Self-Reproduction and Open-ended Evolution
Lab Assignments: 35% (ISE-483), 25% (SSIE-583)
  ● Complete 4/5 assignments based on algorithms presented in class
    ■ Lab 5: May 1st
      ● Ant Clustering Algorithm, (Lab 5 in Brightspace Assignments)
      ● Due May 8th

SSIE – 583 -Presentation and Discussion: 35%
  ● Present and lead the discussion of an article related to the class materials
    ■ Enginet students post/send video or join by Zoom
  ● All presentations completed?
Readings until now

resources

- **Class Book**
    - Chapters 1, 2, 4, 7
    - Chapter 5, (6)

- **Lecture notes**
  - Chapter 1: “What is Life?”
  - Chapter 2: “The Logical Mechanisms of Life”
  - Chapter 3: “Formalizing and Modeling the World”
  - Chapter 4: “Self-Organization and Emergent Complex Behavior”
  - Chapter 5: “Reality is Stranger than Fiction”
  - Chapter 6: “Von Neumann and Natural Selection”
  - Chapter 7: “Modeling Evolution: Evolutionary Computation”
    - posted online @ [http://informatics.indiana.edu/rocha/i-bic](http://informatics.indiana.edu/rocha/i-bic)

- **Other materials**
    - Chapters 1, 2, 3, 5, 7, 8
    - Chapter 6
Projects

- **Due by May 8th 12th** in Brightspace, “Final Project Paper” assignment
  - ALIFE 2023
    - Not to submit to actual conference due date (March 13th)
    - [https://2023.alife.org/](https://2023.alife.org/)
    - 8 pages, author guidelines:
      - /calls/call-for-papers-extended-abstracts
      - MS Word and Latex/Overleaf templates
  - Preliminary ideas by March 27
    - Submit to “Project Idea” assignment in Brightspace.

- Individual or group
  - With very definite tasks assigned per member of group

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**ALIFE 2023**

Tackle a real problem using bio-inspired algorithms, such as those used in the labs.

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**ALIFE 2023**

The 2023 Conference on Artificial Life

Date: 24-28th July, 2023

Venue: Clark Memorial Student Center

Location: Hokkaido University, Sapporo, Hokkaido, Japan
Natural design principles

exploring similarities across nature

- **self-similar structures**
  - Trees, plants, clouds, mountains
    - Morphogenesis
  - Mechanism
    - Iteration, recursion, feedback

- **dynamical systems and unpredictability**
  - From limited knowledge or inherent in nature?
  - Mechanism
    - Chaos, measurement

- **self-organization, collective behavior, emergence**
  - Complex behavior from collectives of many simple units or agents
    - Cellular automata, dynamical networks, morphogenesis, swarms, brains, social systems
  - Mechanism
    - Parallelism, multiplicity, multi-solutions, redundancy

- **evolution**
  - Adaptation, learning, social evolution
  - Mechanism
    - Reproduction, transmission, variation, selection, Turing’s tape

- **Collective behavior** Behavior derived from many inseparable sources
  - Multi-level selection, swarm intelligence, immune system, anticipatory systems, brain-body-environment-culture, embodiment, epigenetics, culture
  - Mechanism
    - Network causality, odularity, control, hierarchy, connectivity, stigmergy, redundancy
Babbage/Lovelace first to try to build it (before Turing)

distinction between numbers that mean things and numbers that (do things) move matter
systems biology models operate in near critical regime, though many are ordered

Dynamical systems capable of computation exist before the edge of chaos
  ● A wider transition due to redundancy.

Most important information transmission and computation in Biology an altogether different process than self-organization
  ● Turing/Von Neumann memory

is self-organization enough?
as a general principle (system) of evolution or **open-ended complexity**

Von Neumann’s generalization of Turing’s tape

5 lectures at University of Illinois

**D** for functions not involved in reproduction
Mutations in D can be propagated *vertically*
Leads to **open-ended evolution**

Description is copied **separately**
Construction: **interpreted** (horizontal transmission)
Copy: **uninterpreted** (vertical Transmission)
what was known?

Erwin Schrödinger (1943-1944)

- puzzled by the persistence of living structures
  - Call to understand how life stores and perpetuates order
  - "[...] chromosomes [...] contain in some kind of code-script the entire pattern of the individual’s future development."
    - "complete (double) copy of the code-script."
- aperiodic crystals as structures that can replicate themselves
  - "We believe a gene—or perhaps the whole chromosome fiber—to be an aperiodic solid."
  - "structure without predictable repetition"
  - DNA is entirely regular
  - Instead of “aperiodicity” we have encoded information: separated description/construction

"Turing invented the stored-program computer, and von Neumann showed that the description is separate from the universal constructor. This is not trivial. Physicist Erwin Schrödinger confused the program and the constructor in his 1944 book *What is Life?*, in which he saw chromosomes as “architect’s plan and builder’s craft in one”. This is wrong. The code script contains only a description of the executive function, not the function itself.” (Sydney Brenner)

Implementing self-reproduction

  - From lectures delivered in 1949 at University of Illinois: “Theory and organization of complicated automata.”
  - Defined an automaton with 29 states
- First Implementation
Implementation of V.N. self-reproducing automata

With mutations (by Tim Hutton)
self-replication and the search for the aperiodic crystal

Does this capture Von Neumann’s threshold of complexity?

- No mutations and evolution possible!
- Reproduction without possibility of selection
  - Trivial Self-reproduction
- No description-construction separation
  - genotype /phenotype
  - Tape without V.N. separation

Complex systems, artificial life, even synthetic biology often search for “crystal-like” replication

not enough for open-ended evolution
Langton’s loop

- **Simpler self-reproduction**
  - a structure whose components constitute the information necessary to its own reproduction
    - System is description and automaton simultaneously
    - Genotype and phenotype simultaneously (Schrodinger?)

- **The Loop**
  - CA with 8 states, 4 neighbors, and 219 neighborhood transition rules
    - a very small subset of the theoretically possible $8^5 = 262,144$ transitions
  - A special initial condition
  - Further simplified and extended
    - Byl’s loop, Reggia, Sayama

![Diagram of Langton's loop with annotations](image)
Variation on Langton’s loop

- More robust to initial conditions and noise
- CA leads to different “species” of loops
  - Competition, diversity
- No real selection
  - Bias on rates of reproduction
- No description-construction separation
  - genotype/phenotype


What about in physical self-reproduction?

- Lipson’s group
  - Does it evolve?
  - No genotype/phenotype


Still looking for Schrodinger’s self-replicating code-script?

Kinematic self-replication in reconfigurable organisms

Significance
Almost all organisms replicate by growing and then shedding offspring. Some molecules also replicate, but by moving rather than growing: They find and combine building blocks into self-copies. Here we show that clusters of cells, if freed from a developing organism, can similarly find and combine loose cells into clusters that look and move like they do, and that this ability does not have to be specifically evolved or introduced by genetic manipulation. Finally, we show that artificial intelligence can design clusters that replicate better, and perform useful work as they do so. This suggests that future technologies may, with little outside guidance, become more useful as they spread, and that life harbors surprising behaviors just below the surface, waiting to be uncovered.

Abstract
All living systems perpetuate themselves via growth in or on the body, followed by splitting, budding, or birth. We find that synthetic multicellular assemblies can also replicate kinematically by moving and compressing dissociated cells in their environment into functional self-copies. This form of perpetuation, previously unseen in any organism, arises spontaneously over days rather than evolving over millennia. We also show how artificial intelligence methods can design assemblies that postpone loss of replicative ability and perform useful work as a side effect of replication. This suggests other unique and useful phenotypes can be rapidly reached from wild-type organisms without selection or genetic engineering, thereby broadening our understanding of the conditions under which replication arises, phenotypic plasticity, and how useful replicative machines may be realized.
Lack of evolvability in self-sustaining autocatalytic networks constraints metabolism-first scenarios for the origin of life

Abstract

A basic property of life is its capacity to experience Darwinian evolution. The replicator concept is at the core of genetics-first theories of the origin of life, which suggest that self-replicating oligonucleotides or their similar ancestors may have been the first “living” systems and may have led to the evolution of an RNA world. But problems with the nonenzymatic synthesis of biopolymers and the origin of template replication have spurred the alternative metabolism-first scenario, where self-reproducing and evolving proto-metabolic networks are assumed to have predated self-replicating genes. Recent theoretical work shows that “compositional genomes” (i.e., the counts of different molecular species in an assembly) are able to propagate compositional information and can provide a setup on which natural selection acts. Accordingly, if we stick to the notion of replicator as an entity that passes on its structure largely intact in successive replications, those macromolecular aggregates could be dubbed “ensemble replicators” (composomes) and quite different from the more familiar genes and memes. In sharp contrast with template-dependent replication dynamics, we demonstrate here that replication of compositional information is so inaccurate that fitter compositional genomes cannot be maintained by selection and, therefore, the system lacks evolvability (i.e., it cannot substantially depart from the asymptotic steady-state solution already built-in in the dynamical equations). We conclude that this fundamental limitation of ensemble replicators cautions against metabolism-first theories of the origin of life, although ancient metabolic systems could have provided a stable habitat within which polymer replicators later evolved.

Exploring the limits of autocatalytic RNA evolution

Ameta et al

Abstract

Discovering autocatalytic chemistries that can evolve is a major goal in systems chemistry and a critical step towards understanding the origin of life. Autocatalytic networks have been discovered in various chemistries, but we lack a general understanding of how network topology controls the Darwinian properties of variation, differential reproduction, and heredity, which are mediated by the chemical composition. Using barcoded sequencing and droplet microfluidics, we establish a landscape of thousands of networks of RNAs that catalyze their own formation from fragments, and derive relationships between network topology and chemical composition. We find that strong variations arise from catalytic innovations perturbing weakly connected networks, and that growth increases with global connectivity. These rules imply trade-offs between reproduction and variation, and between compositional persistence and variation along trajectories of network complexification. Overall, connectivity in reaction networks provides a lever to balance variation (to explore chemical states) with reproduction and heredity (persistence being necessary for selection to act), as required for chemical evolution.

Darwinian properties and their trade-offs in autocatalytic RNA reaction networks

Sandeep Ameta, Simon Arsène, Sophie Foulon, Baptiste Saudemont, Bryce E. Clifton, Andrew D. Griffiths & Philippe Nghe

Nature Communications 12, Article number: 842 (2021) Cite this article

3605 Accesses 4 Citations 19 Altmetric Metrics
Open-ended evolution

Material constraints

- **Not the same as “universal” evolution**
  - The ability to evolve any physical thing whatsoever

- **Genotype/Phenotype** self-reproduction is more powerful than self-inspection because the same material structure does not have to be simultaneously memory and (catalytic) machine
  - Selected self-organization
  - Needs only to reproduce initial conditions

- **Open-endedness in reference to specific genotype/phenotype**
  - Set of building blocks available to a symbol system for genetic memory
    - Anything possibly made of those building blocks, can be encoded in the symbol system and produced by development/self-organization
    - Can *evoloops* lead to all possible “attractor” structures in the same CA space?
    - What about self-reproducing robots?

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**two roles of information**
- data/program (Turing)
- passive/active (Von Neumann)
- description/construction-function (Pattee)
- genotype/phenotype (Biology)

---

why is a genotype/phenotype separation a good thing?

Evolution is possible without codes via self-inspection (beyond autocatalytic networks)...

**Phenotype**
- Dynamics, Rate-dependence, Catalytic, Construction, Function

**Genotype**
- Memory, rate-independence, Inert, inheritance, Description

---

Hypothetical reproduction of organisms based on aminoacid chains is possible

Instead of a ribosome another set of organic machinery would copy aminoacid chains

---

functional products that build up (self-organize) the phenotype

Polypeptide chains of amino acids

Primary Structure

Folding

3-dimensional structure

Secondary and tertiary bonds

- In proteins, it is the 3-dimensional structure that dictates function
  - The specificity of enzymes to recognize and react on substrates
- The functioning of the cell is mostly performed by proteins
  - Though there are also ribozymes

Table 1.4. Amino acid codes

<table>
<thead>
<tr>
<th>Amino Acid</th>
<th>Code</th>
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<tbody>
<tr>
<td>Ala</td>
<td>A</td>
</tr>
<tr>
<td>Arg</td>
<td>R</td>
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<tr>
<td>Asn</td>
<td>N</td>
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<td>Asp</td>
<td>D</td>
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<tr>
<td>Cys</td>
<td>C</td>
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<td>Gin</td>
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<td>Sec</td>
<td>U</td>
</tr>
<tr>
<td>Unk</td>
<td>X</td>
</tr>
</tbody>
</table>

functional products that build up (self-organize) the phenotype
Can consistently produce any configuration from a stable, inheritable description
- Not Just those whose initial conditions are recoverable

Variation on descriptions
- Not on phenotypes

Can reproduce complicated, developed phenotypes
- Because it does not need to reduce the dynamics to recoverable components

Uses memory of initial conditions
- Open-Ended evolution
Under most conditions and types of evolutionary algorithms, coded agents overtake the population in a small number of generations. pattee/rocha.html
With too much genetic variation, the stability of descriptions is lost, resulting in occasional taking over of the population by noncoded agents. pattee/rocha.html
identifying the loci of genetic information

- **Frederick Griffith’s experiment**
  - In 1928: Identified a “transforming principle”

- **Avery’s experiment**
  - Oswald Avery, Colin MacLeod, and Maclyn McCarty
  - 1944: DNA as the loci of “transformation”
    - Chemically knocking off various cellular constituents until trying DNA
    - Considerable resistance in the community accepting this result until the early 1950’s (Schrodinger, Delbruck, phage group)

Initially not well accepted
(No auto-catalysis with DNA)

2 different strains of pneumococcus bacteria
self-replication vs. decoupled, encoded information


“The Turing invented the stored-program computer, and von Neumann showed that the description is separate from the universal constructor. This is not trivial. Physicist Erwin Schrödinger confused the program and the constructor in his 1944 book What is Life?, in which he saw chromosomes as “architect’s plan and builder’s craft in one”. This is wrong. The code script contains only a description of the executive function, not the function itself.” (Sydney Brenner)

two roles of information

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fundamental principle of organized complexity

Leads to open-ended evolution

General principle that includes Natural Selection

Von Neumann described this scheme before the structure of DNA molecule was identified in 1953 by Watson & Crick

semitotic closure

(semiotic coupling)

symbolic memory

code

nonlinear dynamics

Howard Pattee


Pattee, HH [2001] Biosystems 60 (1):5-21
importance of the “external tape”

In mind and culture

“The spoken symbol perishes instantly without material trace, and if it lives at all, does so only in the minds of those who heard it” (Samuel Butler)

### Written language as external symbols

- **Invention resulted in profound cognitive discontinuity**
  - Eric A. Havelock: “The written word—the persistent word—was a prerequisite for conscious thought as we understand it. An irreversible change in human psyche”
  - Walter Ong: “[seeing oral literature as a variant of writing is] “rather like thinking of horses as automobiles without wheels.”
    - “an oxymoron laced with anacronism; (James Gleick)
    - Aleksander Luria studied illiterate people in Uzbekistan: oral people cannot think in oral syllogisms
  - **Vocabulary size**
    - oral language: a few thousand words
    - written language: well over a million words, grows by thousands of words a year

“Spoken words also transport information, but not with the self-consciousness that writing brings. Literate people take for granted their own awareness of words, along with the array of word-related machinery: classification, reference, definition.” (James Gleick)
selfish genes and memes as crystals, information in the wild

“Let the whole outside world consist of a long paper tape”. —John von Neumann, 1948

- the replicator ("crystal") gene and meme
  - Information as its own replicator
    - “The gene has its cultural analog, too: the meme. In cultural evolution, a meme is a replicator and propagator” (James Gleick)
    - What lies at the heart of every living thing [is] information, words, instructions. [...] Think, instead, of a billion discrete, digital characters carved in tablets of crystal. —Richard Dawkins (1986)

- Disembodied information
  - Selfish genes and memes as autonomous crystals are a throwback to Schrödinger
    - Dawkins’ gene/meme is not the von Neumann/Turing code nor the molecular biology gene

- semiotic control networks
  - requires code, dynamics, embodiment, interaction, symbolic control of matter,

“The information has been detached from any person, detached from the speaker's experience. Now it lives in the words, little life-support modules”. (James Gleick)
Network Semiotic Control (cybernetics)

- The power of Turing’s tape in generating complexity is coupling with Von Neumann’s constructor
  - With a universal code, semiotic control can be “plug-and-play”
  - separate but coupled
- Chalmer’s and Clark’s extended mind
  - Cognitive science requires both neuroscience and understanding of semiotic coupling with external tape

“Let the whole outside world consist of a long paper tape.” —John von Neumann, 1948
The human mental machinery led our species to have self-awareness but, at the same time, a sense of justice, willing to punish unfair actions even if the consequences of such outrages harm our own interests. Also, we appreciate searching for novelties, listening to music, viewing beautiful pictures, or living in well-designed houses.

However, why is this so? What is the meaning of our tendency, among other particularities, to defend and share values, to evaluate the rectitude of our actions and the beauty of our surroundings? **The human mental machinery obviously refers to the brain, so the answer to the preceding questions must come from neural considerations.** What brain mechanisms correlate with the human capacity to maintain inner speech, or to carry out judgments of value? To what extent are they different from other primates’ comparable behaviors?

where does cognition lay?

“Let the whole outside world consist of a long paper tape”. —John von Neumann, 1948

Semiotic closure in culture is a general principle (system) of evolution of open-ended complexity
- Are there societies without writing systems capable of constructing complex structures and technology?
  - Brains with symbols are very powerful, but writing systems do not construct.

Brains with tapes
- Same brains (same genes and biochemistry), different collective behavior via external tape.
- Does it make sense to study cognition exclusively by looking at the brain’s molecular level?

Inca Quipus

THANK YOU!

OBRIGADO!