National University of Singapore
Seminar of the School of Computing

Martin Henz

The Quest for Complexity

Artificial Chemistries
Artificial Chemistries: The Quest for Complexity

- Conclusions and Personal Remarks
- Artificial Chemistries
- The Chemistry of Life
- Complexity
- Life

Overview
Attempst to Define Life

Thermodynamic

Genetic

Biochemical

Metabolic

Physiological

Artificial Chemists: The Quest for Complexity
maintain low levels of entropy.

thermodynamic: define living systems in terms of their ability to

life, 1999

and heredity. J. Maynard Smith, E. Szathmary: The Origins of

is called alive. Defining features: multiplication, variation

system that achieves evo-

genetic: Equate life with evolution: Any system that achieves evo-

molecules.

biochem: capable to store hereditary information in nucleic acid

metabolic: exchange of materials between org and surrounding

phys: functional: breathing, moving, etc
Artificial Chemistries: The Quest for Complexity

- Coding for proteins
- Replication through nucleic acid polymers
- Carbon-based, aquatic, self-replicating structures
- Ancestral roots
- All terrestrial life seems to share these early

3.8 billion years ago [Schidlowski, 1988]

Fossil records show single-celled life existed

Some Facts of Life
Liquid water may have appeared only 3.9 billion years ago, which makes the time for development of life very short, possibly zero. Liquid water in sedimentary rocks. Nature 333:313-318, 1988.

M. Schidlowski: A 3.8 billion-year isotopic record of life from carbon.

Earth formed about 4.6 billion years ago.
second memetic evolution
8. Primate societies ← human societies, the origin of language
7. Solitary individuals ← colonies
6. Protists ← animals, plants, fungi
5. Asexual clones ← sexual populations
4. Prokaryote ← eukaryote
3. RNA world ← DNA and protein
2. Independent replicators ← chromosomes
1. Replicating molecules (RNA?) ← populations of molecules enclosed

Major Transitions

It's own self-replication (still unproved).

Idea from Francis Crick: 1968 speculation that RNA can catalyze (DNA) requires enzymes (proteins), enzymes require genes (DNAs) requires enzymes (proteins).

RNA world is a way around the „chicken-egg-problem“ (genes between genes).

2. In today’s chromosomes (sequences of DNA), all genes are linked in a strand (in prokaryotes one strand only). That means that when all genes are replicated, all are replicated. This forces cooperation.

3. RNA can function both as genes and as enzymes.


7. Cooperation/selfishness within societies.


In Maynard Smith, Szathmary. only when there is sex, we can talk about species. see chapter 7.

5. This step gives rise to much more rapid evolution. recombinatin.

4. Disappearance of the rigid cell wall, chromosomes, organelles (mito-
uotes (bacteria): reproduction through mitosis.

DNA and protein interactions are the basic ingredients of prokary-

1986. Term, "RNA world was introduced by Walter Gilbert, Harvard, in


Later Crick wasn't so sure: F. Crick and L. Orgel, Directed

8. Susan Blackmore, "Meme Machining" meme-gene co-evolution
co-evolution (meta, gene-meme)

organisms, colonies

integration (chromosomes, organelles, sex, multicellular

separation (membranes, populations)

(translation)

information processing (coding, error correction, trans-

multiplication, variaiton, heredity

Components of Evolution
Group selection vs individual selection

- Gives rise to cooperation and conflict, selfish gene: Richard Dawkins.

- Hybrid inviability, hybrid infertility, population isolation by geography, habitat, seasonal, mechanical.

- Heredity to unlimited heredity

- Novel types or inheritance systems, or development from limited
Artificial Chemistries: The Quest for Complexity

Conclusions and Personal Remarks

Artificial Chemistries

The Chemistry of Life

Complexity

Life

Overview
using mutual entropy, conditional on "universe"

- Information theoretic complexity (Shannon):

\[ \{ (d) \cap C = s : |d| \} \min = (s) \]

- Algorithmic complexity (Kolmogorov/Chaitin):

- ontological

- descriptive

Notions of Complexity
where $R$ is mutation rate and $l$ is the length of the genome.

to find the information transmission capacity for genomes, $R_l = c$,

information transmission capacity. **Adam! used Shannon complexity**

**Adam!**

Strings have highest complexity! **Adam!**

Minimal length of program for Turing Machine $T$; problem: random

self-replication is possible (he could not characterize in detail). **Adam!**

When he talked about a complexity threshold beyond which mind, when he talked about just a notion of complexity in parts, Von Neumann seemed to have this notion of complexity in collective behavior which is different from the behavior of the systems-like properties (being further decomposable or organized as a system of non-identical components who

(Adam! view, third person view) **Adam!**

in a reasonably complete way: photon, consciousness (first person

several different methods are needed to describe a phenomenon
Conclusions and Personal Remarks

Artificial Chemistries

The Chemistry of Life

Complexity

Life

Overview
and build up protein

TRNA (anticodon) carrying amino acids dock successively to mRNA

...somes

DNA can be transcribed to mRNA, which is transported to ribo-

double-strandedness of DNA allows for error correction

tour different nucleic acids

DNA codes the assembly of proteins out of 20 amino acids using

separation between information and function: DNA and proteins

watery solution of carbon molecules

The Chemistry of Life
(Influenza, Polio)

Hereditarily limited to very simple organisms such as RNA viruses, whereas RNA-based error correction allows "unlimited heredity", whereas DNA-based.

•

acids (Human code)

mon amino acids are coded by multiple combinations of 3 nucleic acids: 64 possible, actually: 20; Redundancy: Roughly: more com-

pare with RNA world; three nucleic acids code for one amino acid with water.

as protein folding, osmosis, transportation; RNA world: problems absolutely necessary: hydrophobic/ hydrophilic reactions such

•
Artificial Chemistries: The Quest for Complexity

Informal theoritical treat inherence betwenn gener-

Informal theoritical: treat inherence betwenn gener-

Informal theoritical: treat inherence betwenn gener-

Informal theoritical: treat inherence betwenn gener-

Informal theoritical: treat inherence betwenn gener-

Kolmogorov/Chaitin Complexity: DNA sequences could

ontological and system-theoretic approach in biology

descriptive classical biology

descriptive classical biology

descriptive classical biology

descriptive classical biology

descriptive classical biology

descriptive classical biology

descriptive classical biology

descriptive classical biology

descriptive classical biology

descriptive classical biology
can be quantified. See Christoph Adam: Artificial Life, 1998.
The learning capacity of the genome, under very rigid assumptions
information channel with noise. Information processing is viewed as
Idea: view genome inheritance from an generation to the next as an
Adam computes information processing capacity during evolution.

(400 genes)
(400 genes)
teria (1.8 million bases, M. genitalium (bacteria) (67 million bases
coli (bacteria) 4.67 million bases (3237 genes) H. influenzae (bact-
(353 genes) 14 million bases (8455 to 8947 bases) E.
(947 genes) 100 million bases (11,800 to 13,800
(6835 genes) Nematode (roundworm) 100 million bases (11,800 to 13,800
(6835 genes) Drosophila (fruit fly) 165 million bases (15,000 to 25,000
(25,000 genes) Caenorhabditis 480 genes, Human 3000 million bases (30,000
problems of redundancy and noise; Simplest known organism: my-
rich structure on many levels of abstraction
morphology, cytolology etc
Conclusions and Personal Remarks

Artificial Chemistry

The Chemistry of Life

Complexity

Life

Overview
Artificial Intelligence

Goals: Scientific study of evolution, optimization, artificial intelligence as it could be

Use artificial chemistries to enable evolutionary processes

Instance available for study

Theory of evolution has the problem of having only one

Artificial Chemistries: Motivation
Physiologically, lack of repeatability Karl Popper suggests that evolution theory is not scientific but meta-
Self-replicating codes

Cellular automata

Rewriting systems

Wet artificial life

Artificial Chemistries: The Quest for Complexity Overview
plex reactions involving double-stranded DNA
-
Wright, Joyce: Use tag for targeted PCR, but com-

polymersase chain reaction, reverse transcription,
-
Bartel, Szostak: Evolution using “tag” molecules,

Guest for missing link in origin of life. Milestones:

that catalyze their own replication.

Goal: Reproducing the RNA world: (sets of) RNA strings

Wet Artificial Life
Chem. 98, 1160, 1994.

Oberholzer, Enzymatic RNA synthesis in self-reproducing vesicles: An
approach: core-and-shell self-reproduction (L. Luisi, P. Wrede, T.
interior (except occasional dilution in a fresh reaction solution); other
M.C. Wright, G.F. Joyce. Continuous in vitro evolution of catalytic
Defining a simple stochastic molecular reactivity algorithm:

- Define reaction algorithm, for example stochastic model:
  \[ s^m \vdash s \rightarrow s + s \]

- Define set of reaction rules \( R \) for the form:

- Define set of molecules \( S \):

Rewriting Systems Principle
The chemical reduction as a single reaction rule

Lambdas-calculus (Alchemy), used by Fontana and Busi,

and Hirokawa, goal-driven, used for optimization

Chemical casting model (CCM), developed by Kanada

Skeletal Machine (Berry, Boudol), additional rule order

opened by Suzuki, Tanaka, similar to the Chemical Ab-

Chemical rewriting systems on multisets (ArMS), developed

Examples: Systems
different variants of the experimental setup

self-replication easy, different levels of organization appear with

optimization

eliminating salesmen etc), quantity defined by local order degree used for
"tray"

casting chemical model: problems can be encoded using links (tray-

chemical chemical systems

cooling/heatling rules, ion rule inspired by CCS, able to model os-
Artificial Chemistries: The Quest for Complexity

- reproduction (evolution) and
- self-replication (nanotechnology, space exploration)

used to study both automatons introduced by John Von Neumann to study self-replicating

Cellular Automata: Background
A cellular automaton is a tuple $(f, N, S, T)$, where

\[ S \leftarrow wS : f \]

such that for all \( i \in N \) and \( c \in T \) we have \( c + i \in T \), \( N \) is a finite set (of size \( u = |N| \) of neighborhood indices, \( S \) is a finite set of states, \( T \) is a regular lattice of cells with dimensionality \( d \), and

Cellular Automaton: Definition
• Of course d-dimensional vector

• d-dimensionality

• tures allowed (hexagonal)

• point lattice: discrete subgroup of Euclidean space, other struc-
quièscient state yields quièscient state •

spacial isotropy •

problem: find the right chemistry

states and $8^{32768}$ different transition functions.

Then there are $8 = 32768$ neighborhood neighbors. Usually neighborhoods is defined using „radius“ •

classes of automata
that for self-replication, only computationally universal suffices. A. Ray Smith showed for construction universality (unfinished work, completed by Pe-

von Neumann constructed 2-dimensional CA with 29 states and the to the same state.

special isotropy: all planar rotations of a neighborhood should map
Wolfram class IV: none of the above

Wolfram class III: "uniformly chaotic" behavior

Wolfram class II: limit cycle behavior

Wolfram class I: limit point behavior

\[ s = 2, \nu = 1, 2 \]

Behavior Classification
a turning machine built in game of life.

of life is of class IV. Look at http://www.rendez-vous.co.uk/go/tw.htm for
conjectured to be capable of universal computation. Conway's game
of life is of class IV most interesting; complex patterns; self-organization;
cidables; Class IV most interesting; complex patterns; self-organization;
Karel Culick and Shen Yu showed that Wolfram's classification is unde-
Artificial Chemistries: The Quest for Complexity

- self-replicative structures for \( p = 2 \)
- probability of getting a non quiescent state is significant

\[
|S| = 2, r = 2, \rho = 2
\]

- Langton analyses CA for \( d = 1, t = 2, \rho = 2 \)
- How to find „interesting“ rule sets?

Langton's Experiments
not necessary for self-replication

construction universally: be able to construct any other automaton

for applets

class I, II, III with IV between II and III; look at urittp://cell-auto.com/inks
Artificial Chemistries: The Quest for Complexity

- Quest for simplest self-replicating structure
- Emphasis on self-replication
- Periodicity
- Defined mostly negatively: absence of unstructured chaos
• amoeba
• avida
• aterra
• Coreworld
• computer viruses
• Self-replicating code
Artificial Chemistries: The Quest for Complexity

- Coreworld generally fragile under mutation, consequence of instruction set
- Different “ecologies” emerge from different parameter settings.
- Self-replicating programs can be easily written, but are not stable.
- Introduce noise through a stochastic copy instruction.
- Use circular memory, Core War instruction set, called Redcode.
- Progammers compete for the memory of a virtual machine.

Developed by Steen Rasnussen out of “Core War”, a game where
memory management using reaper queue

scheduling using slicer queue

pattern based addressing, using nofo and nopl

32 instructions, vaguely based on Intel i860

developed by Tom Ray
Behavior of Terra

- "super-parasites"
- "cheaters"
- symbionts
- immune hosts
- parasites

Different "species" emerge:

• seeded with self-replicating code (80 instructions)
Artificial Chemistries: The Quest for Complexity

- Facilitating
- Replication by copying code into neighbor

- Refined rules for code sharing and migration
- Each cell contains a circular program
- Based on tiers, but two-dimenisonal structure
- Developed by Christopher Adami

AviAl
Artificial Chemistries: The Quest for Complexity

- Parallel implementation allows large-scale experiments
- Speed of execution in a cell
- Similar to avida, but allows targeted evolution by 
regulating the
sandra •

only 5 instruction long
- Target: evolution of self-replication; smallest self-replicators are
amoeba •

Other Chemistries for Self-Reproductive Code
Artificial Chemistries: The Quest for Complexity

Structructions

In population, frequency of genotypes, volatility of in-

use Shannon complexity, based on average string length

Adam on avida

Most developed quantitative analysis performed by Christoph

For quantitative analysis

Tom Ray uses mostly descriptive complexity, no attempt

Complexity in Self-Replicative Code
Conclusions and Personal Remarks

Artificial Chemistries

The Chemistry of Life

Complexity

Life

Overview
Artificial Chemistry: The Quest for Complexity

- Neurons are large (4 microns)

- $\text{m/s}$ speed of signal transmission within neuron

- 5 ms between firing of connected cortical neurons

- Brain is slow

- Duration of generation long (decades for humans)

- Communication bandwidth narrow

- Higher life forms are stuck on earth

- Protein synthesis is slow

Shortcomings of Life
feature size in modern VLSI: 130 nano meter; 30 times smaller!

intelligent brain:

no wonder 10^4 neurons, with 10^4 connections, are needed for a real-time

are so complicated (parallellism).

600ms for adding a single amino acid; average human protein has 450

as, so 27 seconds for assembling one single protein! No wonder, cells
We should do better:

- Hard Artificial Life: thirrd evolution
- exploit feature size and speed
- understand and exploit meta-evolution
- understand and exploit evolution
Let us study “life as it could be” the limitations apparently inherent in carbon-based aquatic chemistry. many of the “impressive facts” about carbon-based life are artifacts of ration, integration look at the major factors in natural life: information processing, sensing