Agent-Based and Mathematical modeling in Semiotic Dynamics

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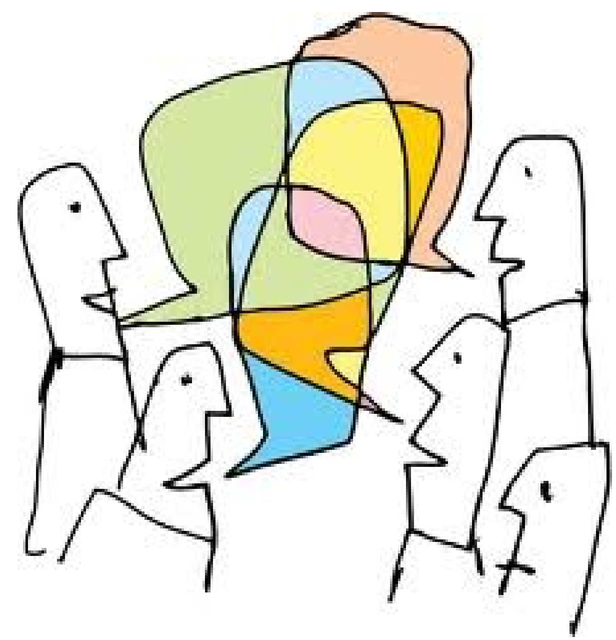
Semiotics, Cognitive Science, and Mathematics: An Interdisciplinary Workshop



March 17 (2011)
Fields Institute, Toronto, Canada

Outline: Three main parts...

First part

Informal, meant to relate what is coming to some of the things mentioned in previous presentations and discussions and introduce my terminology

- Sebeok's thesis
- Cells as semiotic systems
- Manufacturing semiosis
- Conventionalization and semiotic dynamics

Outline: Three main parts...

First part

Informal, meant to relate what is coming to some of the things mentioned in previous presentations and discussions and introduce my terminology

Second part

Technical, a simple, mechanistic model of cellular semiosis.

Third part (if we get there)

Get a head start on the discussion that surely will follow!

– Part I –

Part I: Sebeok's thesis...

“Life = Semiosis”

As a definition of life, this is not a priori useful:

- what is semiosis?
- Does it include interpretation?
- Are there different types of semiosis, e.g. coding (or manufacturing) semiosis, interpretation semiosis, etc.?
- Is there (more than) a terminological issue?

Part I: Sebeok's thesis...

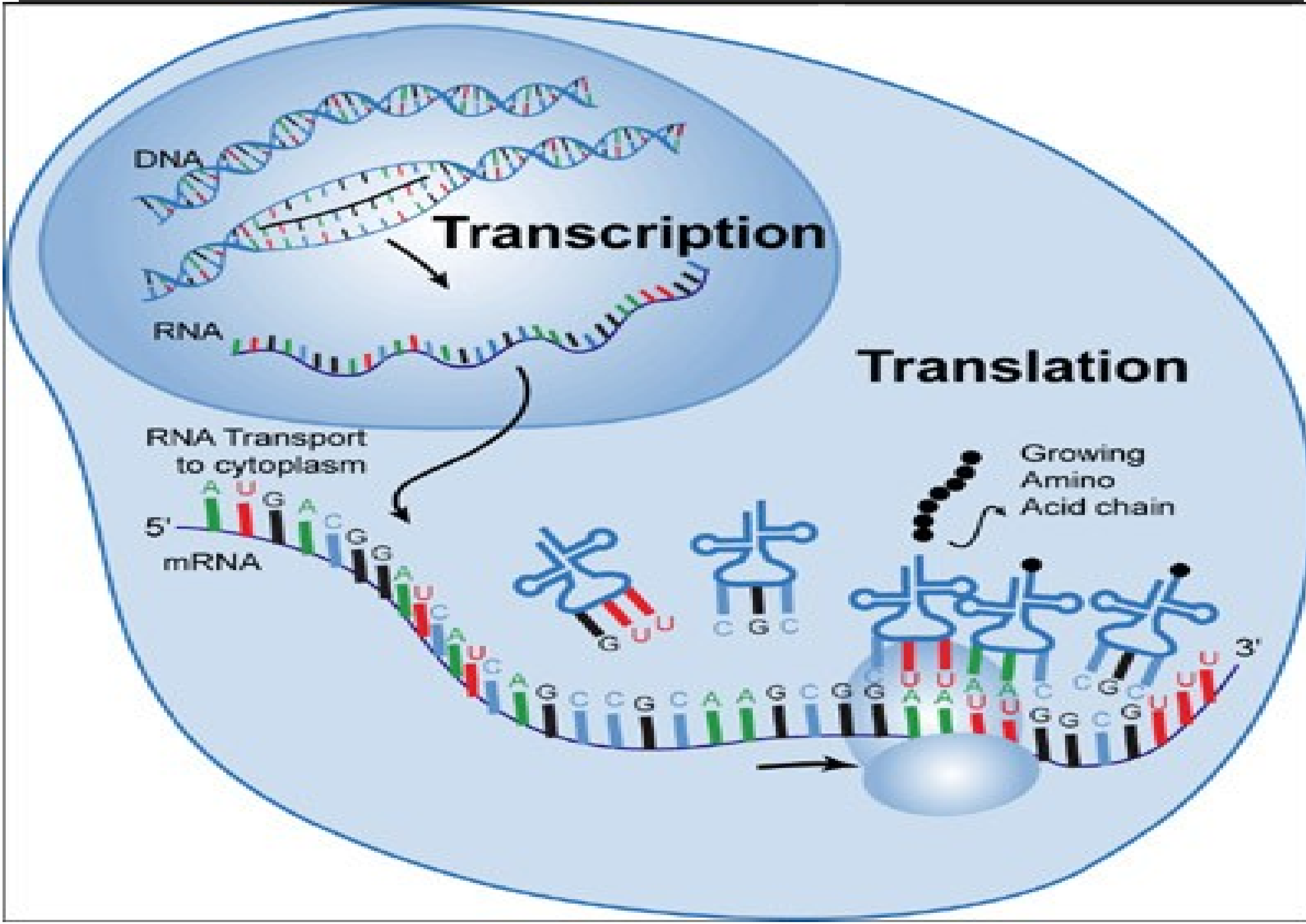
“Semiosis = Life”

As a definition of semiosis on the other hand, we now know where to look for it:

- Cognition and human communication, are part of life, and involve (interpretation) semiosis...

- Cells, as living systems, are semiotic systems... ...although in a much simpler way, making cells an ideal starting point for scientific (naturalistic) biosemiotics

Part I: Cells as semiotic systems...



Part I: Cells as semiotic systems...

Translation=

The production of a protein (a sequence of amino acids) according to a template (mRNA representing a gene) and a code (the genetic code)

It indicates a kind of semiosis because:

1) The genetic code is arbitrary

2) It's structure is determined by three conflicting evolutionary forces, namely the needs for:

- diverse amino-acids,
- error-tolerance and,
- minimal cost of resources.

} Expressivity and precision

Tsvi Tlusty (2010) A colorful origin for the genetic code: Information theory, statistical mechanics and the emergence of molecular codes. Physics of Life Reviews 7

Part I: Cells as semiotic systems...

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The production of a protein (a sequence of amino acids) according to a template (mRNA representing a gene) and a code (the genetic code)

It indicates a kind of semiosis because:

1) The genetic code is arbitrary

2) It's structure is determined by three conflicting evolutionary forces

3) It allows the cell to **manufacture protein**, which is **essential to it's survival**

Part I: Manufacturing semiosis...

- Protein is crucial for the cell to survive (to stay alive)

- It is therefore crucial that the right protein is produced at the right time

- There are however of the order of 10^10 000 different possible protein (there are only 10^80 atoms in the universe)

- And there is no way to assemble protein from protein, e.g. by copying

=> Genes! = `Bauplans' for protein (information)

But how should these **`bauplans'** be read? – There is no fixed ('causal') relationship between nucleotides (the bauplan) and amino acids (the building itself)!

Part I: Manufacturing semiosis...

- Protein is crucial for the cell to survive (to stay alive)

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=> C

But ... fixe ... bauplan) and amino acids (the building itself)!

The cell is **actively manufacturing protein**
by putting the genetic code to use, that is,
by applying it to the information encoded in genes

This is essential to its survival

In accordance with coding biosemiotics, I therefore propose to define transcription as an instance of ***manufacturing semiosis***

Part I: Manufacturing semiosis...

Manufacturing semiosis involves:

1) Two independent worlds or domains:

- Form (genes, providing information)
- Meaning (protein, providing metabolic function)

2) A mapping between form and meaning (tRNA)

3) Pragmatics: the cell (or agent) performing the semiosis and, when put in context, ultimately determining the usefulness or degree of semiosis that is going on

It does not include for instance **which** information (gene) is put to use (= turned into meaning through semiosis)

This requires interaction with the environment (a 2nd code)

Part I: Conventionalization...

- the **structure** of the genetic code is (partly) determined by its usefulness for (manufacturing) semiosis

- Contrary to genes (mRNA), the genetic code has remained the same throughout the entire history of life

- This suggests that forces are at work that prevent it from changing *other than (genetic) evolution*

- What about the dichotomy between code and semiosis? (cf. Kalevi Kull)

If semiosis = code **usage**, then neither is first or second

(cf. usage based linguistics and cognitive science)

Part I: Conventionalization...

- the **structure** of the genetic code is (partly) determined by its usefulness for (manufacturing) semiosis

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This suggests that the dynamics of
coding should be taken into account into models

(If language use determines language itself,
and if language is part of what we want to model
then the coupled dynamics of usage
and change should be taken into account explicitly)

(cf. usage based linguistics and cognitive science)

– Part II –

Part II: Manufacturing semiosis...

1) Two independent worlds or domains

2) A set of possible (arbitrary) mappings between them

3) Pragmatics

Part II: Coding elements as chemical species...

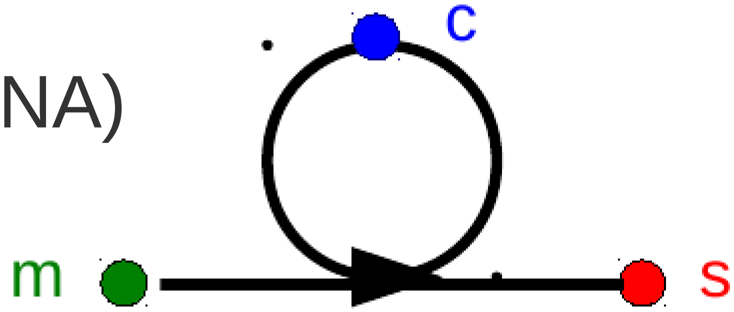
1) Two independent worlds or domains

- Meaning domain M with chemical meaning elements m_i (protein)

- Form domain F with chemical sign elements s_j (mRNA)

2) A set of (arbitrary) mappings between them

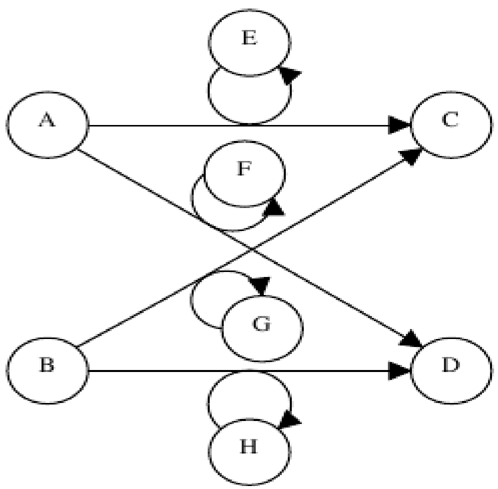
- Chemical adaptors elements c_{ij} (tRNA)



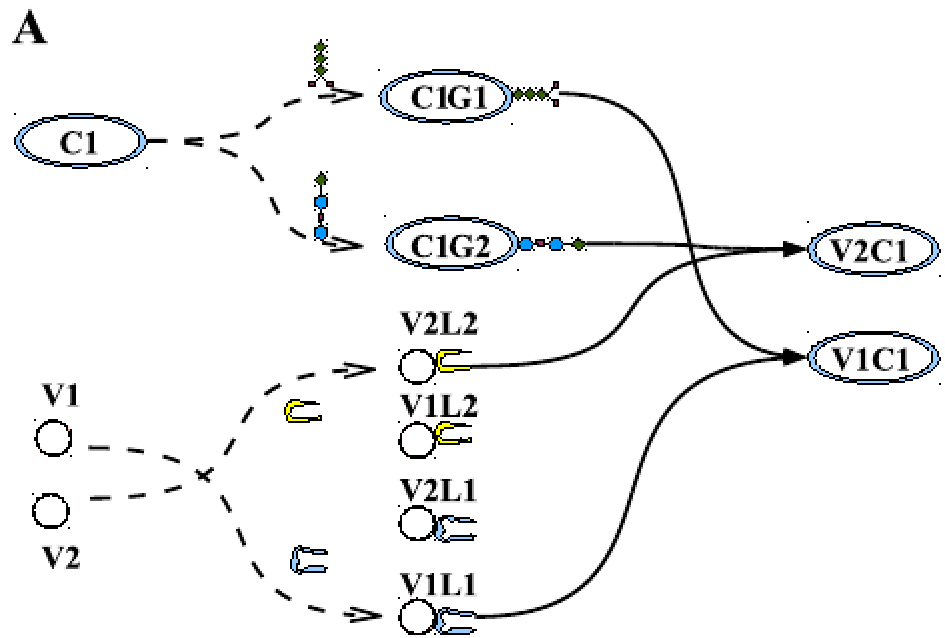
3) Pragmatics

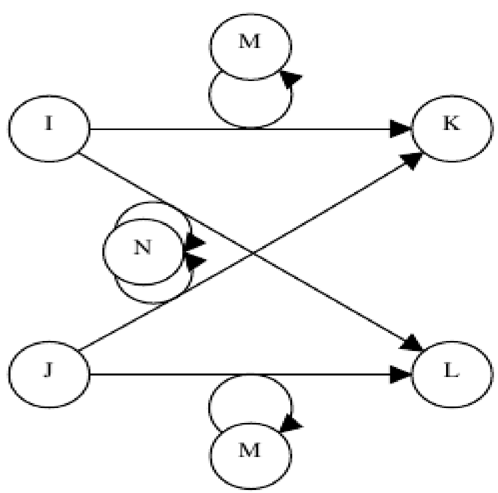
- A cellular agent, interacting with the environment through the secretion and absorption of meaning chemical substances (meaning or form elements, but no adaptors)

Part II: Coding elements as chemical species...

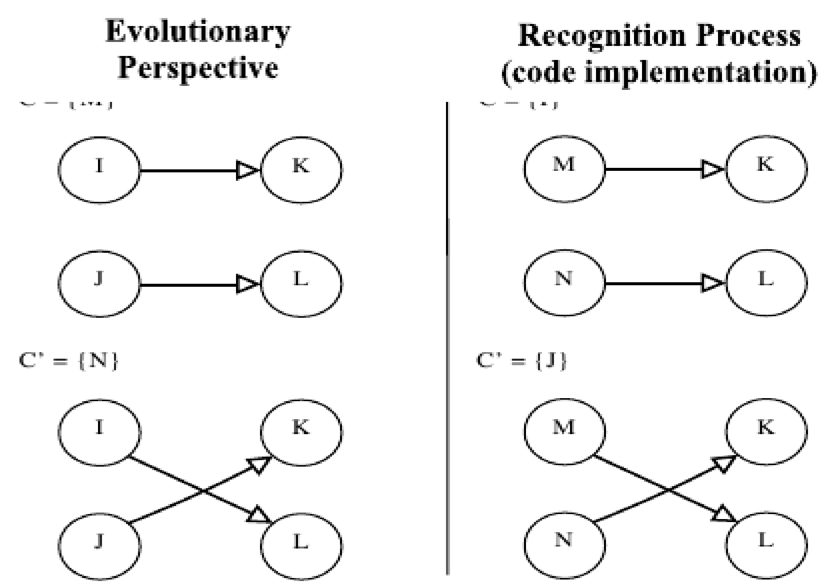


(a) Network view





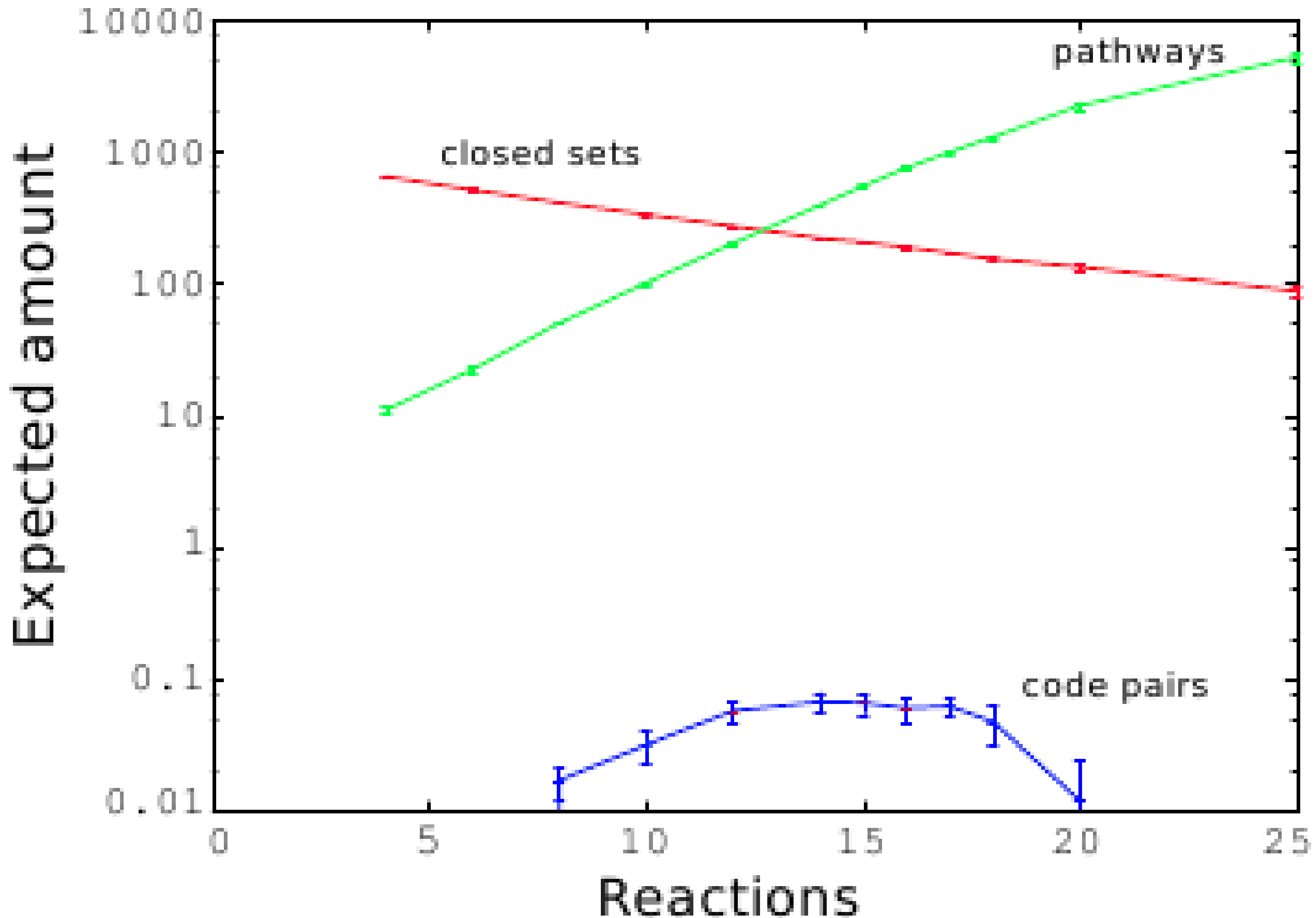
(c) Network view



(d) Code view

[Dennis Gorlich, Peter Dittrich, Stefan Artmann, 2011]

Part II: Coding elements as chemical species...



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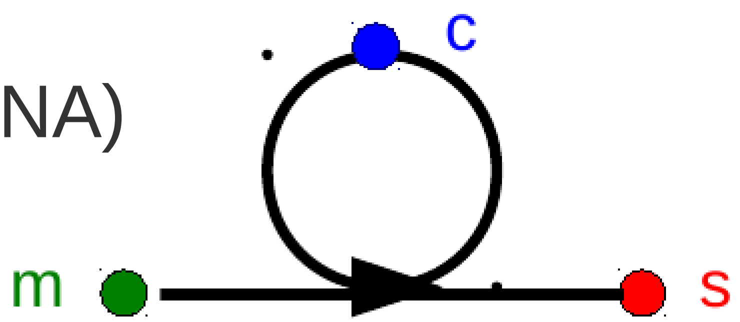

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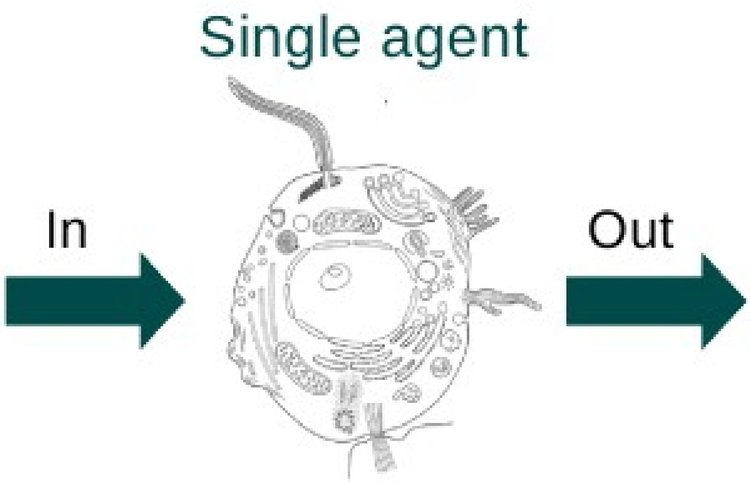
Part II: Cellular agents as chemical reactor tanks...



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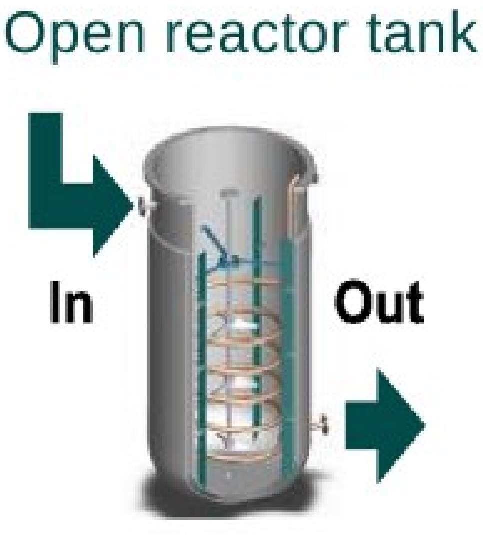


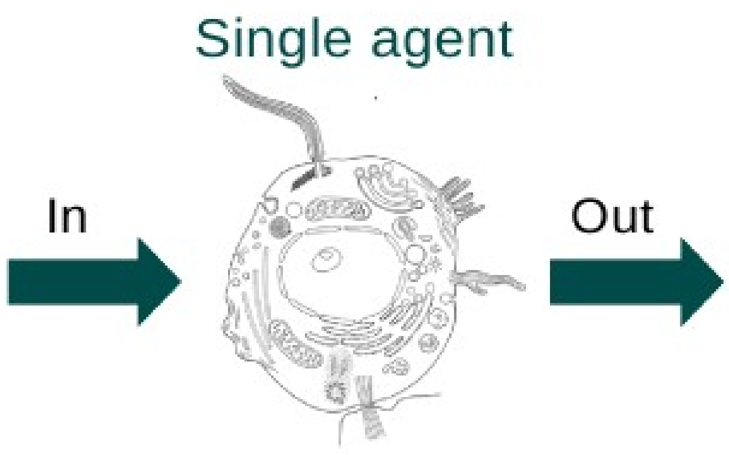
- The in and out flux to the reactor tank represent meanings and signs

- Inside the reactor tank there are also adaptor species (constructions)

- Inside the reactor, species interact according to a construction grammar encoded as an Artificial Chemistry (Dittrich et.al., 2001)

It determines how the code user learns and reacts to the influx

Part II: Cellular agents as chemical reactor tanks...



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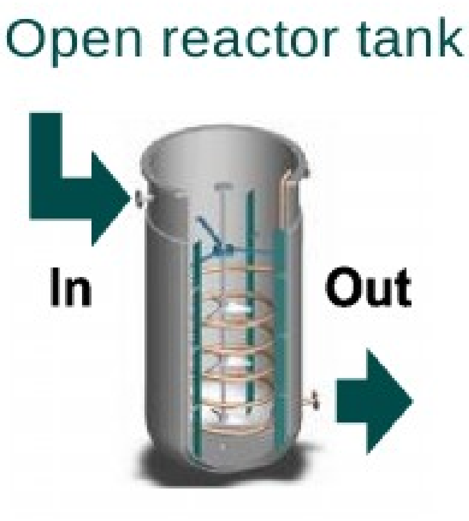


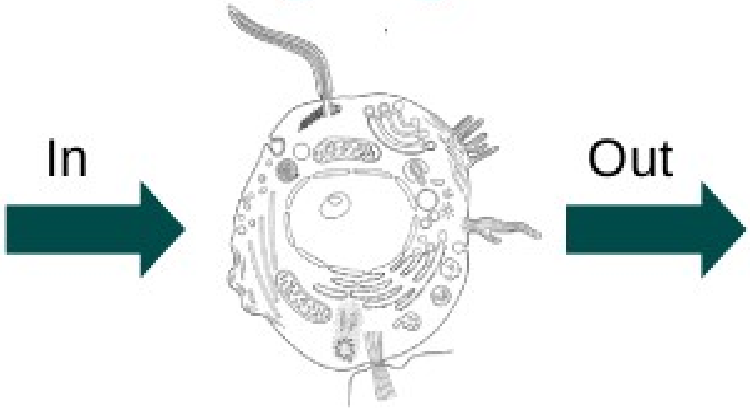
All this is not much different from modeling an agent as a software entity
Running java or lisp code in more traditional modeling...

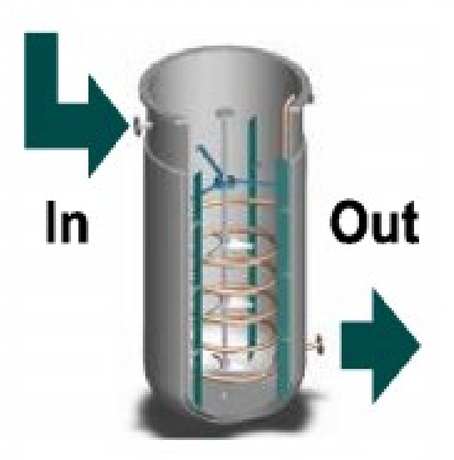
But this way, code users, and how they interact, become mathematically well defined

For example, they can be investigated with the theorems and findings of OrganizationTheory (Dittrich & di Fenizio, 2007) and of Chemical Reaction Network Theory (Feinberg, 1979)

Part II: Cellular agents as chemical reactor tanks...

Single agent ↔ Open reactor tank





$$(1)\begin{cases} \dot{m} &= \rho_m(m^0(t) - m(t)) + R_m(m(t), s(t), c(t)), \\ \dot{s} &= \rho_s(s^0(t) - s(t)) + R_s(m(t), s(t), c(t)), \\ \dot{c} &= R_c(m(t), s(t), c(t)). \end{cases}$$

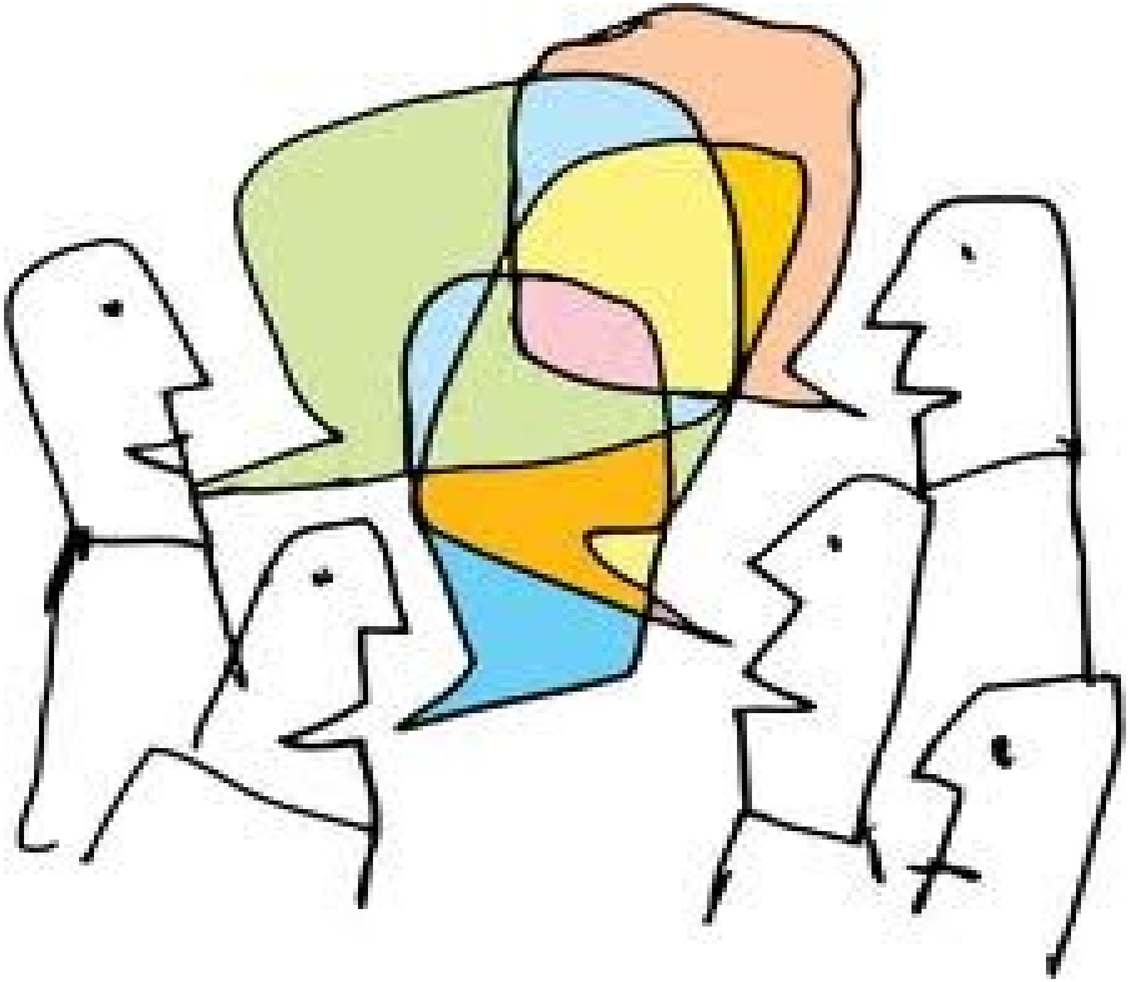
Part II: Conventionalization (De Vylder, 2007)

How can a population of locally interacting agents reach agreement (coordinate as a population), for instance about how to name a certain object?

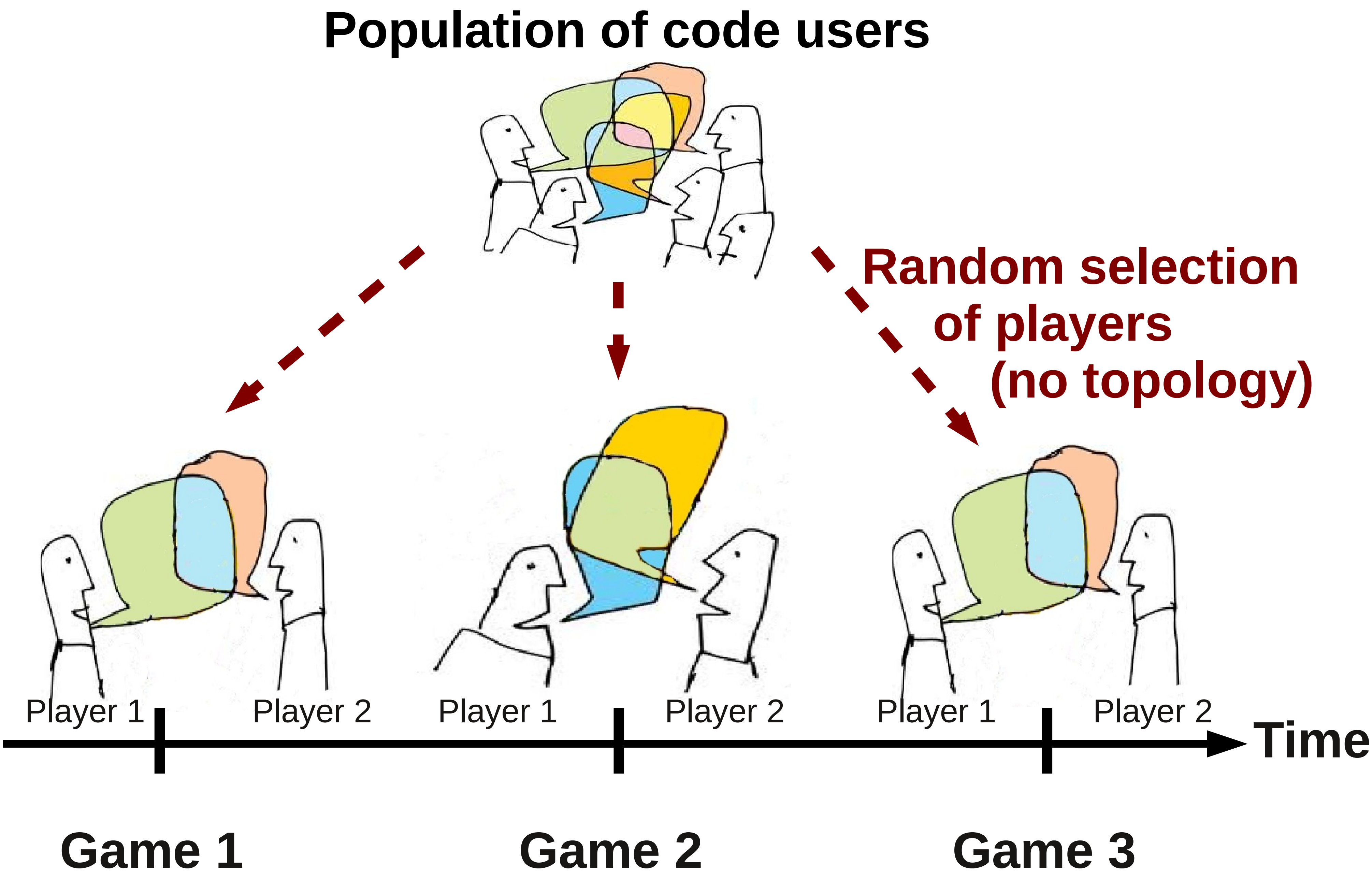
The problem of conventionalization has mostly been Investigated with multi-agent based language game experiments

[Luc Steels, 1997]

Population of code users



Part II: Language games...



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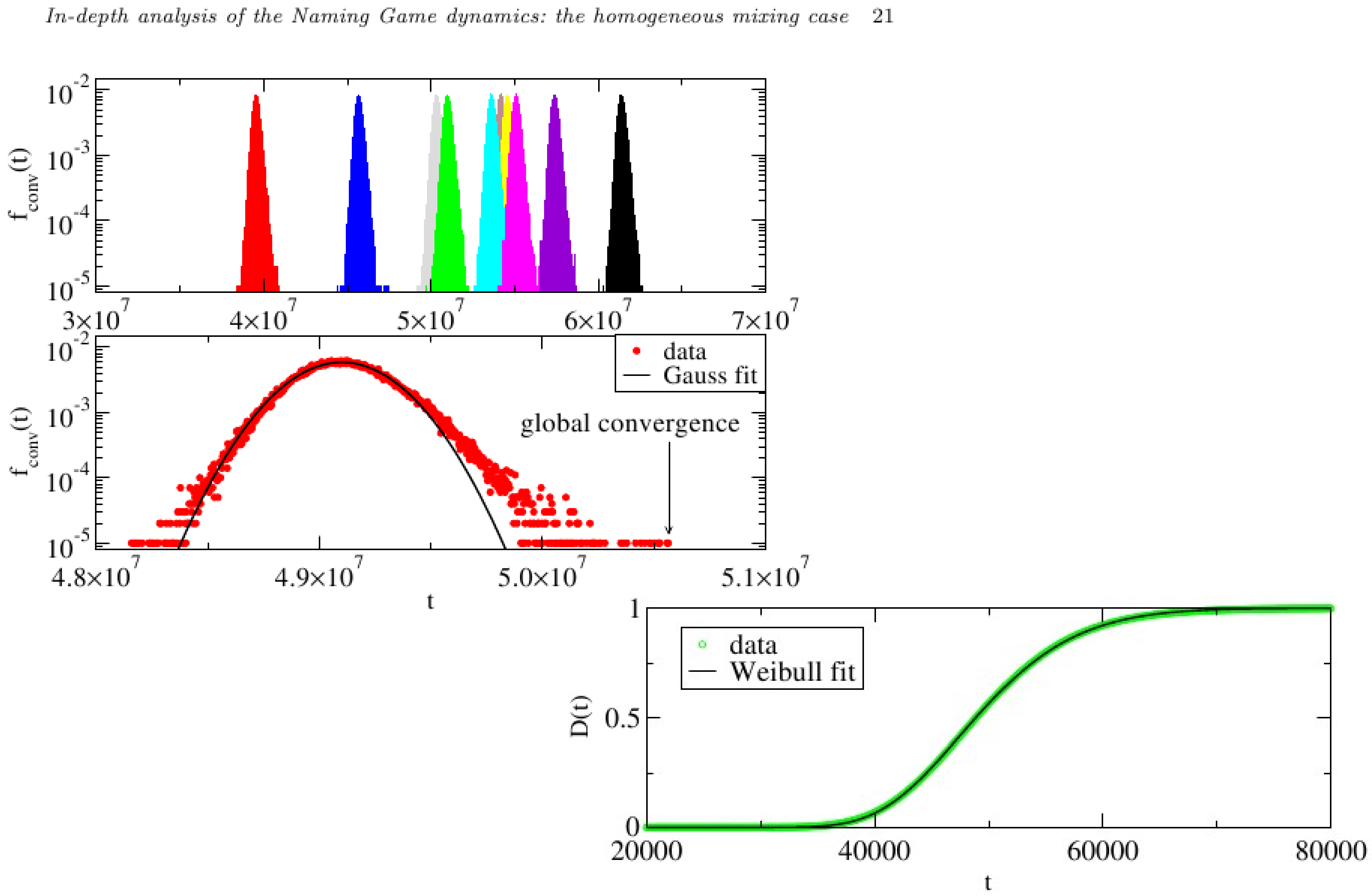
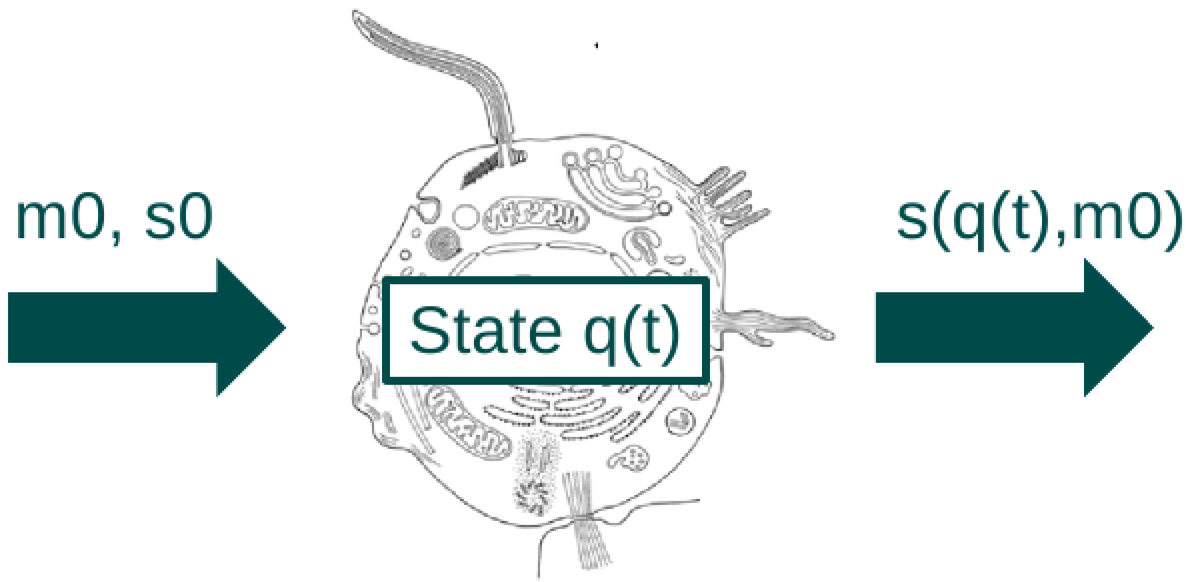


[Andfrea Baronchelli (2007) A statistical mechanics approach to language games]

Part II: Conventionalization (De Vylder, 2007)

How can a population of locally interacting agents reach agreement (coordinate as a population), for instance about how to name a certain object?



The organism randomly interacts with a population of other organisms at times $t_k = t_0 + k\Delta t$ with $k = 0, 1, \ldots$. Let the population behavior s^0 represent the average behavior of other organisms in the population in response to m^0 during interactions. Every interaction, the organism is stochastically influenced by it. In response, it will change its state according to some transition δ. If every interaction lasts a time Δt then schematically we have:

Part II: Conventionalization (De Vylder, 2007)

How can a population of locally interacting agents reach agreement (coordinate as a population), for instance about how to name a certain object?

$$s^0(t_{k+1}) = (1-\beta)s^0(t_k) + \beta s(q(t_k), m^0)$$

$$q(t_{k+1}) = \delta(q(t_k), s^0(t_k), m^0, \Delta t)$$

Part II: Conventionalization (De Vylder, 2007)

$$
\begin{aligned}
q(t_k) &= \delta(q(t_{k-1}), s^0, m^0, \Delta t) \\
&= \delta(q(t_0 + (k-1)\Delta t), s^0, m^0, \Delta t) \\
&= \delta(q(t_0), s^0, m^0, k\Delta t). \\
&\overset{k \text{ large}}{\simeq} \phi(q(t_0), s^0, m^0),
\end{aligned}
$$

with $\phi(q_0, s^0, m^0)$ the organism's *response behavior* defined as the organism's limiting behavior in response to a constant population behavior s^0 for expressing m^0:

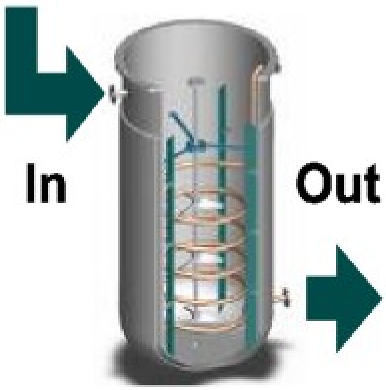
$$
\phi : \langle q_0, s^0, m^0 \rangle \mapsto \left[s(\delta(q_0, s^0, m^0, t), m^0) \right]_{t \to \infty}
$$

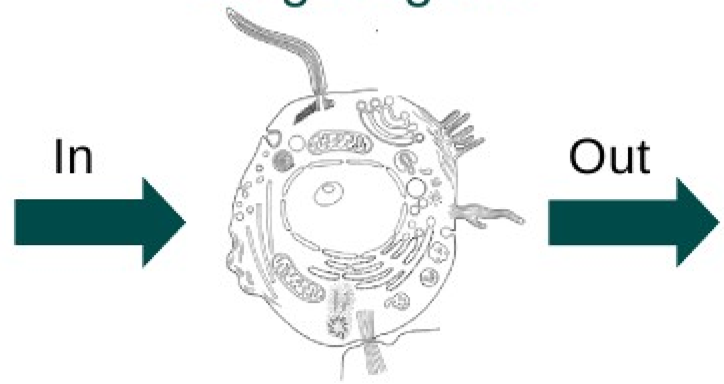
$$
\begin{aligned}
s^0(t_k + \Delta t) - s^0(t_k) &= \beta(-s^0(t_k) + s(q(t_k))) \\
&\simeq \beta(-s^0(t_k) + \phi(q_0, s^0, m^0))
\end{aligned}
$$

$$
\boxed{\frac{d}{dt} s^0 = \alpha(\phi(q_0, s^0, m^0) - s^0)}
$$

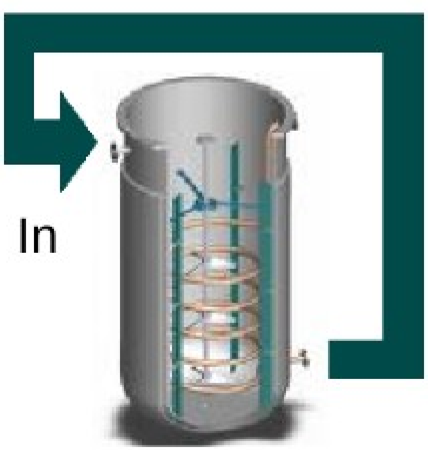
Part II: Conventionalization (De Vylder, 2007)

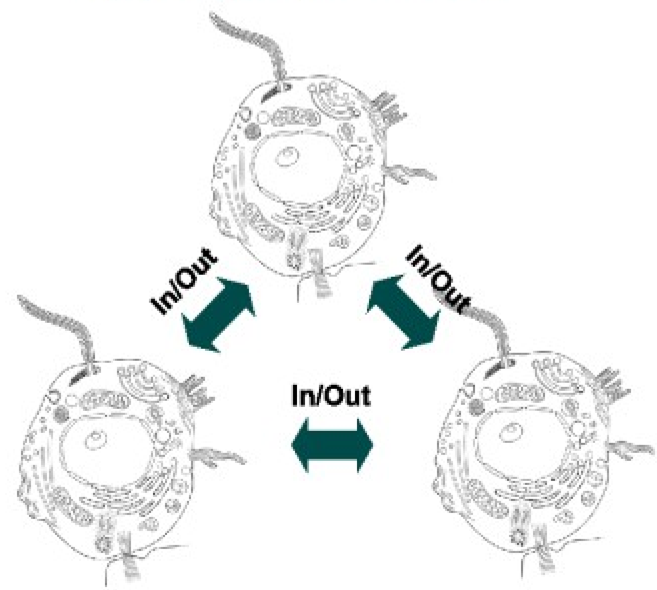
Open reactor tank ↔ Single agent





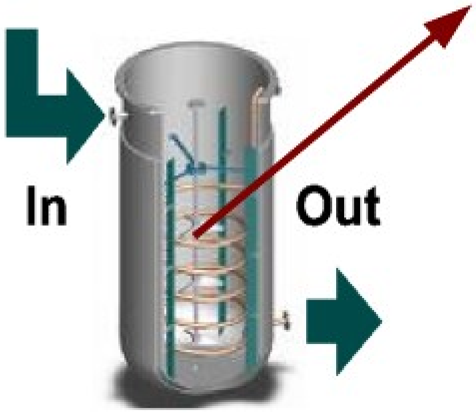
Closed reactor tank ↔ Agent population





Part II: Conventionalization (De Vylder, 2007)

Open reactor tank



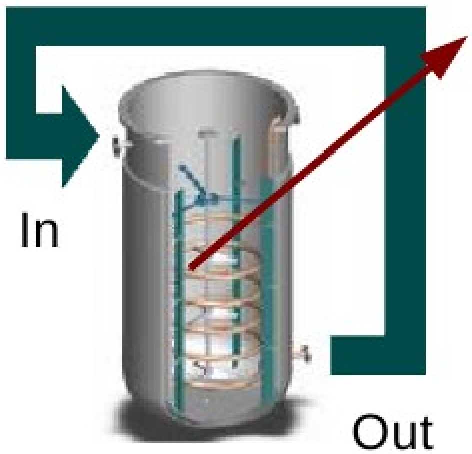
Artificial Chemistry

↓

Differential Equations

$$(1)\begin{cases} \dot{m} = \rho_m(m^0(t) - m(t)) + R_m(m(t), s(t), c(t)), \\ \dot{s} = \rho_s(s^0(t) - s(t)) + R_s(m(t), s(t), c(t)), \\ \dot{c} = R_c(m(t), s(t), c(t)). \end{cases}$$

Closed reactor tank



Artificial Chemistry

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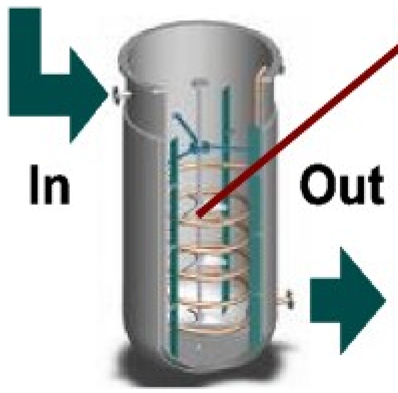
Differential Equations

$(1) + \rho_m = \rho_s = 0$

Part II: Conventionalization (De Vylder, 2007)

Open reactor tank



Artificial Chemistry

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Differential Equations

The stationary states for a certain influx or population behavior correspond to the response behaviors of the agent

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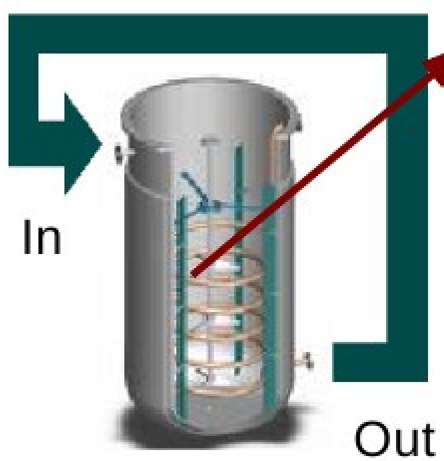
Closed reactor tank



Artificial Chemistry

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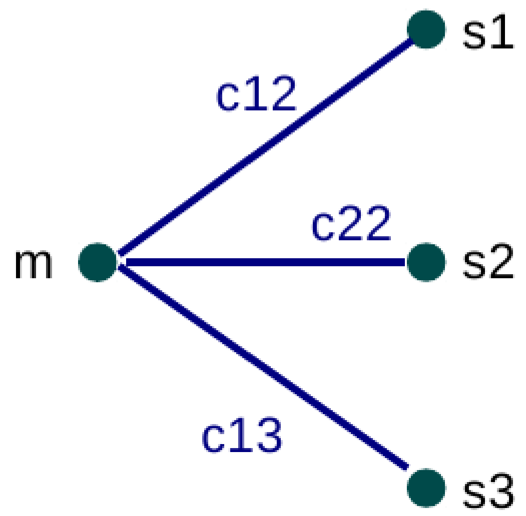
Differential Equations

The stationary states for zero influx determine the population behaviors

Part II: The Naming Game (Steels 1997, Baronchelli 2008)

Species:



Artificial Chemistry:

$m + cj \rightarrow sj$

+

K1 K2

$si + cj \rightarrow si + ci$ Or $si + cj \rightarrow sj + cj$

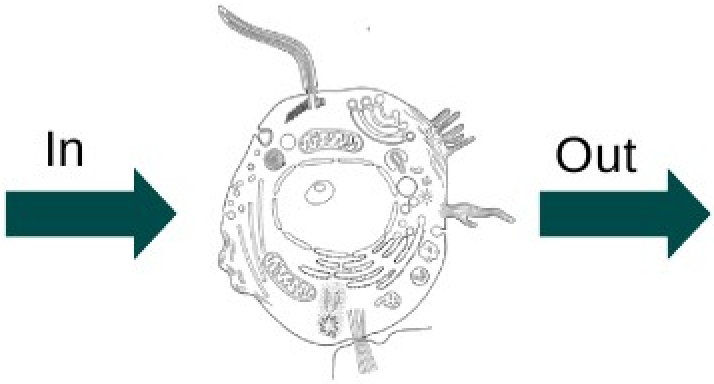
(De Beule “Introducing dynamics into the field of Biosemiotics”, Biosemiotics, 2010)

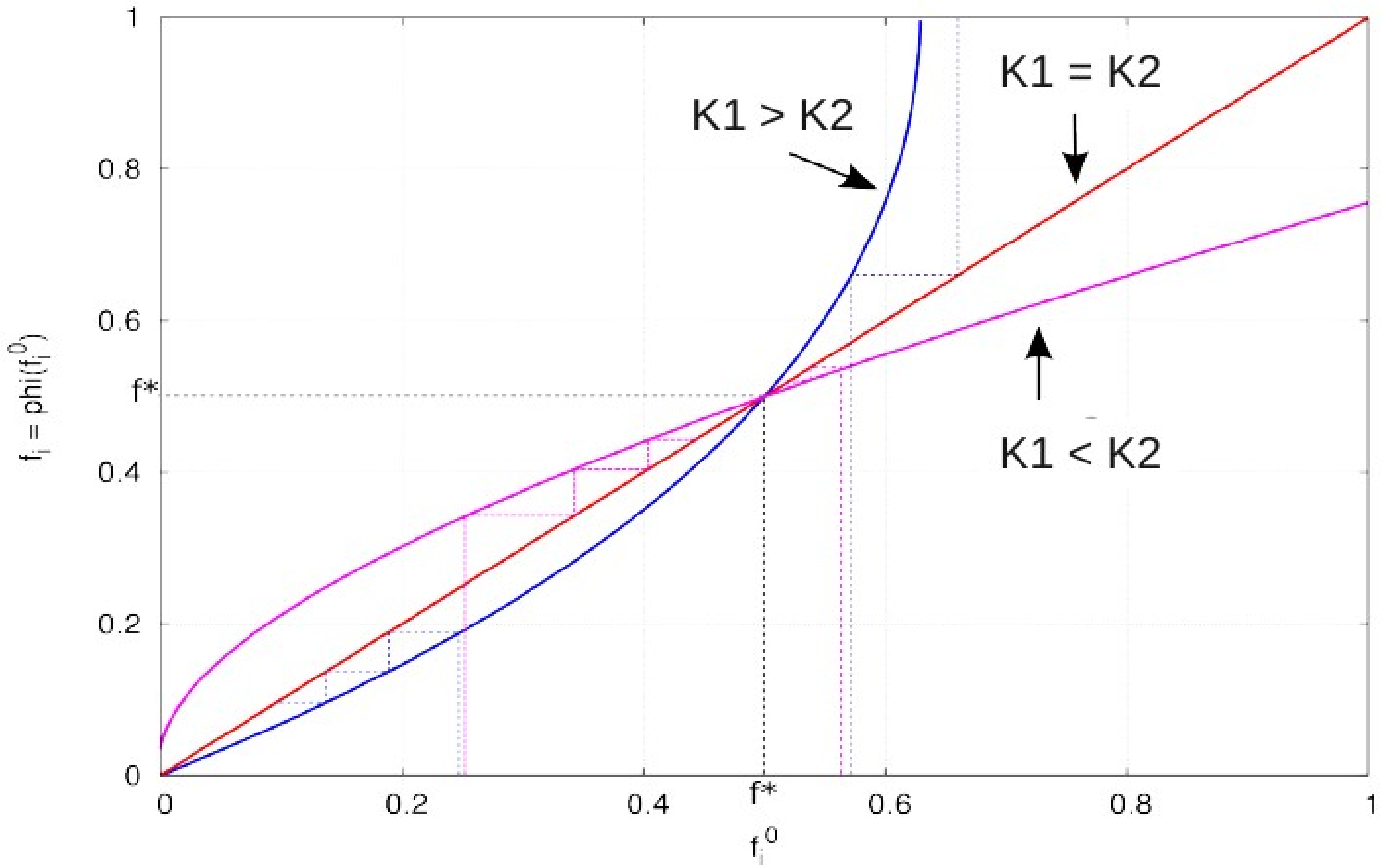
Part II: The Naming Game (Steels 1997, Baronchelli 2008)

Differential equations:

$$\begin{aligned}
\dot{s}_j &= \rho_s(s_j^0 - s_j) + m^0((1+s_j)c_j - s_j) \\
&\quad -m^0\kappa_1(s_j\sigma_c - c_j\sigma_s) \\
\dot{c}_j &= -m^0((1+s_j)c_i - s_j) \\
&\quad +m^0\kappa_2(s_j\sigma_c - c_j\sigma_s),
\end{aligned}$$

Part II: Response Analysis (single agent)

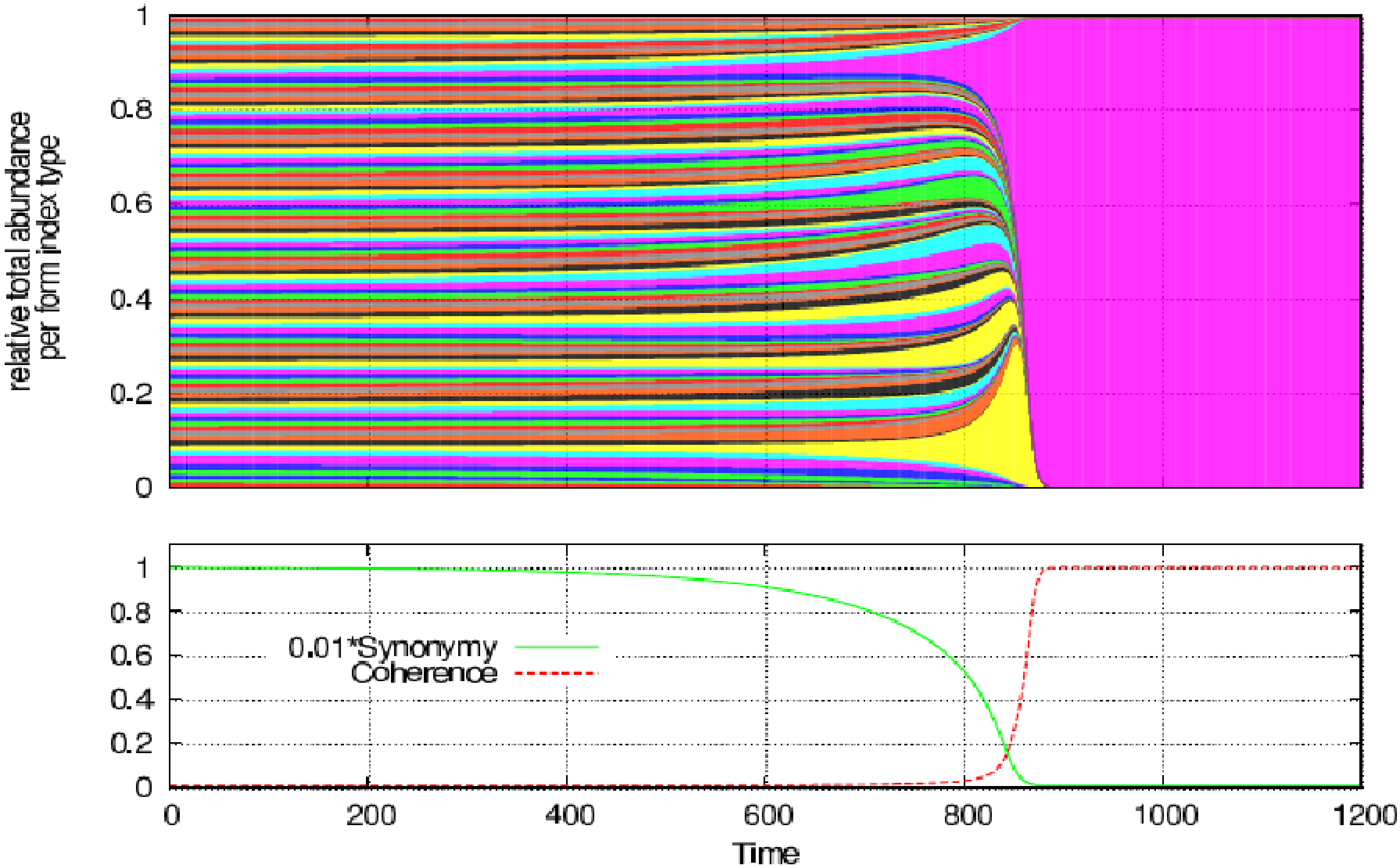




Part II: Response Analysis (population)

$$\mathrm{Coh(t)} = \frac{1}{(\sigma_c)^2} \sum_{i=1} (c_i(t))^2.$$

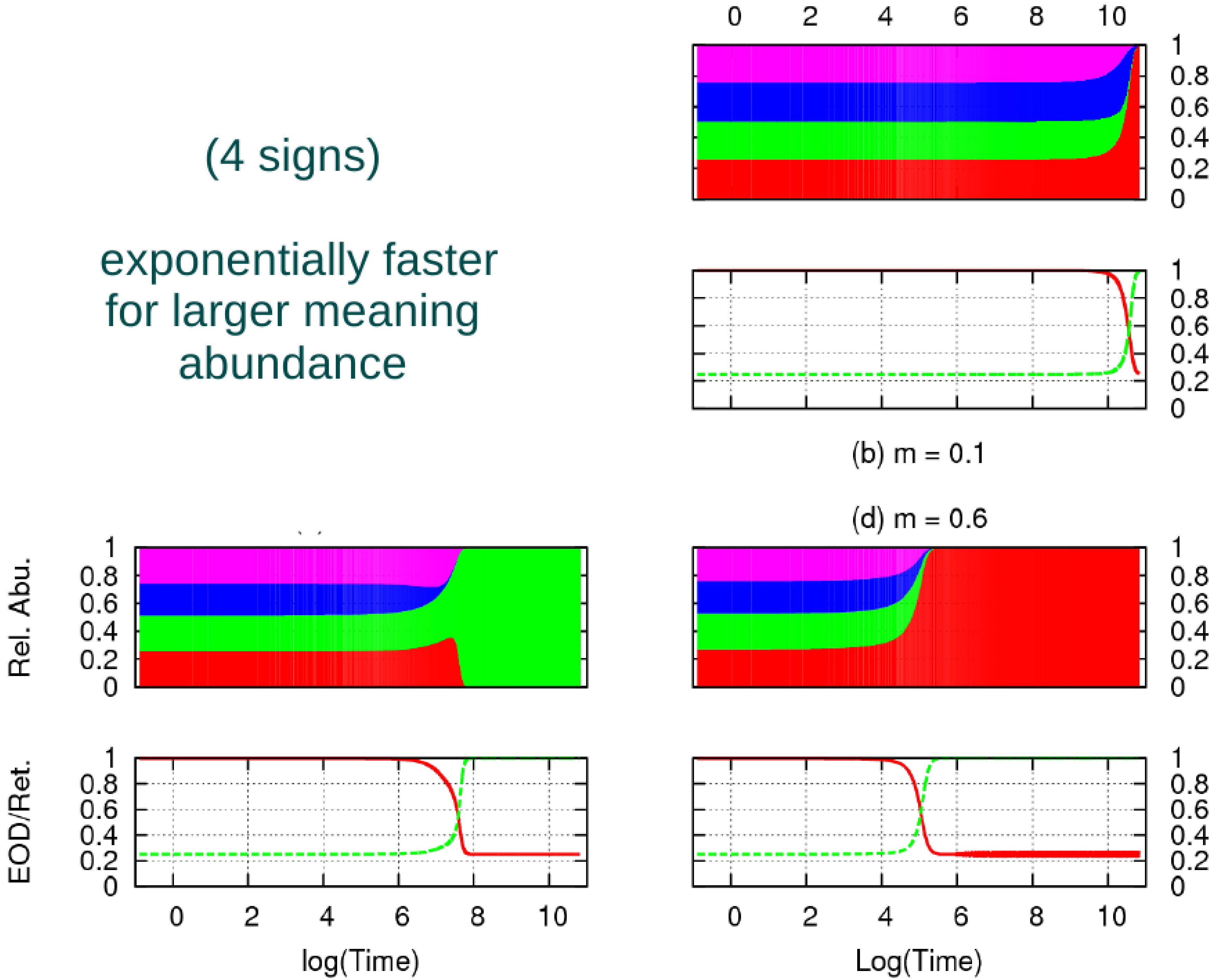
$$\mathrm{Red(t)} = \frac{1}{\sigma_c} \exp\left(-\frac{1}{\sigma_c} \sum_{i=1}^{n_s} c_i(t) \log(c_i(t)) \right)$$



Part II: The Naming Game

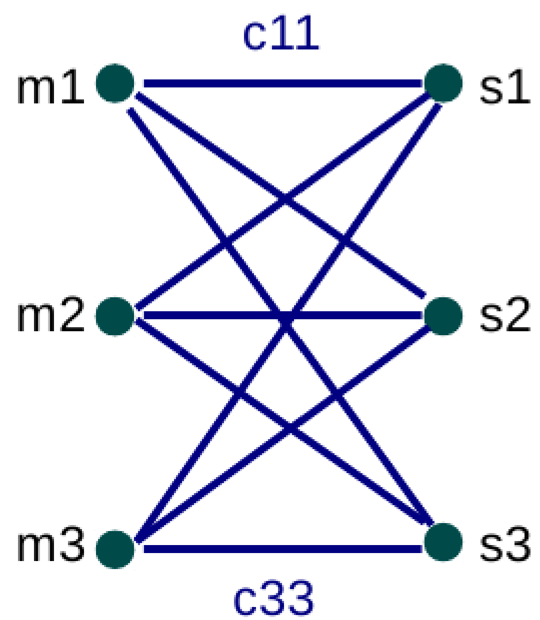
(4 signs)

exponentially faster for larger meaning abundance

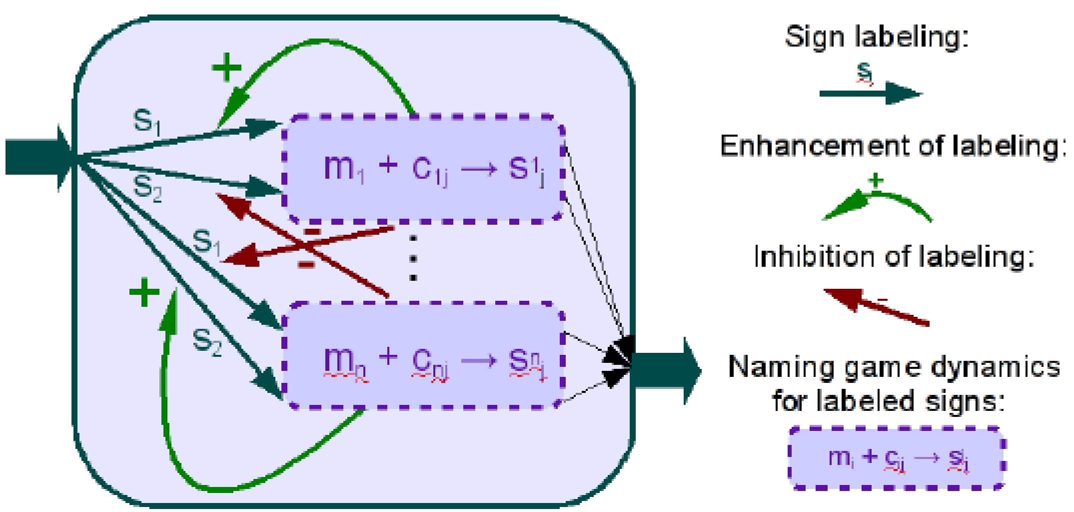


Part II: The Guessing Game

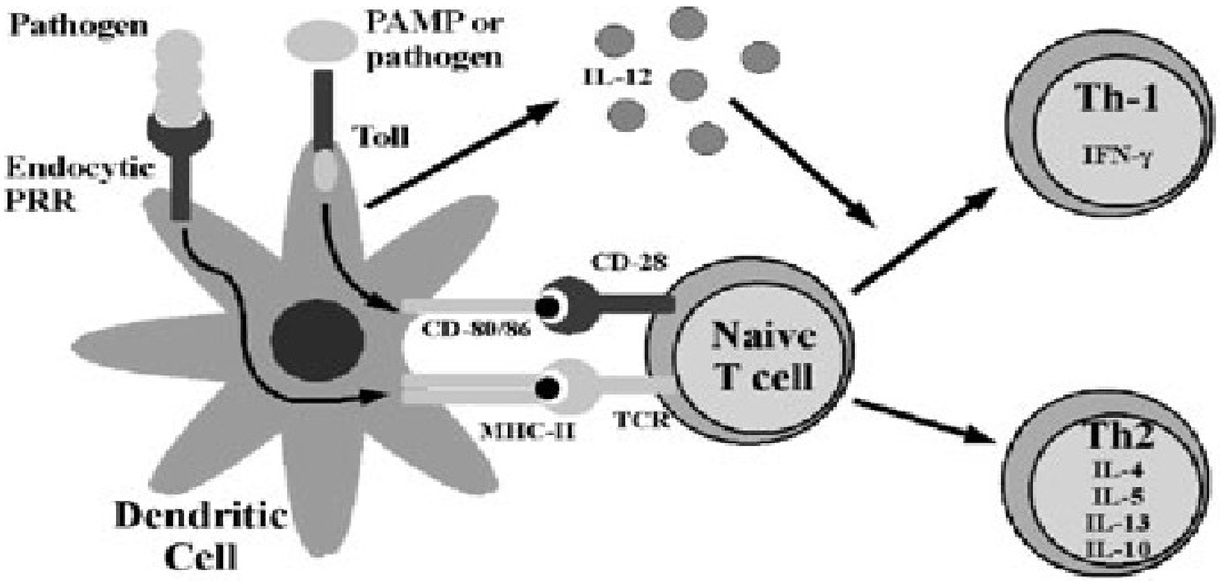
Species:

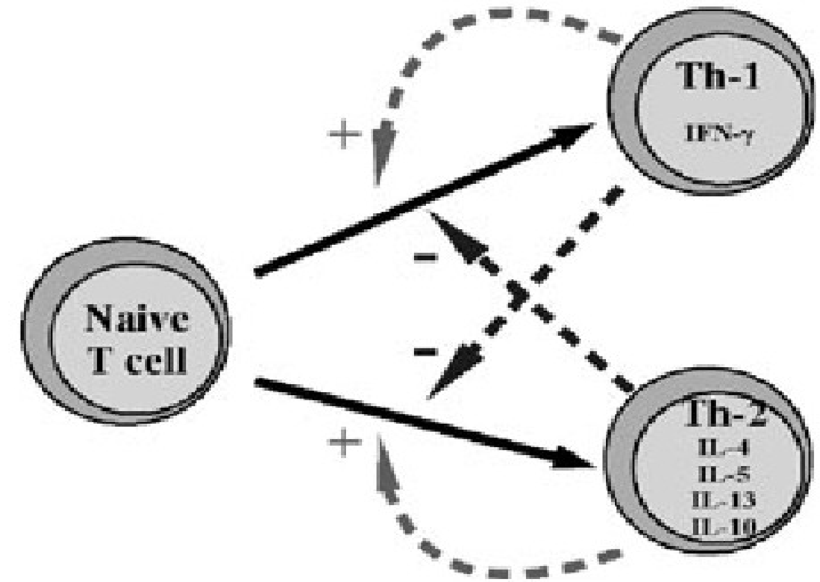


Artificial Chemistry:



Part II: Immune System Regulation





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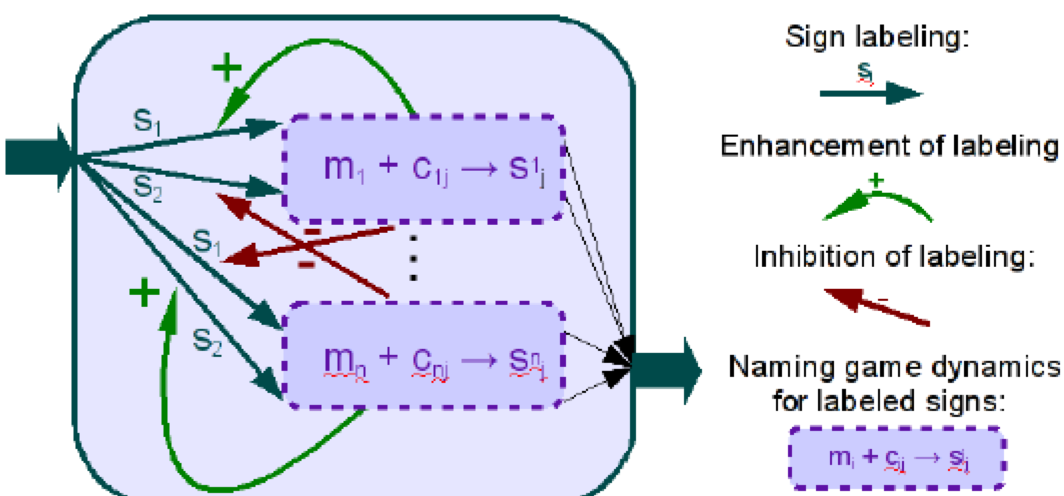
Artificial Chemistry:



Part II: The Guessing Game

Differential equations:

$$\dot{s}_j = +\rho_s(s_j^0 - s_j) + k_r \sum_{i=1}^{N_m} m_i^0 \sum_{j' \neq j} (s_{j'} c_{ij} - s_j c_{ij'})$$

$$- \rho_l \sum_{i=1}^{N_m} \left(m_i^0 (\epsilon_1 + c_{ij}) \Big(\sum_{i' \neq i} \frac{\epsilon_2}{\epsilon_2 + c_{i'j}} \Big) s_j - s_j^i \right)^3,$$

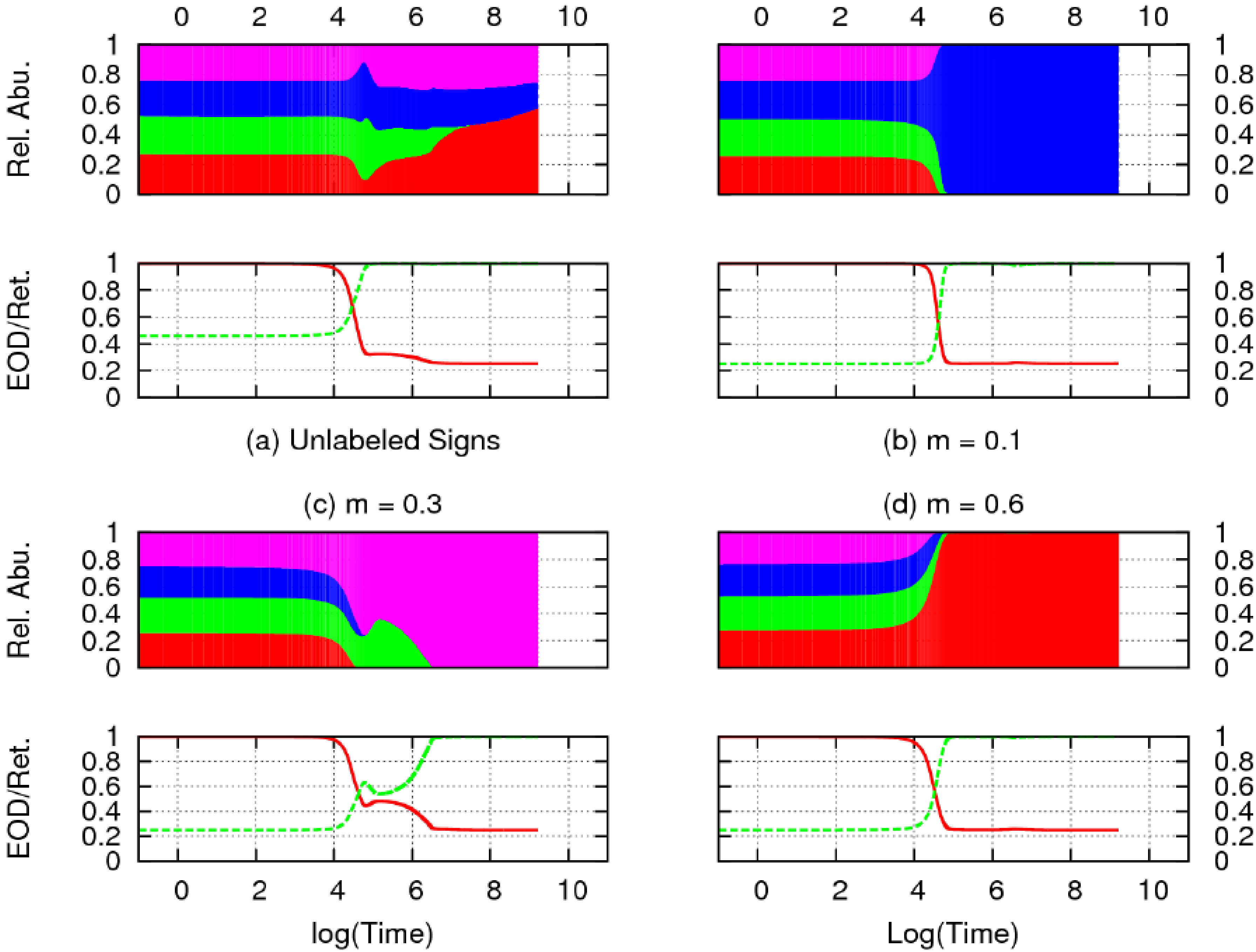
$$\dot{s}_j^i = +\rho_l \left(m_i^0 (\epsilon_1 + c_{ij}) \Big(\sum_{i' \neq i} \frac{\epsilon_2}{\epsilon_2 + c_{i'j}} \Big) s_j - s_j^i \right)^3,$$

$$+ m_i^0 ((1 + s_j^i) c_{ij} - s_j^i)$$

$$\dot{c}_{ij} = -m_i^0 ((1 + s_j^i) c_{ij} - s_j^i) + m_i^0 \kappa_2 (s_j \sigma_c^i - c_j \sigma_s^i)$$

Movie...

Part II: The Guessing Game



– Part III –

Part III: And beyond...

Naming game (for example, a name for a person, e.g. "Jo")

1 meaning, N_s signs → 1 meaning, 1 sign

IOC/Guessing game ("Jo", "Mary", ...)

N_m meanings, $N_s > N_m$ signs → N_m meanings, N_m signs

Compositionality ("big Jo", "big Mary", "small Jo", ...)

structured meanings and signs → Conventional Compositional encoding

Grammar ("Mary kicks Jo", "Jo kicks Mary", ...)

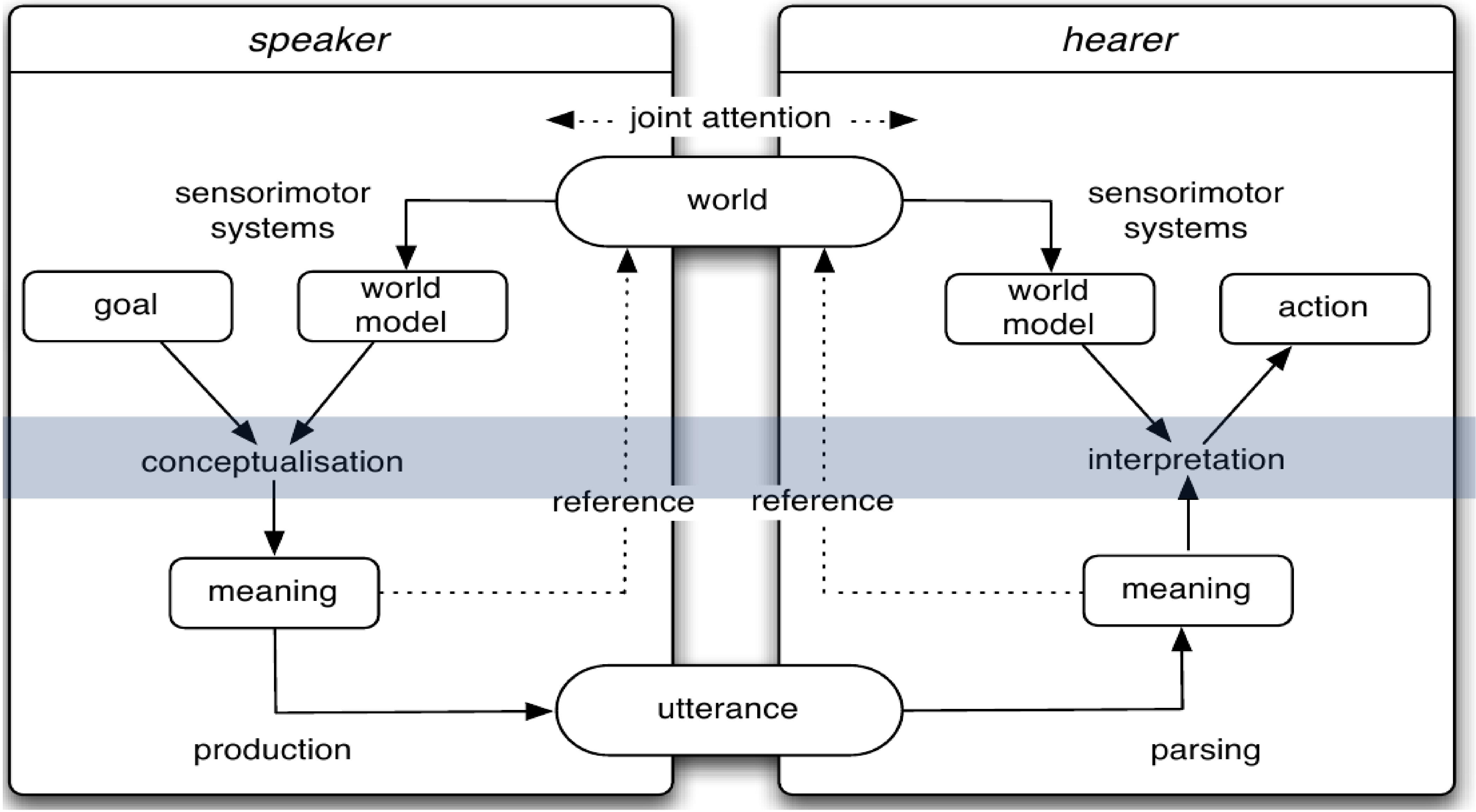
structured meanings and signs → Conventional Grammatical encoding

Levels of complexity and expressiveness through re-use

Hypothesis:
The solution to each next level will contain the mechanisms taking care of the previous

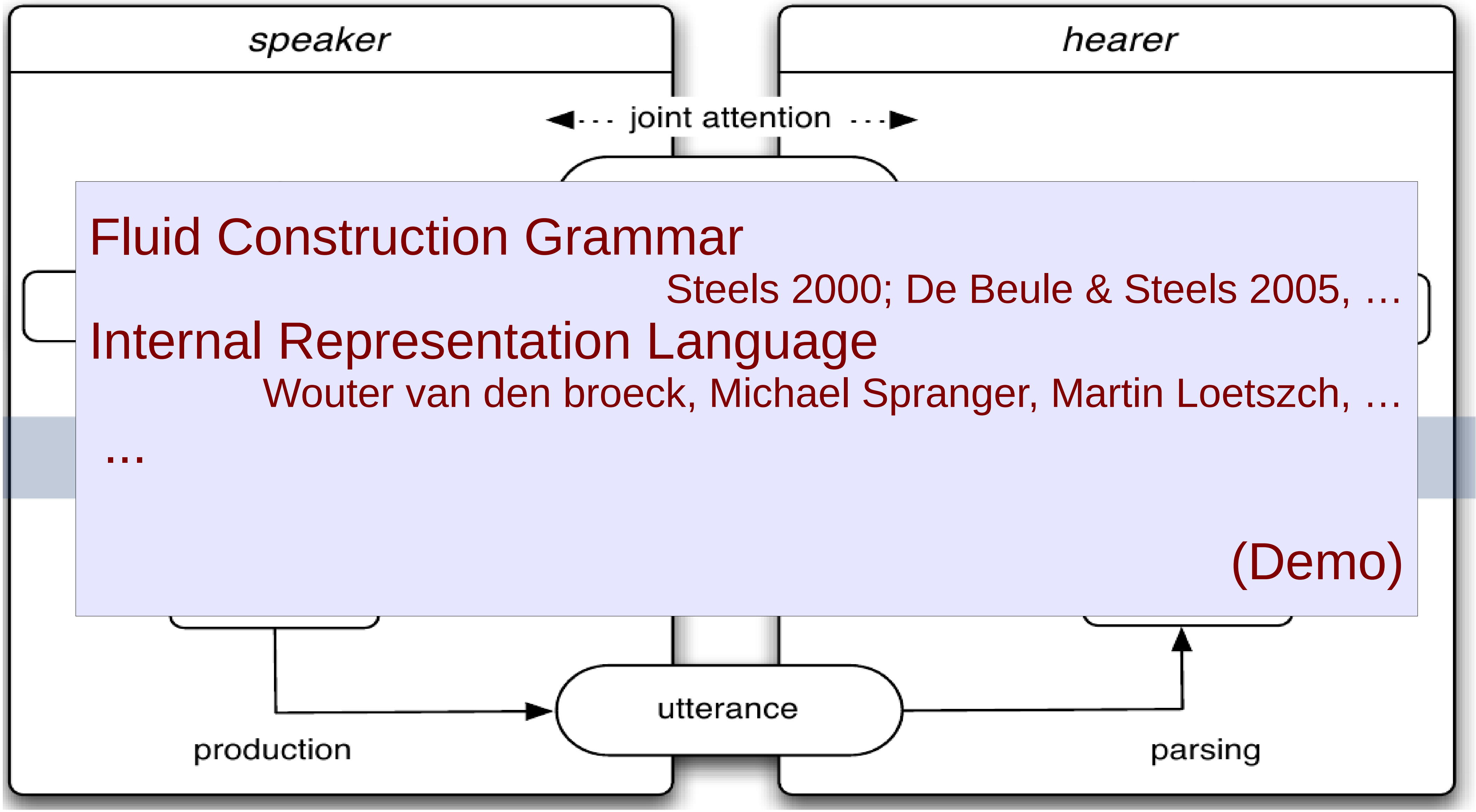
Part III: And beyond...

Whole Systems Approach



Part III: Robotics...

Whole Systems Approach



Fluid Construction Grammar

Steels 2000; De Beule & Steels 2005, …

Internal Representation Language

Wouter van den broeck, Michael Spranger, Martin Loetszch, …

...

(Demo)

Two main views on word learning

- Word learning as **mapping**
  - Enumerate list of plausible candidates and prune given new exposure
  - (Initial list is too great, thus word learning constraints are required)
  - Bloom, Siskind, Gleitman, Markman, most cross-situational models, ...
- Word learning as **shaping**
  - No enumeration but instead start from uncertain (fuzzy) first guess and shape on new exposures
  - (Initial hypotheses can be shaped by constraints but less mandatory)
  - Bowerman, Choi, Tomasello, Gentner, ...

Part III: Empirical data...

Demos...

The end...

Thank you!