Fundamental conceptual issue

physics/chemistry:
matter, force, energy, reaction rates,
molecular binding affinities…

biology:
instructions, transcription, editing, translation,
coding, signals, instructions…

information!

physics/chemistry ⟶ biology

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Review

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biocomplexity, biophysics, astrobiology

The algorithmic origins of life

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Although it has been notoriously difficult to pin down precisely what is it that makes life so distinctive and remarkable, there is general agreement that its informational aspect is one key property, perhaps the key property. The unique informational narrative of living systems suggests that life may be characterized by context-dependent causal influences, and, in particular, that top-down (or downward) causation—where higher levels influence and constrain the dynamics of lower levels in organizational hierarchies—may be a major contributor to the hierarchal structure of living systems. Here, we propose that the emergence of life may correspond to a physical transition associated with a shift in the causal structure, where information gains direct and context-dependent causal efficacy over the matter in which it is instantiated. Such a transition may be akin to more traditional physical transitions (e.g. thermodynamic phase transitions), with the crucial distinction that determining which phase (non-life or life) a given system is in requires dynamical information and therefore can only be inferred by identifying causal architecture. We discuss some novel research directions based on this hypothesis, including potential measures of such a transition that may be amenable to laboratory study, and how the proposed mechanism corresponds to the onset of the unique mode of (algorithmic) information processing characteristic of living systems.

Life = information management

Informational hallmarks of life

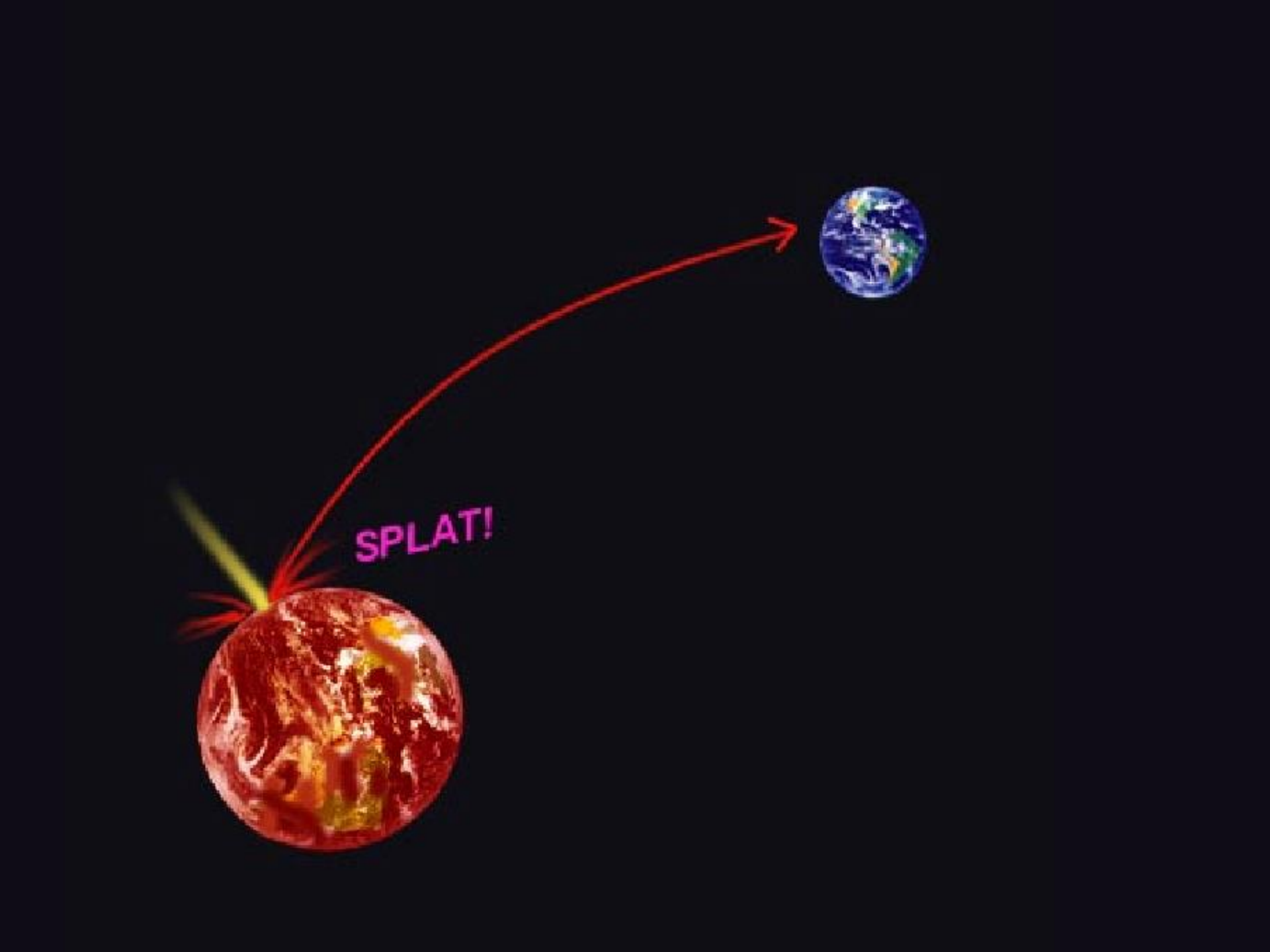
*Digital information storage
*Analog and digital information processing
*Explicitly encoded information: *context dependent*
*Physical separation of information storage from information processing
*Dynamics is a function of the physical state
*Top-down and bottom-up causation

The origin of life

When?

Where?

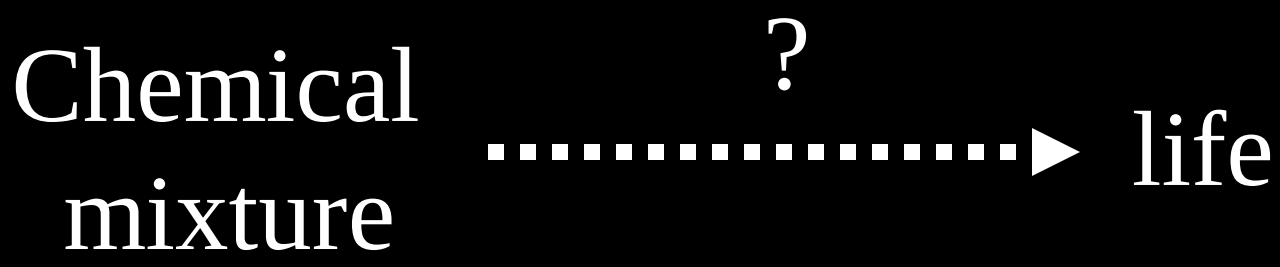
How?

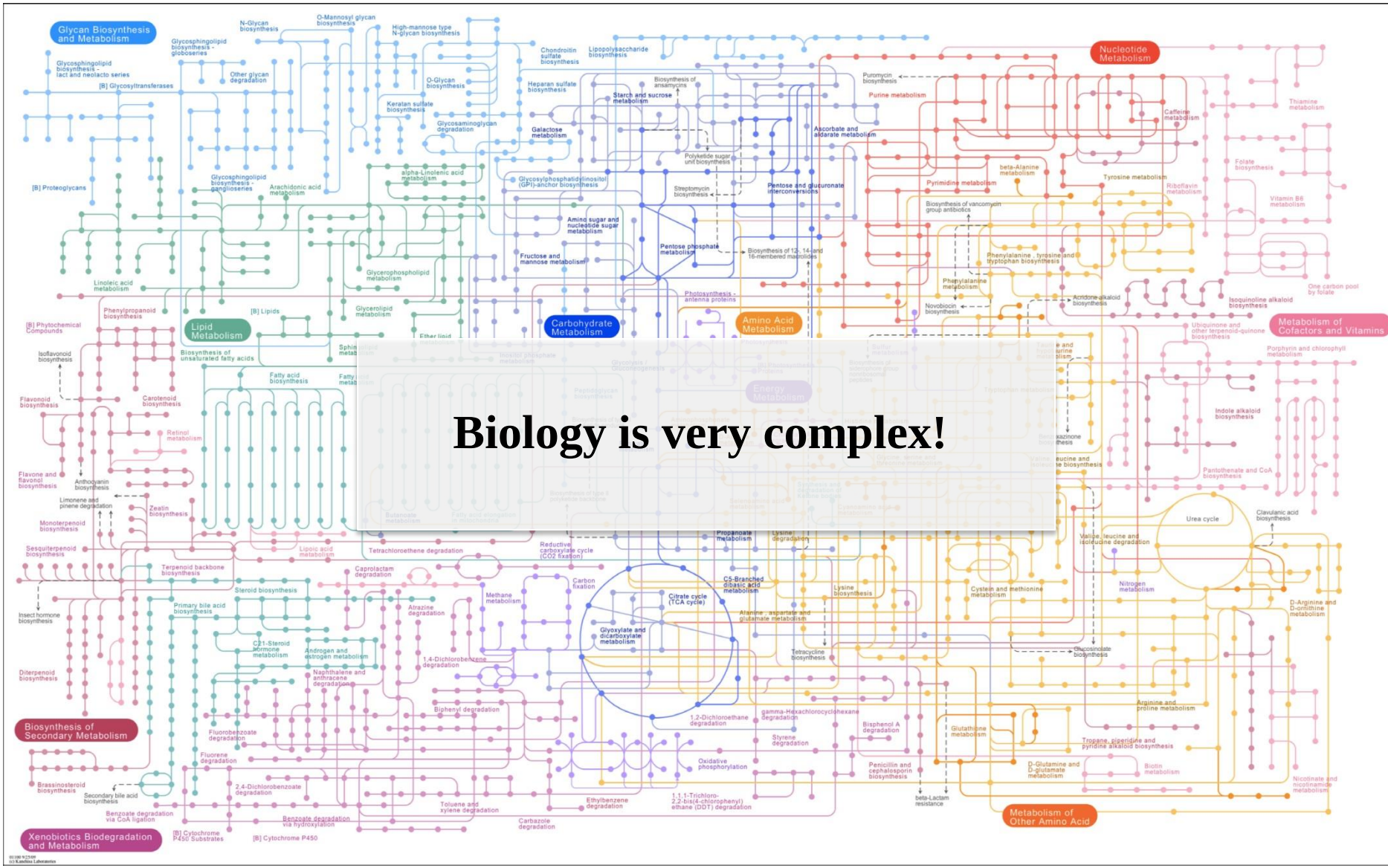

SPLAT!

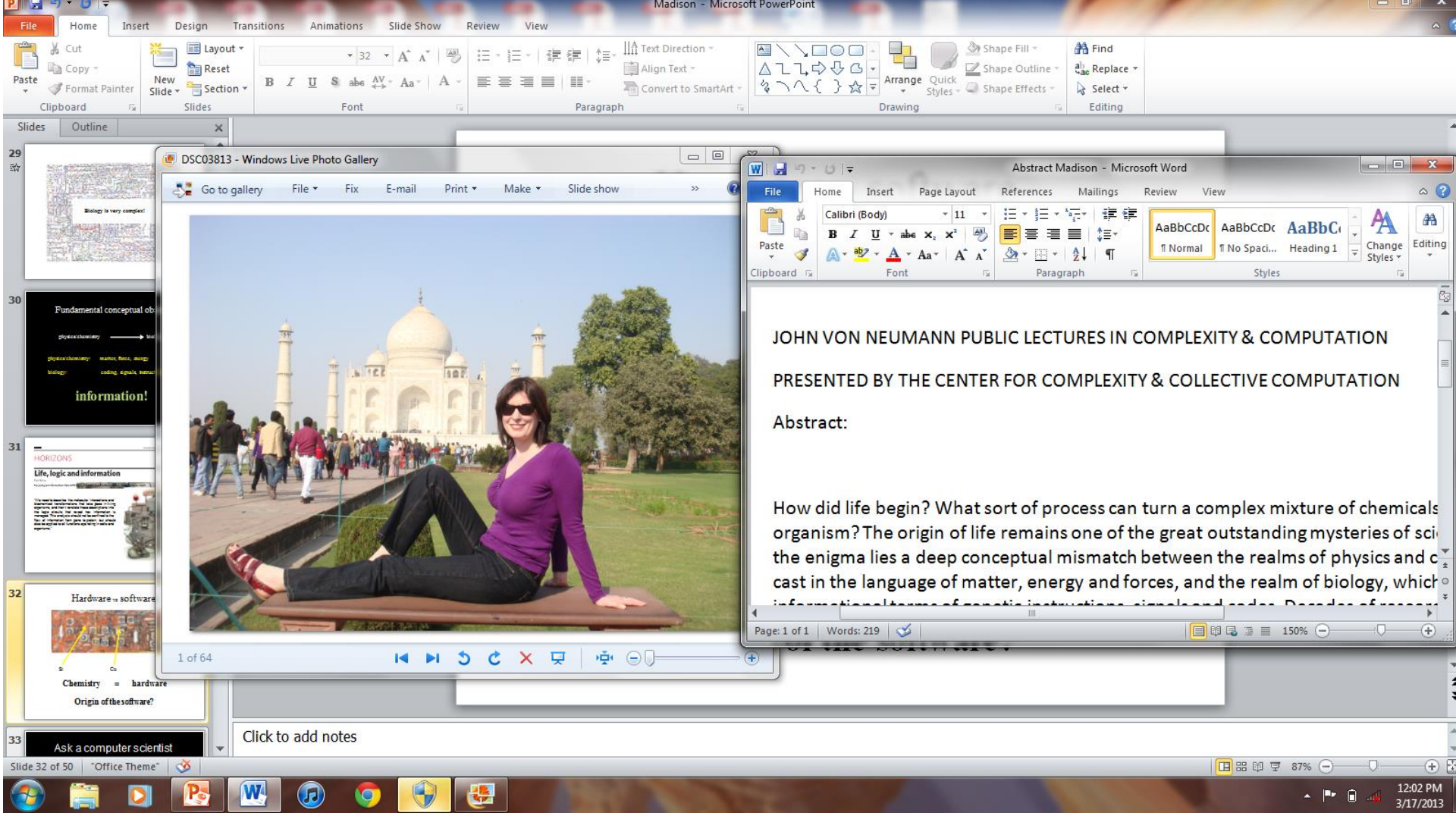
How did life begin?

If we do not know the process that transformed non-life into life we cannot estimate the probability for it to happen

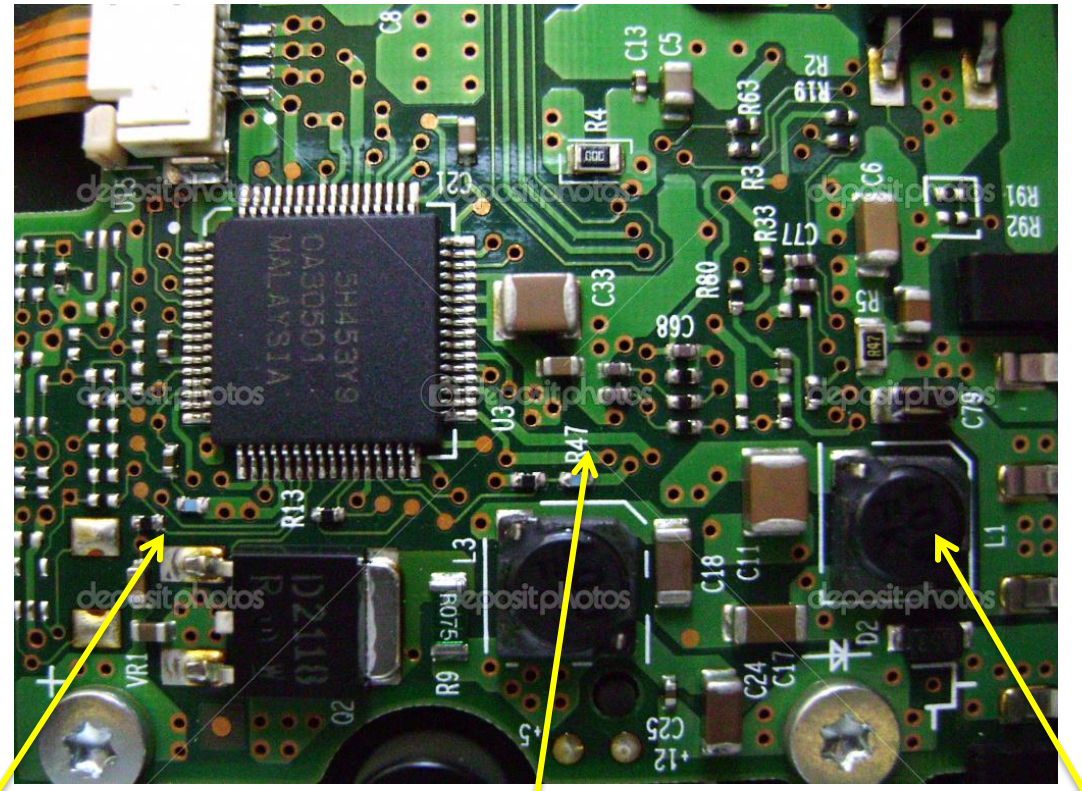
Bizarre fluke? Or chemical inevitability?


Chemical
mixture
?
life


Glycan Biosynthesis and Metabolism
Lipid Metabolism
Carbohydrate Metabolism
Amino Acid Metabolism
Nucleotide Metabolism
Metabolism of Cofactors and Vitamins
Biosynthesis of Secondary Metabolism
Xenobiotics Biodegradation and Metabolism
Metabolism of Other Amino Acid
Energy Metabolism
Biology is very complex!



Explain Windows!



Chemistry = hardware

Software?

von Neumann on Self-Replication
Trivial v. Non-Trivial

Some examples of **trivial** replicators:

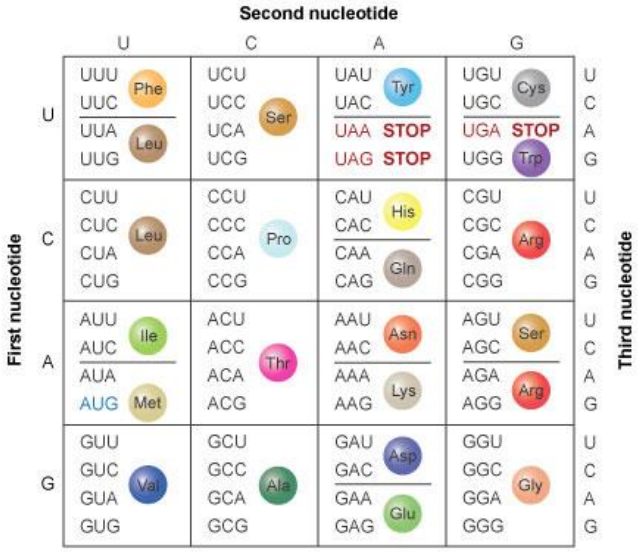
- Crystals
- Computer viruses
- Memes
- Non-enzymatic template replicators
- Lipid vesicles

Replication operation is implicit in local physics/chemistry

Information Flow, Universality, and Programmability in Life

Ribosomes can be instructed by DNA to make *any* combination of amino acids from a set of 20.

Non-Trivial Self-Replicators are *programmable* – they can produce any constructible object in their universality class, including themselves.



Genetic code

But…

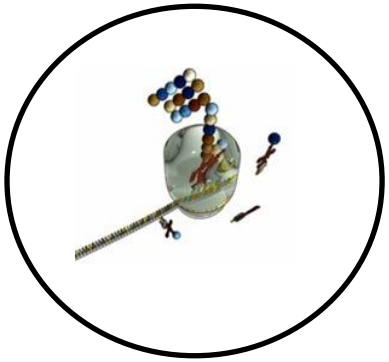
that's not all!

Biological information: not just “any old bits”. It *does stuff!*

Shannon information
i.e. “bits”

Biological information
functional/semantic/contextual/“meaningful”

A C
G G
T A
A G
T T
C A
G A
T T
A T



Which is “junk”?

context is all

Genetic information flows from *local* to *global*, or “bottom up”

But…

even that's not all!

Top-down Causation by Information Control

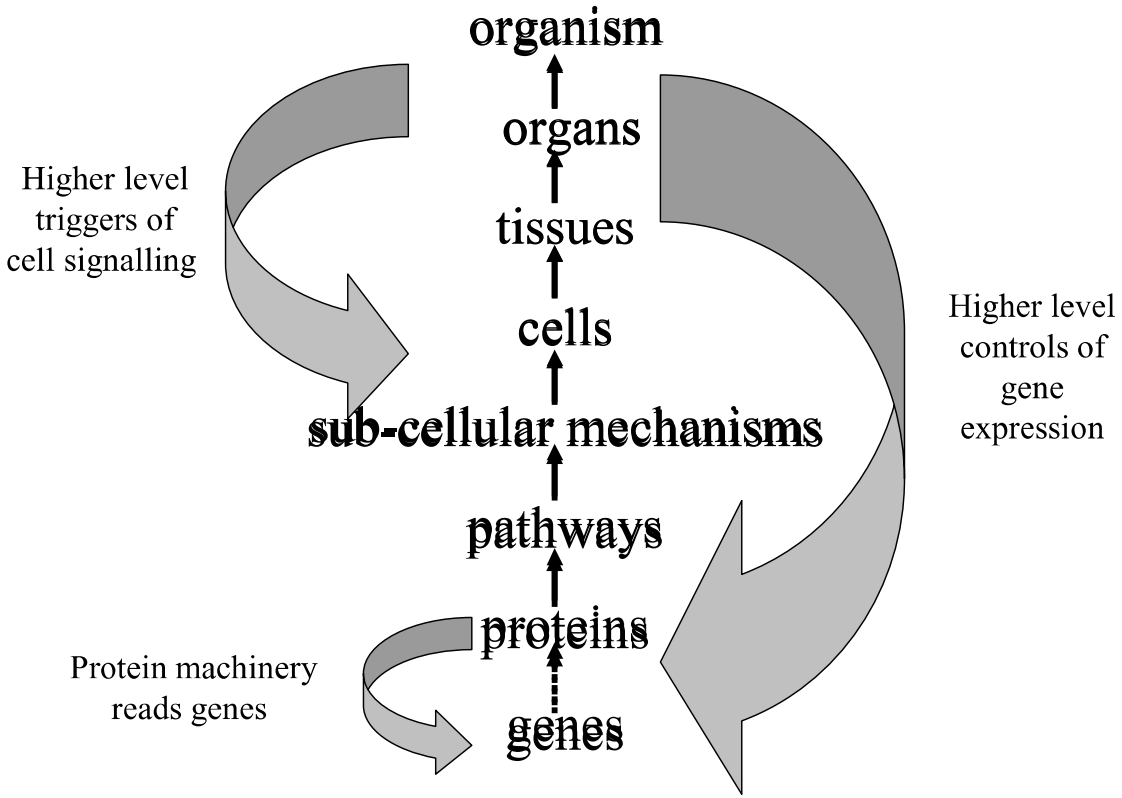
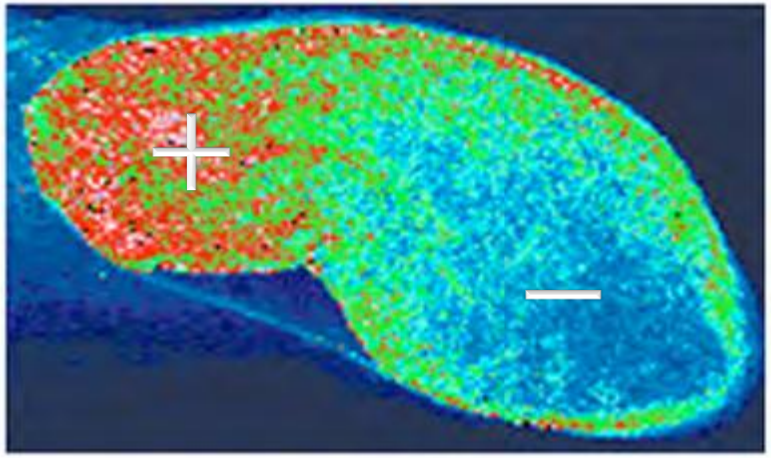
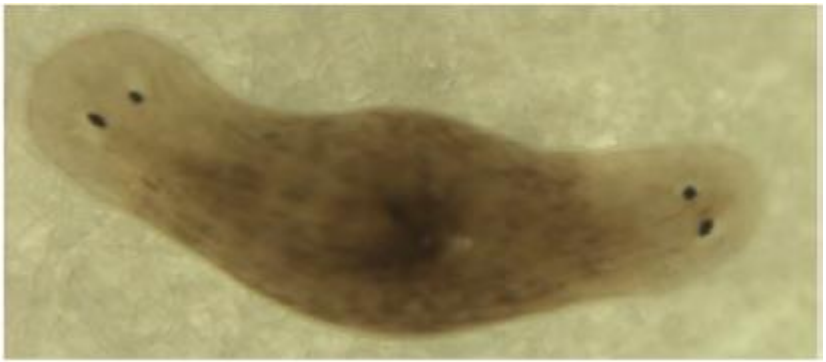


Figure from D. Noble. Claude Bernard, the first systems biologist, and the future of physiology. *Experimental Physiology* (2012) 93:1 -16.

Michael Levin, Tufts University

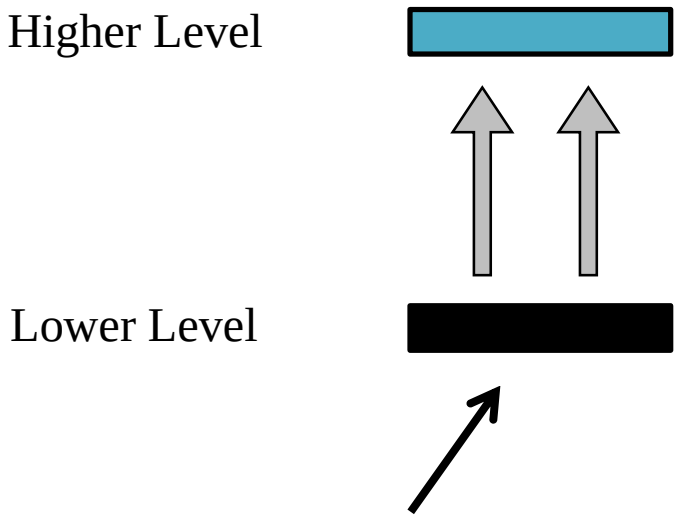




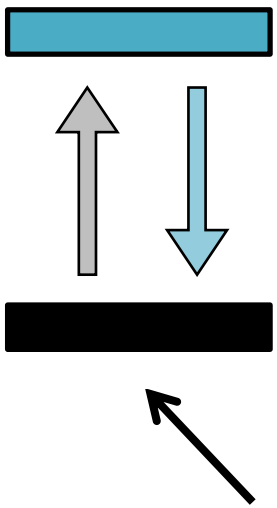
Electric fields can affect gene expression!
“Epigenetics”

Top-down causation

The Origin of Life as a Transition in Informational and Causal Architecture



Bottom-up causation,
i.e. standard physics

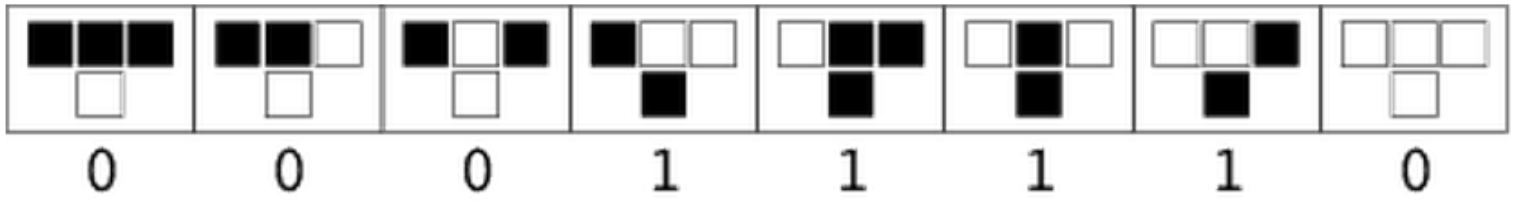


Top-down causation occurs when a ‘higher’ level influences a ‘lower’ level

State-dependent dynamical rules

Elementary Cellular Automaton

DOWNLOAD
Mathematica Notebook



256 rules

Global state ⟺ Local rules

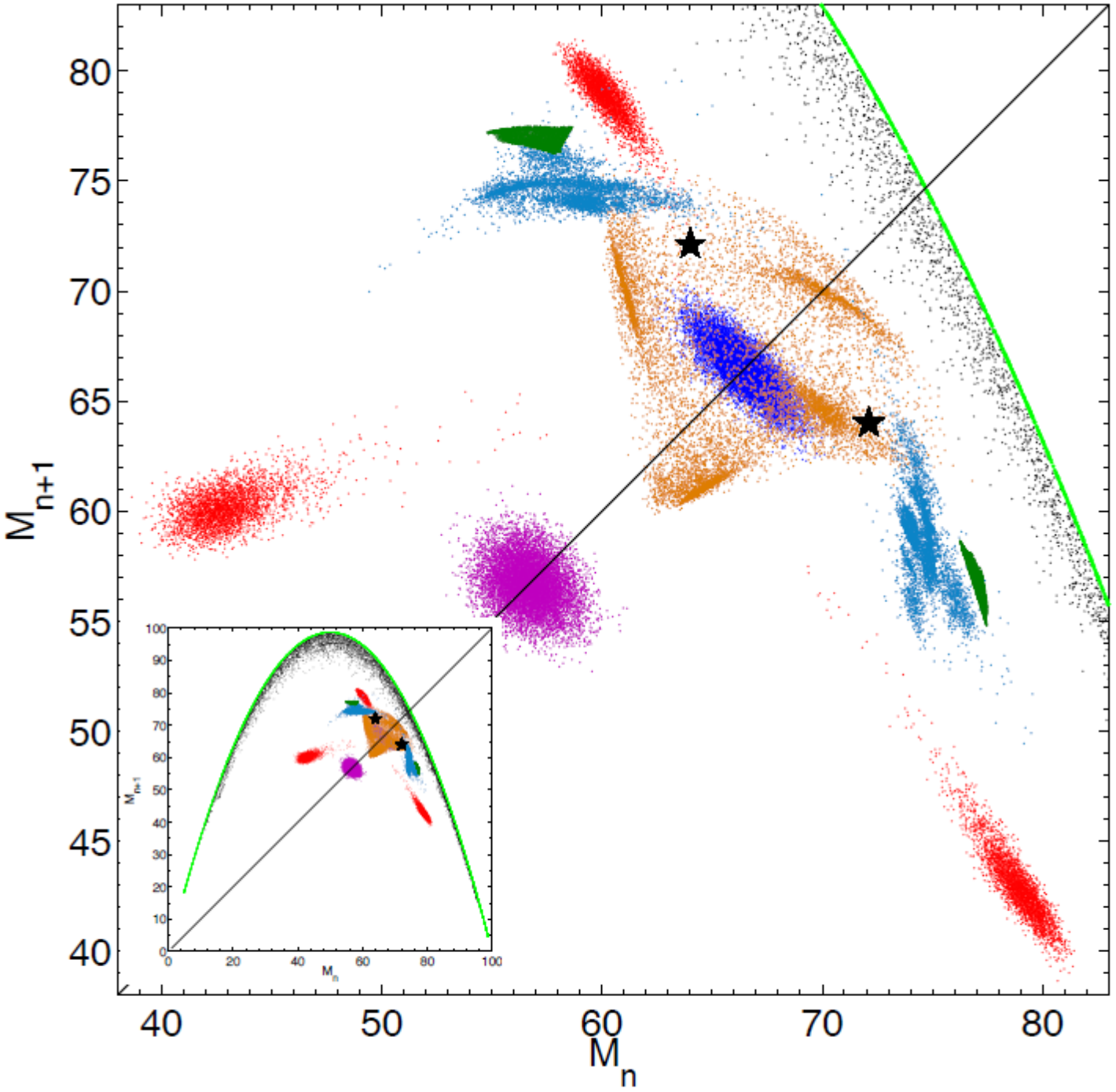
Emergent self-organization

N dynamical elements obeying logistic equation and coupled to a mean “field”

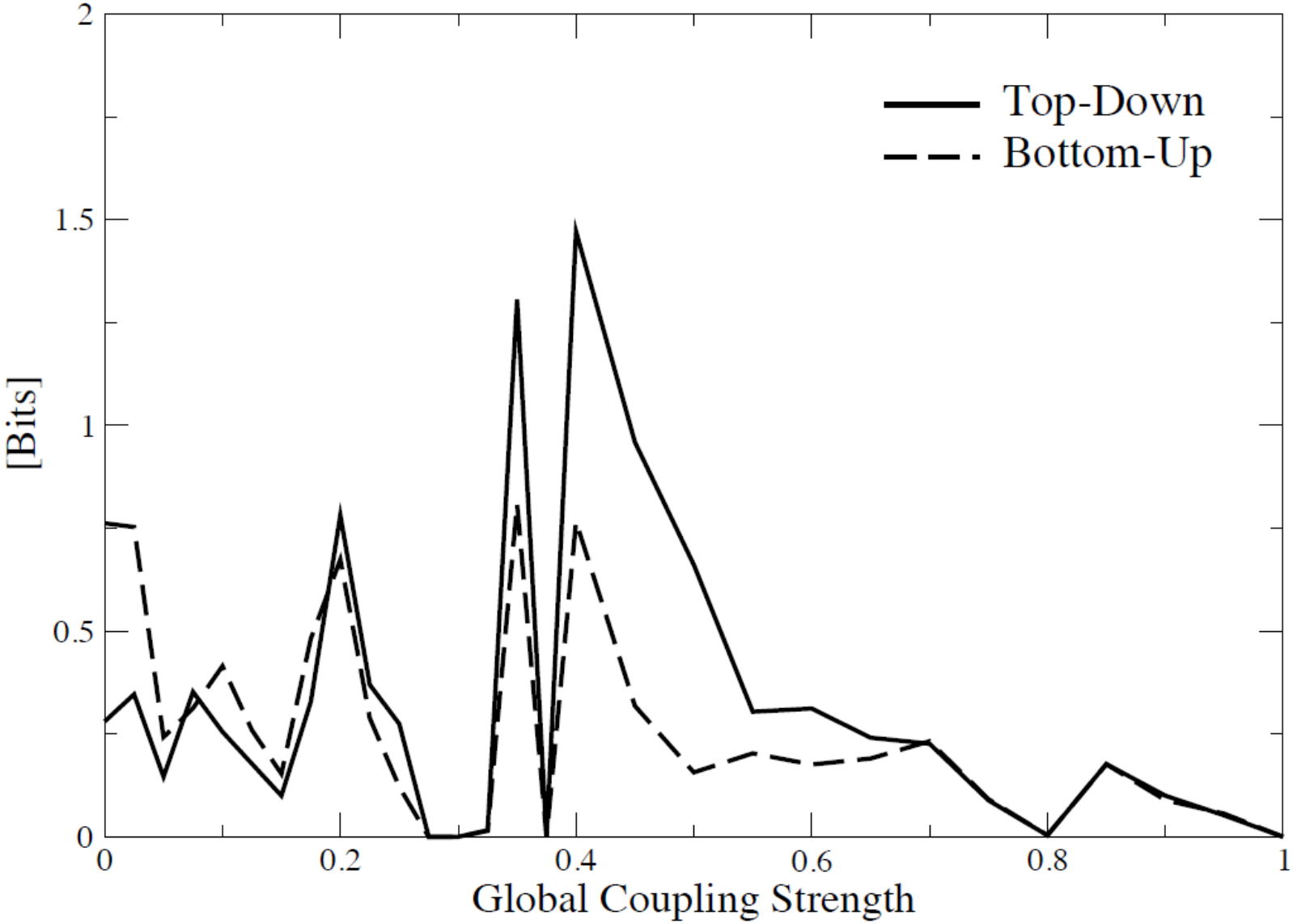
$$x_{i,n+1} = (1-\epsilon) f_i(x_{i,n}) + \epsilon\, m_n \quad ; \quad (i = 1, 2, \ldots N)$$

$$f_i(x_{i,n}) = r_i x_{i,n}\left(1 - \frac{x_{i,n}}{K}\right)$$

$$m_n = \frac{1}{N}\sum_{j=1}^{N} f_j(x_{j,n})$$


80
75
70
65
60
55
50
45
40
M_{n+1}
40
50
60
70
80
M_n
100
90
80
70
60
50
40
30
20
10
0
M_{n-1}
0
20
40
60
80
100
M_n

Transfer Entropy as a measure of information flow



So how did it all start?

How did:

1. Software emerge from hardware?
2. Non-trivial, programmable, construction emerge from “dumb molecules”?
3. Digital information storage and processing emerge from analog information?
4. Instructional or contextual information emerge from “mere bits” (Shannon information)?
5. Top-down information flow emerge from bottom-up information flow?