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Artificial Chemistries

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Abstract

An artificial chemistry is, in a broad sense, a man-made system which is similar to a chemical system. More precisely – but not covering every type – an artificial chemistry can be defined by a set of objects and a set of reaction rules which specify how the objects interact. The tutorial focuses on abstract artificial chemistries where there is no direct one-to-one relationship between artificial and real chemistry on the molecular/object and reaction/interaction level. In the first part the tutorial gives an introduction to the concept of artificial chemistries discussing two examples: a non-constructive and a constructive artificial chemistry. In the second part the tutorial will review current research activities along the following three application domains: modeling, information processing and optimization.

Artificial Chemistry Webpage:
http://ls11-www.cs.uni-dortmund.de/achem

What is an Artificial Chemistry ? (I)

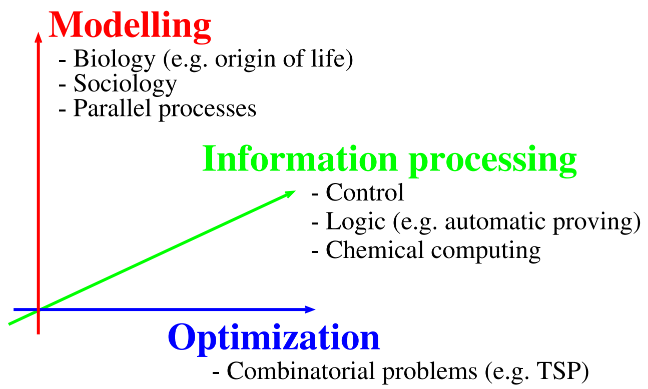
An Artificial Chemistry consists of

1. a set of objects (called molecules),
2. a set of interaction rules (called collision or reaction rules), and
3. a definition of the population dynamics.

What is an Artificial Chemistry ? (II)

1. **Objects**
   abstract symbols, numbers, lambda-expressions, binary strings, proofs, character sequences, abstract data structures, etc.
2. **Reaction rules**
   string matching, string concatenation, lambda-calculus, abstract finite-state machines, Turing machines, matrix multiplication, simple arithmetic operation, cellular automata, boolean networks, electronic hardware, etc.
3. **Dynamics**
   ordinary differential equation (ODE), difference equation, meta-dynamics, explicit collision simulation, cellular automaton, well-stirred reactor, 3-D Euclidean space, self-organizing topology, etc.

Motivation (I)



Example A: A Constructive Number-Devision Chemistry

1. **Objects**
   abstract symbols, numbers, lambda-expressions, binary strings, proofs, character sequences, abstract data structures, etc.

2. **Reaction rules**
   string matching, string concatenation, lambda-calculus, abstract finite-state machines, Turing machines, matrix multiplication, simple arithmetic operation, cellular automata, boolean networks, electronic hardware, etc.

3. **Dynamics**
   ordinary differential equation (ODE), difference equation, meta-dynamics, explicit collision simulation, cellular automaton, well-stirred reactor, 3-D Euclidean space, self-organizing topology, etc.

Example A: Objects and Reaction Rules

1. **Objects**

$$S = \{2, 3, \ldots\}$$

2. **Reaction rules**

$$s_1 + s_2 \longrightarrow s_1 + s_3 \quad \text{with} \quad s_3 = \begin{cases} s_2/s_1 & \text{if} \quad s_2 \mod s_1 = 0 \\ s_2 & \text{otherwise} \end{cases}$$

3. **Dynamics**
   (next slide)

Example A : Population Dynamics

Population:
$P[1], P[2], \ldots, P[M]$

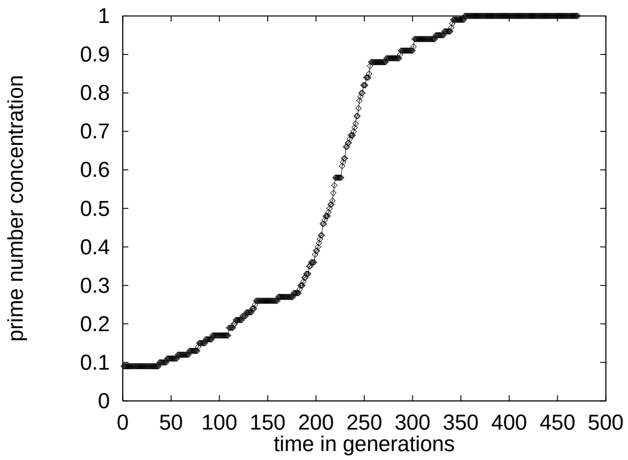
Reaction scheme:

$$s_1 + s_2 \longrightarrow s_1 + s_3$$

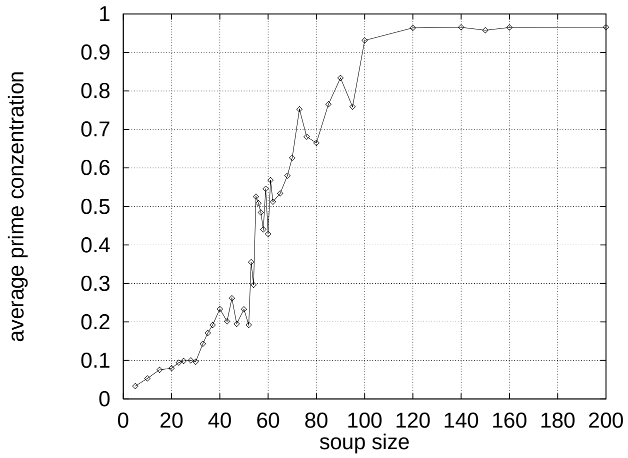
```
while ¬terminate() do
    i1 := randomInteger(1, M);
    s1 := P[i1];
    i2 := randomInteger(1, M);
    s2 := P[i2];
    s3 := reaction(s1, s2)
    if s3 ≠ 0 then
            P[i2] := s3;
    fi
od
```

[Ehrenfest and Ehrenfest, 1907]

Example A: Behavior of a Single Run



Example A: Dependence on Population Size



Example B: A Non-Constructive System

Motivation for the example:

- Demonstrate different methods to simulate dynamics
- Terminology / Classification
  1. Constructive vs. non-constructive
  2. Explicit vs. implicit
  3. Analogous vs. abstract models

Example B: Objects and Reaction Rules

1. **Objects**

$$S = \{1, 2\}$$

2. **Reaction rules**

$$\begin{array}{rcl} 1+1+X & \longrightarrow & 1+1+2 \\ 1+2+X & \longrightarrow & 1+2+2 \\ 2+1+X & \longrightarrow & 2+1+2 \\ 2+2+X & \longrightarrow & 2+2+1 \end{array} \quad \text{or shortly} \quad \begin{array}{rcl} 1+1 & \Longrightarrow & 2 \\ 1+2 & \Longrightarrow & 2 \\ 2+1 & \Longrightarrow & 2 \\ 2+2 & \Longrightarrow & 1 \end{array}$$

3. **Dynamics**
   (next slide)

Example B: Population Dynamics

Population:
$P[1], P[2], \ldots, P[M]$

Reaction scheme:

$s_1 + s_2 + X \longrightarrow s_1 + s_2 + s_3$

while $\neg terminate()$ **do**
    $i_1 := randomInteger(1, M)$;
    $s_1 := P[i_1]$;
    $i_2 := randomInteger(1, M)$;
    $s_2 := P[i2]$;
    $s_3 := reaction(s_1, s_2)$
    if $s_3 \neq 0$ **then**
        $P[randomInteger(1, M)] := s_3$;
    fi
od

or shorter

while $\neg terminate()$ **do**
    $P[randomInteger(1, M)] :=$
        $reaction(P[randomInteger(1, M)], P[randomInteger(1, M)])$;
od

Example B: Ordinary Differential Equation Model

Given: $1+1 \Longrightarrow 2 \quad 1+2 \Longrightarrow 2$
$\qquad\quad 2+1 \Longrightarrow 2 \quad 2+2 \Longrightarrow 1$

	1	2
1	2	2
2	2	1

reaction table

x_1 : concentration of 1
x_2 : concentration of 2 $\qquad x_1 + x_2 = 1, \quad s_1 \geq 0, \quad s_2 \geq 0$

$$\frac{dx_1}{dt} = x_2 x_2 - x_1 \Phi(t)$$
$$\frac{dx_2}{dt} = x_1 x_1 + 2 x_1 x_2 - x_2 \Phi(t) \qquad \text{with} \quad \Phi(t) = (x_1 + x_2)^2$$

$\Phi(t)$: dilution flux $\qquad$ here $\Phi(t) = 1$

Example B: Catalytic Network Equation

[Stadler et al., 1993]

Given reactions of the form: $\quad i + j \overset{\alpha_{ij}^k}{\Longrightarrow} k$

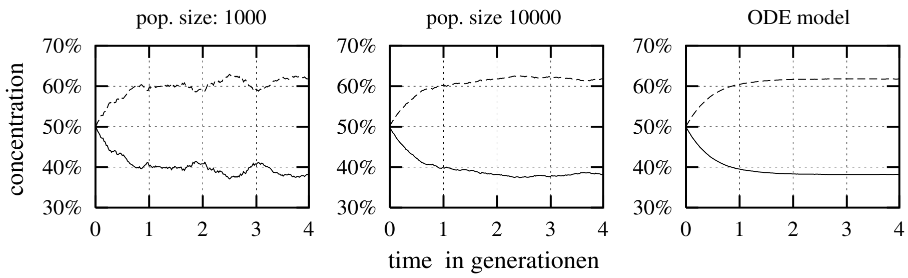
$$\boxed{\frac{dx_k}{dt} = \sum_{i=1}^{n} \sum_{j=1}^{n} \alpha_{ij}^k x_i x_j - x_k \Phi(t), \qquad k = 1, \ldots, n}$$

$$\Phi(t) = \sum_{i,j,k=1}^{n} \alpha_{ij}^k x_i x_j$$

$$\alpha_{ij}^k = \begin{cases} 1 & \text{if } i + j \Longrightarrow k \text{ exists} \\ 0 & \text{otherwise} \end{cases}$$

see also [Hofbauer and Sigmund, 1988, Banzhaf, 1993]

Example B: Comparison: Explicit Collisions vs. ODE Model



Constructive Dynamical System

[Fontana, 1992, Fontana et al., 1994]

- New components can appear.
- Dynamics of the system may change.
- Components are not given explicitly at the beginning.
- Weakly constructive: New components are generated randomly.
- Strongly constructive: New components are generated through action of other components.

Explicit or Implicit Populations (I)

Explicit population

e.g. as an array $P[]$:

$P[1] = 1$
$P[2] = 1$
$P[3] = 2$
$P[4] = 2$
$P[5] = 1$

Implicit population

e.g. as an array $N[]$:

$N[1] = 3$
$N[2] = 2$

Explicit or Implicit Populations (II)

Explicit population

+ concentration proportional selection: $O(1)$
- concentration of type i: $O(M)$
+ finite populations with high diversity
+ easy to implement
+ flexible (e.g. space)
+ easy to distribute on a parallel machine

Implicit population

- concentration proportional selection $O(\log(M))$
+ concentration of type i: $O(\log(M))$
+ large/infinite populations with low diversity
+ memory efficient
+ easy monitoring

Methods for Dynamical Simulation - Overview

1. **Stochastic molecular collisions**
   e.g. [Fontana and Buss, 1996]
2. **Continuous differential or discrete difference equations**
   e.g. [Segr and Lancet, 1998, Banzhaf, 1994]
3. **Metadynamics**
   e.g. [Bagley and Farmer, 1992]
4. **Mixed approaches**
   e.g. [Zauner and Conrad, 1998]
5. **Symbolic analysis of the equations**
   e.g. [Farmer et al., 1986]

Explicit vs. Implicit Definition of Molecules and Rules

- Implicit definition of molecules: description how to construct molecules.
  e.g. $S = \{0, 1\}^*$ (binary strings)
- Resulting representation of the molecule is called structure.
  e.g. 110001001 or 110110
- An implicit definition of reaction rules refers to the structure of a molecule.
  e.g. $s_1 + s_2 \Longrightarrow s_3$, with $s_3 = s_1 \wedge s_2$ (AND-reaction)
- Note: Explicit definitions on one level may lead to implicit molecules and reactions rules on a higher level, e.g. [Mayer and Rasmussen, 1998]

Level of Abstraction: Analogous vs. Abstract

1. **Analogous model or analogous AC**

   - There is a relation of each molecules/reaction of the AC to a molecule/reaction in real chemistry.
   - e.g. DNA computing models

2. **Abstract model or abstract AC**

   - No relation to real chemistry on molecular/reaction level.
   - Similarity on macroscopic level.
   - e.g. Number-division chemistry (Example A).

Measuring Time

- Time should be measured by "number of collisions" relative to the population size.
- Here,

$$1\ \text{generation} = \frac{\text{number of collisions}}{\text{population size } M}$$

- Assumption: constant temperature, equal velocity distribution, equal molecular size, well-stirred homogeneous reactor. Thus, collision rate constant.

Part II: Methods for Structure-Function Mapping

1. Rewriting or production systems
2. String operations
3. Abstract automata
4. Arithmetic operations
5. Core-Wars-like systems or assembler automata
6. Lattice molecular systems
7. Others

Rewriting or Production Systems - Overview

1. **Lambda-Calculus**
   [Fontana, 1992, Fontana and Buss, 1996]
2. **Chemical Abstract Machine (CHAM)**
   [Berry and Boudol, 1992]
3. **Chemical Rewriting System on Multisets (ARMS)**
   [Suzuki and Tanaka, 1997]
4. **Chemical Casting Model**
   [Kanada and Hirokawa, 1994]

Lambda-Calculus and AlChemy (I)

[Fontana, 1992, Fontana and Buss, 1996]

1. **Objects**:

- Molecule := normalized λ-expressions, e.g.: $\lambda x_1.(x_1)\lambda x_2.x_2$
- λ-expression := word over alphabet $A = \{\lambda, ., (,)\} \cup V$
- $V = \{x_1, x_2, \ldots\}$ is an infinite set of variable names.
- The set of λ expressions, Λ, is defined for $x \in V, M \in \Lambda, N \in \Lambda$ by

$$\begin{array}{rl} x \in \Lambda & \text{variable name} \\ \lambda x.M \in \Lambda & \text{abstraction} \\ (M)N \in \Lambda & \text{application} \end{array}$$

Interpretation of a Lambda-Expression

1. **Abstraction** $\lambda x.M$
   - Function definition
   - x: formal parameter
   - M: function body
2. **Application** $(M)N$
   - Application of function M on data N
   - Formalized by the β-rule:

$$(\lambda x.M)N = M[x \longleftarrow N]$$

Example: Abstraction and Application of a λ-Expression

- $A = \lambda x_1.(x_1)\lambda x_2.x_2$
- $B = \lambda x_3.x_3$
-

$$(A)B \Longrightarrow (\lambda x_1.(x_1)\lambda x_2.x_2)\lambda x_3.x_3 \Longrightarrow (\lambda x_3.x_3)\lambda x_2.x_2 \Longrightarrow \lambda x_2.x_2$$

Lambda-Calculus and AlChemy (II)

[Fontana, 1992, Fontana and Buss, 1996]

1. **Reaction**:

- Simplest way:

$$reaction(A, B) = normalForm((A)B)$$

- General form:

$$reaction(A, B) = normalForm(((\Phi)A)B)$$

- Φ: a "fixed" λ-expression which specifies the reaction mechanism.

AlChemy: Typical Experiments

- Explicit simulation of collisions and molecules.
- Explicit population of size $M = 1000 - 3000$.
- Populations dynamics like Example B.

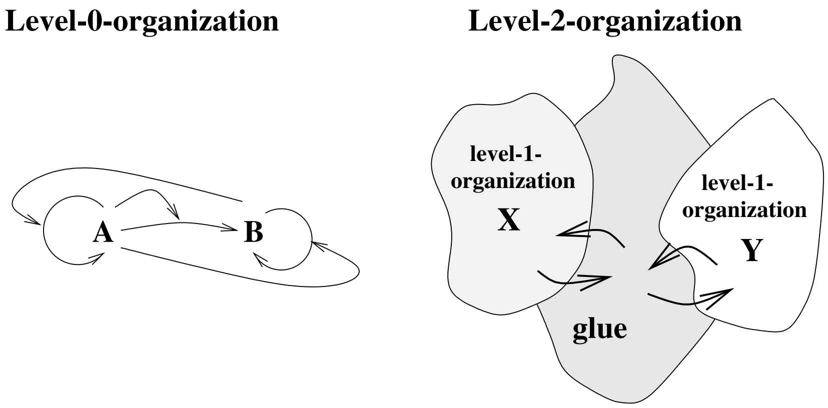
$$s_1 + s_2 + X \longrightarrow s_1 + s_2 + s_3$$

- Reactor initialized with random λ-expressions.

AlChemy: Observations and Results (I)

1. **Level-0-organization**
   - consists of a few closely coupled replicators
   - diversity reduces quickly, often only one surviving self-replicating object type.
2. **Level-1-organization**
   - are composed of a huge, even infinite, number of objects.
   - appeared when self-replication is disabled.
   - represented in the reactor only by a fraction of its objects.
   - very stable.
3. **Level-2-organization**
   - consists of two (or more) co-existing level-1 organization
   - interaction *must* be moderated by a "glue"

AlChemy: Observations and Results (II)



AlChemy: Observations and Results (III)

1. **Syntactical closure**
   - Surviving organizations have similar syntactical structure.
   - Objects can be described by a grammer.

2. **Semantic closure**
   - Relationship can be described by an algebra.
   - Algebra specifies semantics independently from λ-calculus.

String Operations - Overview

$$abab + aaabbbaaaab + aaaabbbb \rightleftharpoons abab + aaabbbaaaabaaaabbbb$$

1. **Autocatalyic polymer systems**
   [Kauffman, 1986, Farmer et al., 1986]
   [Wills and Henderson, 1997]

2. **Emergence and evolution of metabolisms**
   [Bagley and Farmer, 1992, Bagley et al., 1992]

3. **Information processing in spatial enzyme-polymer systems**
   [Shackleton and Winter, 1998]

4. **DNA computing models**
   [Adleman, 1994]

Emergence of a Metabolism in a Polymer AC

[Bagley and Farmer, 1992]

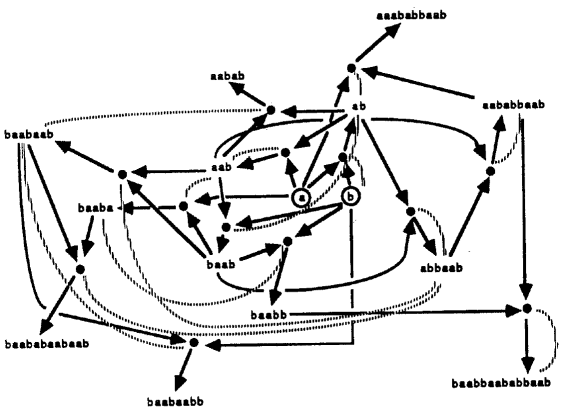
1. **Objects**
   character sequences: $S = \{a, b\}^*$
2. **Reaction**

$$s_1 + s_2 + s_3 \rightleftharpoons s_1 s_2 + s_3$$

3. **Dynamics**
   Metadynamics

A Typical Reaction Network

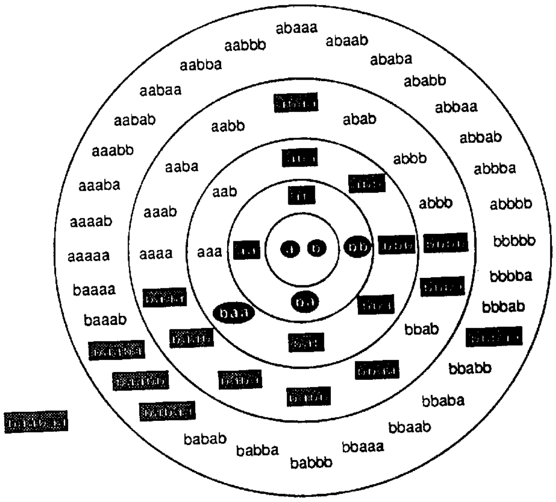
from [Bagley and Farmer, 1992]



a,b : food set

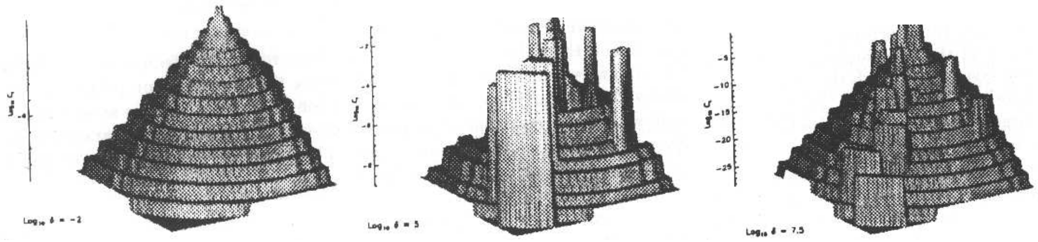
The Mandala

from [Bagley and Farmer, 1992]



Emergence of a Metabolism

from [Bagley and Farmer, 1992]



Arithmetic Operations - Overview

1. **Natural number chemistry**
   [Berry and Boudol, 1992, Banzhaf et al., 1996]
2. **Matrix reaction**
   [Banzhaf, 1993]

4-Bit Matrix Reaction

[Banzhaf, 1993]

1. **Objects**
   4-bit binary strings : $S = \{0,1\}^4$
2. **Reaction**

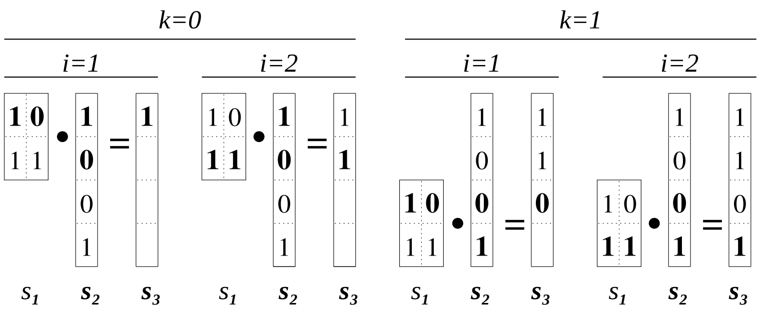
$$s_1 + s_2 \Longrightarrow s_3$$

   (a) Fold s_1 to an operator matrix M.
   (b) Multiply M with substrings of s_2.
   (c) The products are concatenated to form s_3.
3. **Dynamics**
   Similar to Example B.

4-Bit Matrix Reaction - Example

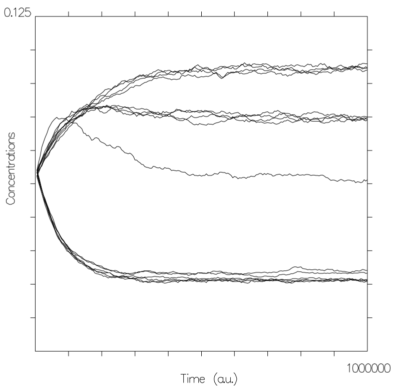
$$s_1 + s_2 \Longrightarrow s_3$$

$$1011 + 1001 \Longrightarrow 1101$$



4-Bit Matrix Reaction - Simulation

from [Banzhaf, 1993], p. 6



population size $M = 10^5$, topological-horizontal folding

Matrix Reaction - Observation

1. Spontaneous formation of metabolic networks.
2. ODE model can describe dynamics of 4-bit systems.
3. ODE model insufficient for larger systems.
4. Strings in surviving metabolism have similar structure.

⇒ Syntactical and semantic closure.

(But hard to find for variable length systems.)

Abstract Automata

1. **Turing machine like, RNA motivated**
[McCaskill, 1988, Thürk, 1993]
2. **Machine-Tape Interaction**
[Ikegami and Hashimoto, 1995]
3. **Finite state machine, abstract**
[Dittrich, 1995, Dittrich and Banzhaf, 1998]

Machine-Tape Interaction

[Ikegami and Hashimoto, 1995]

1. **Objects**
- Tapes: 7-bit circular binary strings $S_T = \{0, 1\}^7$
- Machines: 16-bit binary strings (4-bit head, 4-bit tail, 8-bit transition table)
2. **Reactions**

$$M_i + T_j + X \longrightarrow M_i + T_j + M_k + T_l, \quad X \text{ implicit, } [X] = const.$$

3. **Dynamics**
- implicit population (integer vector)

Machine-Tape Interaction - Observations (I)

I. Low noise [Ikegami and Hashimoto, 1995]

1. Simple Autocatalyic loops
2. Reaction cycles are similar to hypercyclic organizations [Eigen and Schuster, 1977].
3. Eigen/Schuster type networks:

$$M_i + T_j \Longrightarrow M_k + T_j, \quad M_k + T_l \Longrightarrow M_i + T_l$$

4. Eigen/Schuster type networks do not perform any active mutation.

Machine-Tape Interaction - Observations (II)

II. Medium noise [Ikegami and Hashimoto, 1995]

1. Reaction network is destabilized by parasites.
2. After long transient phase ($\approx$ 1000 gen.) a very stable, dense reaction network appears, called core network.
3. Core network maintains high diversity even if the noise is deactivated.
4. The active mutation rate is high.
5. Double autocatalytic networks emerge. Example:

$$M_i + T_j \Longrightarrow M_k + T_l, \quad M_k + T_l \Longrightarrow M_i + T_j$$

Machine-Tape Interaction - Observations (III)

III. High noise [Ikegami and Hashimoto, 1995]

1. Only small, degenerated core networks emerge.
2. Low diversity and very low (even no) active mutation.

Self-evolution in an Automaton Chemistry

[Dittrich, 1995, Dittrich and Banzhaf, 1998]

1. **Objects**
   32-bit binary strings $S = \{0,1\}^{32}$

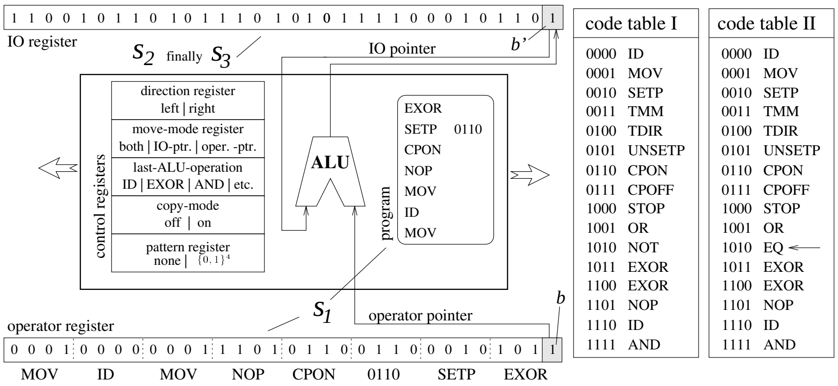
2. **Reactions**

$$s_1 + s_2 + X \Longrightarrow s_1 + s_2 + s_3 \quad X \text{ implicit, } [X] = const.$$

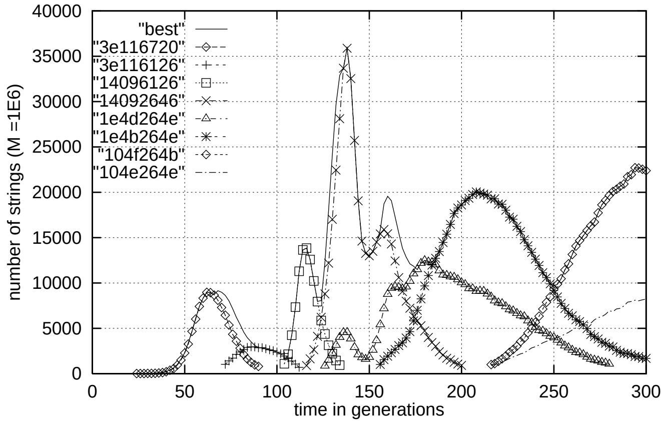
   - s_1 folded to an automaton A.
   - A is applied to s_2 to produce product s_3.

3. **Dynamics**
   explicit population, single collision simulation

Automata Reaction

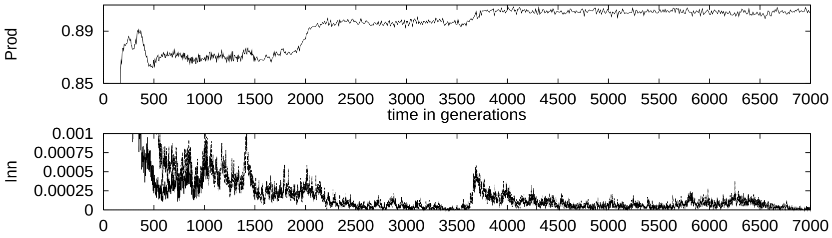


Early Evolutionary Phenomena

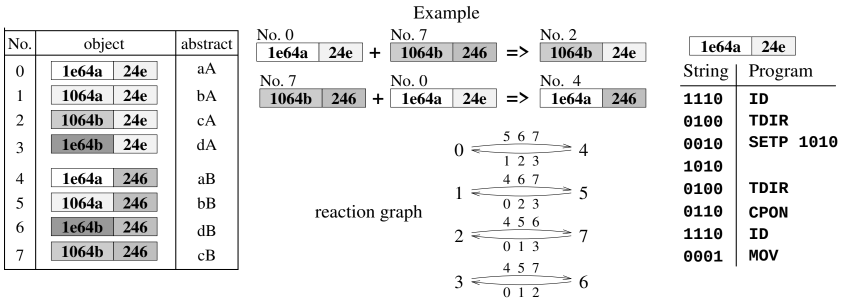


Long-Time Behavior

from [Dittrich and Banzhaf, 1998]



Emergent Cross-over - Example for Syntactical Closure



Lattice Molecular Systems - Overview

1. **Autopoiesis model**
   [Varela et al., 1974, McMullin and Varela, 1997]

2. **Lattice polymer automaton**
   [Rasmussen and Smith, 1994]

3. **Lattice molecular automaton**
   [Mayer and Rasmussen, 1998]

4. **Self-replicating cell**
   [Ono and Ikegami, 1999]

Core-Wars-like Systems

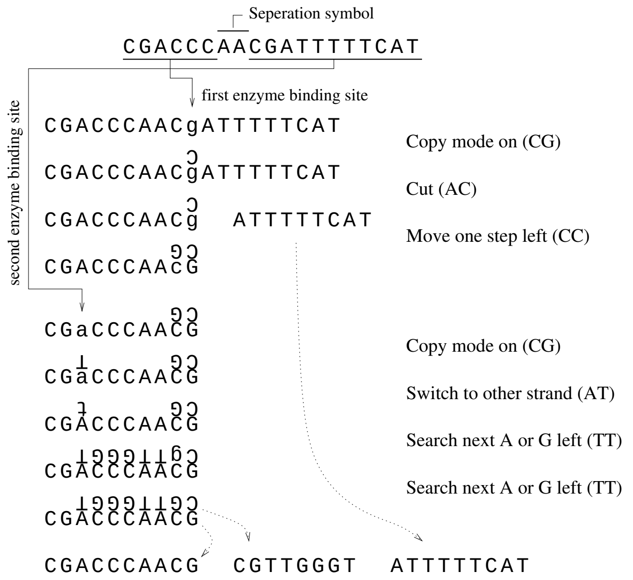
1. **Core Wars**
   [Dewdney, 1984]
2. **Coreworld**
   primordial, [Rasmussen et al., 1990]
3. **Tierra**
   species diversification, cambrian explosion, [Ray, 1992]
4. **Avida**
   spatial auto-catalytic self-replication, [Adami, 1998]
5. **Spontaneous generation of self-replicators**
   [Pargellis, 1996], see also Primordial Soup
6. **COSMOS**
   [Taylor and Hallam, 1998]

Other Approaches

1. **Typogenetics**
   [Hofstadter, 1979, Morris, 1989, Varetto, 1993]
2. **Physical Self-Assembling Systems**
   [Hosokawa et al., 1994]
3. **Self-modifying genetic programming**
   [Koza, 1994]
4. **Explicit 3-D simulation of complex macro-molecular dynamics**
   [Zauner and Conrad, 1998]
5. **Parallel reconfigurable hardware**
   [McCaskill et al., 1994]
6. **Chemical Casting Model**
   [Kanada and Hirokawa, 1994]
7. **Cellular automata and boolean networks**
   [Dittrich, 1995]

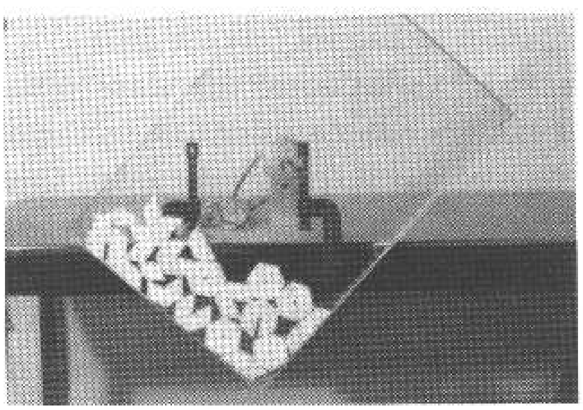
Typogenetics

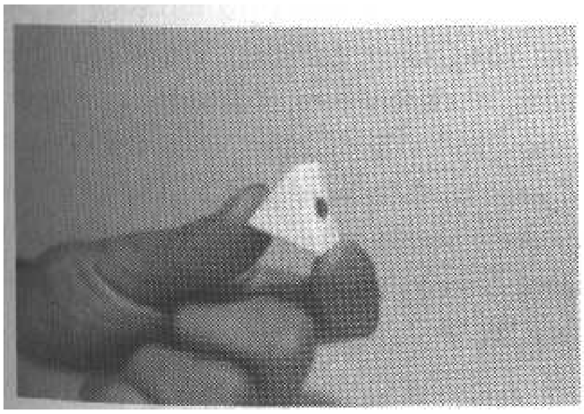
[Hofstadter, 1979]



Physical Self-Assembling System

from [Hosokawa et al., 1994]





Chemical Information Processing

1. **Microscopic Chemical Computing**
   - Example A (number-division chemistry)
   - DNA computing [Adleman, 1994]
   - Conformational computing [Conrad and Zauner, 1998]

2. **Macroscopic Chemical Computing**
   - Enzyme kinetics [Hjelmfelt and Ross, 1994, Arkin and Ross, 1994]
   - Artificial hormone system for coherent robot behavior [Brooks, 1994]
   - Metabolic robot control [Ziegler et al., 1998]
   - Reaction-diffusion and excitable media (Adamatzky et al., 1998)
   - Parity computation and hypercyclic memory [Dittrich, 1995, Banzhaf et al., 1996]

Application of Chemical Computing

1. **Artificial Chemical Computing**
   - Cell growth in ANN (others (?)), [Astor and Adami, 1998]
   - Chemical communication among cells, "neural gas", [Husbands, 1998]
   - Hormone system, (Brooks, 1996) (Creatures)
   - Subsystem in ecological/agent simulations
   - Robust low-level control

2. **Real Chemical Computing**
   - Enzyme kinetic
   - DNA computing
   - Conformational driven computing
   - Chemo-optical computing

Outlook and Challenges

1. Theory for constructive dynamical systems.

2. Phenomenology of artificial chemistries.

3. Methods for observation and analysis.

4. Conditions of emergent and self-improving hierarchical organizations.

5. Potential for application:
   - Modeling
   - Information processing
   - Optimization

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References

[Adami, 1998] Adami, C. (1998). *Introduction to Artificial Life*. Springer, New York.

[Adleman, 1994] Adleman, L. M. (1994). Molecular computation of solutions to combinatorial problems. *Science*, 266:1021–1024.

[Arkin and Ross, 1994] Arkin, A. and Ross, J. (1994). Computational functions in biochemical reaction networks. *Biophysical Journal*, 67:560–578.

[Astor and Adami, 1998] Astor, J. C. and Adami, C. (1998). Development of evolution of neural networks in an artificial chemistry. In Wilke, C., Altmeyer, S., and Martinetz, T., editors, *Third German Workshop on Artificial Life*, pages 15–30. Verlag Harri Deutsch, Frankfurt a. M.

[Bagley and Farmer, 1992] Bagley, R. J. and Farmer, J. D. (1992). Spontaneous emergence of a metabolism. In Langton, C. G., Taylor, C., Farmer, J. D., and Rasmussen, S., editors, *Proceedings of the Workshop on Artificial Life (ALIFE '90)*, volume 5 of *Santa Fe Institute Studies in the Sciences of Complexity*, pages 93–140, Redwood City, CA, USA. Addison-Wesley.

[Bagley et al., 1992] Bagley, R. J., Farmer, J. D., and Fontana, W. (1992). Evolution of a metabolism. In Langton, C. G., Taylor, C., Farmer, J. D., and Rasmussen, S., editors, *Proceedings of the Workshop on Artificial Life (ALIFE '90)*, volume 5 of *Santa Fe Institute Studies in the Sciences of Complexity*, pages 141–158, Redwood City, CA, USA. Addison-Wesley.

[Banzhaf, 1993] Banzhaf, W. (1993). Self-replicating sequences of binary numbers – foundations i and ii: General and strings of length n = 4. *Biological Cybernetics*, 69:269–281.

[Banzhaf, 1994] Banzhaf, W. (1994). Self-organization in a system of binary strings. In Brooks, R. and Maes, P., editors, *Artificial Life IV*, pages 109–119, Cambridge, MA. MIT Press.

[Banzhaf et al., 1996] Banzhaf, W., Dittrich, P., and Rauhe, H. (1996). Emergent computation by catalytic reactions. *Nanotechnology*, 7(1):307–314.

[Berry and Boudol, 1992] Berry, G. and Boudol, G. (1992). The chemical abstract machine. *Theoretical Computer Science*, 96(1):217–248.

[Brooks, 1994] Brooks, R. A. (1994). Coherent behavior from many adaptive processes. In Cliff, D., Husbands, P., Meyer, J.-A., and Wilson, S., editors, *From animals to animats 3*, pages 22–29. MIT Press, Bradford Book, Cambridge MA.

[Conrad and Zauner, 1998] Conrad, M. and Zauner, K.-P. (1998). Conformation-driven computing: A comparison of designs based on DNA, RNA, and protein. *Supramolecular Science*, 5(5-6):787–790.

[Dewdney, 1984] Dewdney, A. K. (1984). In the game called core war hostile programs engage in a battle of bits. *Sci. Amer.*, 250:14–22.

[Dittrich, 1995] Dittrich, P. (1995). *Selbstorganisation in einem System von Binärstrings mit algorithmischen Sekundärstrukturen* . diploma thesis, Dept. of Computer Science, University of Dortmund, Informatik XI, D-44221 Dortmund, Germany.

[Dittrich and Banzhaf, 1998] Dittrich, P. and Banzhaf, W. (1998). Self-evolution in a constructive binary string system. *Artificial Life*, 4(2):203–220.

[Ehrenfest and Ehrenfest, 1907] Ehrenfest, P. and Ehrenfest, T. (1907). Üeber zwei bekannte Einwände gegen das Boltzmannsche H-Theorem. *Physikalische Zeitschrift*, 8(9).

[Eigen and Schuster, 1977] Eigen, M. and Schuster, P. (1977). The hypercycle: a principle of natural self-organisation, part a. *Naturwissenschaften*, 64(11):541–565.

[Farmer et al., 1986] Farmer, J. D., Kauffman, S. A., and Packard, N. H. (1986). Autocatalytic replication of polymers. *Physica D*, 22:50–67.

[Fontana, 1992] Fontana, W. (1992). Algorithmic chemistry. In Langton, C. G., Taylor, C., Farmer, J. D., and Rasmussen, S., editors, *Proceedings of the Workshop on Artificial Life (ALIFE '90)*, volume 5 of *Santa Fe Institute Studies in the Sciences of Complexity*, pages 159–210, Redwood City, CA, USA. Addison-Wesley.

[Fontana and Buss, 1996] Fontana, W. and Buss, L. W. (1996). The barrier of objects: From dynamical systems to bounded organization. In Casti, J. and Karlqvist, A., editors, *Boundaries and Barriers*, pages 56–116. Addison-Wesley.

[Fontana et al., 1994] Fontana, W., Wagner, G., and Buss, L. W. (1994). Beyond digital naturalism. *Arficial Life*, 1/2:211–227.

[Hjelmfelt and Ross, 1994] Hjelmfelt, A. and Ross, J. (1994). Pattern recognition, chaos, and multiplicity in neural networks of excitable systems. *Proc. Natl. Acad. Sci. USA*, 91:63–67.

[Hofbauer and Sigmund, 1988] Hofbauer, J. and Sigmund, K. (1988). *Dynamical Systems and the Theory of Evolution.* University Press, Cambridge UK.

[Hofstadter, 1979] Hofstadter, D. R. (1979). *Gödel, Escher, Bach: An Eternal Golden Braid.* Basic Books,Inc., New York.

[Hosokawa et al., 1994] Hosokawa, K., Shimoyama, I., and Miura, H. (1994). Dynamics of self-assembling systems - analogy with chemical kinetics. In Brooks, R. and Maes, P., editors, *Artificial Life IV*, pages 172–180, Cambridge, MA. MIT Press.

[Husbands, 1998] Husbands, P. (1998). Evolving robot behaviours with diffusing gas networks. In *Evolutionary Robotics (Proc. of EvoRob'98)*, LNCS 1468, pages 71–86, Berlin. Springer.

[Ikegami and Hashimoto, 1995] Ikegami, T. and Hashimoto, T. (1995). Active mutation in self-reproducing networks of machines and tapes. *Artificial Life.*

[Kanada and Hirokawa, 1994] Kanada, Y. and Hirokawa, M. (1994). Stochastic problem solving by local computation based on self-organization paradigm. In *27th Hawaii Int'l Conf. on System Science*, pages 82–91.

[Kauffman, 1986] Kauffman, S. A. (1986). Autocatalytic sets of proteins. *J. Theor. Biol.*, 119:1–24.

[Koza, 1994] Koza, J. B. (1994). Artificial life: Spontaneous emergence of self-replicating and evolutionary self-improving computer programs. In Langton, C. G., editor, *Artificial Life III*, pages 225–262, Reading, MA. Addison-Wesley.

[Mayer and Rasmussen, 1998] Mayer, B. and Rasmussen, S. (1998). The lattice molecular automaton (LMA): A simulation system for constructive molecular dynamics. *Int. J. of Modern Physics C*, 9(1):157–177.

[McCaskill et al., 1994] McCaskill, J., Chorongiewski, H., Mekelburg, D., Tangen, U., and Gem, U. (1994). Configurable computer hardware to simulate long-time self-organization of biopolymers. *Ber. Bunsenges. Phys. Chem.*, pages 1114–1115.

[McCaskill, 1988] McCaskill, J. S. (1988). Polymer chemistry on tape: A computational model for emergent genetics. Internal report, MPI for Biophysical Chemistry, Göttingen, Germany.

[McMullin and Varela, 1997] McMullin, B. and Varela, F. J. (1997). Rediscovering computational autopoiesis. In Husbands, P. and Harvey, I., editors, *Fourth European Conference on Artificial Life*, pages 38–47, Cambridge, MA. MIT Press.

[Morris, 1989] Morris, H. C. (1989). Typogenetics: A logic for artificial life. In Langton, C. G., editor, *Artificial Life*, pages 341–368. Addison-Wesley.

[Ono and Ikegami, 1999] Ono, T. and Ikegami, T. (1999). Model of self-replication cell capable of self-maintenance. In *Proc. European Conf. on Artificial Life (ECAL99).*

[Pargellis, 1996] Pargellis, A. N. (1996). The spontaneous generation of digital "life". *Physica D*, 91(1-2):86–96.

[Rasmussen et al., 1990] Rasmussen, S., Knudsen, C., Feldberg, R., and Hindsholm, M. (1990). The coreworld: Emergence and evolution of cooperative structures in a computational chemistry. *Physica D*, 42:111–134.

[Rasmussen and Smith, 1994] Rasmussen, S. and Smith, J. (1994). Lattice polymer automaton. *Ber. Bunsenges. Phys. Chem.*, 98(9):1185–1193.

[Ray, 1992] Ray, T. S. (1992). An approach to the synthesis of life. In Langton, C. G., Taylor, C., Farmer, J. D., and Rasmussen, S., editors, *Artificial Life II: proceedings of the second artificial life workshop*, pages 371–408, Redwood City, CA. Addison-Wesley.

[Segr and Lancet, 1998] Segr, D. and Lancet, D. (1998). A statistical chemistry approach to the origin of life. *Chemtracts.*

[Shackleton and Winter, 1998] Shackleton, M. A. and Winter, C. S. (1998). A computational architecture based on cellular processing. In Holcombe, M. and Paton, R., editors, *Information Processing in Cells and Tissues*, pages 261–272, New York. Plenum Press.

[Stadler et al., 1993] Stadler, P. F., Fontana, W., and Miller, J. H. (1993). Random catalytic reaction networks. *Physica D*, 63:378–392.

[Suzuki and Tanaka, 1997] Suzuki, Y. and Tanaka, H. (1997). Symbolic chemical system based on abstract rewriting and its behavior pattern. *Artificial Life and Robotics*, 1:211–219.

[Taylor and Hallam, 1998] Taylor, T. and Hallam, J. (1998). Replaying the tape: An investigation into the role of contingency in evolutio. In Adami, C., Belew, R., Kitano, H., and C.Taylor, editors, *Proceedings of "Artificial Life VI"*, pages 256–265, Cambridge MA. MIT Press.

[Thürk, 1993] Thürk, M. (1993). *Ein Modell zur Selbstorganisation von Automatenalgorithmen zum Studium molekularer Evolution.* PhD thesis, Universit"at Jena, naturwissenschaftliche Fakult"at.

[Varela et al., 1974] Varela, F. J., Maturana, H. R., and Uribe, R. (1974). Autopoiesis: The organization of living systems. *BioSystems*, 5(4):187–196.

[Varetto, 1993] Varetto, L. (1993). Typogenetics: An artificial genetic system. *Journal of Theoretical Biology*, 160:185–205.

[Wills and Henderson, 1997] Wills, P. and Henderson, L. (1997). Self-organisation and information-carrying capacity of collectively autocatalytic sets of polymers: ligation systems. In Bar-Yam, Y., editor, *Proc. of Int. Conf. on Complex Systems, Nashua, NH.*

[Zauner and Conrad, 1998] Zauner, K.-P. and Conrad, M. (1998). Conformation-driven computing: Simulating the context-conformation-action loop. *Supramolecular Science*, 5(5-6):791–794.

[Ziegler et al., 1998] Ziegler, J., Dittrich, P., and Banzhaf, W. (1998). Towards a metabolic robot controller. In Holcombe, M. and Paton, R., editors, *Information Processing in Cells and Tissues*, pages 305–318, New York. Plenum Press.