Fundamental conceptual issue

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

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

information!
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 hierarchical 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?
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
Biology is very complex!
EXPLAIN WINDOWS!
Chemistry = hardware

Software?
Some examples of trivial replicators:

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

Replication operation is implicit in local physics/chemistry
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.
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”

Which is “junk”?

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

even that’s not all!
Top-down Causation by Information Control

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

256 rules

Global state ↔ Local rules
Emergent self-organization

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

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

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

\[ m_n = \frac{1}{N} \sum_{j=1}^{N} f_j(x_{j,n}) \]
Transfer Entropy as a measure of information flow

![Graph showing Transfer Entropy with 'Top-Down' and 'Bottom-Up' lines against Global Coupling Strength.](image-url)
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?