The long read

Do we need a new theory of evolution?

A new wave of scientists argues that mainstream evolutionary theory needs an urgent overhaul. Their opponents have dismissed them as misguided careerists – and the conflict may determine the future of biology

by Stephen Buranyi

https://www.theguardian.com/science/2022/jun/28/do-we-need-a-new-theory-of-evolution

INSTITUTE FOR UNIVERSAL BIOLOGY
NASA ASTROBIOLOGY INSTITUTE

Topological scaling laws and the statistical mechanics of evolution

Nigel Goldenfeld

Department of Physics and
Carl R. Woese Institute for Genomic Biology
University of Illinois at Urbana-Champaign

Funded by NASA grant NNA13AA91A to the NASA Astrobiology Institute for Universal Biology

Propaganda

Life is Physics: Evolution as a Collective Phenomenon Far From Equilibrium

Nigel Goldenfeld[1] and Carl Woese[1,2]

PHILOSOPHICAL TRANSACTIONS A
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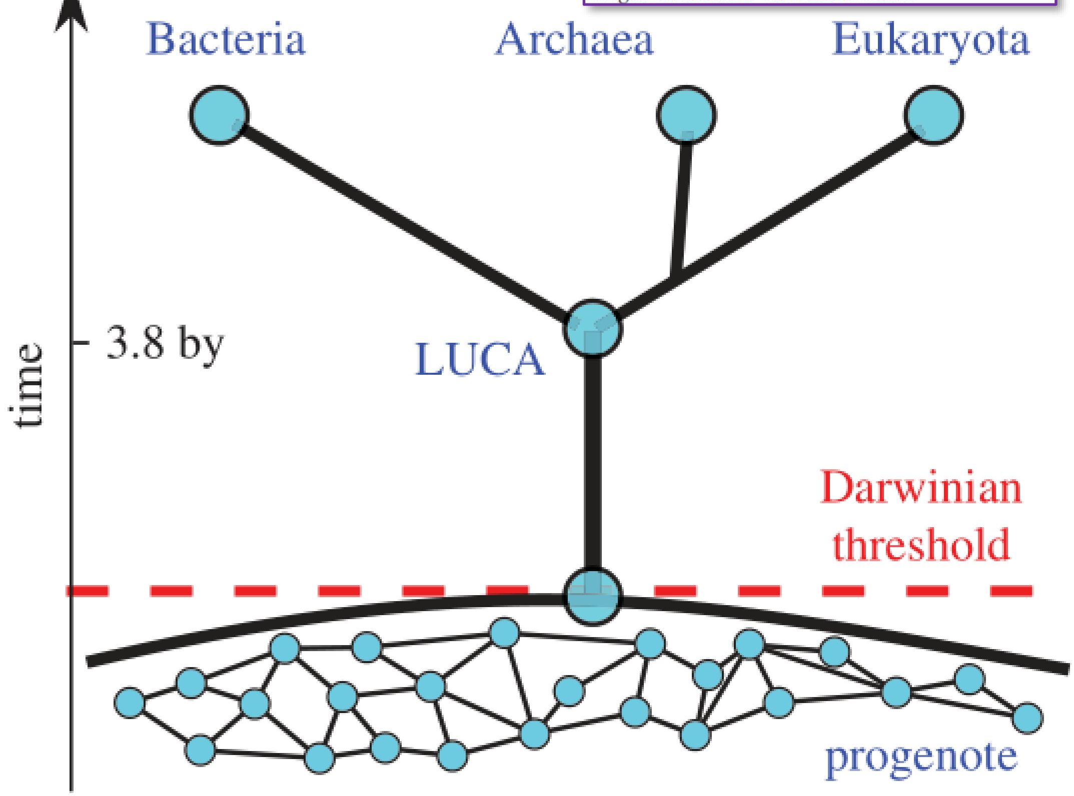
Research

Universal biology and the statistical mechanics of early life

Nigel Goldenfeld[1], Tommaso Biancalani[1,2] and Farshid Jafarpour[1,3]



Scale-invariant topology and bursty branching of evolutionary trees emerge from niche construction

Chi Xue[a,b,c], Zhiru Liu[a,b,c], and Nigel Goldenfeld[a,b,c,1]

[a]Loomis Laboratory of Physics, University of Illinois at Urbana–Champaign, Urbana, IL 61801; [b]Carl R. Woese Institute for Genomic Biology, University of Illinois at Urbana–Champaign, Urbana, IL 61801; and [c]Institute for Universal Biology, University of Illinois at Urbana–Champaign, Urbana, IL 61801

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PRL 100, 058102 (2008) PHYSICAL REVIEW LETTERS week ending 8 FEBRUARY 2008

Cascade of Complexity in Evolving Predator-Prey Dynamics

Nicholas Guttenberg and Nigel Goldenfeld
Department of Physics and Institute for Genomic Biology, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois, 61801-3080, USA

(Received 31 July 2007; published 5 February 2008)

We simulate an individual-based model that represents both the phenotype and genome of digital organisms with predator-prey interactions. We show how open-ended growth of complexity arises from the invariance of genetic evolution operators with respect to changes in the complexity, and that the dynamics which emerges shows scaling indicative of a nonequilibrium critical point. The mechanism is analogous to the development of the cascade in fluid turbulence.

PNAS

Collective evolution and the genetic code

Kalin Vetsigian*, Carl Woese†‡§, and Nigel Goldenfeld*‡¶

Departments of *Physics and †Microbiology and ‡Institute for Genomic Biology, University of Illinois at Urbana–Champaign, Urbana, IL 61801

A dynamical theory for the evolution of the genetic code is presented, which accounts for its universality and optimality. The central concept is that a variety of collective, but non-Darwinian, mechanisms likely to be present in early communal life generically lead to refinement and selection of innovation-sharing protocols, such as the genetic code. Our proposal is illustrated by using a simplified computer model and placed within the context of a sequence of transitions that early life may have made, before the emergence of vertical descent.

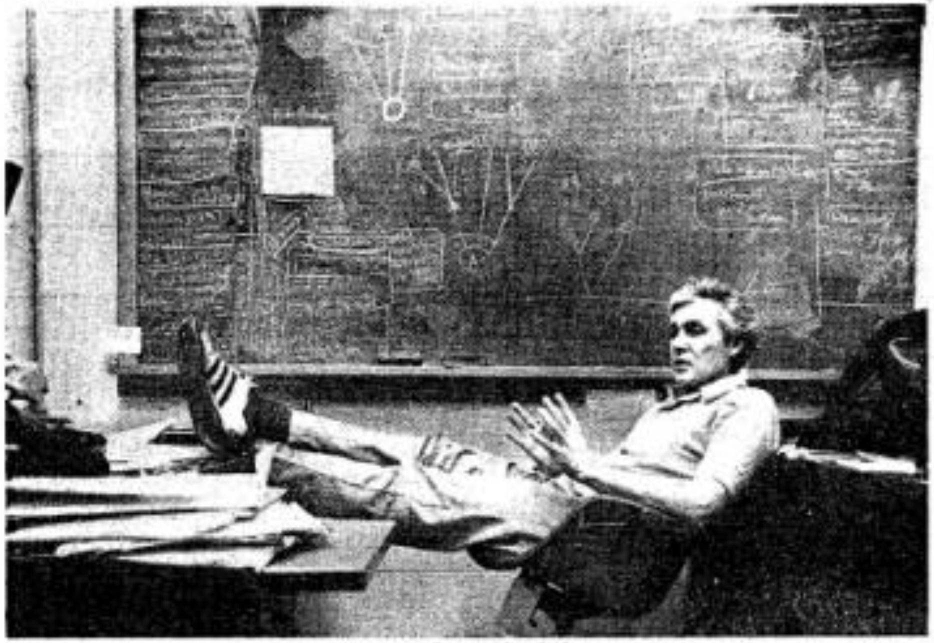
10696–10701 | PNAS | July 11, 2006 | vol. 103 | no. 28

NG, T. Biancalani, F. Jafarpour (2017)

"All the News That's Fit to Print"

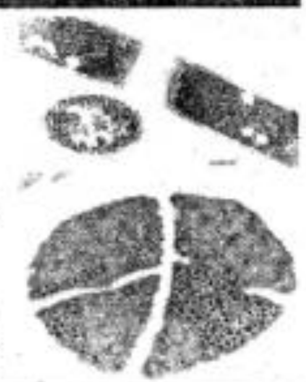
The New York Times

VOL.CXXVII..No.43,748 · NEW YORK, THURSDAY, NOVEMBER 3, 1977



The New York Times/Paul Sirer

Dr. Carl R. Woese, leader of research team, in his office at the University of Illinois. Photo at right shows the newly discovered microorganism: top, a chain of two organisms, each one-thousandth-of-a-millimeter long; center, a cross section of the chain; bottom, an organism dividing into four cells.



Scientists Discover a Form of Life That Predates Higher Organisms

By RICHARD D. LYONS
Special to The New York Times

URBANA, Ill., Nov. 2—Scientists studying the evolution of primitive organisms reported today the existence of a separate form of life that is hard to find in nature. They described it as a "third kingdom" of living material, composed of ancestral cells that abhor oxygen, digest carbon dioxide and produce methane.

the group investigating the evolution of microorganisms.

The genetic tracking efforts of the scientific group, which spanned five years, were made public today by two of the Federal agencies that supported the research, the National Aeronautics and Space Administration and the Nation-

U.N. COUNCIL AGREES ON ARMS-BAN TERMS AGAINST SOUTH AFRICA

Black Nations Accept Revised Draft —Embargo May Be Acted On as Early as Tomorrow

By KATHLEEN TELTSCH
Special to The New York Times

UNITED NATIONS, N.Y., Nov. 2—The 15 members of the Security Council agreed at a private meeting today on the terms of a revised proposal for a mandatory embargo on arms sales to South Africa to influence it to change its repressive racial practices.

Except for some minor details, the Council members agreed on the text of a resolution calling for such an embargo, and this was accepted later by the 49-nation African bloc of the United Nations, which had pressed unsuccessfully for economic sanctions.

The agreement today means that the resolution is likely to be approved without a vote as a statement of consensus by the Council, possibly as early as Friday.

First Such Step Against a Member

This would be the first time that the Council has imposed the punitive measure of sanctions against a United Nations member.

The new text goes part way toward meeting the position of the 49 African countries, which brought a complaint to the Council after South Africa's severe crackdown on Oct. 19 against black organizations and individuals and their supporters.

The draft resolution calls on all countries, including those not in the United Nations, to "cease forthwith" any provision to South Africa of arms, ammunition of all types, military vehicles and equipment and spare parts. In response to demands by African countries, the revised text included calls for a review

CONVICTION IS UPHELD

Vance Welcomes Offer by Soviet As 'Major Step'

By BERNARD GWERTZMAN
Special to The New York Times

WASHINGTON, Nov. 2—Secretary of State Cyrus R. Vance said today that Leonid I. Brezhnev's proposal for a moratorium on all underground nuclear detonations — for peaceful uses as well as weapons tests—marked "a major step forward" toward a comprehensive test ban, but that differences persisted on the duration of such an accord.

At a news conference, Mr. Vance underscored Washington's satisfaction with the proposal. But reflecting the ambiguous state of Soviet-American relations, Mr. Vance also confirmed a report in The New York Times that the Administration had been urging the Russians not to proceed with pending trials of dissidents lest they could harm overall relations.

'A Mixed Set of Factors'

"Let me say that the relationships between ourselves and the Soviet Union are always a mixed set of factors," he said. "We have areas in which we may be making progress; there are other areas in which we may be standing still; and there are still other areas in which we may be retrogressing. And today is like any other time in that there are all of these different kinds of currents and crosscurrents flowing in our relationships."

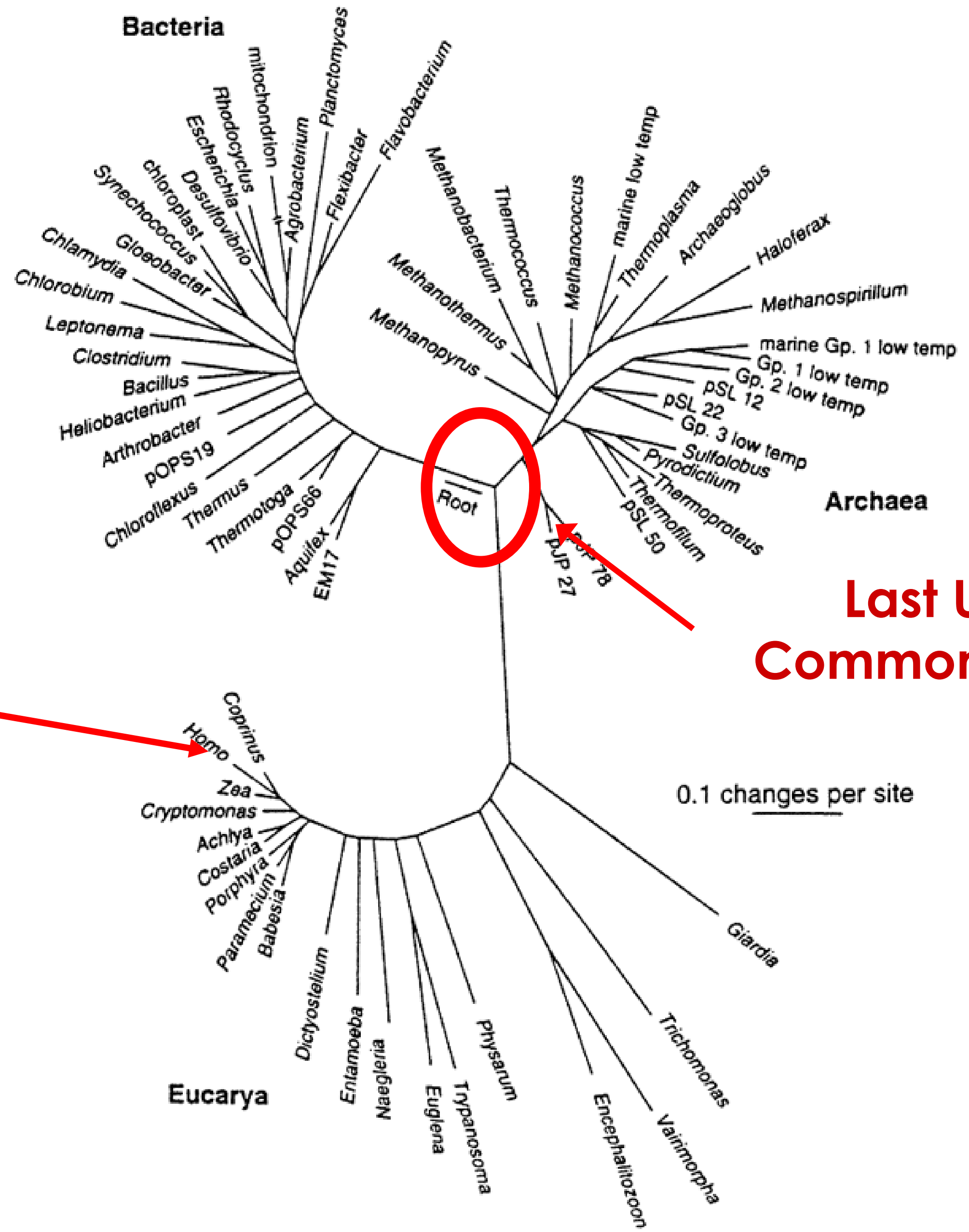
On the whole, there has been an improvement in relationships over the last

Continued on Page A3, Column 1

CARTER MAKES PLEA TO JEWS ON MIDEAST

He Calls on Leaders to Support

The Tree of Life

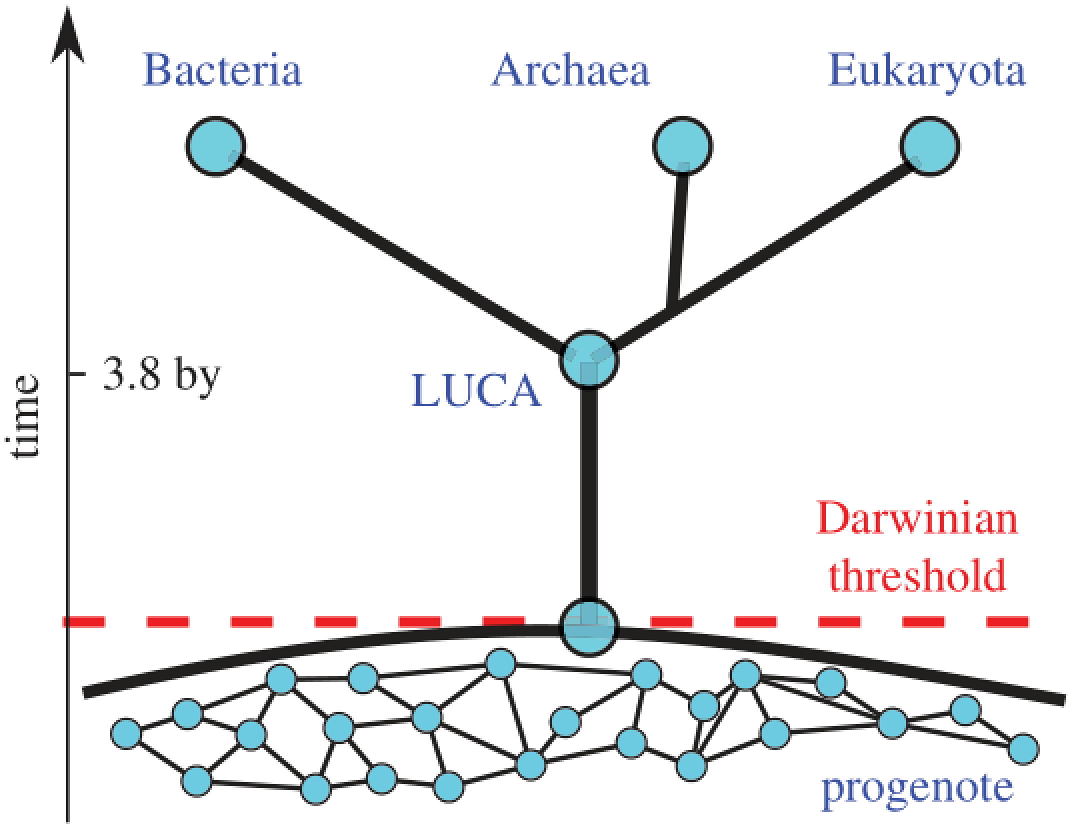


Last Universal Common Ancestor ?

You are here

- NR Pace, Science 1997

Phase diagram of life



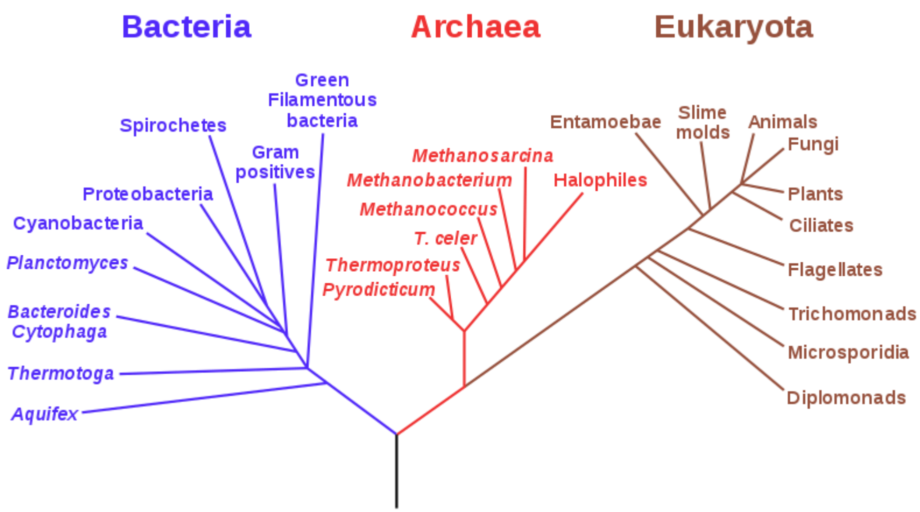
Slow evolution

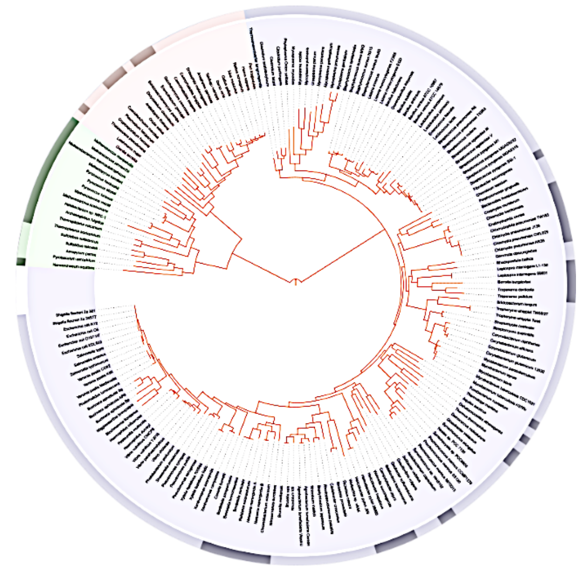
Rapid evolution

- Inexorable transitions: collective network phase of life, transitions to vertical evolution

NG, T. Biancalani, F. Jafarpour (2017)

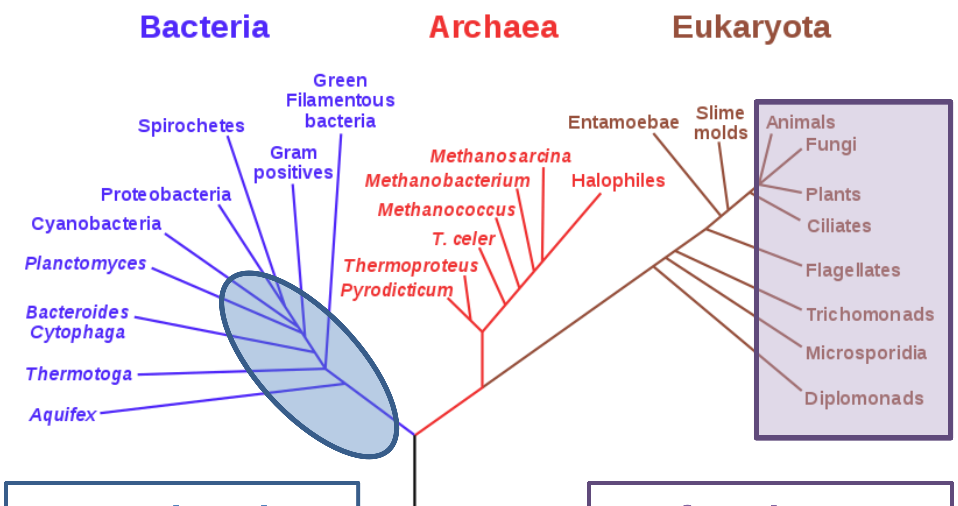
Phylogenetic Trees

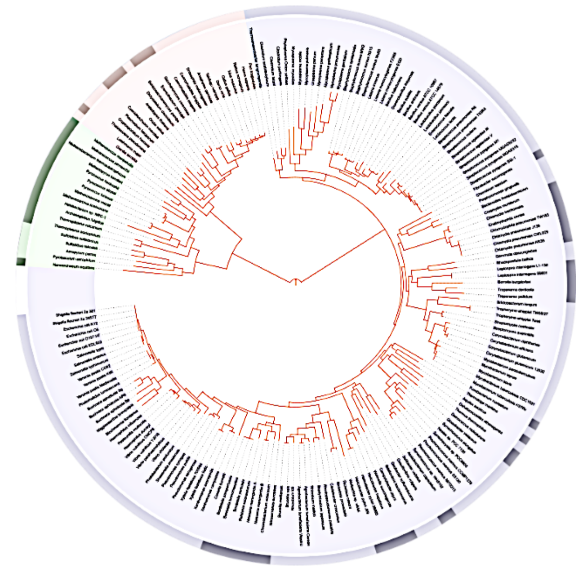




Wikipedia, Creative Commons

Phylogenetic Trees





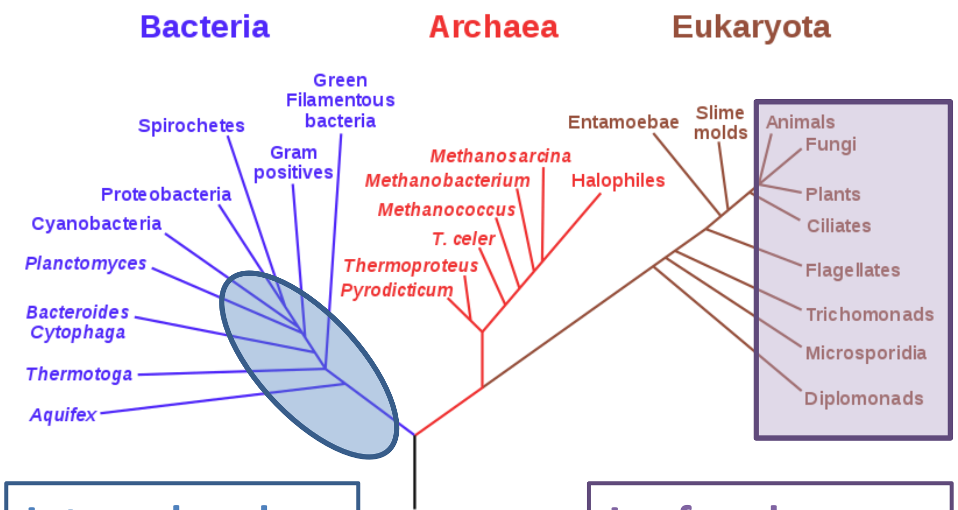
Internal nodes
hypothetical taxonomic units

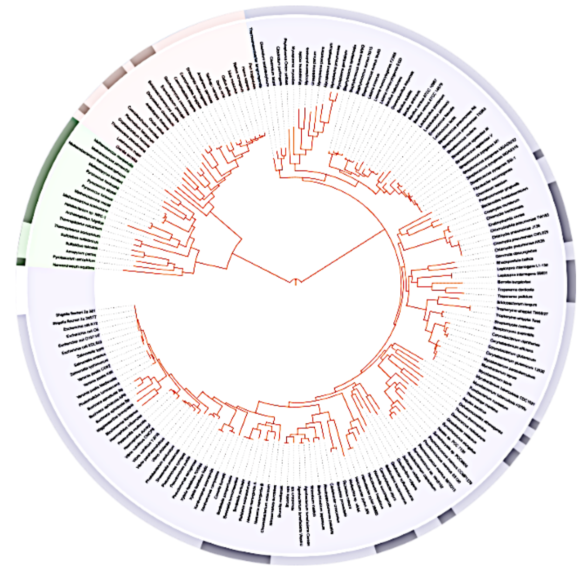
Leaf nodes
observed extant taxonomic units

Ancestor nodes are derived by comparing the relatedness of sequencing data of descendant species.

Wikipedia, Creative Commons

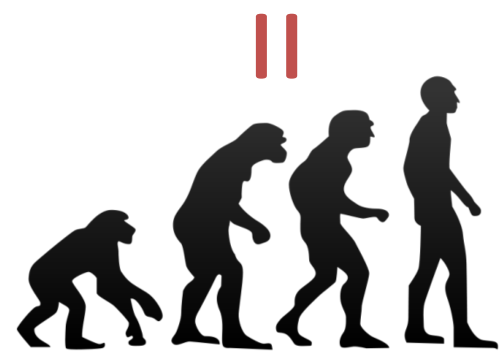
Phylogenetic Trees





Internal nodes
hypothetical taxonomic units

Leaf nodes
observed extant taxonomic units



Phylogenetic trees represent the trace of the evolutionary process

Wikipedia, Creative Commons

Phylogenetic trees are the Feynman diagrams of evolution

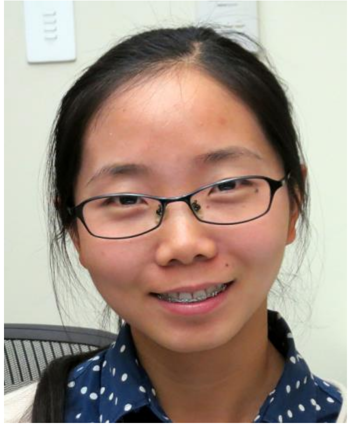
What can we learn about the large-scale structure of the evolutionary process from the world-lines of all the world’s species?

Scale-invariant topology and bursty branching of evolutionary trees emerge from niche construction

Chi Xue[a,b,c], Zhiru Liu[a,b,c], and Nigel Goldenfeld[a,b,c,1]

[a]Loomis Laboratory of Physics, University of Illinois at Urbana–Champaign, Urbana, IL 61801; [b]Carl R. Woese Institute for Genomic Biology, University of Illinois at Urbana–Champaign, Urbana, IL 61801; and [c]Institute for Universal Biology, University of Illinois at Urbana–Champaign, Urbana, IL 61801

PNAS | April 7, 2020 | vol. 117 | no. 14 | 7879–7887



Chi Xue & Zhiru Liu

NSF

Center for the Physics of Living Cells

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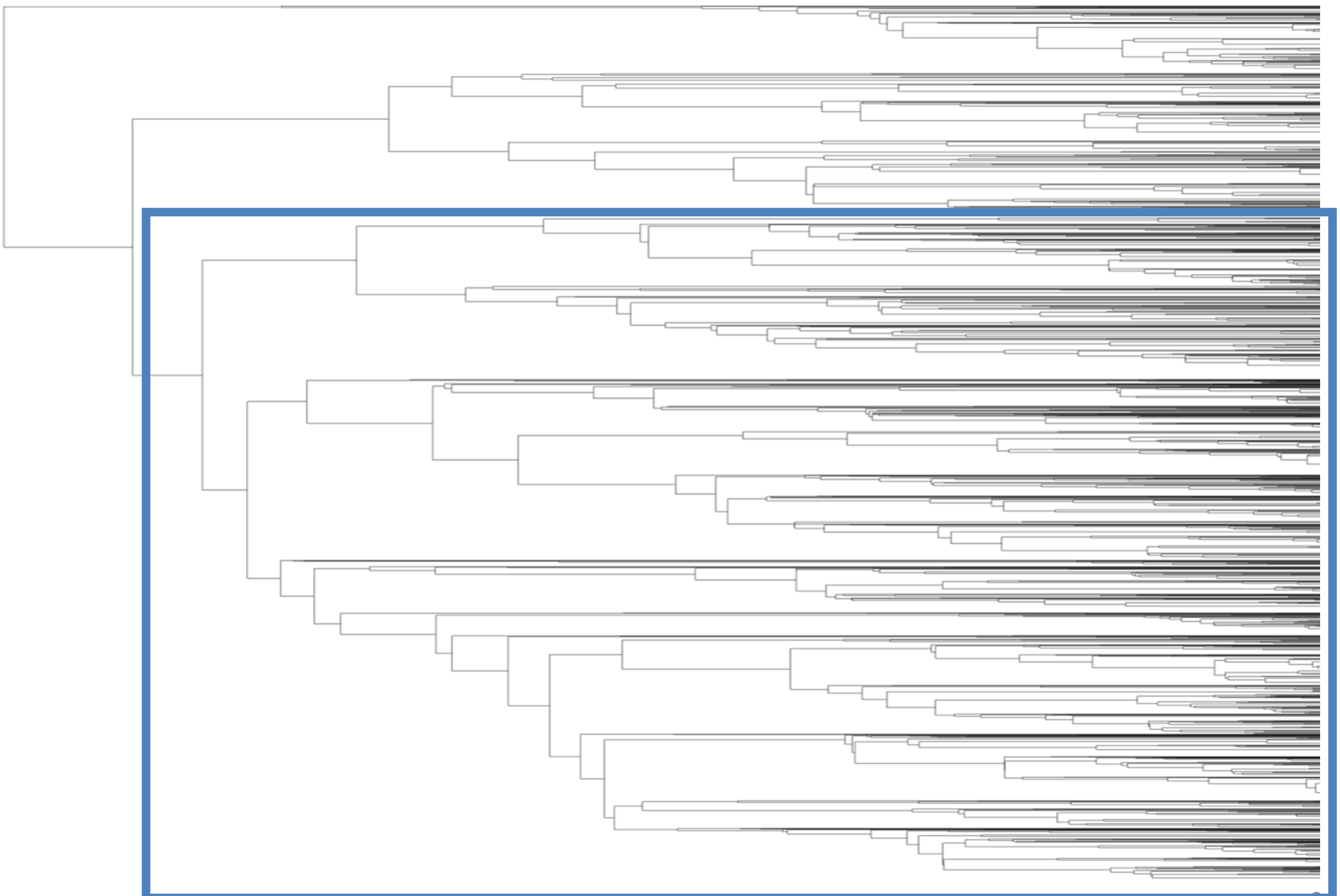
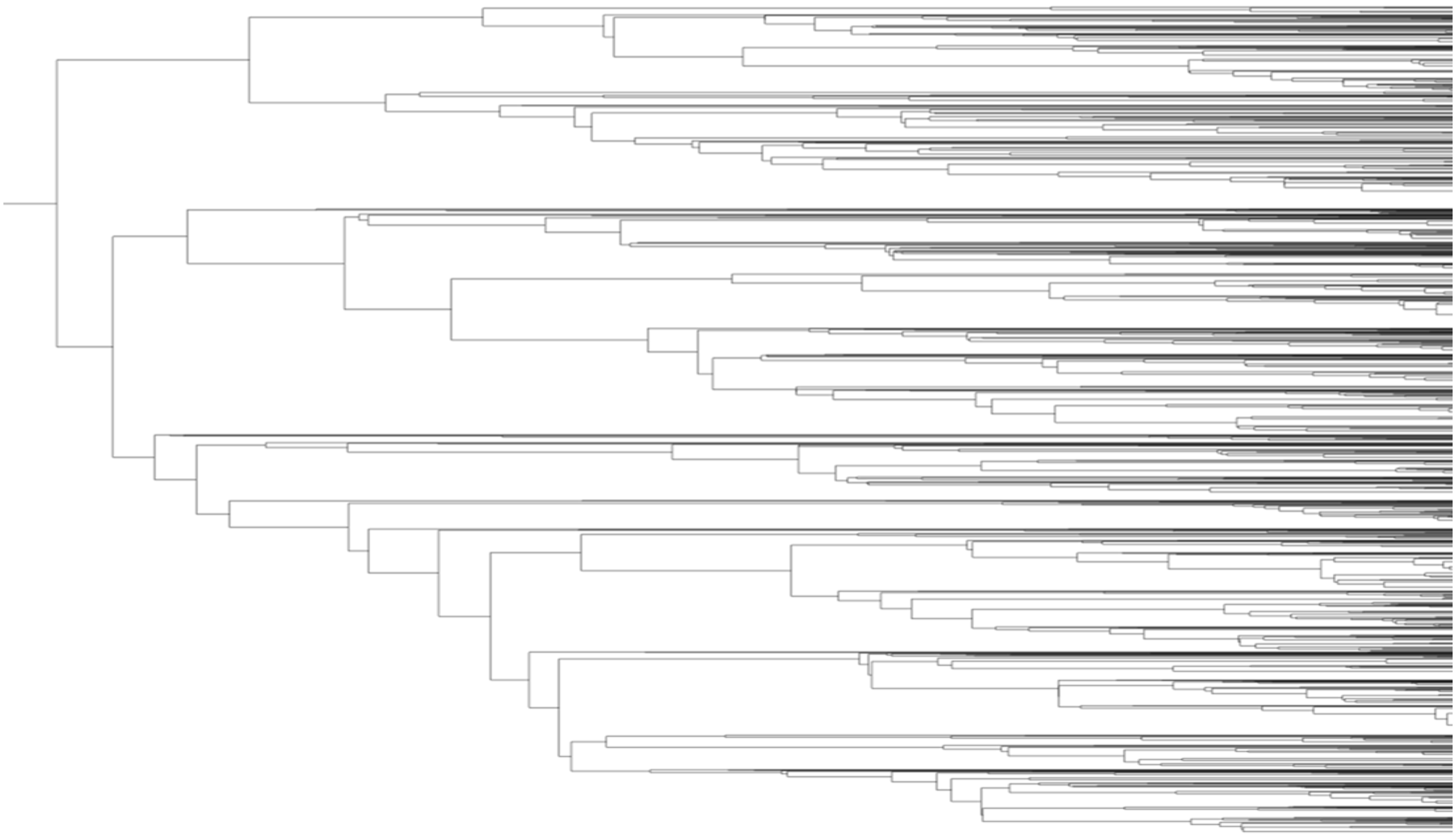
Phylogenetic Trees are self-similar



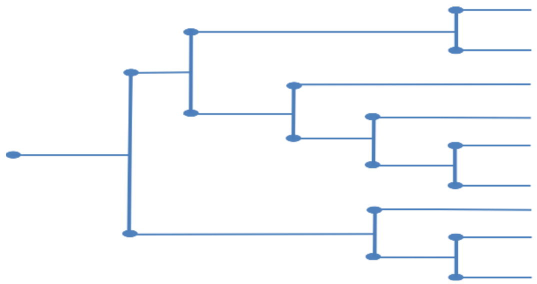
Phylogenetic Trees are self-similar



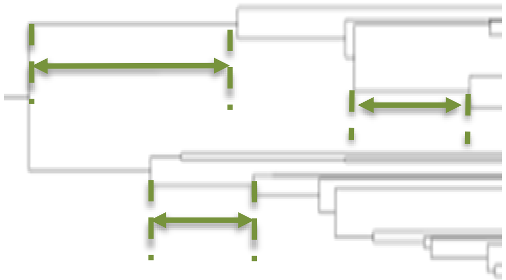
Phylogenetic Trees are self-similar

- Need quantitative descriptions of the structure

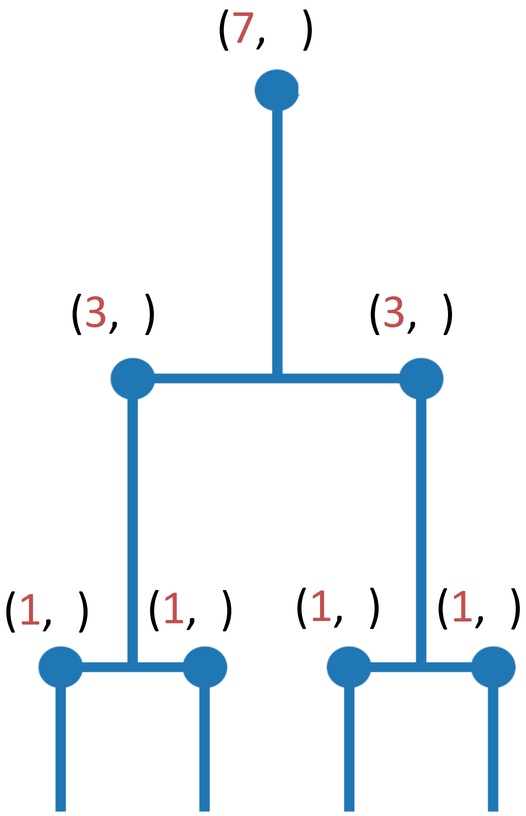
- Two aspects:
  - Topology (structure unaffected by change in edge length or arrangement)



  - Edge lengths (time scales in the evolutionary process)



Description for tree topology



Node i

A_i: the size, or number of nodes, of the subtree S_i rooted at node i.

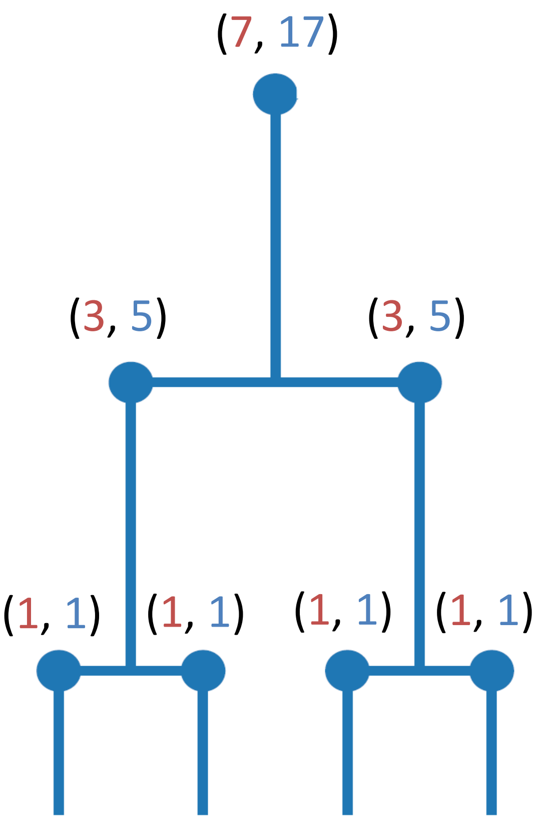
$A(\text{leaf}) = 1$

$A(i) = 1 + A(i \to \text{left}) + A(i \to \text{right})$

E. A. Herrada *et. al.* PLoS one, **3**, e2757 (2008)

P. Jeraldo (2012); NG (2014)

Description for tree topology



<u>Node i</u>

A_i: the size, or number of nodes, of the subtree S_i rooted at node i.

$$A(\text{leaf}) = 1$$
$$A(i) = 1 + A(i \rightarrow \text{left}) + A(i \rightarrow \text{right})$$

C_i: the cumulative size, or summation of A, of the subtree S_i.

$C(A)$

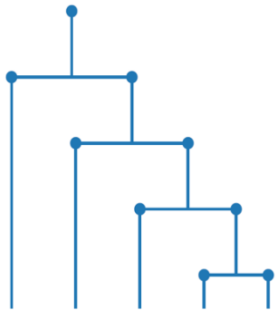
$$C(\text{leaf}) = 1$$
$$\mathrm{C}(i) = A(i) + C(i \rightarrow \text{left}) + C(i \rightarrow \text{right})$$

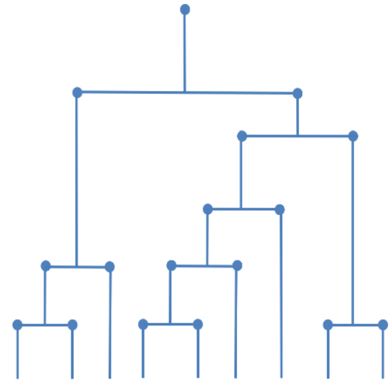
Note: Mirroring left and right branches does not change $C(A)$.

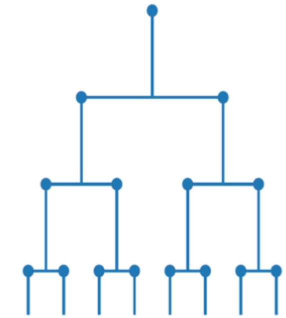
E. A. Herrada *et. al.* PLoS one, **3**, e2757 (2008)

P. Jeraldo (2012); NG (2014)

Description for tree topology







$C(A) \sim A^2$

$C(A) \sim A^\eta, \eta \approx 1.44$

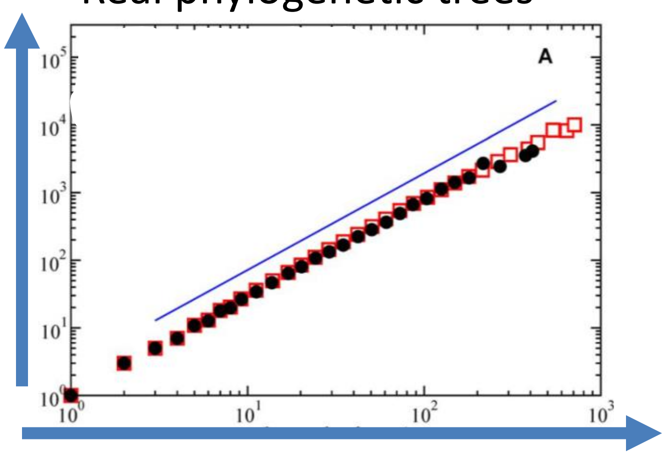
$C(A) \sim A \ln A$

Completely unbalanced

Completely balanced

Real phylogenetic trees

$C(A)$

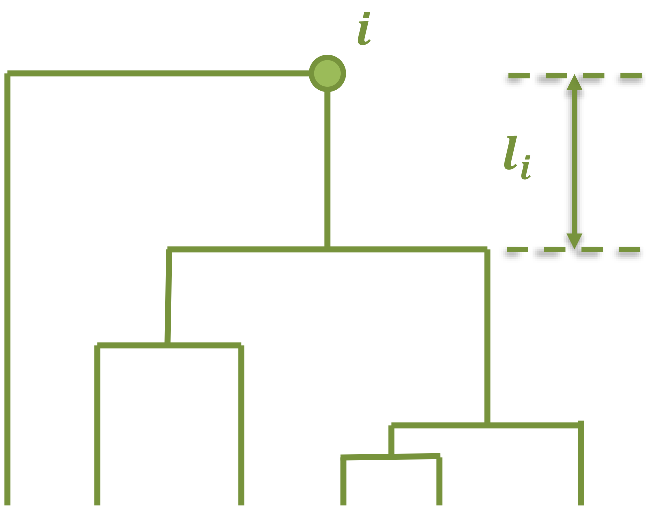


A

P. Jeraldo (2012); NG (2014)

E. A. Herrada *et. al.* PLoS one, **3**, e2757 (2008)

Description for edge lengths



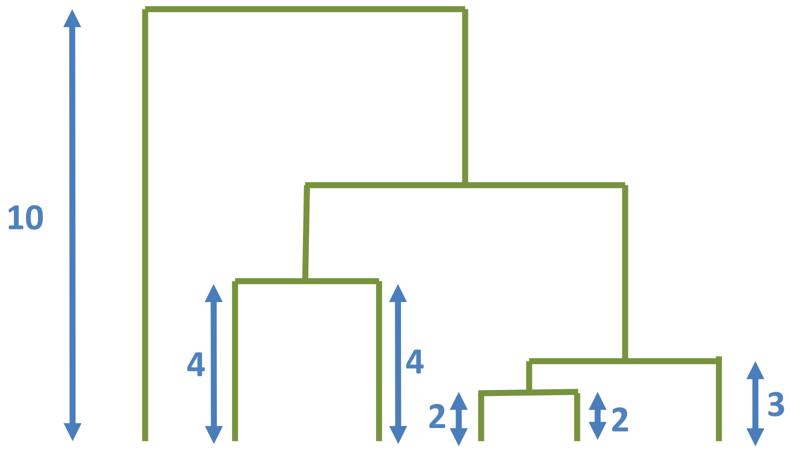
Let $\{i\}_k$ be all nodes that define a clade with k tips

Let l_i be the edge length between i and its branching point

$$S(k) = \sum_{i \in \{i\}_k} l_i$$

James P. O'Dwyer *et. al.* PNAS, 112(27), 8356-8361.

Description for edge lengths



Let $\{i\}_k$ be all nodes that define a clade with k tips

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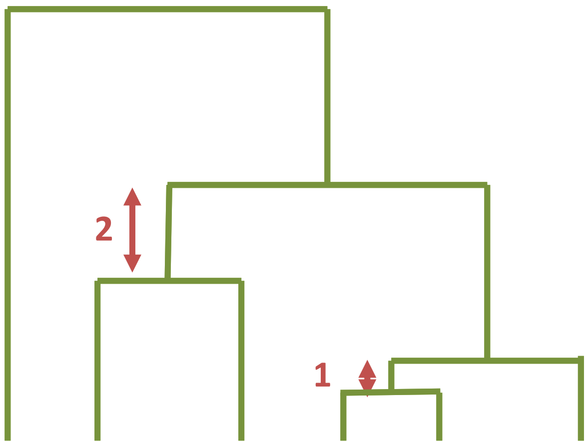
k	1	2	3	4	5
$S(k)$	25				

James P. O'Dwyer *et. al.* PNAS, 112(27), 8356-8361.

Description for edge lengths



Let $\{i\}_k$ be all nodes that define a clade with k tips

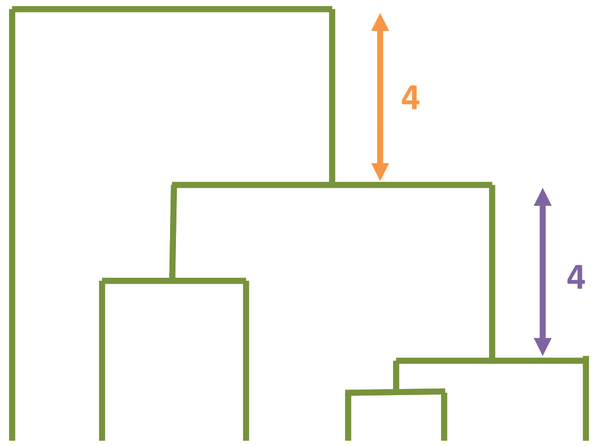
Let l_i be the edge length between i and its branching point

$$S(k) = \sum_{i \in \{i\}_k} l_i$$

k	1	2	3	4	5
$S(k)$	25	3			

James P. O'Dwyer *et. al.* PNAS, 112(27), 8356-8361.

Description for edge lengths



Let $\{i\}_k$ be all nodes that define a clade with k tips
Let l_i be the edge length between i and its branching point

$$S(k) = \sum_{i \in \{i\}_k} l_i$$

k	1	2	3	4	5
$S(k)$	25	3	4	0	4

James P. O'Dwyer *et. al.* PNAS, 112(27), 8356-8361.

Description for edge lengths

$S(k) \sim k^{-2}$

$S(k) \sim k^{-\alpha}$, $\alpha \in [1.3, 1.7]$

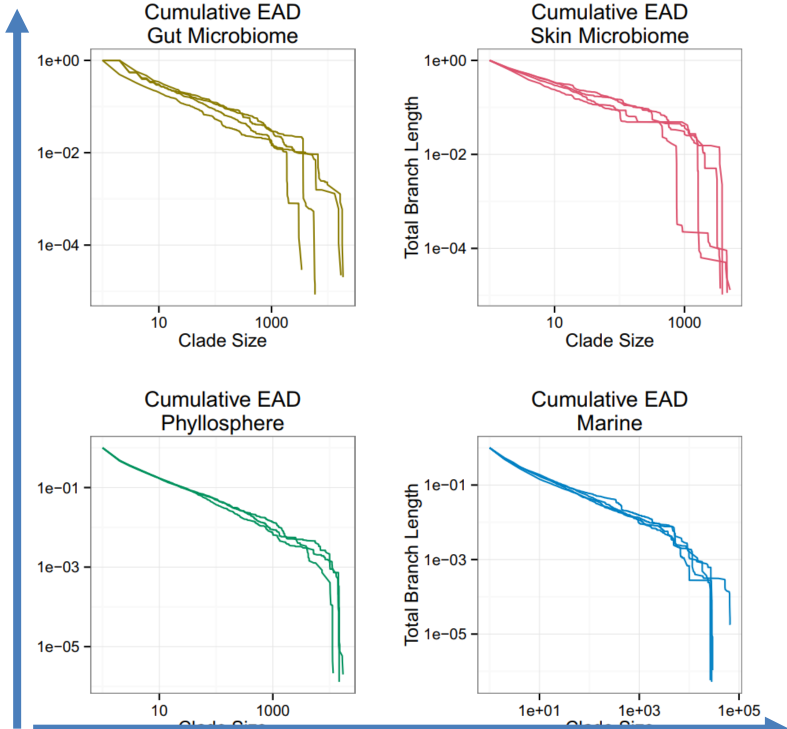
$S(k) \sim k^{-1}$

Yule process
- Neutral model with exponentially growing community

Real phylogenetic trees

Kingman coalescent
- Neutral model with fixed community size

$S(k)$
Cumulative Edge Length

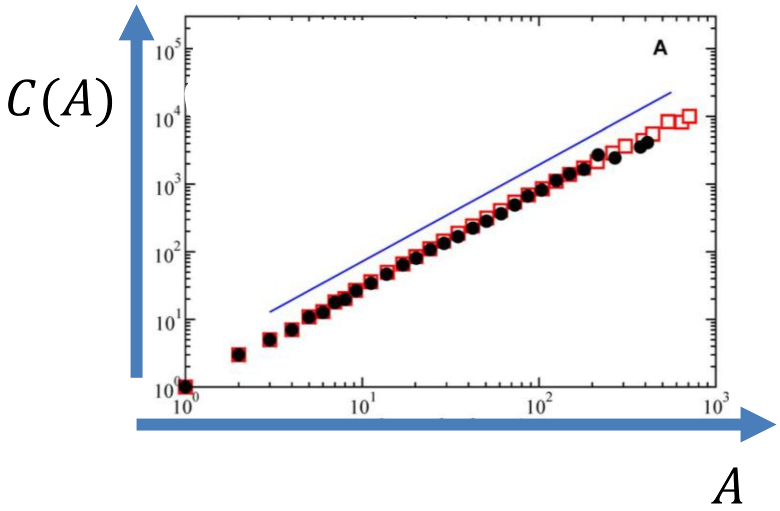


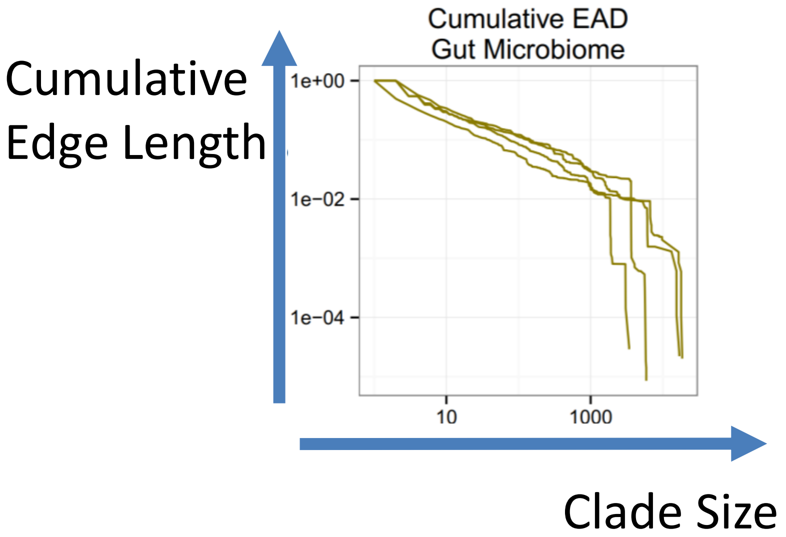
k - Clade Size

James P. O'Dwyer *et. al.* PNAS, 112(27), 8356-8361.

Phylogenetic trees are self-similar

- The topological measure and the edge length distribution capture the large-scale structure of evolution





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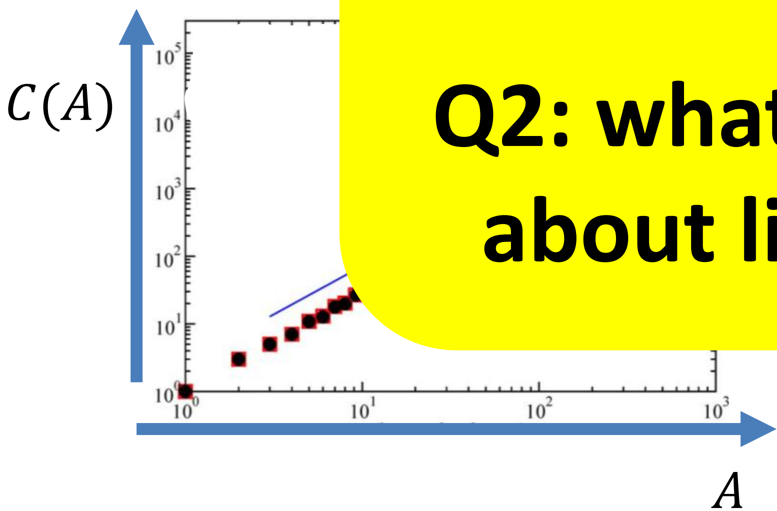
Phylogenetic trees are self-similar

- The topol… …length distribu… …cture of evol…

Q1: origin of these non-trivial power laws?

Q2: what do they tell us about living systems?



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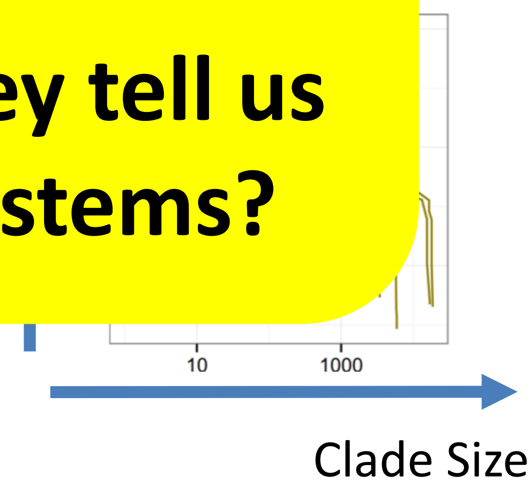
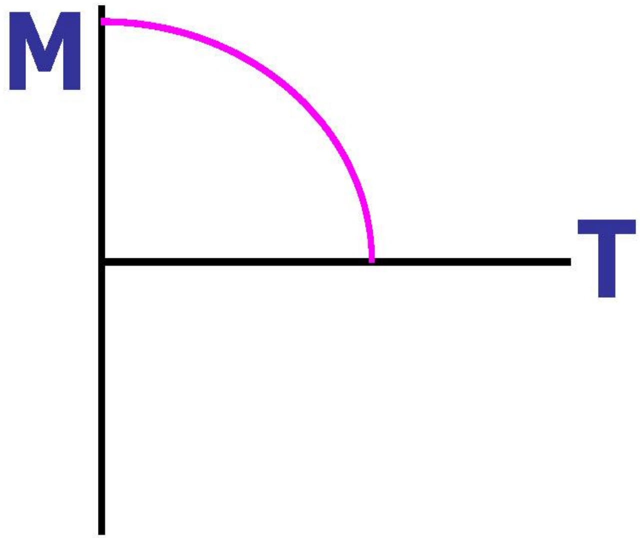


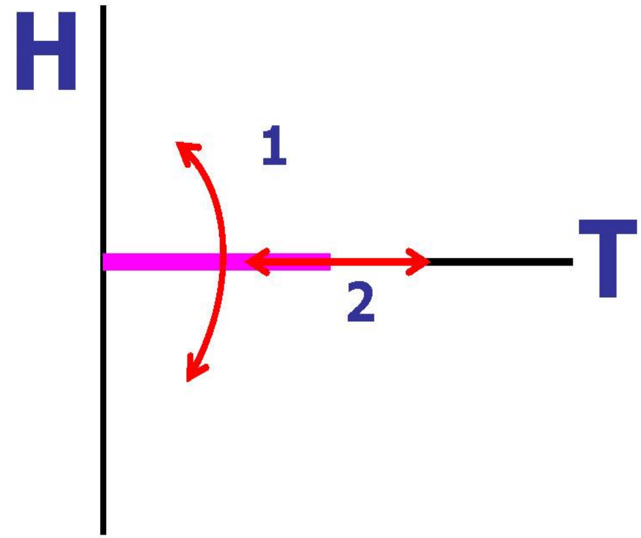
James P. O'Dwyer *et. al.* PNAS, 112(27), 8356-8361.

Is there universality in physics?

Critical phenomena in magnets



$M \sim M_0[|T - T_c|/T_c]^\beta$ for $H = 0$ as $T \to T_c$



Critical isotherm: $M \sim H^{1/\delta}$ for $T = T_c$

- Widom (1963) pointed out that both these results followed from a *similarity formula*:

$$M(t,h) = |t|^\beta f_M(h/t^\Delta)$$

where $t \equiv (T - T_c)/T_c$ for some choice of exponent Δ and scaling function $f_M(x)$

Universality at a critical point

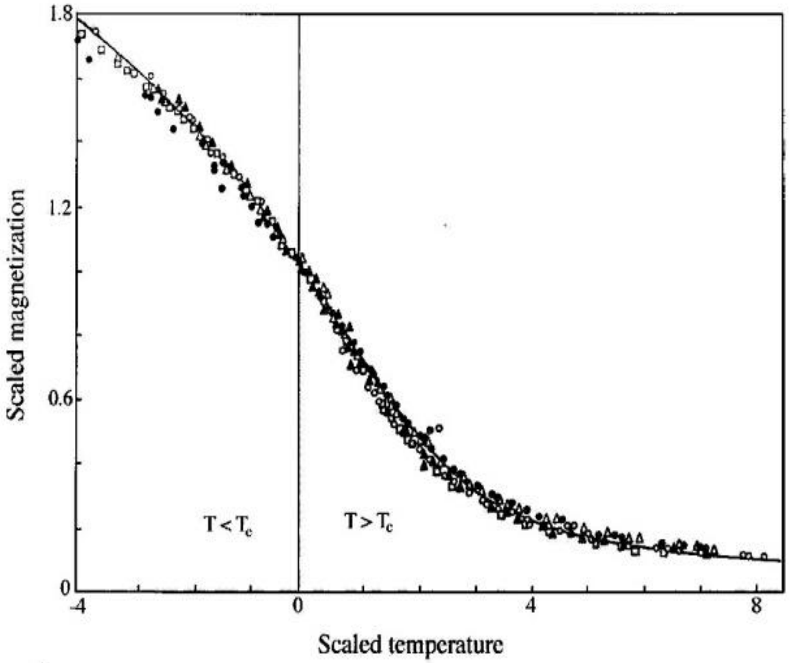


FIG. 1. Experimental *MHT* data on five different magnetic materials plotted in scaled form. The five materials are $CrBr_3$, EuO, Ni, YIG, and Pd_3Fe. None of these materials is an idealized ferromagnet: $CrBr_3$ has considerable lattice anisotropy, EuO has significant second-neighbor interactions. Ni is an itinerant-electron ferromagnet, YIG is a ferrimagnet, and Pd_3Fe is a ferromagnetic alloy. Nonetheless, the data for all materials collapse onto a single scaling function, which is that calculated for the $d=3$ Heisenberg model [after Miloševć and Stanley (1976)].

Stanley (1999)

- **Magnetization M of a material depends on temperature T and applied field H**
  - **M(H,T) ostensibly a function of two variables**
- **Plotted in appropriate scaling variables get ONE universal curve**
- **Scaling variables involve critical exponents**

Universality at a critical point

A model …

Gives a precise prediction in agreement with experiment!

materials collapse onto a single scaling function, which is that calculated for the $d=3$ Heisenberg model [after Milošević and Stanley (1976)].

Stanley (1999)

Universality at a critical point

A model of a model of a model of a model of a model

Landau theory

Classical Heisenberg

Quantum Heisenberg

Electronic structure

Quantum chemistry

Gives a precise prediction in agreement with experiment!

Non-systematic approximations

materials collapse onto a single scaling function, which is that calculated for the $d=3$ Heisenberg model [after Milošević and Stanley (1976)].

Stanley (1999)

Origin of non-trivial power laws

$$\hat{G}(\mathbf{k}, T_c) \propto a^{\eta} k^{-2+\eta}$$

Anomalous exponent

Correlation function

Lattice spacing

Wavenumber

- Power laws at "second order" phase transitions
- Correlation function has units of [Length]^2
- Scale interference: limit of a → 0
  - If η = 0, the limit exists and G ~ k^{-2} (Landau theory)
  - If η non-zero, the limit is singular, then cannot set a = 0. G scales with a non-trivial power law.

System remembers the small scale details even though the correlation length is diverging to infinity!

Origin of non-trivial power laws

$$\hat{G}(\mathbf{k}, T_c) \propto a^{\eta} k^{-2+\eta}$$

Anomalous exponent

Correlation function

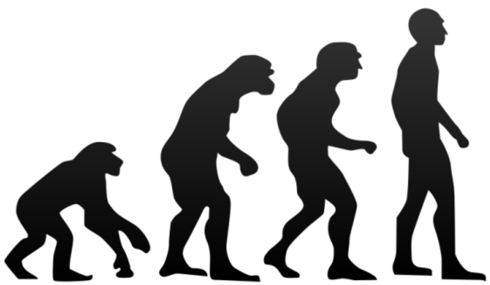
Lattice spacing

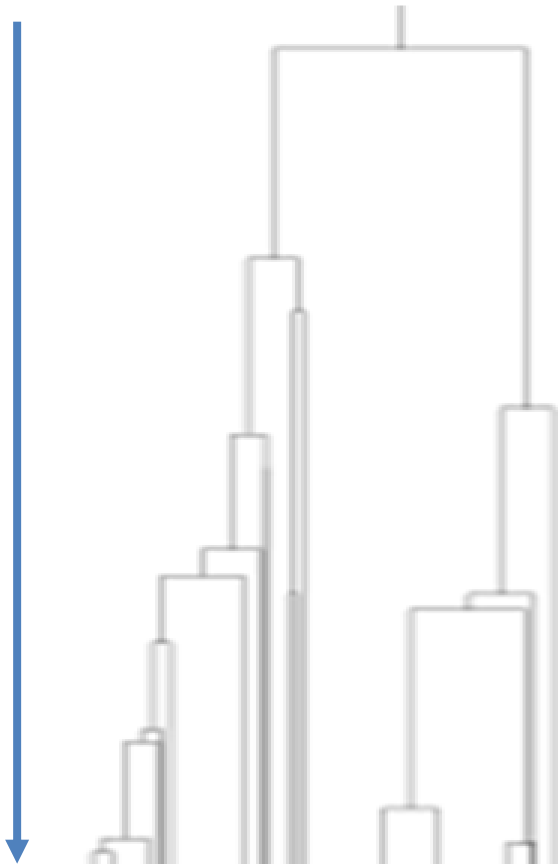
Wavenumber

- P s
- C
- S
  - aly
  - If limit is singular, then cannot set a = 0 and there is an anomalous exponent

Is there scale interference in evolution?

How could scaling laws arise?





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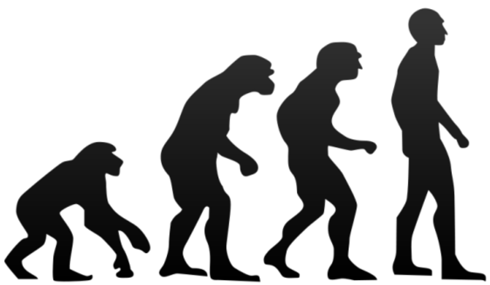
How could scaling laws arise?



Evolution

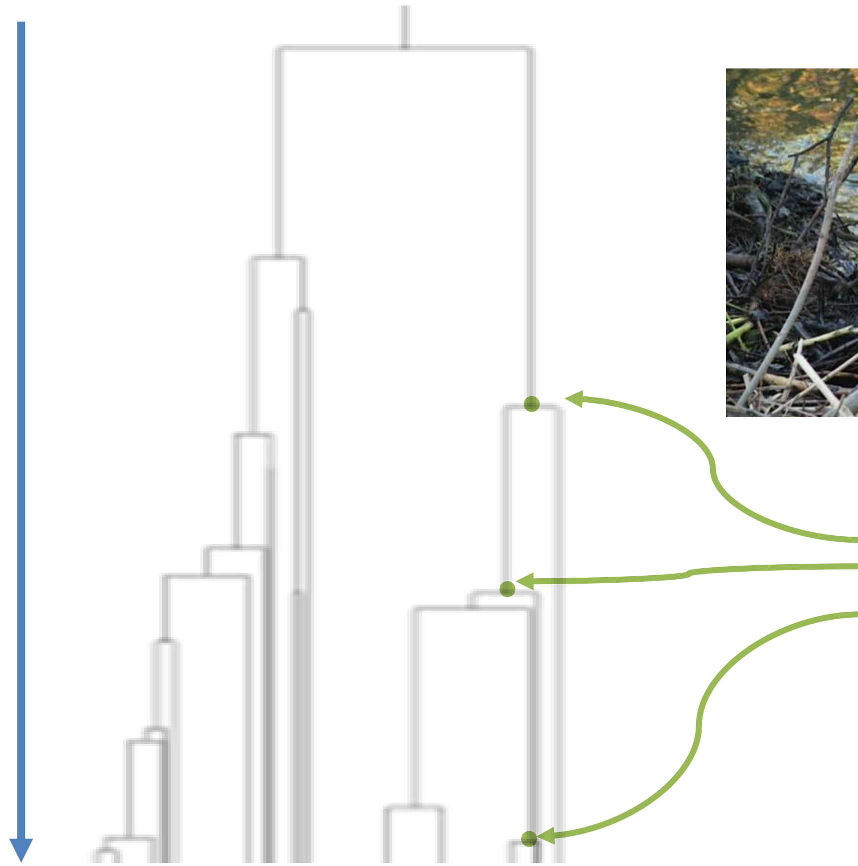


Photo by Cheryl Reynolds

Ecology

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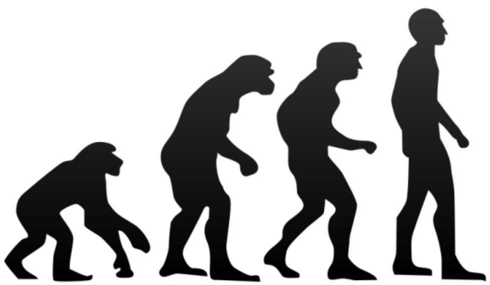
How could scaling laws arise?



Evolution

Long time scale

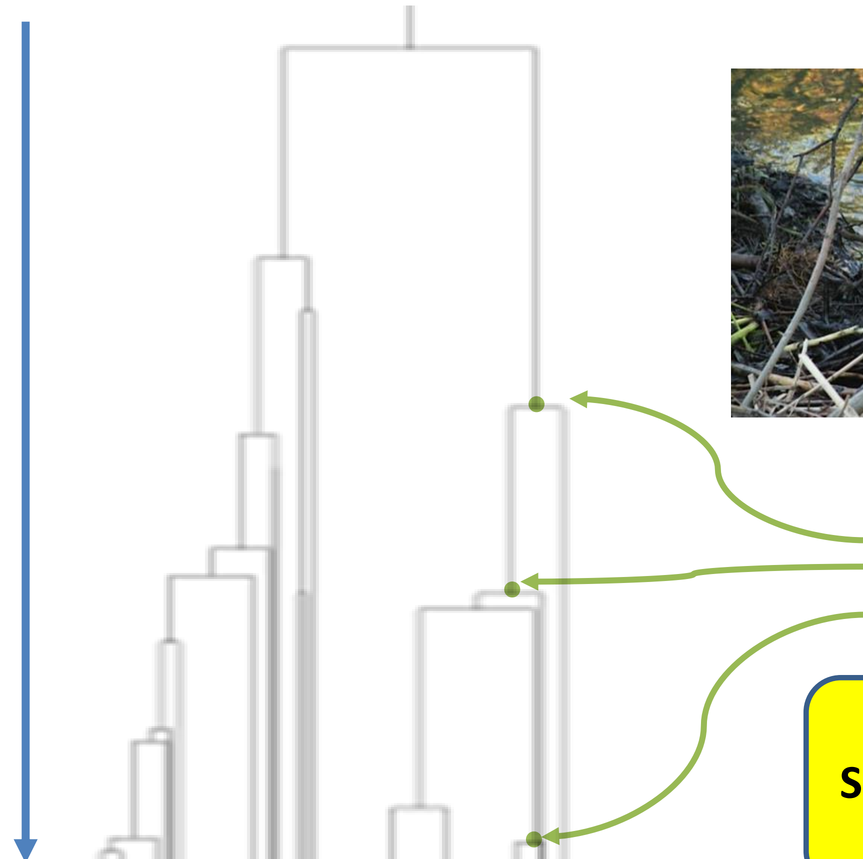


Photo by Cheryl Reynolds

Ecology

Short time scale

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How could scaling laws arise?

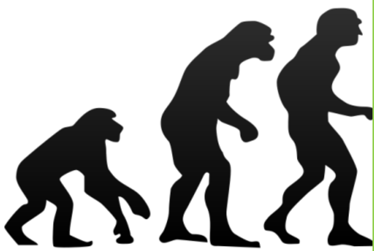


Photo by Cheryl Reynolds

In drawing a phylogenetic tree we set

$$\frac{\text{Ecological time scale}}{\text{Evolutionary time scale}} = 0$$

Evolutio[n]

[E]cology

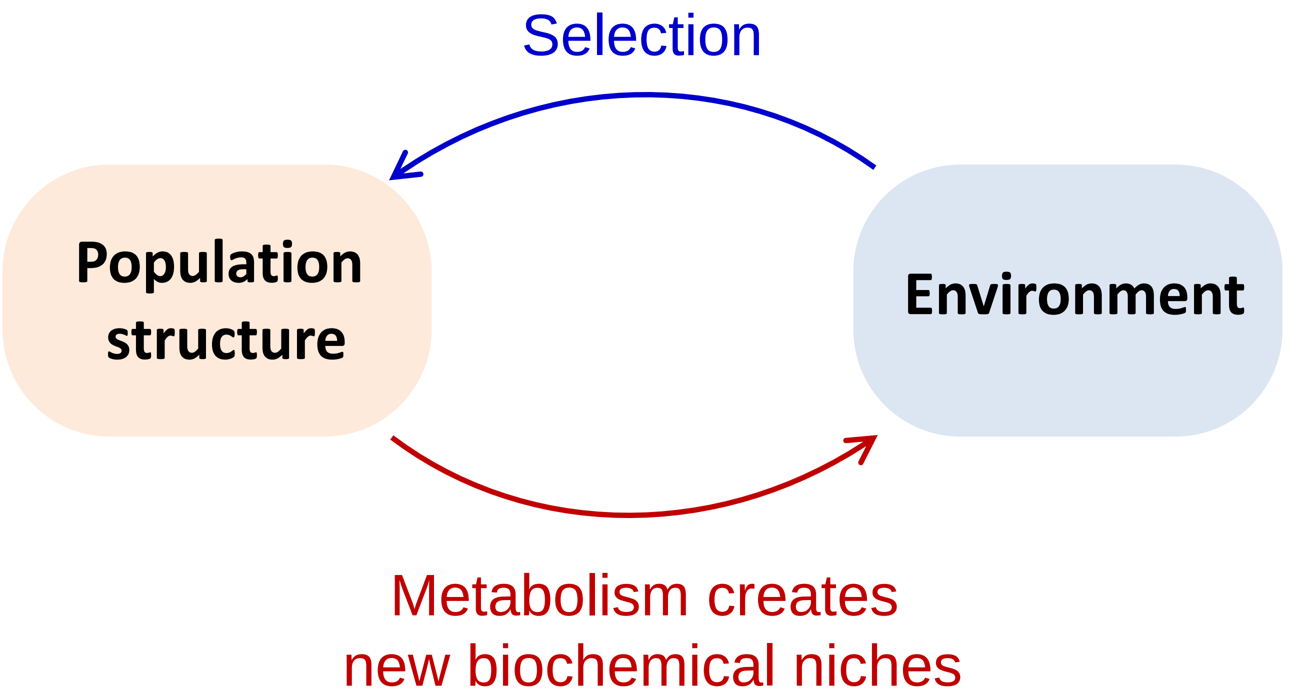
Long time scale

Short time scale

Wikipedia, Creative Commons

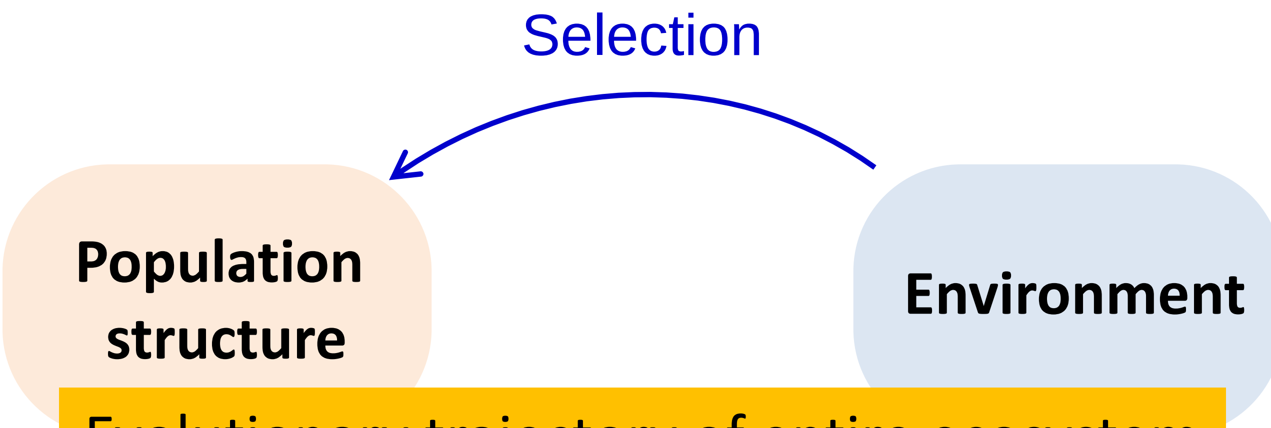
Questions

Rapid evolution:
evolutionary time scale ~ environmental time scale



Questions

Rapid evolution:
evolutionary time scale ~ environmental time scale



Evolutionary trajectory of entire ecosystem can be affected by rapid evolution

Metabolism creates new biochemical niches

Time-scale separation

In drawing a phylogenetic tree we set

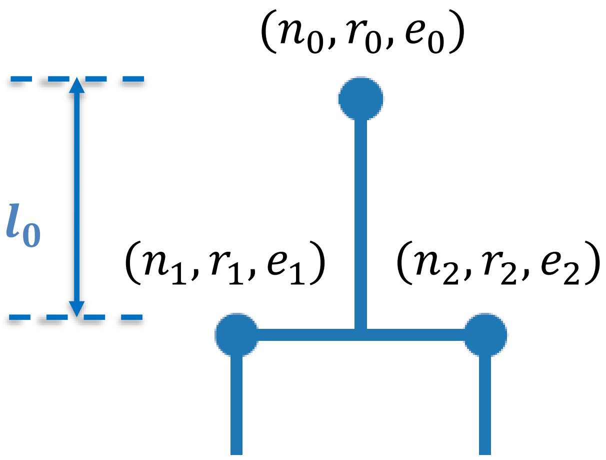
$$\frac{\text{Ecological time scale}}{\text{Evolutionary time scale}} = 0$$

- Feedback between ecology and evolution
  ➔time scale separation not valid

Idea: Niche construction

- Niche: The position of a species in its ecosystem
- Niche construction: mutual interaction between a species and the ecosystem
- The survival and diversification of a species depend on its niche - ecology
- The niche of a species is correlated with its ancestor's - evolution

Minimal model for eco-evo dynamics



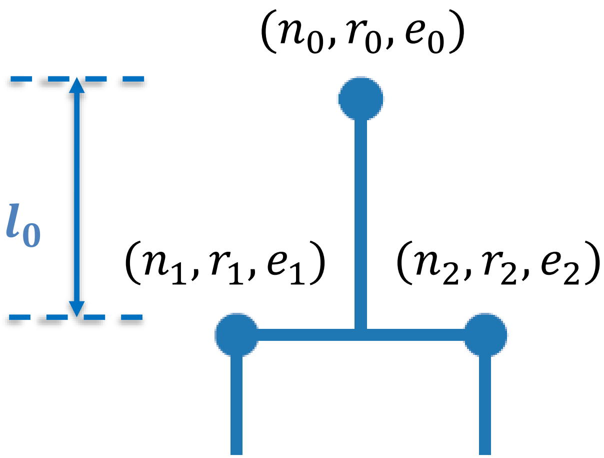
Niche = total available growth space or evolutionary degrees of freedom of the organism

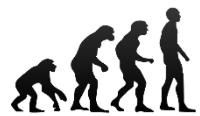
An organism with a large niche value, has a large number of possible ways to adapt to the environment

n: available niche
r: speciation rate
e: extinction probability

l_i follows exponential distribution with rate r

Minimal model for eco-evo dynamics





$$n_1 = n_0 + \Delta n_1$$
$$n_2 = n_0 + \Delta n_2$$

$$\frac{\Delta n_i}{n_0} \sim N(\mu_n, \sigma_n^2)$$

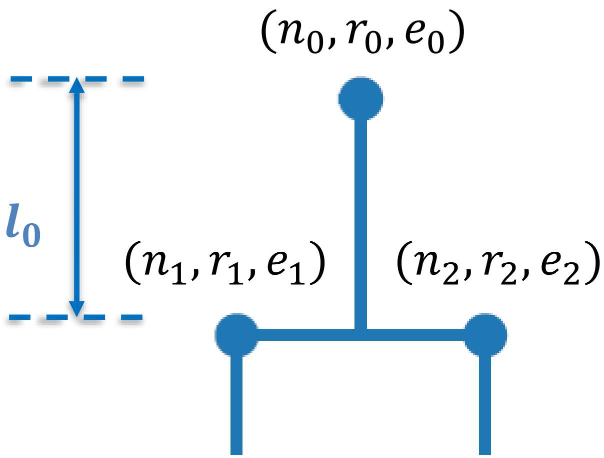
Inheritance

n: available niche
r: speciation rate
e: extinction probability

l_i follows exponential distribution with rate r

Wikipedia, Creative Commons

Minimal model for eco-evo dynamics



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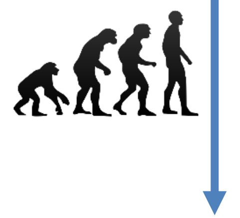

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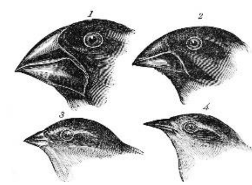
Inheritance

+



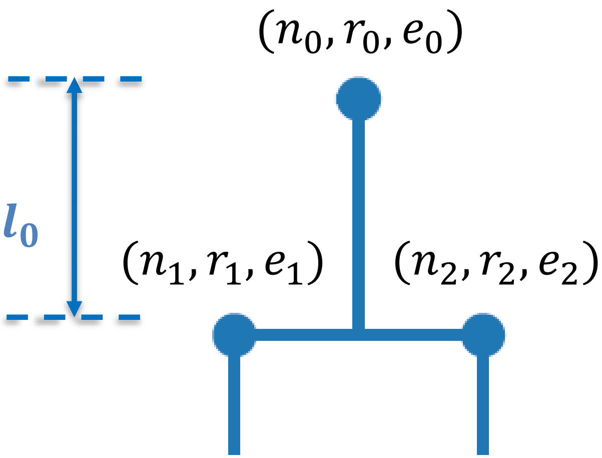
$$r(n) = \begin{cases} n, & n \geq 0 \\ r_\epsilon, & n < 0 \end{cases}$$

Speciation

More niches, more likely to speciate

Wikipedia, Creative Commons

Minimal model for eco-evo dynamics



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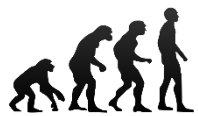

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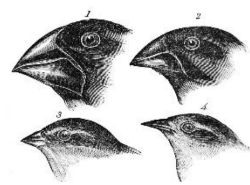


$$r(n) = \begin{cases} n, & n \geq 0 \\ r_\epsilon, & n < 0 \end{cases}$$

Speciation

More niches, more likely to speciate

+

$$e(r) = \frac{r}{r + R_0}$$

Extinction

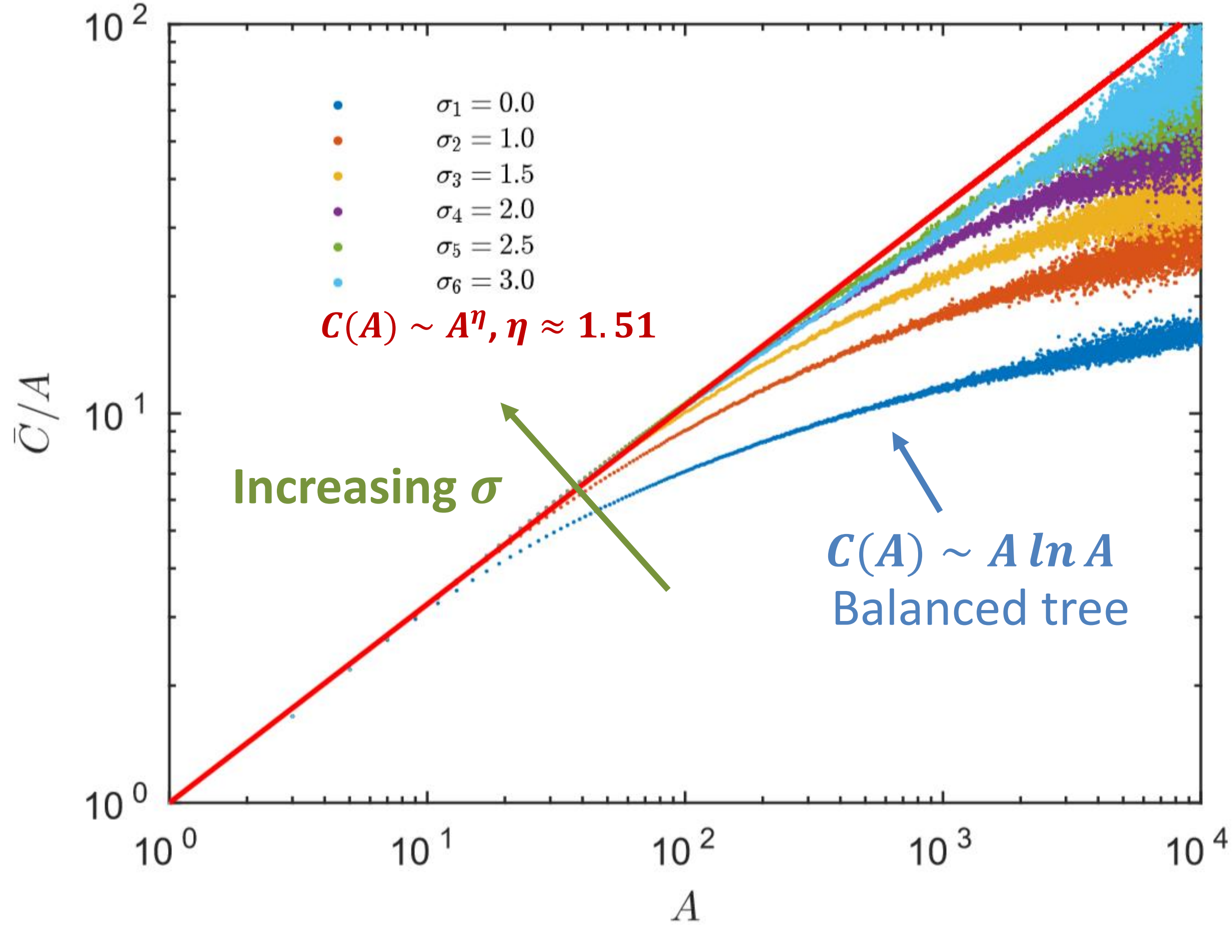
Bounding the growth rate of the tree.

Wikipedia, Creative Commons

Minimal model – topology

$$\frac{\Delta n_i}{n_0} \sim N(0, \sigma_n^2)$$

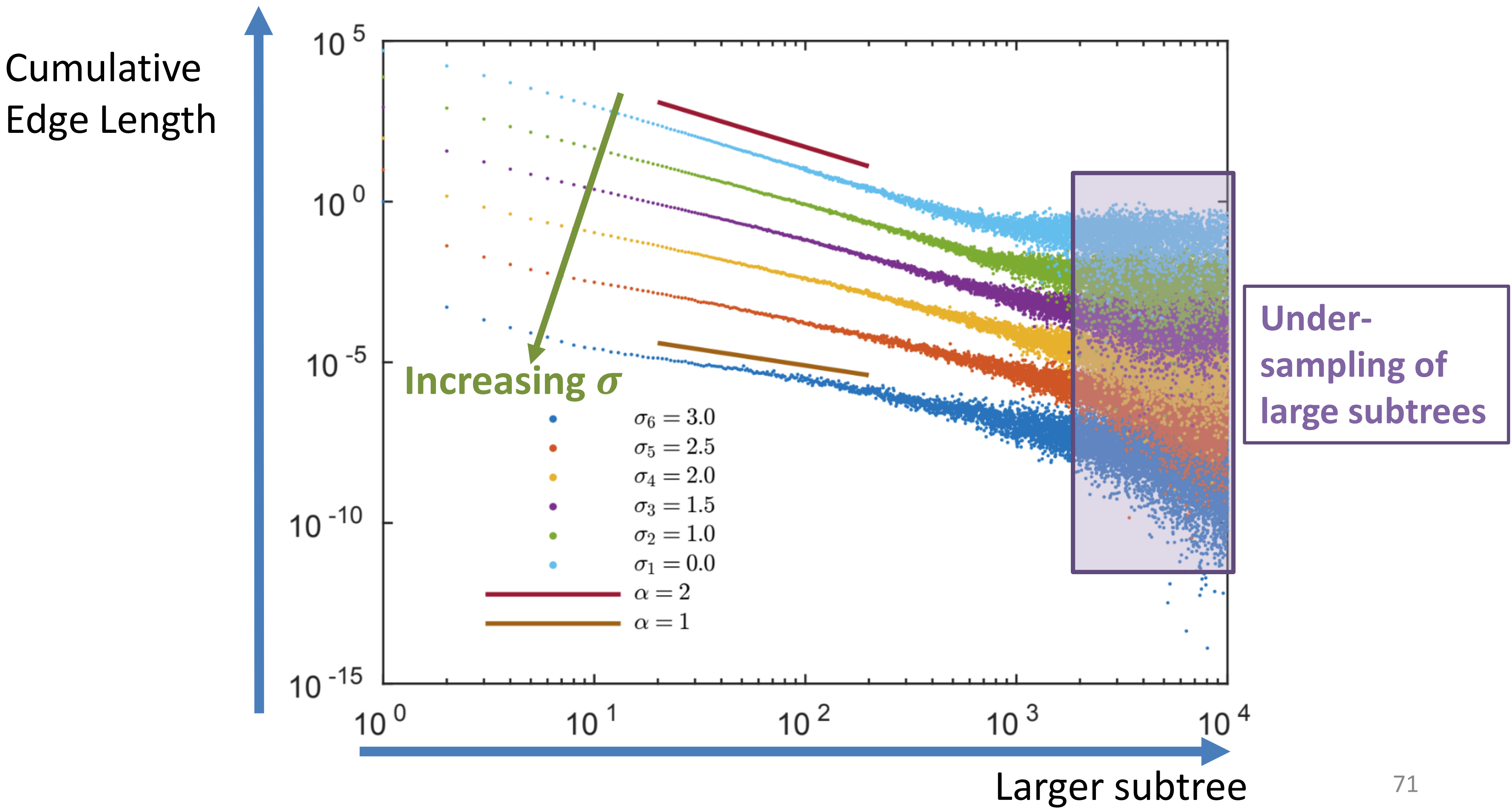
Robust against change in other parameters



Minimal model – edge length

$$\frac{\Delta n_i}{n_0} \sim N(0, \sigma_n^2)$$

Robust against change in other parameters



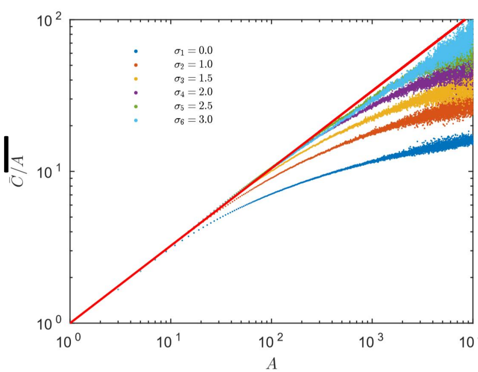
Niche model reproduces scaling

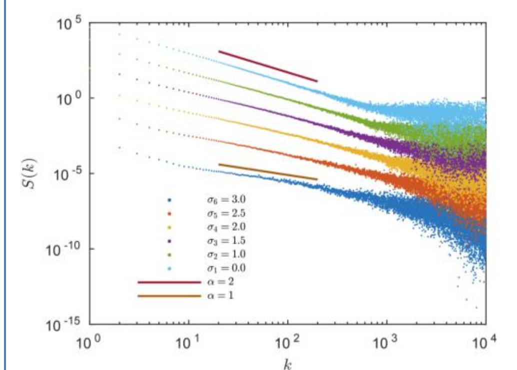
- Model can reproduce both scaling laws with exponents close to real trees

Topology

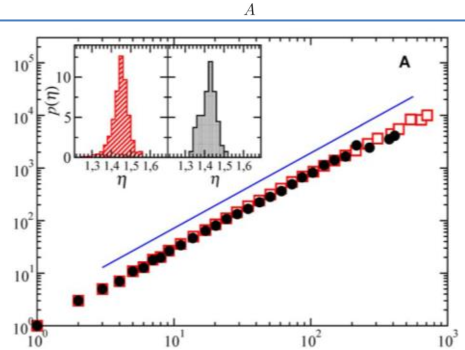
Edge Length

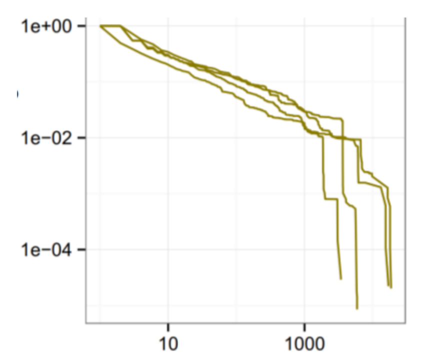
Niche Model





Real data





E. A. Herrada *et. al.* PLoS one, **3**, e2757 (2008)

James P. O'Dwyer *et. al.* PNAS, 112(27), 8356-8361.

Summary

- **Q1: origin of these non-trivial power laws?**
  - **Niche construction and the interplay between ecological process and evolutionary processes**

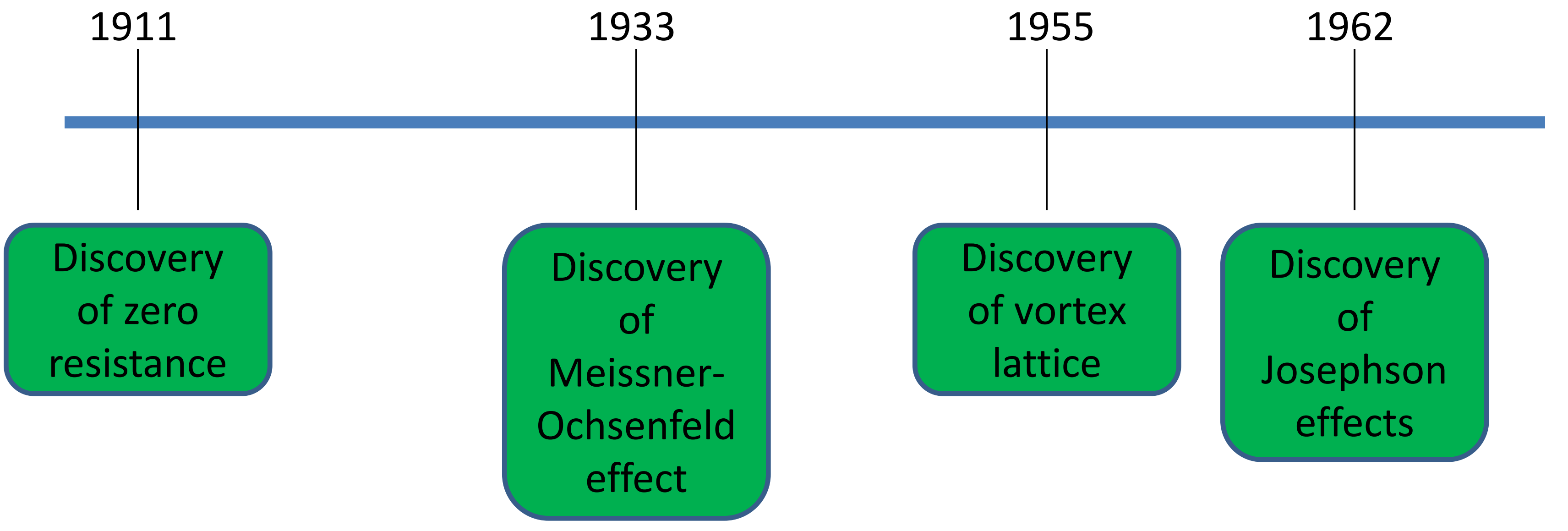
- **Q2: what do they tell us about living systems?**
  - **Evolution is more than just mutations, HGT, etc. One must take into account the ecological dynamics that lead to genetic fixation, even on time scales of billions of years**
    - **Competition**
    - **Predation**
    - **Range expansion**
    - **Metabolic cross-feeding**

Some questions …

- Do we learn new physics when we study biological physics?
  - or is it just insanely complicated soft material science?
- What are the universal phenomena in biology?
- Do they reveal anything important?
- What do we miss by not understanding universal phenomena?

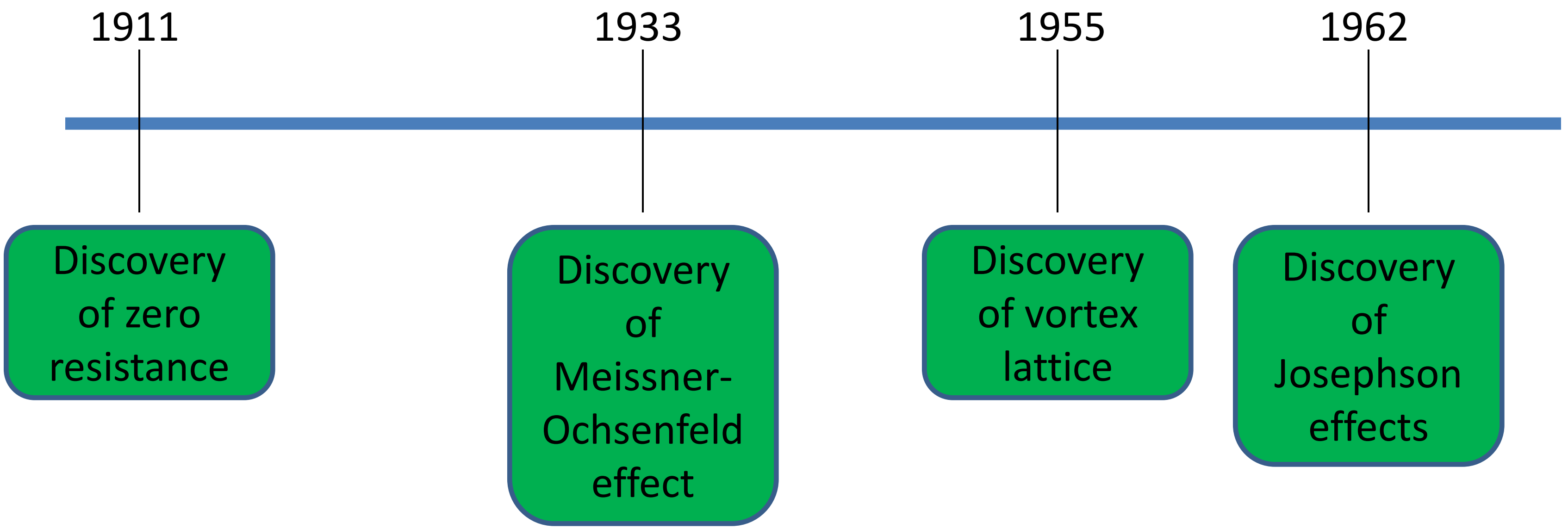
What do we miss by not understanding universal phenomena?

Superconductivity



- Why did it take so long to make these discoveries?
- Derive easily from off-diagonal long-range order in a charged condensate coupled to an Abelian gauge field (electromagnetism)!

Superconductivity



- Universal aspects of superconductivity
- Apply to all materials: classic superconductors (phonon-mediated), high Tc superconductors (?-mediated), color superconductivity in quark stars, …

Levels of description

Superconductivity	**Biology**
• Quantum chemistry and materials science	• Atoms and molecules
• BCS theory for interacting Cooper pairs	• Elasticity theory for DNA; phase transitions for liquid-liquid intracellular complexes
• Ginzburg-Landau theory for ODLRO + EM	• Dynamics of evolving systems

Levels of description answer different questions

Superconductivity	**Questions answered**
• Quantum chemistry and materials science	• How do specific materials instantiate the BCS mechanism?
• BCS theory for interacting Cooper pairs	• What is the basic mechanism in weakly coupled Cooper pair superconductors?
• Ginzburg-Landau theory for ODLRO + EM	• Why does the phenomenon of superconductivity exist?

Levels of description answer different questions

Biology

- Atoms and molecules
- Elasticity theory for DNA; phase transitions for liquid-liquid intracellular complexes
- Dynamics of evolving systems

Questions answered

- How do specific biopolymers interact, fold, undergo template-directed synthesis, …
- What are the basic functional cellular processes?
- Why does the phenomenon of life exist?

Levels of description = levels of universality

Superconductivity

- Quantum chemistry and materials science
  - Specific materials
- BCS theory for interacting Cooper pairs
  - Weak coupling
- Ginzburg-Landau theory for ODLRO + EM
  - All superconductors

Biology

- Atoms and molecules
  - Specific biopolymers
- Elasticity theory for DNA; phase transitions for liquid-liquid intracellular complexes
  - Physics of sub-cellular components
- Dynamics of evolving systems
  - All life

Why do we need universal level?

Superconductivity

- Ginzburg-Landau theory for ODLRO + EM
  - All superconductors
- Failure to predict response to EM fields:
  - Meissner effect, vortex lattice, Josephson effects

Biology

- Dynamics of evolving systems
  - All life
- Failure to predict response to selective perturbations:
  - antibiotics, insecticides, herbicides, chemotherapy resistance

Why do we need universal level?

Superconductivity

By regarding superconductors as collections of atoms, we are missing the emergent laws that act at the system scale and govern the large-scale response to EM fields

We know how to solve this problem

Biology

- Dynamics of evolving systems
  - All life
- Failure to predict response to selective perturbations:
  - antibiotics, insecticides, herbicides, chemotherapy resistance

Why do we need universal level?

Superconductivity

By regarding superconductors as collections of atoms, we are missing the emergent laws that act at the system scale and govern the large-scale response to EM fields

We know how to solve this problem

Biology

By regarding biology as complicated physical systems, we are missing the emergent laws that act at the system scale and govern the large-scale response to control perturbations

We do not know how to solve this problem yet

Some questions …

- **Do we learn new physics when we study biological physics?**

  YES: LARGE FLUCTUATIONS, SELF-ORGANIZATION INTO EVOLVABLE, MODULAR, SELF-PROGRAMMING STRUCTURES

- **What are the universal phenomena in biology?**

  GENETIC CODE, HOMOCHIRALITY, PATTERNS OF GENE EXPRESSION, DISTRIBUTION OF SPECIES, METABOLISM, …

- **Do they reveal anything important?**

  PHASE DIAGRAM OF LIFE, CELL STRUCTURE AND PRINCIPLES

  But universality can obscure microscale lower levels of description

- **What do we miss by not understanding universal phenomena?**

  RESPONSE AND CONTROL OF BIOLOGICAL SYSTEMS

“Ask not what physics can do for biology; ask what biology can do for physics”

Stanislaw Ulam