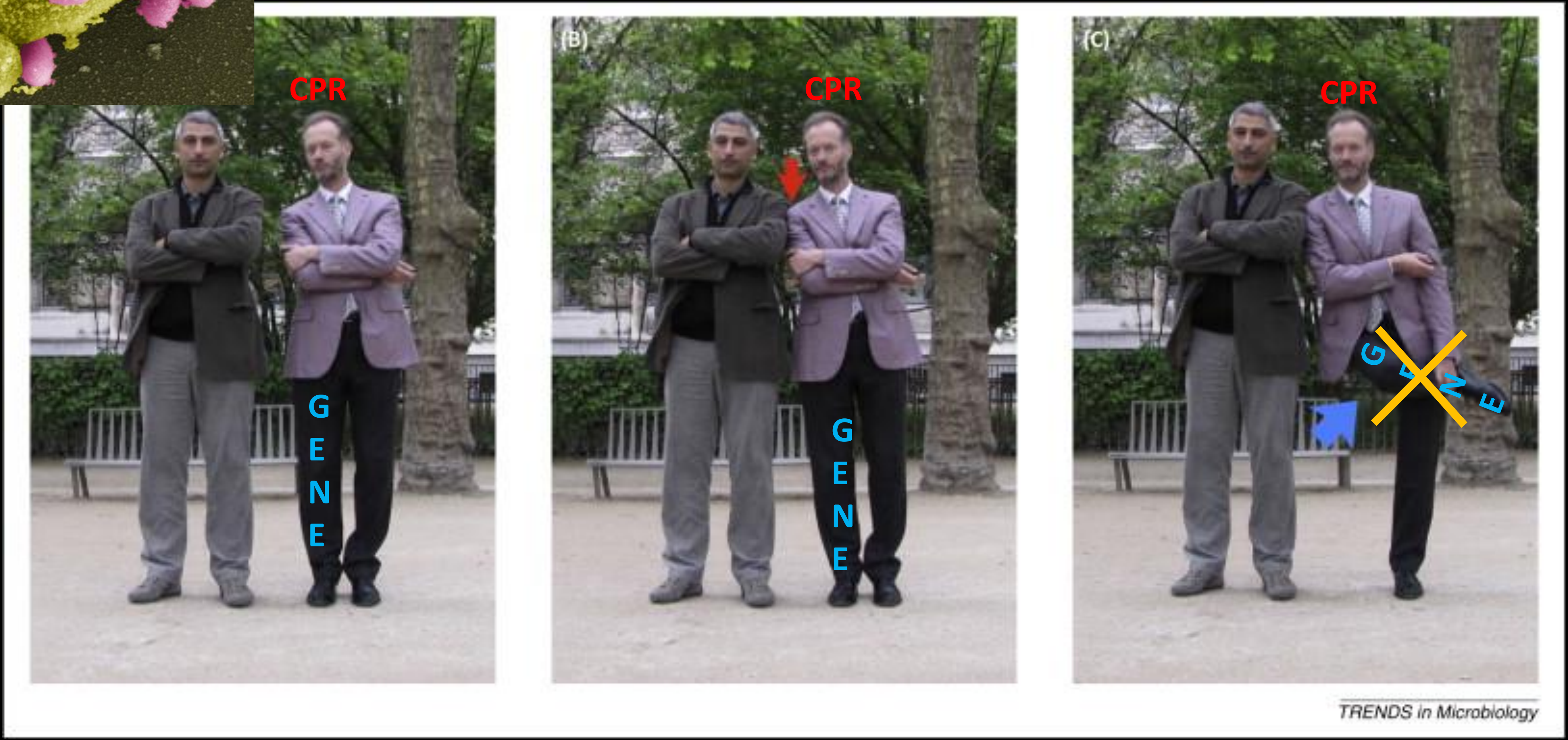
Some ultra-small microbes are involved in collective reactions by metabolic hand-offs



Castelle *et al.* Cell 2018

Ultra-small cells would have lost some of their genes in the context of interactions with other organisms.

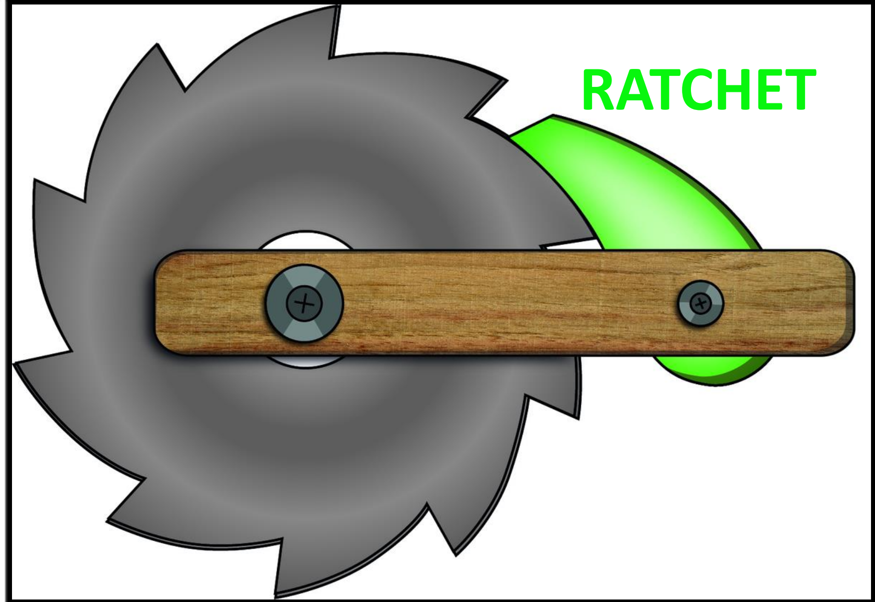




(Sélosse et al. Trends in Micro., 2014)

Such interactions lead to counter-intuitive predictions.

PRE-SUPPRESSION



(Gray & Doolittle, Science, 2010)

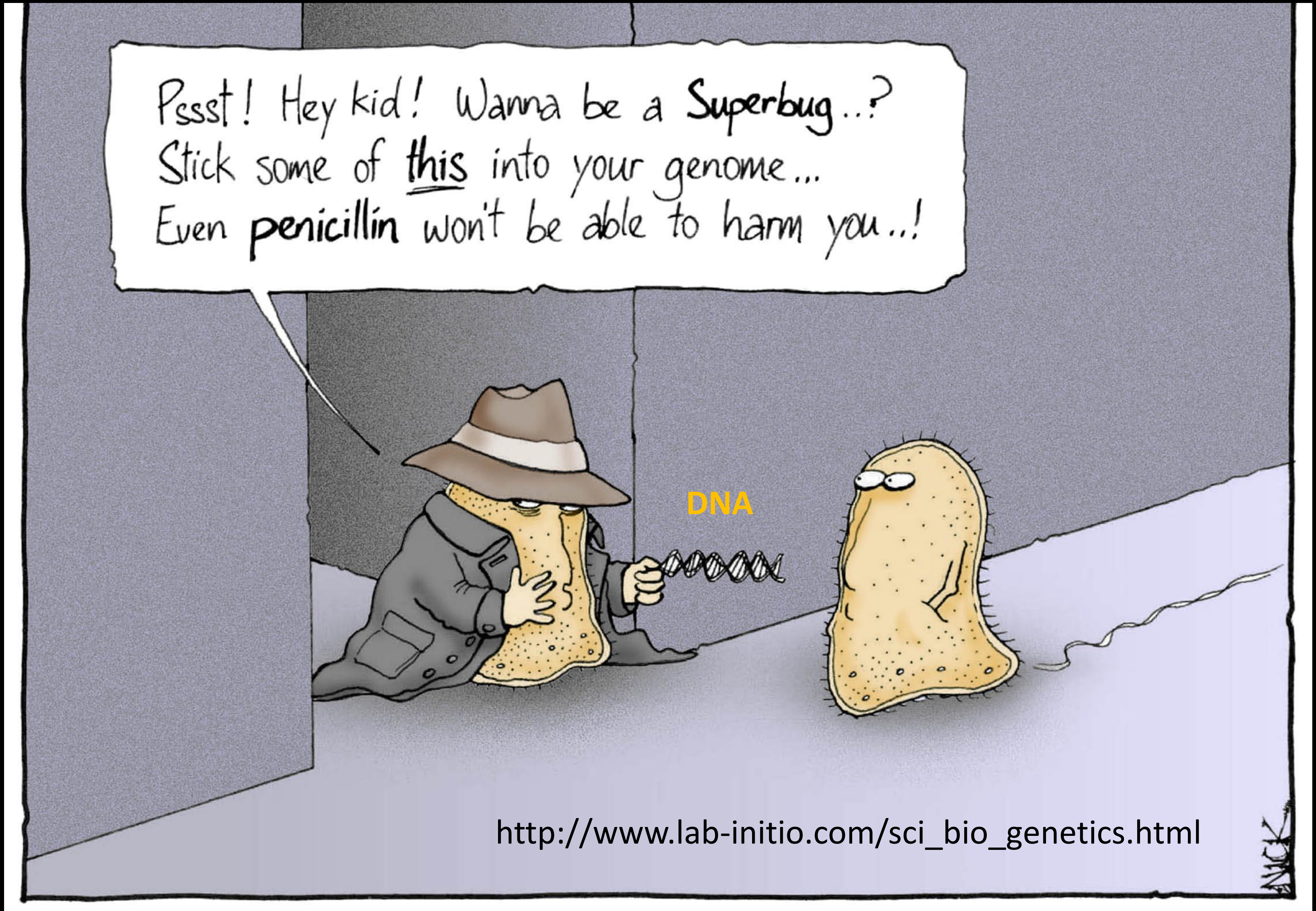
Such dependances are difficult to reverse, thus complex microbial communities, with non autonomous cells, are expected to evolve over time.

This kind of explanation contrasts with a more classic vision.

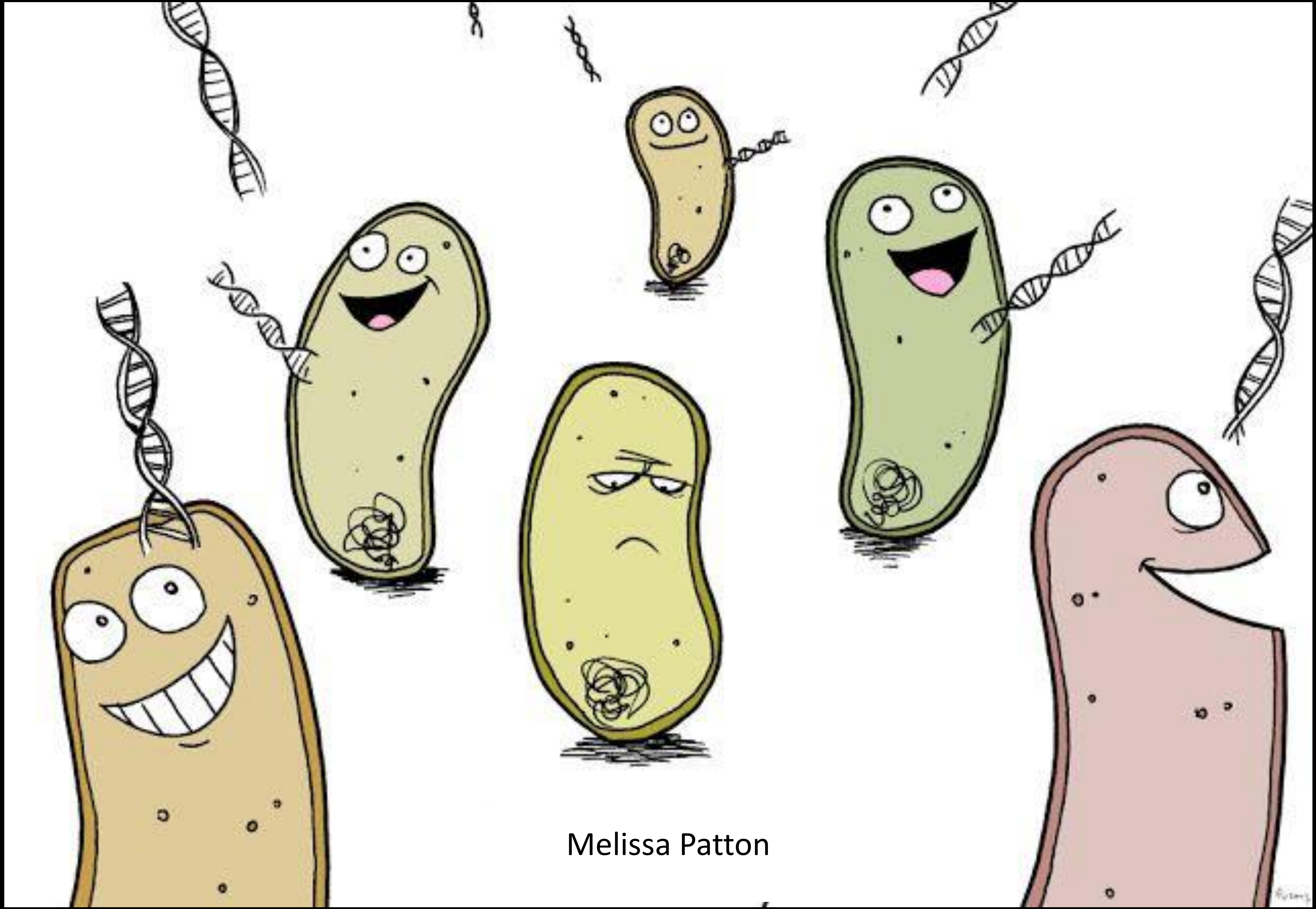
Survival of the fittest (within a population/species)

Complementation (within a community)

Other ex, horizontal gene transfer is a process by which an organism receives genes from a neighbor, rather than from an immediate ancestor.



Gene sharing allows microbes to evolve very fast.

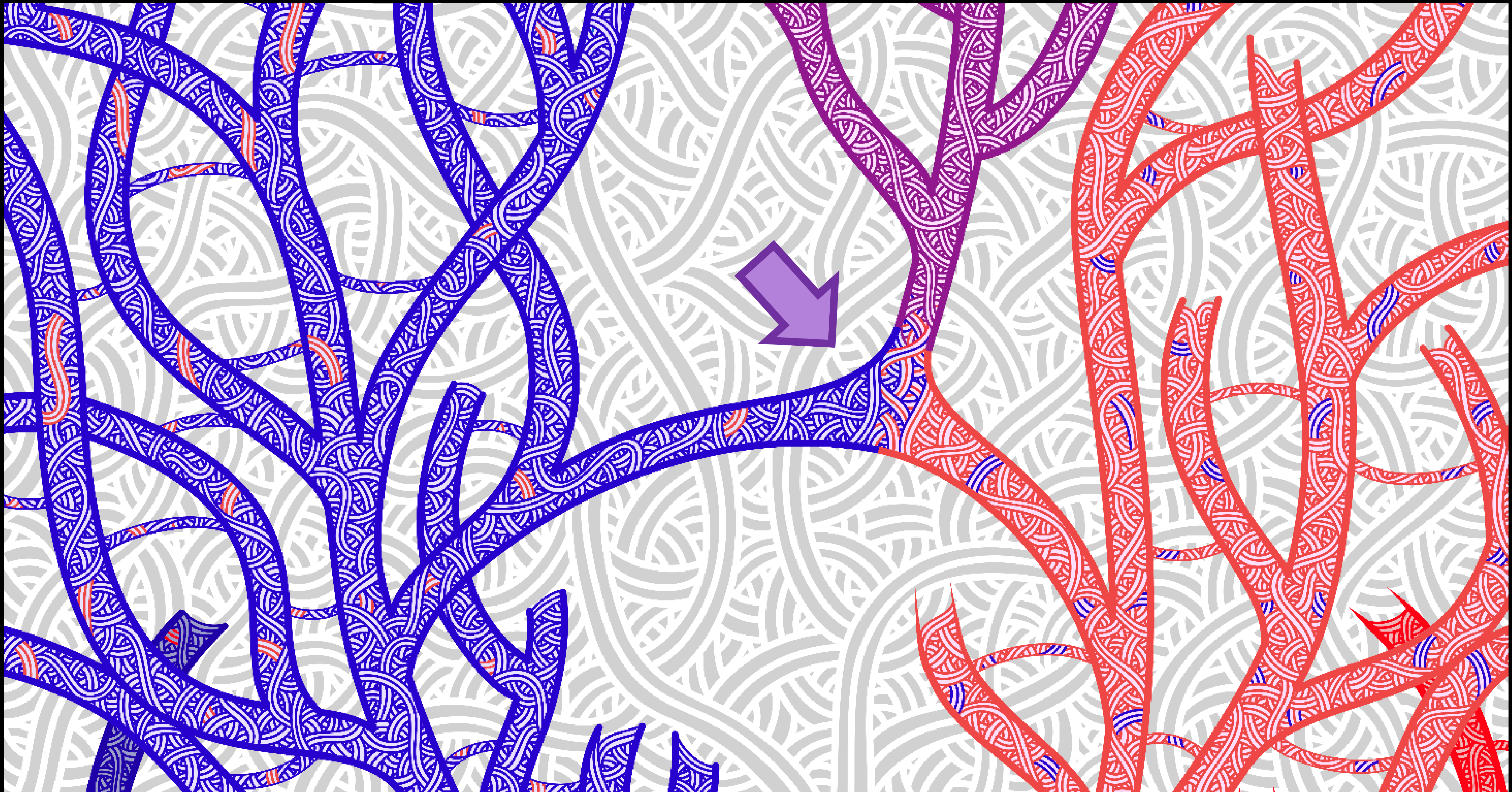


Melissa Patton

Horizontal transfer produces mosaic organisms.

An extreme case : our origins, due to a symbiosis between Bacteria and Archaea that produced a new kind of cells.

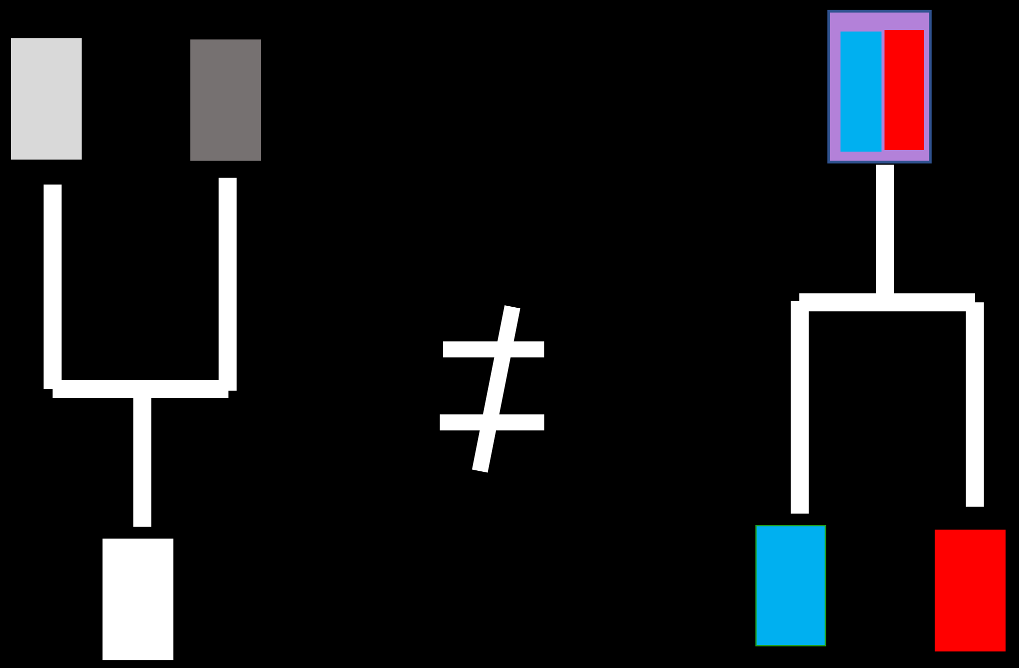
Jordane Saget



This dual origin contrasts with a classic evolutionary scenario.

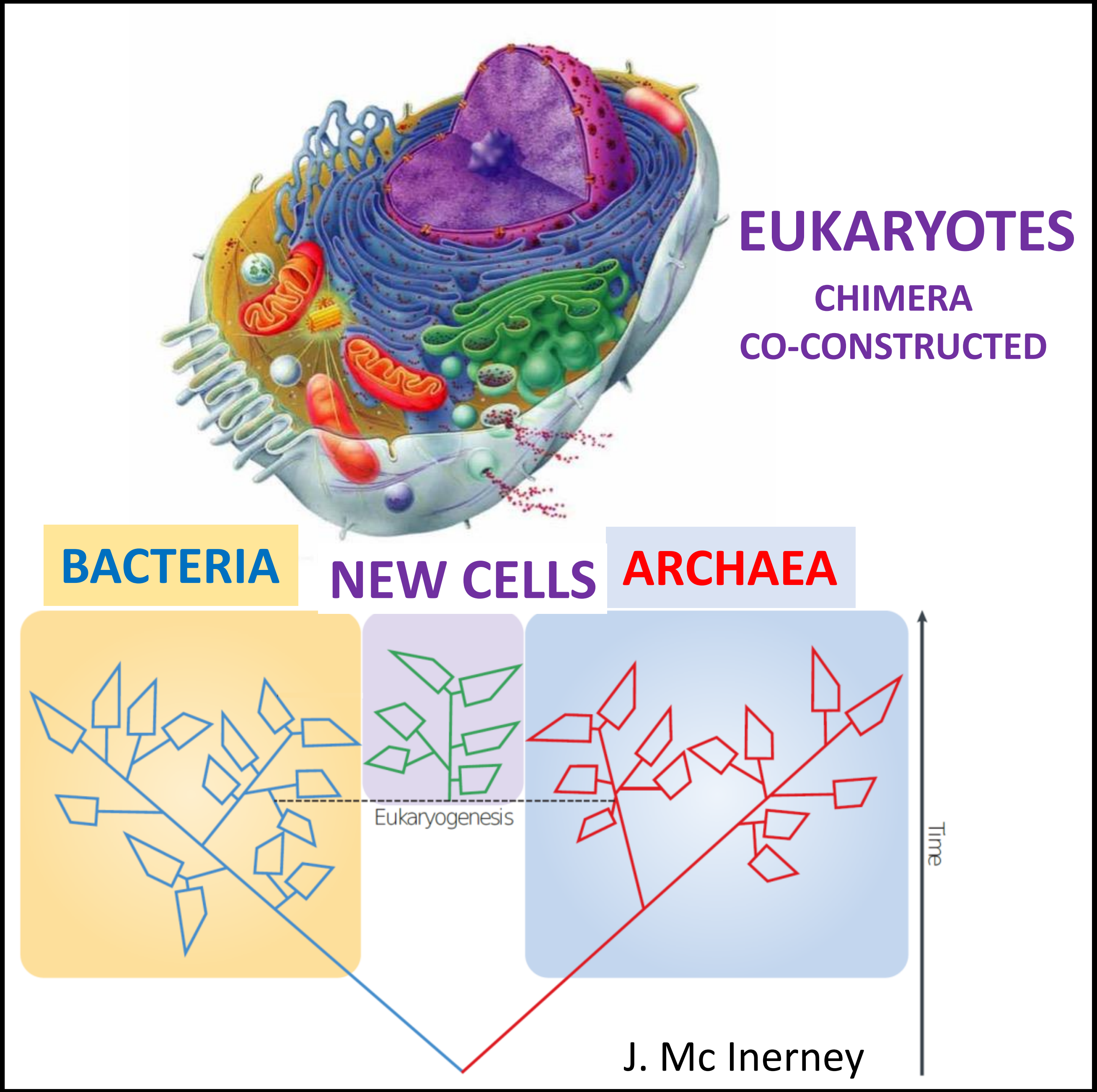
Classic model

New model

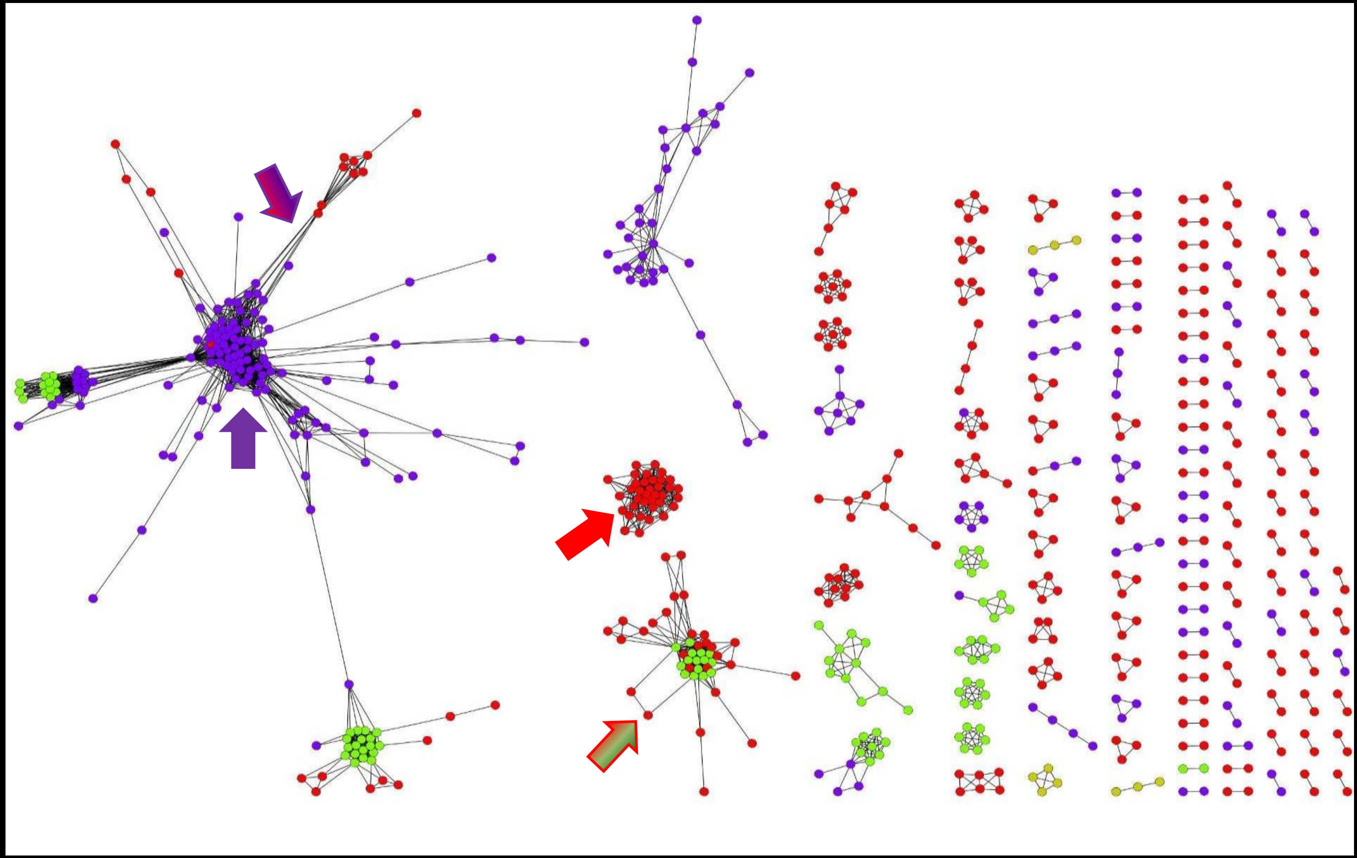


1 ancestor

2 ancestors



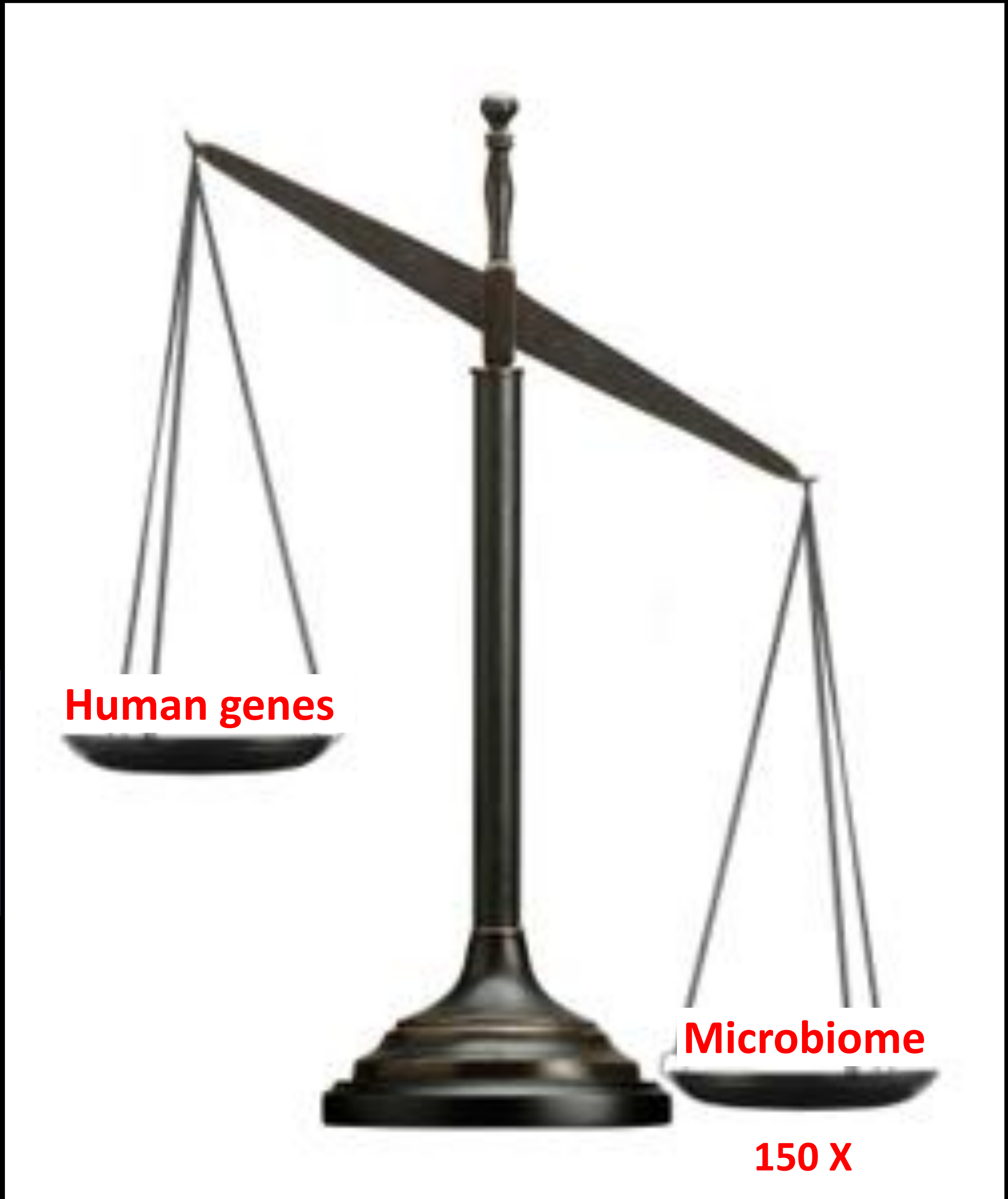
To retrace the multiple origins of such entities requires an expanded formalism.



Halary et al. PNAS 2010

Moreover, our human cells (eukaryotes) do not live alone.

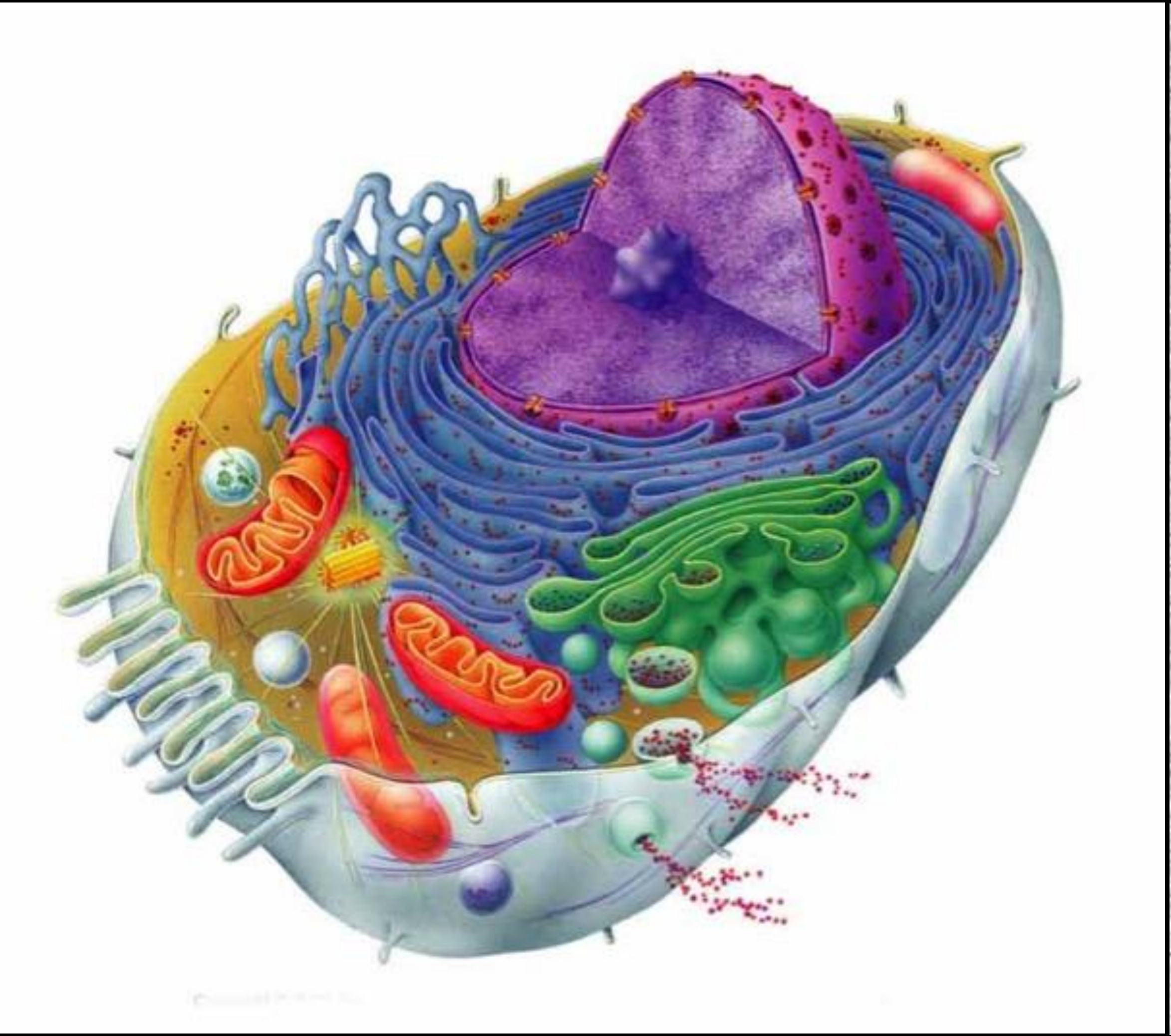
The impact of extant microbes on human biology is thus re-evaluated.

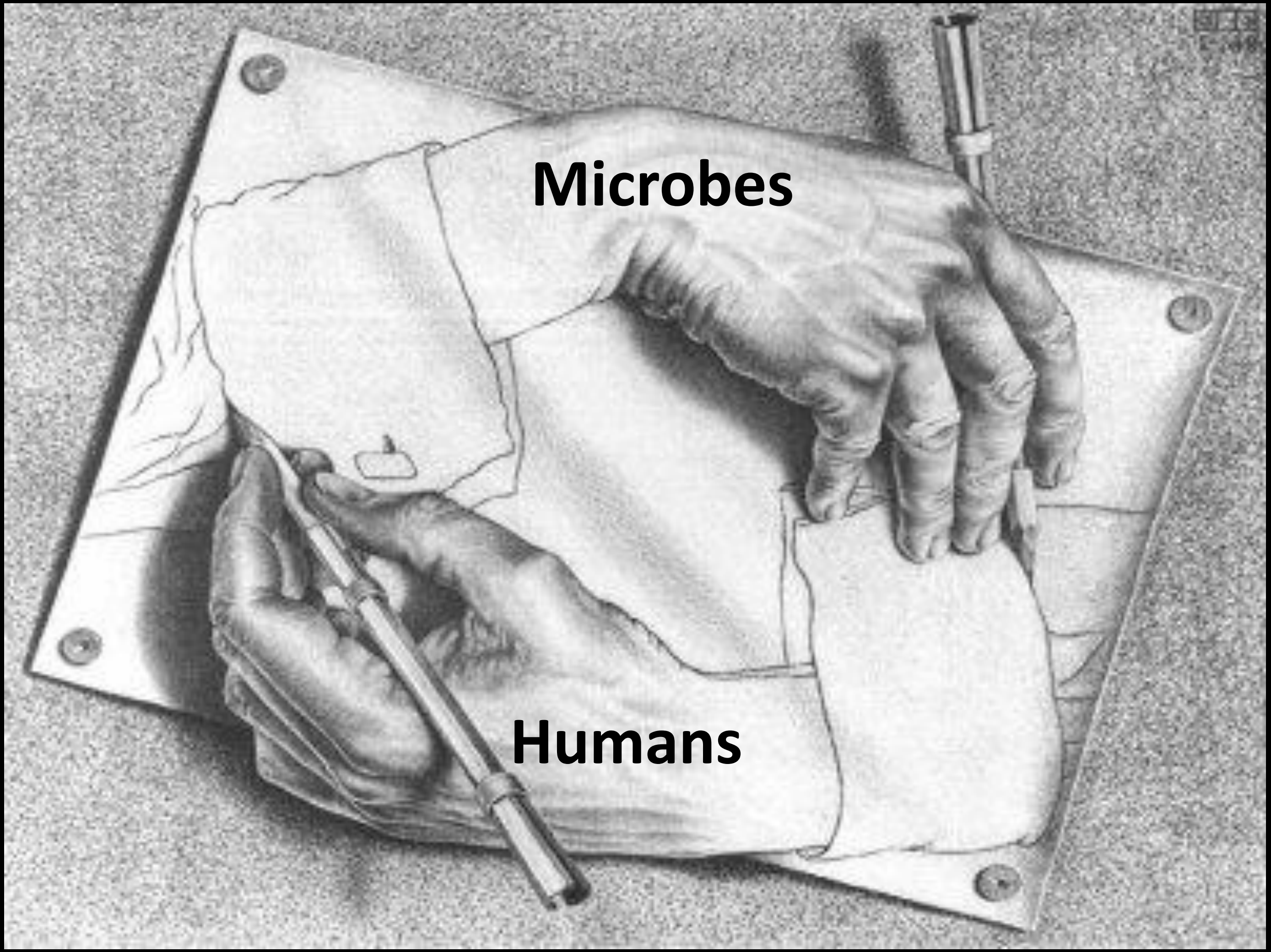


Not only do our microbes interact together, but they also interact with our cells.

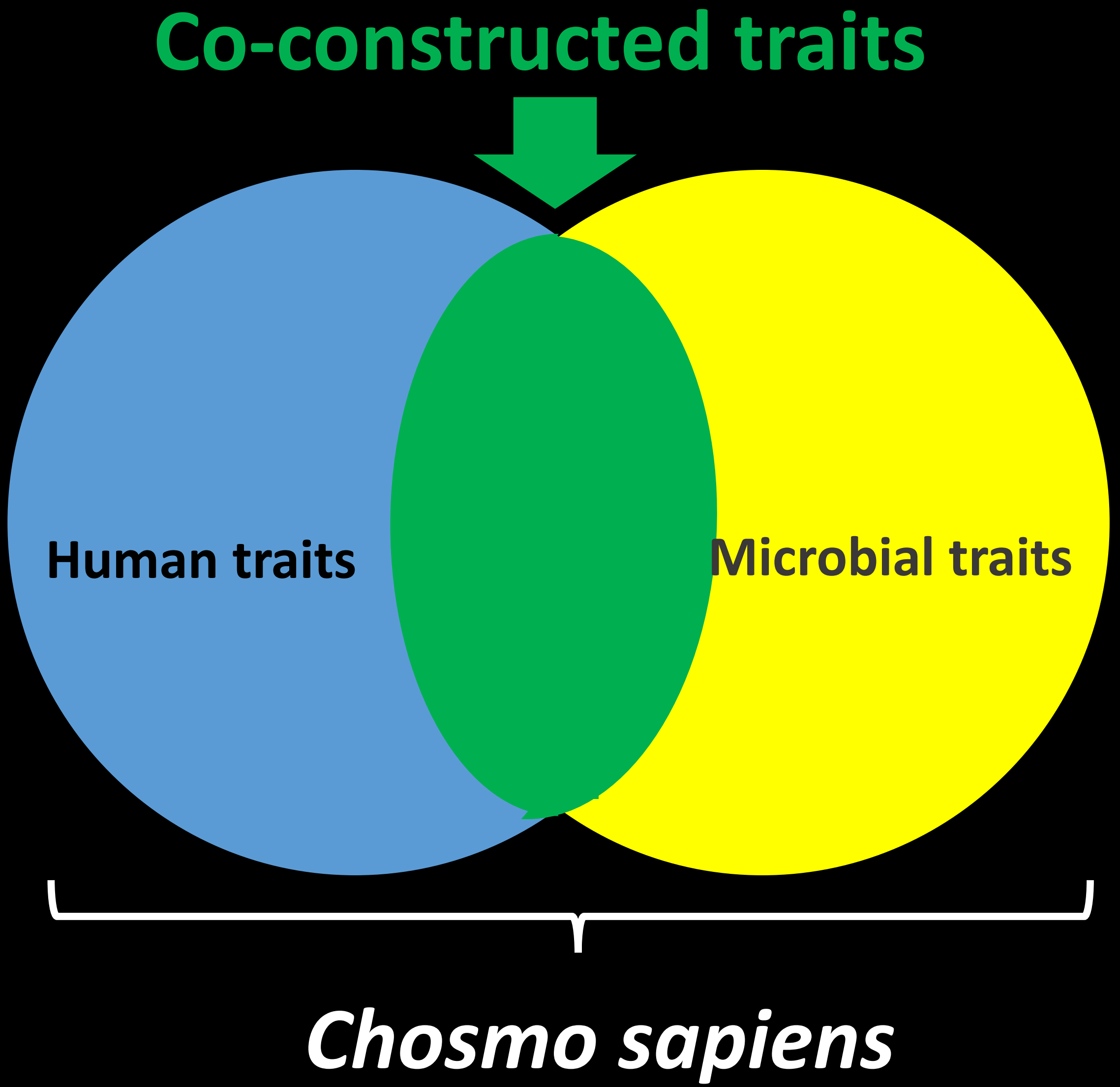
Scott F Gilbert

Microbes have co-constructed our species– and they still do it.

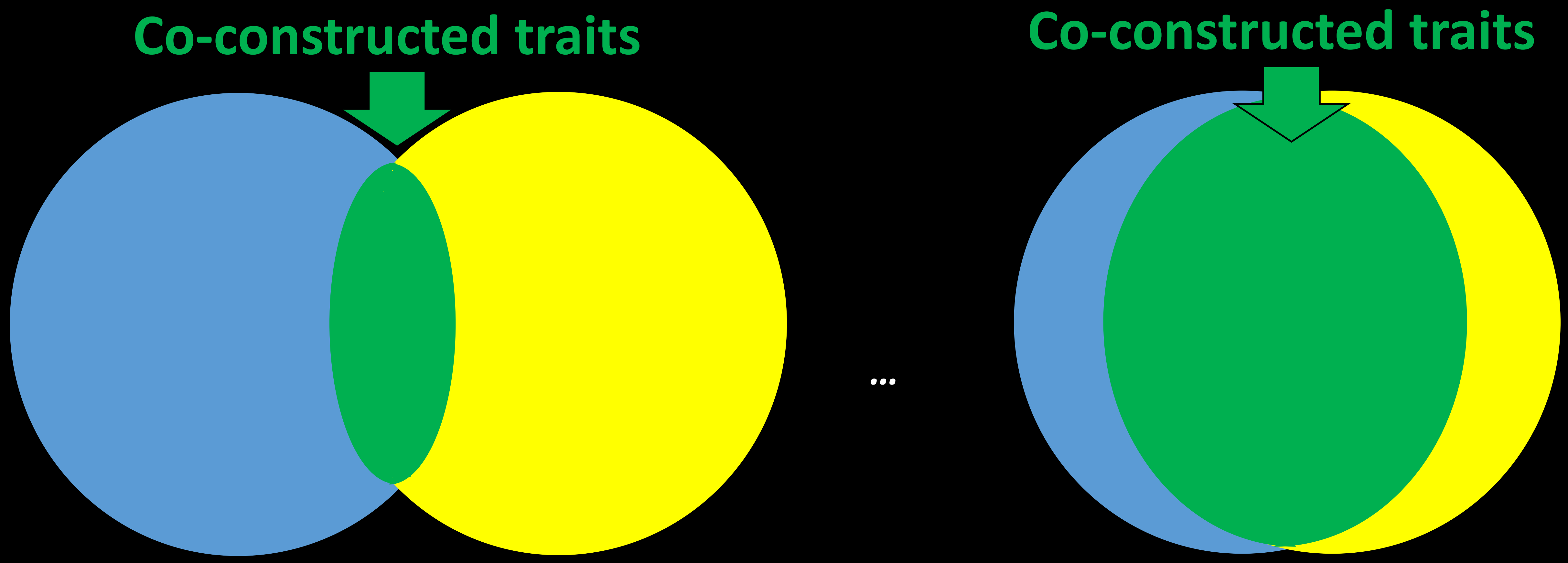




Homo sapiens is discovering *Chosmo sapiens*.



The extent of this co-construction is under study.

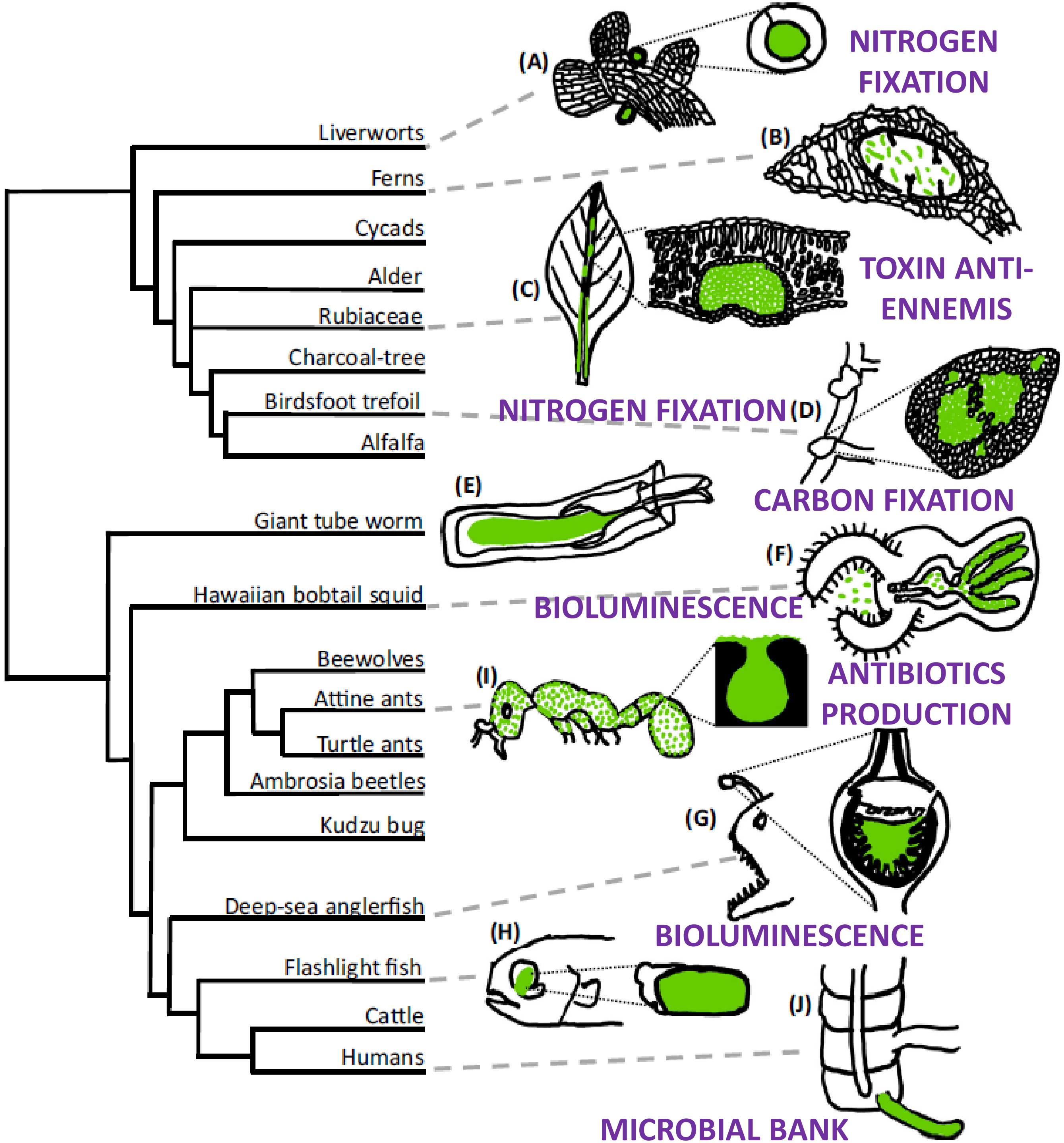


Vascularization, bones, digestion, immunity, obesity, behavior…

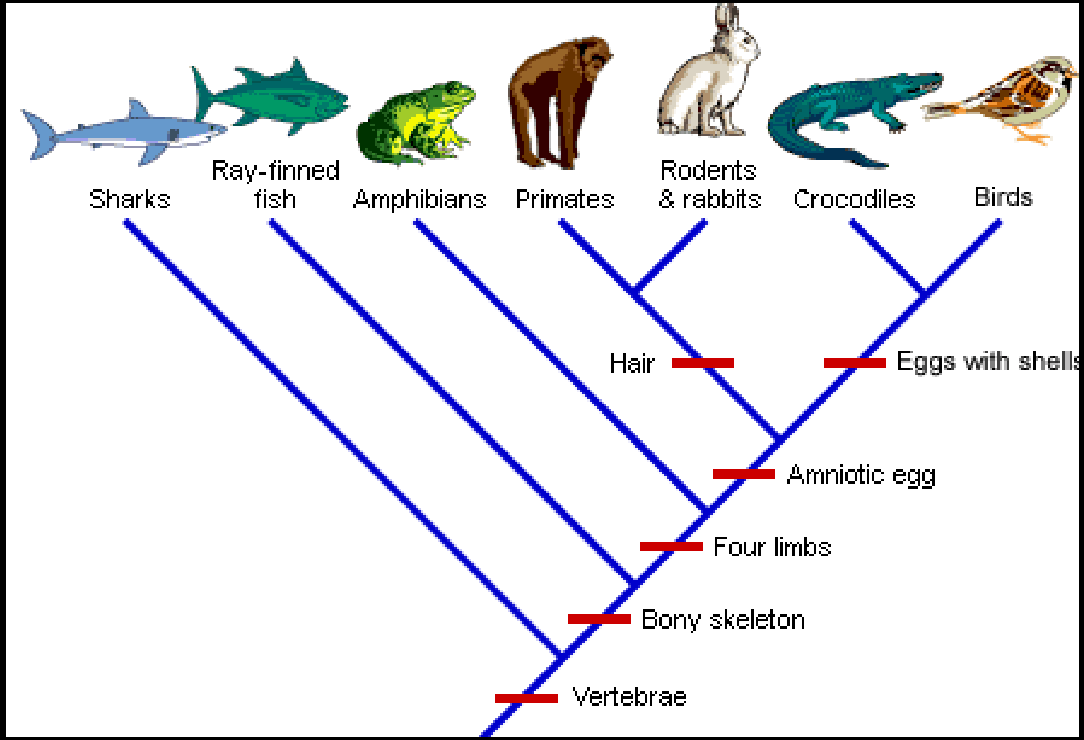
This conclusion holds for very many other species…

Functions of « symbiotic organs» are described in an increasingly large number of animals and plants…

Fronk &.Sachs, Trends in Ecology & Evolution, 2022

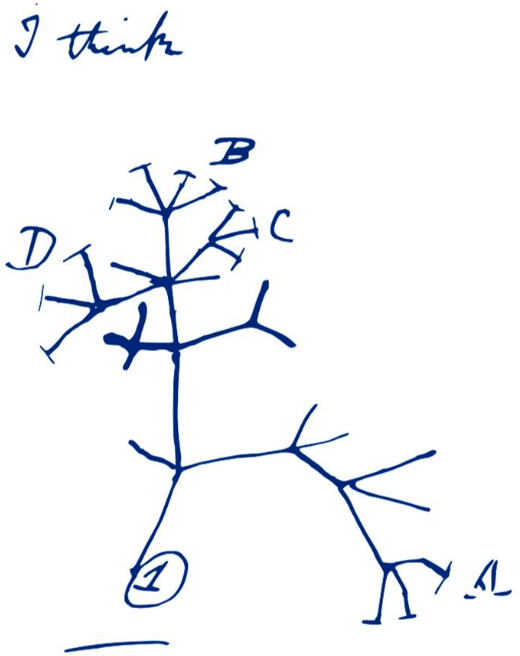


Problem: a classic tree of the mere hosts lineages does not describe the processes responsible for co-constructed traits.



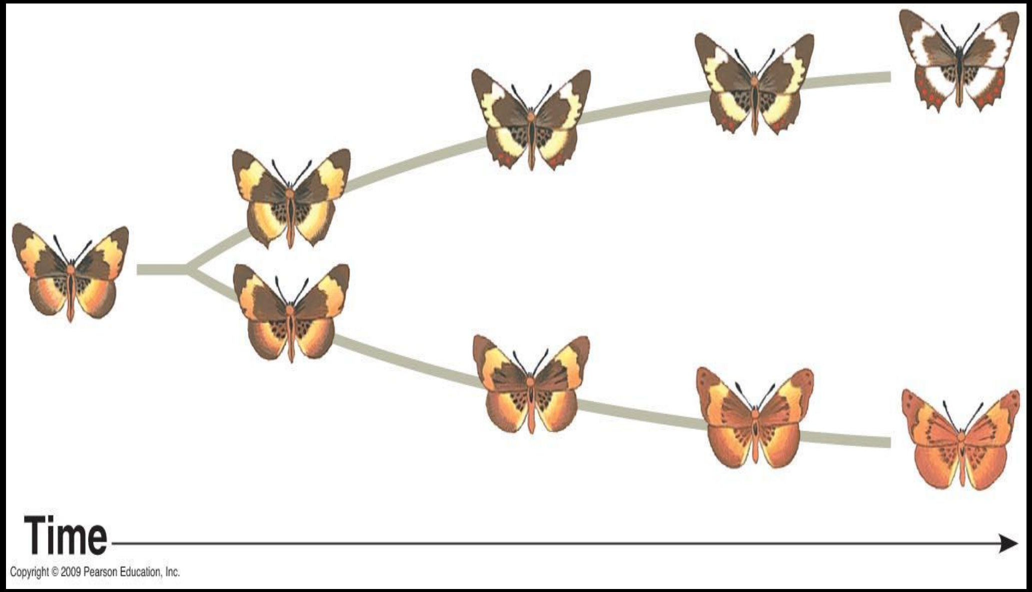
To sum up, evolution has produced complex organisations

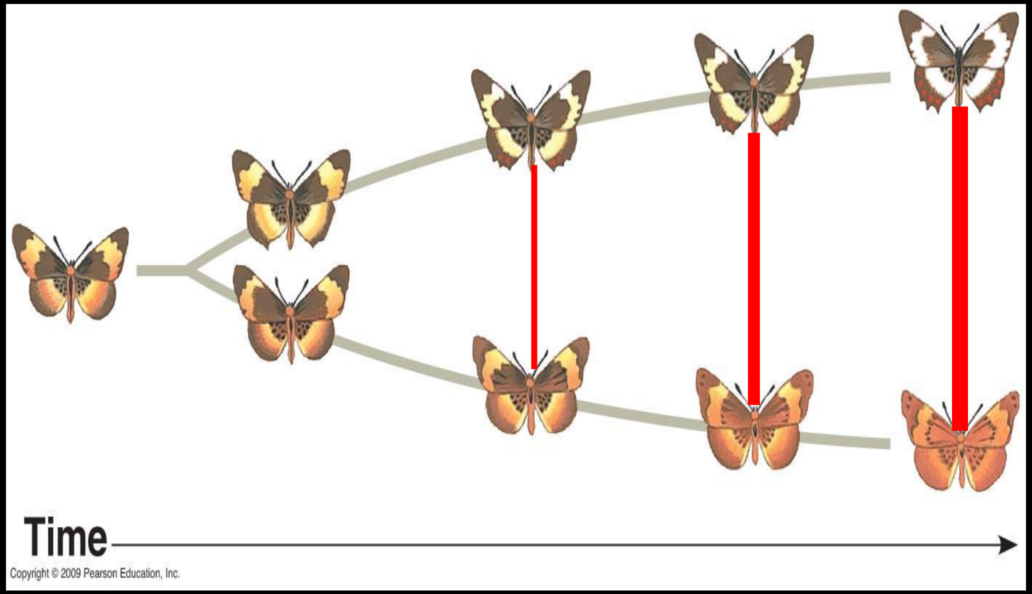
- Multi-agents
- Multi-lineages
- Multi-level
- Nested
- Interconnected



An enhanced evolutionary biology seems warranted.

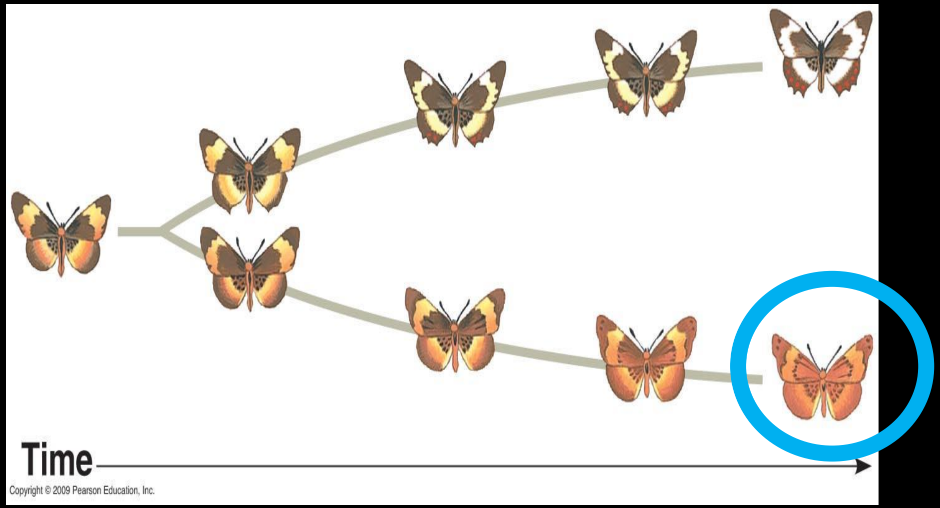
Even the model of evolution by natural selection can be further generalized.





(Doolittle & Inkpen, PNAS 2018)

Even the model of evolution by natural selection can be further generalized.



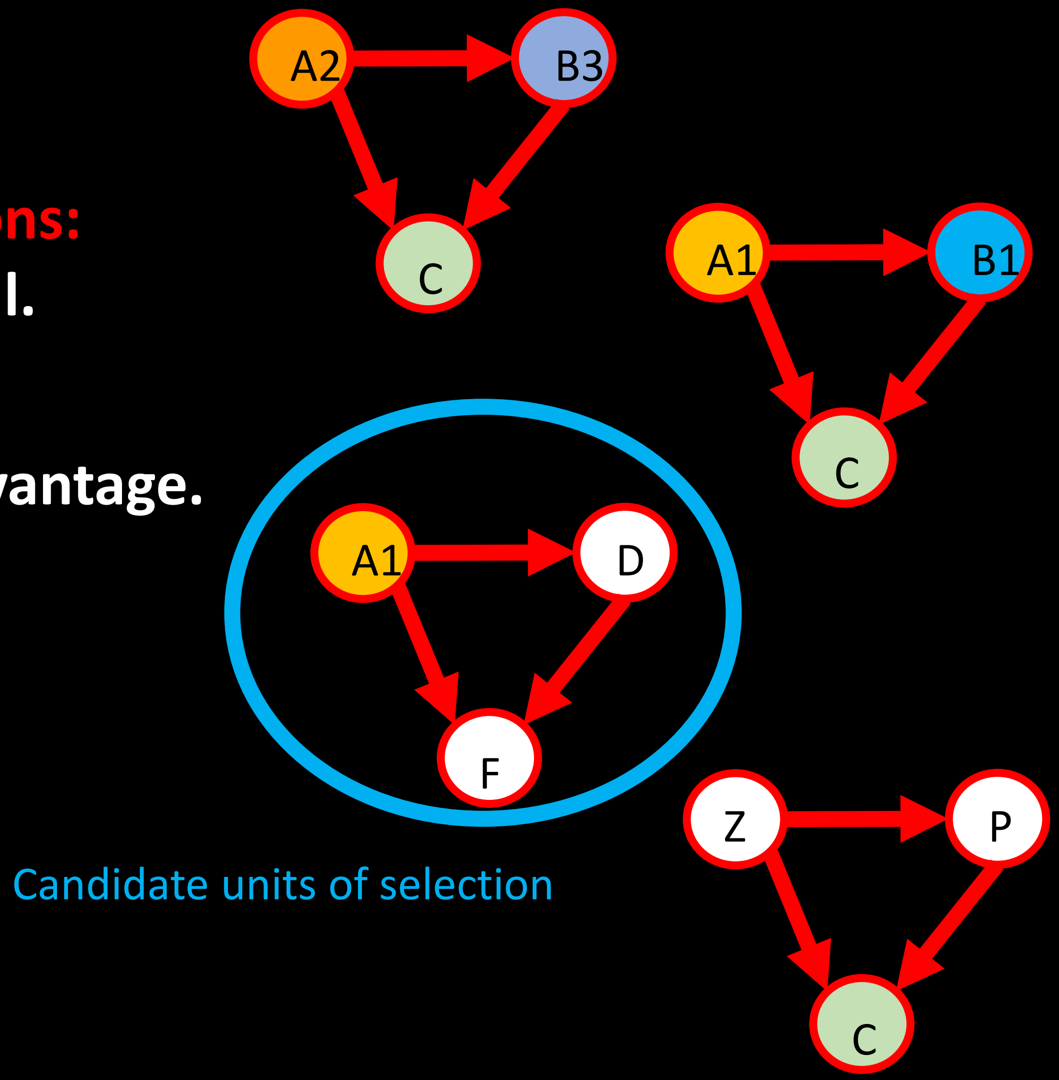
- **Variation:**
not all entities to consider as evolving are identical.

- **Differential fitness:**
different traits can confer survival or reproductive advantage.

- **Inheritance:**
Variation can be, in part, reproduced.

Even the model of evolution by natural selection can be further generalized.

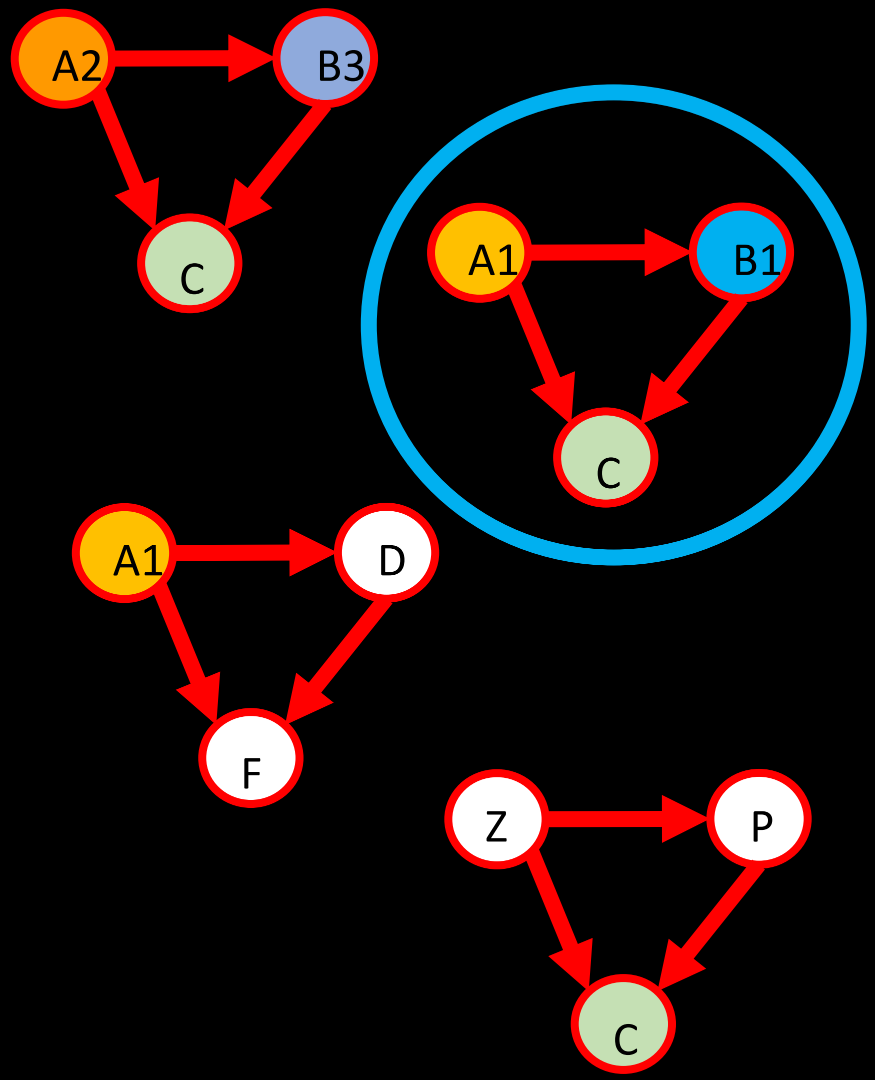
- **There are variation in the population of interactions:**
  not all entities to consider as evolving are identical.
- **Some interactions show differential fitness:**
  different patterns display survival or re-productive advantage.
- **Inheritance:**
  Some interactions can be re-produced



(Doolittle & Inkpen, PNAS 2018)

Some interactions with such properties will have their frequency change; or their robustnesss/resilience change wrt others and therefore may be seen under that more general framework as units of selection.

- **There are variation in the population of interactions:** **not all entities to consider as evolving are identical.**
- **Some interactions show differential fitness:** **different patterns display survival or re-productive advantage.**
- **Inheritance:** **Some interactions can be re-produced**



(Doolittle & Inkpen, PNAS 2018)

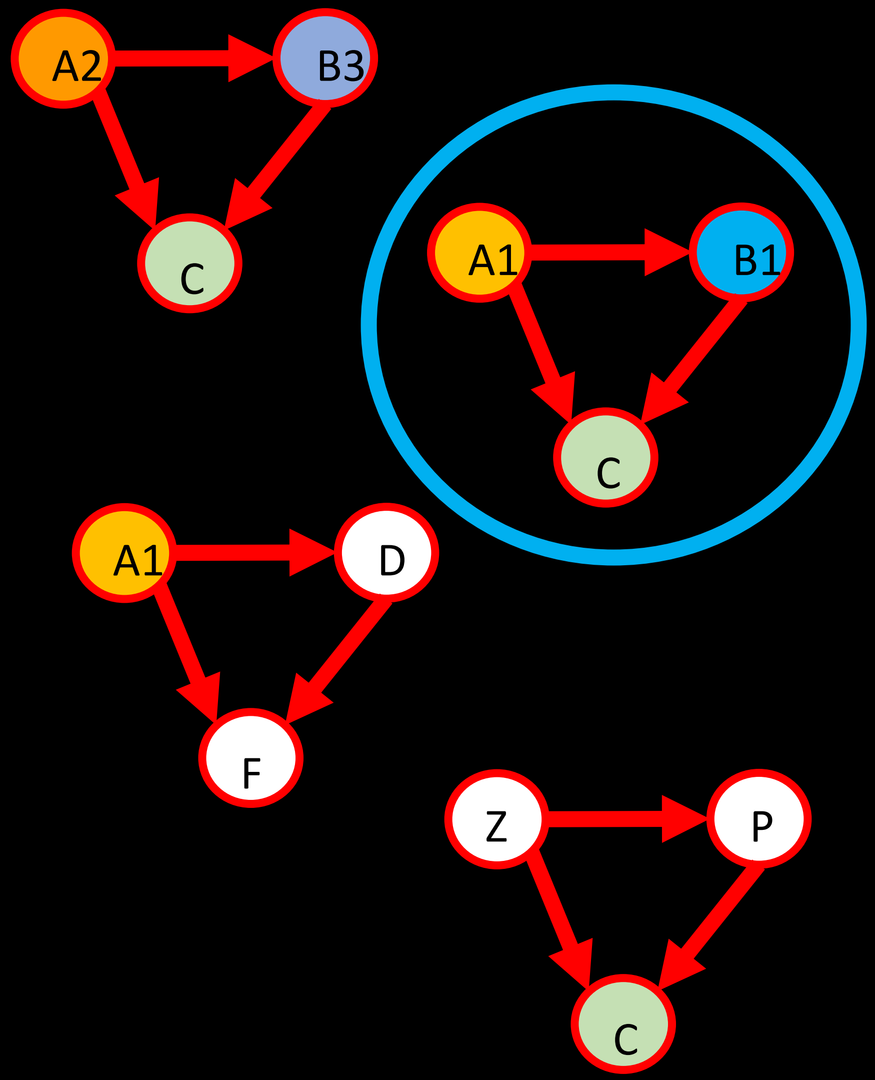
Interestingly, these units of selection **may not correspond to traditional lineages**: they can also form **functional units** that occur again and again or change/evolve.

- **There are variation in the population of interactions:**
not all entities to consider as evolving are identical.

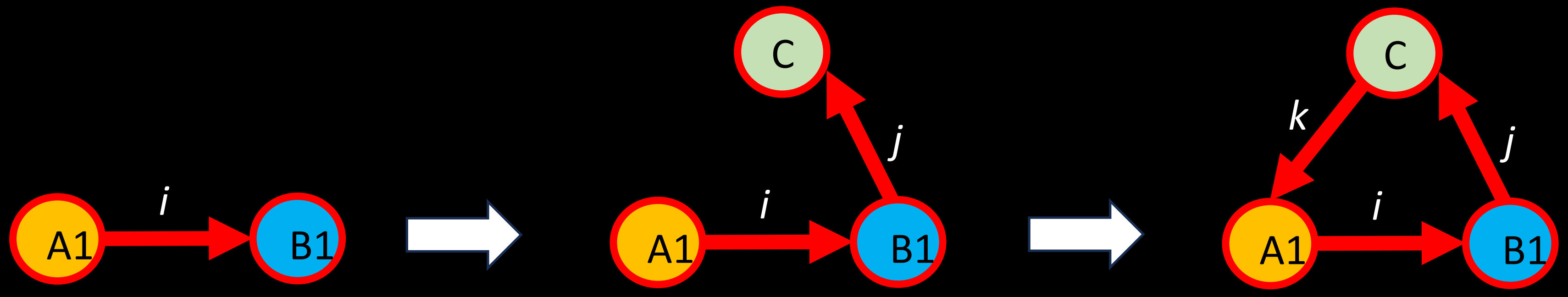
- **Some interactions show differential fitness:**
different patterns display survival or reproductive advantage.

- **Inheritance:**
Some interactions can be re-produced

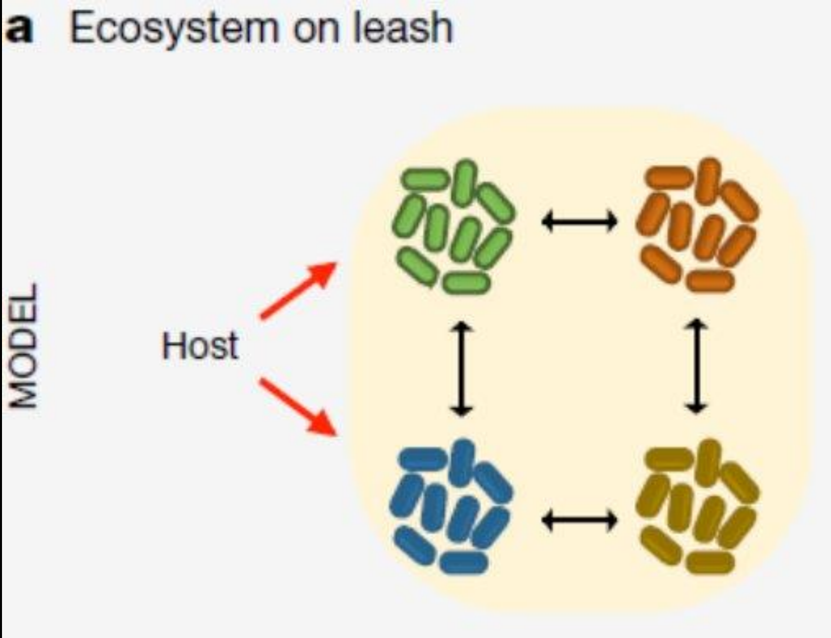
(Doolittle & Inkpen, PNAS 2018)



The bottom line is that
« partners mutate, interaction pattern change and dependencies/interdependencies can evolve».

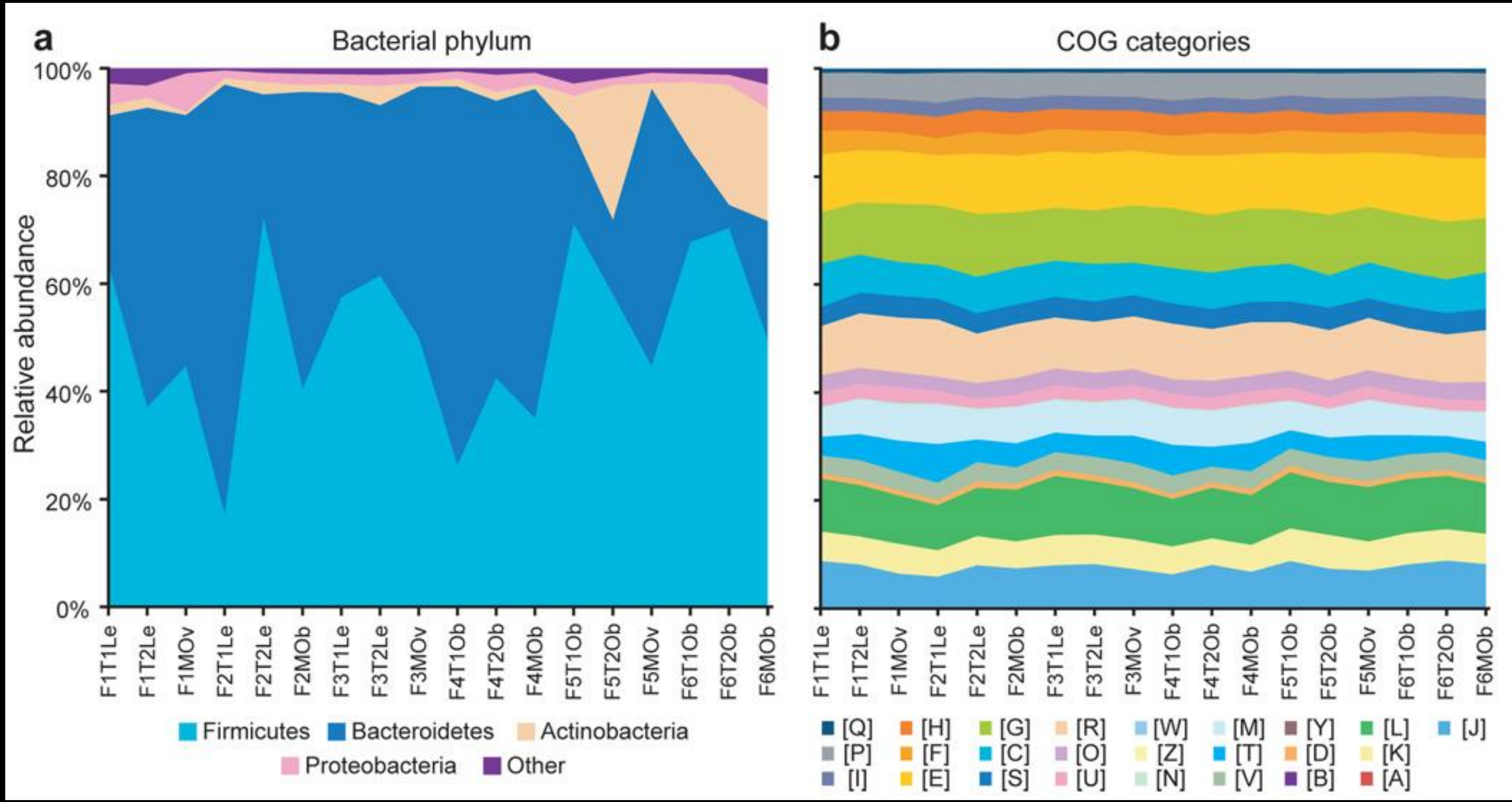


This situation typically occurs within host-associated microbiomes.



Foster *et al.* Nature 2017

Mammalian gut



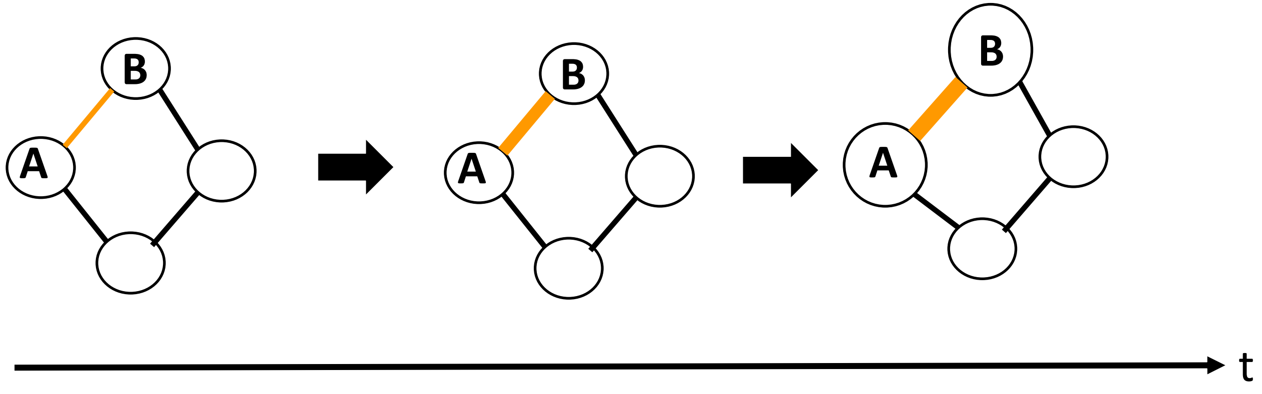
Turnbaugh *et al.* Nature 2009; Dinsdale et al. Nature, 2008; Doolittle & Zhaxybayeva, Bioscience, 2010 ; Yachi & Loreau, PNAS 1999

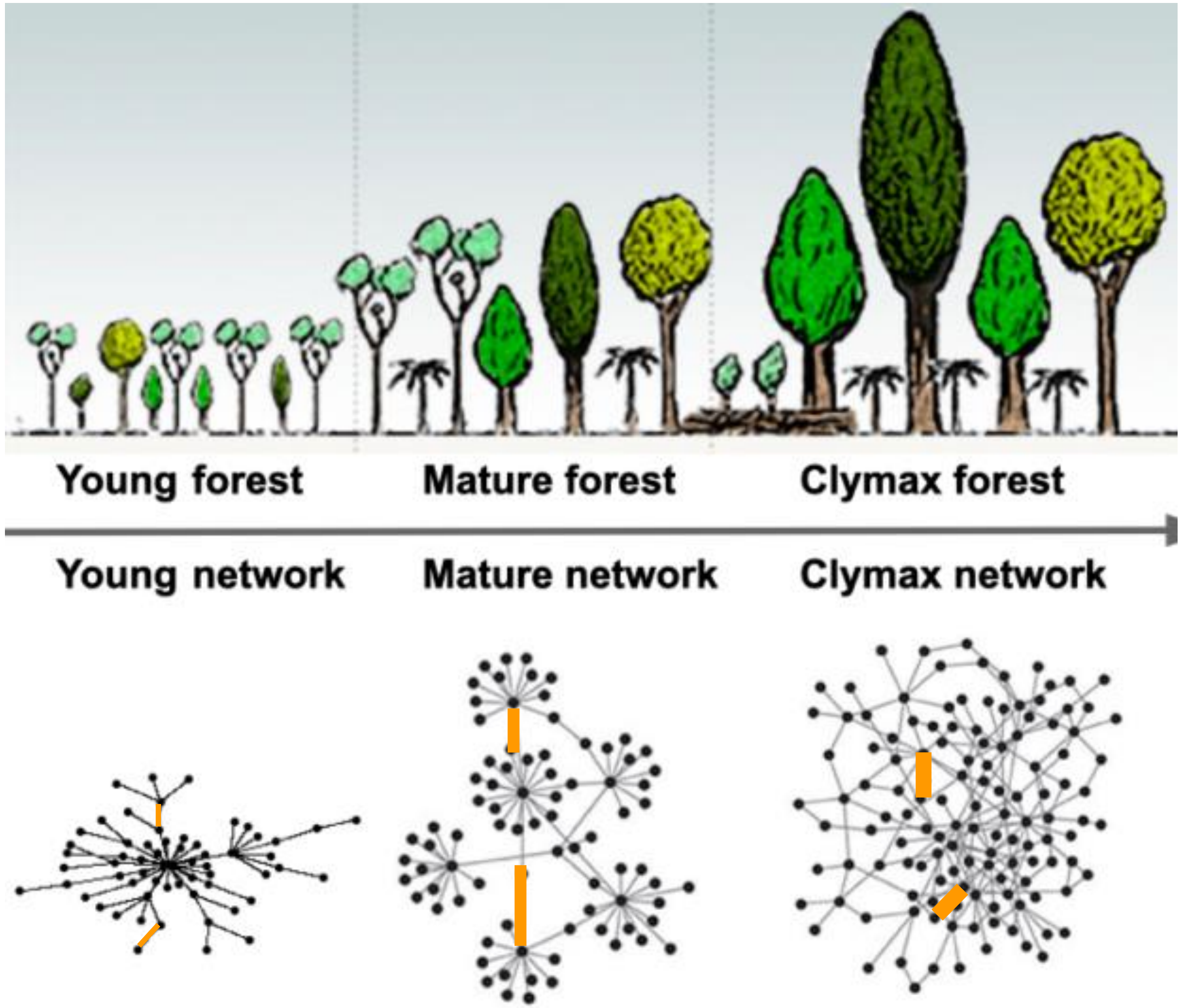
Interactions can get selected and evolve. This departs from a classic organismal-centered perspective on evolution.

More generally, it can be used to investigate the evolution of processes sustaining Life.

Explaining the evolution of organisations, typically that of ecosystems, is a broader issue than infering relatedness between species.

Network comparisons could highlight interactions that may be under some form of selection*

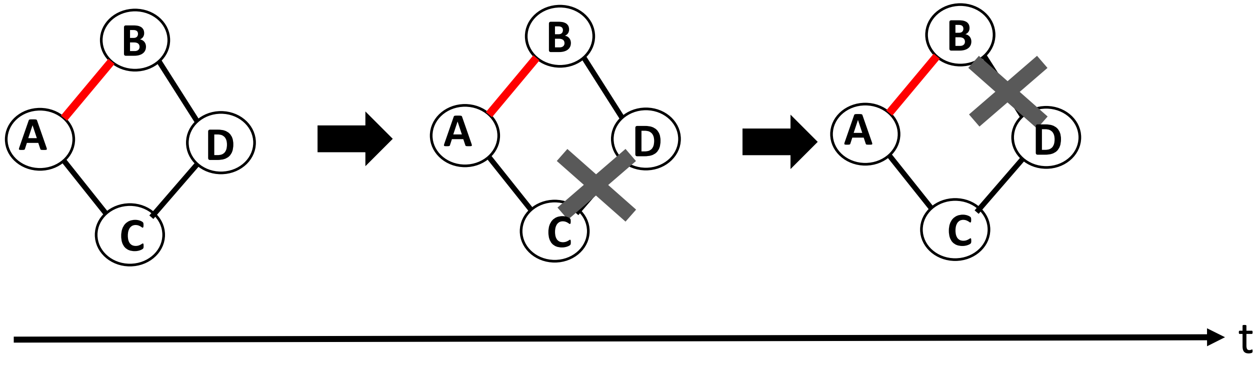


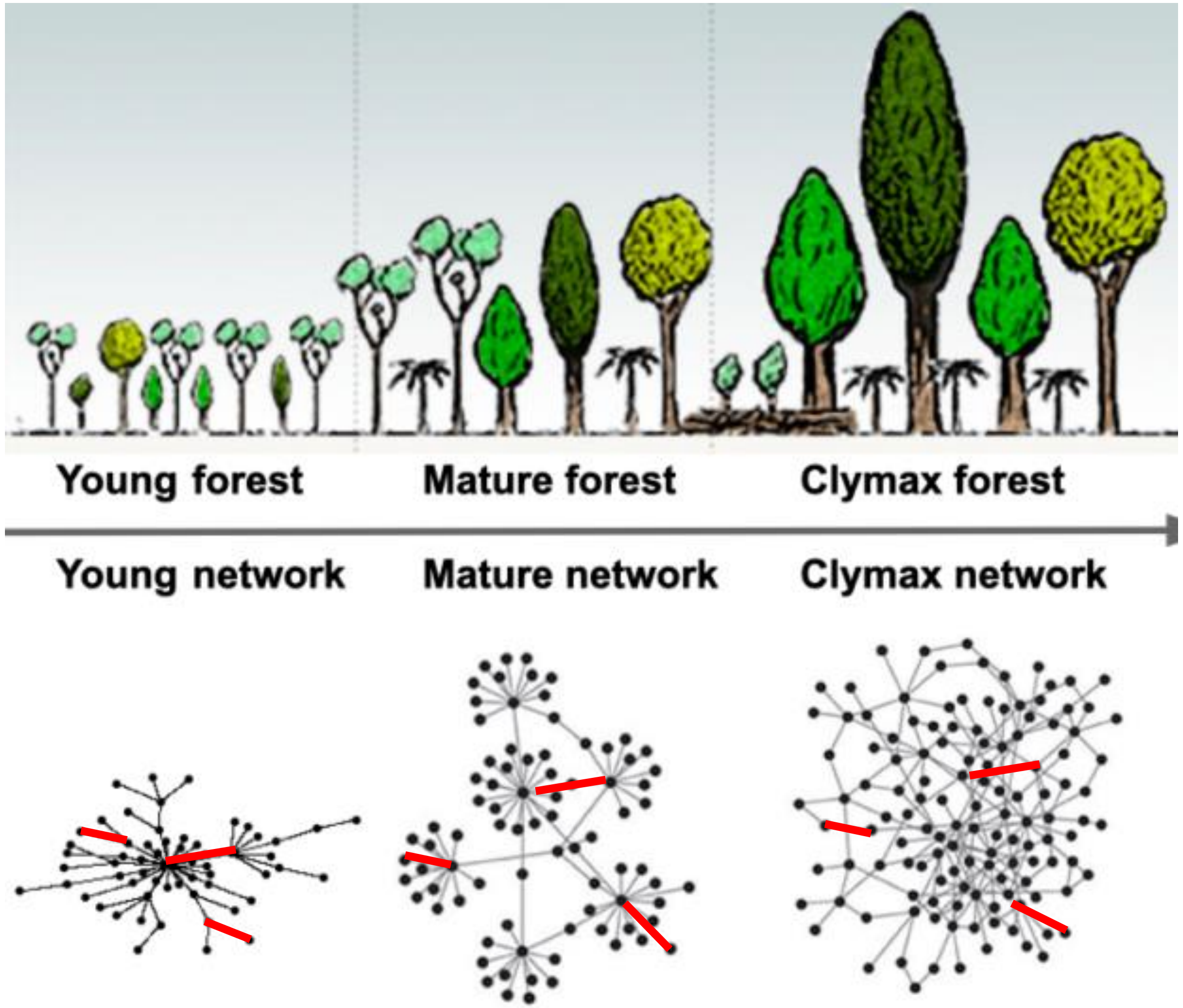


* e.g., increase in strength and relative abundance in the system

Network comparison could unravel interactions with critical structural roles, possibly as a result of selection.

One could check if some interactions within a system appears **robust**



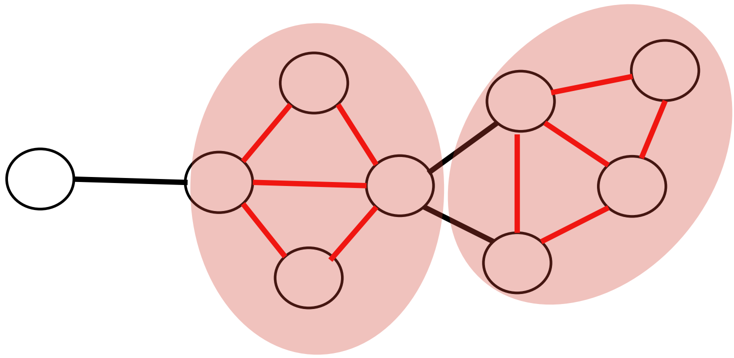


* e.g., occur at consecutive time points – and for how long

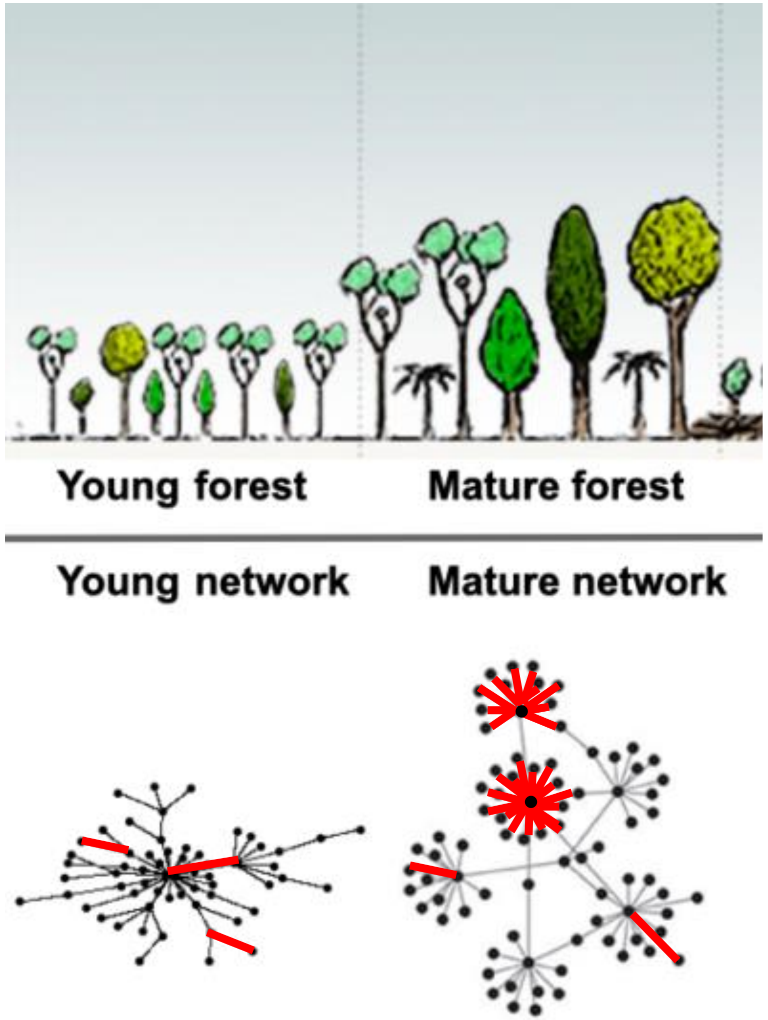
Network analyses could report architectures that may be the result of selection.

One could check if if a system displays **modules of robust* interactions**

Network at t

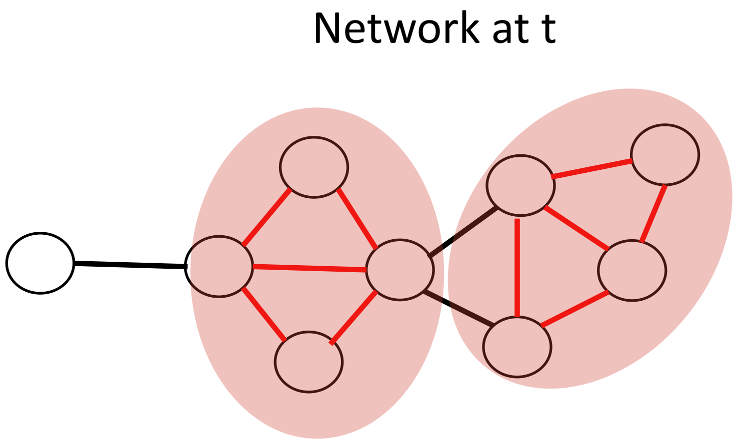


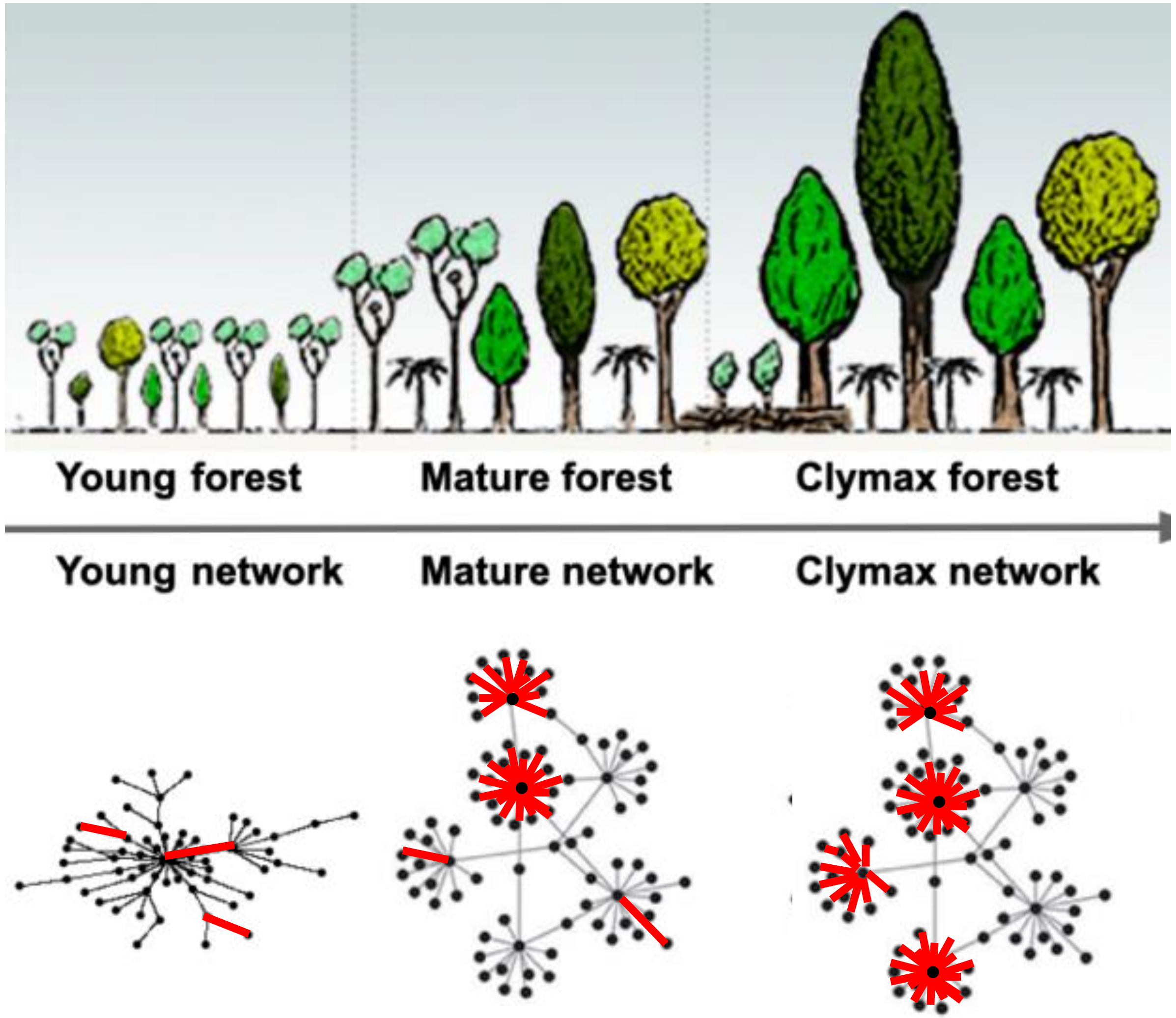
* e.g., tight clusters of robust edges



Network analyses could show whether and how the persistence – hence the fitness- of an ecosystem changes.

One could check if if a system **robustness and its modularity* increases**

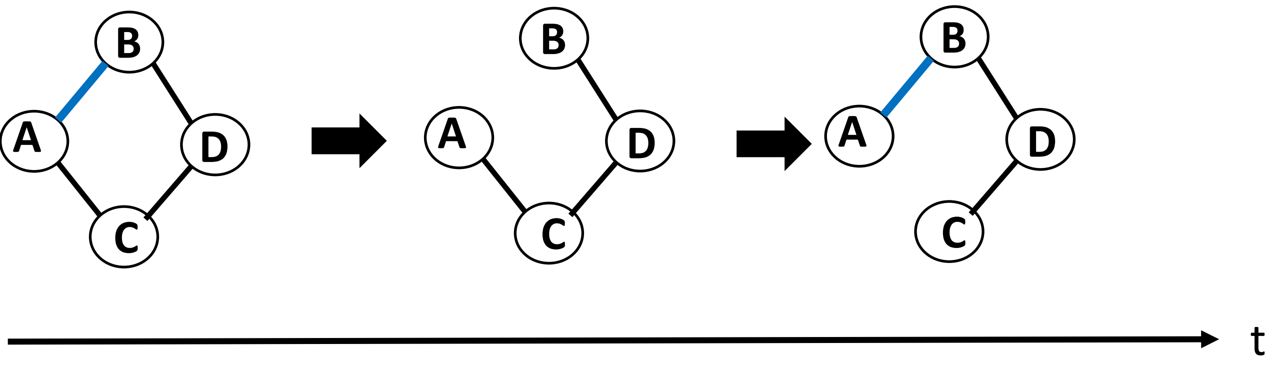


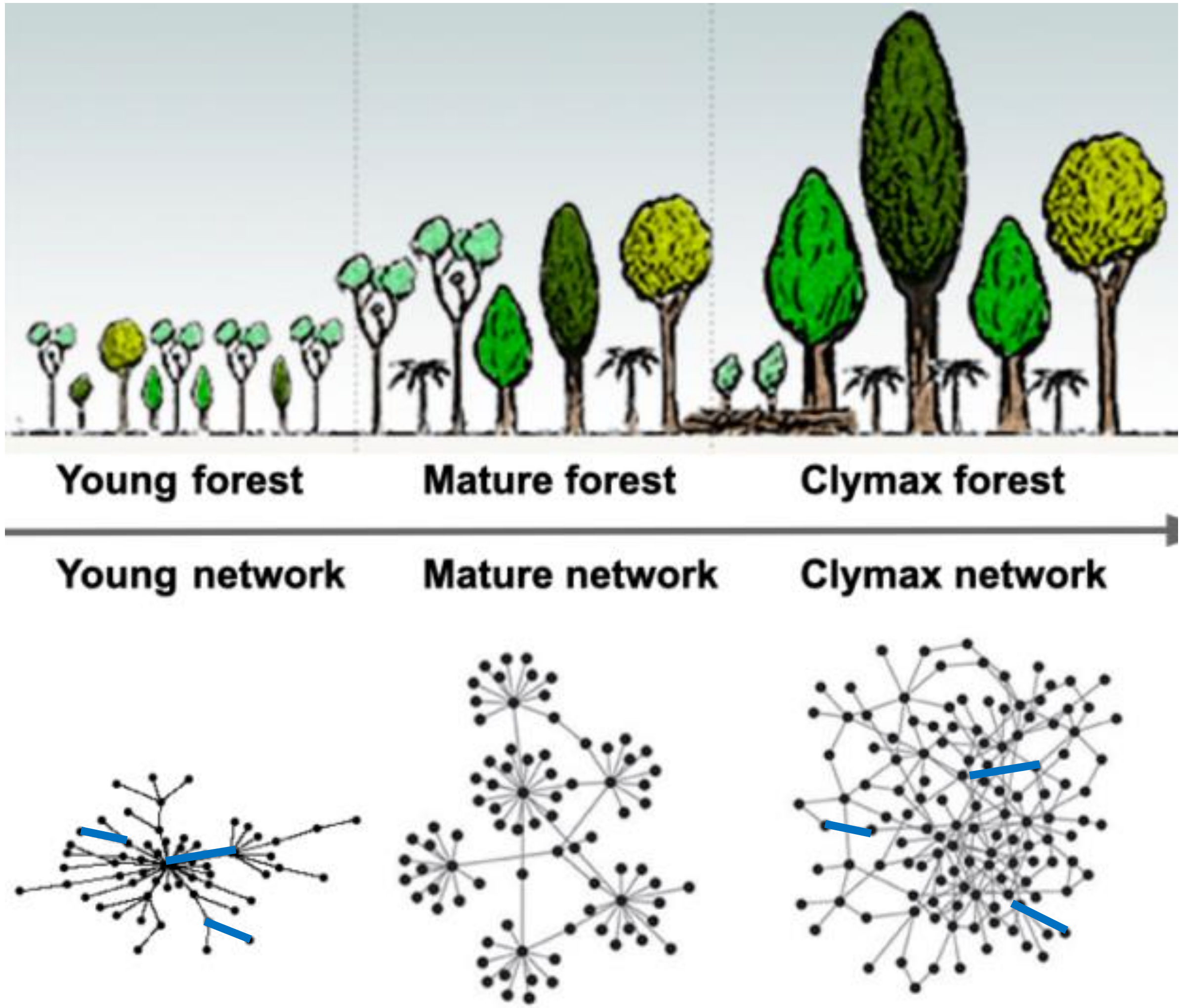


* e.g., tight clusters of robust edges

Network comparison could unravel interactions with critical structural roles, possibly as a result of selection.

One could check if some interactions within a system appears **resilient***

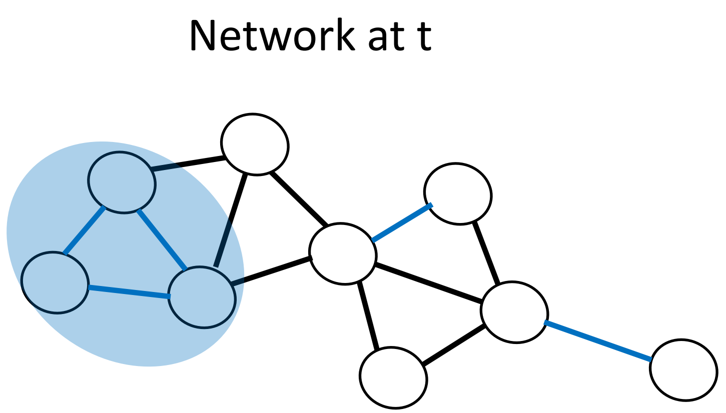


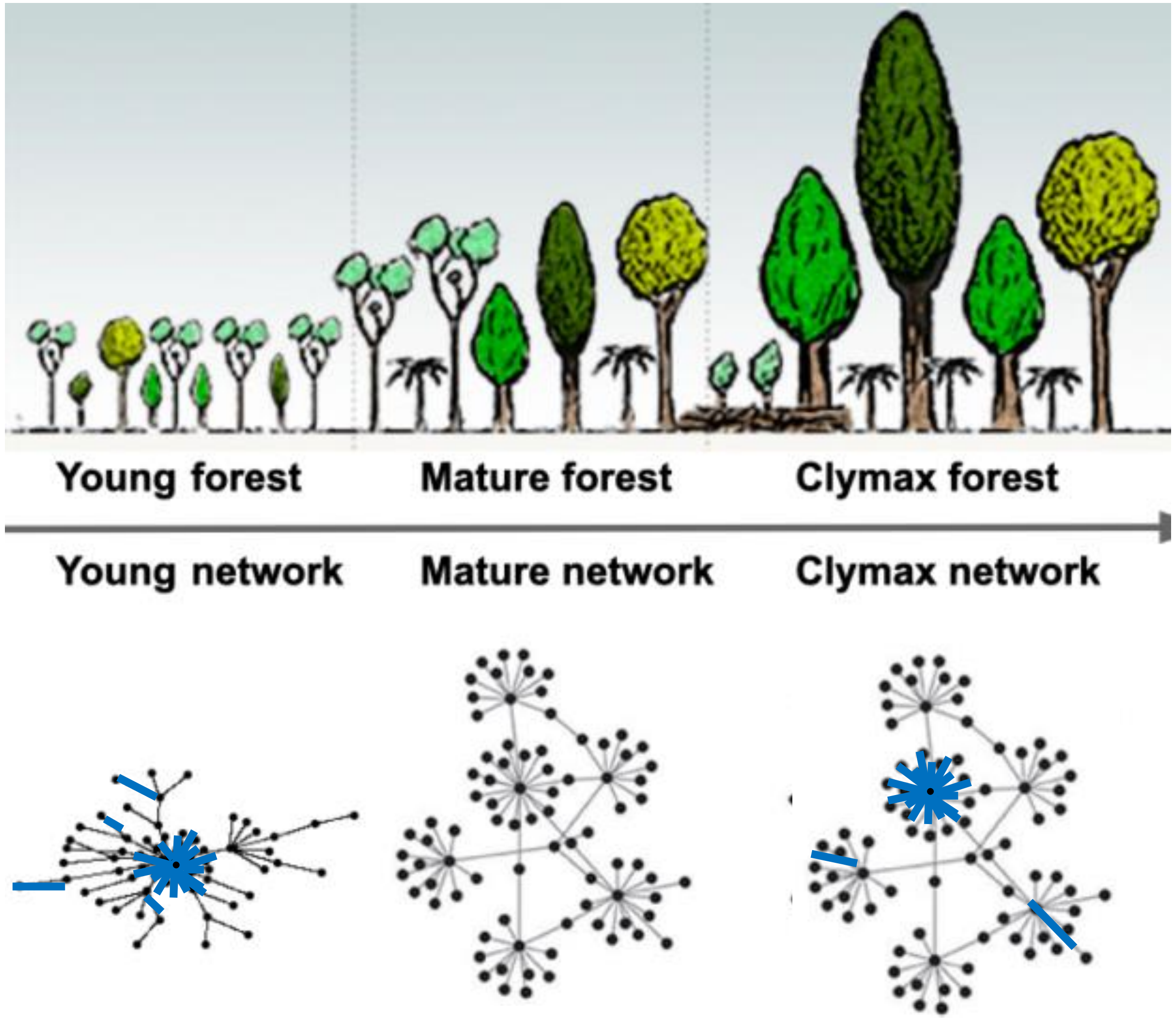


* e.g., occur at disjoint time points – and for how long

Network analyses could report architectures that may be the result of selection.

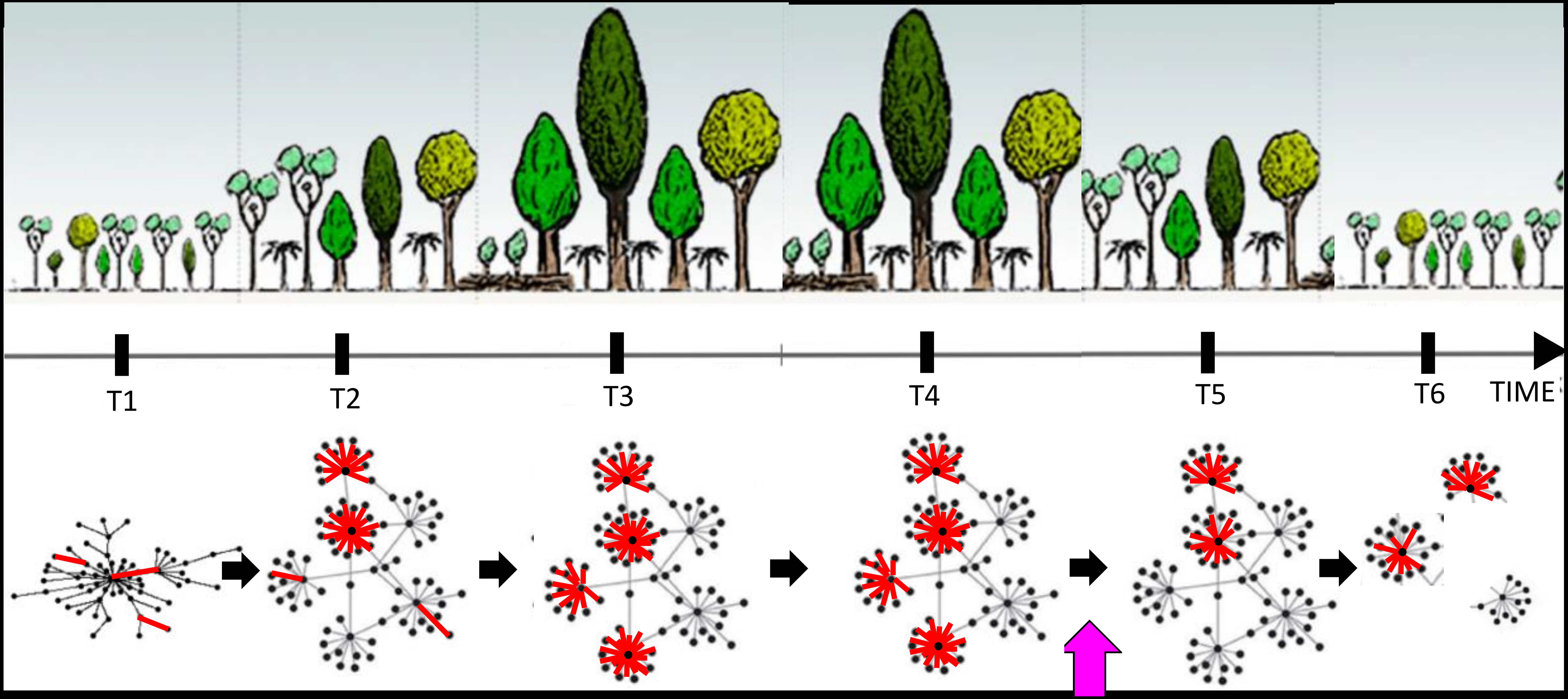
One could check if if a system increasingly displays **modules of resilient* interactions.**





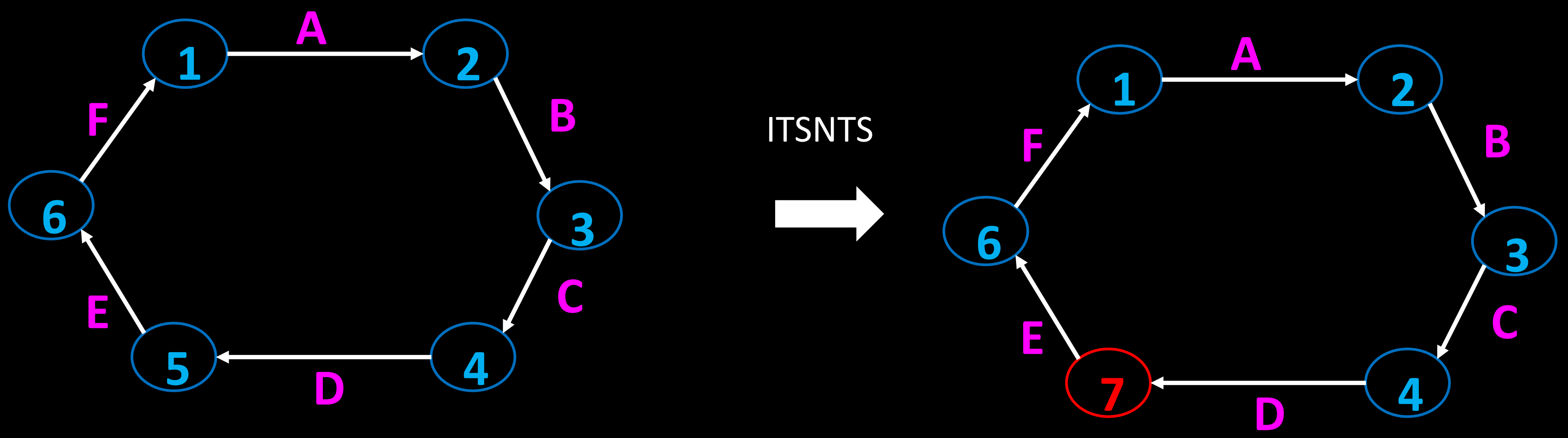
* e.g., tight clusters of resilient edges

If network analyses show whether and how the persistence – hence the fitness- of an ecosystem changes, then simple metrics may capture tipping points in the evolution of these ecosystems.



e.g. experiencing phase transition due to time or some human action….

« It is the song, not the singers » (Doolittle & Inkpen, PNAS 2018)



Original song: ABCDEF
Original singers: 1,2,3,4,5,6

Re-produced song ABCDEF
Different singers: 1,2,3,4,7,6

➡ Interaction patterns as new objects of study for evolutionary biology

Modeling interaction networks opens up new research avenues for evolutionary biology.

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PROBLEMS & PARADIGMS

Prospects & Overviews

Modeling the evolution of interconnected processes: It is the song and the singers

Tracking units of selection with interaction networks

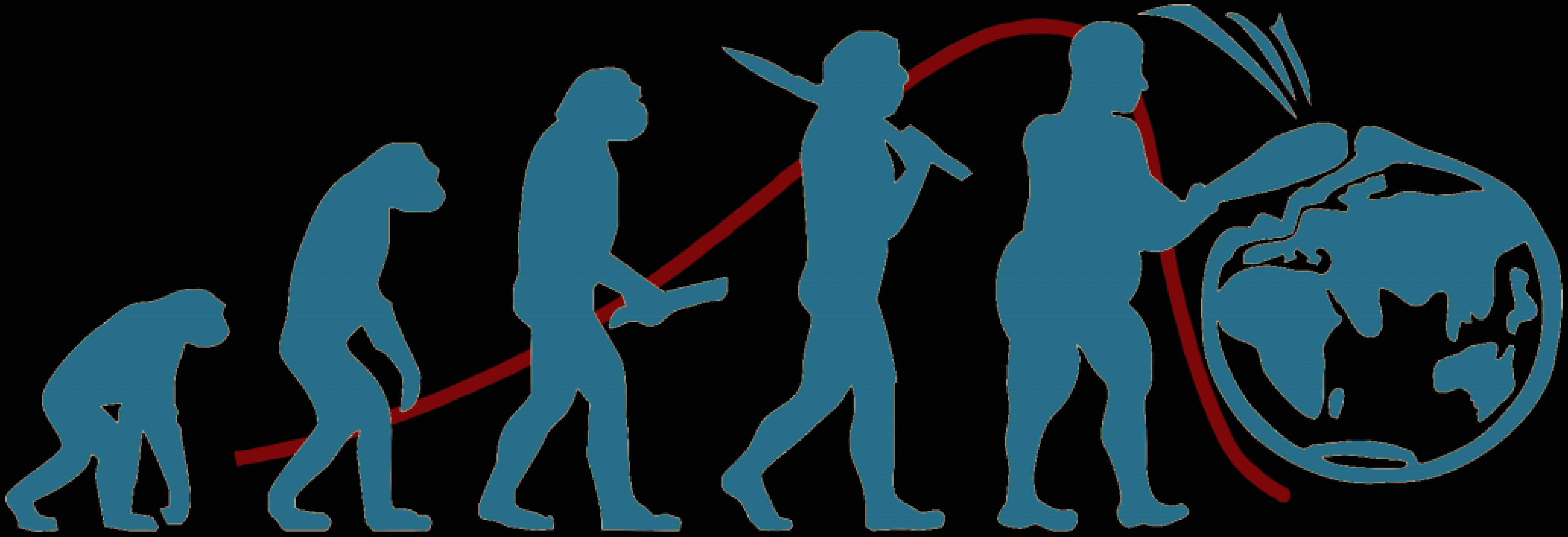
Eric Bapteste[1] | François Papale[2]

Conclusion

- Classic model do not focus interactions and on the evolution of interactions

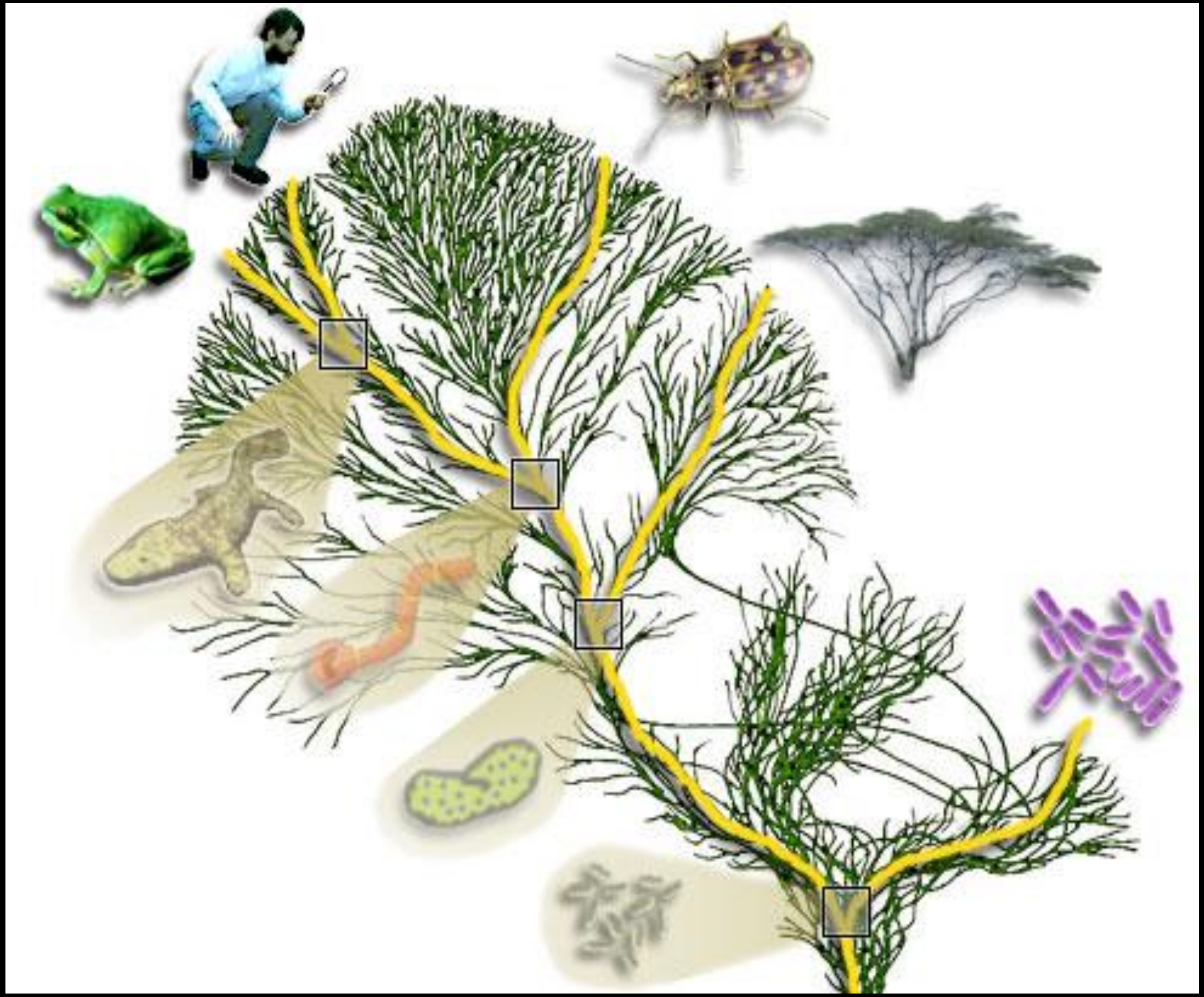
- A more inclusive framework could be useful to better understand the stability of the living world while accounting for dependences/interdependences.

- Enhanced evolutionary biology studies could contribute to this at multiple scales.

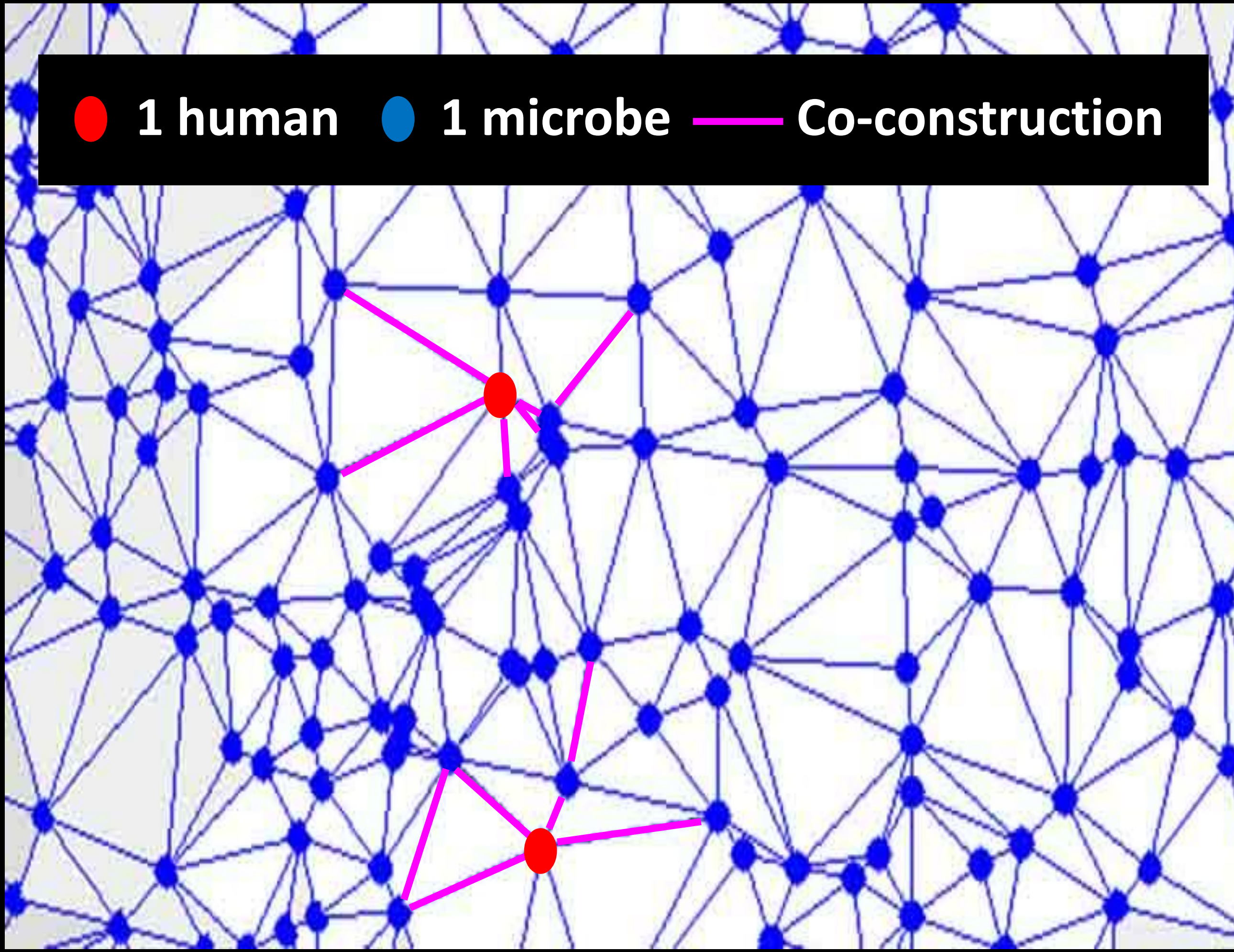


Evolutionary biology may also have something to say about the future history and diversity of life.

So, we could adopt 2 different evolutionary perspectives : Trees focus on relatedness, networks on organization.



Microbes: **too distants** to really matter



Some microbes: **very close** and important

What **aspects of our biology are** co-constructed, or worse **manipulated by interspecific interactions,** that we should not ignore for our own good?

Component of a network, our future shall look like our past.

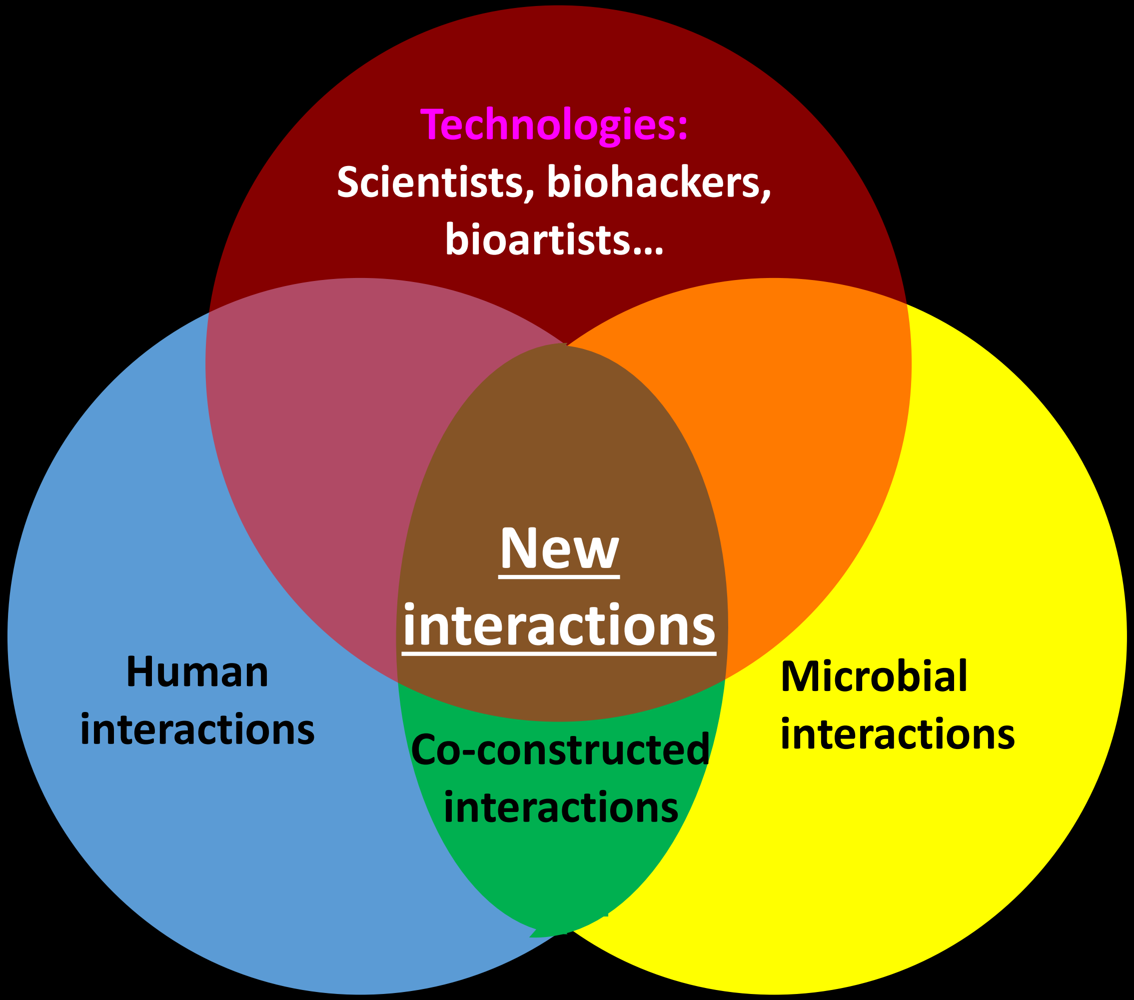
Contingent

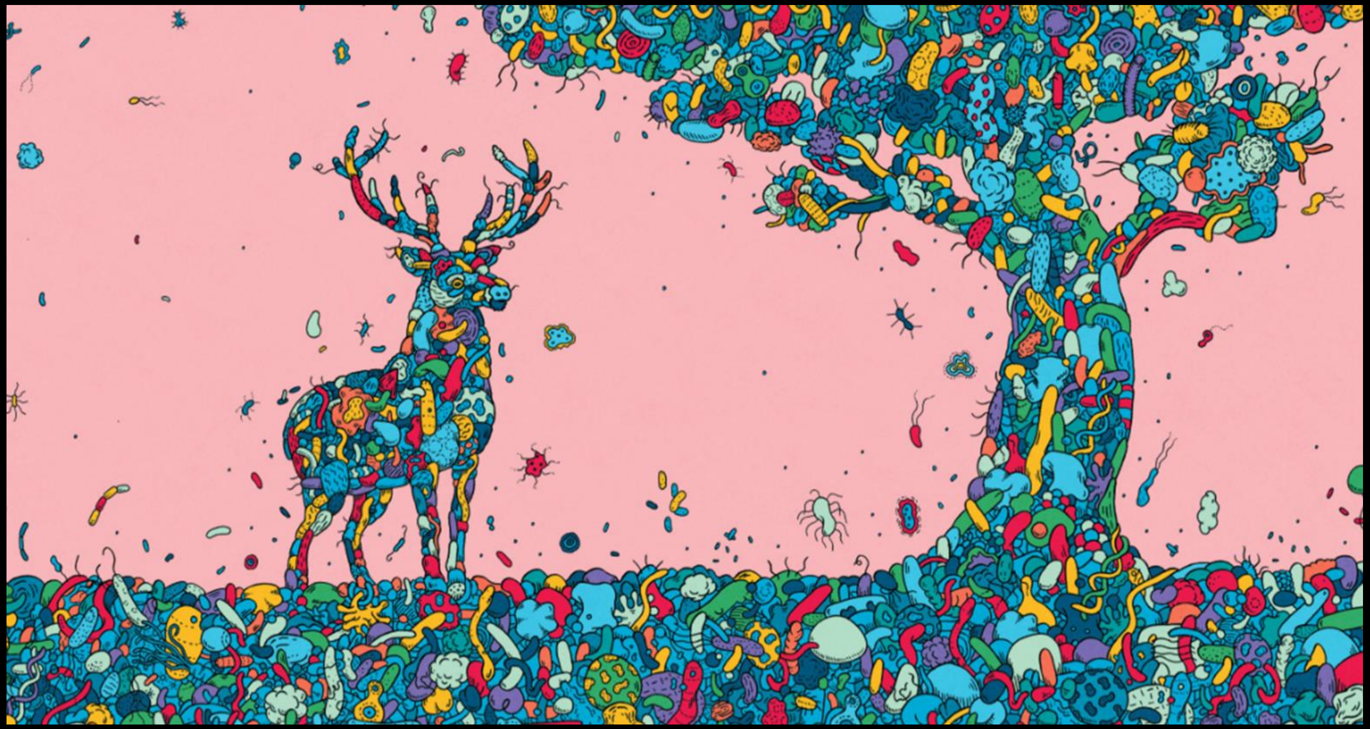
Chimeric

Evolvable

Intertwinned

Most plants and animals are likewise connected: our own species should act responsibly.





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