Randomness Increases Order in Biological Evolution, But … what is biological randomness?

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F. Bailly, G. Longo. **Mathematics and Natural Sciences. The physical singularity of Life.** Imperial College, 2011

G. Longo, MM.aël Montévil. Randomness Increases Order in Biological Evolution. C. Calude's conference on "**Computations, Physics and Beyond**", Auckland, NZ, Feb. 21-24, 2012; LNCS (Dinneen et al. eds), Springer, 2012

Randomness
from Physics to in Biology

Physical Determination (Classical)

Laplace's view:

A) determination *implies* predictibility

and

B) determination =/= randomness

[Laplace, Philosophie des Probabilités, 1786]

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A) determination *implies* predictibility (**false**: Poincaré, 1890)

and

B) determination =/= randomness (= **determ**. unpredictab., 1890)

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Thus, Poincaré ***broadened*** *determinism*

by including classical randomness: a fluctuation/perturbation *below measure*, may yield an observable effect, over time:

"et nous avons un phénomène aléatoire", [**Poincaré**, 1902]

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Turing, 1950:

From the LCM to the DSM (*Discrete State Machine*):

my DSM is **laplacian!**

Turing, 1952:

Morphogenesis as a "continuous dynamics", non-linear ("exponential drift", dynamic unpreditability = classical randomness: **Poincaré**)

Consequences from Physical Determination (Classical)

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*[**J. Monod**, Le **hasard** et la **nécessité**, 1970]*

Consequences of the **Laplacian view**:

the "DNA is a program" theory, since

any *predictable determination* is **programmable**

Consequences from Physical Determination (Classical)

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Schrödinger, What is life? 1944*:*

*« In calling the structure of the chromosomes a code-script, we mean that the all-penetrating mind, **once conceived by Laplace**… could tell from their structure how the egg would develop… . »*

*Schrödinger's **right consequences** of his principles!*

Today, the code-script has been fully decoded…

More on randomness *as* deterministic unpredictability

Classical/Relativistic systems are State Determined Systems:

*randomness is an **epistemic** issue*

Examples: dies, coin tossing, a double pendulum ...

the Planetary System (Poincaré, 1890; Laskar, 1992)… **finite** (short and long) **time unpredictability**

(*the dies, a SDS, 'know' where they go*: along a geodetics, determined by Hamilton's principle).

•

Recall **Laplace:**

- infinitary daimon: **OK** (over space-time *classical* continua);
- determination *implies* predictability (except singularities): **Wrong!**
  - *The role of physical measurement*

Quantum unpredictability as intrinsic indeterminism

Quantum Mechanics is ***not*** deterministic:

intrinsic/objective role of probabilities in constituting the theory:

- measure of conjugated variables;
- entanglement, no hidden variables.

Schrödinger's idea: the **equational determination** of a "*law of probability*" (thus back to the indeterministic nature of QM)

Quantum Mechanics: you ***can't even think*** of an infinitary daimon (key difference: measure of conjugate variables).

Recent survey/reflections: [Bailly, Longo, 2011], [Longo, Paul, 2008]

Physical Randomness and Irreversibility

1 - Classical randomness = deterministic unpredictability

2 - Quantum randomness = intrinsic undetermination (& entanglement)

Different probabilities, **different** theories of randomness ...

Yet, common points:

- Randomness = unpredictability

- Randomness is *correlated to* (co-present with) **irreversiblity** of time (classically: bifurcations … ; quantum: measurement)

Cf also **Thermodynamics**: II principle; diffusion as random paths.

Some more philosophy

1 - Laplace (strong, fantastic) program: the (*written*) equational determination allows to deduce/predict completely the properties of the physical World

(Newton: “one has to write and solve equations” …)

Poincaré: *No, it does not work* (1892: deterministic unpredictability)

Some more philosophy

1 - Laplace (strong, fantastic) program: the ***(written) equational determination*** allows to deduce/predict completely the properties of the physical World

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2 - Hilbert program: the ***finite axiomatic writing*** of Mathematics allows to formally deduce/predict completely the properties of Mathematics

Gödel: *No, it does not work* (1931: undecidability)

Provable correlations between *consequences*, as forms of randomness

Towards Biology

3 - Crick, Monod ….

"the ***finite string*** of DNA base letters A, C, T, G *completely determine* embryogenesis, ontogenesis … evolution"

More: « the DNA code ... is the *program* for the *behavioral computer* of this individual » (Mayr 1961)

And the ***two ways interactions***

DNA – proteome/cell/organisms/ecosystem ?

None (Crick's central Dogma, 1958), or just « noise », « bad copies »

Randomness (= noise) is "laplacian" (extraneous to determination and theory)

The constitutive role of randomness in Biology

One of the crucial « change of perspective », in Biology:

Randomness is **not noise** and it *implies* **variability** *implies* **diversity**

An essential component of structural stability

Compare: Randomness as intrinsic to Quantum Mechanics
(change measure and the « structure of determination »)

Kupiec, 1983 ….

Buiatti M., Longo G. *Randomness and Multilevel Interactions in Biology,* Ongoing work.

Biological relevance of randomness

Each mitosis (cell division), a critical phase transition:

Asymmetric partitions of proteomes; differences in DNA copies; changes in membranes …

In multicellular organisms: varying reconstruction of tissues' matrix (collegen structure, cell-to-cell connections)

Not « noise », « mistakes » in polymerase as a Turing's program,

but non-specificity and randomness is at the core not only of *variability* and *diversity* (the main biological invariants), but even of **cell differentiation** (in embrogenesis: sensitivity in a critical transition; e.g. variability in Zebrafisch, N. Peyreiras, ongoing).

Randomness enhances robusteness, by diversity : ecosystem, organism ...

Which form of randomness ?

Quantum Randomness in Biology

Quantum tunneling: non-zero probability of passing any physical barrier (cell respiration, Gray, 2003; destabilizing tautomeric enol forms – migration of a proton: Perez, 2010)

Quantum coherence: electron transport (in many biogical processes: Winkler, 2005)

Proton transfer (quantum probability): RNA mutations (G-C pairs: Ceron-Carrasco, 2009)

Empowered **metabolic random** activities by (water)

"QED coherence" (Del Giudice, 2005; Plankar, 2011)

REFERENCES IN:

Buiatti M., Longo G. *Randomness and Multilevel Interactions in Biology,*

Downloadable

Classical Randomness in Biology

Non linear affects (molecular level):

- Molecular **enthalpic oscillations**
- **Turbulence** in the cytoplasm of Eukaryote cells
- ....

(see also J.-J. Kupiec, A. Paldi, T. Heams, B. Laforge ...)

Classical *and* Quantum Randomness in Biology

Molecular level:

non linear dynamics (classical)

and **quantum processes *superpose***

That is:

They happen ***simultaneously*** and ***interfere*** (not analyzed in Physics)

Morover:

a quantum effect may be **amplified** by a (classical non-linear) dynamics

Proper (?) Biological Randomness 1

Randomness ***within*** other levels of organization *in an organism*:

- [*Besides:* **Molecular activities** (classical+quantum randomness)]
- **Cellular dynamics** and **interactions in a tissue**
- **Developmental dynamics** (contact inhibition between cells: Soto et al., 1999)
- **Fractal bifurcations** (mammary glands development, *ongoing work*)

Proper Biological Randomness 2:

Recall: since Poincaré, randomness as "planetary **resonance**"

Extended to general non-linear dynamics:

at **one level** of (mathematical) determination

(*far from equilibrium*: Pollicott-Ruelle resonance, dynamical entropy in open systems (Gaspard, 2007))

Proper Biological Randomness 2:

Recall: since Poincaré, randomness as "planetary **resonance**" …

Extended to general non-linear dynamics:

at **one level** of (mathematical) determination

(*far from equilibrium*: Pollicott-Ruelle resonance, dynamical entropy in open systems (Gaspard, 2007))

Bio-resonance (Buiatti, Longo, 2011):

Randomness ***between*** different levels of organization *in an organism*:

thus, resonance (as interference) between **different levels** of (mathematical) **determination**

The mathematical challenge: the Mathematics (of Physics) does **not** deal with **heterogeneous structures** (of determination)

Bio-resonance

Physical resonance (at equilibrium / far from equilibrium) is related to "destabilization" (growth of entropy or disorder)

Bio-resonance includes "integration and regulation", thus

it ***stabilizes*** and ***destabilizes***

Examples:

- The lungs, the drosophila eyes …
- In embryogenesis …
- In "colonies" of *Myxococcus Xanthus,* a prokaryote, and *Dictyostelium discoideum,* an eukaryote (Buiatti, Longo, 2011)

Randomness in critical transitions

Life is (not only) a dynamics, a process, but an

extended (permanent, ongoing … in time, space ..) **critical transition**

(Bailly, Longo, Montévil: book and papers)

A critical **interval**, not just a (mathematical) point, as in Physics.

Key understanding: **continual symmetry changes**

In Physics, the *determination* of trajectories is ***given by symmetries*** (the conservation properties)

An biological (ontophylogenetic) trajectory is a ***cascade of symmetry changes.***

The '**double**' irreversibility of Biological Time

Increasing complexity (Gould) in evolution is the result of a **random *asymmetric* diffusion**

F. Bailly, G. Longo. *Biological Organization and Anti-Entropy*, in **J. of Biological Systems**, Vol. 17, n.1, 2009.

Evolution, morphogenesis and death are strictly irreversible, but their irreversibility is proper, it ***adds on top*** of the physical irreversibility of time (thermo-dynamical):

e. g., **increasing order induces (also some) disorder**.

Thesis (the role of randomness):

a random event is (always) correlated to a **symmetry breaking**.

One more reason for an ***intrinsic***, proper Biological Randomness. *END*

Some references (*more on* http://www.di.ens.fr/users/longo)

Buiatti M., Longo G. *Randomness and Multilevel Interactions in Biology,* In progress (*downloadable http://www.di.ens.fr/users/longo*).

Bailly F., Longo G. **Mathematics and the Natural Sciences. The Physical Singularity of Life.** *Imperial College Press*, London, 2011.

Bailly F., Longo G., *Randomness and Determination in the interplay between the Continuum and the Discrete*, **Mathematical Structures in Computer Science,** 17(2), pp. 289-307, 2007**.**

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But … what is biological randomness?

Randomness Increases Order in Biological Evolution

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Evolution and “Complexity”

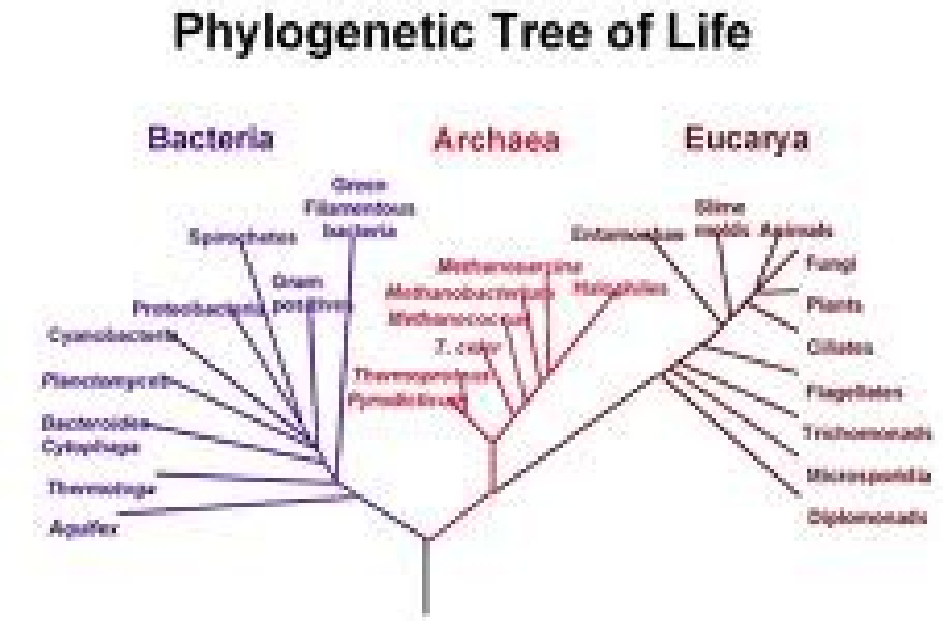
J.-S. Gould's fight against the ***wrong*** image (progress?):

S.J. Gould. **Full house: The spread of excellence from Plato to Darwin** . Three Rivers Pr, 1997.

Growing complexity in Evolution?

Which “complexity”?

Evolutionary complexity?



However: Gould's growth of "morphological" complexity [**Full House**, 1989]

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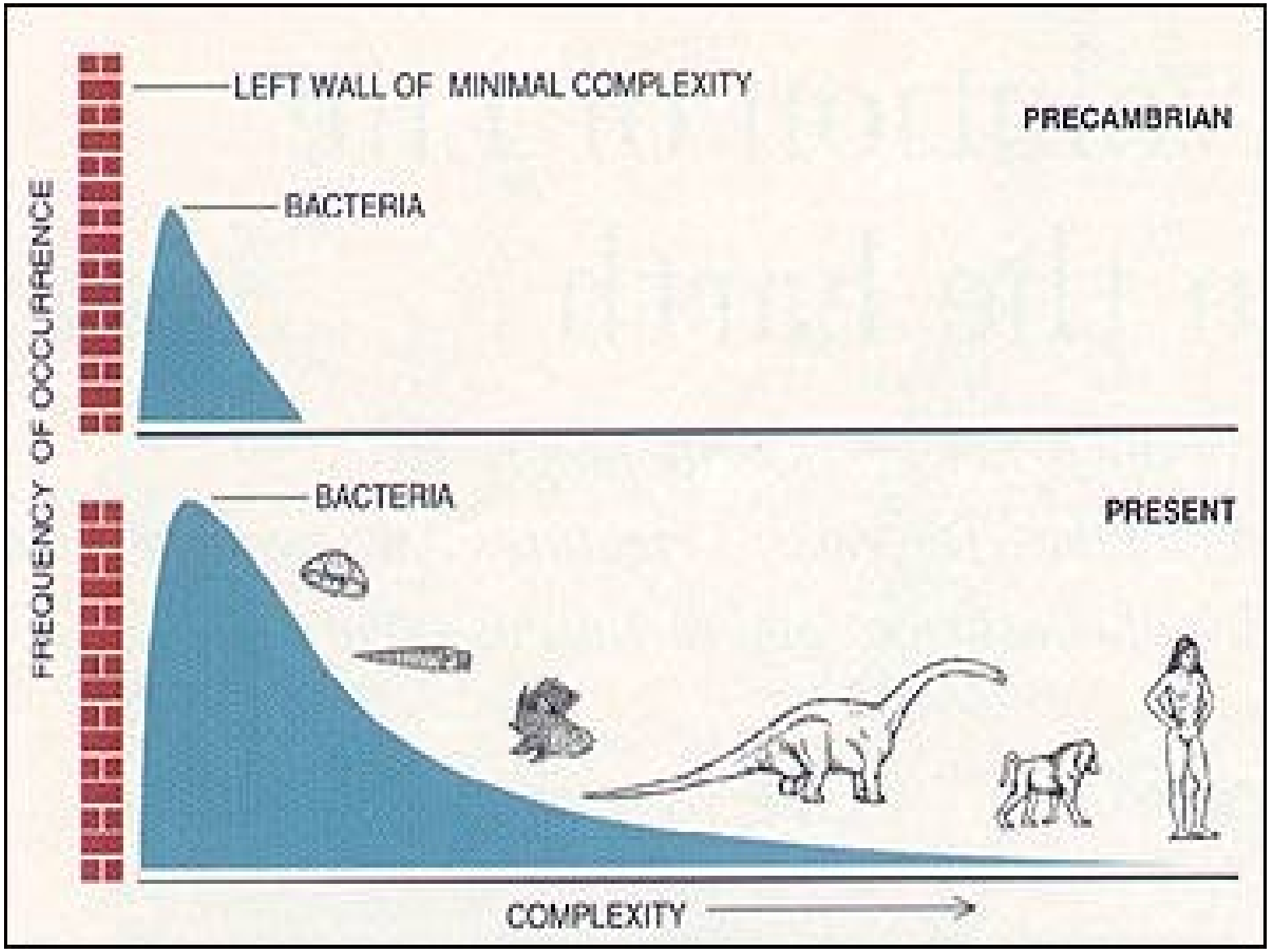


Random increase of complexity [**Gould**, 1989]

Asymmetric Diffusion *Biased Increase*

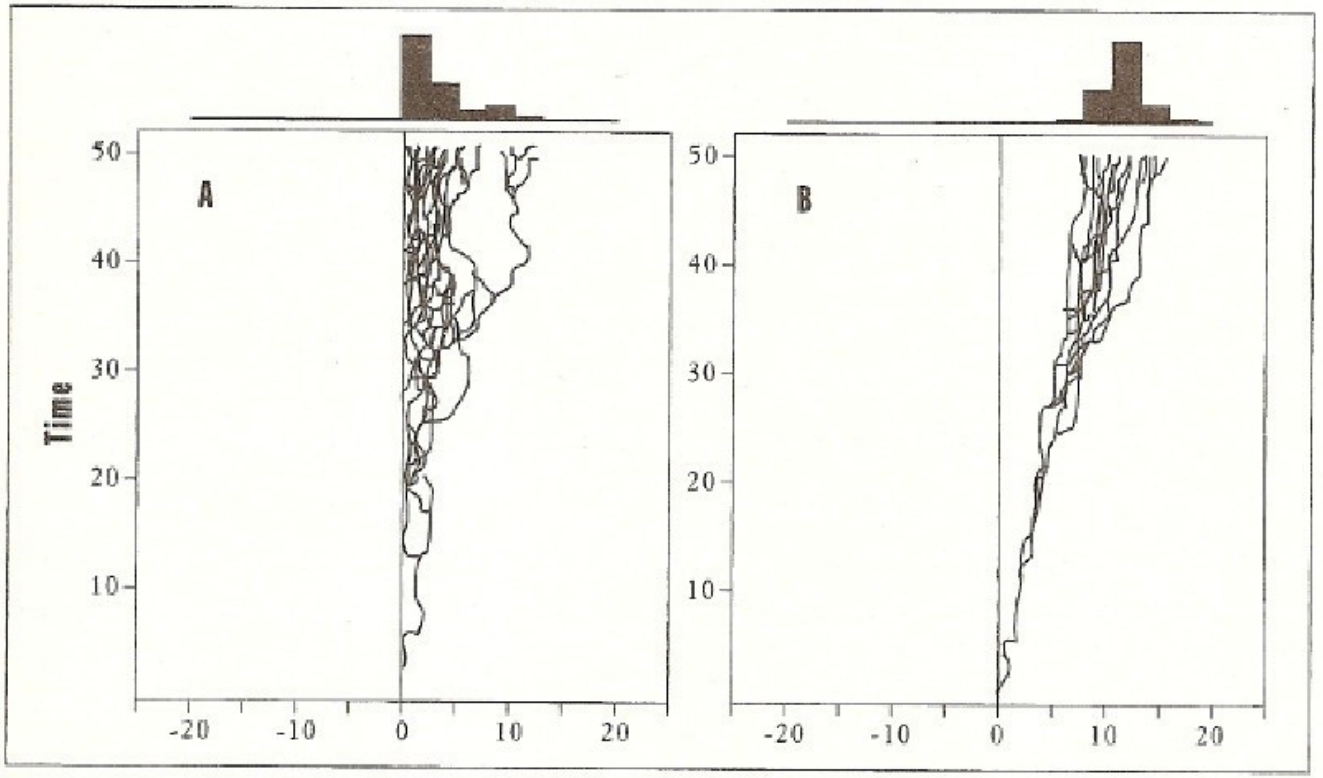


FIGURE 33

Passive and driven trends in McShea's terminology. A passive trend *(A)* begins near a left wall, retains a constant mode at this beginning position, and expands in the only open direction toward the right. In a driven trend *(B)*, both minimum and maximum values increase through time.

How to understand increasing complexity?

No way to explain this in terms of random mutations (only):

1. DNA's (genotype) **random mutations** statistically have probability 0 to cause globally increasing complexity of phenotype (examples: mayfly (ephemeral); equus…[Longo, Tendero, 2007])

1. Darwin's evolution is **selection of the *incompatible*** ("the best" makes no general sense)

1. Greater probabilities of **survival** and reproduction ***do not imply*** greater **complexity** (bacteria, … lizard…) [Maynard-Smith, 1969]

Gould's idea: symmetry breaking in a diffusion…

Mathematical analysis as a distribution of
Biomass (density) over Complexity (bio-organization)

F. Bailly, G. Longo. *Biological organization and anti-entropy*. **J. Bio-systems,** 17-1, 2009.

Derive Gould's empirical curb from

- general (mathematical) **principles**,
- specify the phase space
- explicit (and correct) the time dependence

Write a suitable **diffusion equation** inspired by Schrödinger operatorial approach

Note: any diffusion is based on **random paths**!

Morphological Complexity along phylogenesis and embryogenesis

Specify (quantify) Gould's informal "complexity" as *static morphological complexity* **K**

$$\mathbf{K} = \alpha K_c + \beta K_m + \gamma K_f \qquad (\alpha + \beta + \gamma = 1)$$

- K_c (combinatorial complexity) = cellular combinatorics as differentiations between cellular lineages (tissues)
- K_m (phenotipic complexity) = topological forms and structures (e.g., connexity and fractal structures)
- K_f (relational complexity) = metabolic relations, neuronal and cellular (interaction) networks

Main idea: formalize **K** as **anti-entropy**, -S ≠ negentropy

(not 0-sum, coding dependent) …. in balance equations…

The theoretical frame: analogies

.... by a *conceptual* ***analogy*** with **Quantum Physics**:

In ***Quantum Physics*** (a "wave diffusion" in Hilbert Spaces):

* The determination is a ***dynamics*** of a ***law of probability***:

(Schrödinger Eq.) $ih\partial\psi/\partial t = h^2\partial^2\psi/\partial x^2 + v\psi$

• In our approach to ***Complexity*** in *Biological Evolution*:

* The determination is a ***dynamics*** of a ***potential of variability*:**

(PV) $\partial f/\partial t = D_b\partial^2 f/\partial K^2 + \alpha_b f$

What is f ? (PV) a diffusion equation, in *which spaces*?

Random walks …

The theoretical frame: dualities

.... by *conceptual* ***dualities*** with **Quantum Physics**:

In ***Quantum Physics*** (Schrödinger equation):

- **Energy** is an ***operator***, *H(f)*, the "main" physical observable.
- **Time** is a ***parameter***, $f(\underline{x}, t)$,

The theoretical frame: dualities

.... by *conceptual* ***dualities*** with **Quantum Physics**:

In ***Quantum Physics*** (Schrödinger equation):

- **Energy** is an ***operator***, *H(f)*, the "main" physical observable.
- **Time** is a ***parameter***, *f(x, t)*,

In our approach to ***Complexity*** in *Biological Evolution*:

- **Time** is an ***operator***, identified with entropy production **σ**
- **Energy** is a ***parameter***, *f(x, e)* (e.g. energy as bio-mass in scaling-allometric equations: $Q = kM^{1/n}$)

Our *f* is the density of bio-mass over complexity K (and time t):

m(t, K)

A **diffusion** equation:

$$\partial m/\partial t = D_b \partial^2 m/\partial K^2 + \alpha_b m(t,K) \quad (3)$$

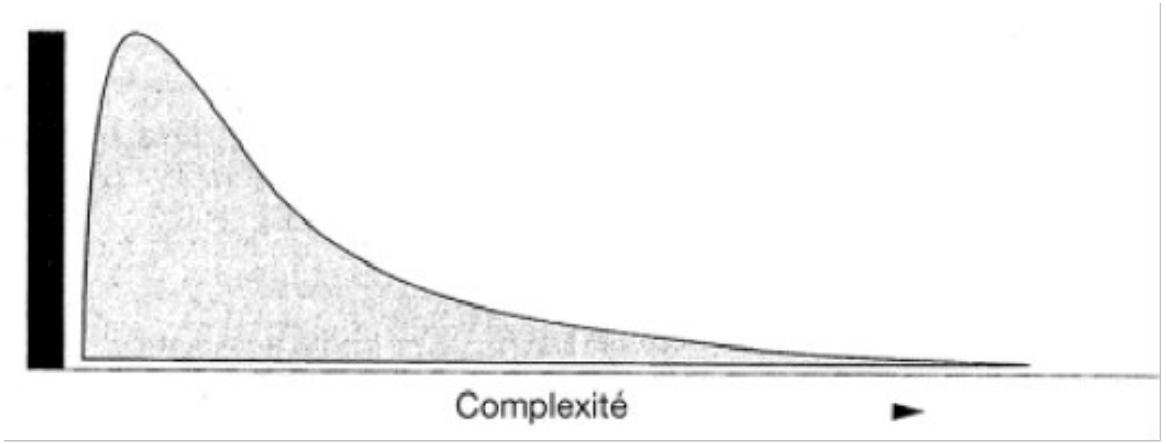
A **solution**

$$m(t,K) = (A/\sqrt{t})\, \exp(at) \exp(-K^2/4Dt)$$

models Gould's asymmetric diagram for Complexity in Evolution (a diffusion : *random paths…), **also along** **t*** :

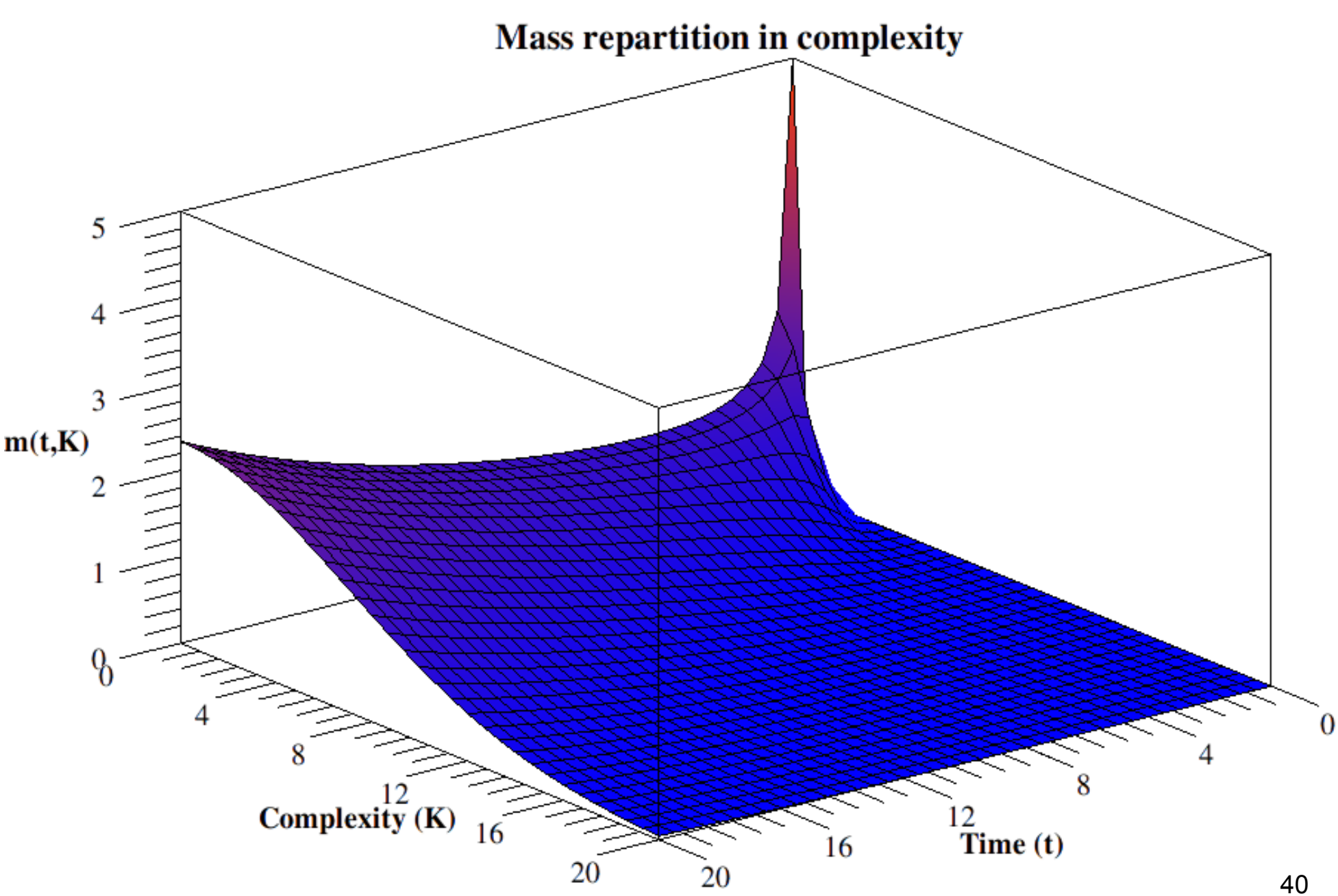
(biomass and the **left wall** for complexity, archeobacteria original formation)

biomass



F. Bailly, G. Longo. *Biological Organization and Anti-Entropy…*

(Implementation by **Maël Montevil**; “ponctuated equilibria” smoothed out)



Some references (papers downloadable)

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