A Short Course on Biosemiotics

1. Functional approach to the origin of life: emergence of signs in autocatalytic systems

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Biosemiotics - a new discipline

Biosemiotics = Biology + Semiotics

Biology: Study of living organisms

Semiotics: Theory of signs; Theory of knowledge and meaning

Term “biosemiotics” was first used by Friedrich S. Rothschild in 1962

It became firmly established in 1992 with the publication of the book “Biosemiotics” edited by Thomas Sebeok

Major resources on biosemiotics:

International Society for Biosemiotic Studies http://www.biosemiotics.org/

Gatherings in Biosemiotics. 12th meeting in Tartu, Estonia - July 2012

Published > 20 books

Journal of biosemiotics

Main ideas of biosemiotics

1. Life has informational nature (life is coextensive with semiosis). Thus, we need to understand what is information and how to study it.
2. Cybernetics started studying information processes, but its ideas appear not sufficient for biological applications. Cybernetics studies the quantity of information rather than the meaning.
3. Semiotics (theory on signs and meanings) can help to study how and why useful functions emerge, persist, and evolve in living organisms
4. Biosemiotics rejects dualism and attempts to explain the origin of life and mind. Ideas and even logic are tools developed by evolving agents. But life is qualitatively different from non-living systems.
5. Biosemiotics assumes that organisms develop their own models of the world (Umwelts) which may be different from human models
6. Biosemiotics assumes creative capacity of life, which comes neither from external divine powers nor from internal supernatural forces. Instead, creativity is fully compatible with physics and chemistry (but not explained by them) and is a product of evolution.

Biosemiotics: historical overview

Jakob von Uexküll (1909):

Life is based on modeling of the environment

Conrad Waddington (1960):

Genes are switches between stable developmental paths (creods)

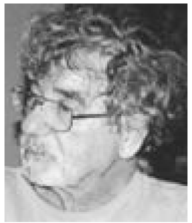
Howard Pattee (1969):

“How Does a Molecule Become a Message?”

1995: Semiotic closure

Gregory Bateson (1972):

Information as "a difference which makes a difference."




Maturana, H. & Varela, F. (1980):
Autopoiesis: unity of structure and function, self-sustainability

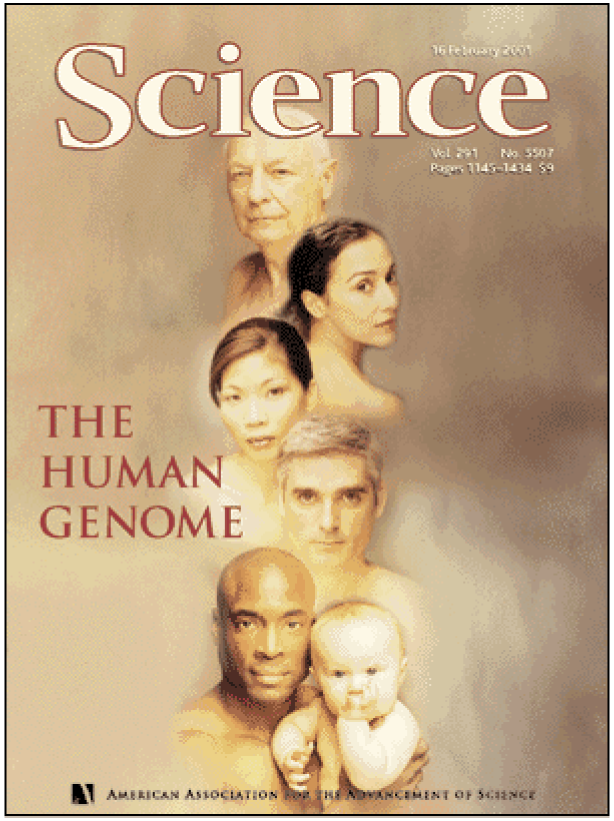
Thomas Sebeok (1992):

Biosemiotics: Life is coextensive with semiosis


Hoffmeyer J. & Emmeche C. (1991):

Code duality: signs can be copied and interpreted

Genomic revolution in biology and semiotics



- Biochemistry: DNA is a chemical molecule
- Howard Pattee: Genome is a text written in a special language
- Nucleus is a brain of a cell
- Biologists need to recognize that the genome carries “meaning” or a kind of “knowledge”

Flavors of biosemiotics

1. Semiotics of Charles Peirce (Sebeok, Hoffmeyer, Favarau, Kull)

   Semiotics of Charles Peirce is based on the philosophy of objective idealism. He thought that meanings of signs are part of nature (as Plato's ideas), and organisms discover sign relationships rather than make their own. Peirce did not accept the notion of "Creative Evolution" of Henry Bergson.

2. Hermeneutics of Gadamer (Chebanov, Markoš)

   Biohermeneutics assumes "dance, play, and self-presentation of the living". This flavor of biosemiotics is most tightly linked with human semiosis, art, literature, and religion. It is also close to vitalism. Biohermeneutics is interested in the dialogue of humans with animals and other organisms.

3. Organic codes (Barbieri)

   Mechanistic version of biosemiotics, where meanings are material things (e.g., proteins) manufactured by agents (codemakers). Meaning is a correspondence between two sets of objects (e.g., nucleotides and aminoacids). Barbieri rejects subjectivity in coding and modeling.

4. Pragmatism / instrumentalism (Sharov, Cariani, Witzany)

   Living organisms are creative agents who invent instruments to perform novel functions. Meanings are useful conventions within communication system. Meanings belong to agents, not to nature. Multiplicity of useful representations of the same reality.

The origin of life

What is Life?

Aristotle: to be alive means to have a soul (Anima)

Aristotle's soul is not supernatural, it is a natural phenomenon and should be studied by science. Soul is a form, not matter

Three kinds of souls:

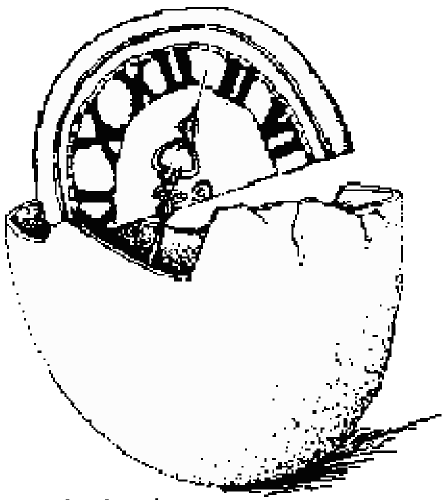
1. **Nutritive** = ability capture resources and reproduce itself
2. **Sensitive** = ability to perceive the world, memorize, evaluate, and anticipate
3. **Rational** = ability to make abstract models and use logic

Using scientific terminology: life has informational nature

Then: What is information?
Why information is used by both organisms and mechanisms?

Organisms versus mechanisms

S. Dali



A. Astrin

Mechanisms are manufactured and programmed by humans

Organisms are self-producing and self-programmed systems

Bridging the gap:

Organisms depend on the function of molecular mechanisms (e.g. ribosomes)

Some mechanisms can self-assemble (e.g., spaceships, nano-systems)

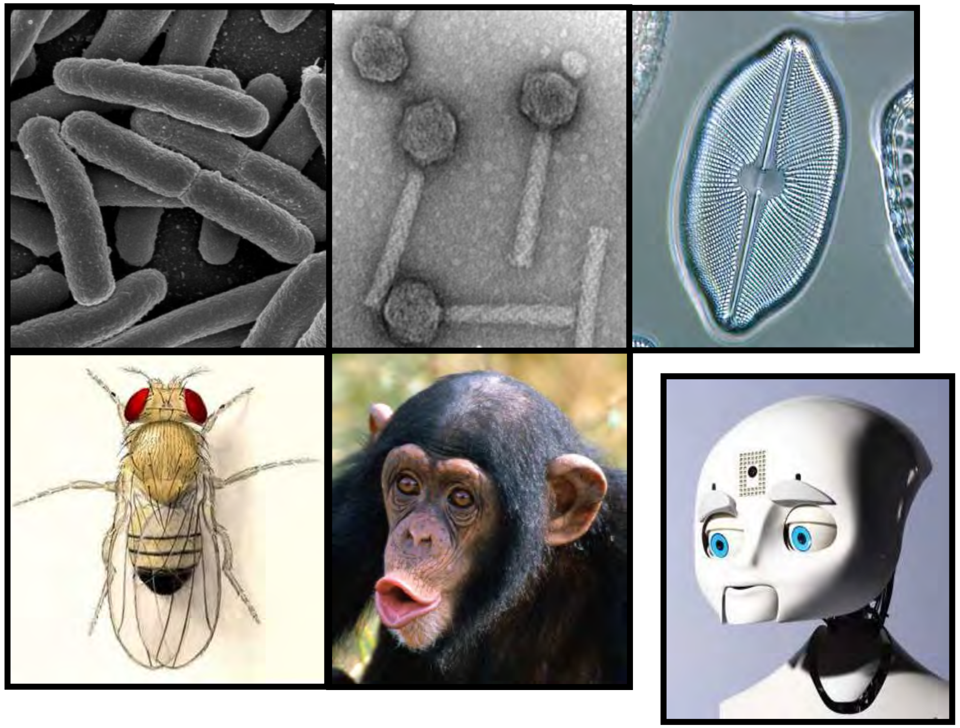
Synthetic biology can produce artificial organisms (Venter)

Theory of agents

Living organisms are “natural agents”

Relational biology (Rashevsky, Rosen) suggested a functional approach:

Systems should be compared by their **functions** rather than material composition



Can we say that a system is “alive” if it performs some functions of living organisms?

It is better to use the term “agent”

Agent is a goal-directed system whose actions are encoded and/or controlled by functional information

Agent types

1. Autonomous, dependent
2. Autopoietic, semi-autopoietic, non-autopoietic
3. Autotrophic, non-autotrophic
4. Bounded, diffused (swarm agents)
5. Sub-agents, super-agents
6. Master-agents, slave-agents

Agents are products of other agents

Complex agents do not self-assemble by chance. They can only be produced by other agents

Because life appeared before man-made mechanisms, all agents are the products of life

Difference between agents and non-agents is more important than the difference between living and non-living systems

Principle of gradualism:

Functional complexity of produced agents cannot be much higher than the functional complexity of parental agents

This principle does not contradict to the origin of life because primordial agents were extremely simple

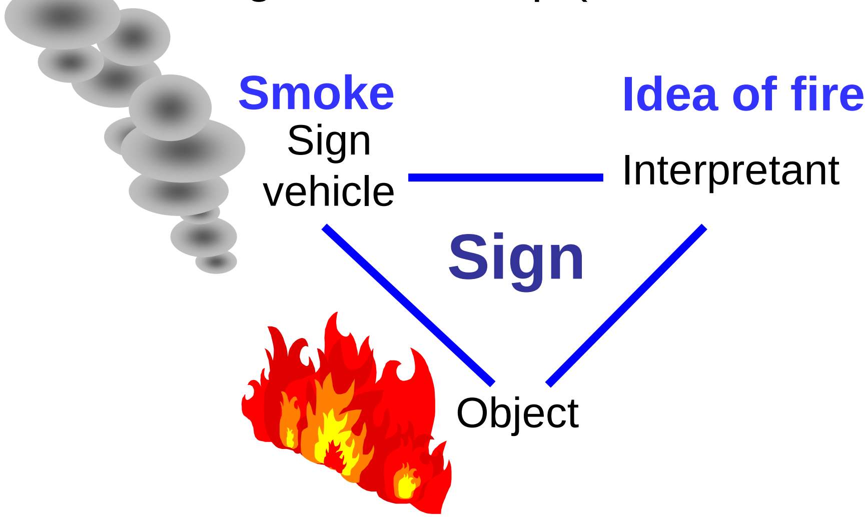
Functional Information

Functional information is a collection of signs that helps agents to preserve, control, and disseminate their functions

Adjective “functional” is used to distinguish it from quantitative approaches to information developed by Shannon and Kolmogorov

What is sign?

Sign relationship (Charles Peirce)



Biosemiotic notion of sign

Sign is a material object that is ised by agents to encode and control their functions

Signs differ from resources and tools

However, in certain cases, resources or tools may play the role of signs

Signs are meaningful only in relation to specific agents

Being a sign - is not a physical feature

An object is a sign only in relation to the class of agents, who use it as a sign (I call it “communication system”)

Signs are not universal. Signs for one class of agents are junk for another class of agents

In particular, DNA sequence has meaning only in relation to organisms who can interpret it

Life is based on communication of agents

Autocommunication: memory and heredity

Memory is a transfer of functional information to the future state of the same agent.

It is necessary to preserve functions of the agent over the life span

Heredity is a long-term “memory” that spans over many generations of organisms

Functional information is transferred to a new agent who already has a minimal interpretational module to process it

Structural and functional approaches to the origin of life

Structural approach:

What is the probability that some simple proto-organism (e.g., with a membrane, DNA, ribosomes, etc.) gets assembled by chance?

The probability = zero.

Functional approach:

Imagine a simplest system where signs that encode some functional and heritable properties

First proto-organisms were not "frankensteins" assembled from parts but they were fully functional and autonomous from the start (however the functions were very simple at the start).

Hereditary molecules should be self-sustainable (autocatalytic)

Autocatalysis = reaction, whose rate is positively affected by one of the products

Autocatalytic cycle = closed sequence of reactions with a positive feedback via products generated after several downstream reactions

The catalyst is not affected by the reaction, or
The catalyst is restored after the reaction or reaction cycle

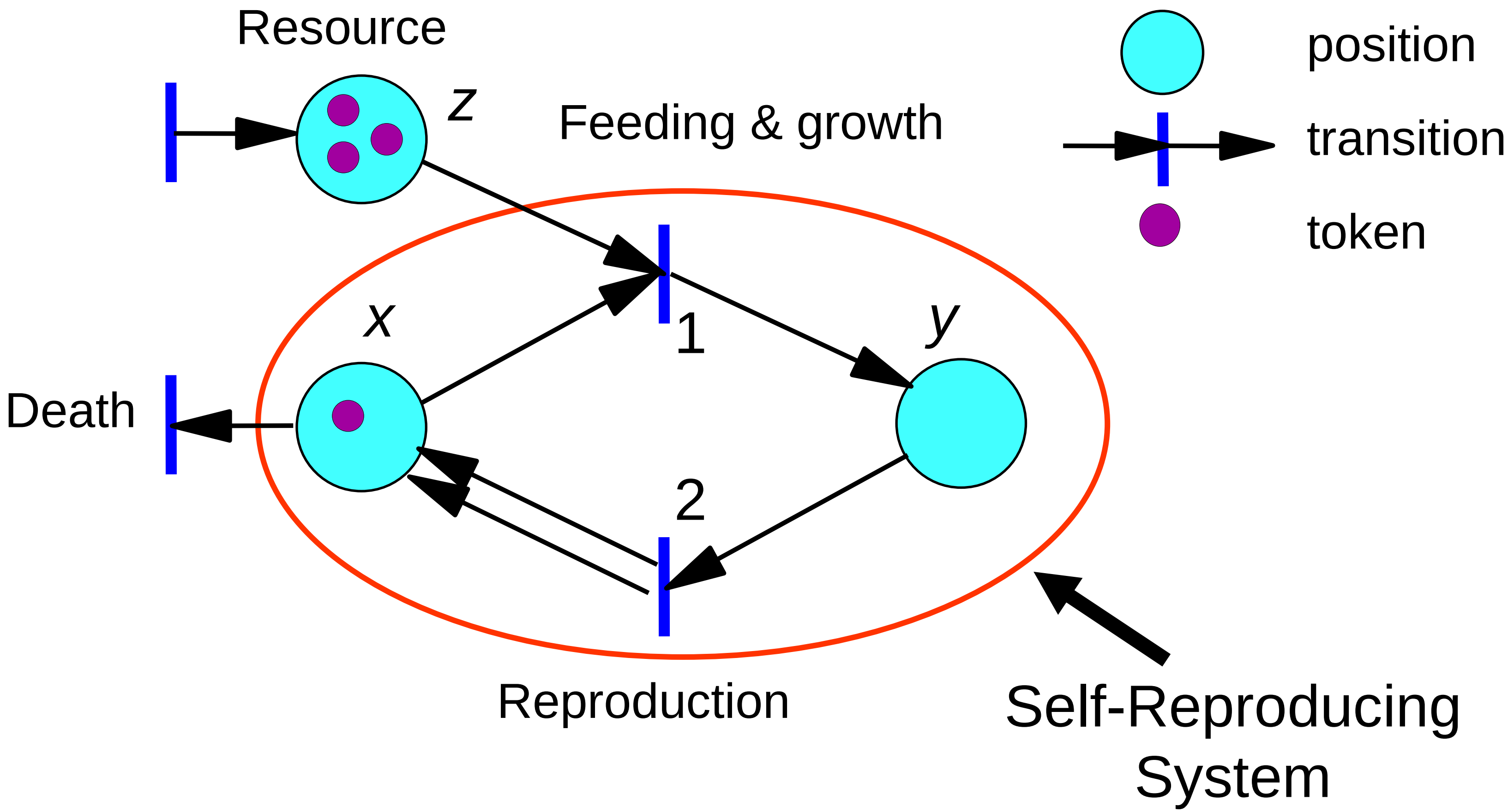
Copying of molecules: (Szathmáry):

a) template-based (mostly passive)
b) processive replication (active self-production = autocatalysis)

Even passive copying is autocatalytic (original is needed to make a copy).

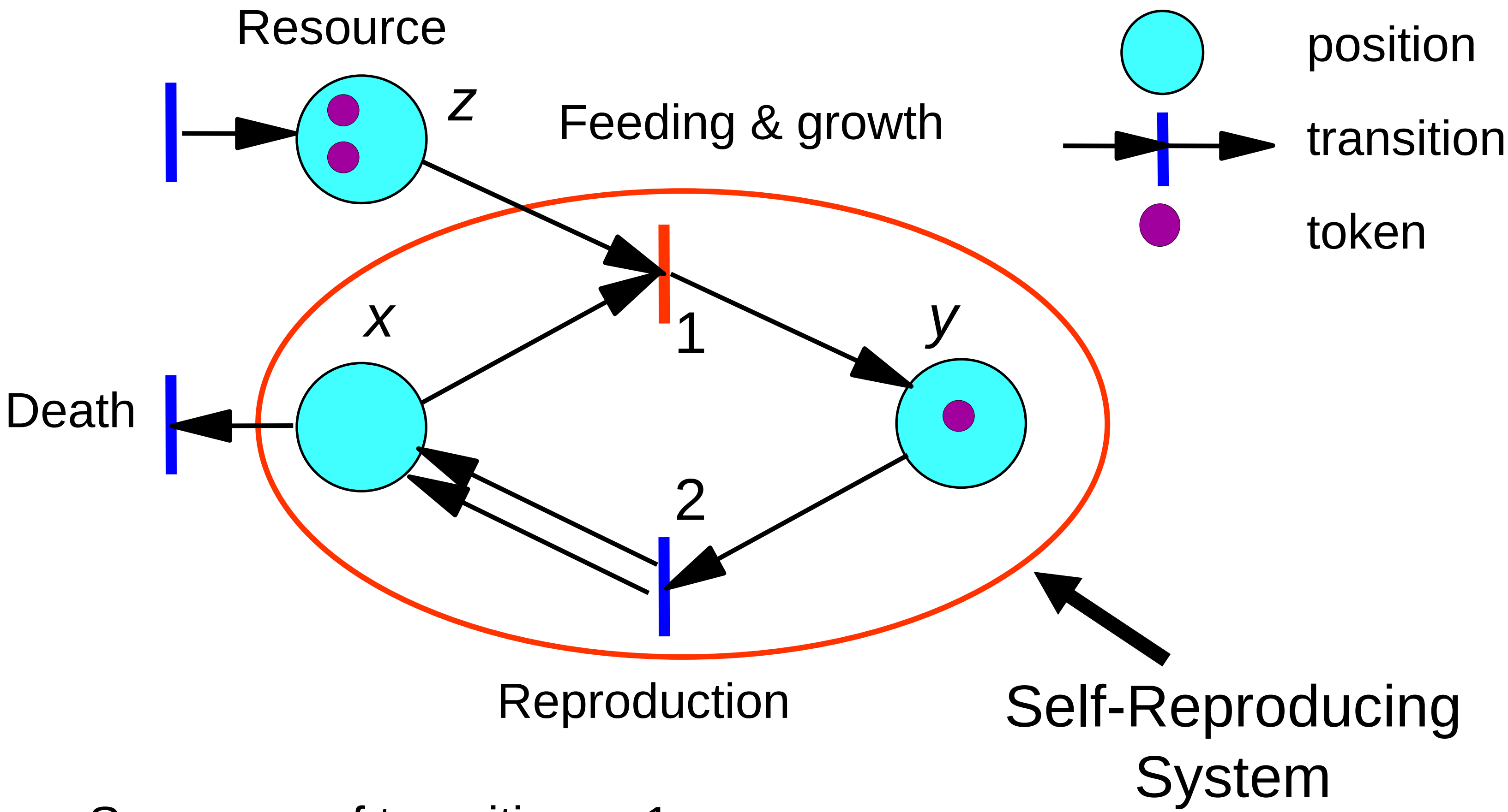
Both types of copying = strong autocatalysis, i.e., no reaction in the absence of the product

A Petri-Net model of a self-reproducing (autocatalytic) system



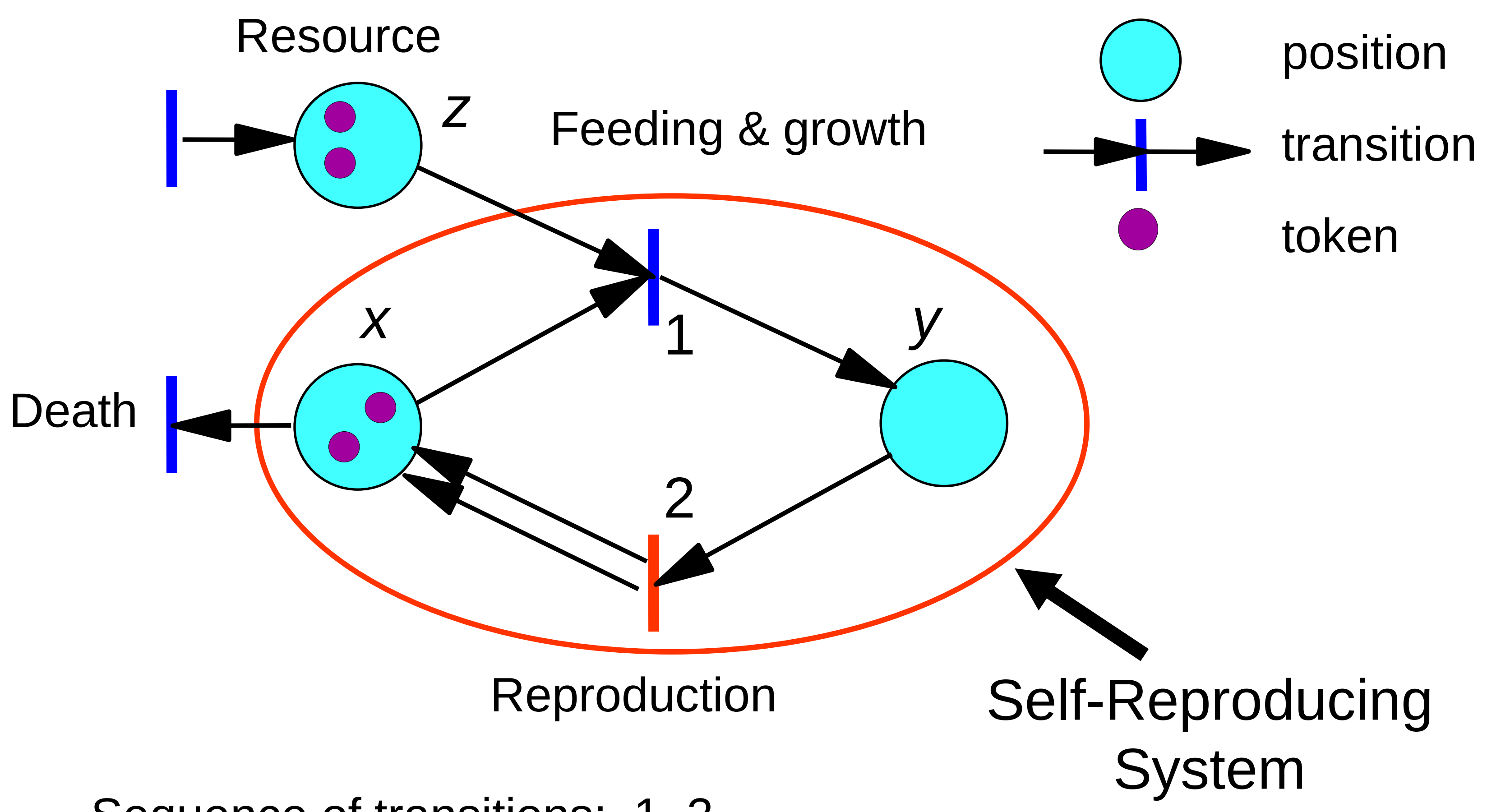
Sharov, A.A. 1991. Self-reproducing systems: structure, niche relations and evolution. BioSystems, 25: 237-249.

A Petri-Net model of a self-reproducing (autocatalytic) system



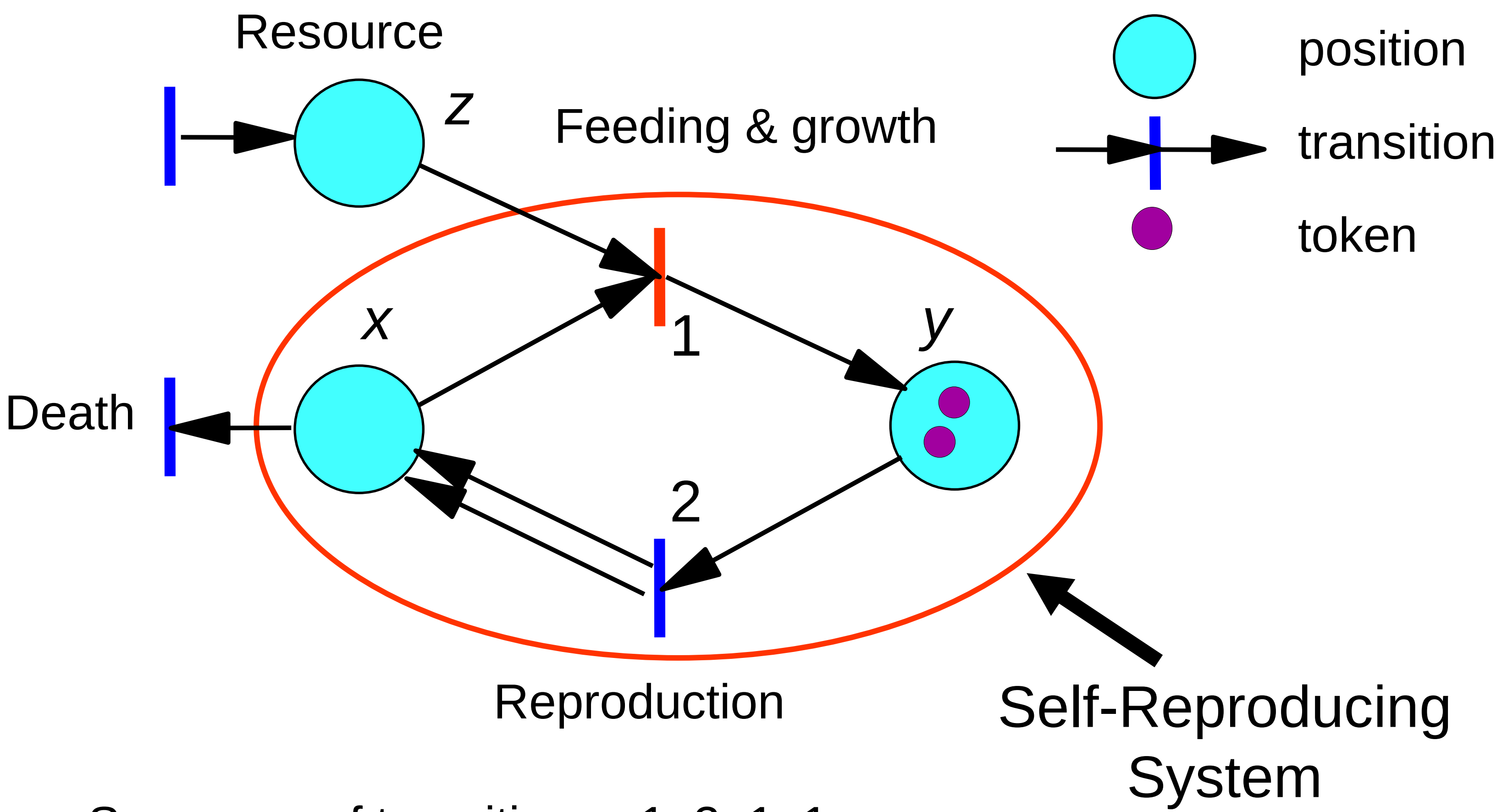
Sequence of transitions: 1

A Petri-Net model of a self-reproducing (autocatalytic) system



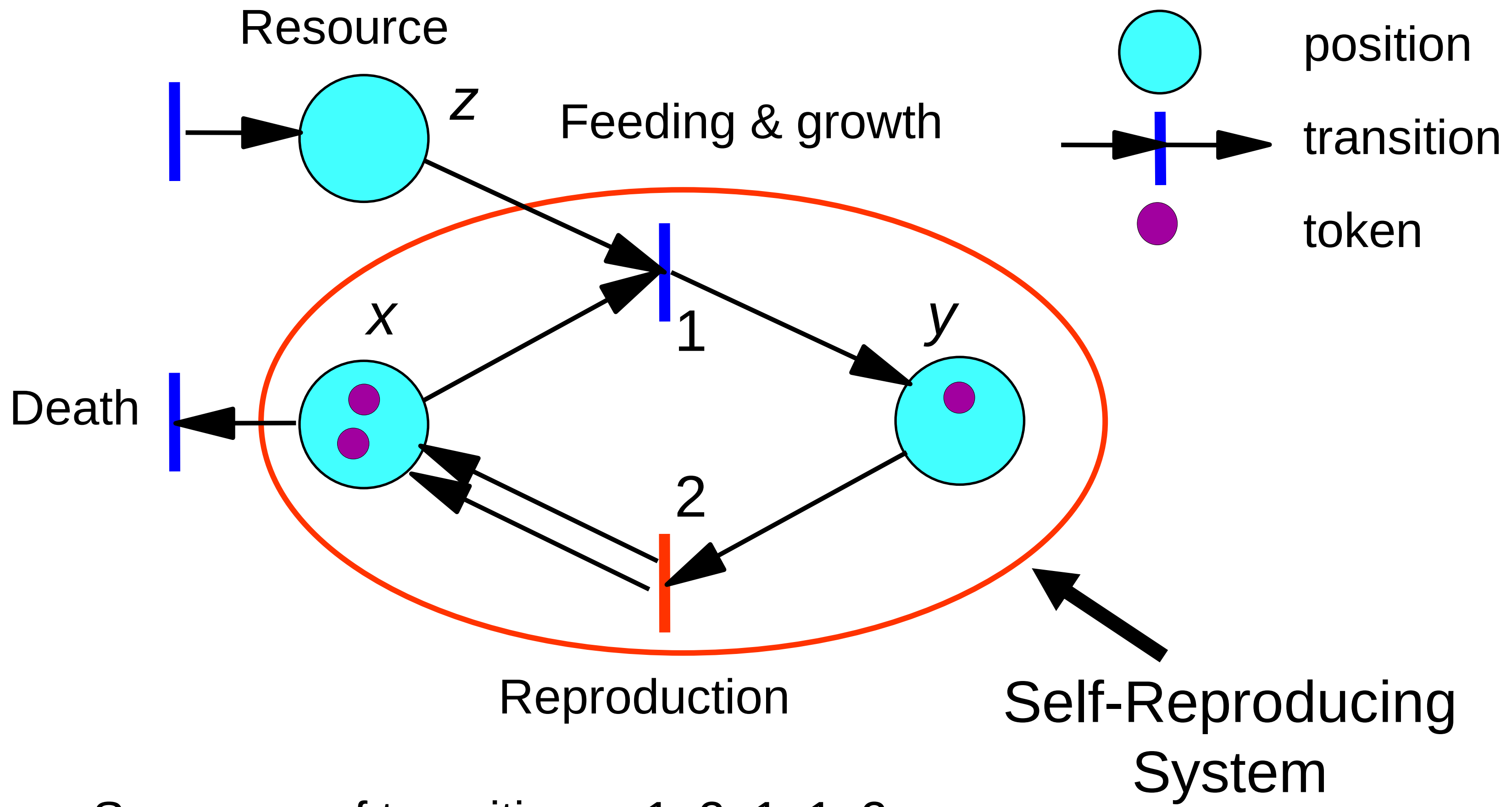
Sequence of transitions: 1, 2

A Petri-Net model of a self-reproducing (autocatalytic) system



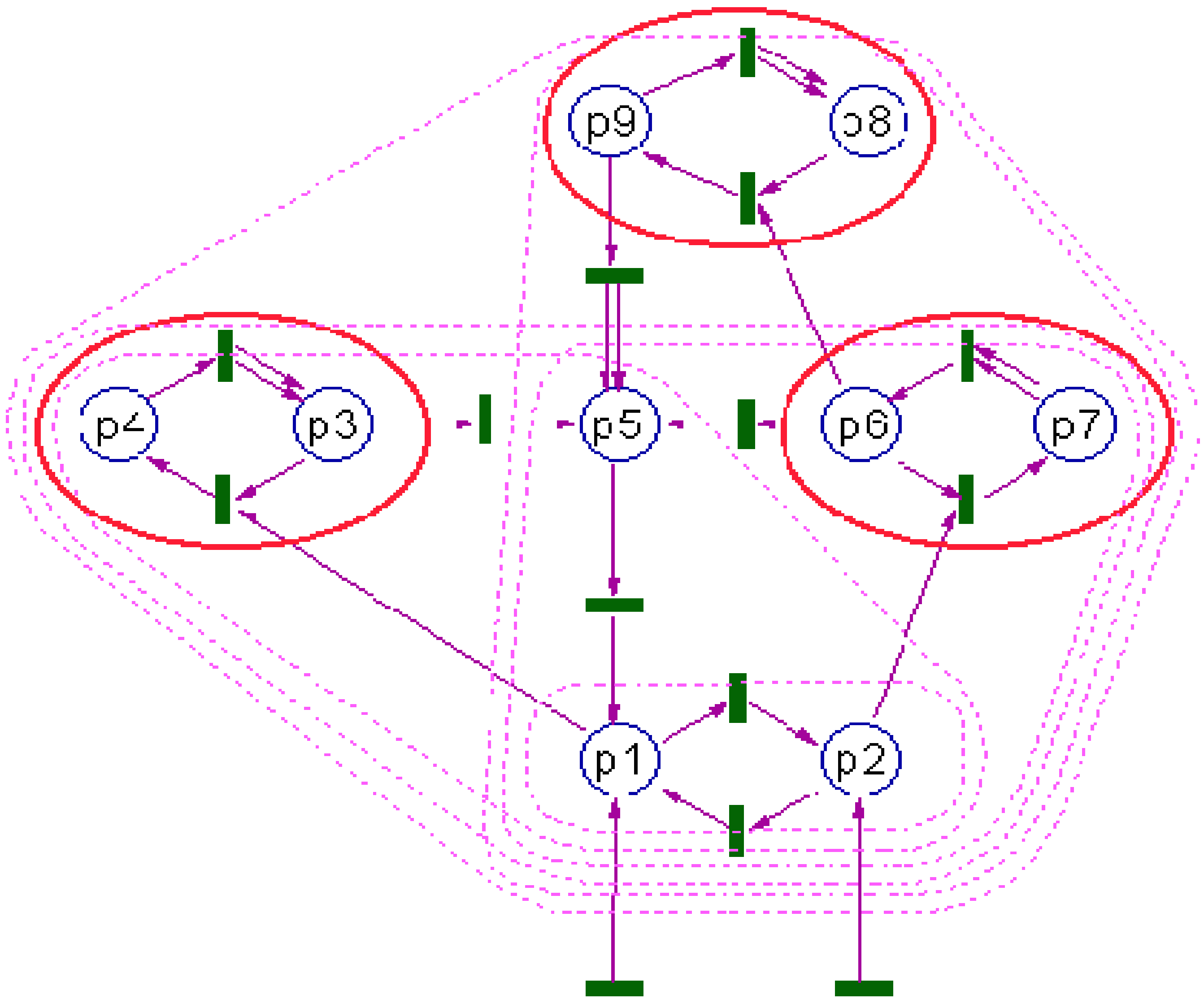
Sequence of transitions: 1, 2, 1, 1

A Petri-Net model of a self-reproducing (autocatalytic) system



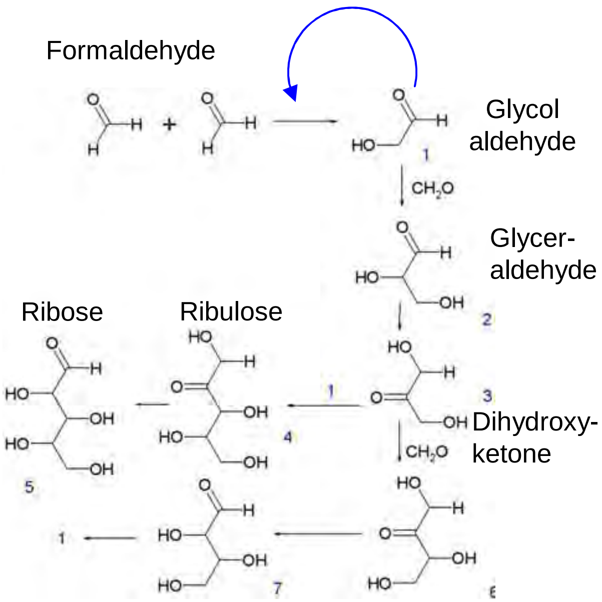
Sequence of transitions: 1, 2, 1, 1, 2

Complex Petri-net with three self-reproducing subsystems

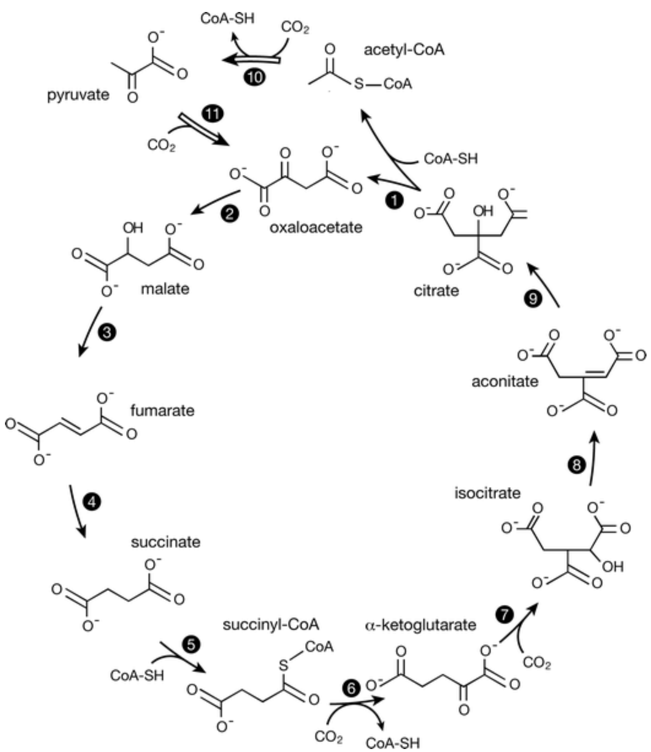


Examples of autocatalysis in the models of the origin of life

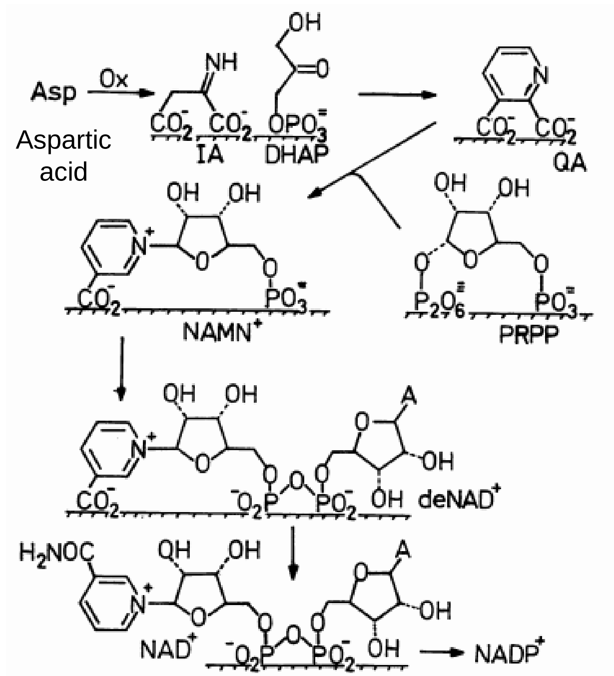
Formose reaction



Reverse Krebs cycle (Morowitz 2000)



Autocatalysis of NADP$^+$ (Wächtershäuser 1988)



Autocatalysis is not enough for a sign

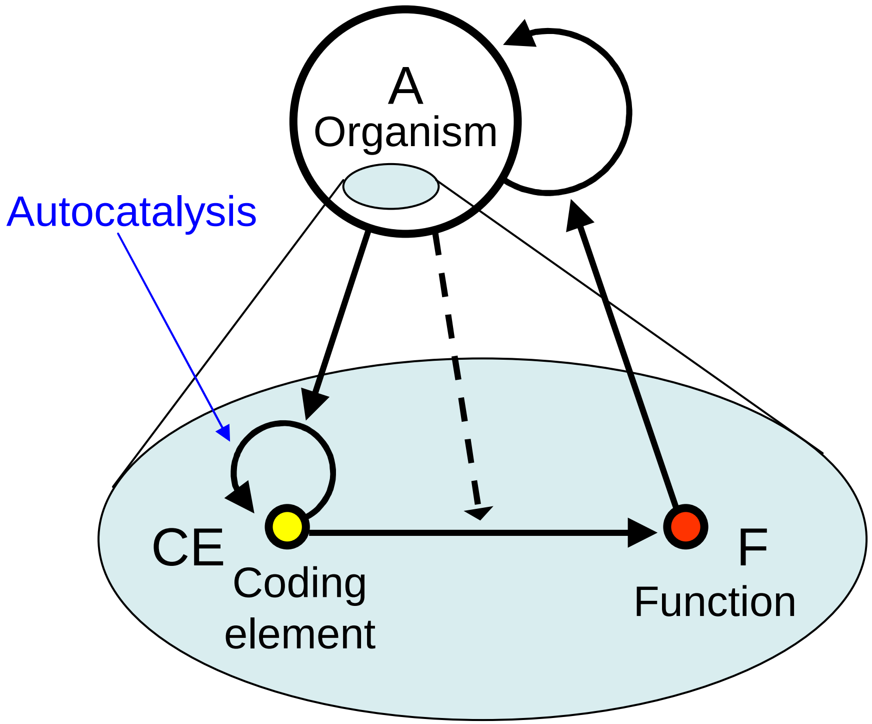
Autocatalysis is rather abundant in the non-living world:

1. Crystal growth
2. Rust growth
3. Nuclear fission (non-chemical)

To be a sign, an autocatalytic molecule should encode some features of a larger system (proto-organism) which are mutually beneficial for the molecule and for the larger system.

- Proto-organism needs to be separated from the environment
- Proto-organism should be able to reproduce
- Coding molecule should affect positively the rate of reproduction

Coding relation and its components

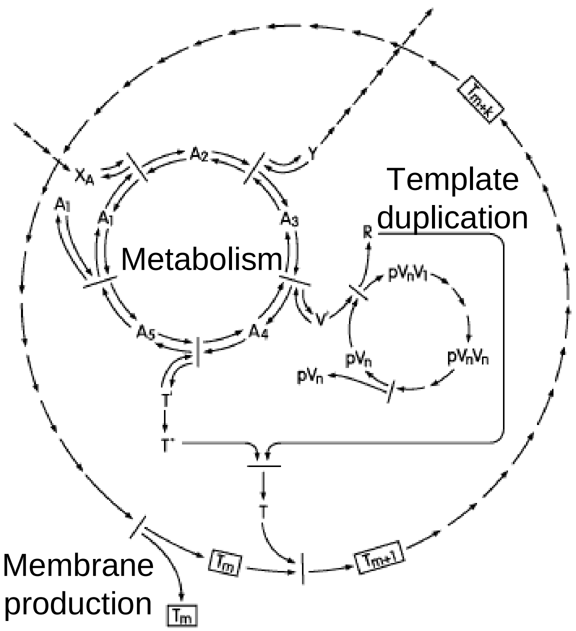


1. Coding element (CE) is a viable and irreplaceable self-reproducing system within organism A
2. CE induces or modifies some function F (i.e., behavior and/or development) of the organism A
3. Survival and/or reproduction of A is enhanced by function F

- This is a two-level system where coding is a cooperative relation between these levels
- Semantic closure: self-sustained interpretation of a sign (message)
- Coding relation is specific to life and marks the start of its origin

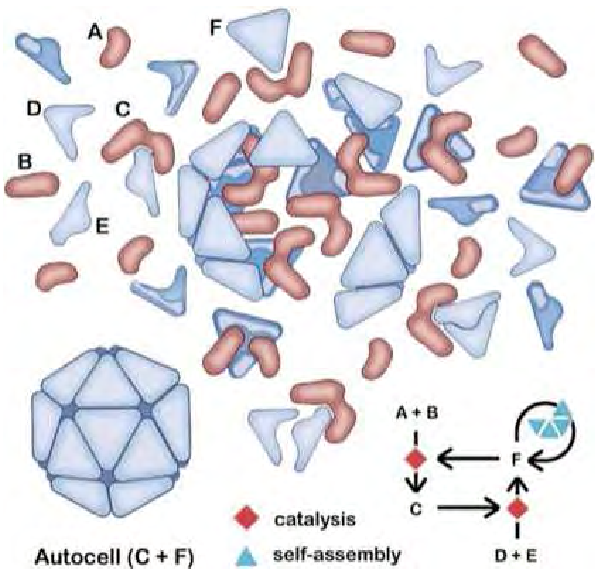
Examples of coding relations in the models of the origin of life

“Chemoton” (Gánti 1971)



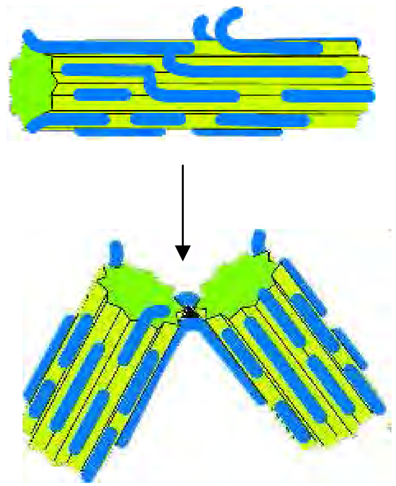
Has an enclosure
Too complex to emerge

“Autocell” (Deacon 2006)



Requires complex resources

“Sweet crystal” (Ferris 1996)



Requires a “genetic takeover” (Cairnes-Smith 1982)

Coenzyme autocatalytic network on the surface of oil microspheres

Why coenzymes?

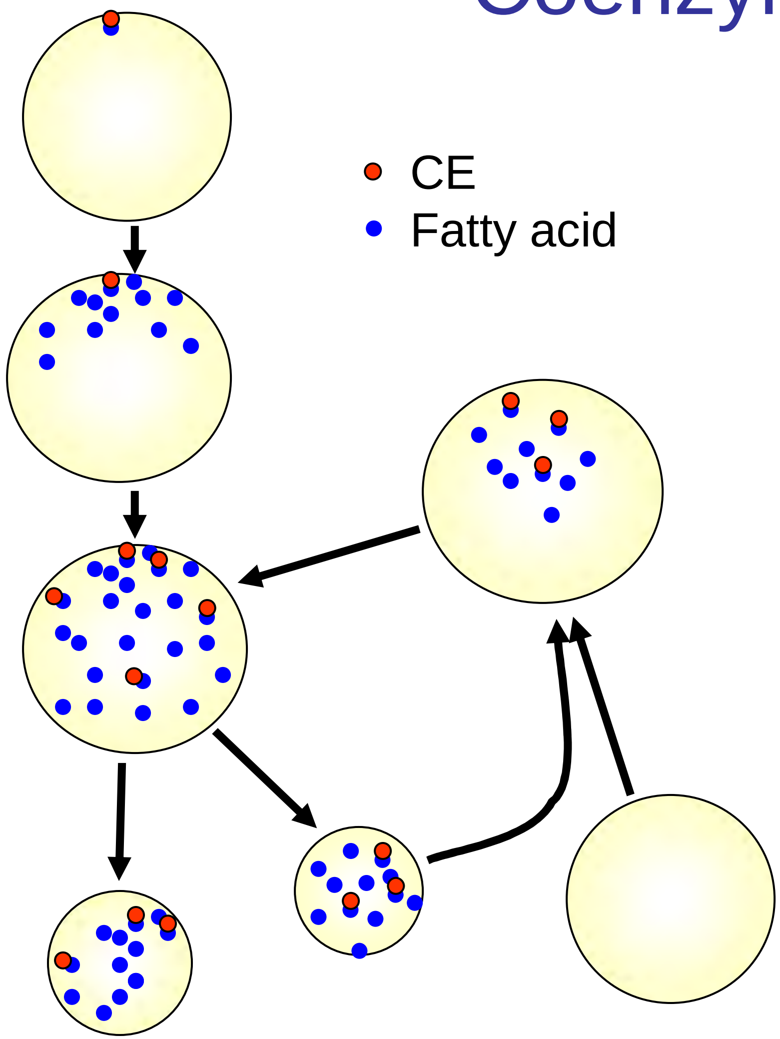
1. First CE should be a catalyst
2. First CE should be a simple non-polymeric molecule
3. Many coenzymes are similar to nucleic acids (CoA, NAD, ATP), thus initial coenzyme-like molecules (CLMs) may be predecessors of both nucleic acids and contemporary coenzymes

Why oil microspheres?

1. Hydrocarbons are most abundant organic molecules in the universe.
2. Liquid hydrocarbons are expected to be present on early terrestrial planets (Marcano et al. 2003)
3. Liquid hydrocarbons can be synthesized abiogenically in hydrothermal vents (Holm and Charlou 2001, Proskurowski et al. 2008)
4. Oil microspheres self-assemble in water environment and can provide carbon resource for the autocatalytic network

First CEs on the oil microsphere

"Coenzyme World"

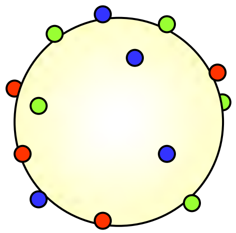


Assume that a CEs can anchor to the oil microsphere via rare fatty acid molecule.

The function of a CE is to oxidize hydrocarbons to fatty acids, which provides additional anchoring sites for new CEs. Also this may help to capture resources for CE synthesis

Accumulation of fatty acids increases the chance of a microsphere to split into smaller ones, and small microspheres can infect other oil microspheres (i.e., capture new oil resource)

Combinatorial coding

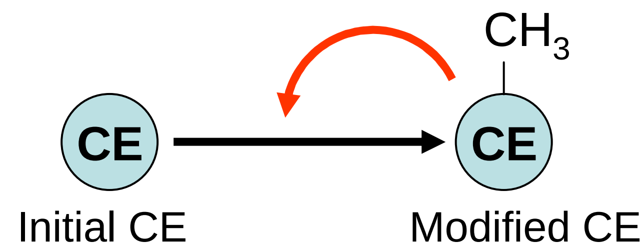


Multiple independent CE on the surface of oil microspheres
I call it “combinatorial” because CEs are transferred to offspring in random combinations

How additional CEs may appear in evolution?

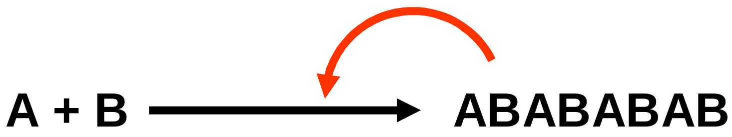
1. De-novo formation of a new coding relation
2. Modification of the existing CE
3. Polymerization of CEs

Example of modification of the existing CE: →



Function: methylation of other molecules

Example of polymerization: →



Function: polymerization of other molecules

Cooperation between CEs

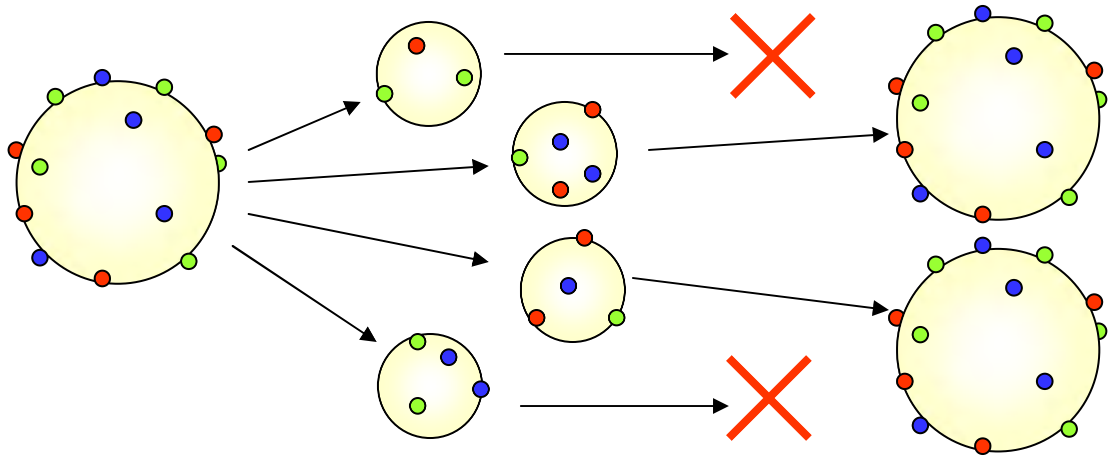
Proto-organism is similar to an ecosystem

Competition (for space or other resources) → Competitive exclusion **or** Co-existence

However, proto-organisms differ from ecosystems because they can (a) reproduce and (b) degrade (=die).
Because of the coding relation, CEs share the fate of the proto-organism

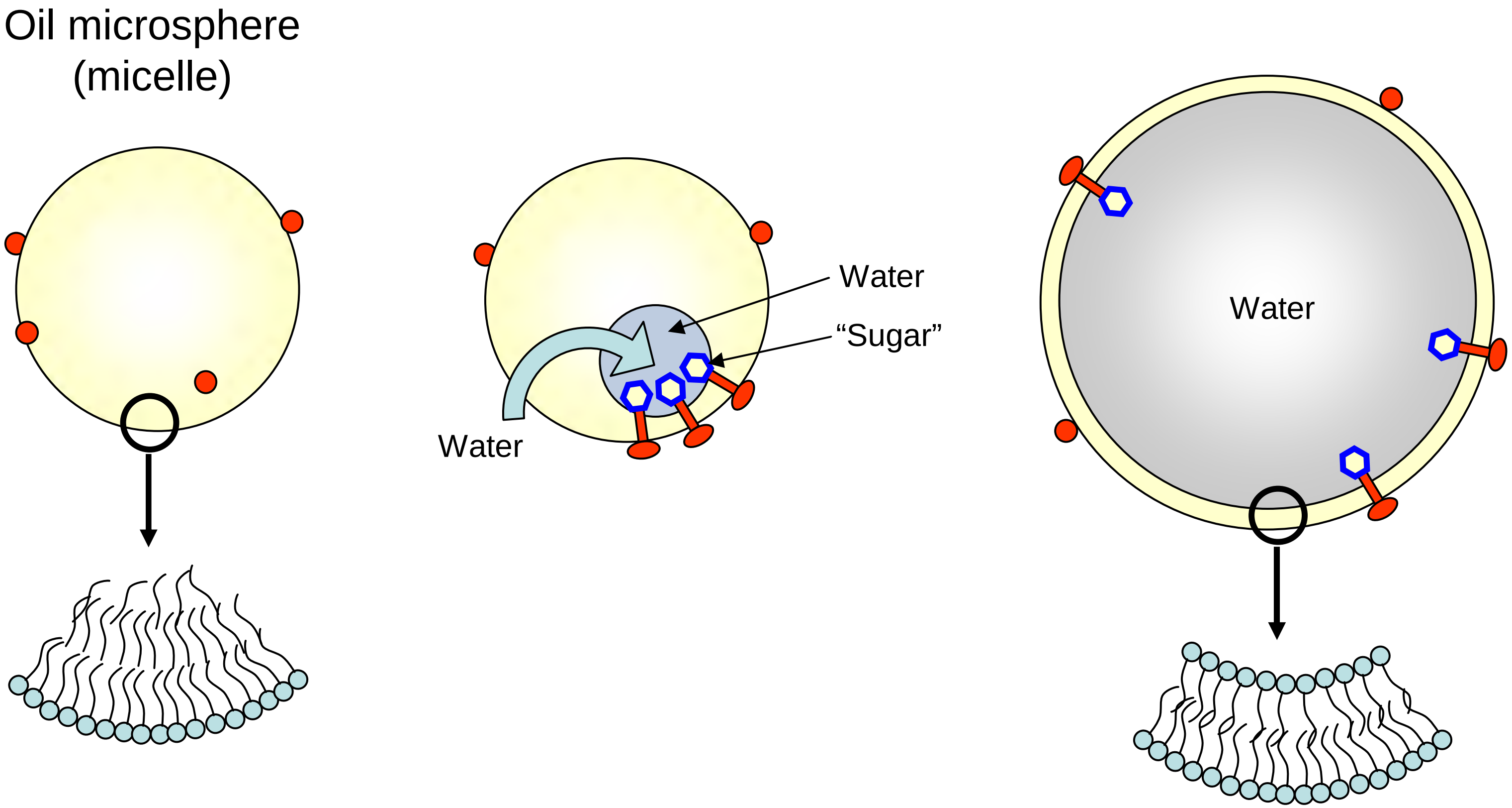
Cooperation develops by group selection → Co-existence

How to preserve a full set of CEs in the process of reproduction?



Stochastic corrector model
(Szathmáry 1999)

Origin of bilayer membrane



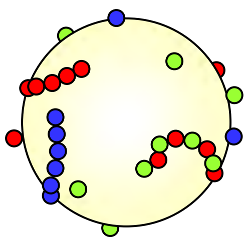
Origin of a Universal Code

Universal code = development of generic rules for generating new CEs

It can be defined in a formal way as a language based on a fixed alphabet and syntax, so that any text in this language can become a CE.

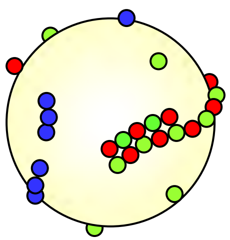
In chemical terminology, universal coding requires polymeric molecules as CEs and a generic mechanism of their replication.

Step 0



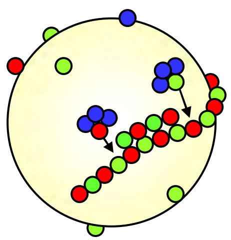
Synthetic polymers, random or with repeats

Step 1



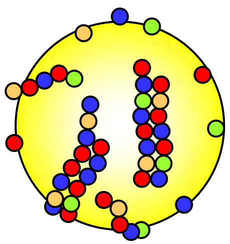
Alignment of polymers to perform some function. Emergence of complementary pairing

Step 2



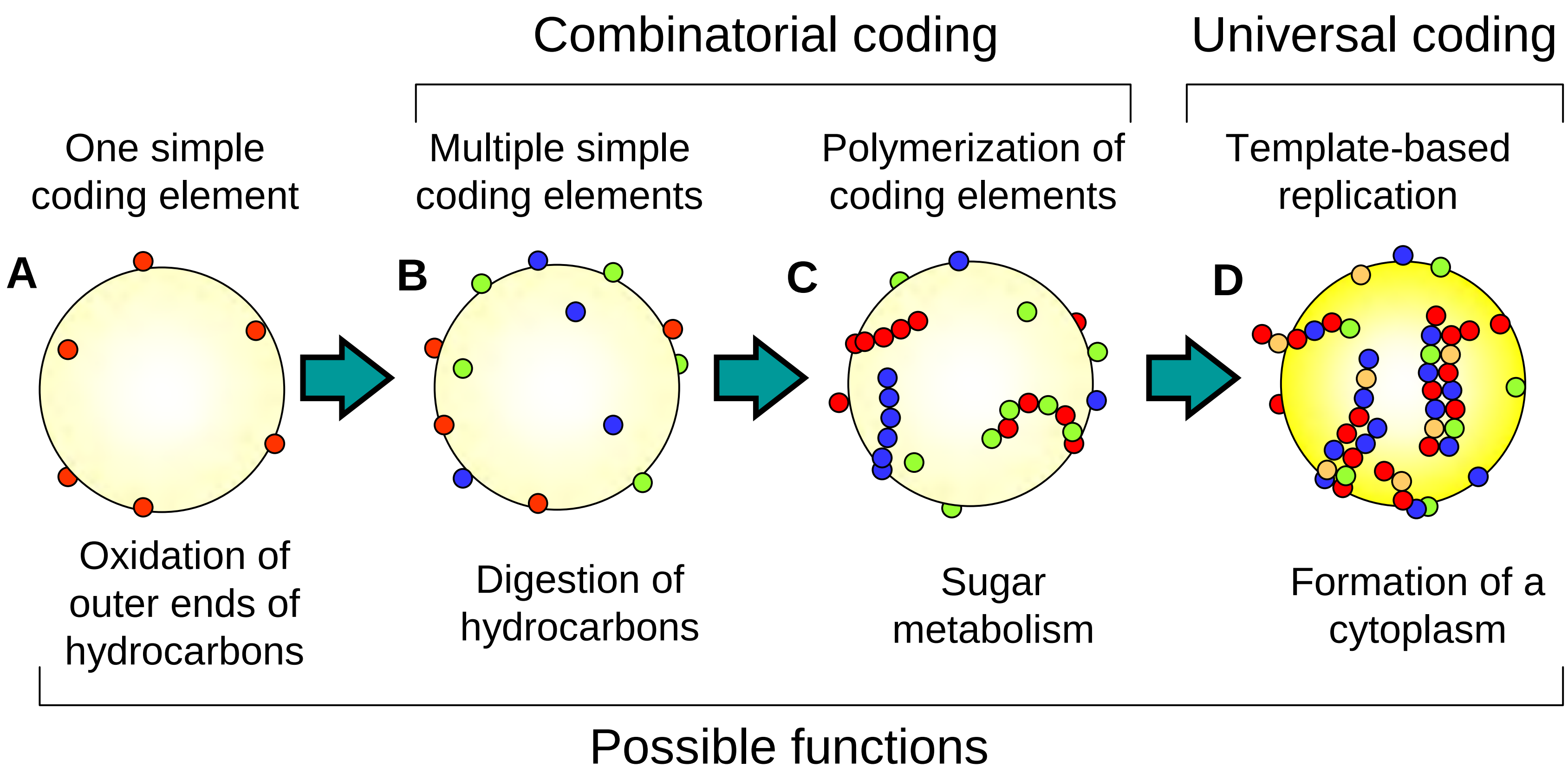
Elongation of polymers using over-hanging template, which is restricted to some simple repeats

Step 3



Universal template-based replication of polymers with any sequence

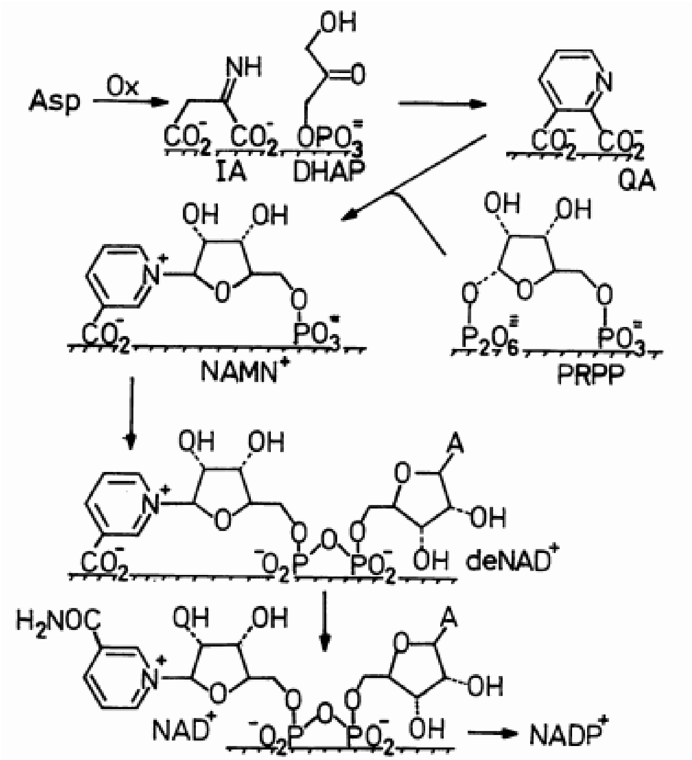
Summary of the hypothesis



Alternative scenarios

Theory of surface metabolism by Wächtershäuser (1988)

Autocatalysis on a solid (e.g., pyrite) surface



What is missing:

Manipulation of the environment in a way that is beneficial for the autocatalysis

It is possible that coding elements appeared first on solid surfaces and then moved to oil microspheres

Conclusions

- Coenzyme-like molecules (CLMs) are most simple candidates to perform hereditary functions before the emergence of nucleic acids
- Coding relation links autocatalytic coding elements, proto-organism, and encoded function of the proto-organism
- In the proposed model of the origin of life, CLMs modify (encode) surface properties of oil microspheres, to which they are anchored. Advantages: compartmentalization, reproduction, carbon source, dispersal, modification of surface properties.
- Transition from coenzyme world to RNA world is seen via diversification of coding elements, their polymerization on the surface of microspheres and subsequent development of template-based synthesis.