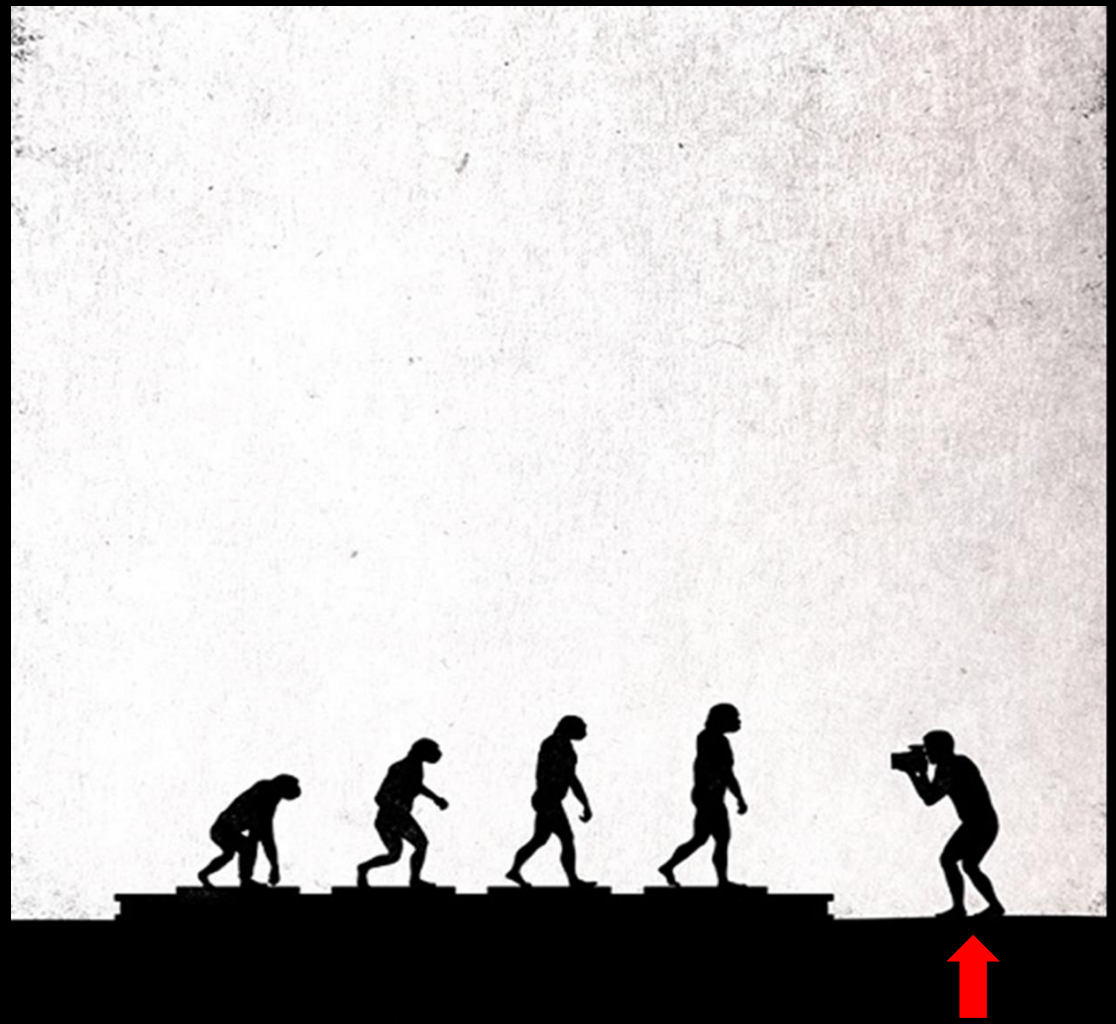
# (Inter)dependency and resilience in the living world: An evolutionary biology perspective

**Dr. Eric Bapteste**



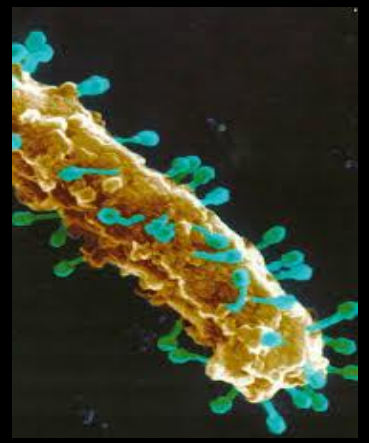
I am an evolutionary biologist.



An evolutionary biologist

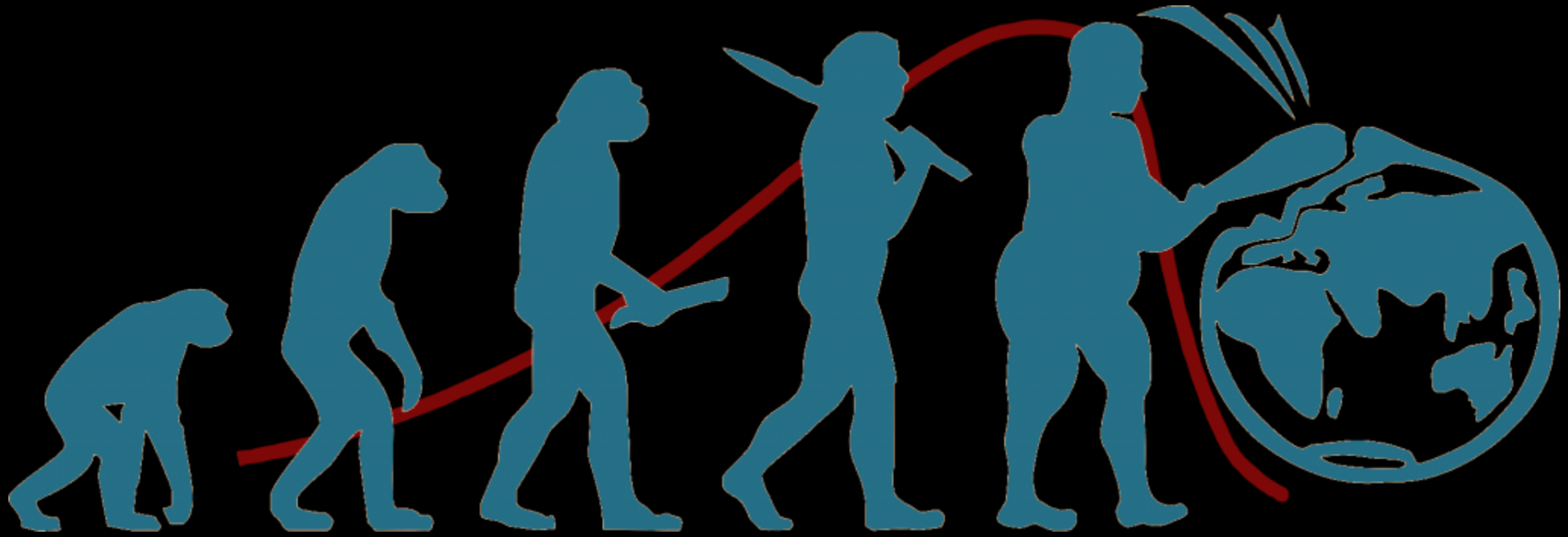
Evolutionary biology tries to explain the history and diversity of life.

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



I investigate these issues using networks, focusing on interactions.

Today, I feel I was invited but not just to discuss about the past.



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

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

## A/ Introducing an expanded evolutionary biology

### 1/ An intuitive observation:

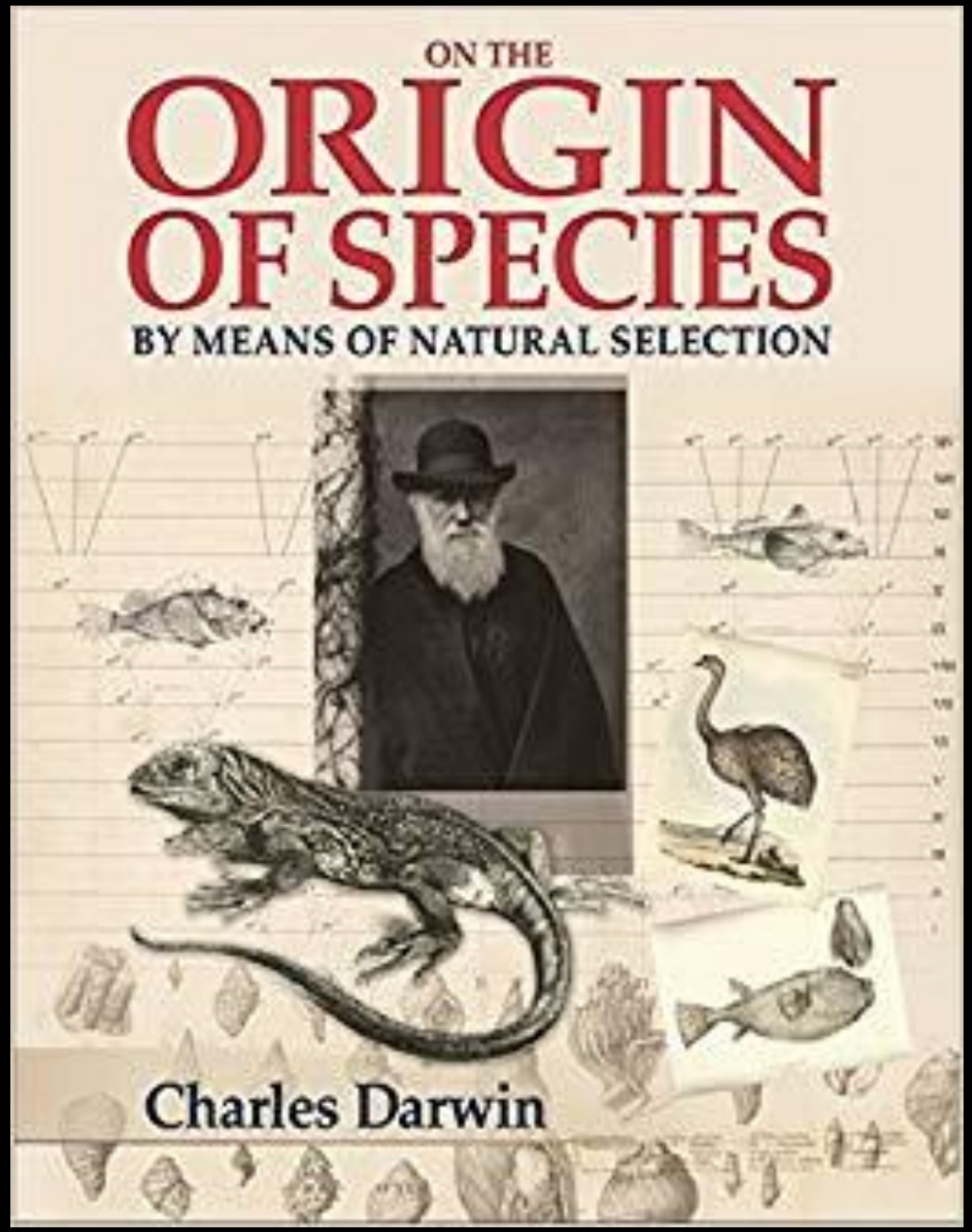
Biology relies on interactions, therefore evolutionary biology should describe the evolution of interactions

### 2-4/ New research avenues in evolutionay biology

## B/ Associated intuitions on the resilience and (inter)dependency of the living world

## C/ Conclusion

# A/ Introducing an expanded evolutionary biology



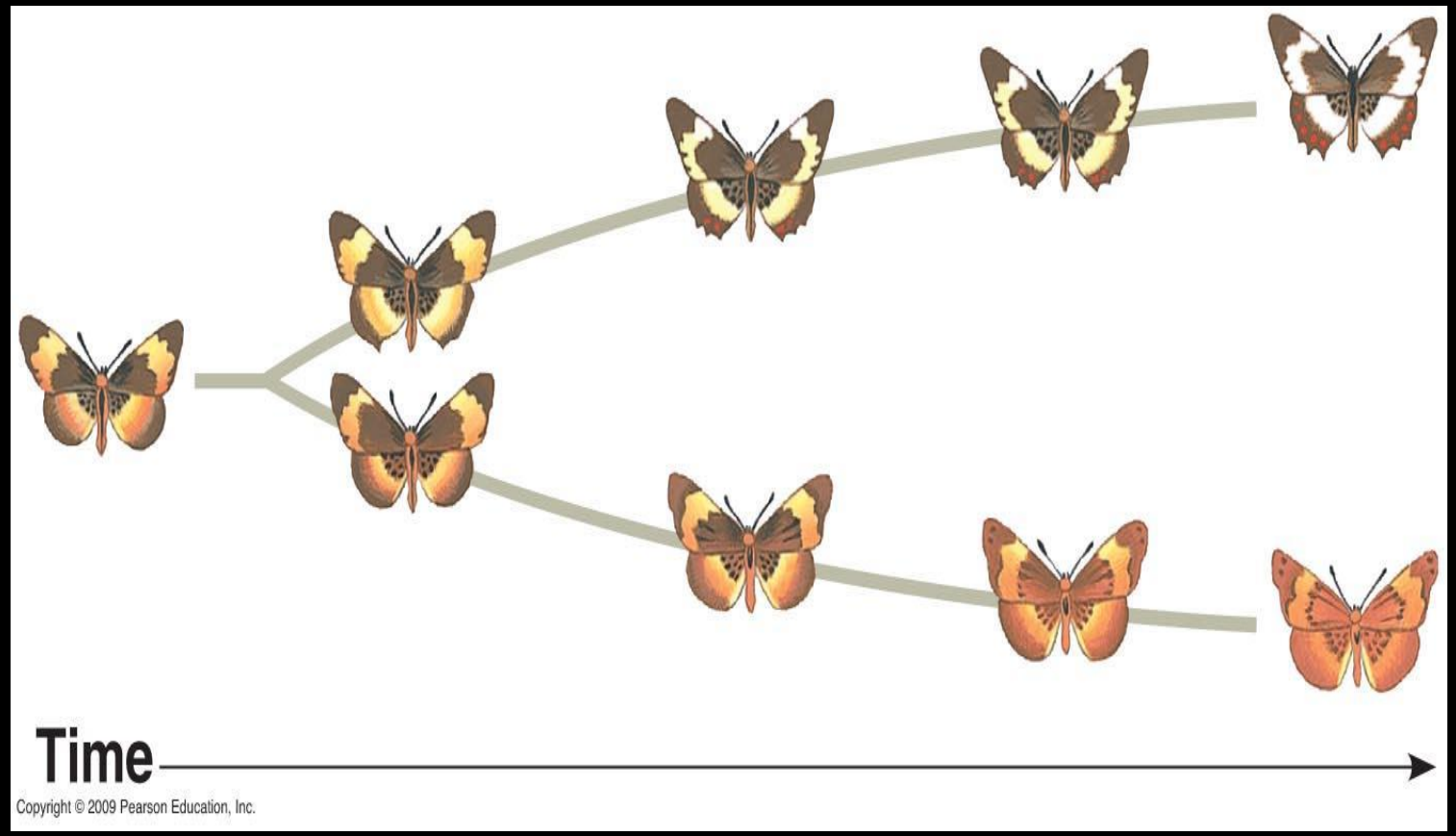

1859

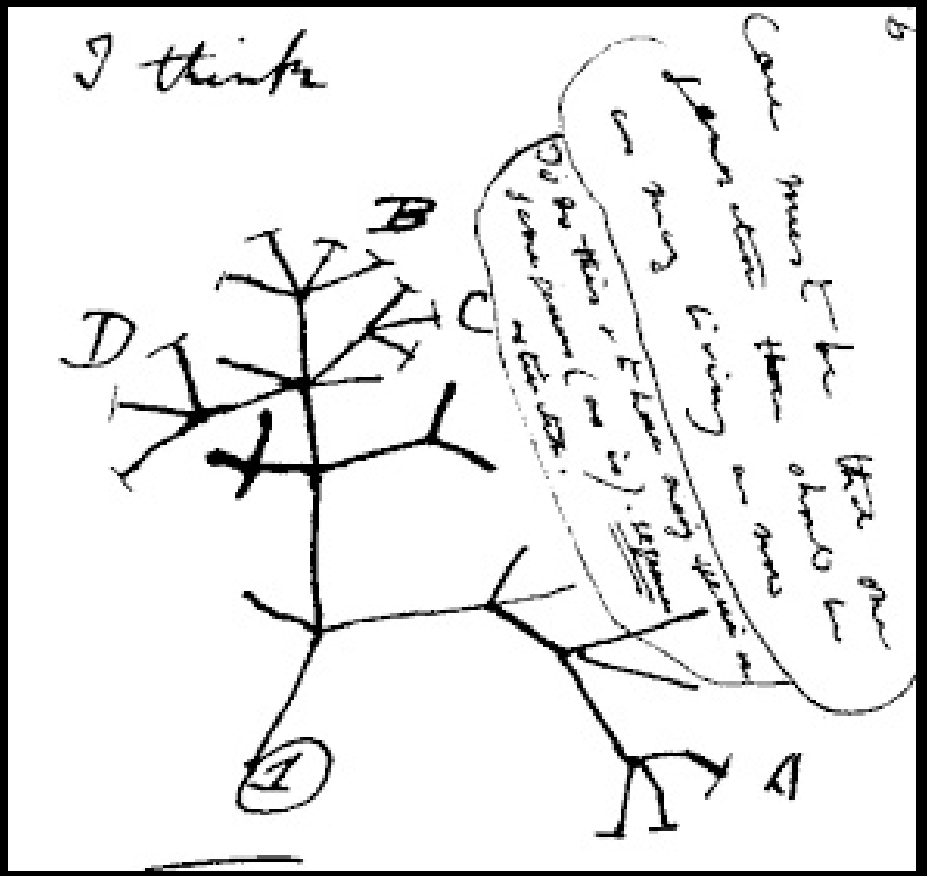
This book presented:

- **1 process**: descent with modification

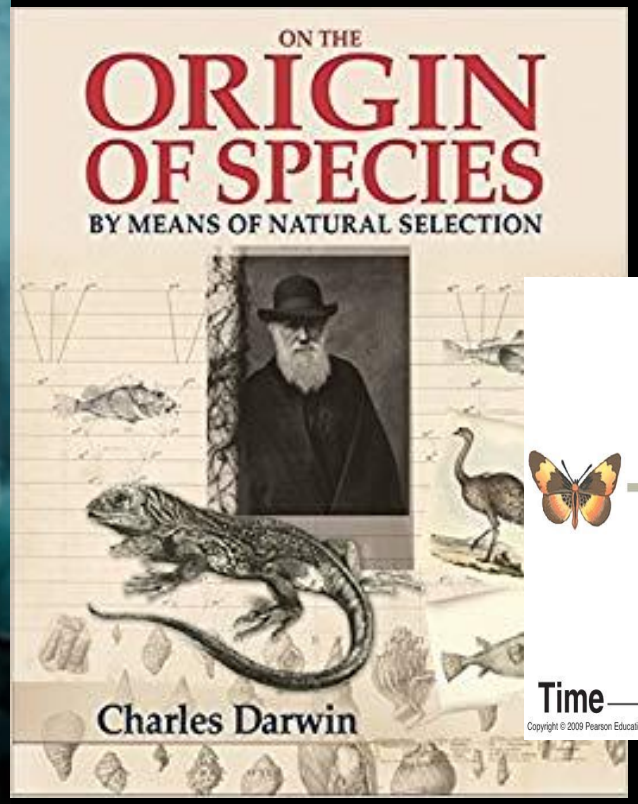
- **3 conditions** for its realization (variation, inheritance, differential fitness)

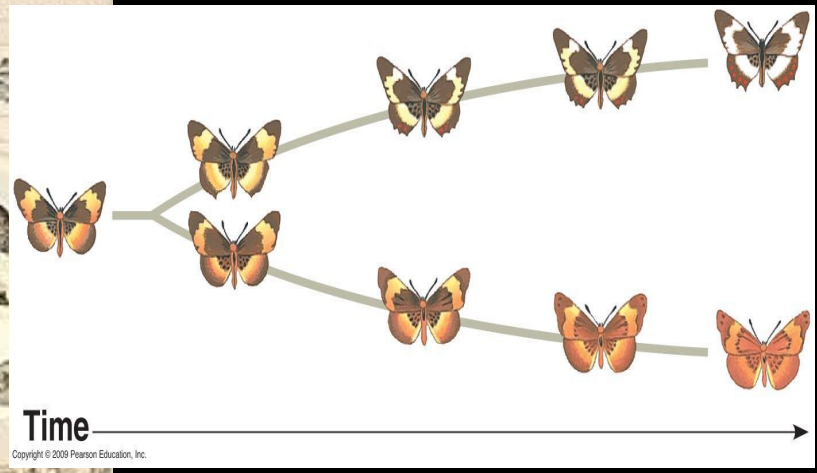
- **2 bold hypotheses**: ***natural selection*** + ***tree of life***



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



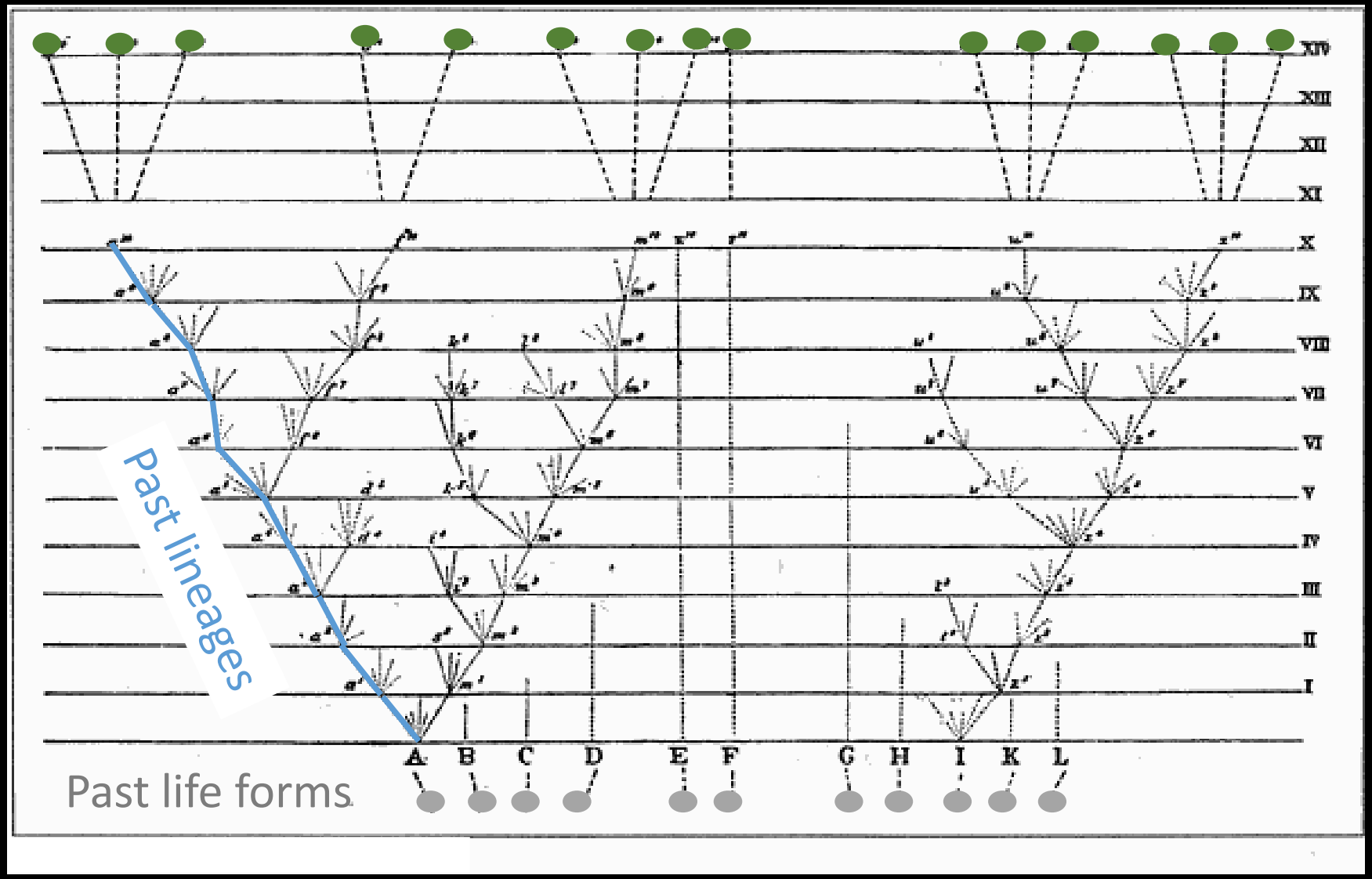

- the **production of (advantageous) variation**
- the **transmission of that (advantageous) variation to offsprings**
- An **increased ability of organisms with advantageous variations to produce more offsprings,**

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

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

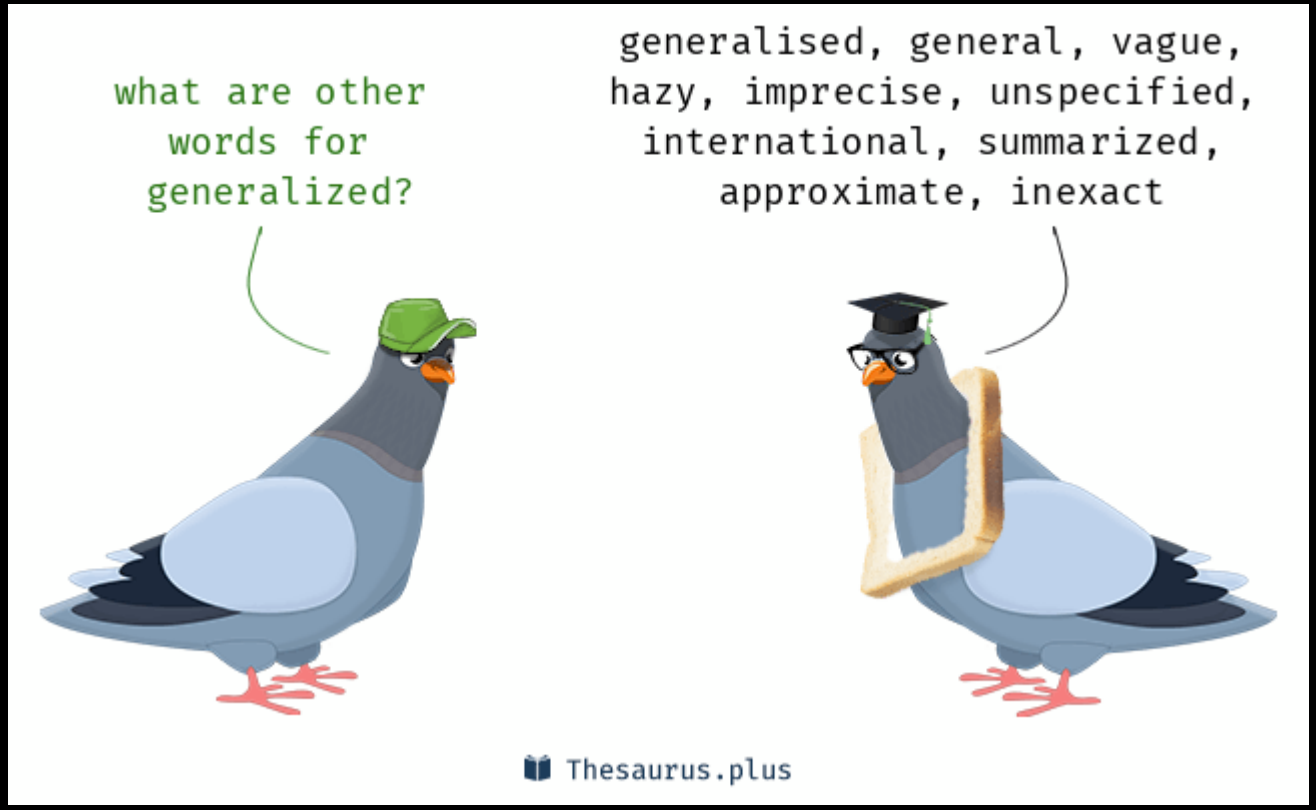
PRESENT

PAST




C. Darwin 1859

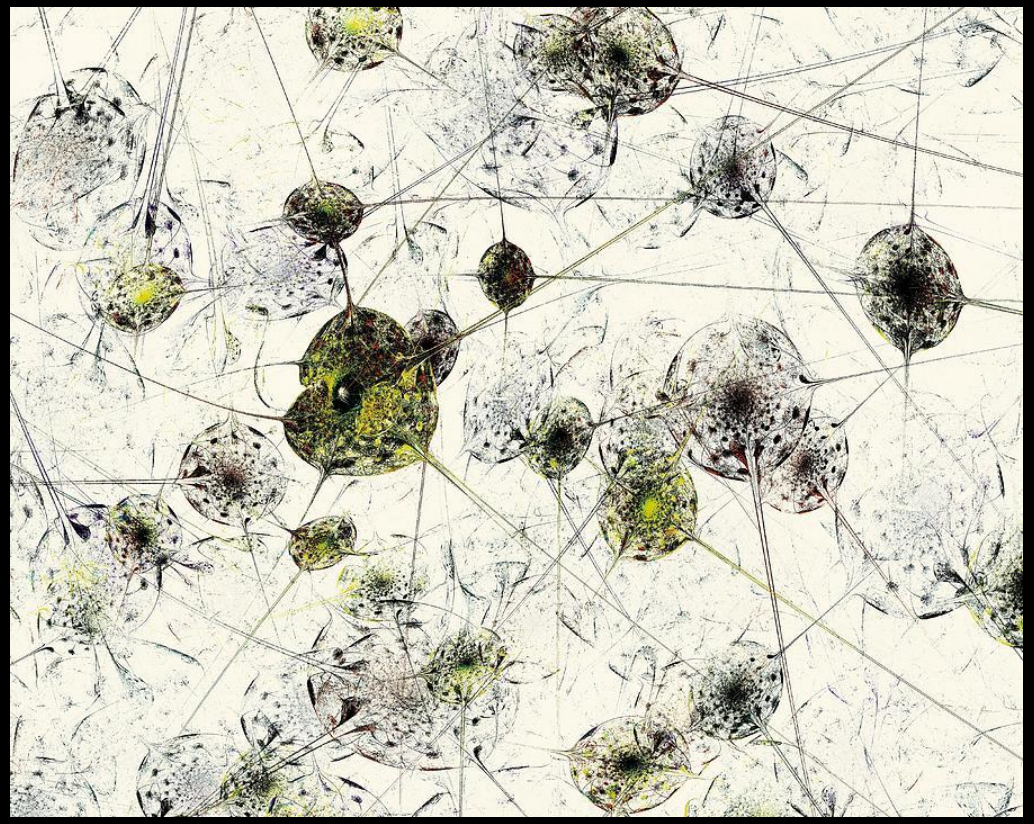
Importantly, this simple, possibly schematic version of evolutionary biology can be generalized/expanded to better account for interactions, e.g. interdependencies and resilience.



## 1/ An intuitive observation

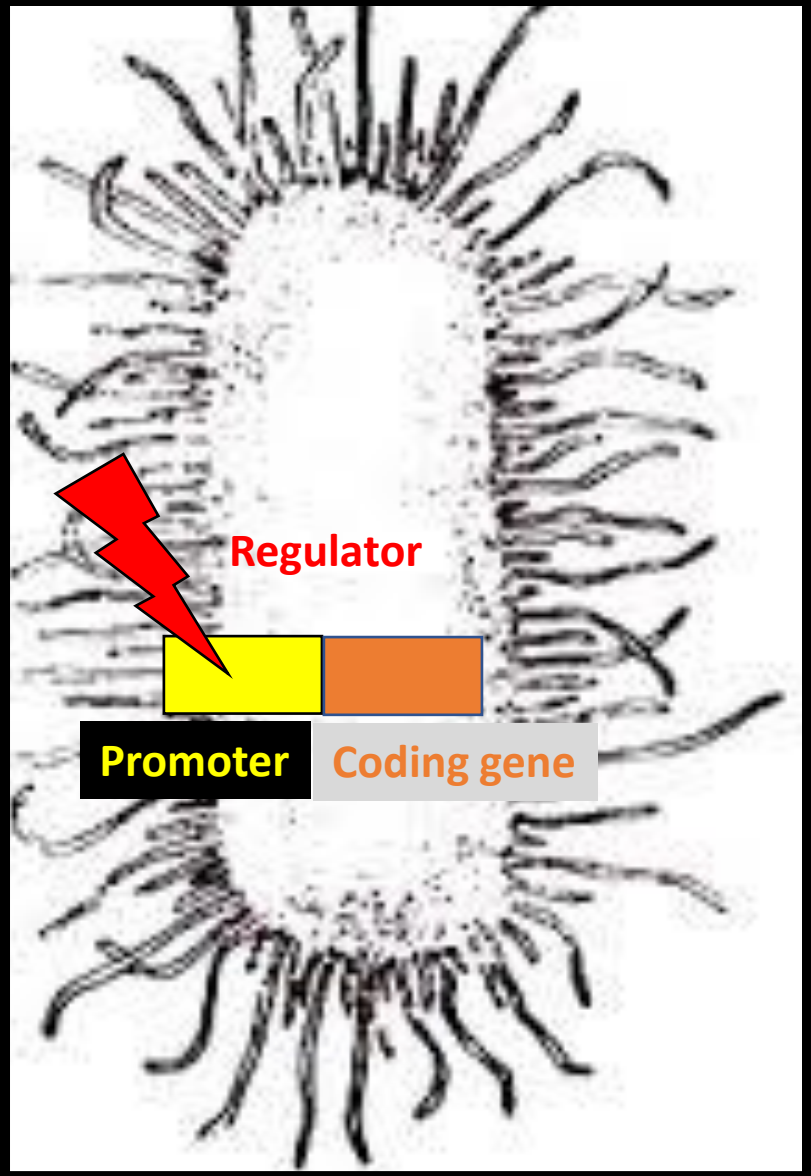
Biology relies on interactions, therefore evolutionary biology should describe the evolution of interactions.

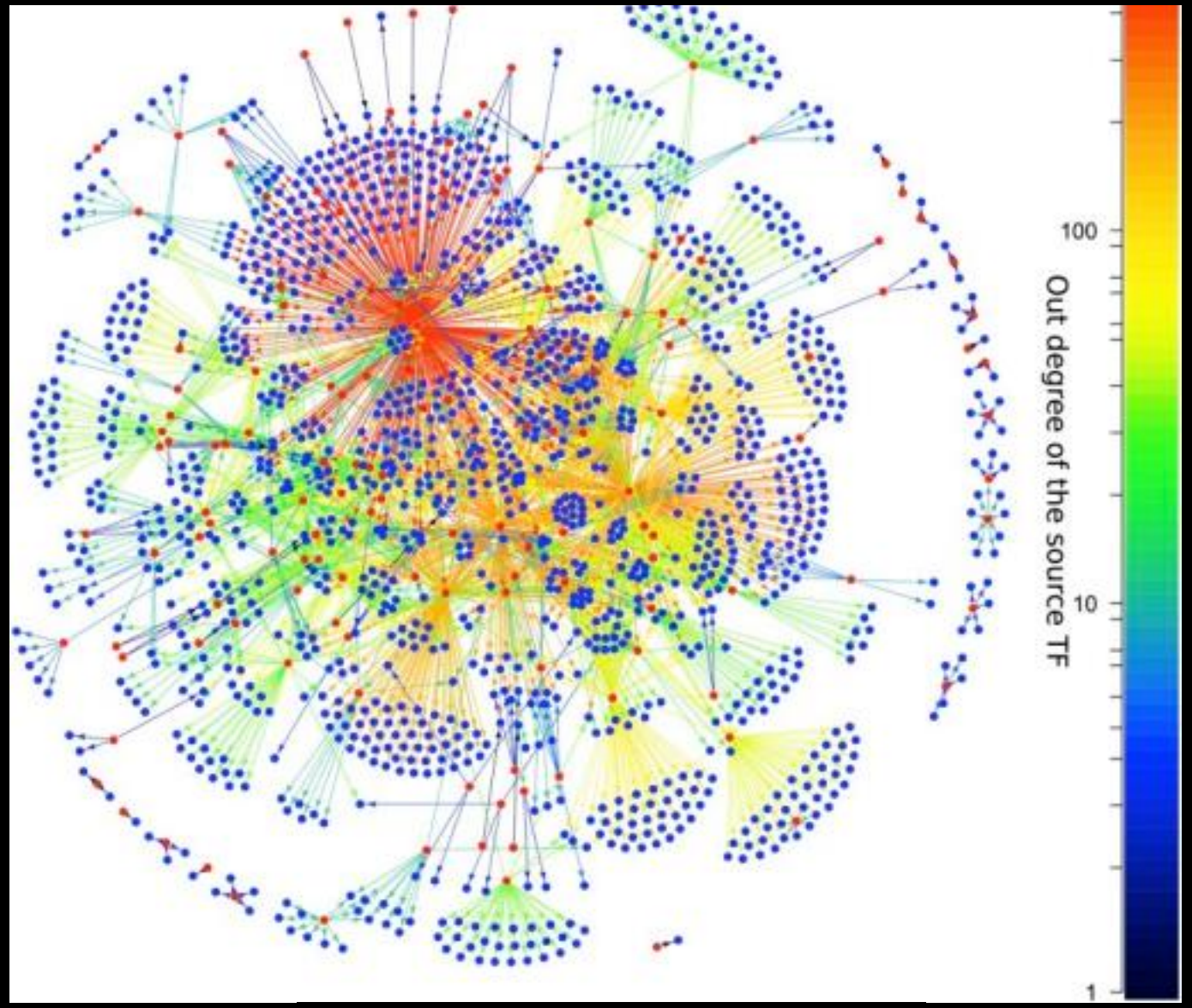
There are **interactions everywhere in organisms**, even in simple cells.



A. Malakhova

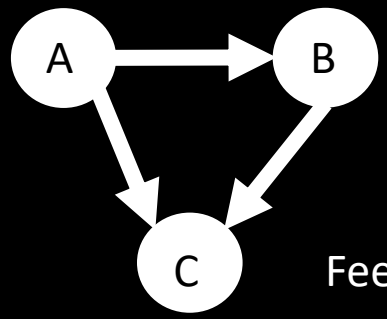
# For instance, 2 representations of *E. coli*
# left morphological; right: emerging from gene regulatory networks



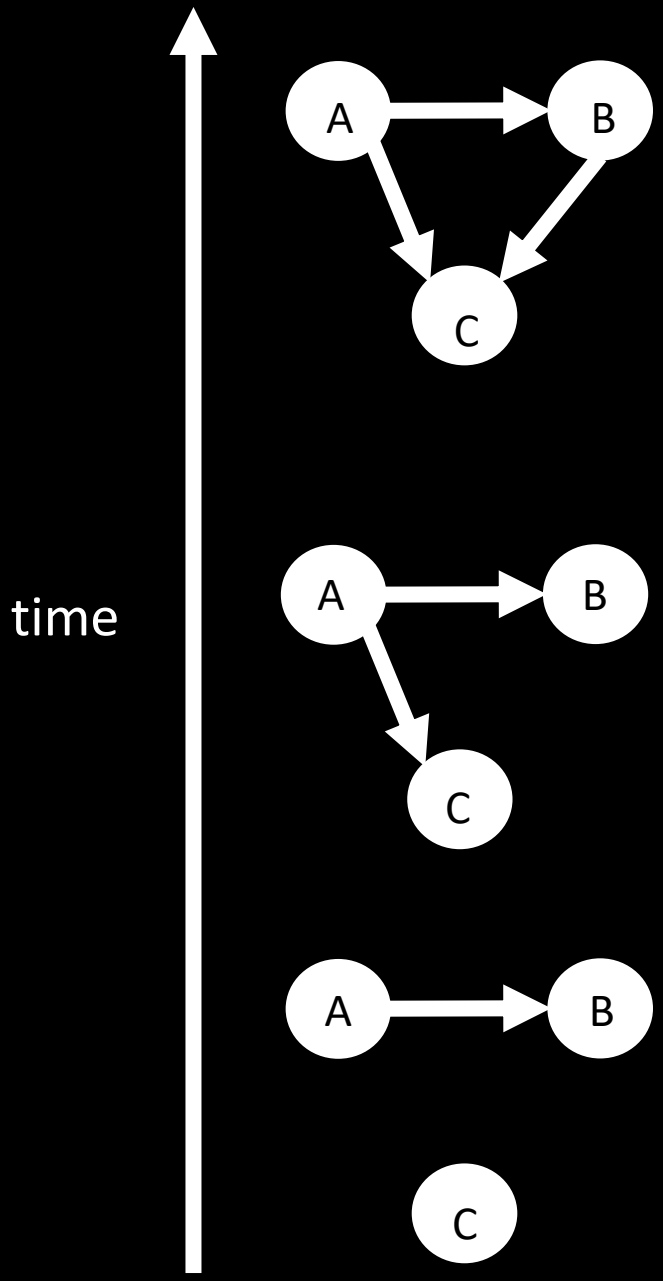

Regulators Other genes

# The architecture of these networks is informative.




Feed-forward loop

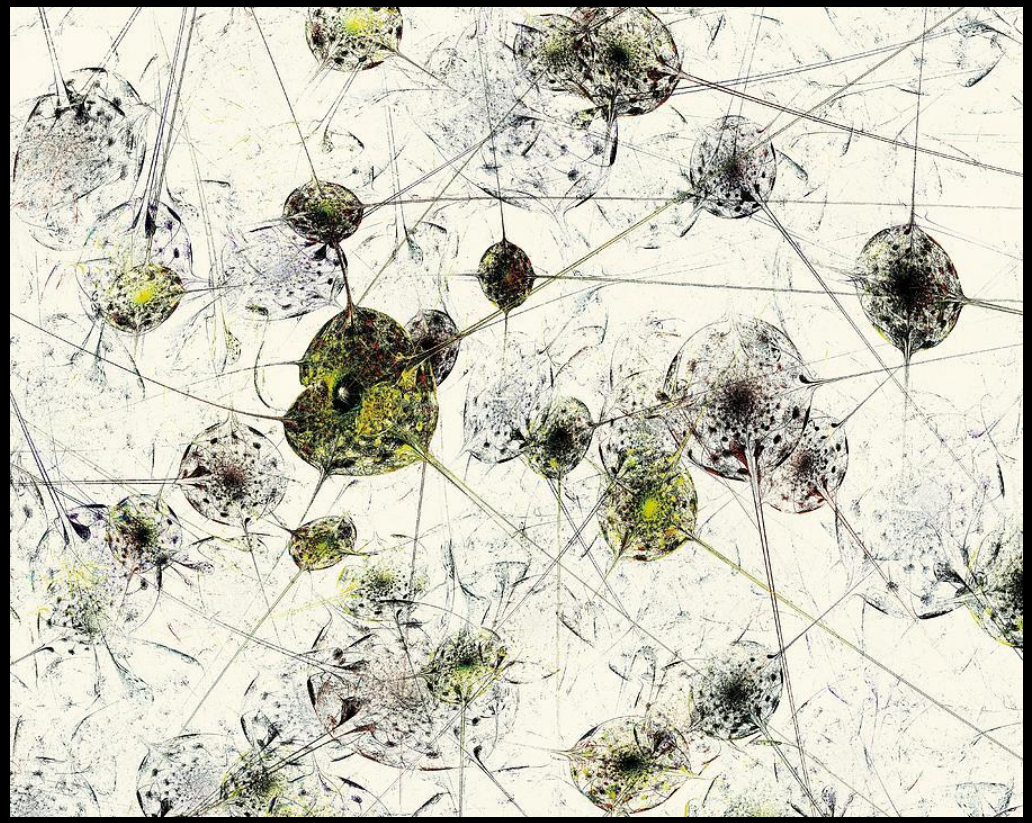
**This introduces new biological questions: how did the architecture of such networks evolve?**




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

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

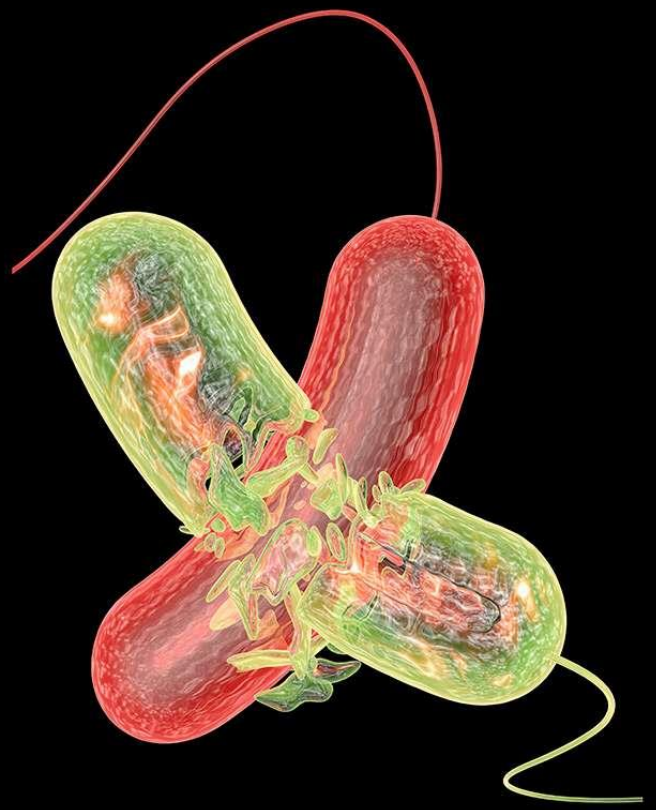
- **Organisms**, even simple cells, **belong to networks**.



A. Malakhova

# Microbes interact in many ways.

- **Competition**

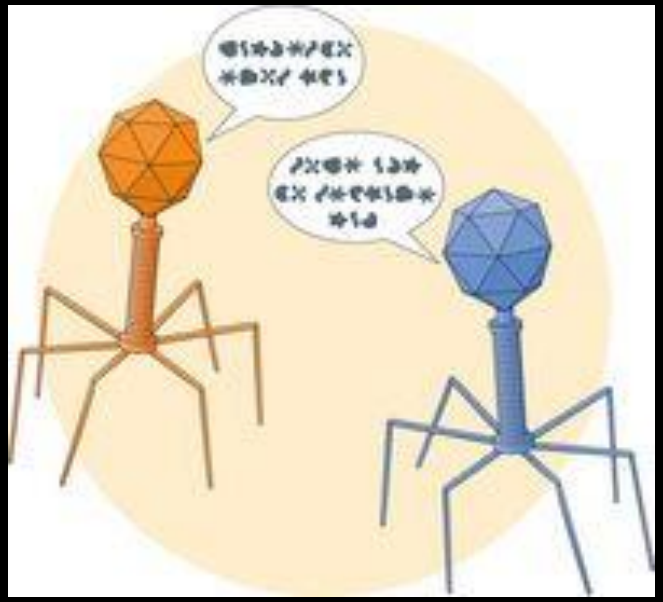


Alfred Pasieka/SPL

- **Cooperation**

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

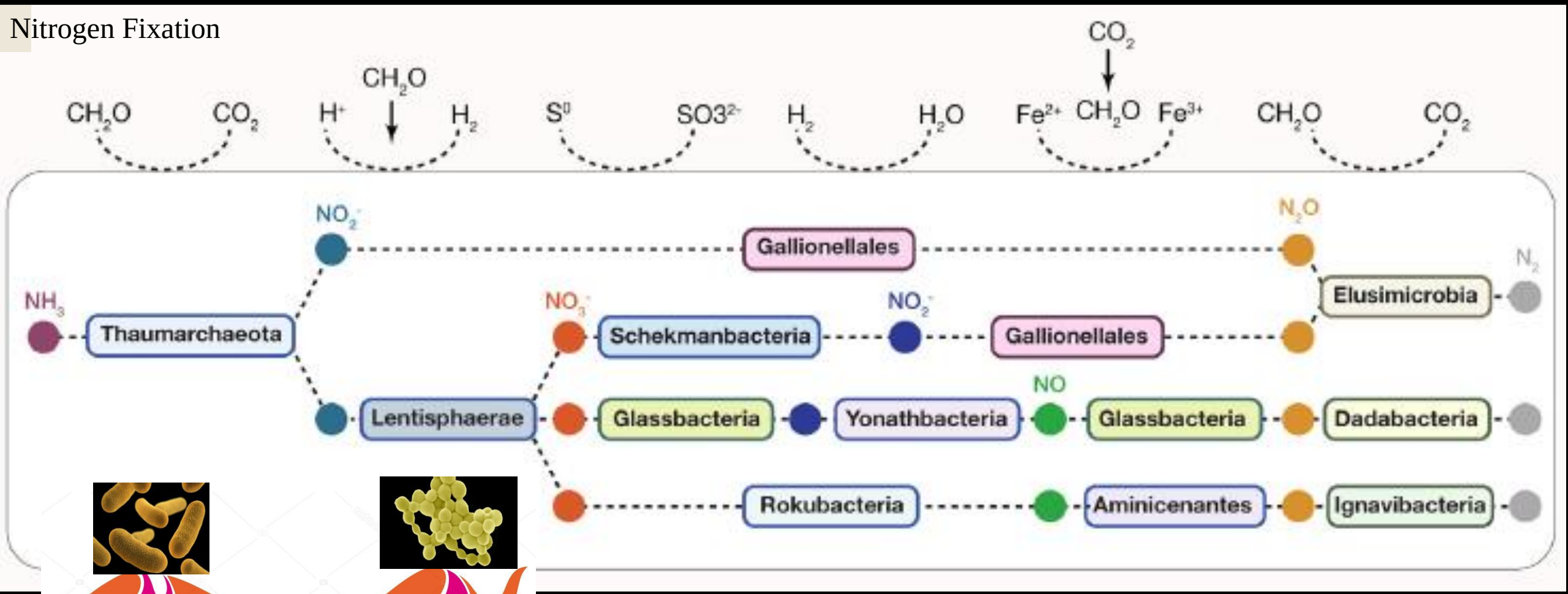
- **Communication**



Erez *et al.*, Nature

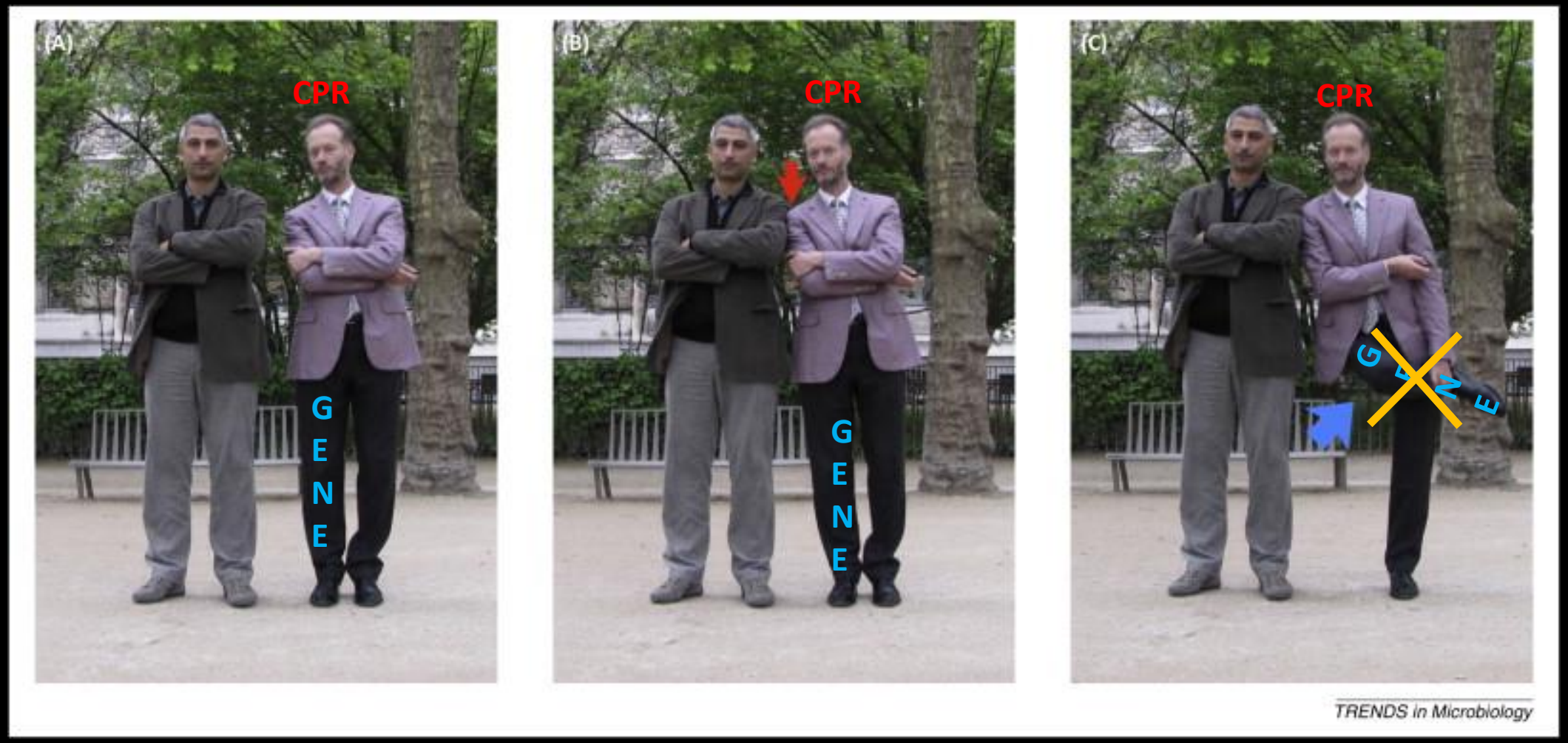
# Some ultra-small microbes are involved in collective reactions by metabolic hand-offs

Nitrogen Fixation




Castelle *et al.* Cell 2018

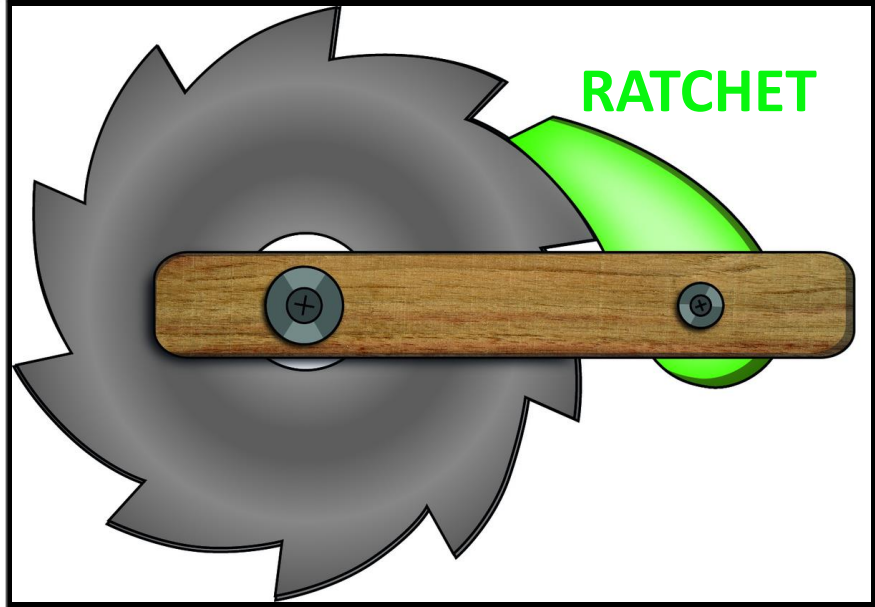
# Ultra-small cells would have lost some of their genes in the context of interactions with other organisms.




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

# Such interactions lead to counter-intuitive predictions.


**PRE-SUPPRESSION**




*(Gray & Doolittle, Science, 2010)*

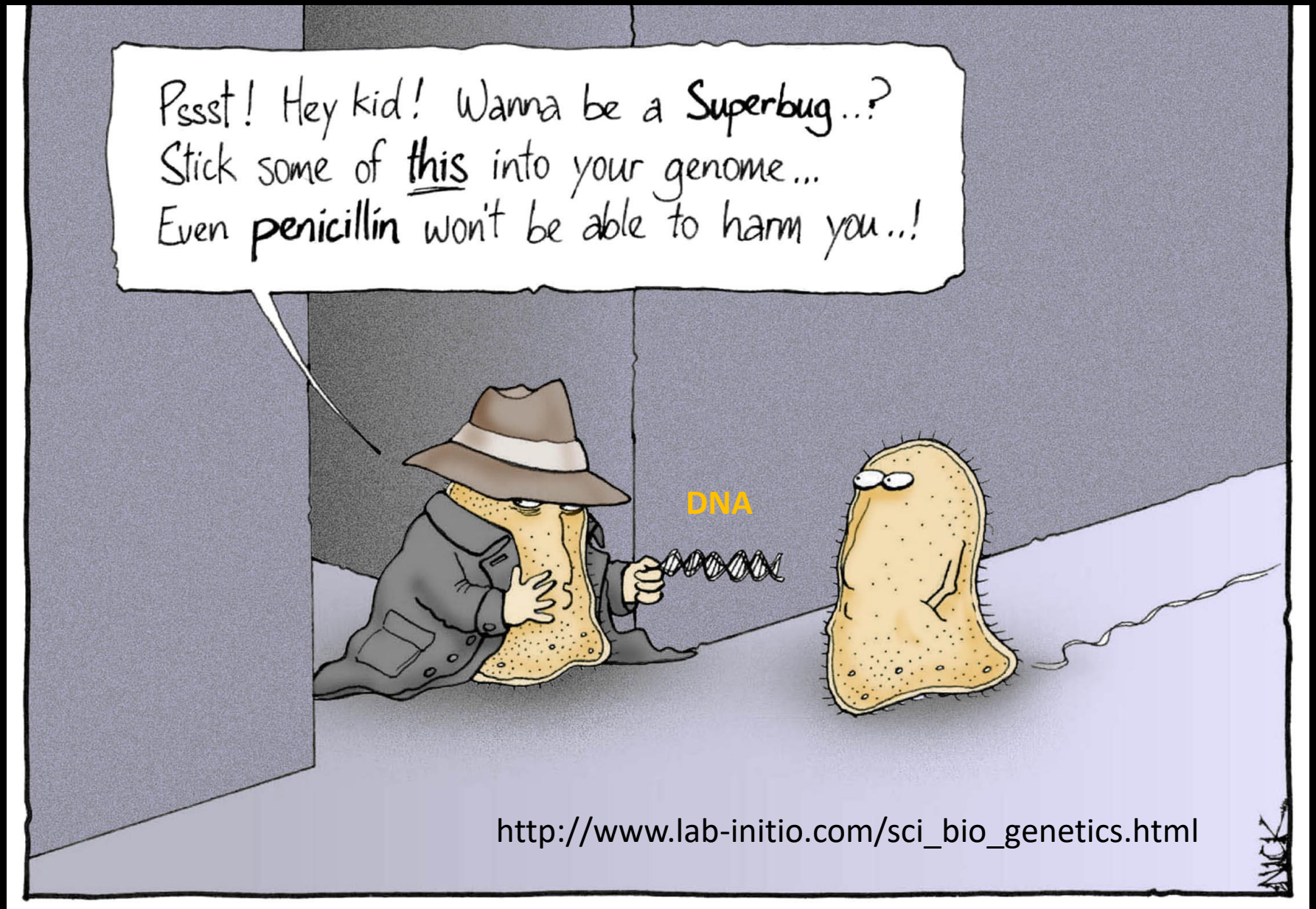
Such dependances are difficult to reverse, thus complex microbial communities, with non autonomous cells, are expected to evolve over time.

**This kind of explanation contrasts with a more classic vision.**

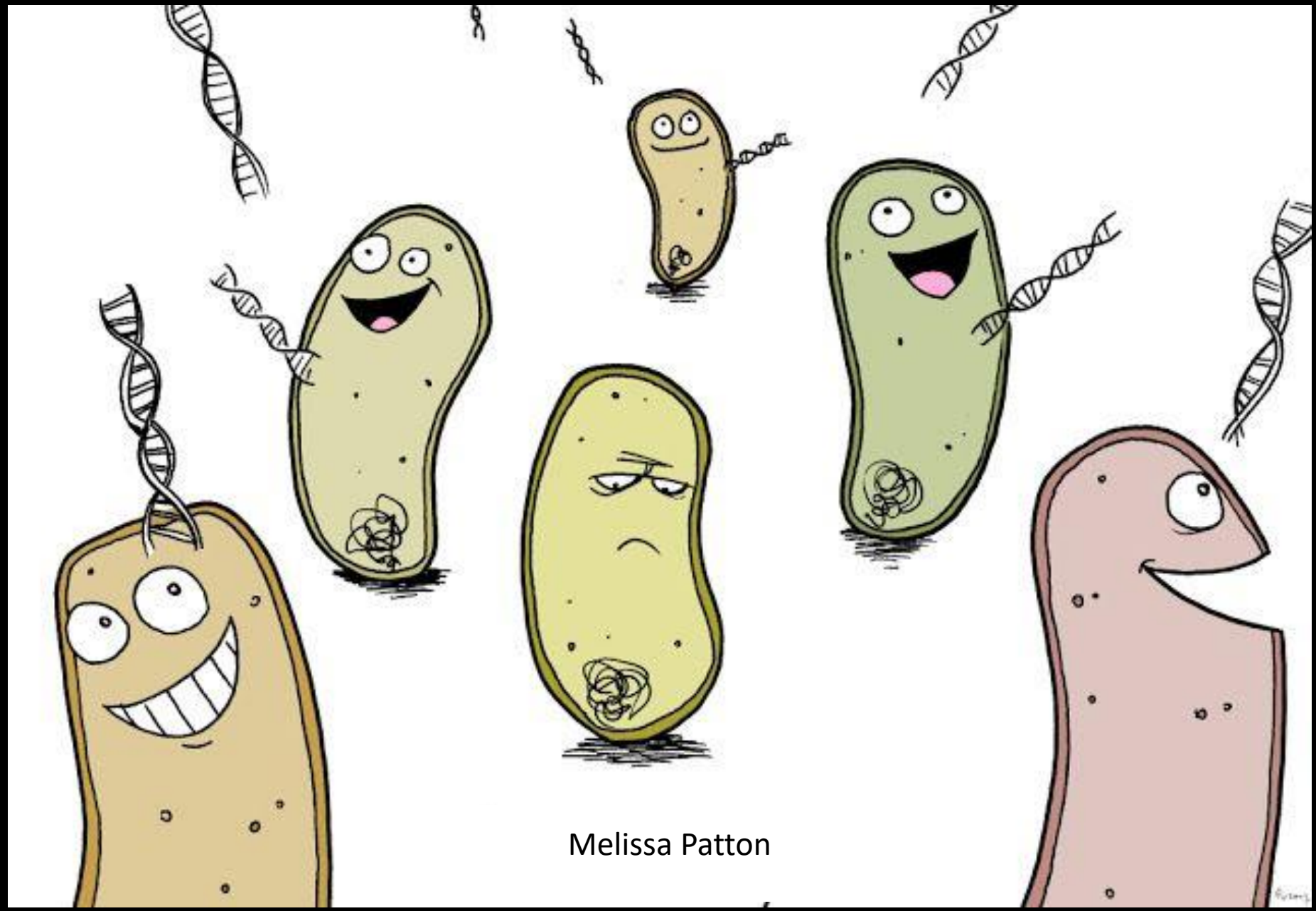
***Survival of the fittest (within a population/species)***

***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.**

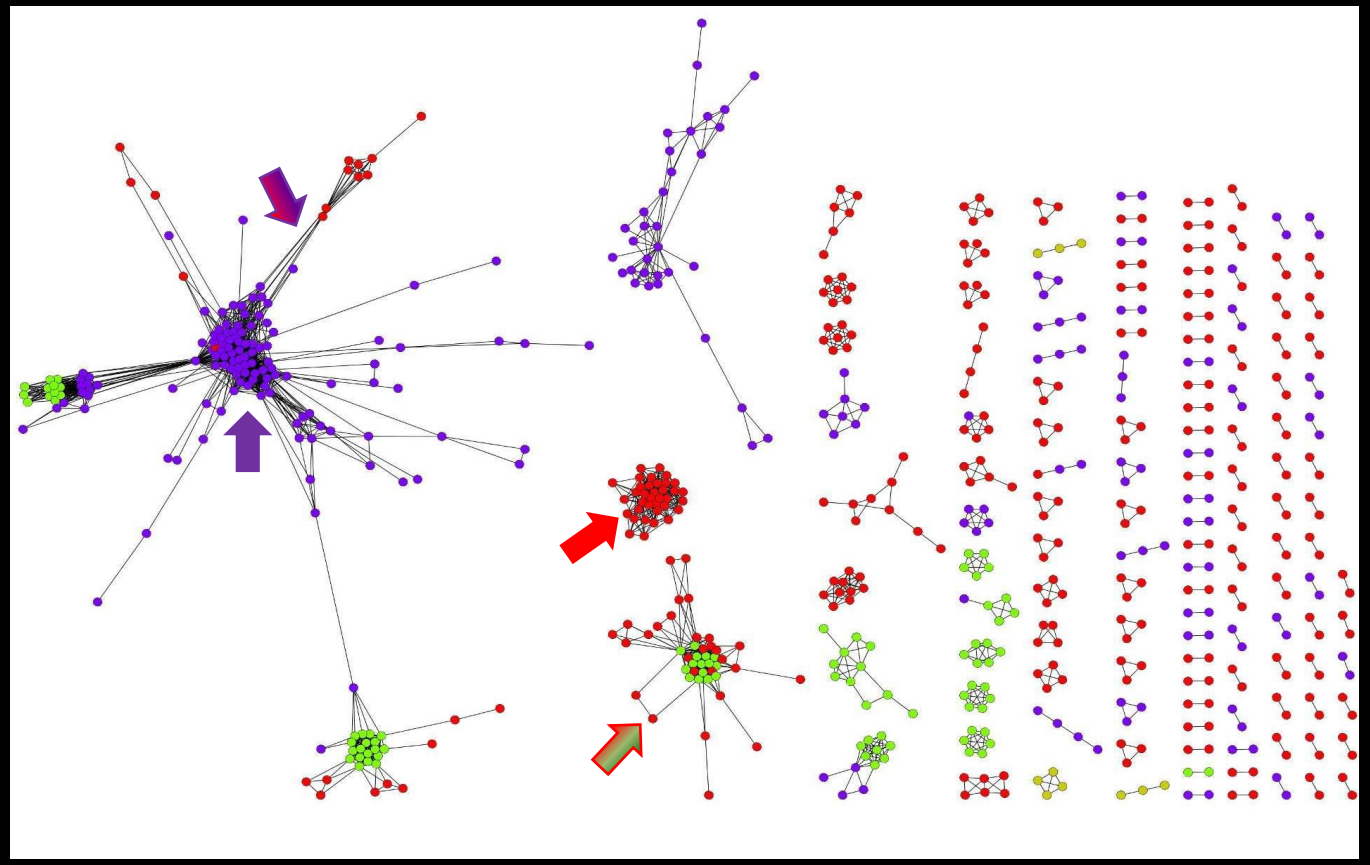


# Gene sharing allows microbes to evolve very fast.



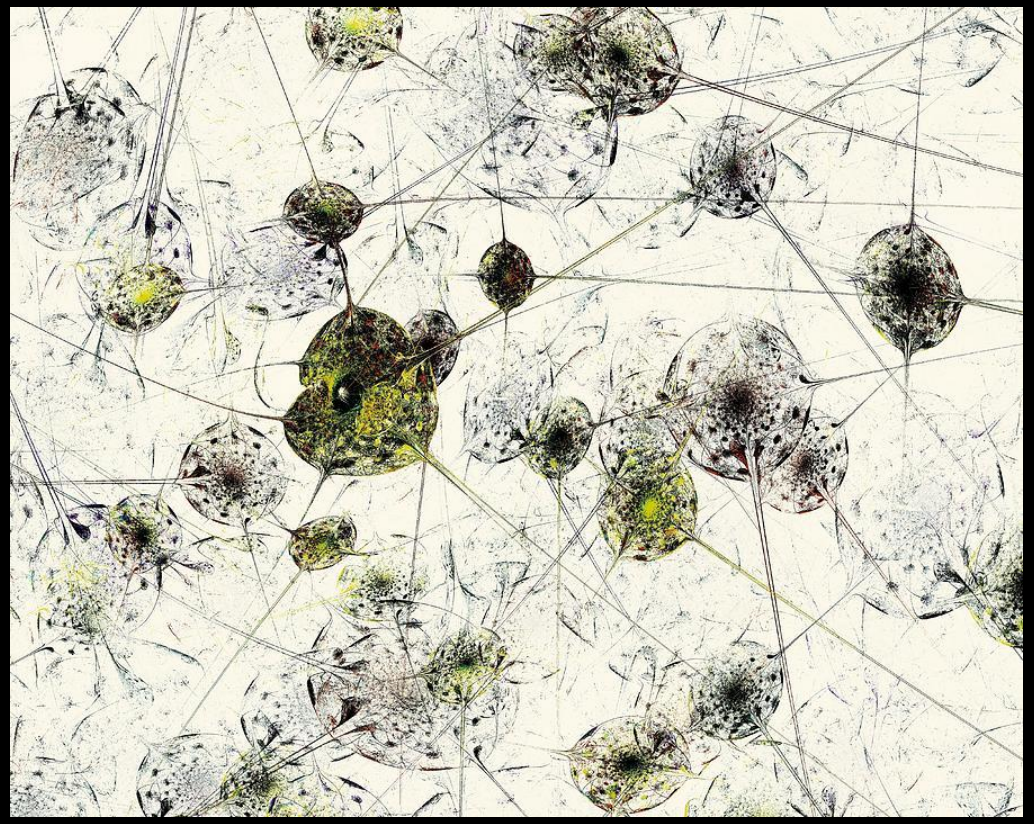
# Horizontal transfer produces mosaic organisms.

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



Halary et al. PNAS 2010

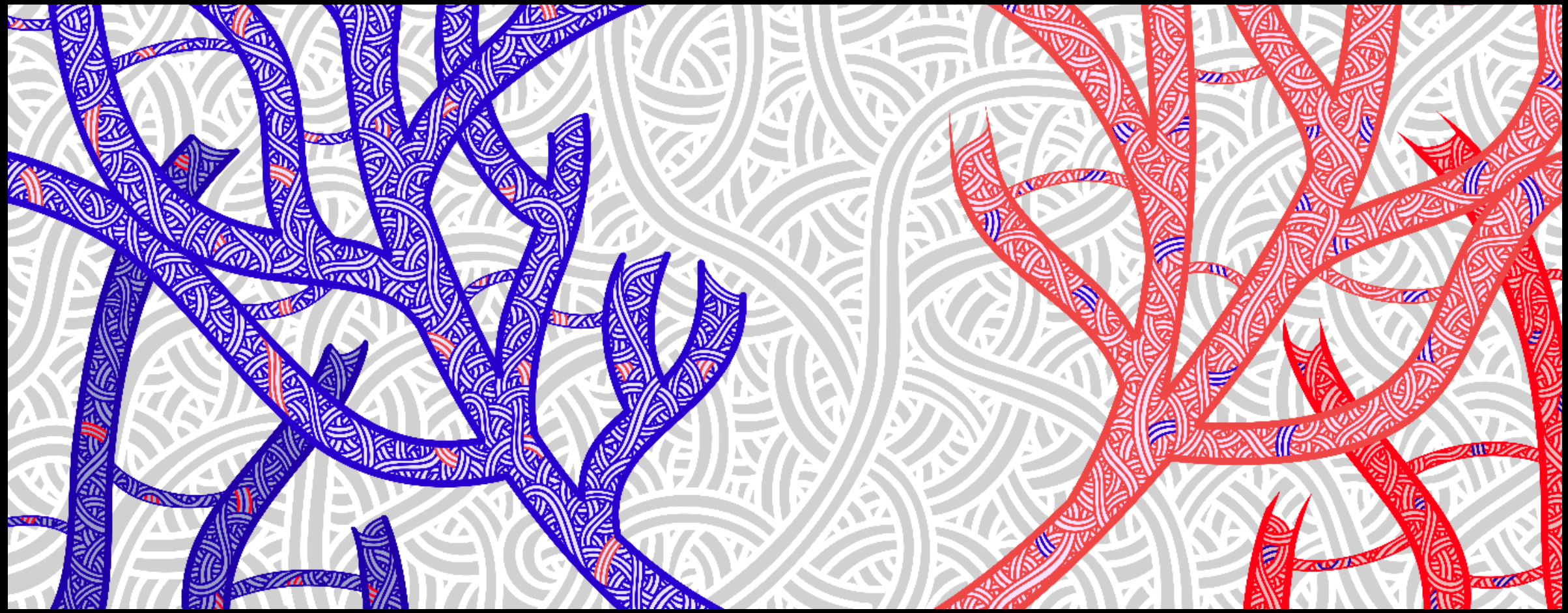
- These interactions **affect the evolution of species**, ours included.



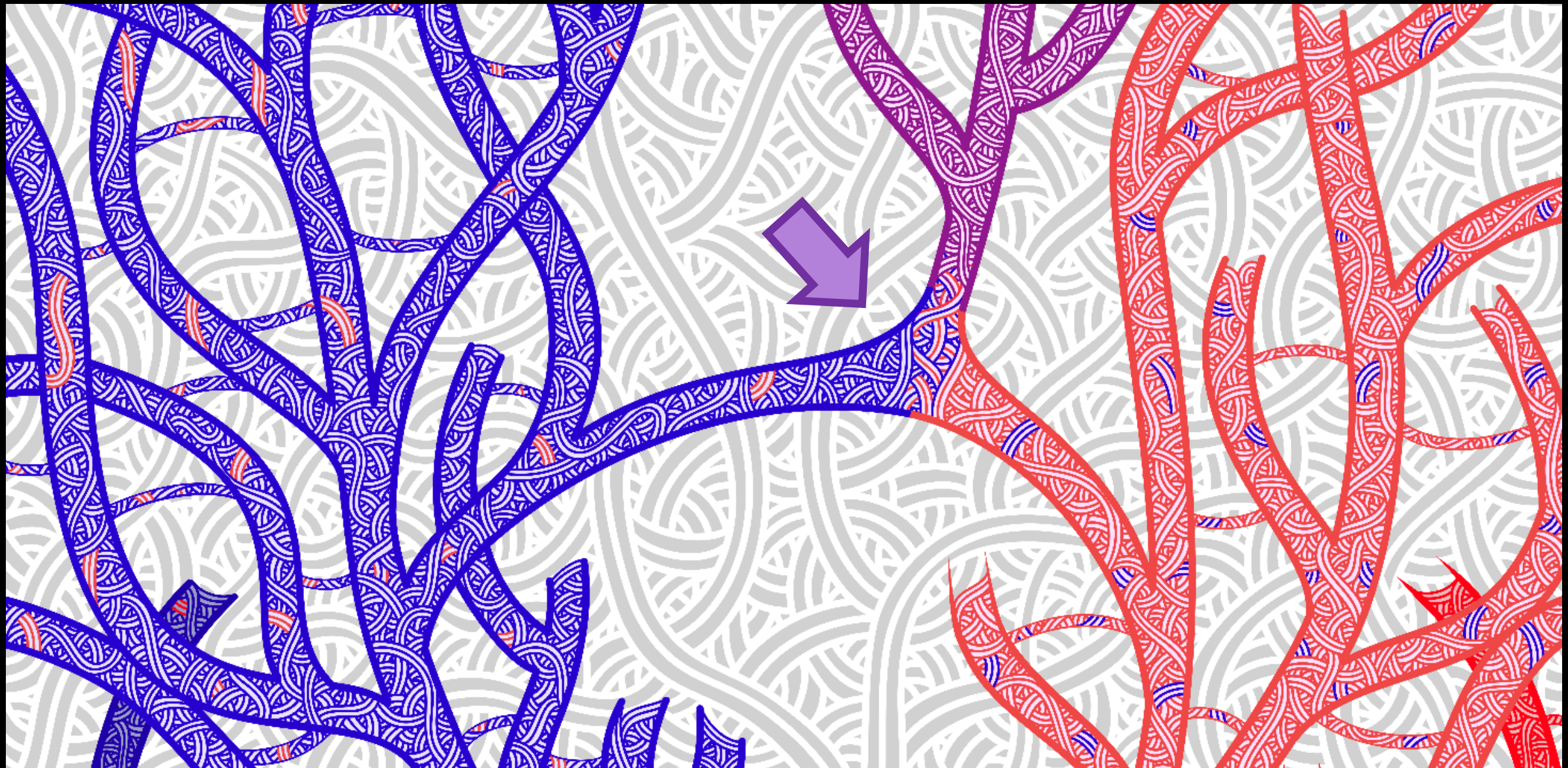
A. Malakhova

# During 1,5 Bya, Bacteria and Archaea populated Earth, multiplied, diverged, interacted and exchanged genes.

Jordane Saget



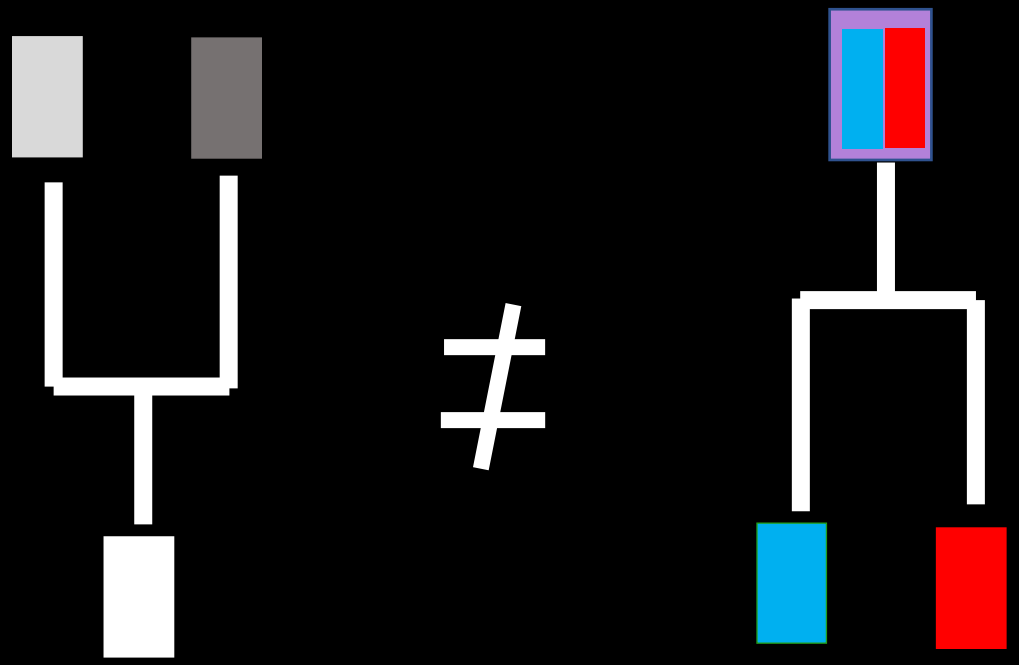
2 Bya ago, a symbiosis between Bacteria and Archaea produced a new kind of cells.



# This dual origin contrasts with a classic evolutionary scenario.

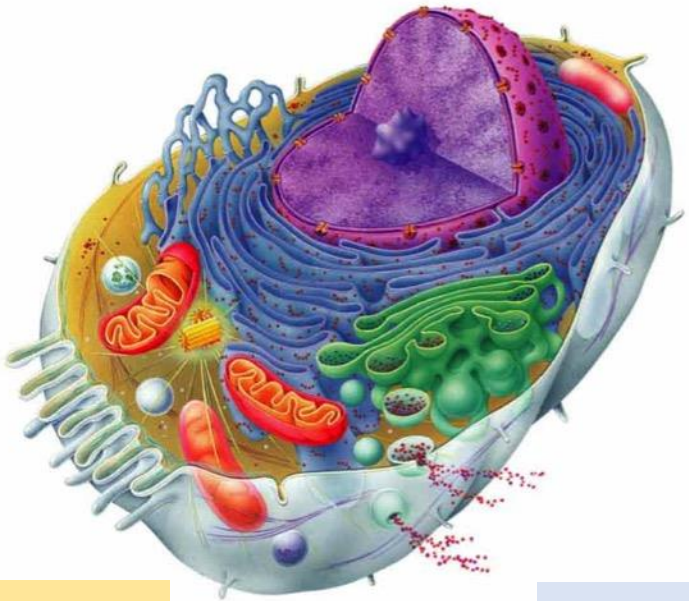
Classic model

New model



1 ancestor

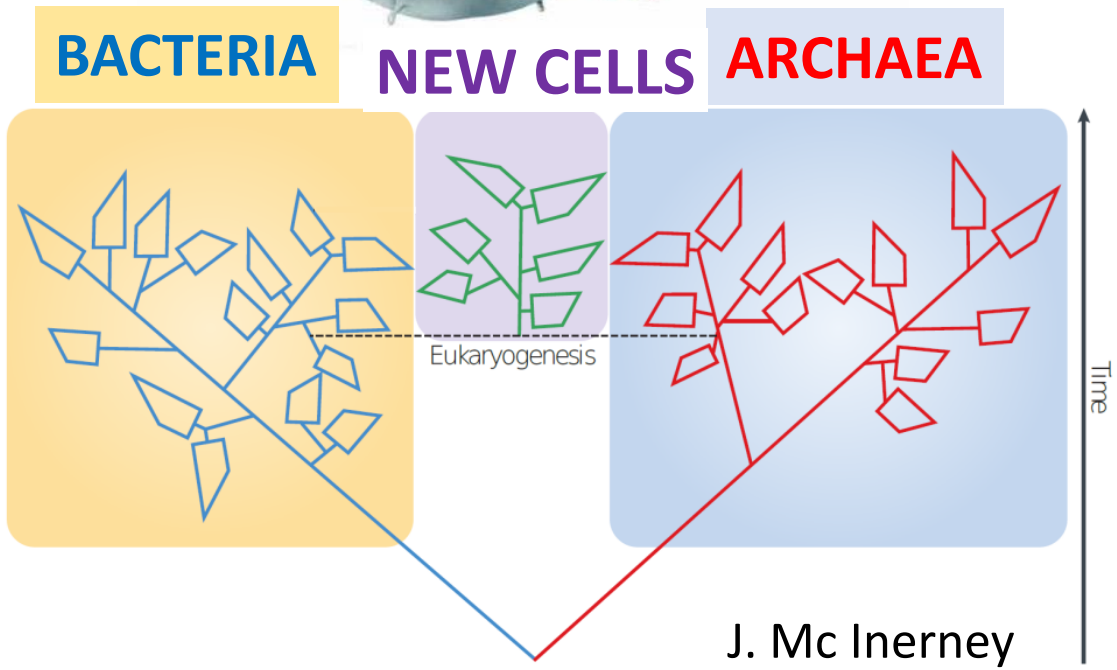
2 ancestors



EUKARYOTES

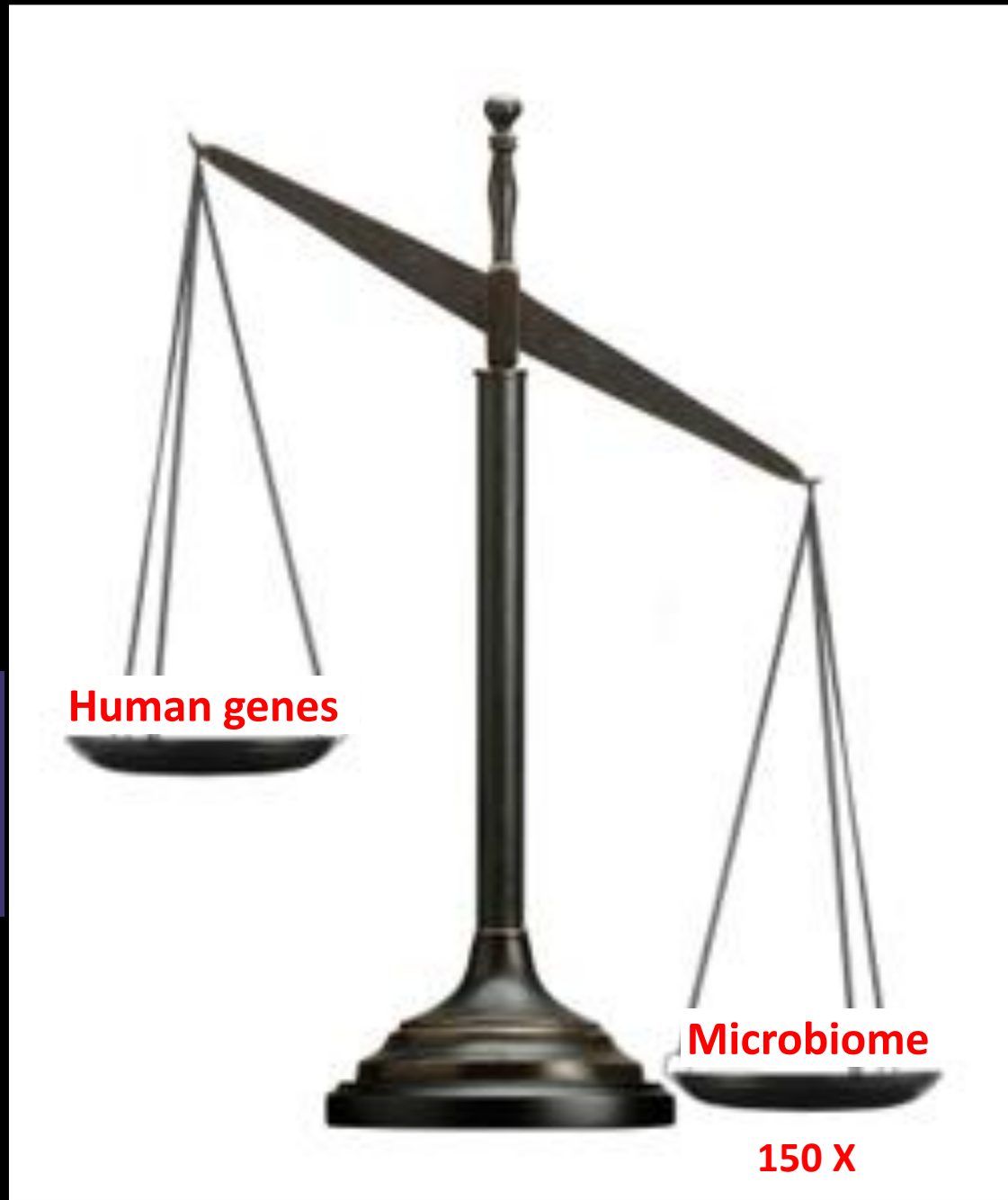
CHIMERA

CO-CONSTRUCTED



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

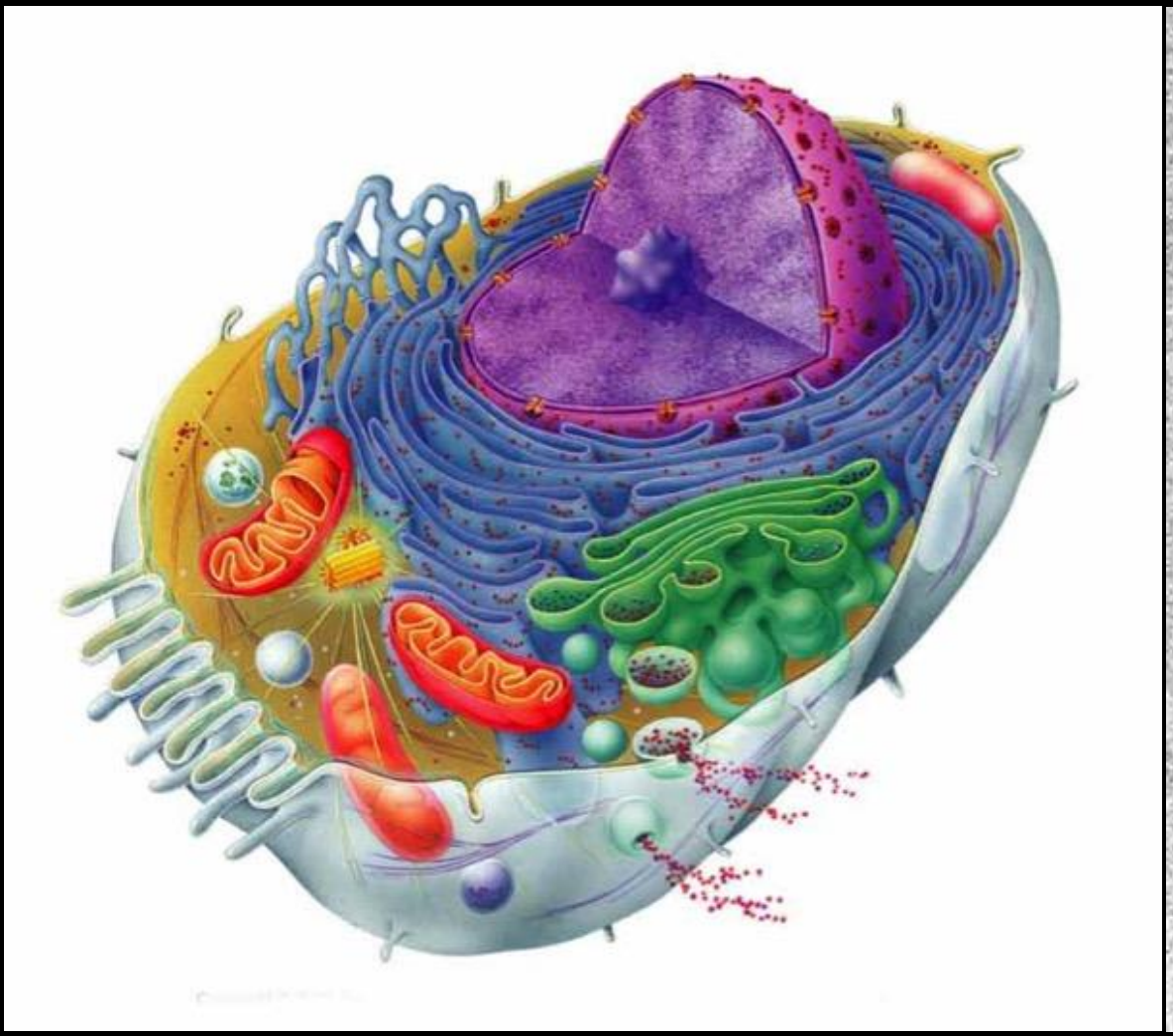
# The impact of extant microbes on human biology is thus re-evaluated.

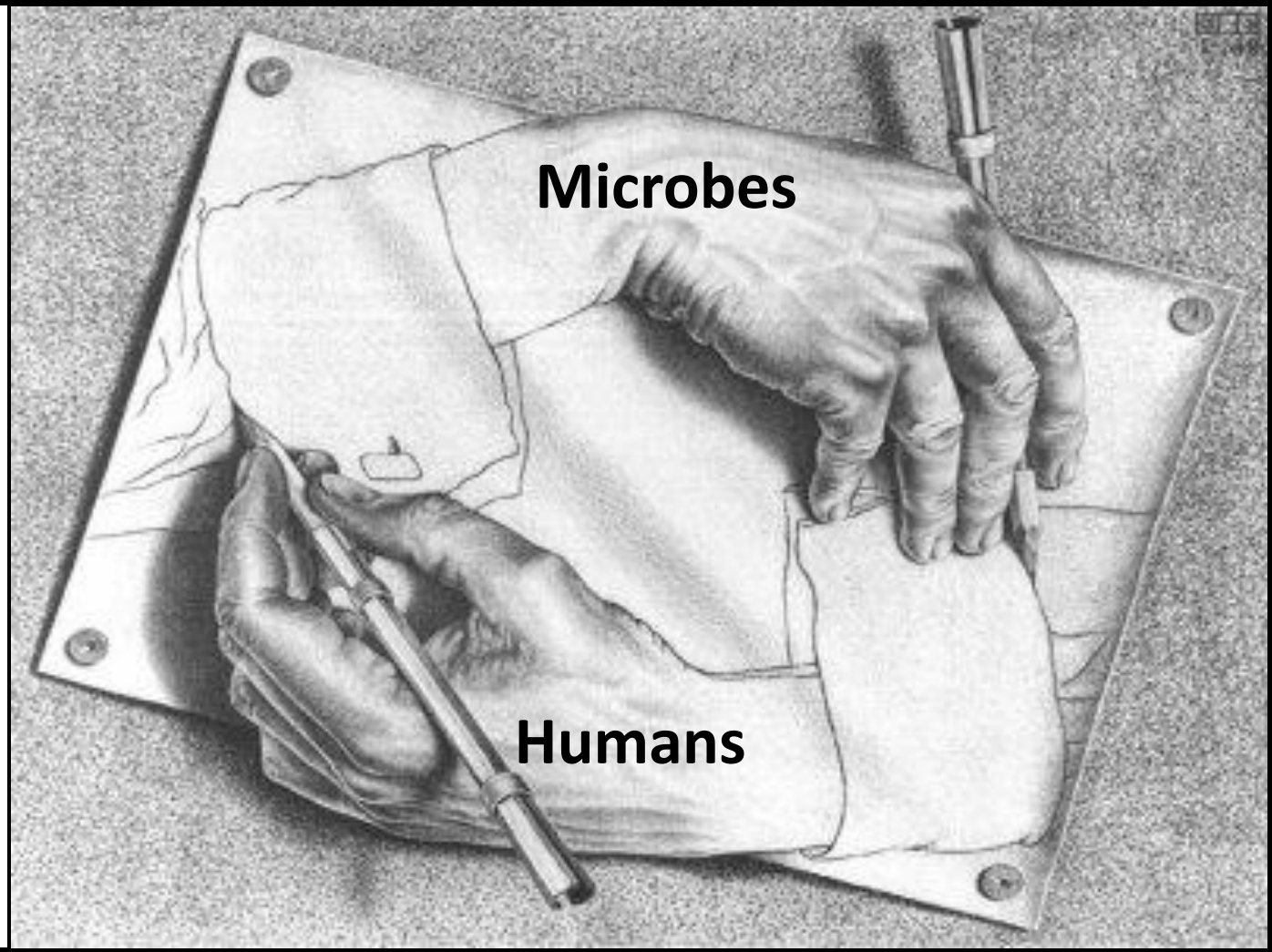



# Not only do our microbes interact together, but they also interact with our cells.

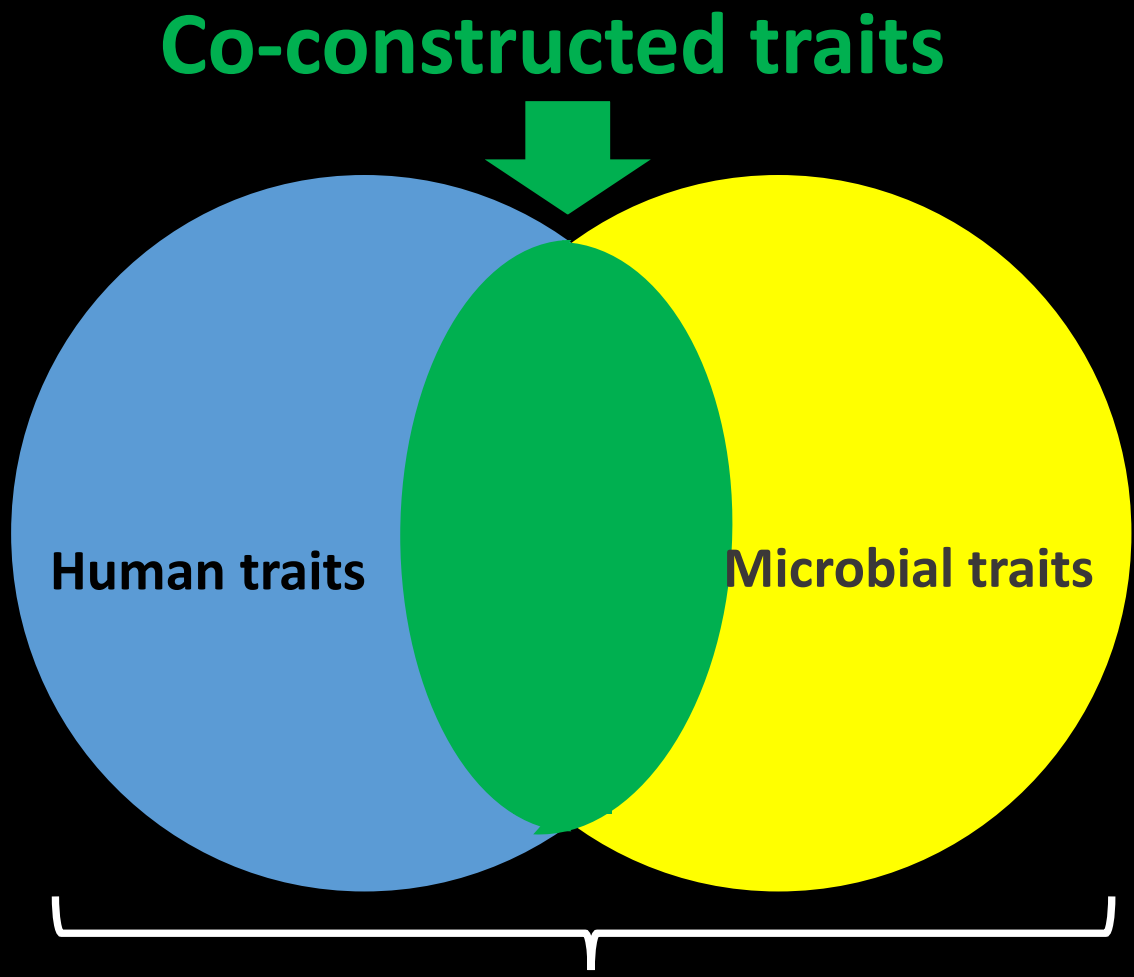
*Scott F Gilbert*

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



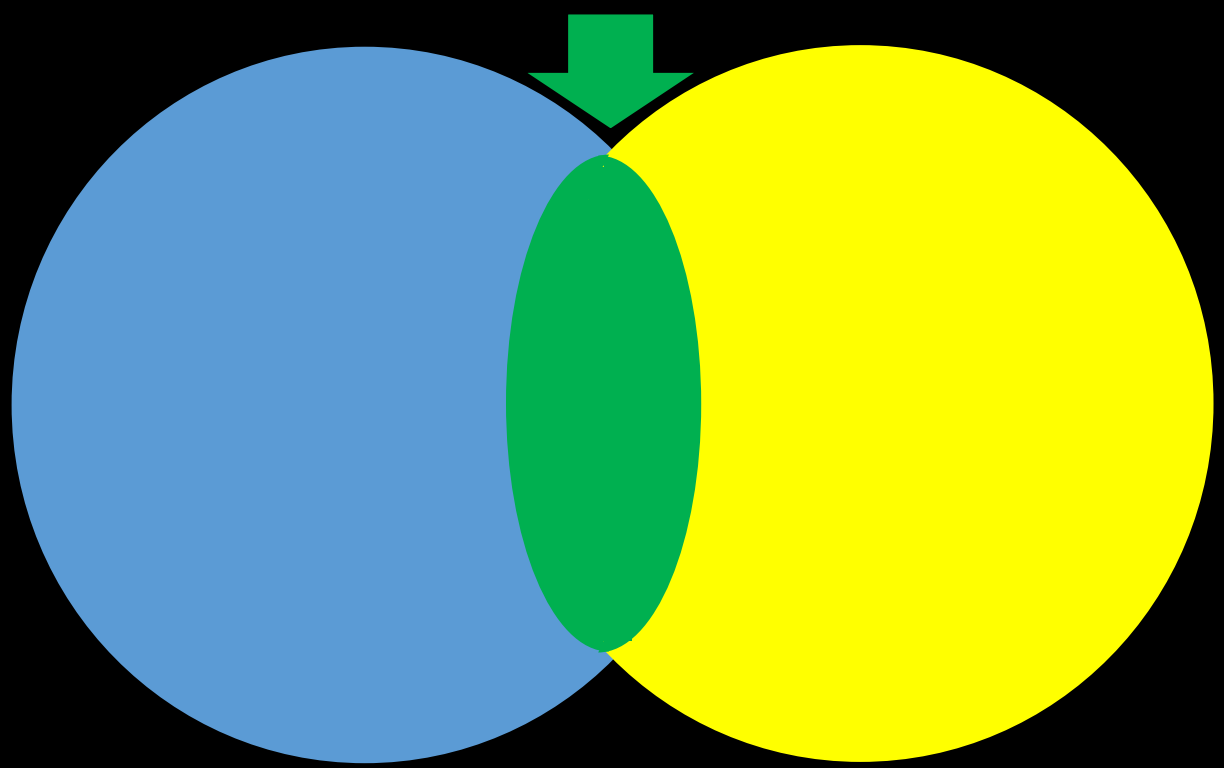


# *Homo sapiens* is discovering *Chosmo sapiens*.

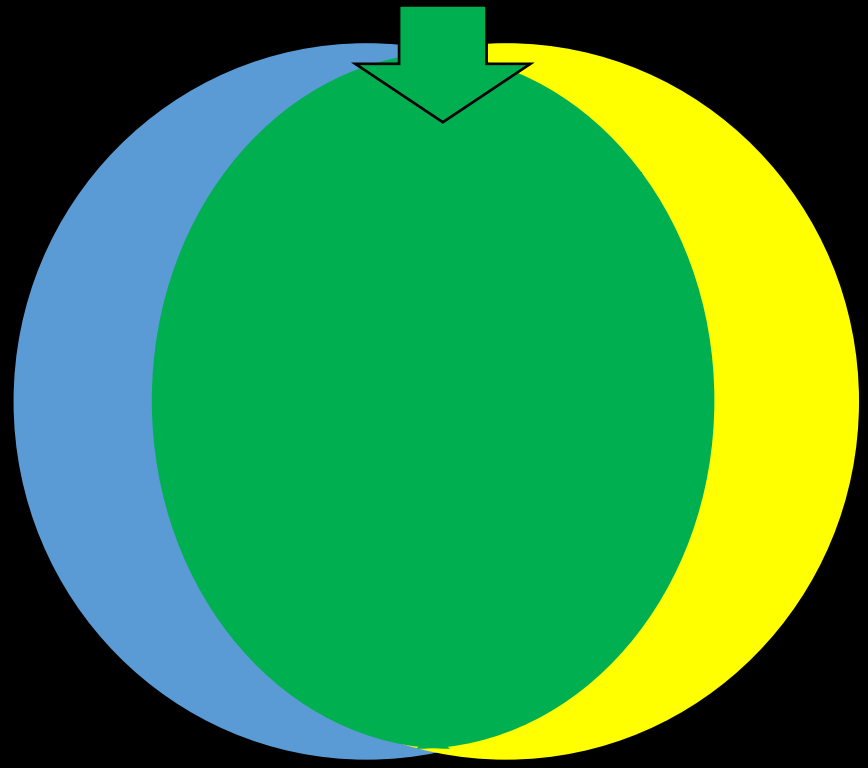
# The extent of this co-construction is under study.

Co-constructed traits



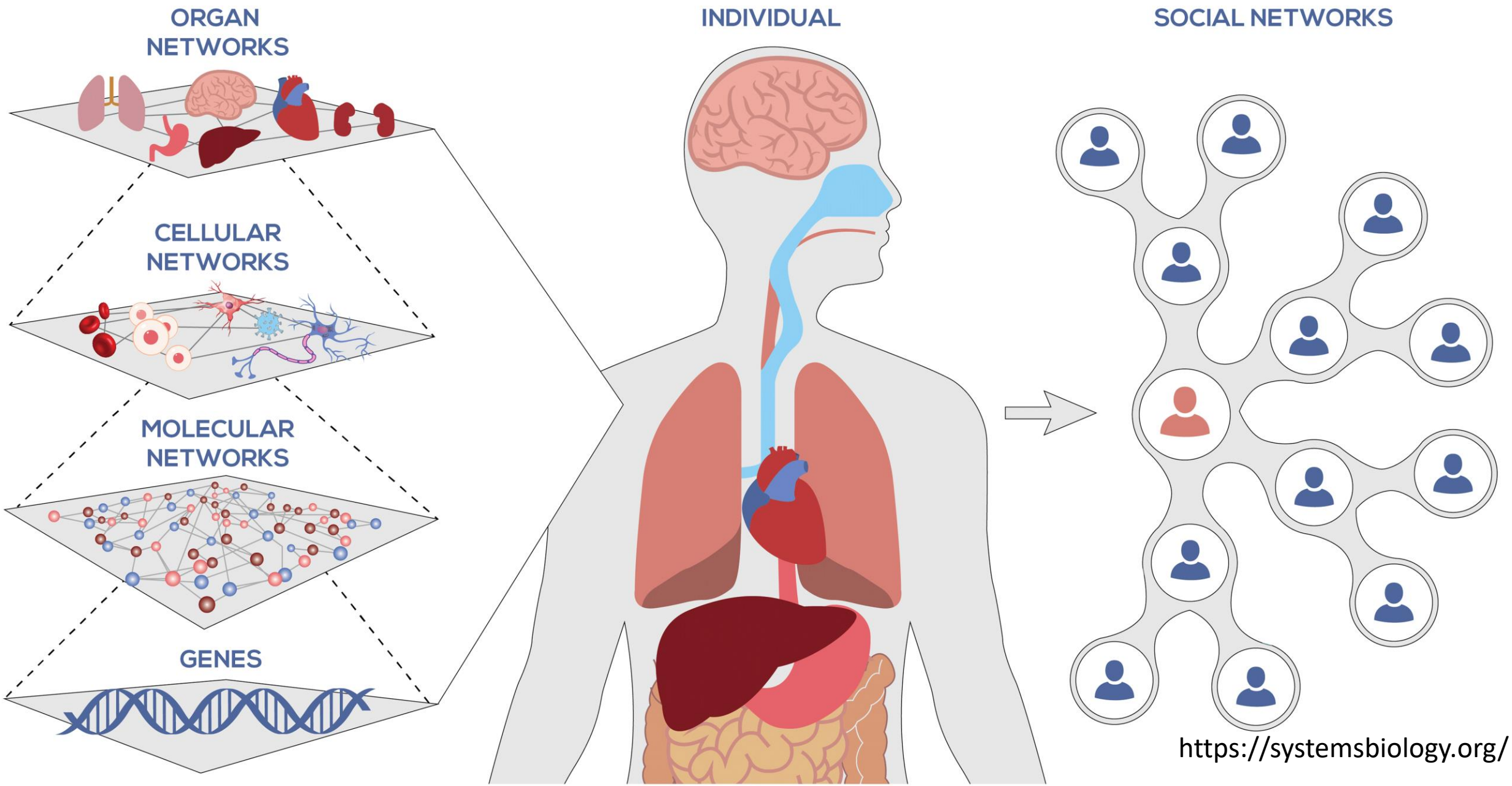
...

Co-constructed traits



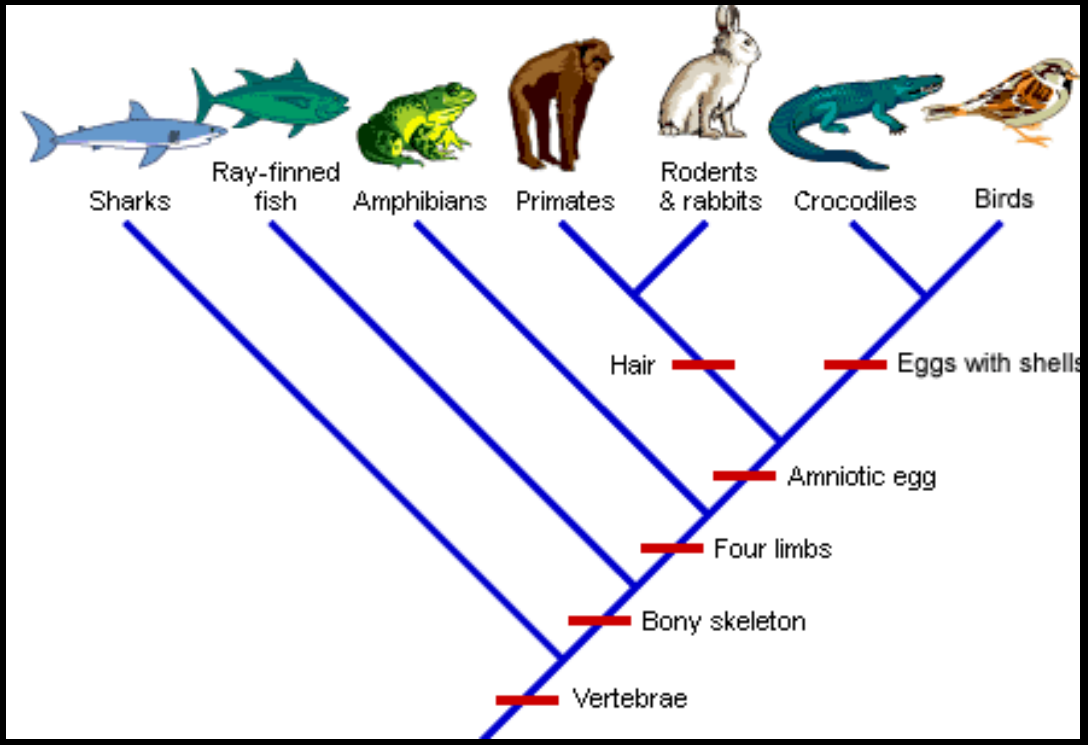
Vascularization, bones, digestion, immunity, obesity, behavior…

# We are composed of networks and part of networks.




https://systemsbiology.org/

# This conclusion holds for very many other species…

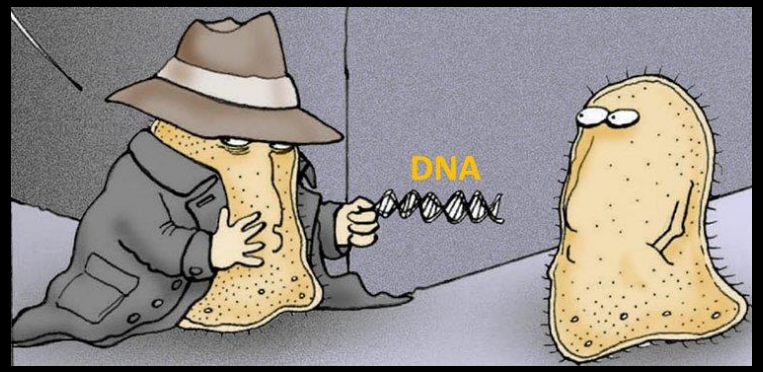


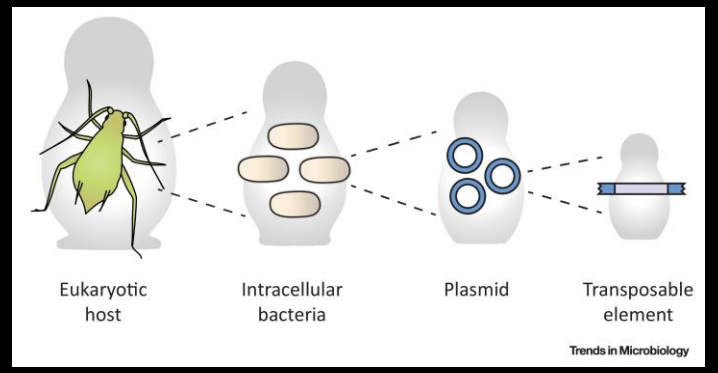

**Problem: a** classic **tree of the mere hosts lineages does not describe the processes responsible for co-constructed traits.**

**In fact, interspecific interactions can contribute to fundamental processes of evolution.**

- **Variation**: may come from such interactions

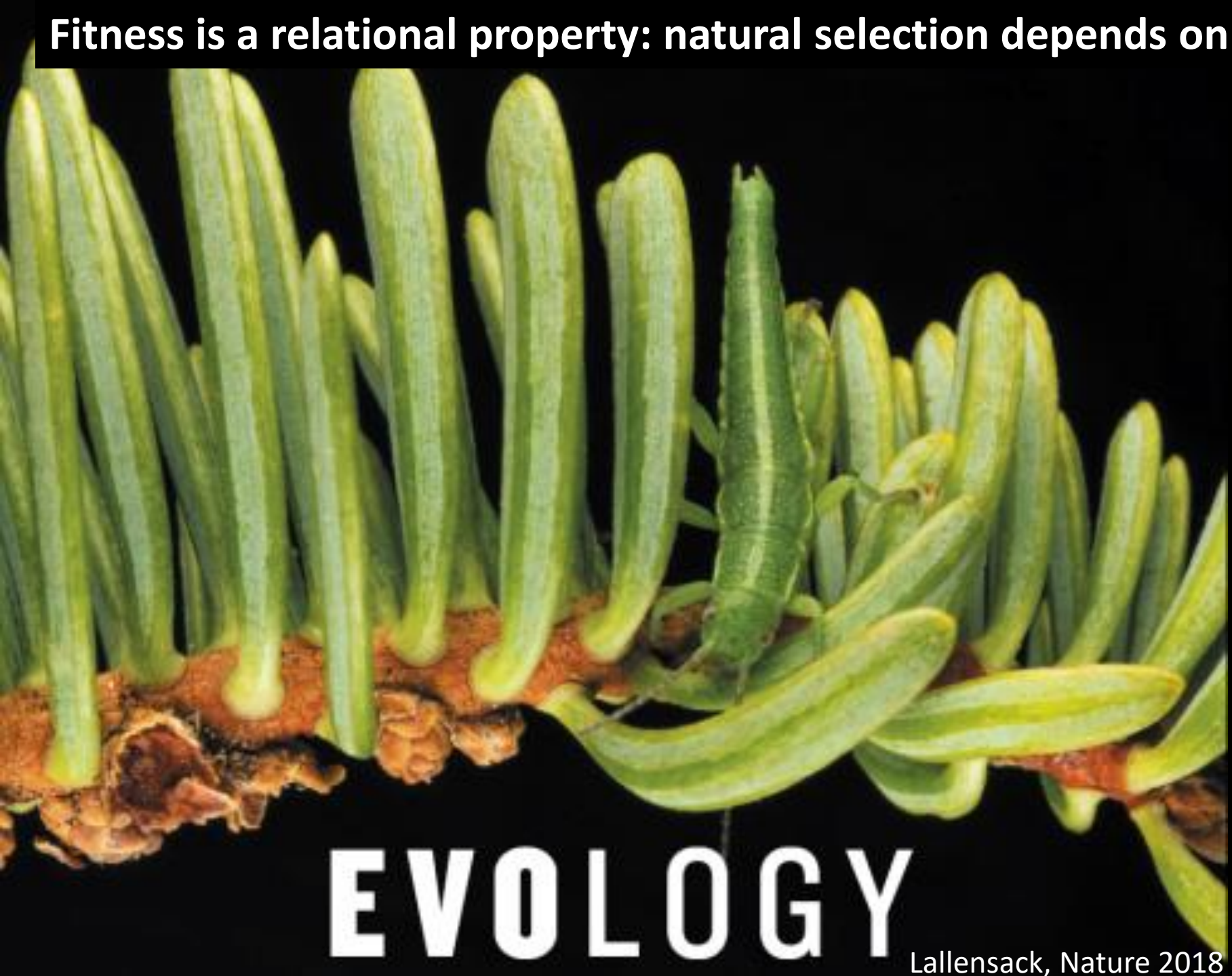
- **Transmission**: may involve such interactions




- **Fitness**: may depend on such interactions

# Fitness is a relational property: natural selection depends on the ecological network




Lallensack, Nature 2018

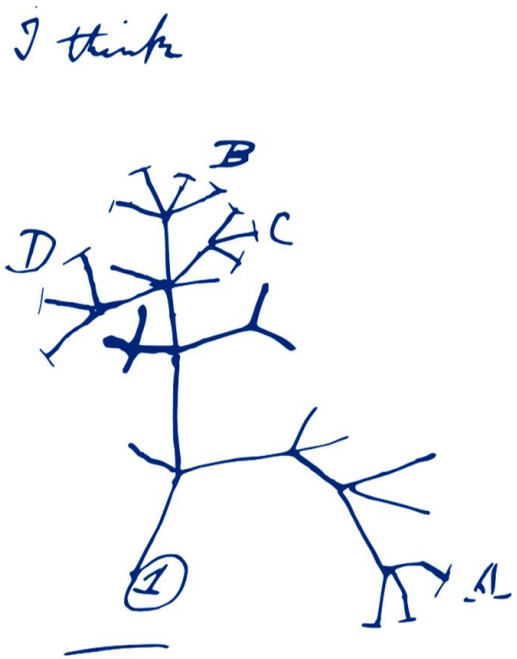
Farkas *et al.* **relocate** 1,500 **green or striped stick insects** so that some insects' coloration clashed with their new home.

Suddenly maladapted, these insects became targets for hungry birds, and that caused a **domino effect**[1]. Birds drawn to bushes with mismatched stick insects stuck around to eat other residents, such as caterpillars and beetles, stripping some plants clean.
**"It affects the entire community."**

All this happened because of an out-of-place evolutionary trait.

# To sum up, evolution has produced complex organisations

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

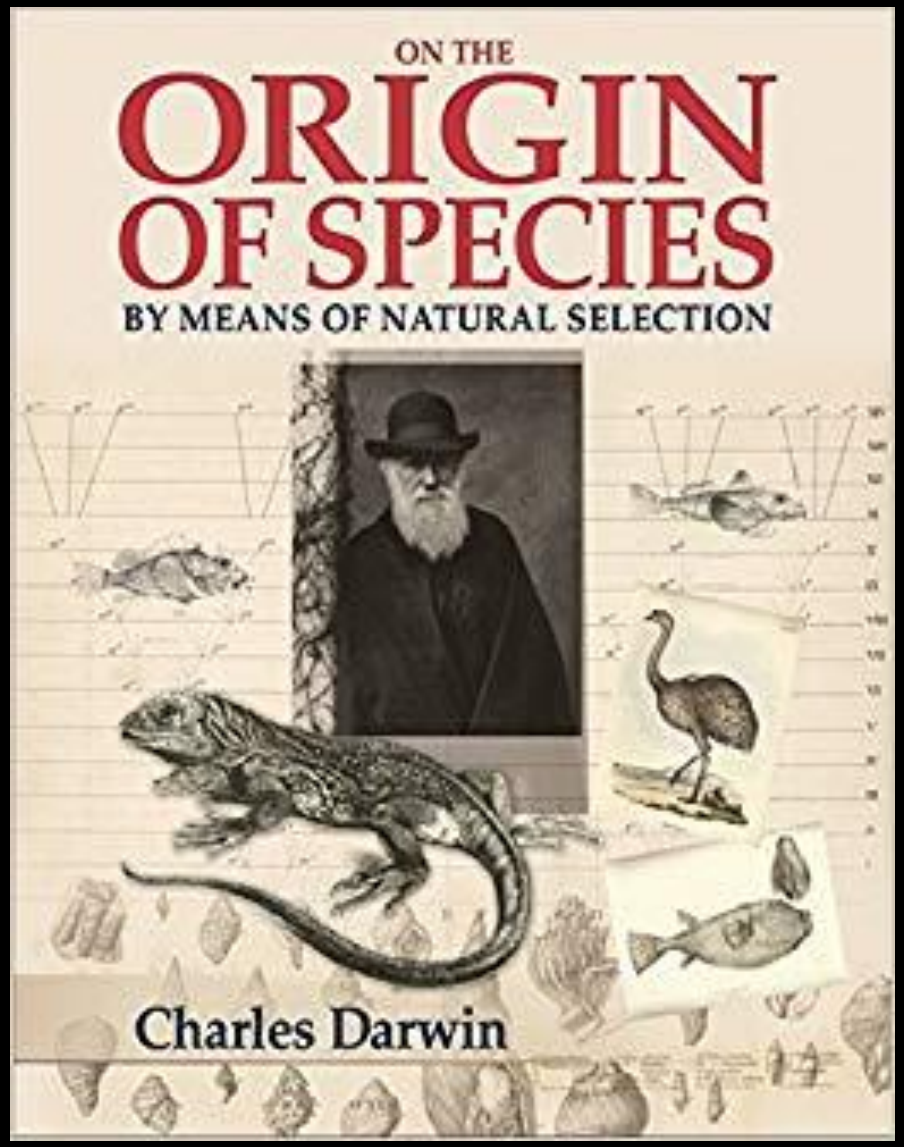


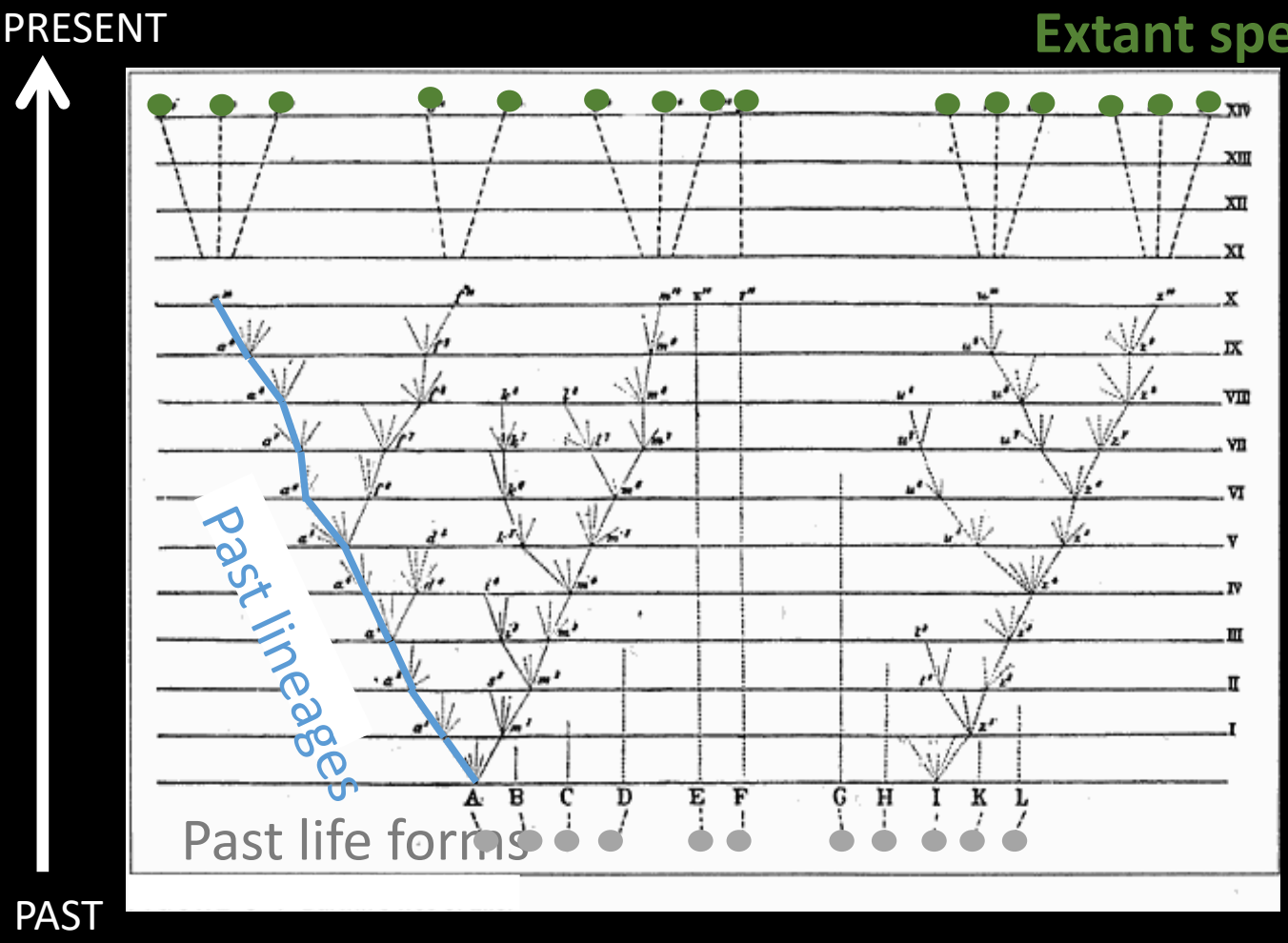

**An enhanced evolutionary biology seems warranted.**

# 2/ Exploring a first, novel research avenue

Expecting more diverse outcomes from natural selection than simple lineages, diverging as branches on a single tree.

# As suggested before, evolutionary biology uses natural selection to explain a tree-like pattern of evolution.



However, the connection between natural selection and a tree-like evolutionary pattern is not necessary.

PNAS

INAUGURAL ARTICLE

# Pattern pluralism and the Tree of Life hypothesis

W. Ford Doolittle* and Eric Bapteste

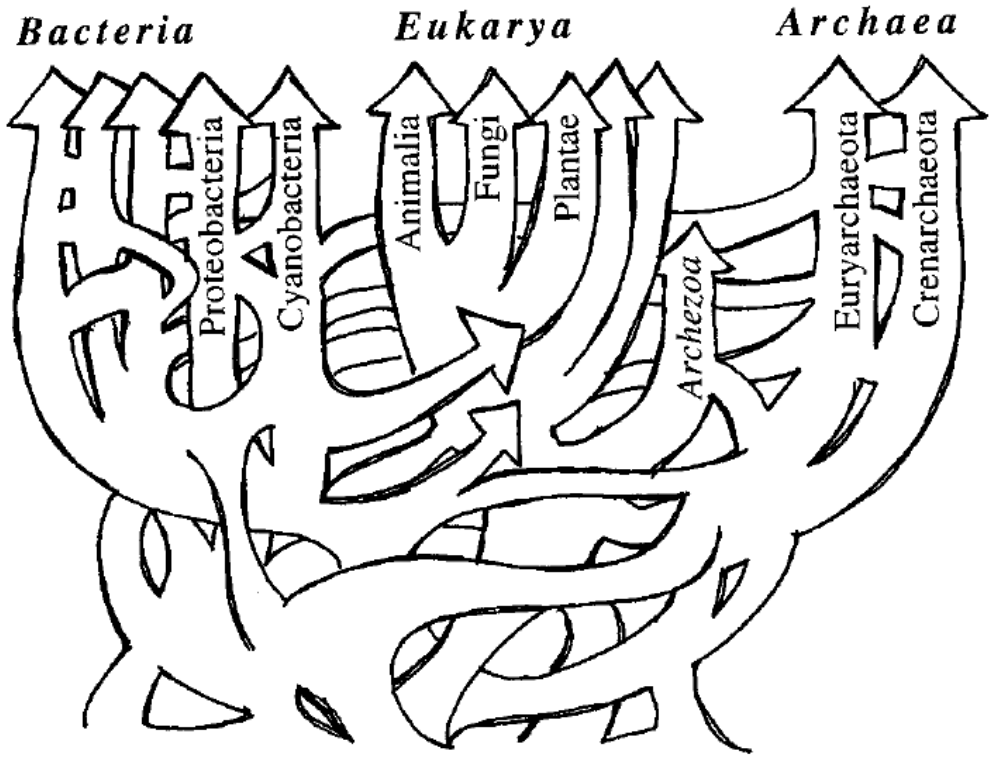
Department of Biochemistry and Molecular Biology, Dalhousie University, Halifax, NS, Canada B

This contribution is part of the special series of Inaugural Articles by members of the National A

Contributed by W. Ford Doolittle, December 5, 2006 (sent for review November 11, 2006)

**Darwin claimed that a unique inclusively hierarchical pattern of relationships between all organisms based on their similarities and differences [the Tree of Life (TOL)] was a fact of nature, for which evolution, and in particular a branching process of descent with modification, was the explanation. However, there is no indepen-**

discussing its
data.
This exerc
many areas
of the TOL

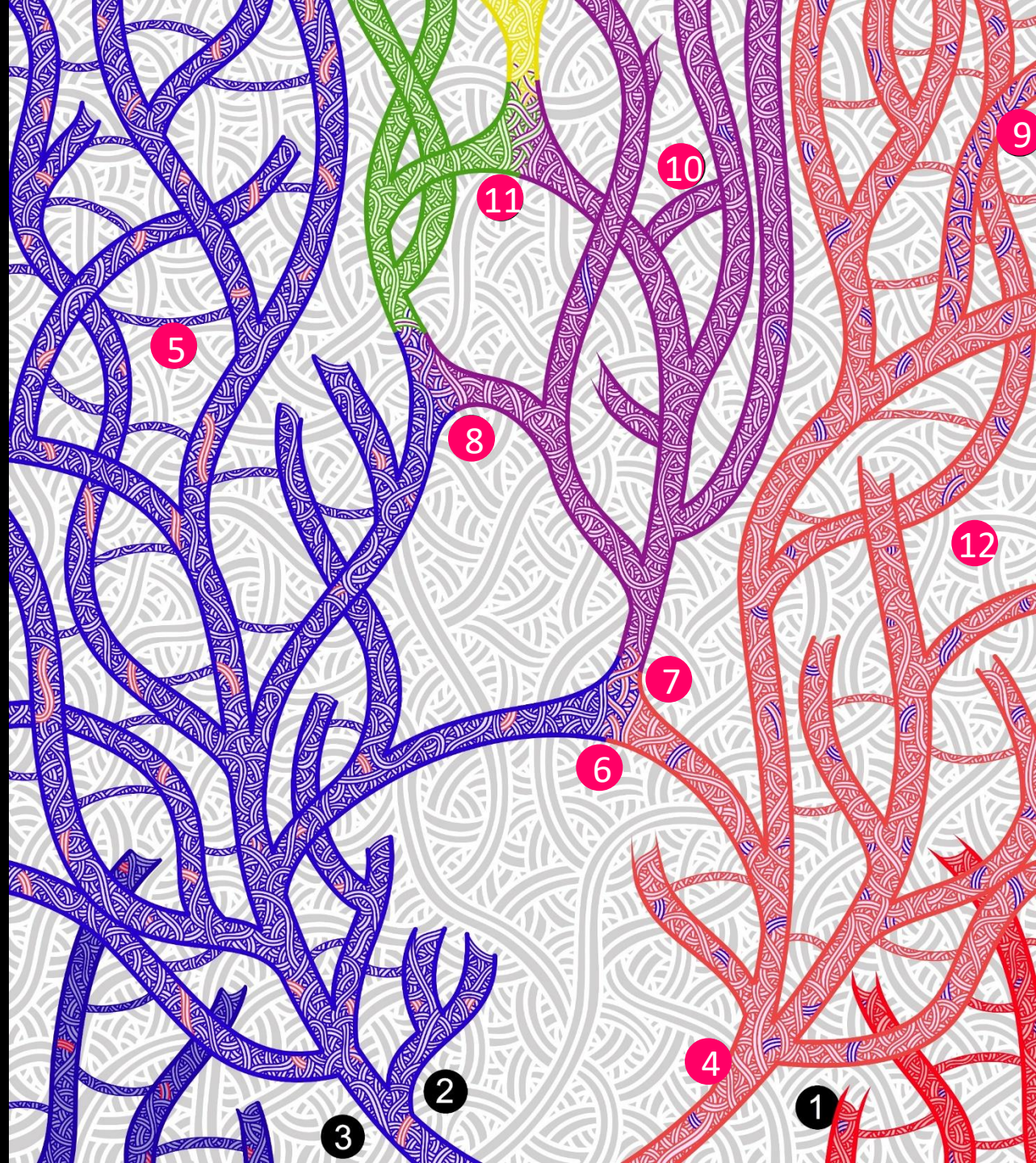



Doolittle, Science, 1999

# Many phenomena of reticulated evolution are now known

1) Extinction
2) Divergence
3) Coalescence

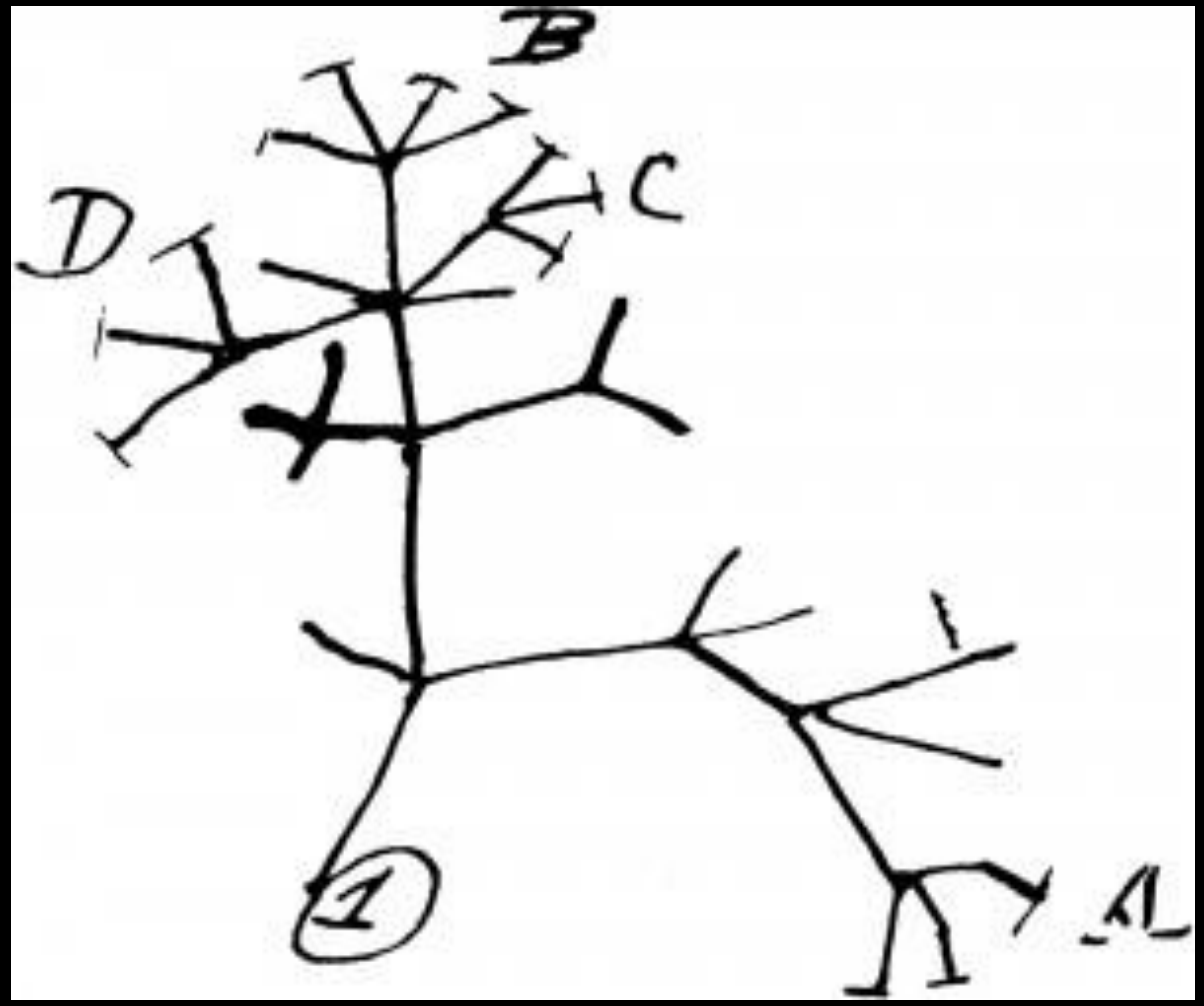
4) Molecular interactions, within lineages
5) DNA transfer, intra-Domain
6) Primary endosymbiosis (mitochondria)
7) Evolution of chimeric genes
8) Primary endosymbioses (plasts)
9) Massive inter-Domain DNA transfer (Haloarchaea)
10) Introgression
11) Secondary endosymbioses (plasts).
12) Non genetic interaction (grey background)

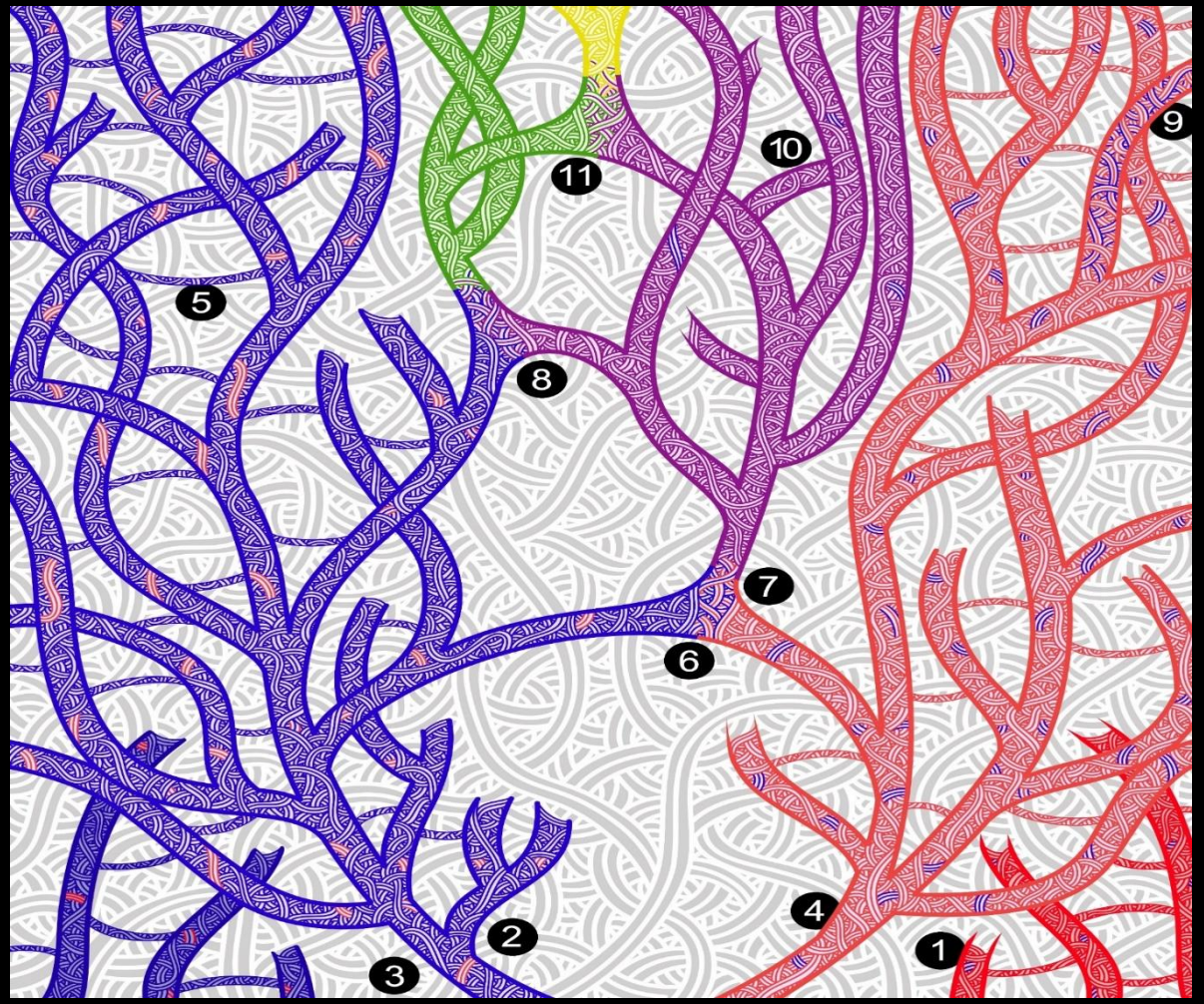



Papale et al. Trends in Micro 2020

# More evolutionary outcomes can be embraced by enhancing the theory

## Tree and networks are two different things…

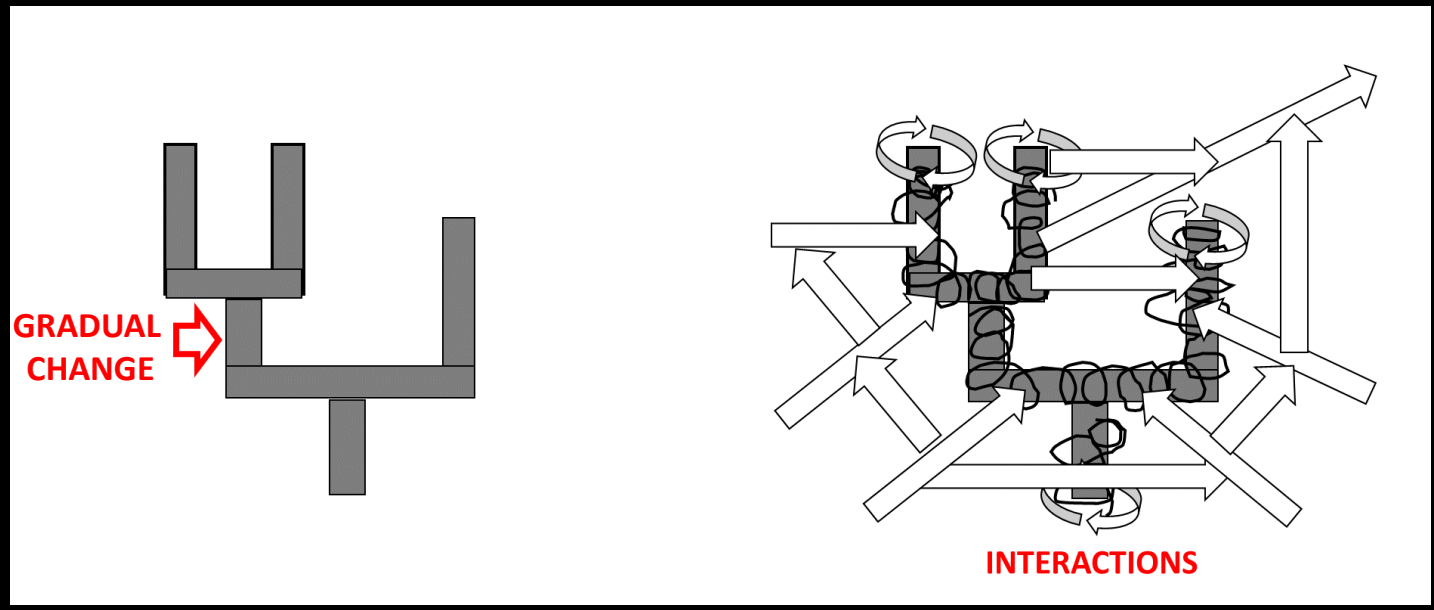



**The model to the left does not to predict that to the right.**

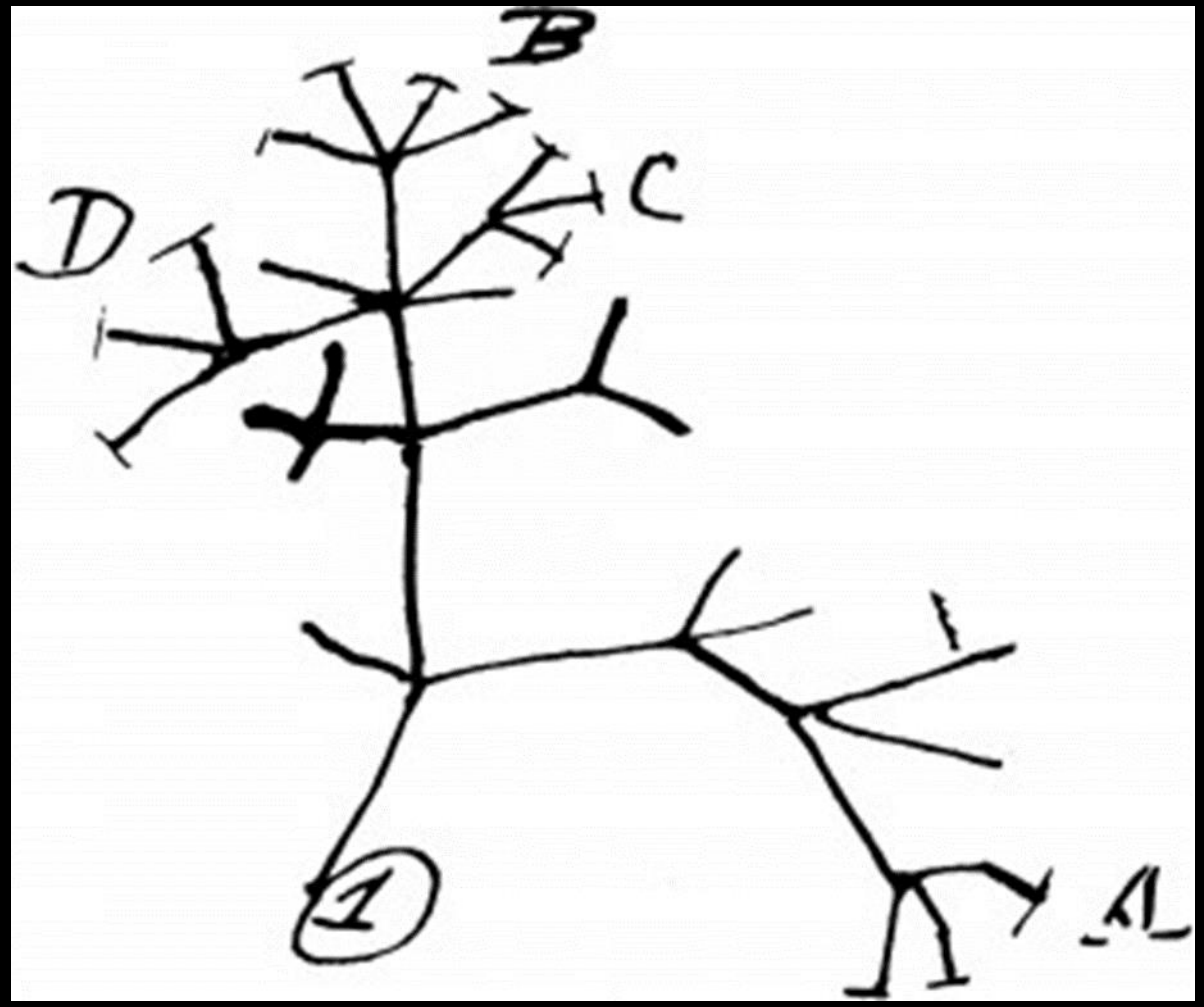
## 3/ Exploring a second research avenue

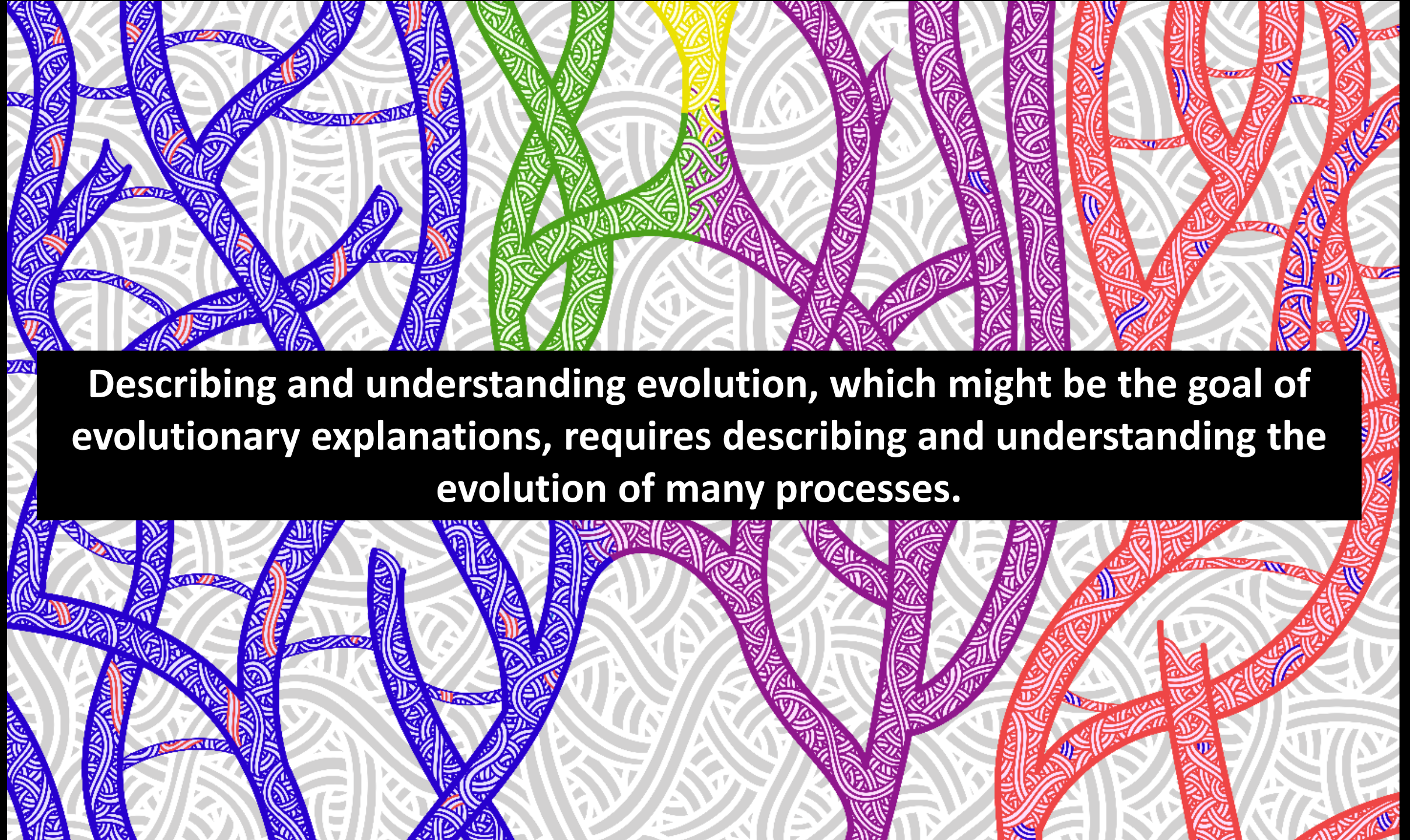
Coupling natural selection with an assumed plurality of evolutionary patterns, to open evolutionary studies to more objects/phenomena.



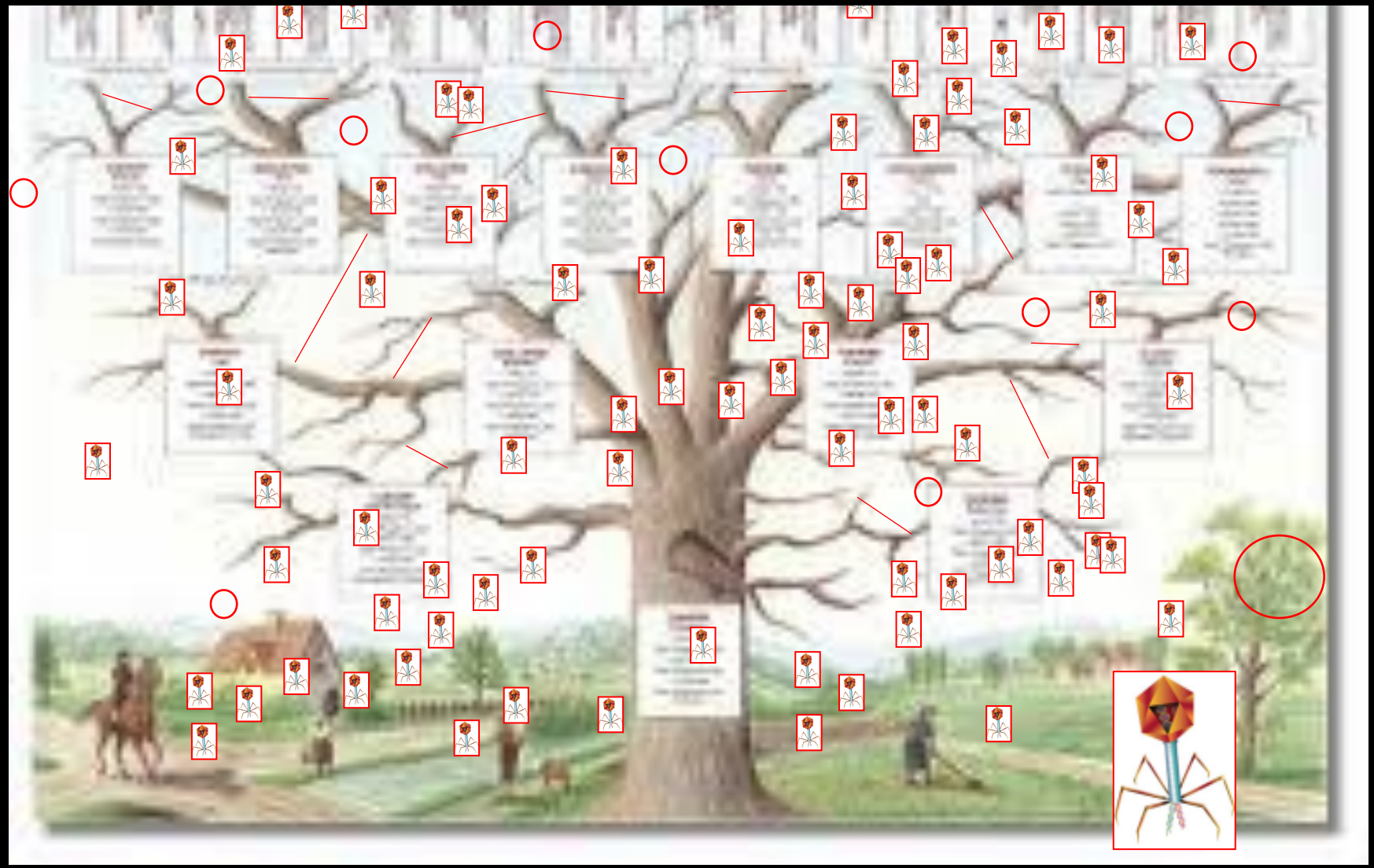

Bapteste, Huneman BMC Biology 2018

# The process of vertical descent with modification matters, but…

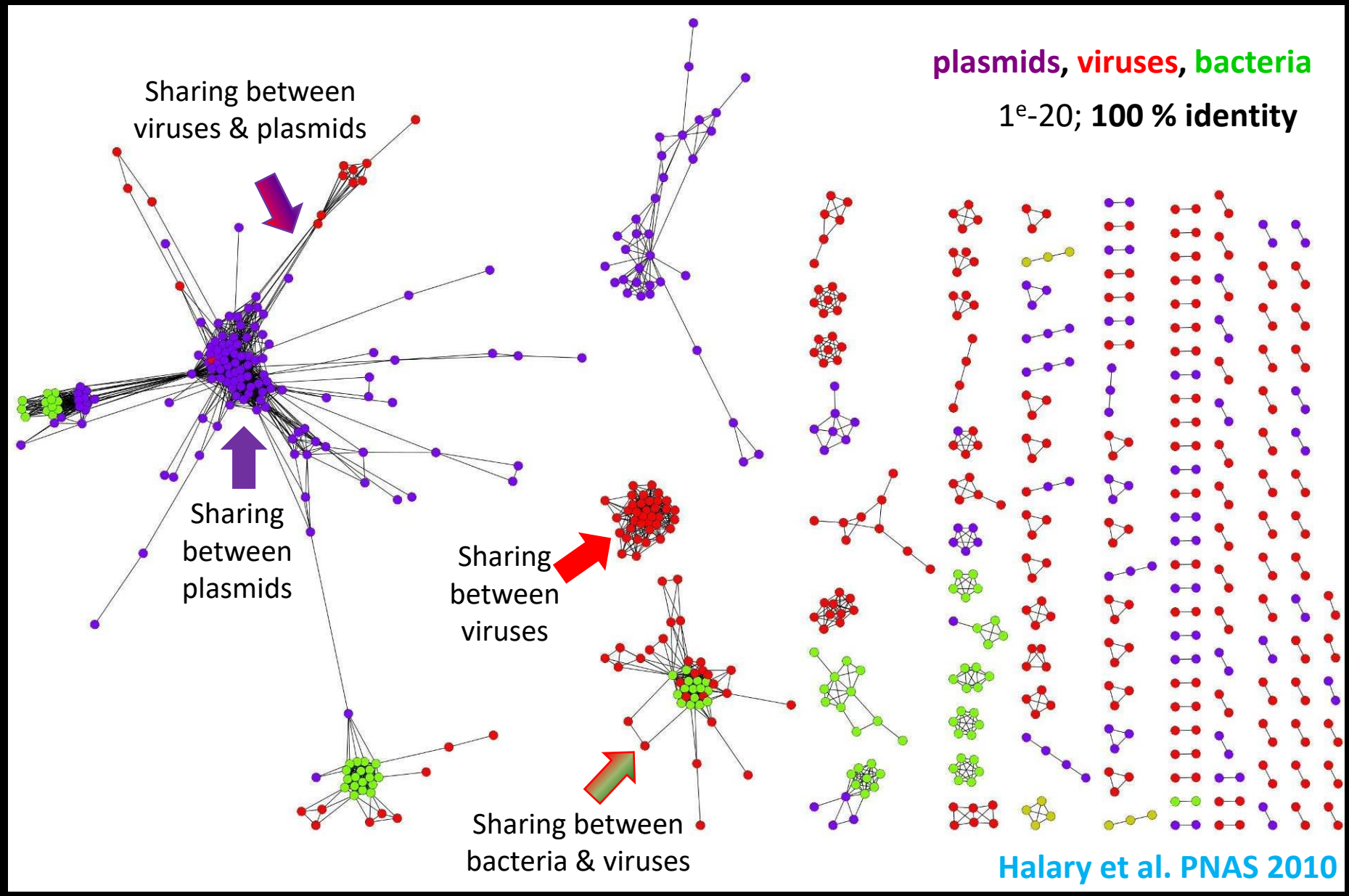



Describing and understanding evolution, which might be the goal of evolutionary explanations, requires describing and understanding the evolution of many processes.

Let me elaborate upon a few additional examples:
when evolving entities are not arising from a single last common ancestor, a single genealogical tree cannot represent their entire evolutionary history.

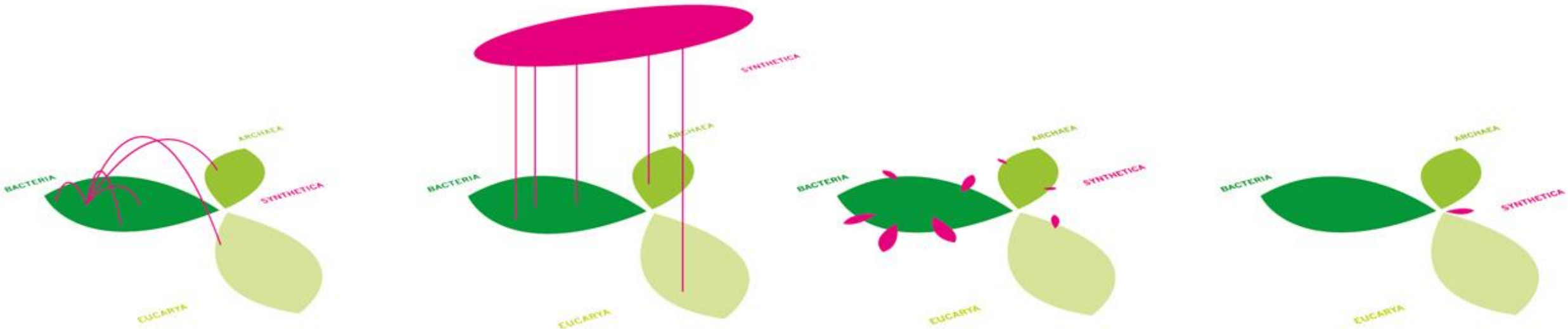


# Alternative patterns – such as networks of gene sharing- allow to study the evolution of both organisms and mobile elements (sometimes merged, sometimes separated at the gene level).



# A similar case for pattern pluralism could be made for Synthetic organisms (Synthetica).

**Even though they may not share a unique common ancestry with natural organisms, the evolution of Synthetica may deserved to be tracked**

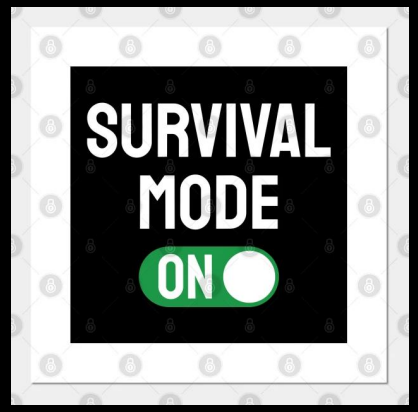



ALEXANDRA DAISY GINSBERG The Synthetic Kingdom: A Natural History of the Synthetic Future 2009

**While pattern pluralism  appears sound, one kind of evolutionary pattern, the interaction network, however, is especially likely to support an especially broad evolutionary thinking.**

## 4/ Exploring a third  research avenue

Embracing a simpler, persistence-based account of natural selection, coupled with interaction network modeling, to open evolutionary studies to even more objects/phenomena.

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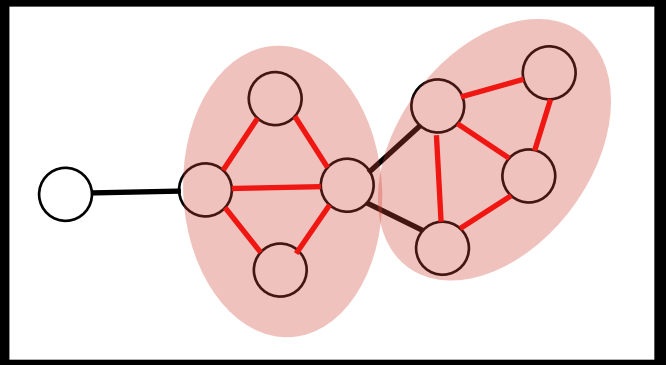
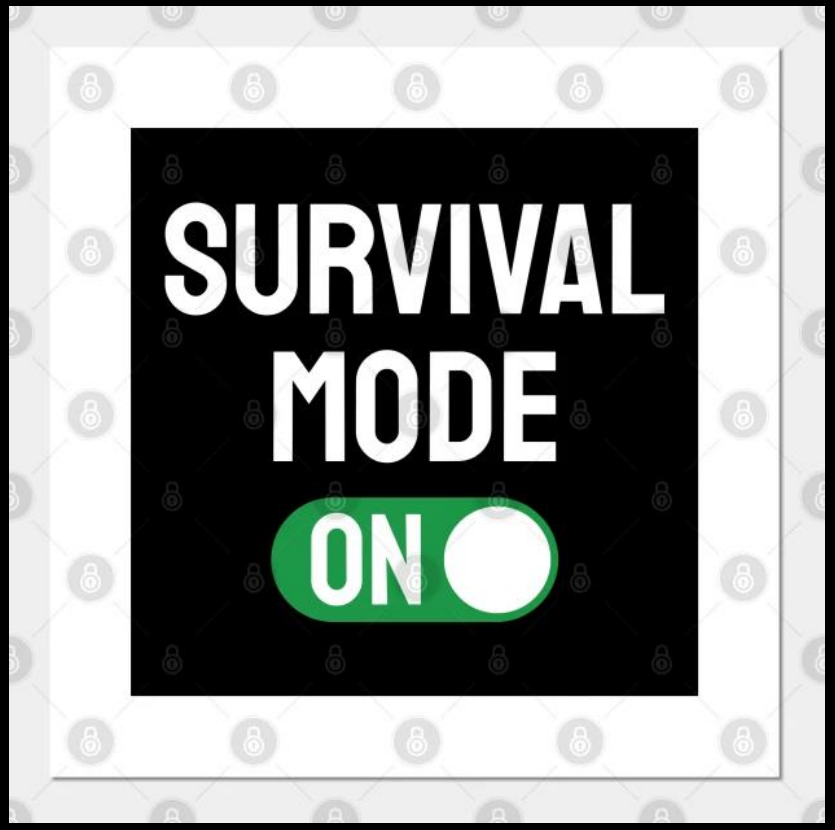


My persistence-based account of selection is deliberately very naïve.

Whatever property produces differential persistence between entities can support a form of selection.

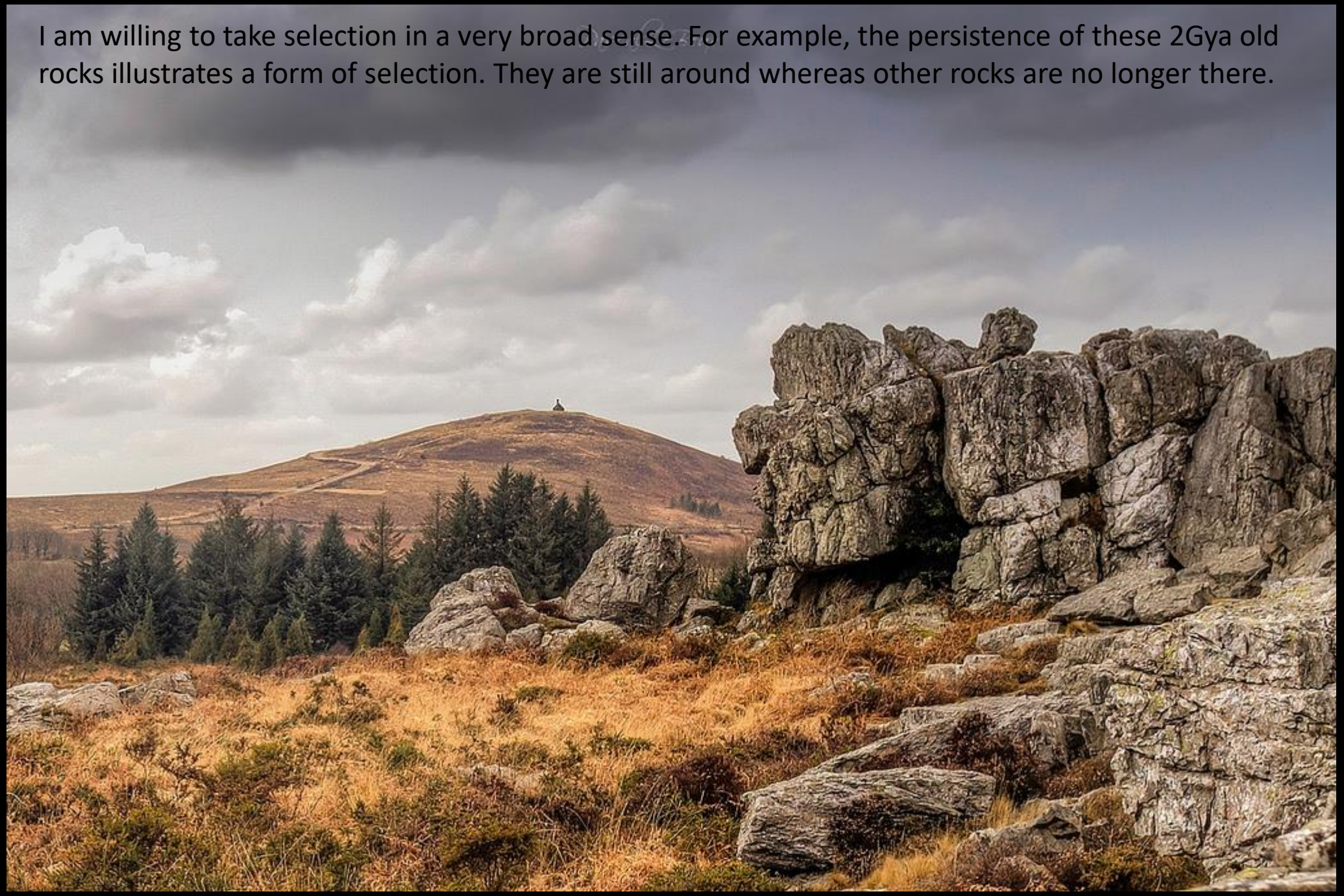



F. Doolittle

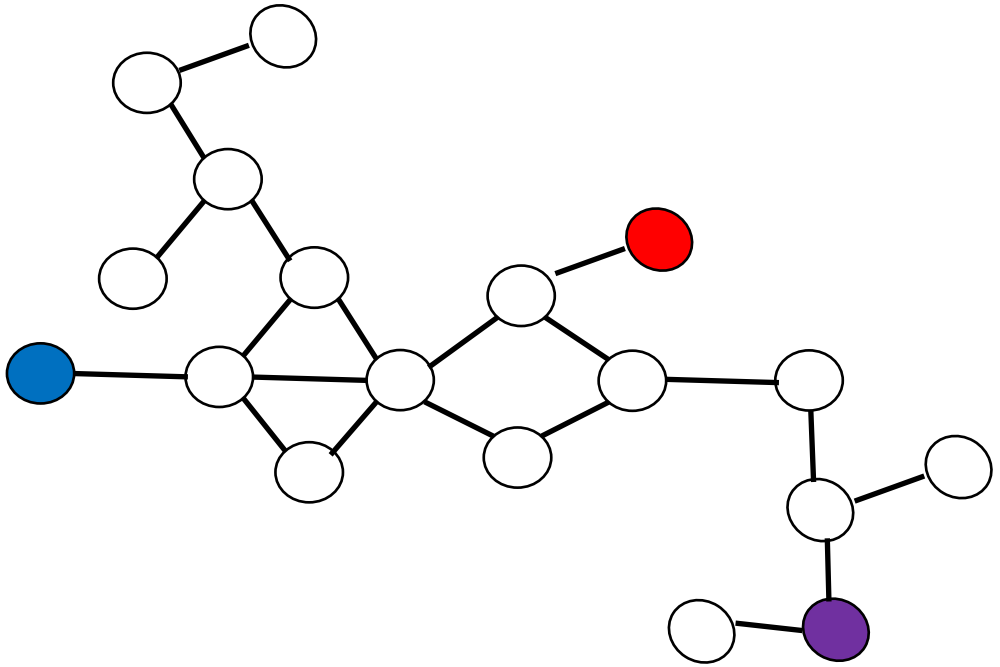
F. Bouchard

Enhanced persistence= a form of increased fitness

I am willing to take selection in a very broad sense. For example, the persistence of these 2Gya old rocks illustrates a form of selection. They are still around whereas other rocks are no longer there.



My conception of an interaction network is also very simple.



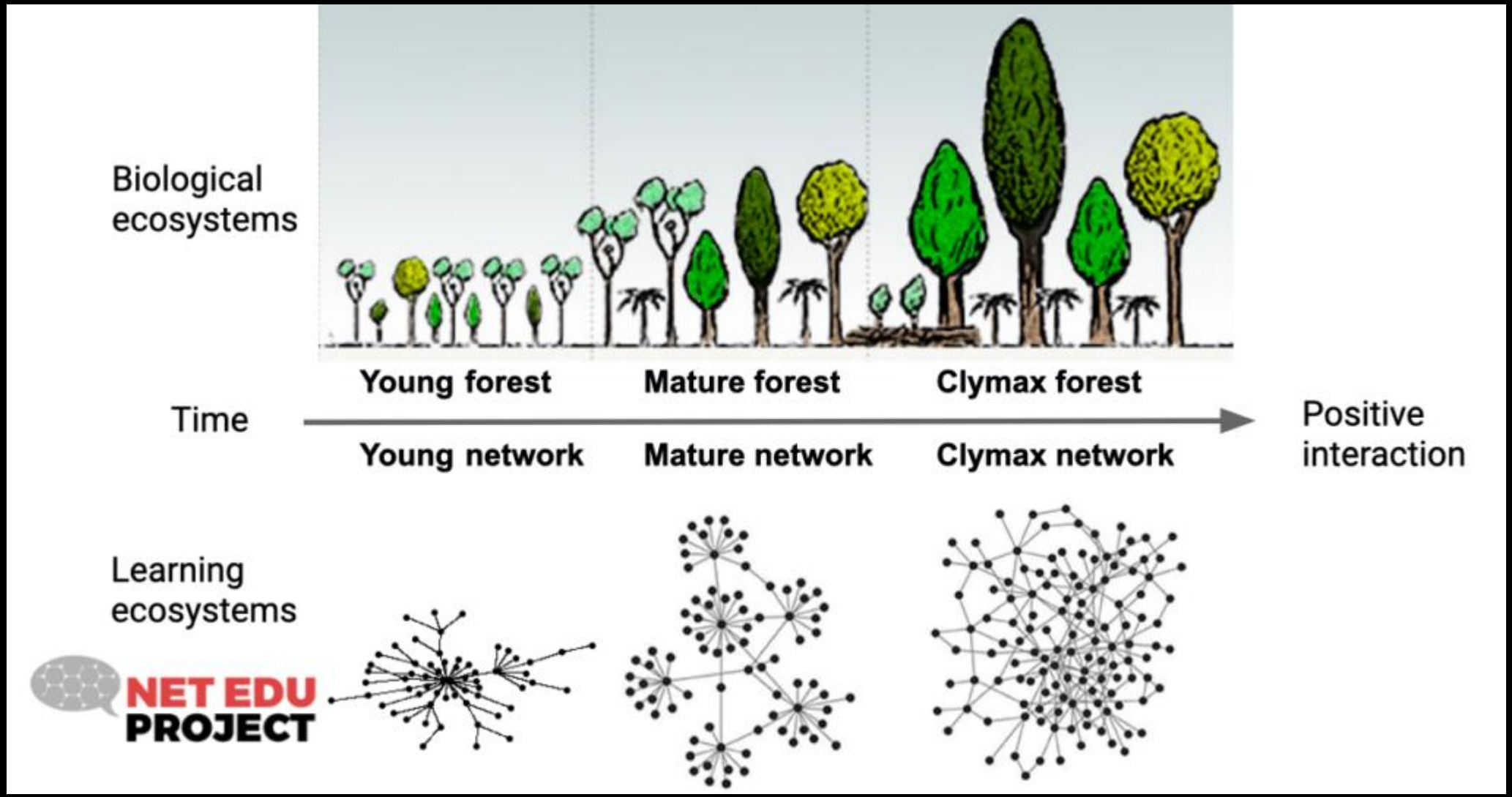
**Interaction network**

**Entity from family 1**
**Entity from family 2**
**Entity 3**

But this simple model can be used to track the dynamics
– and even the evolution- of very complex phenomena

Watson et al. Trends in Micro 2020.

# This modeling is used for instance to track key aspects of the dynamics of ecosystems.




https://www.neteduproject.org/2020/11/13/how-learning-ecosystems-evolve-and-how-can-leaders-weave-the-whole-process/

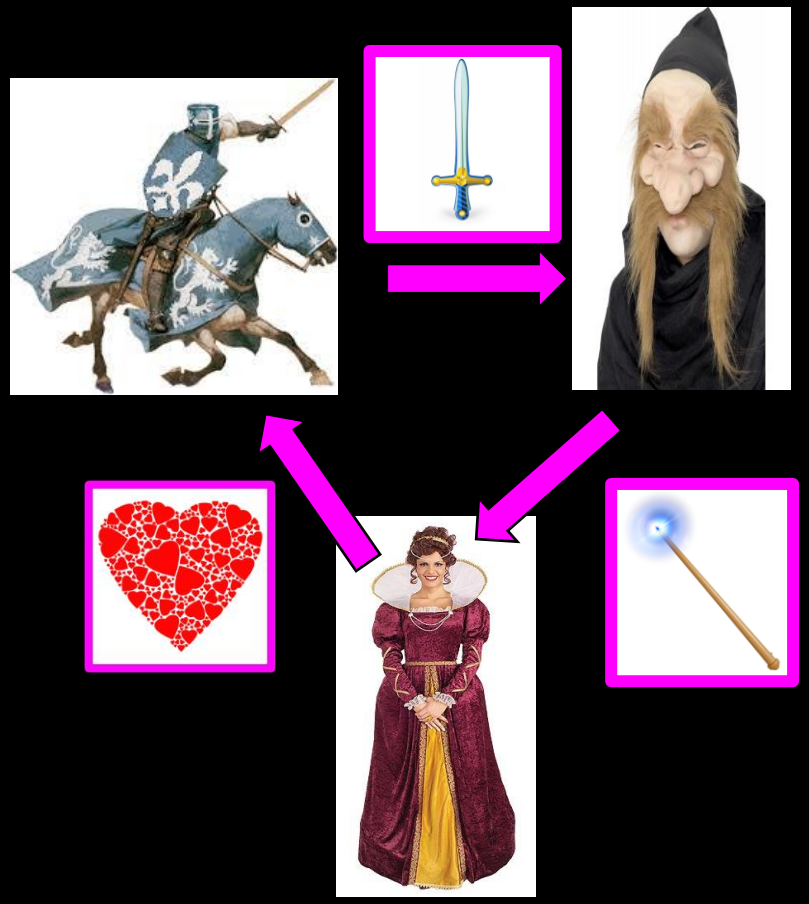
# More generally, it can be used to investigate the evolution of processes sustaining Life.

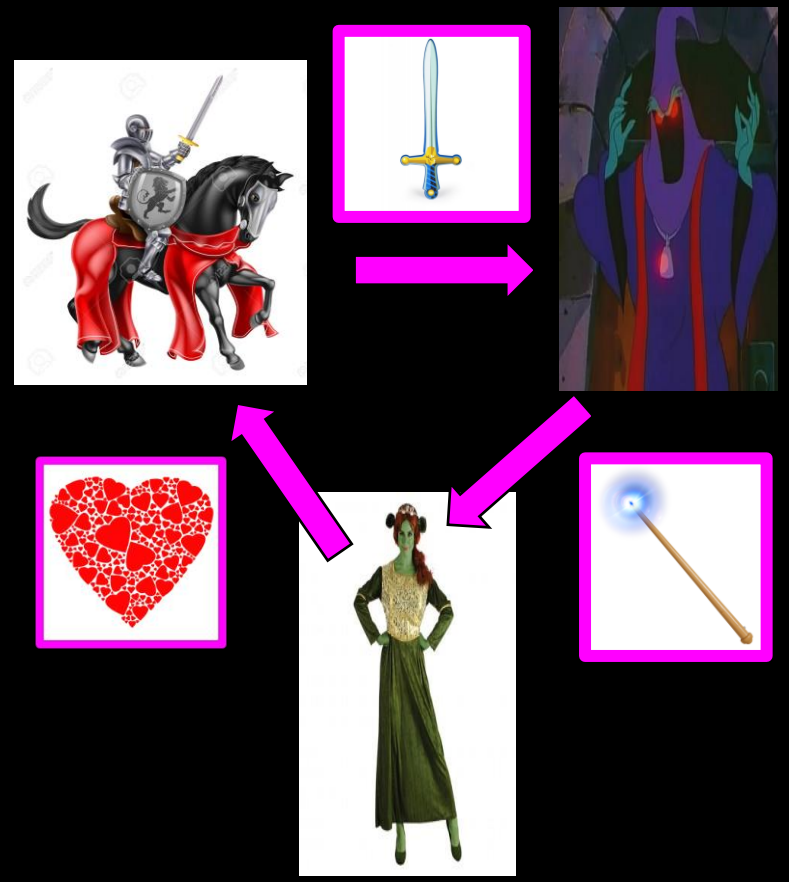

**Explaining the evolution of organisations, typically that of ecosystems, is a broader issue than infering relatedness between species.**

**This approach could provide very different insights on the evolution of interdependencies and resilience in the living world …**

**Usually, evolutionary biology studies focus on individual entities, and their lineages.**

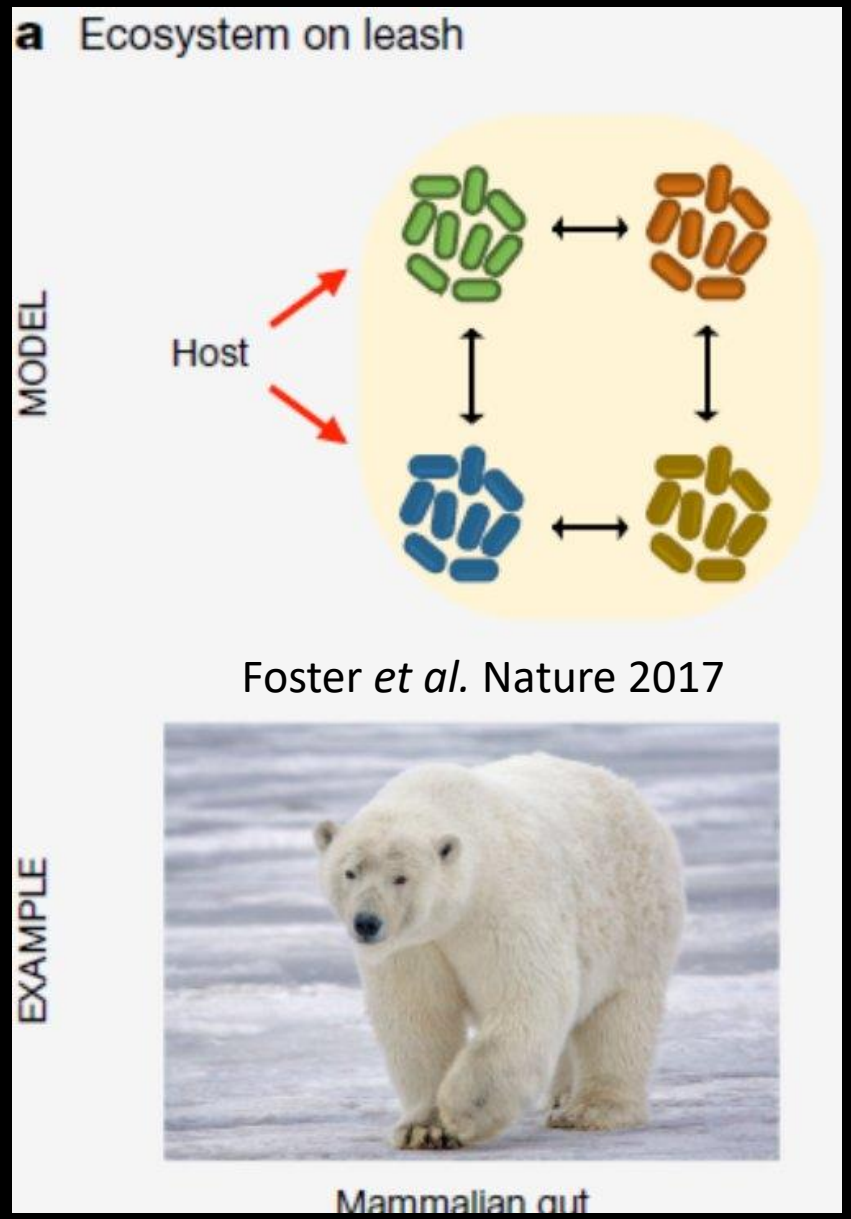
Networks allows to investigate processes to which these traditional biological objects take part.



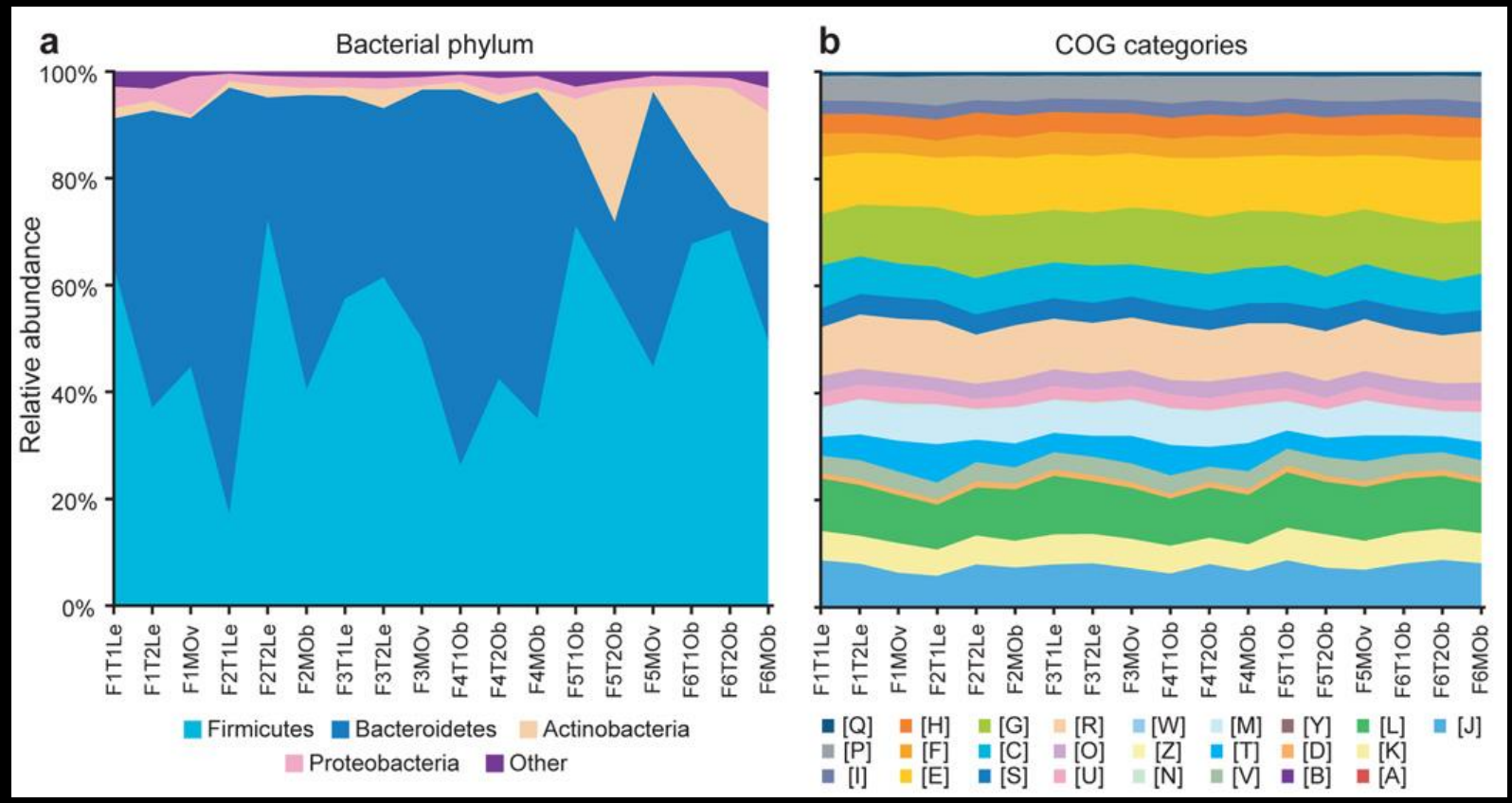


➡ Some interaction patterns re-occurs

# This situation typically occurs within host-associated microbiomes.




Foster *et al.* Nature 2017

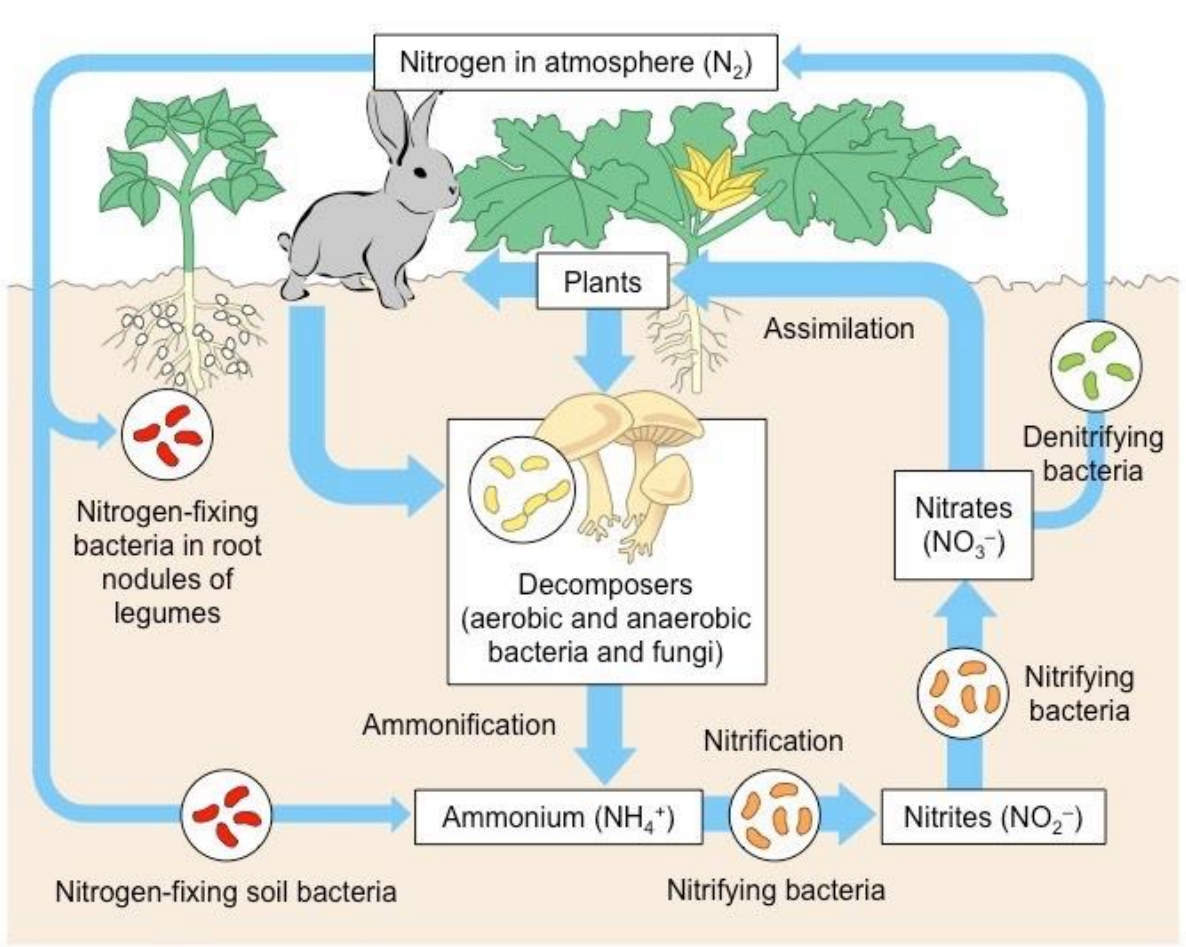


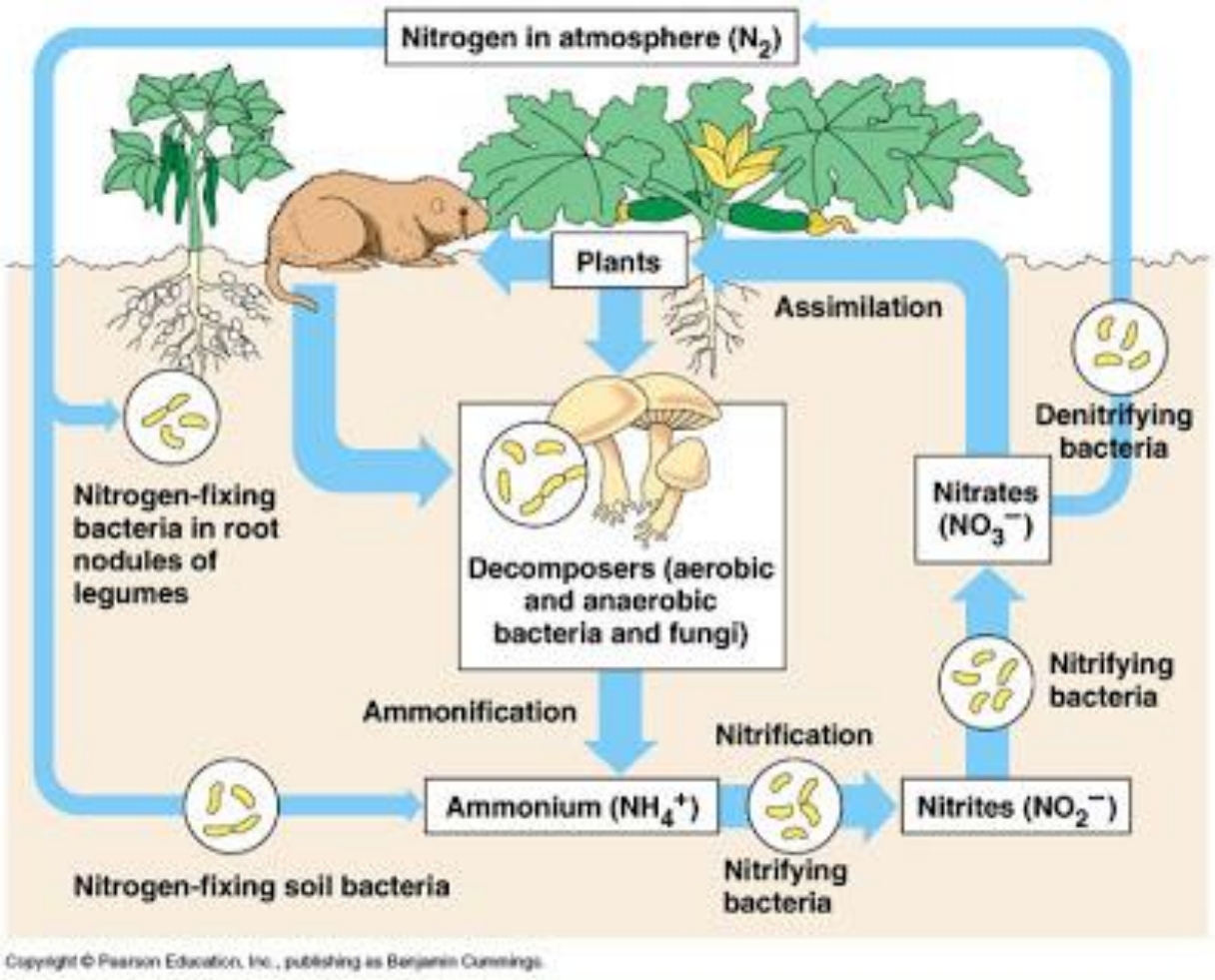


Turnbaugh *et al.* Nature 2009; Dinsdale et al. Nature, 2008; Doolittle & Zhaxybayeva, Bioscience, 2010 ; Yachi & Loreau, PNAS 1999

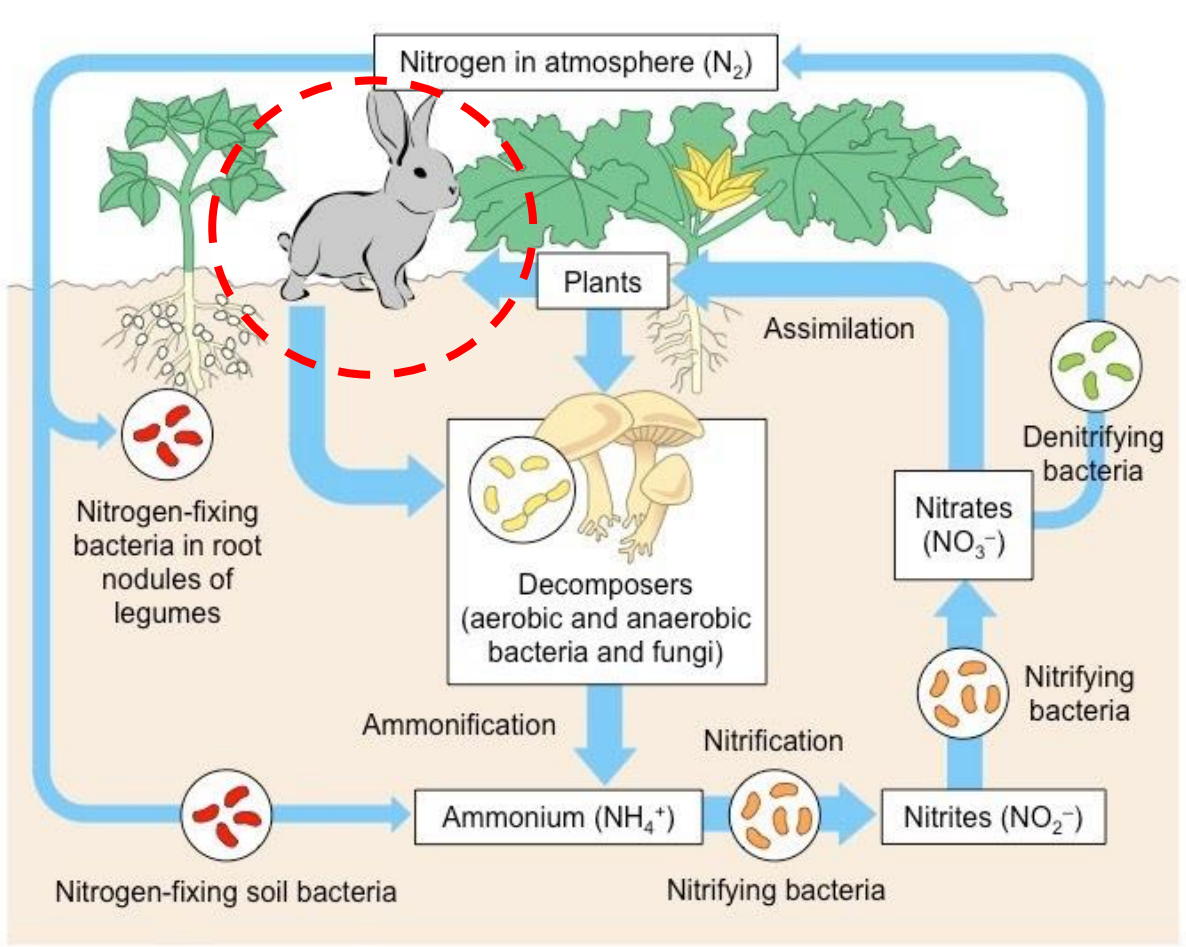
**An ecosystem can get selected** and evolve. This departs from a classic organismal-centered perspective on evolution.

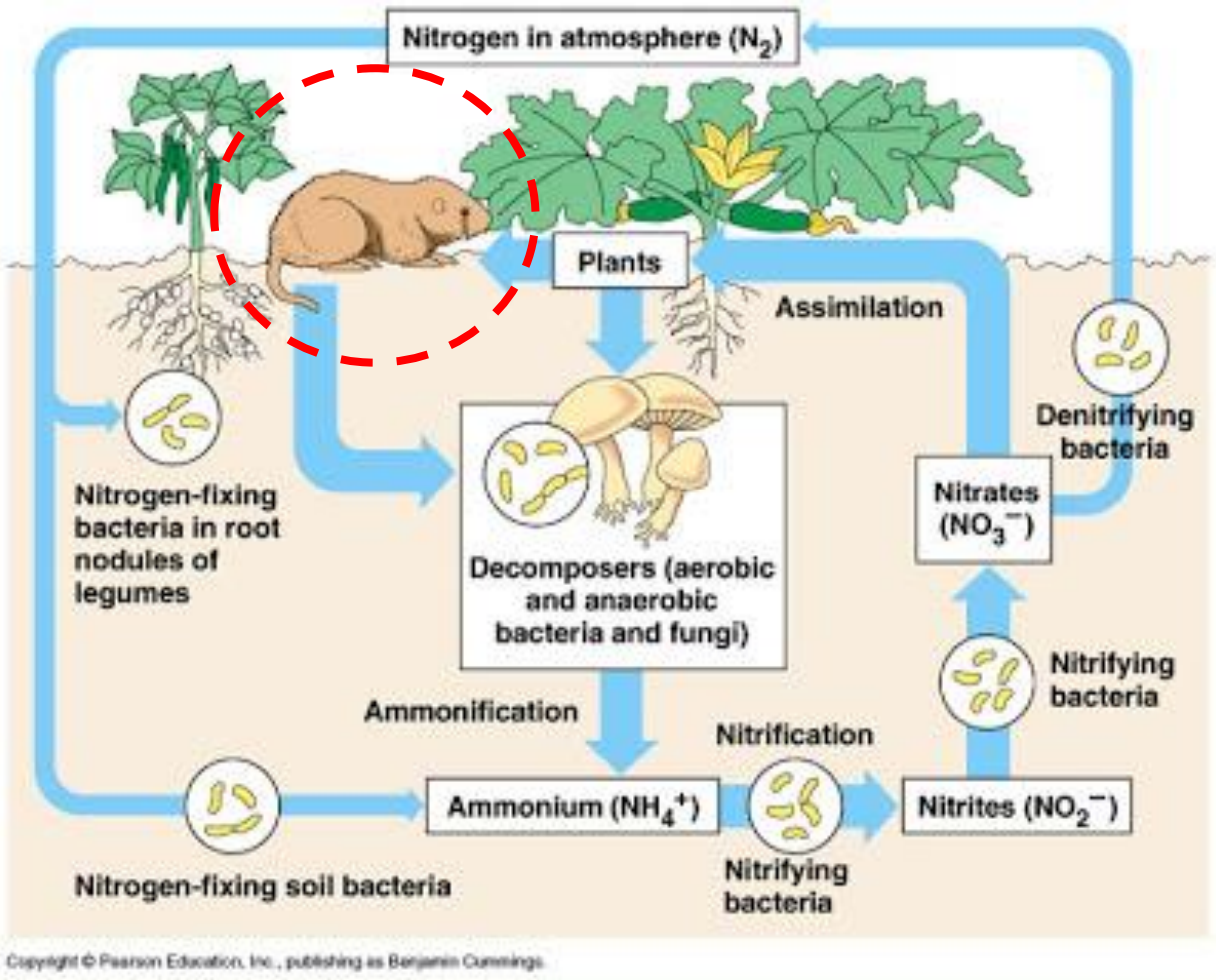
# Reccurent interactions forming functional assemblages is also possibly observed in biogeochemical cycles.



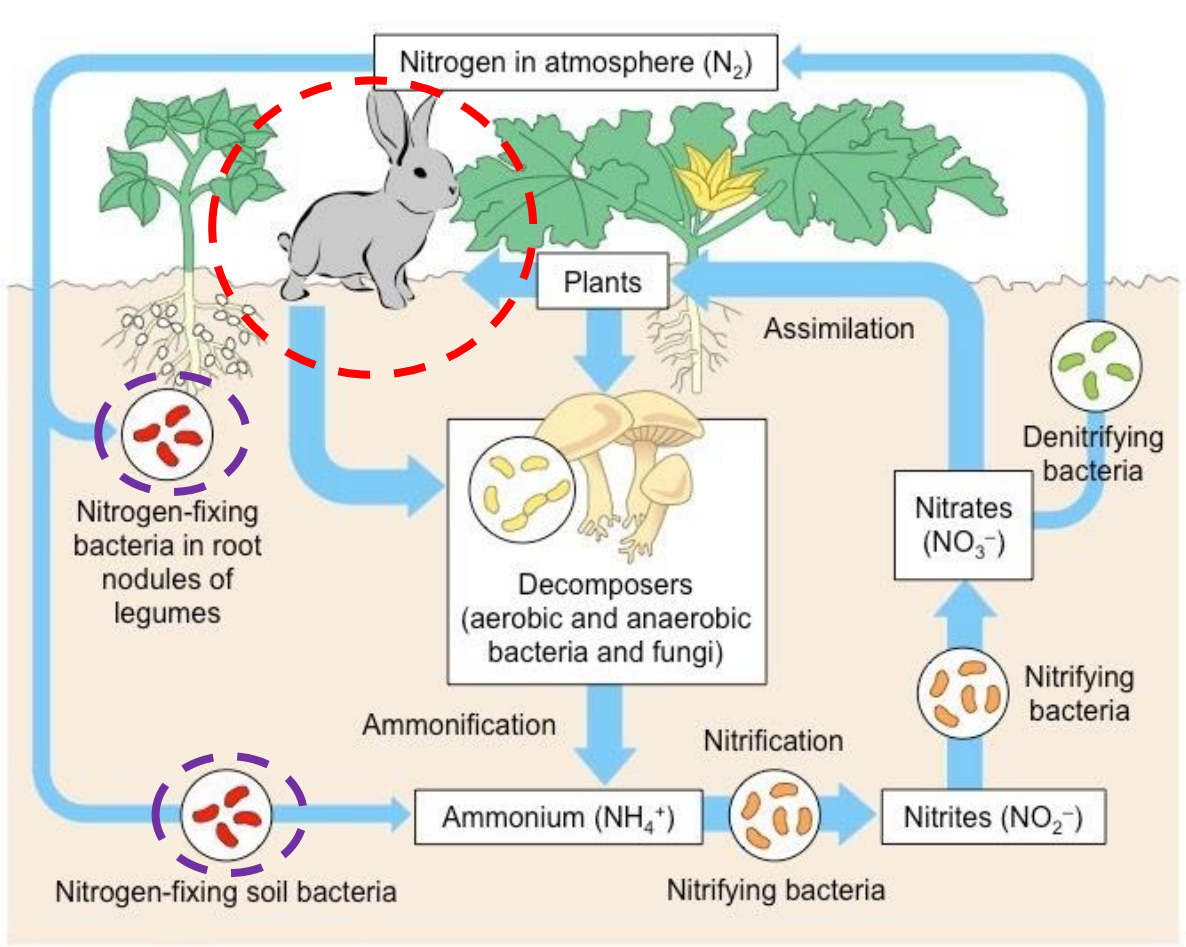



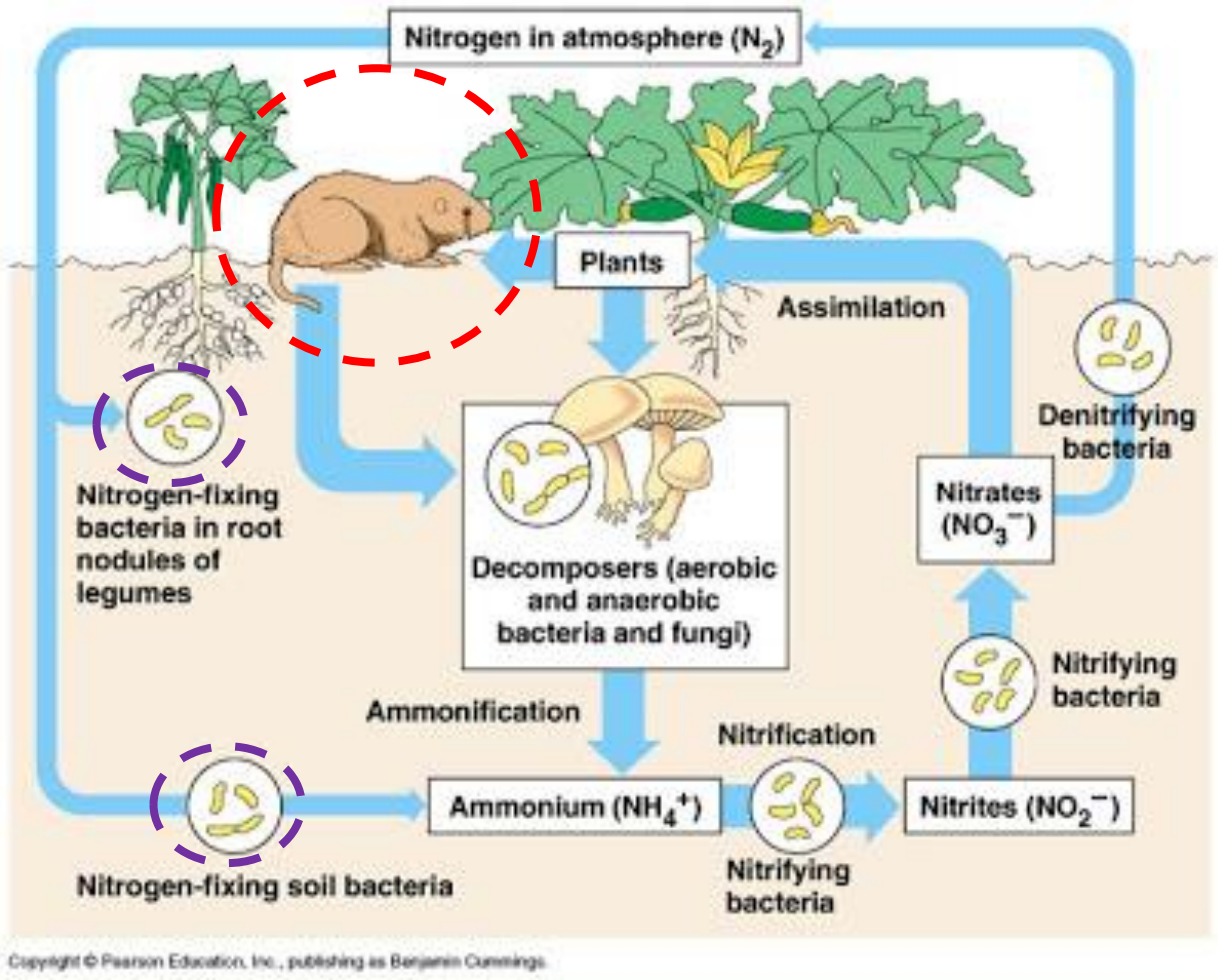
# Nitrogen fixation can be mediated by sets of different actors.



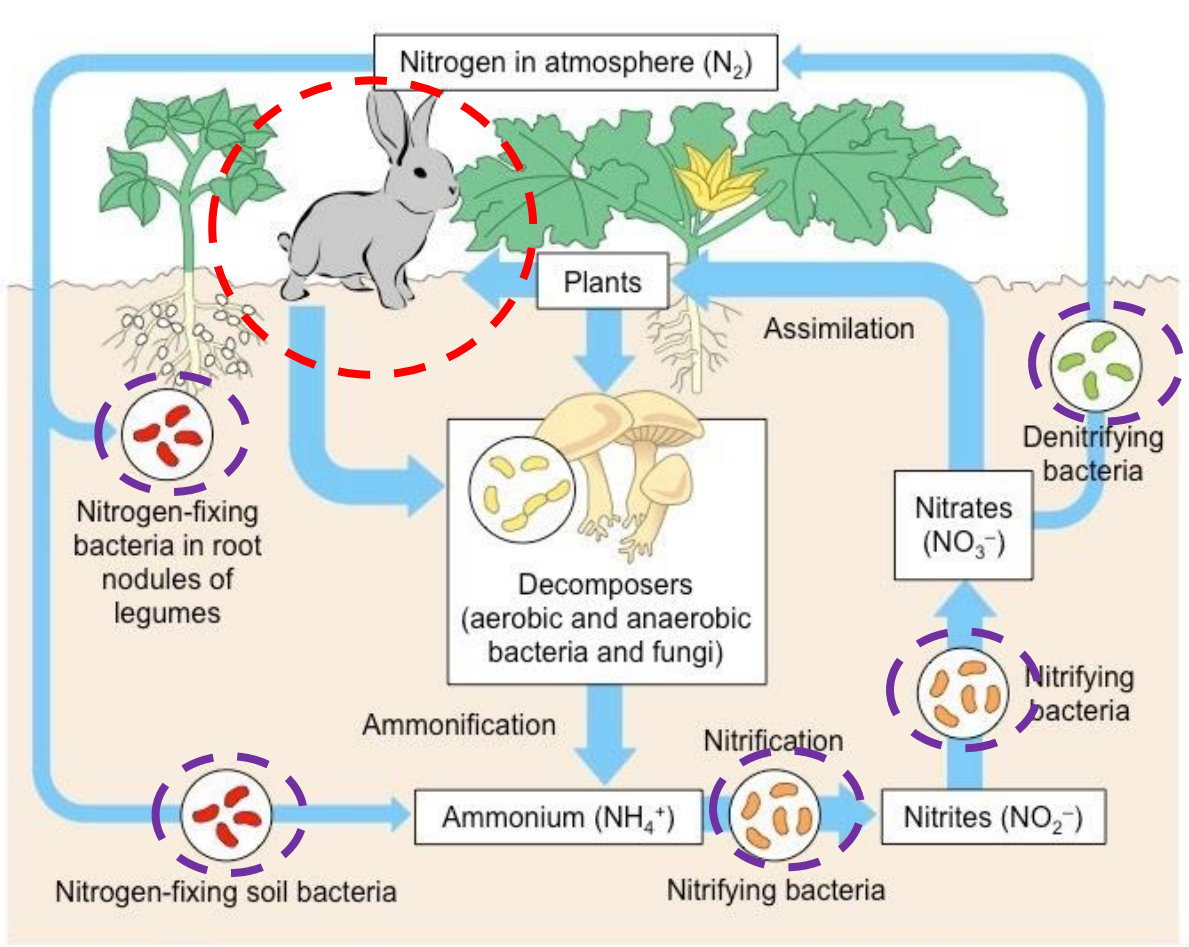



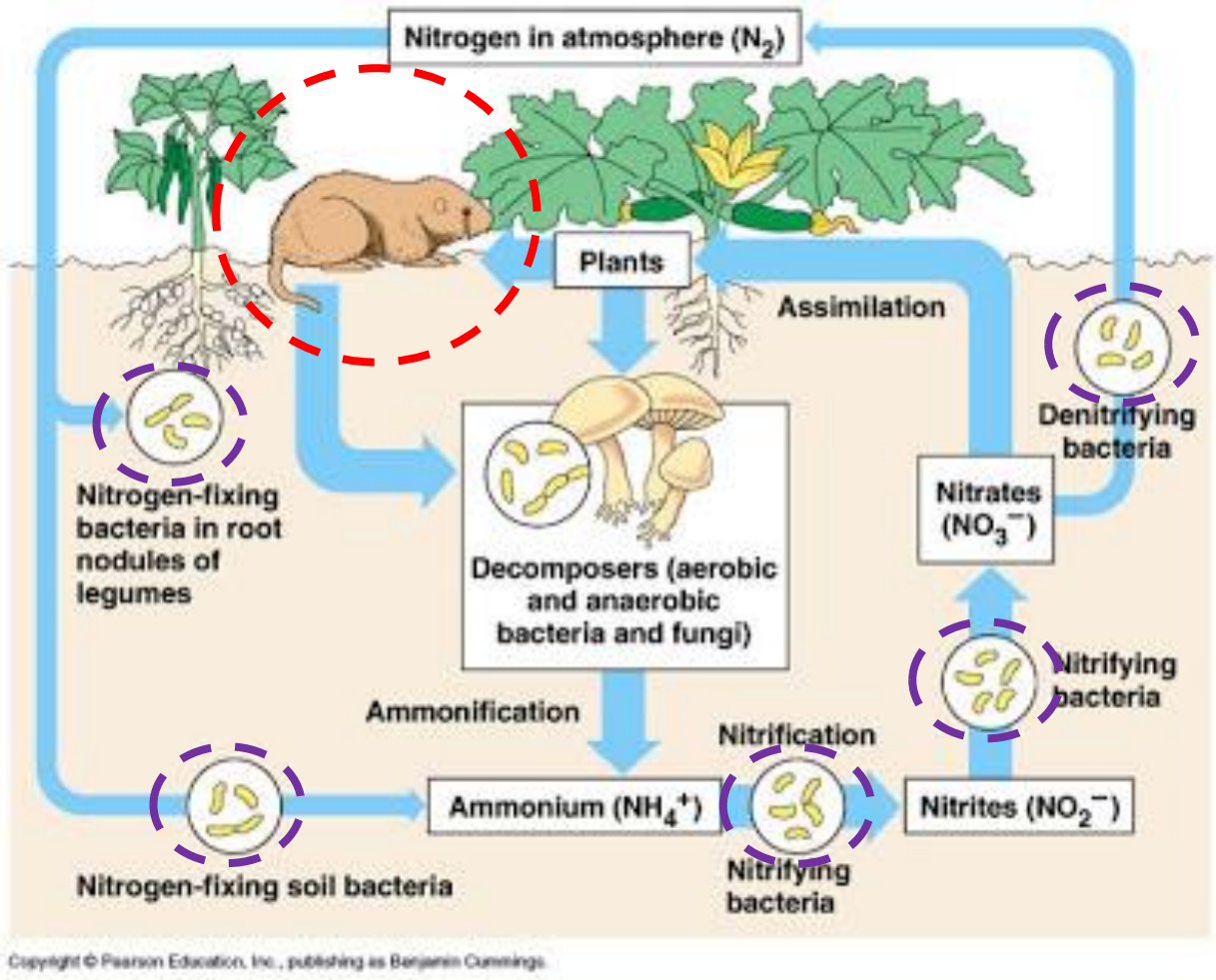
# Nitrogen fixation can be mediated by sets of different actors.



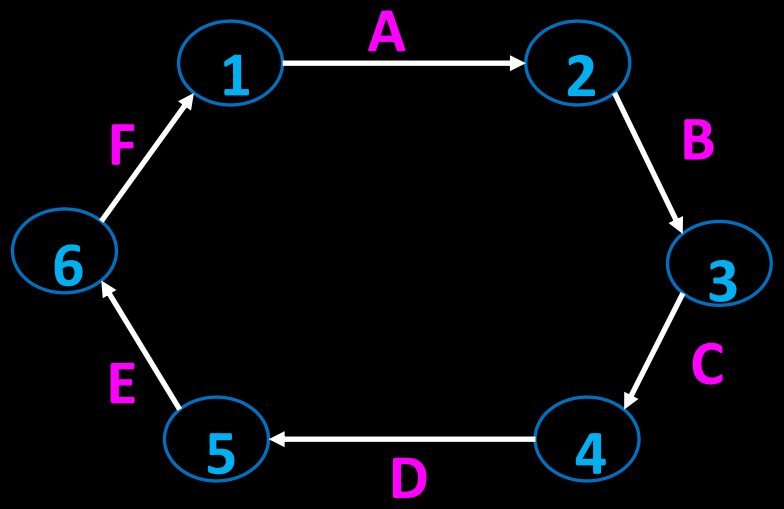



# Comparisons of labeled interaction network might unravel another kind of under-appreciated units of selection.

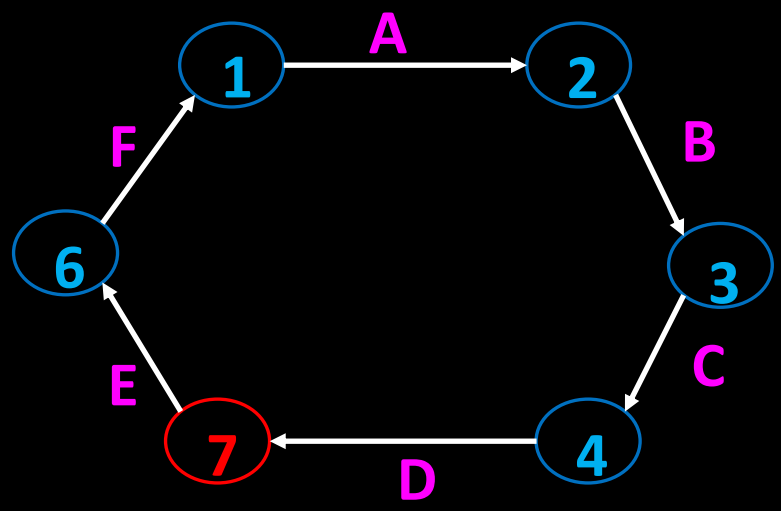


# « It is the song, not the singers » (Doolittle & Inkpen, PNAS 2018)




ITSNTS



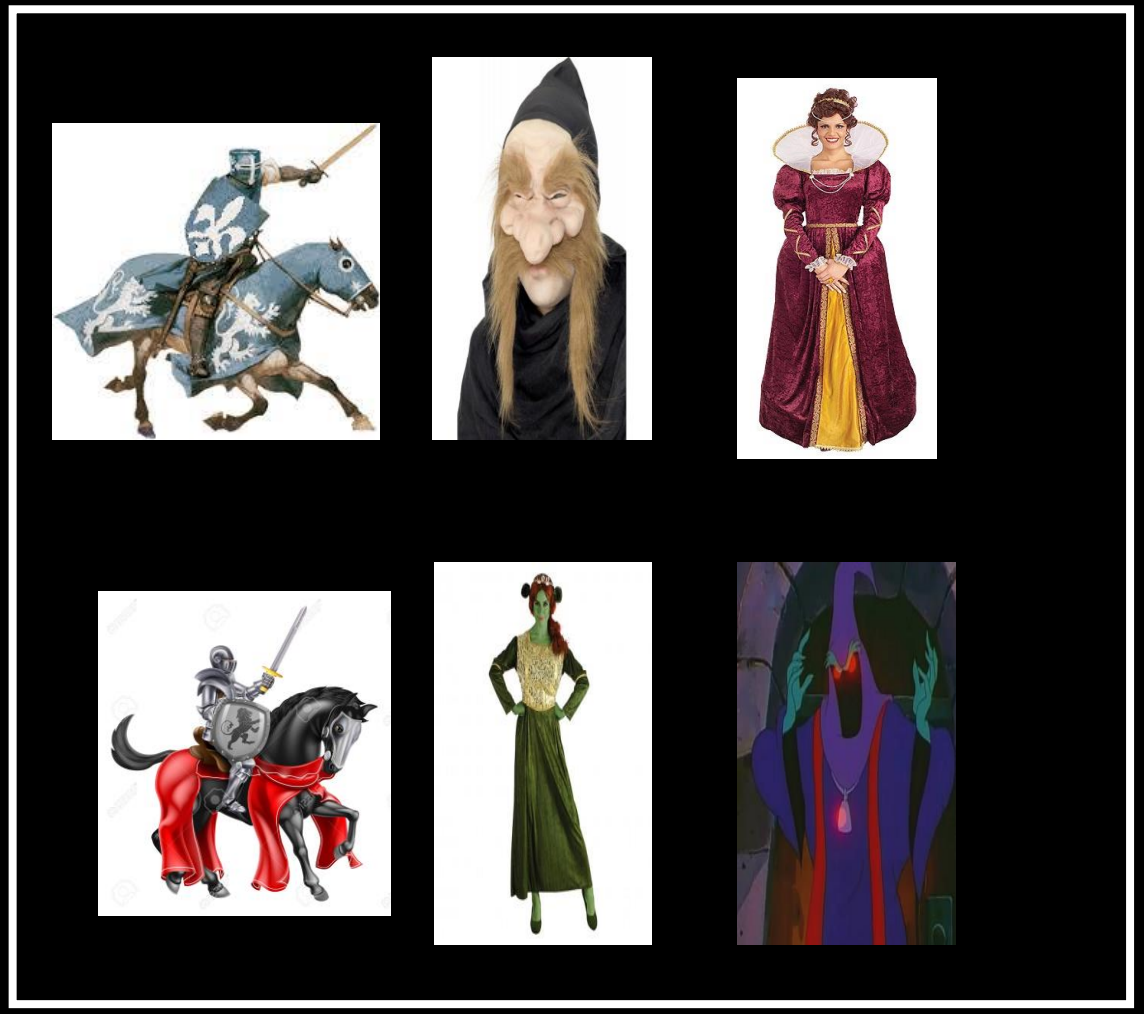

Original song: ABCDEF
Original singers: 1,2,3,4,5,6

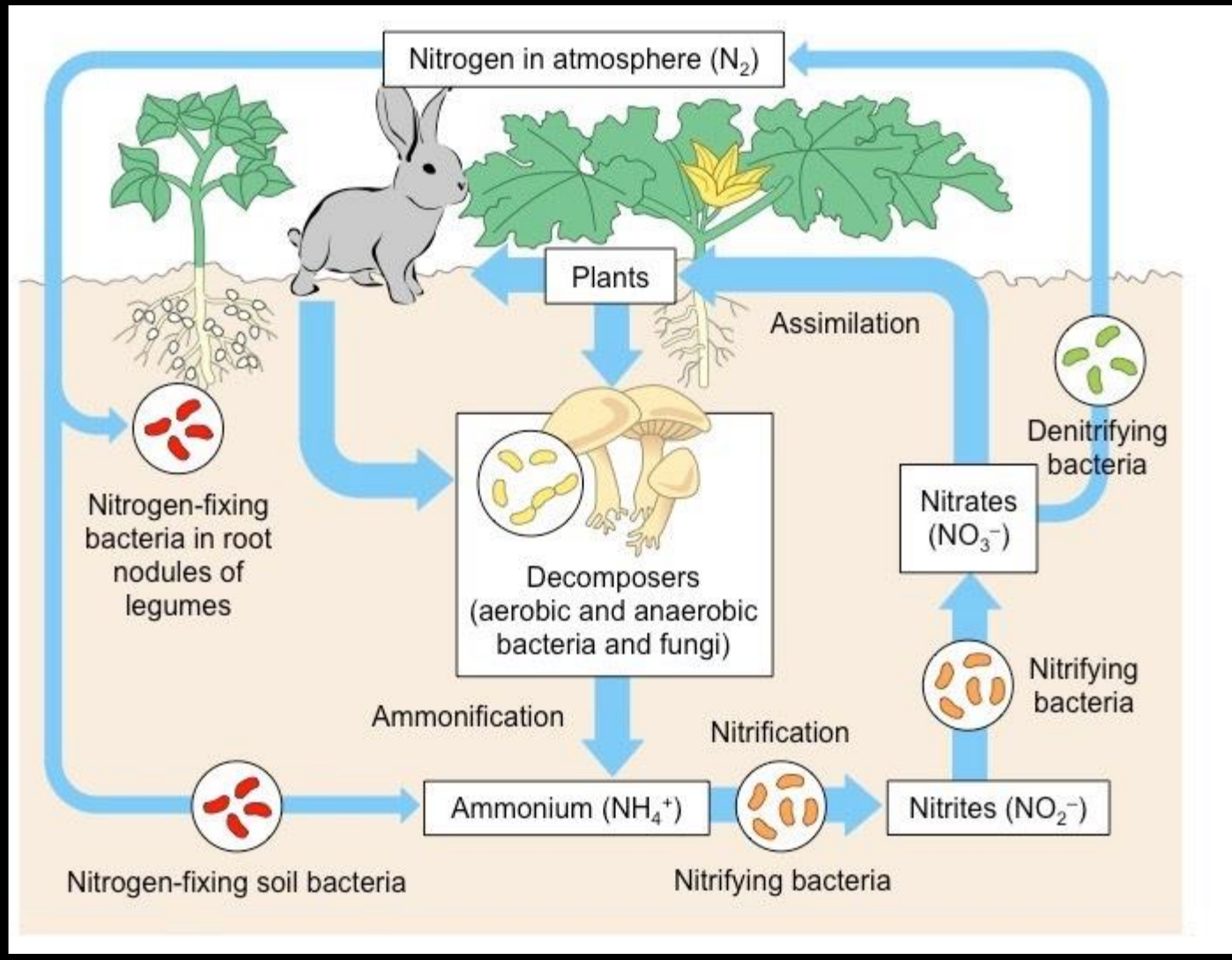
**Re-produced** song ABCDEF
**Different** singers: 1,2,3,4,7,6

➡ **Interaction patterns as new objects of study for evolutionary biology**

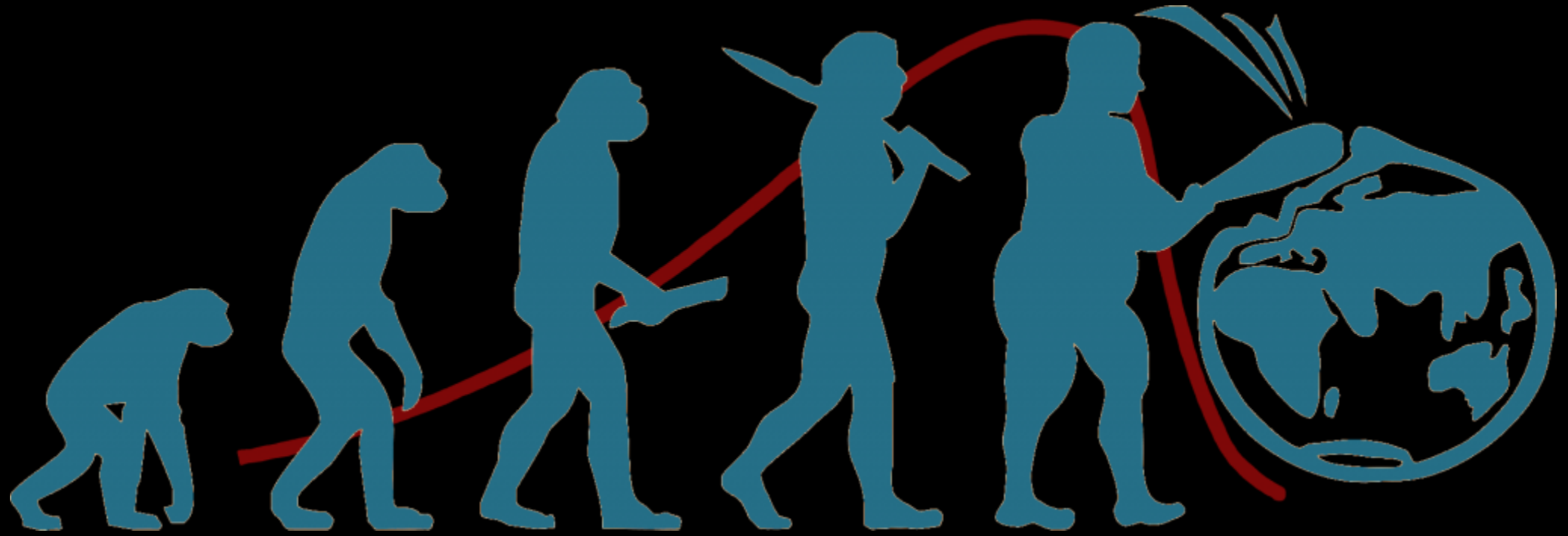
# A contemporary evolution theory proposes to explain such phenomena

- Invisible, if one does not consider interactions between individuals,
- Ubiquitous, if one considers these interactions.



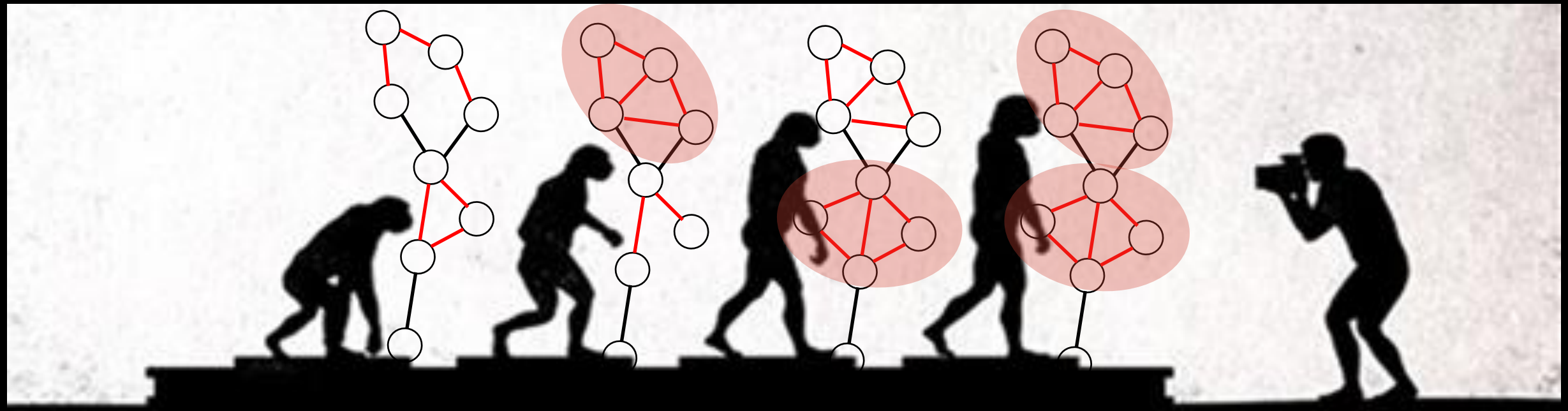


**Some of these selected interactions may be critical for the sustainability and continued evolution of Life on Earth.**



**Could we make educated guess about which interactions might be concerned?**

# B/ Evolutionary-minded intuitions on the persistence of evolved systems



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

Received: 9 April 2020 | Revised: 18 September 2020 | Accepted: 24 September 2020

DOI: 10.1002/bies.202000077

BioEssays WILEY

PROBLEMS & PARADIGMS

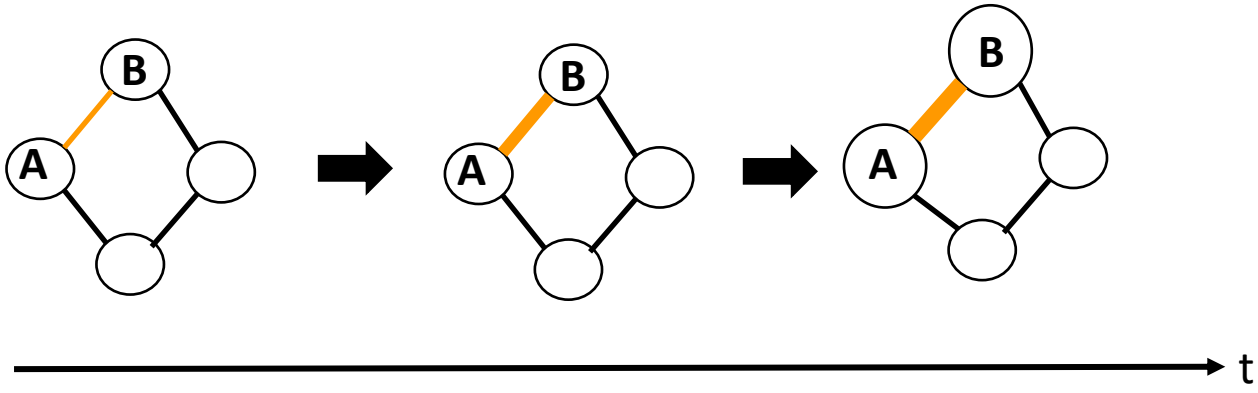
Prospects & Overviews

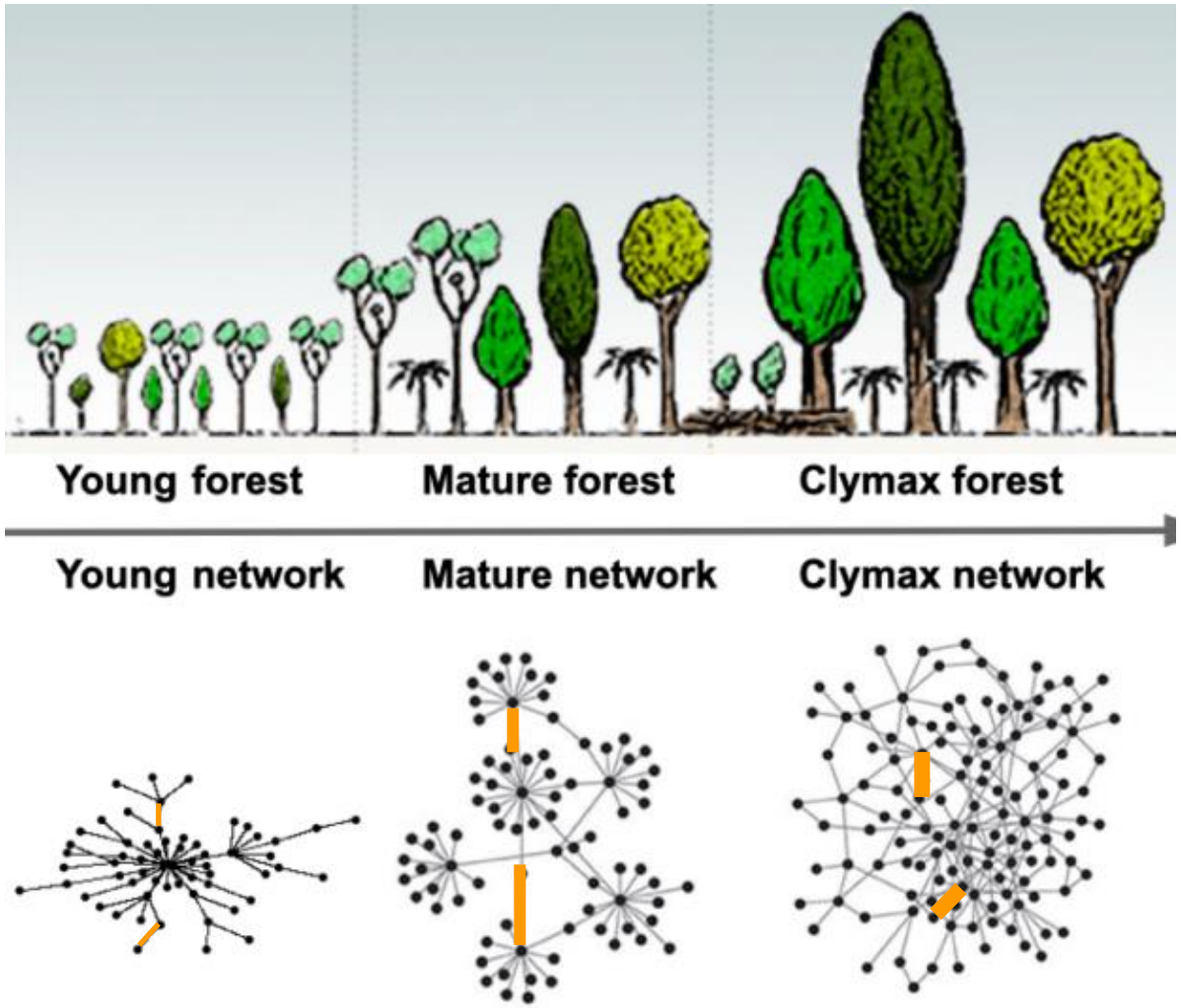
# Modeling the evolution of interconnected processes: It is the song and the singers

## Tracking units of selection with interaction networks

Eric Bapteste[1] | François Papale[2]

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

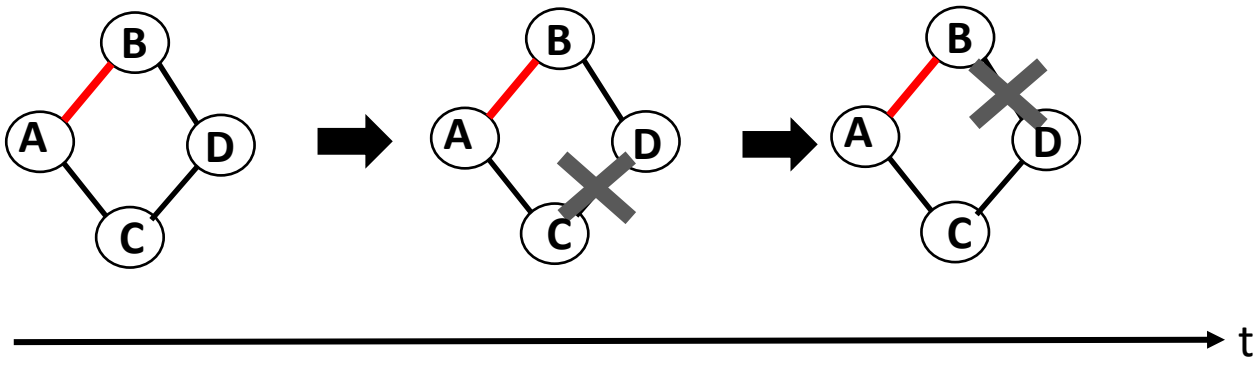


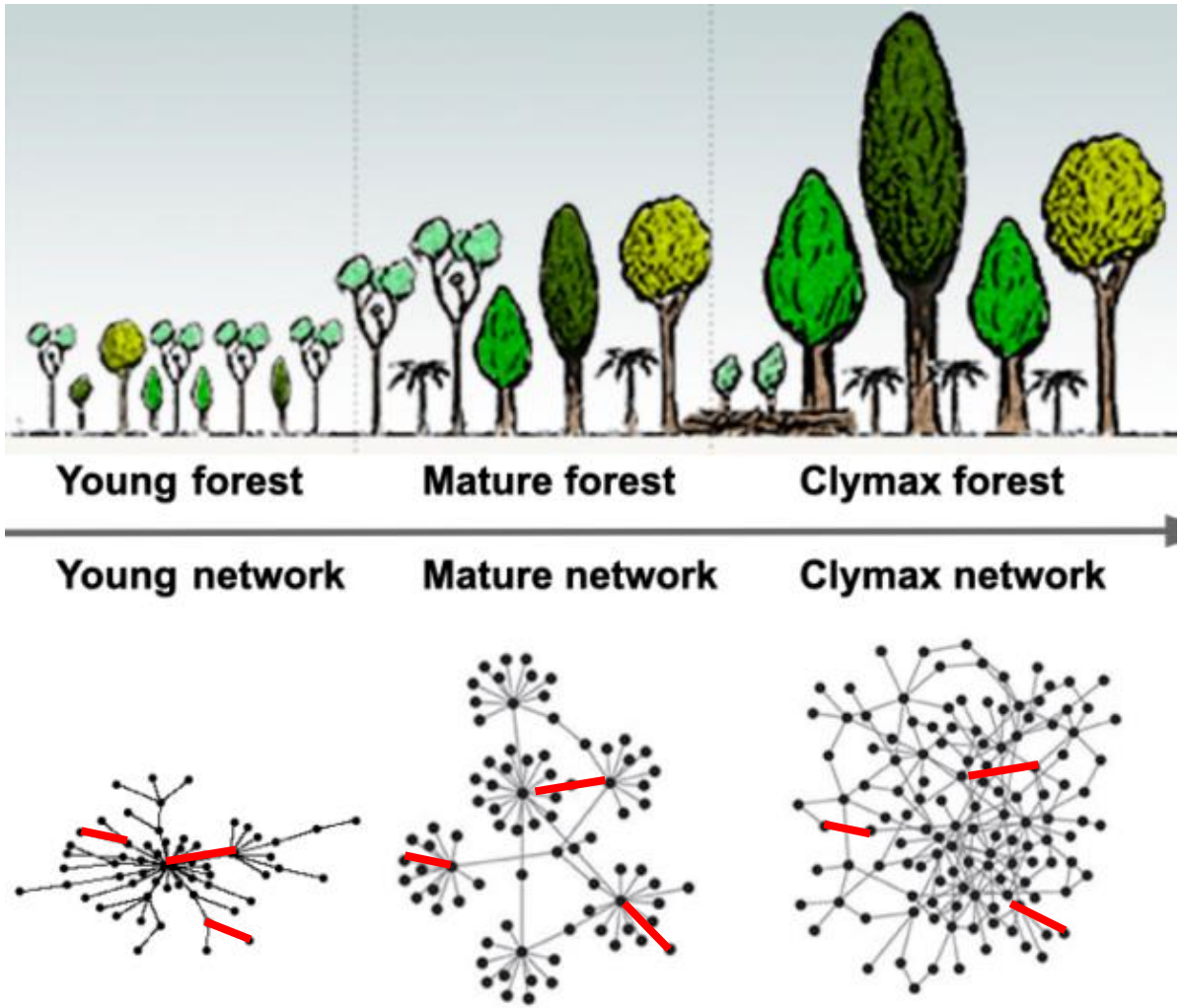

* e.g., increase in strength and relative abundance in the system

# 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**



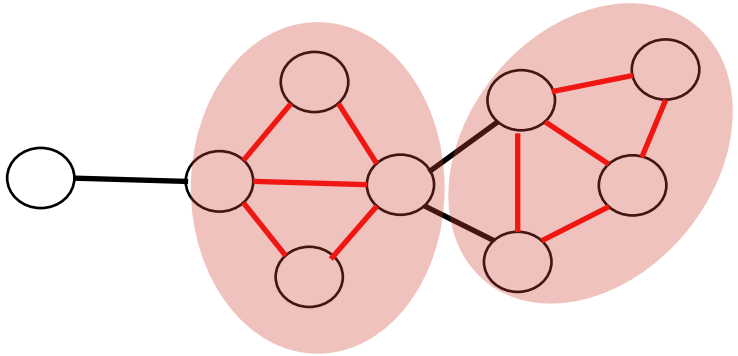

* e.g., occur at consecutive time points – and for how long



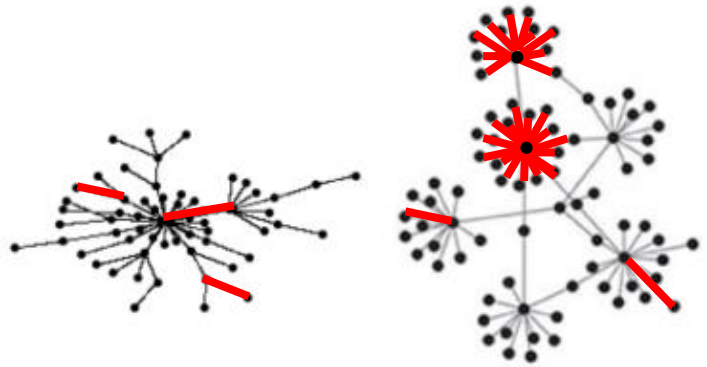
# Network analyses could report architectures that may be the result of selection.

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

Network at t



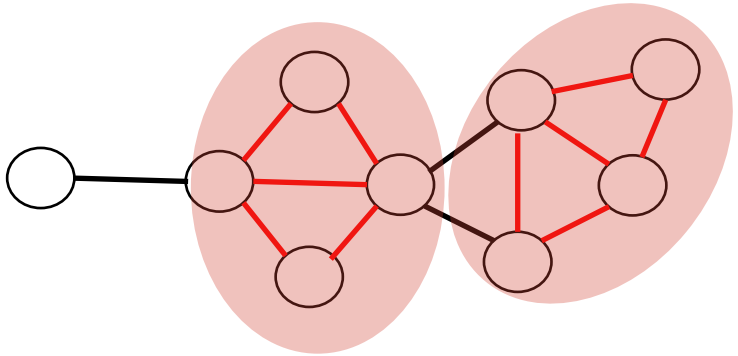
* e.g., tight clusters of robust edges

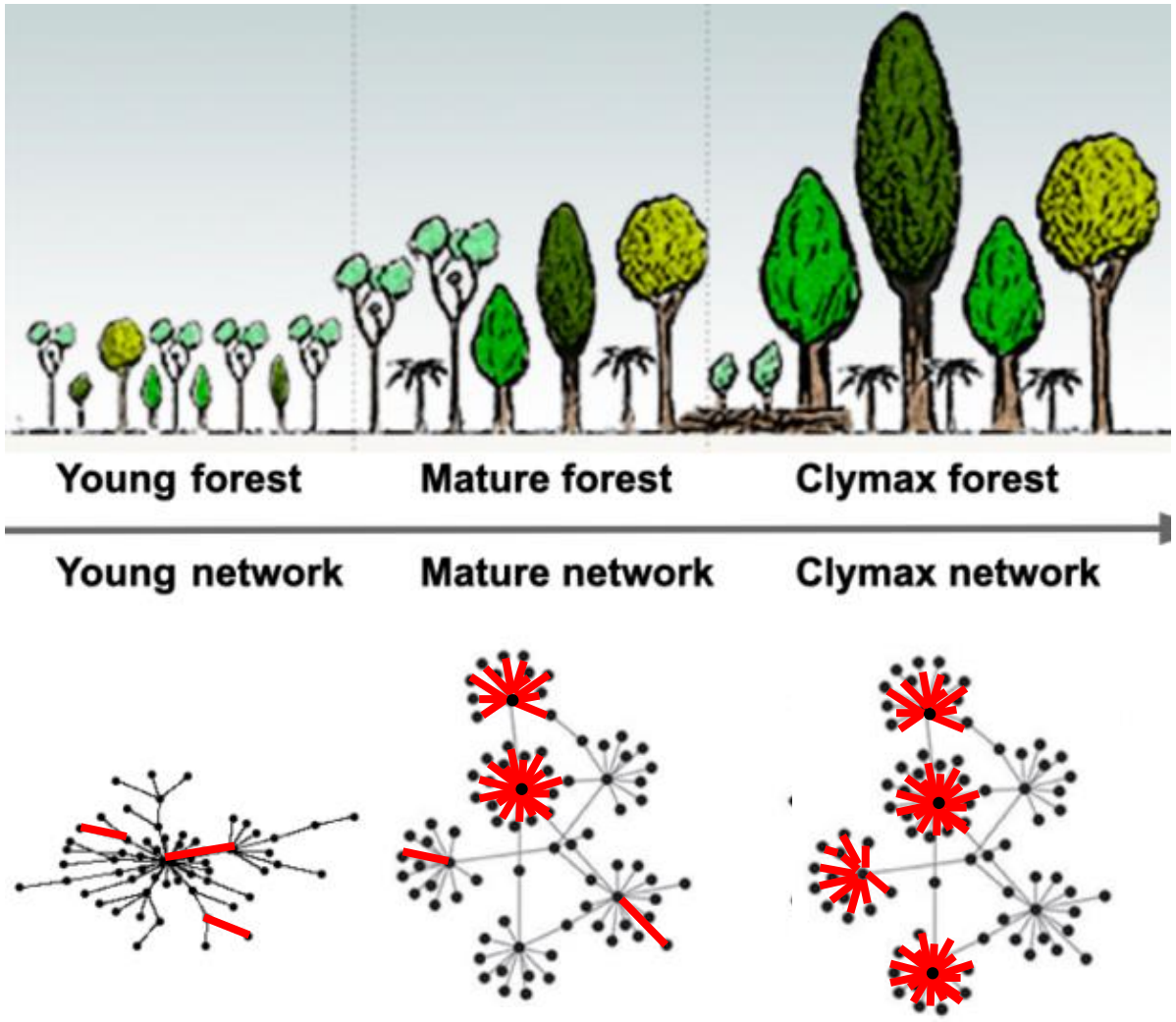
**Network analyses could show whether and how the persistence – hence the fitness- of an ecosystem changes.**

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

Network at t

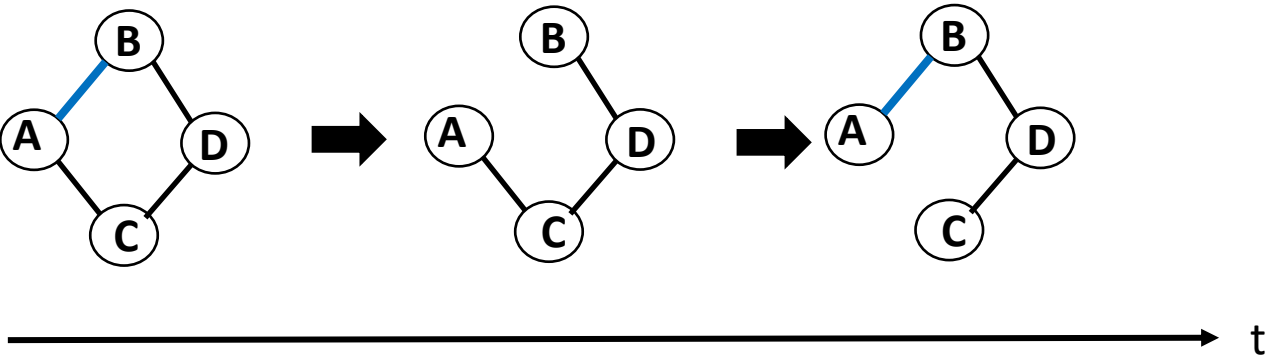


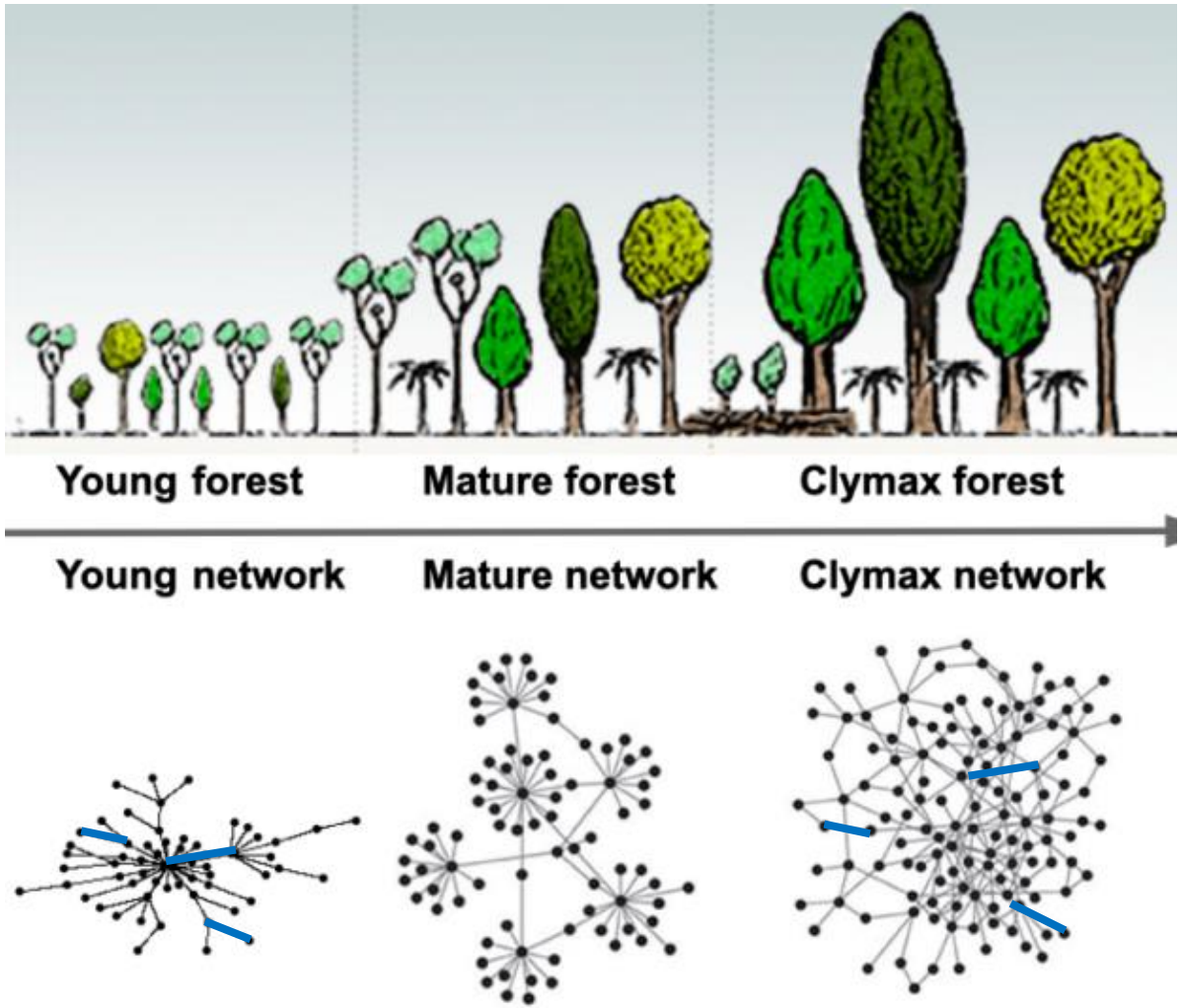
* e.g., tight clusters of robust edges



# 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***



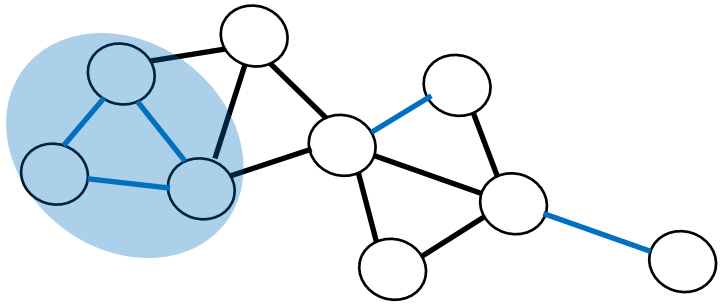




* e.g., occur at disjoint time points – and for how long

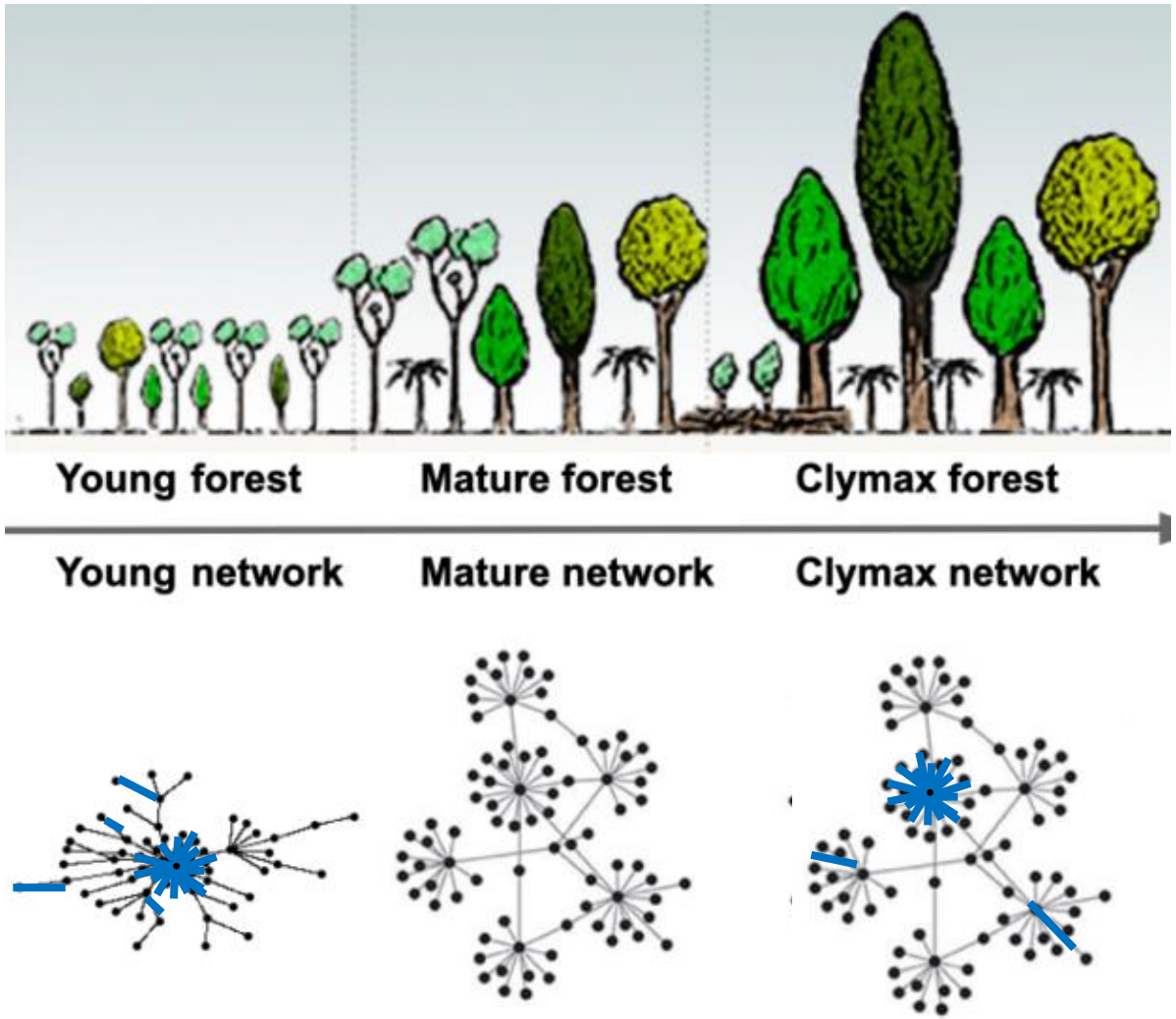
# Network analyses could report architectures that may be the result of selection.

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

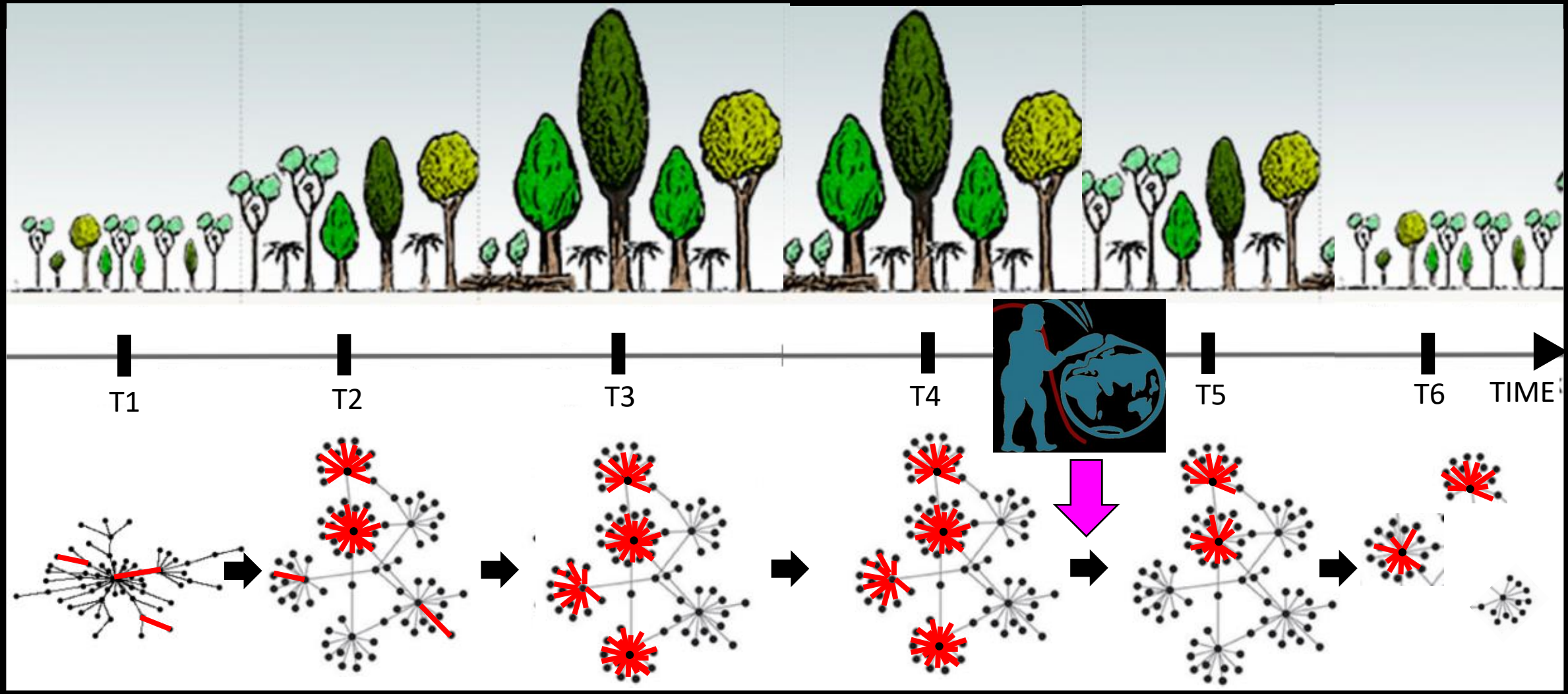
Network at t



* e.g., tight clusters of resilient edges

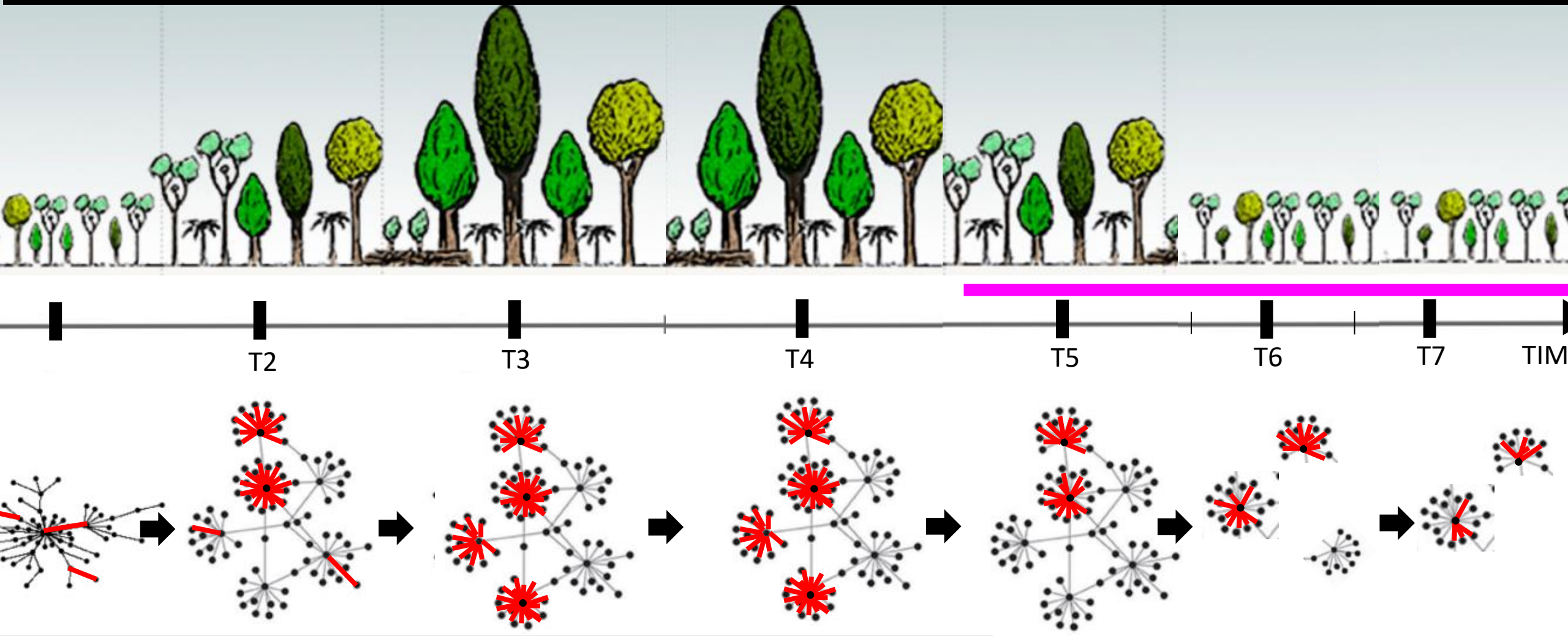


**If network analyses show whether and how the persistence – hence the fitness- of an ecosystem changes, then simple metrics may capture tipping points* in the evolution of these ecosystems.**



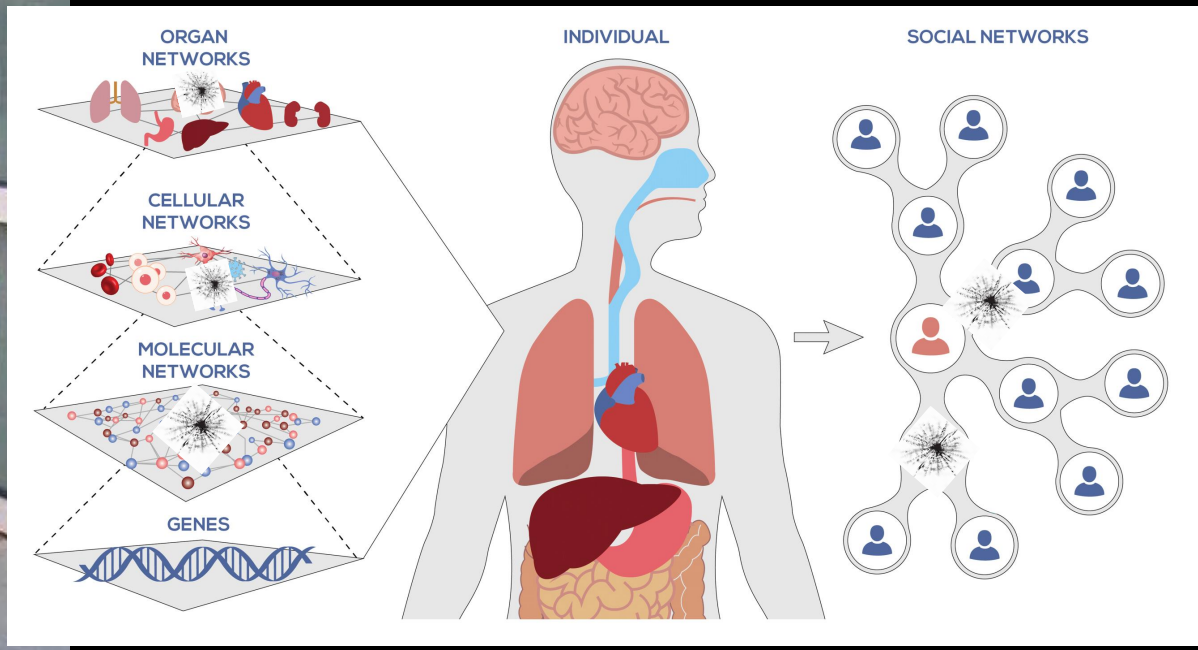

* e.g. phase transition due to some human action….

Or it could identify systems undergoing selection shadow,
i.e. systems that behave consistently with a decreasing selection intensity,
or even that behave as if the selection they were exposed to has gone away.



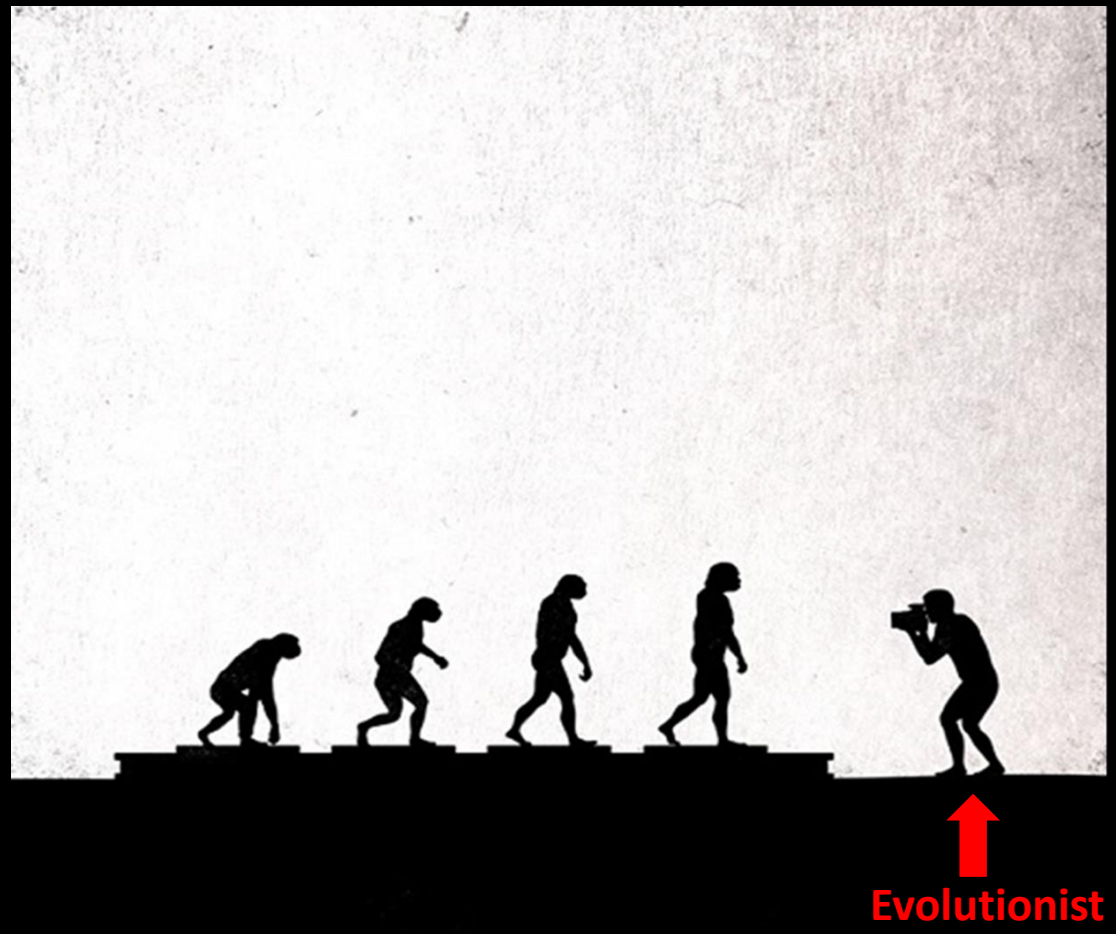

e.g. progressively decomposing along their weakest interactions, becoming **less fit**.

**The next dynamic steps, under such a shadow selection, would then depend on drift and on the robustness/resilience of formerly selected inner networks.**

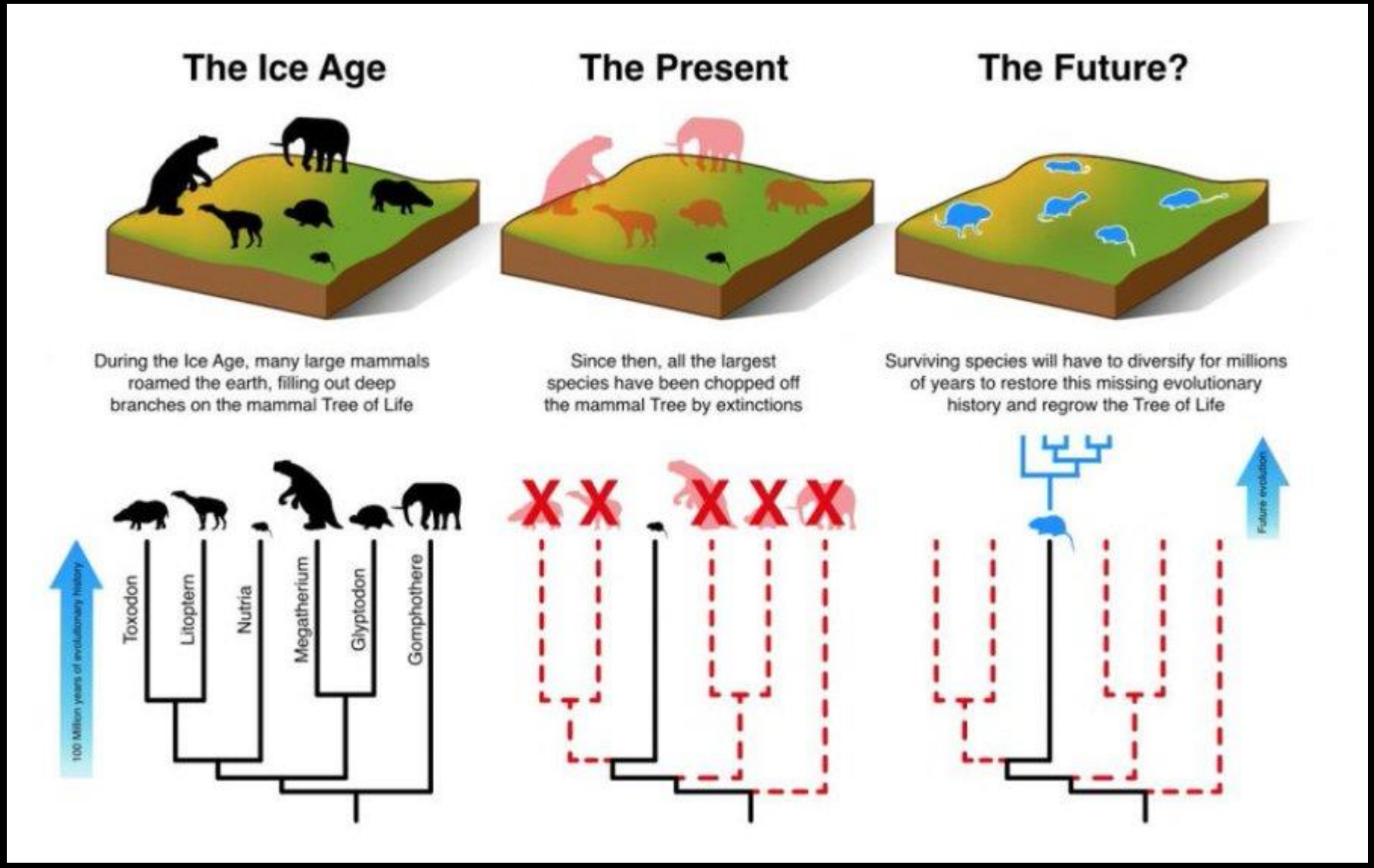


# C/ Conclusion

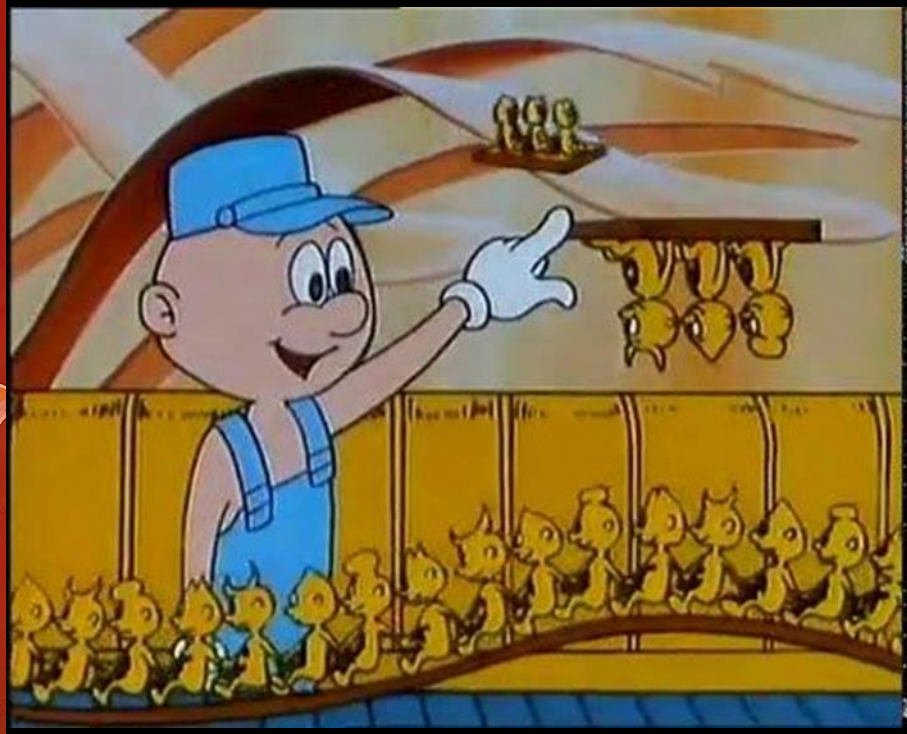
# The traditional focus of evolutionary biology is quite specific: evolution is seen firstly via the prism of relatedness.



# So, the traditional evolutionary viewpoint on the future resilience of the living world would usually be something like this.



# Yet, the biological world is not only about relatedness: it is also about organisational complexity , e.g. dependencies and interdependencies.

# And such organizational complexity may also be – in part – the result of evolution.

**More complex entities**, involved in more complex interactions, than that suggested by the classic evolutionary biology framework can **vary**, **have a selective value and feature in inheritance**.

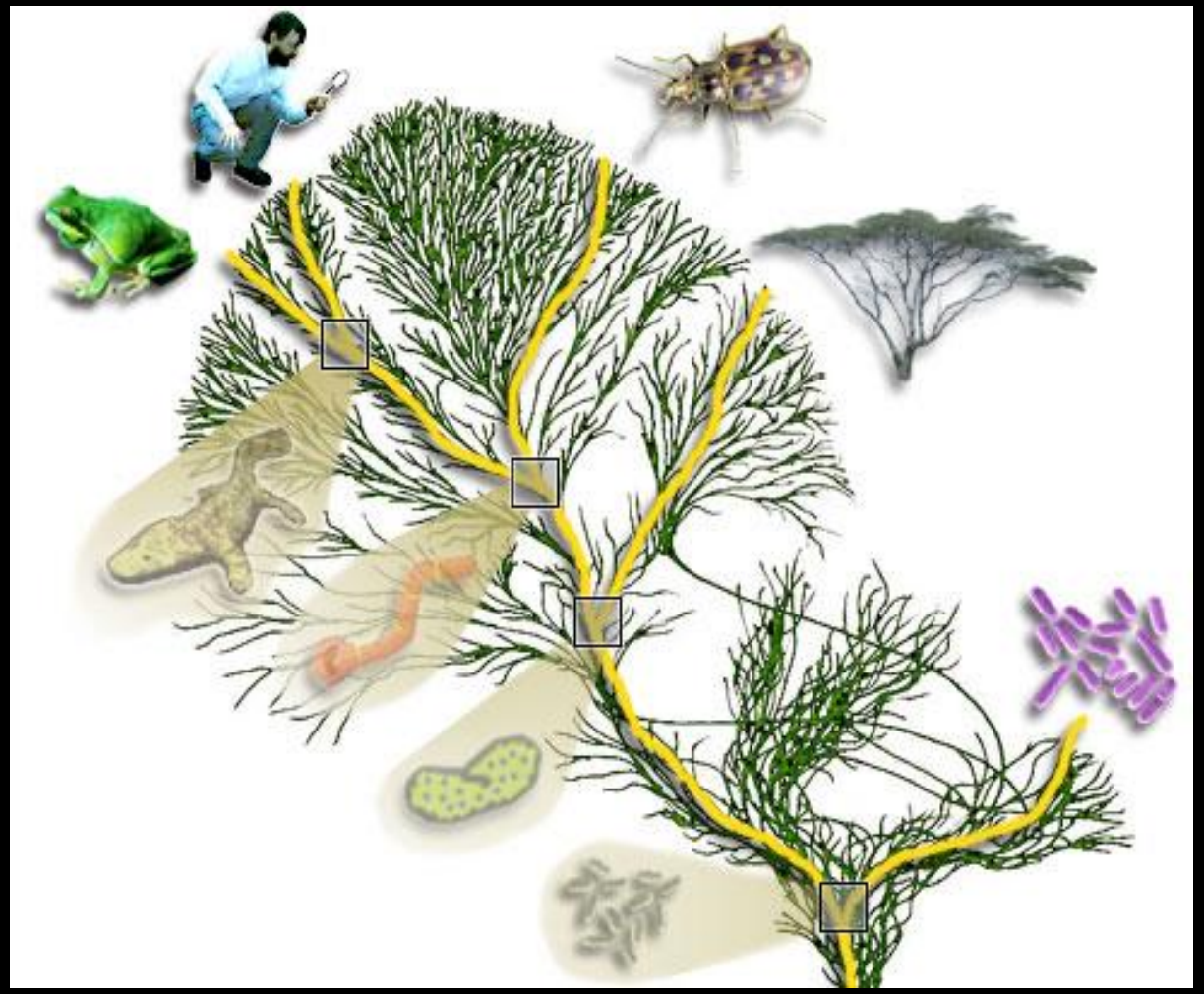
Papale et al. Trends in Micro 2020

# This realization is hardly new

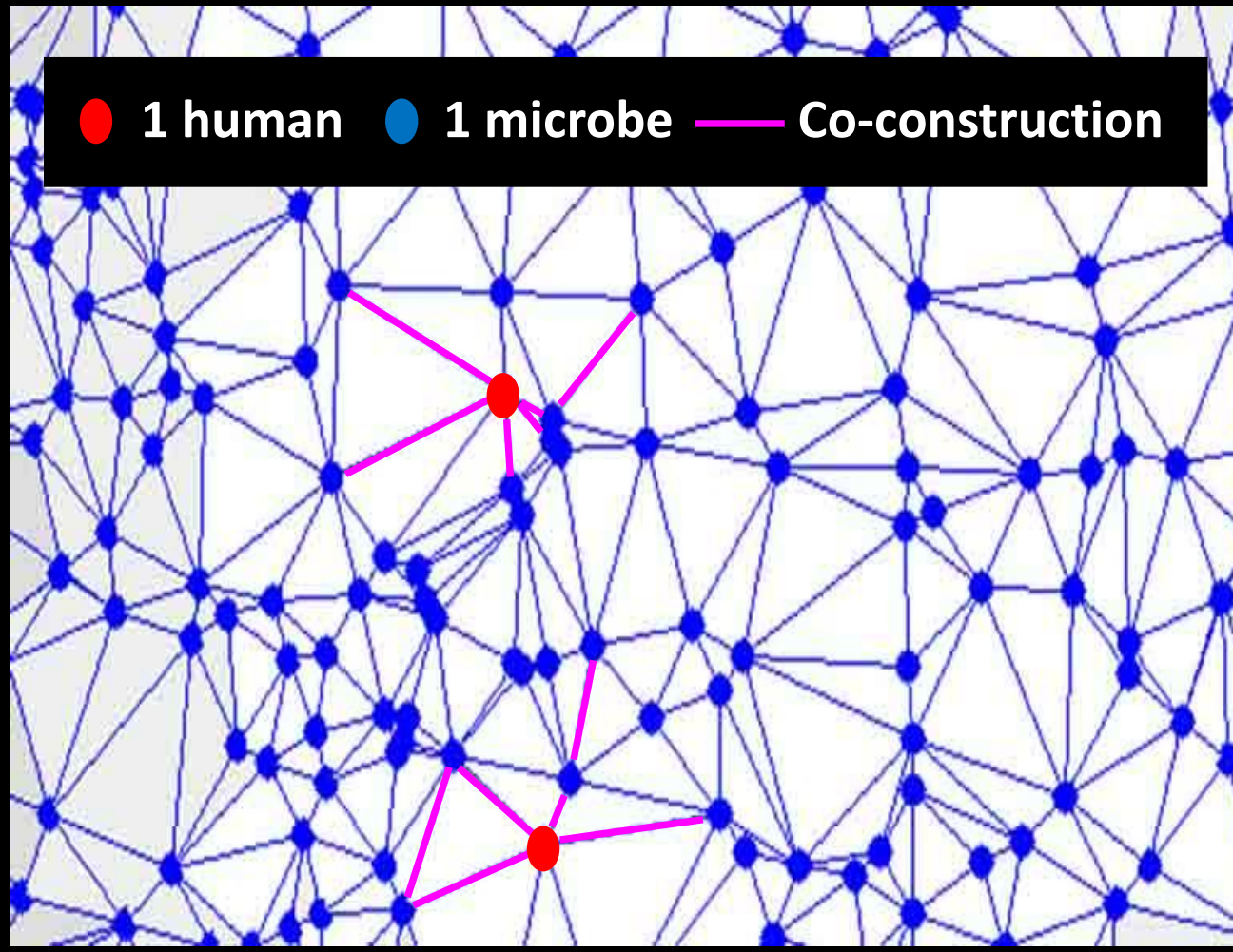

➡ One must also consider **interactions** between components of the living world

# So, we could adopt 2 different evolutionary perspectives :

# Trees focus on relatedness, networks on organization.

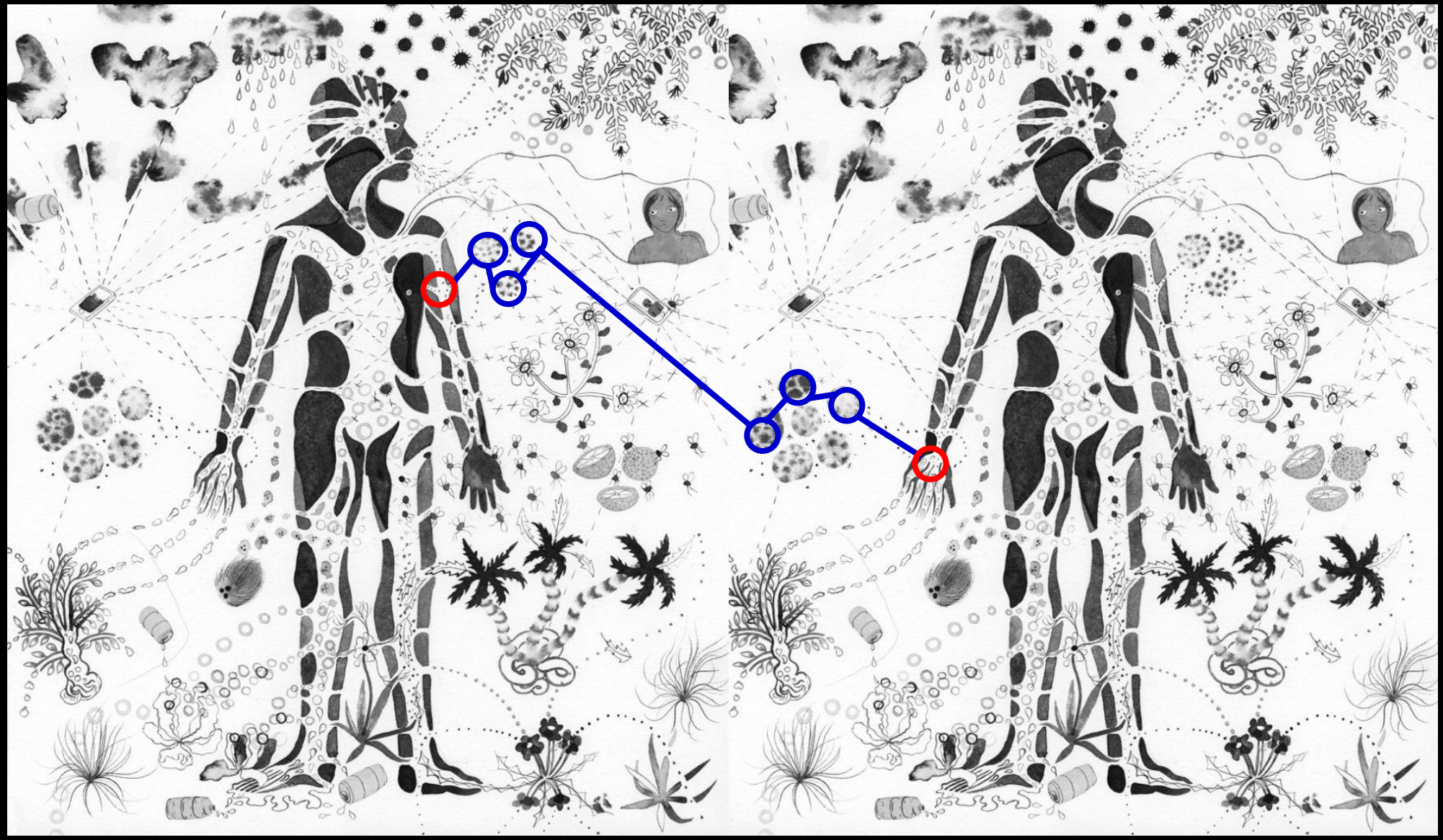


Microbes: **too distants to really matter**

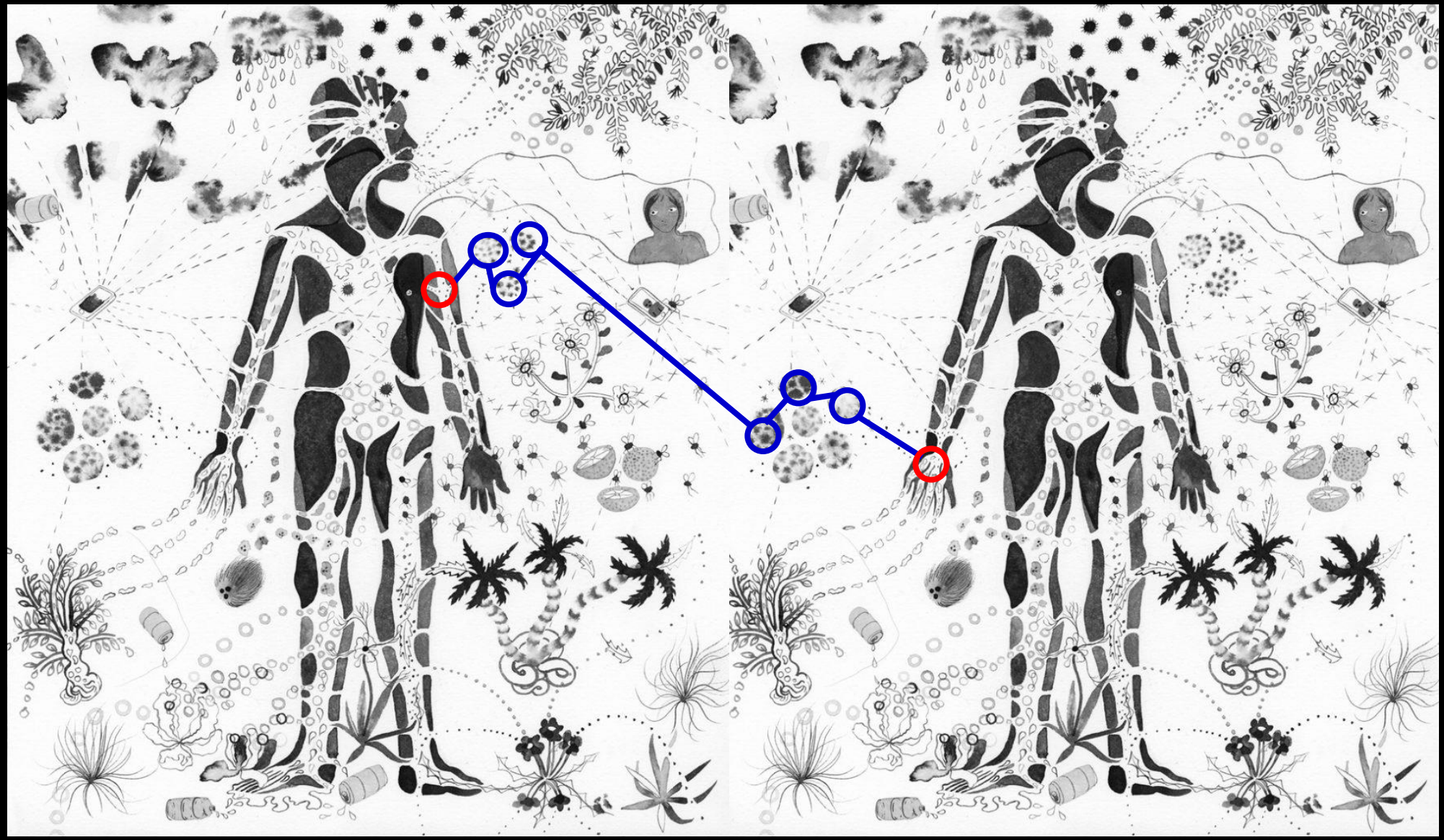



Some microbes: **very close and important**

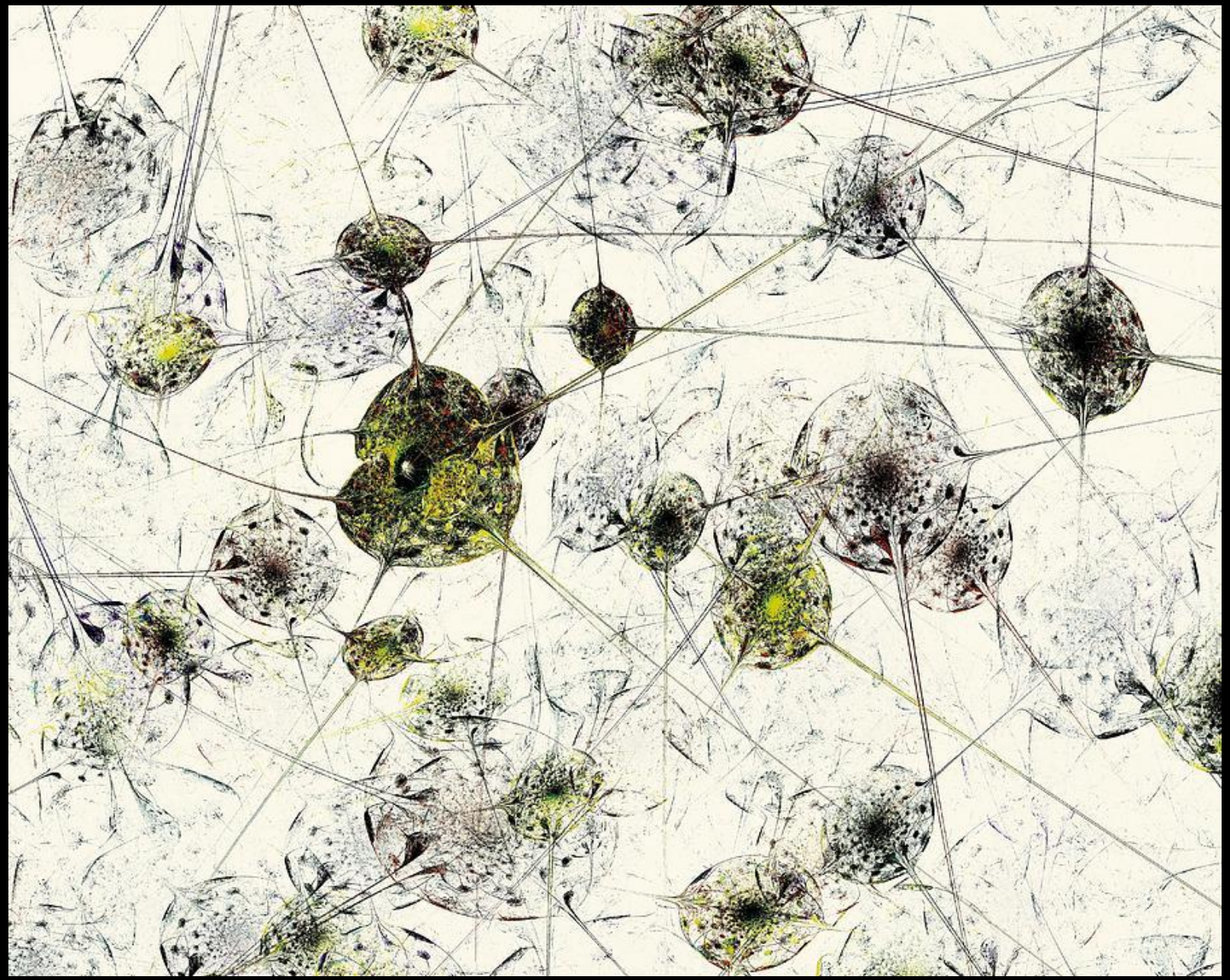
# We belong to a network, connected by (interacting) microbes.



# We are the components of a network, not an isolated branch on a tree.

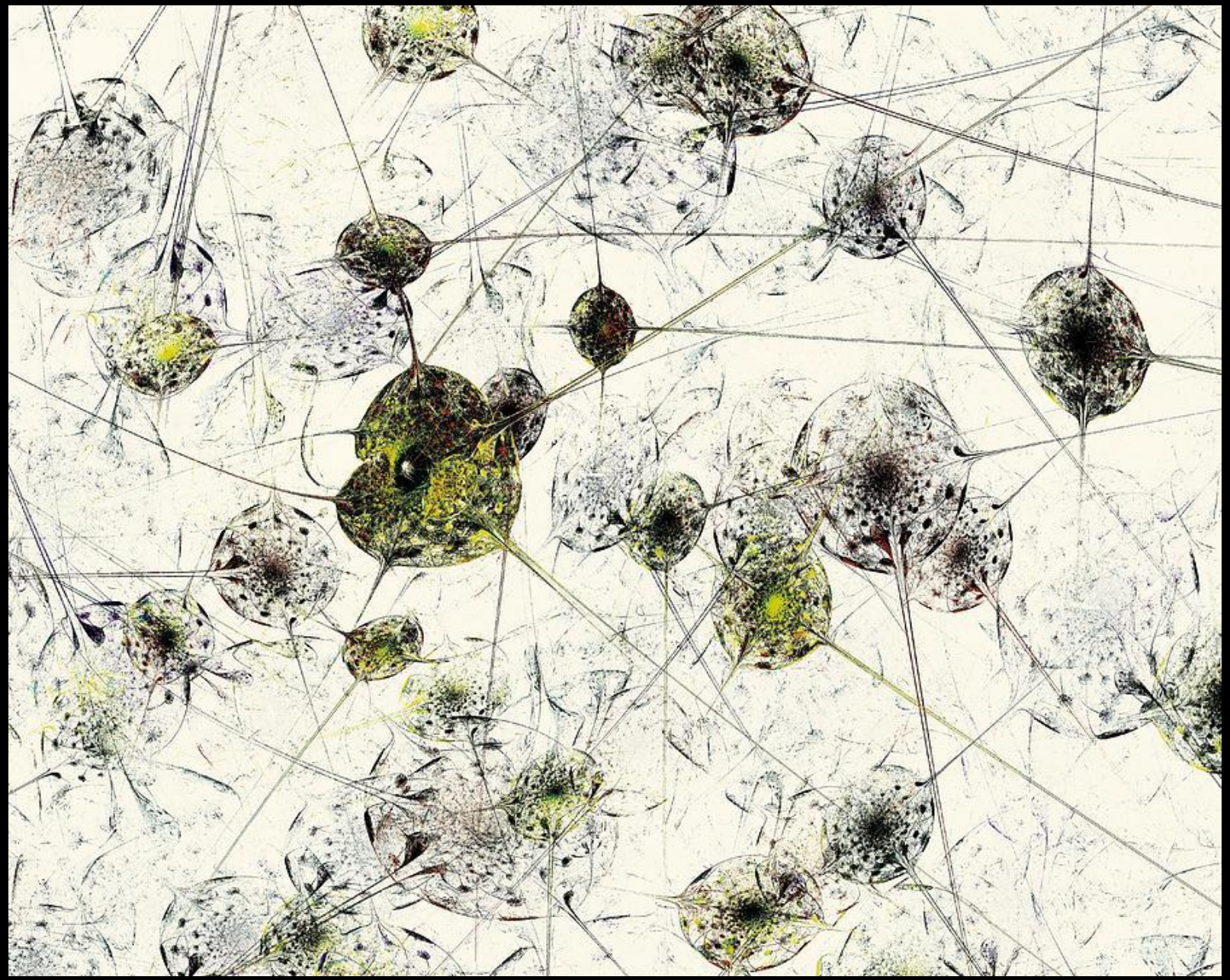


# But it is not just about us...



A. Malakhova

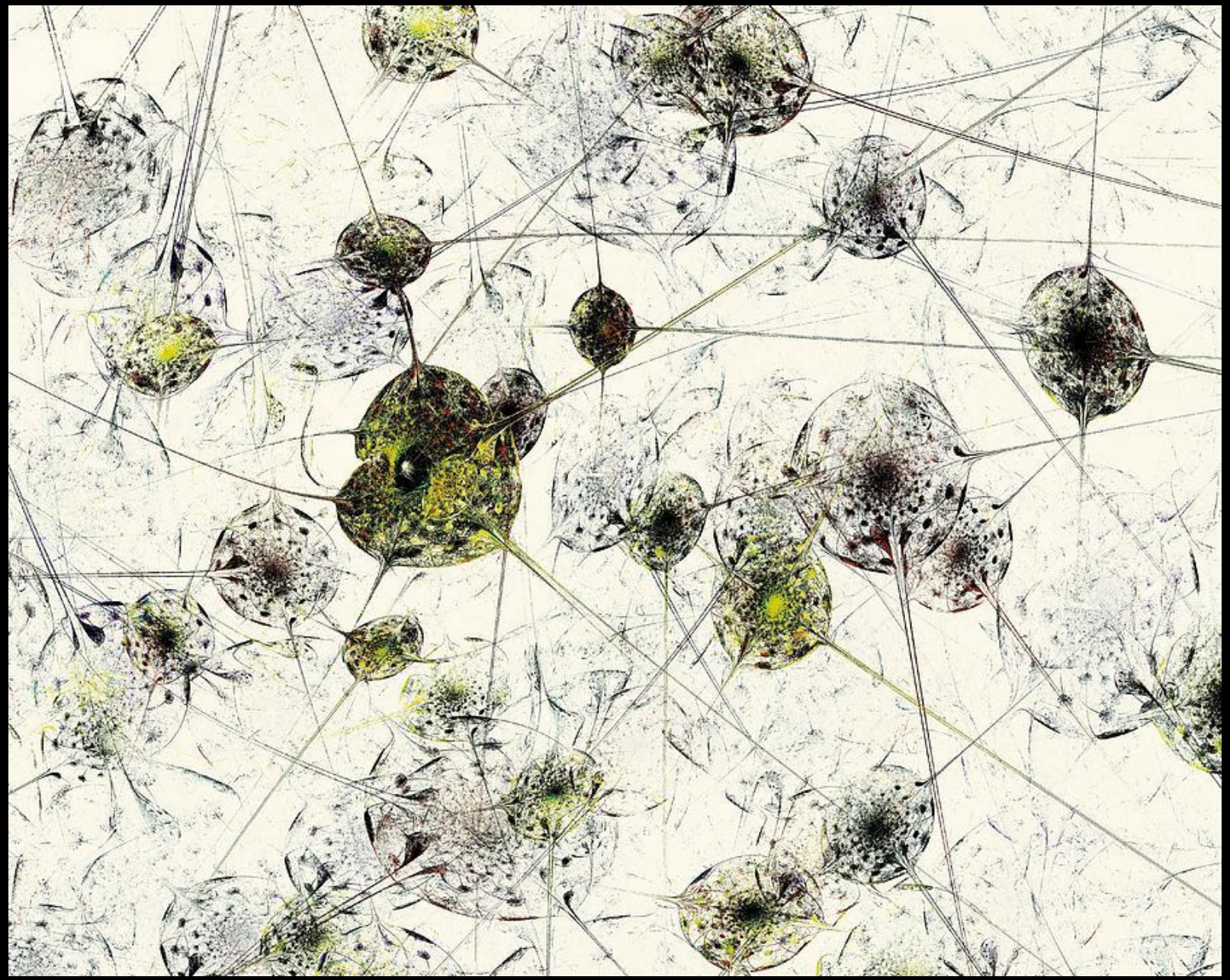
- There are **interactions everywhere within organisms**, even in single cells.



A. Malakhova

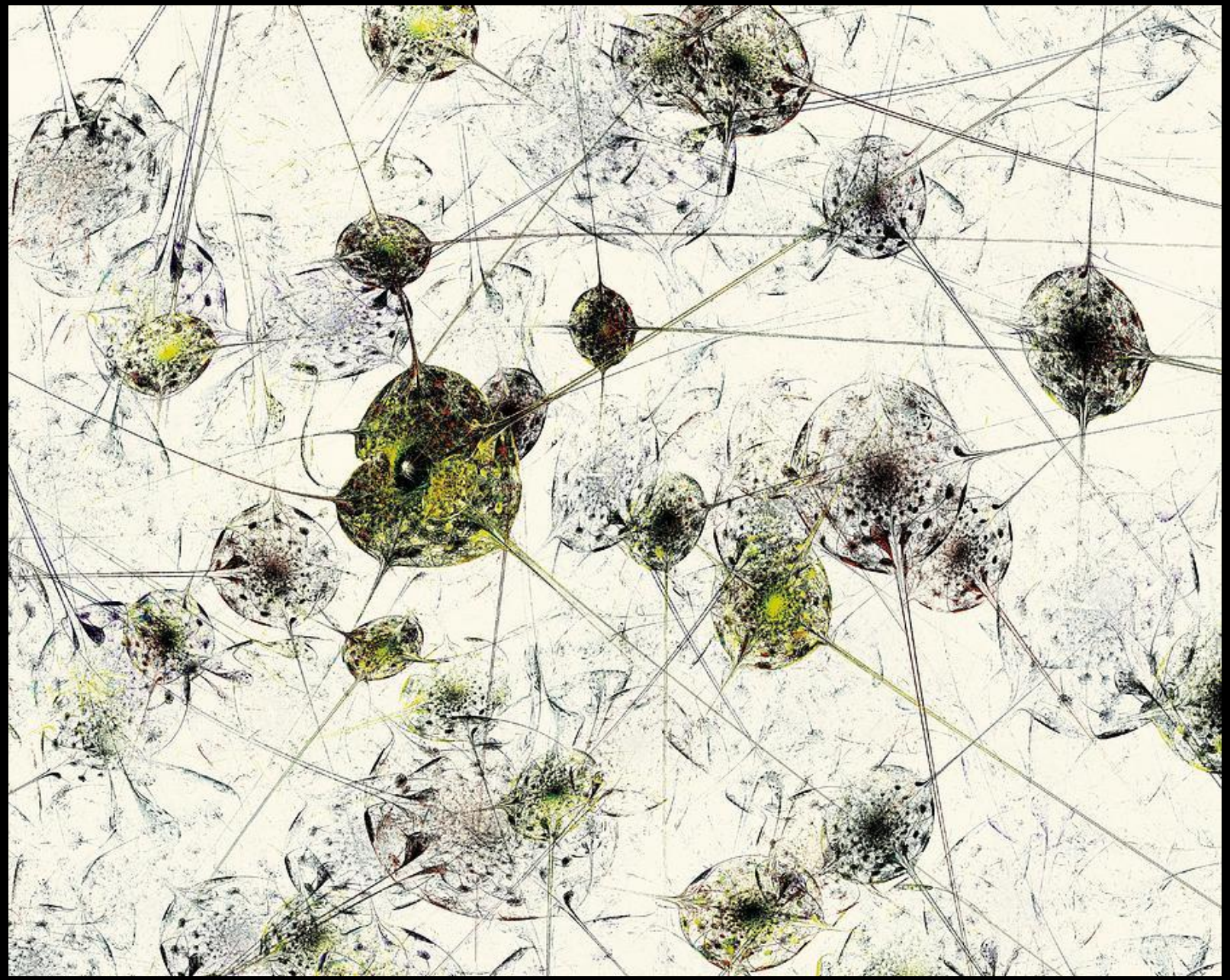
- There are **interactions everywhere within organisms**, even in single cells.

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



A. Malakhova

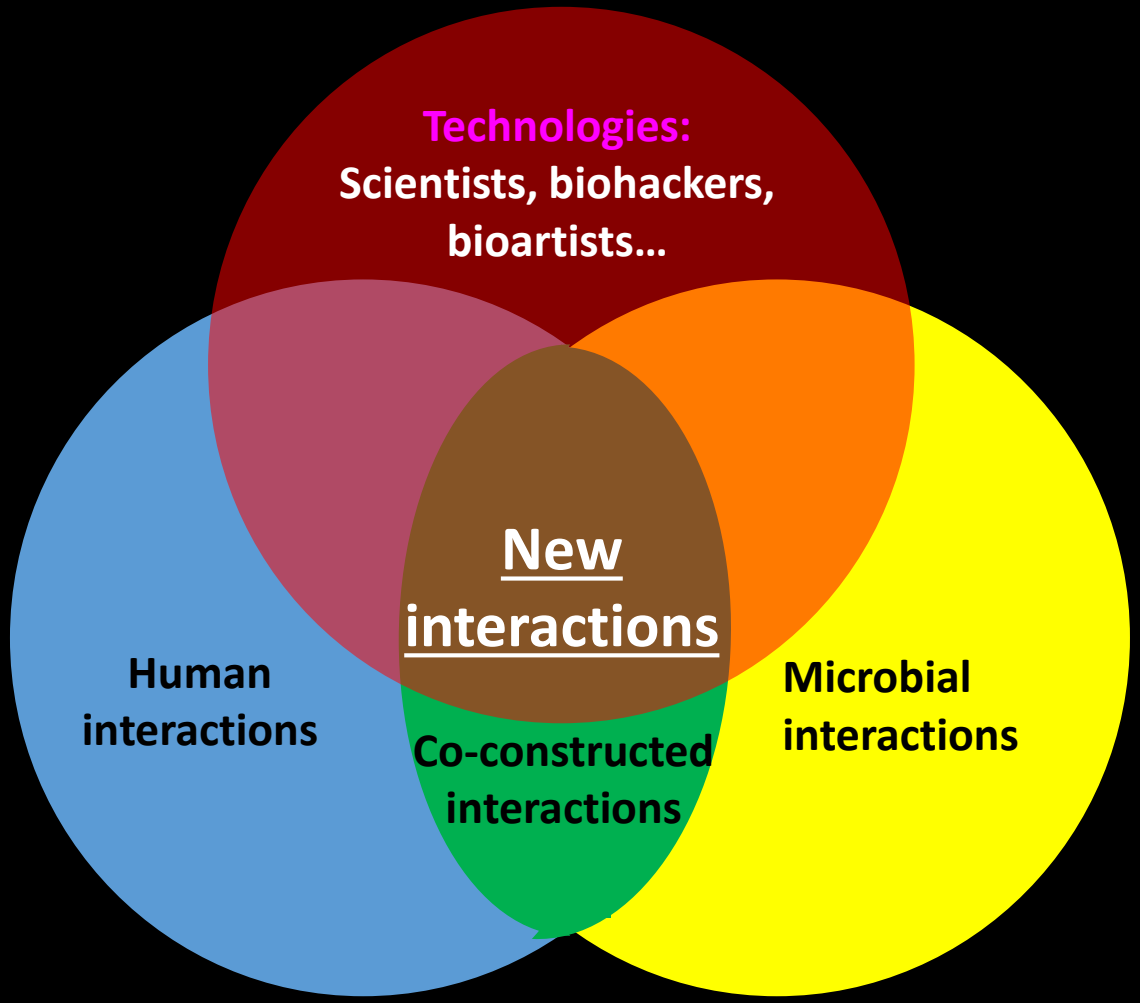
- There are **interactions everywhere within organisms**, even in single cells.
- **Organisms**, even single cells, **belong to networks**.
- These interactions **affect the evolution of species**, ours included.

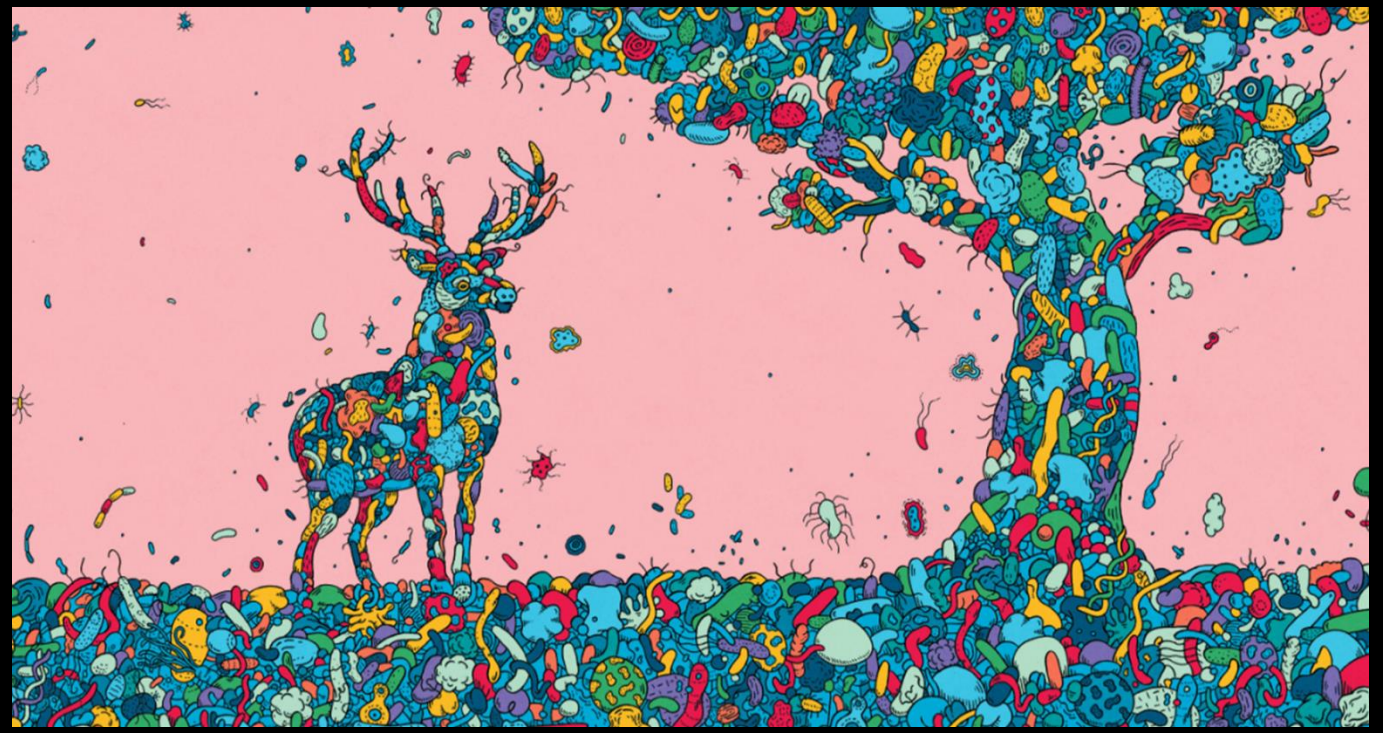


A. Malakhova

- There are **interactions everywhere within organisms**, even in single cells.
- **Organisms**, even single cells, **belong to networks**.
- These interactions **affect the evolution of species**, ours included.
- All of this **deeply transform the evolutionay theory.**

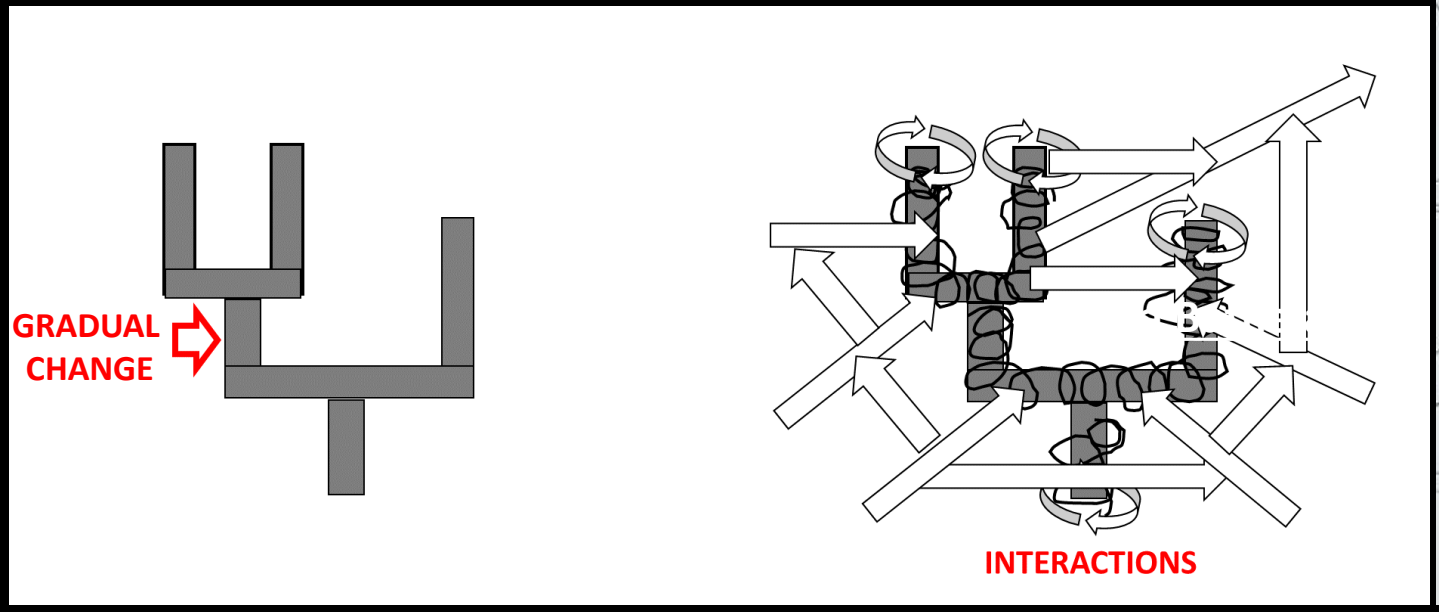
# Most plants and animals are likewise connected: our own species should act responsibly.

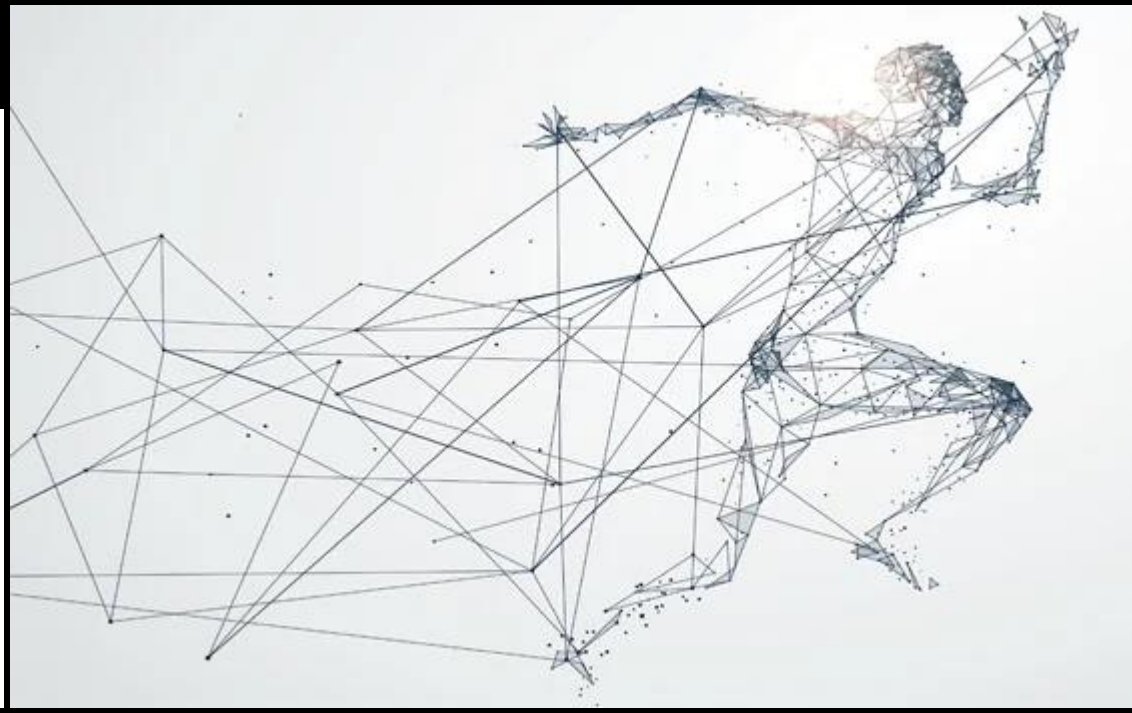


Andrew Rae

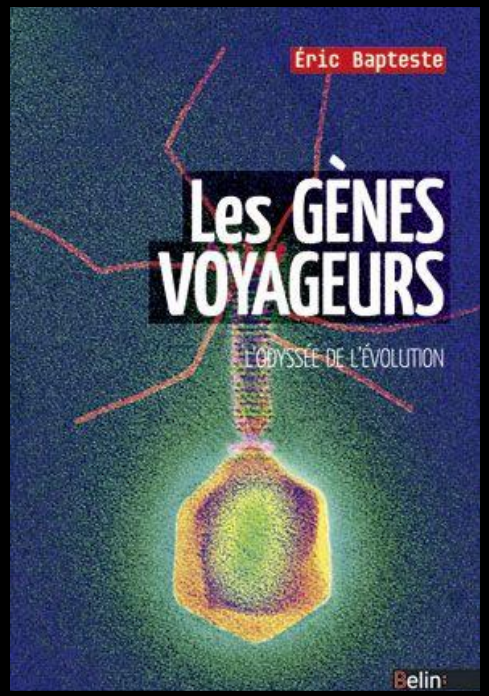
# One possible strategy to assume our responsibility might be to openly analyze interaction networks.

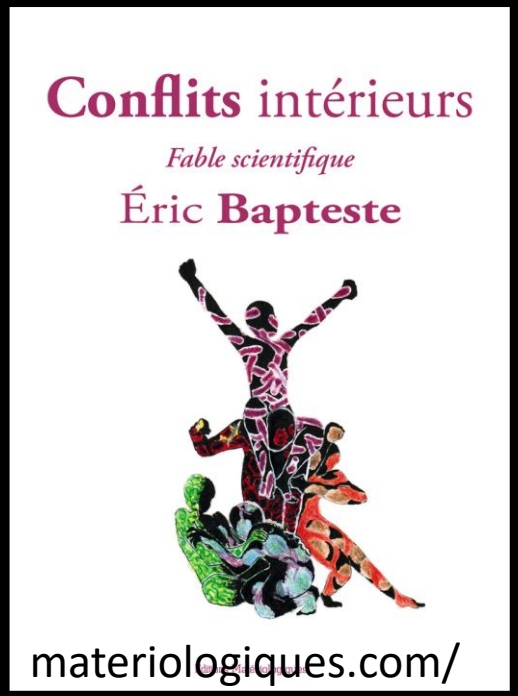


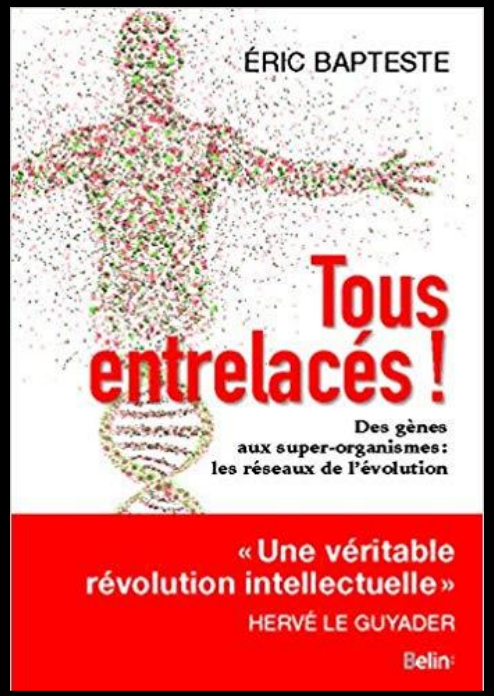



# Because such networks will soon be everywhere in biology, they may contribute, in some instances, to enhance our understanding of the resilience and interdependencies in the living world.

# Thanks a lot for your attention.





And thanks to all my wornderful colleagues: Phil Lopez, Ed Corel, François Papale, Jordane Saget, Philippe Huneman, Andrew Watson, Ford Doolittle, Frédéric Bouchard, Debashish Bhattacharya, François-Joseph Lapointe, …