Turing’s Tape, Von Neumann
And the design principle of open-ended, multi-level complexity
Assignments: 35%
- Students will complete 4/5 assignments based on algorithms presented in class

Lab meets in I1 (West) 109 on Lab Wednesdays
- Lab 0: January 14th (completed)
  - Introduction to Python (No Assignment)
- Lab 1: January 28th
  - Measuring Information (Assignment 1)
  - Graded
- Lab 2: February 11th
  - L-Systems (Assignment 2)
  - Graded
- Lab 3: March 25th
  - Cellular Automata & Boolean Networks (Assignment 3)
  - Graded
- Lab 4: April 8th
  - Genetic Algorithms (Assignment 4)
  - Being graded
- Lab 5: April 22nd
  - Ant Clustering Algorithm (Assignment 5)
  - Due May 4th
Readings until now

- **Class Book**
    - Chapters 1, 2, 3, 7, 8
    - Chapter 5, all sections
    - Section 7.7, 8.3.1, 8.3.6, 8.3.8-10

- **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”
  - posted online @ http://informatics.indiana.edu/rocha/i-bic

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Projects

- Due by **May 6th** in Oncourse
  - ALIFE 15 (14)
    - Actual conference due date: 2016
    - [http://blogs.cornell.edu/alife14nyc/](http://blogs.cornell.edu/alife14nyc/)
    - 8 pages (LNCS proceedings format)
    - [http://www.springer.com/computer/lncs?SGWID=0-164-6-793341-0](http://www.springer.com/computer/lncs?SGWID=0-164-6-793341-0)
  - Preliminary ideas **overdue**!
- Individual or group
  - With very definite tasks assigned per member of group

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Natural design principles

exploring similarities across nature

- self-similar structures
  - Trees, plants, clouds, mountains
  - Morphogenesis
- Mechanism
  - Iteration, recursion, feedback
- Unpredictability
  - From limited knowledge or inherent in nature?
  - Mechanism
  - Chaos, measurement
- Emergence, and self-organization
  - Complex behavior from collectives of many simple units or agents
  - Cellular Automata, development, morphogenesis, brains
- Mechanism
  - Parallelism, multiplicity, multi-solutions, redundancy
- (open-ended) Evolution
  - Adaptation, novelty, creativity, learning
  - Mechanism
  - Reproduction, transmission, variation, selection
- Collective behavior, network causality
  - Behavior derived from many inseparable sources
  - Environment, ant colonies, embodiment, epigenetics, culture, immune systems, economic markets
- Mechanism
  - Interactivity, stigmergy, non-holonomic constraints

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Turing’s tape

a fundamental principle of computation

- “On computable numbers with an application to the Entscheidungsproblem”
  - Turing machine, universal computation, decision problem
- Machine’s state is controlled by program, while data for program is on external tape
  - every machine can be described as a number that can be stored on the tape for another machine
    - Including a Universal machine
- distinction between numbers that mean things (data) and numbers that do things (program)
Charles Babbage (1791 – 1871) and Ada Lovelace (1815-1852)

The analytical engine had an “external tape”

Turing on programs (numbers as instructions):
“[Babbage] had all the essential ideas [and] planned such a machine, called the Analytical Engine. […]”

- general-purpose mechanical digital computer.
  - Separated memory store from a central processing unit (or ‘mill’)
  - able to select from among alternative actions consequent upon the outcome of its previous actions
    - Conditional branching: Choice, information
  - Mechanical cogs not just numbers
    - Variables (states/configurations)
- Programmable
  - instructions on punched cards

“It is only a question of cards and time, […] and there is no reason why (twenty thousand) cards should not be used if necessary, in an Analytical Engine for the purposes of the mathematician”. Henry Babbage (1888)
universal constructor

Universal Constructor
Given a description, produces any automaton from available parts.

distinction between numbers that mean things and numbers that do things.

two roles of information
Data/Program (Turing)
Description/Construction
Passive/Active

Von Neumann, J. [1949]. “Theory and organization of complicated automata.” 5 lectures at University of Illinois

Von Neumann

universal constructor

Description
Representation of automaton $X$

Universal Constructor
Given a description, produces any automaton from available parts.

distinction between numbers that mean things and numbers that do things.

two roles of information
Data/Program (Turing)
Description/Construction
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Von Neumann, J. [1949]. “Theory and organization of complicated automata.” 5 lectures at University of Illinois
universal constructor for replication

Universal Constructor

Available parts

\[ \phi(A) \]

Description

Makes a copy of itself
But the copy cannot keep on copying

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Von Neumann’s generalization of Turing’s tape as a general principle (system) of **self-replication**

Description is copied **separately**
- Construction: **interpreted** (horizontal transmission)
- Copy: **uninterpreted** (vertical Transmission)

- operations
- universal copier

Φ(A,B,C)
Von Neumann’s generalization of Turing’s tape as a general principle (system) of evolution (of open-ended complexity)

\[ \Phi(A, B, C, D) \]

D for functions not involved in reproduction
Mutations in D propagated vertically
Leads to open-ended evolution
Von Neumann described this scheme before structure of DNA was identified

distinction between numbers that mean things and numbers that do things.

two roles of information
- data/program (Turing)
- description/construction
- passive/active
- genotype (vertical) / phenotype (horizontal)

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)
Von Neumann’s generalization of Turing’s tape

the cybernetics of biocomplexity

“What English speakers call “computer science” Europeans have known as informatique, informatica, and informatik. Now even biology has become an information science, a subject of messages, instructions, and code. Genes encapsulate information and enable procedures for reading it in and writing it out. […] The body itself is an information processor. [...]. DNA is the quintessential information molecule.” (James Gleick)

(most?) fundamental principle of organized complexity
Mutations in D can be propagated only vertically
Leads to open-ended evolution

Informatics as a science
modeling and analysis of physical phenomena
General principle that includes Darwin/Mendel’s Natural Selection
Von Neumann described this scheme before structure of DNA molecule was identified in 1953 by Watson & Crick

“What lies at the heart of every living thing […] is information, words, instructions…. If you want to understand life, don’t think about vibrant, throbbing gels and oozes, think about information technology.” (Richard Dawkins.)

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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 (replicator structures)
  - “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)


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self-replication and the search for the aperiodic crystal
not enough for open-ended evolution

- 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

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**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

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**Sheath**: state ‘2’

- Creates left elbow

**Inner cells**: “genetic information”

- Extends sheath
Hiroki Sayama: A New Structurally Dissolvable Self-Reproducing Loop Evolving in a Simple Cellular Automata Space, *Artificial Life*, vol.5, no.4, pp.343-365, 1999

More recent: [http://necsi.org/postdocs/sayama/sdsr](http://necsi.org/postdocs/sayama/sdsr)


**Variation on Langton’s loop**

- More robust to initial conditions and noise
- CA leads to different “species” of loops
  - competition
- 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
identifying the loci of genetic information
the discovery of the genetic tape

- 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 (Schroedinger, Delbruck, phage group)
decoupled information

What other biochemical components can be **fossilized** this way?


Orlando, L. et al. [2013] Nature doi.org/10.1038/nature12323
The “information turn”

- Unlike Schrödinger, Turing and Von Neumann had no direct effect on molecular biology
- But the “external tape” separated from the constructor (semiotic closure) has become an unavoidable principle of organization of biocomplexity
- A new synthesis?
  - In 1971 Brenner: “in the next twenty-five years we are going to have to teach biologists another language still, [...] where a science like physics works in terms of laws, or a science like molecular biology, to now, is stated in terms of mechanisms, maybe now what one has to begin to think of is algorithms. Recipes. Procedures.”

“The concept of the gene as a symbolic representation of the organism — a code script — is a fundamental feature of the living world and must form the kernel of biological theory. [...] at the core of everything are the tapes containing the descriptions to build these special Turing machines.” (Sydney Brenner)

Genotype
DNA

Replication

Inherited variation

Germ cell line

Germ cell line

Environmental ramifications

Amino acid chains

Development, regulation

Phenotype

Organism

Genotype

Phenotype/phenotype

Transcription

Translation

Genetic information at work

Informatics
Luis Rocha 2015

Biologically Inspired computing
Venter’s experiment with synthetic genome


riding genetic control of phenotype via the “external tape”
Is life Fuzzy?

- List of properties
  - Growth
  - Metabolism
  - Reproduction
  - Adaptibility
  - Self-maintenance (autonomy)
  - Self-repair
  - Reaction
  - Evolution
  - Choice

- Threshold of complexity
  - Categorization and Control
  - Function (self-reference)
  - Open-ended evolution
  - Information

Requires two roles of information:
- data/program (Turing Tape)
- description/construction (V.N. S.R.)
- passive/active
- genotype (vertical) / phenotype (horizontal)

How to identify it?

viruses, candle flames, the Earth, certain robots?
autonomy and semiotic closure

the tape is not necessarily self-contained in cells, brains, or machines

semiotic closure

two roles of information
data/program (Turing)
description/construction
passive/active
genotype/phenotype

decoupling and externalization enable collective, multi-level behavior


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Sequences from RNA and DNA viruses found in host genomes account for 6 to 14% of host genomes. 

~8% of human DNA.

Endogenous retroviruses (ERVs) comprise more DNA than host proteome.

exciting and strange discoveries about design principles of life come from the “external tape” in biology

- DNA transfer from bacteria to the fly [Dunning Hotopp, 2007]
- importance of non-coding RNA in life
- Exploiting “automaton C”
- eukaryotic complexity [Taft et al, 2007]
- patterning [Martello et al, 2007]
- essential gene regulation and development [Mattick, 2005, 2007]
- epigenetic neural development and modulation [Mehler and Mattick, 2007]
- non-transcribed RNA involved in extra-genomic inheritance
- most of the evolutionary innovation responsible for differences between marsupials and placental mammals occurs in non-protein coding DNA [Mikkelsen et al, 2007]

evidence for the importance of the external symbolic tape

"We've found at least one species where the parasite's entire or nearly entire genome has been absorbed and integrated into the host's [...] The host's genes actually hold the coding information for a completely separate species." Jack Werren

Exciting and strange discoveries about design principles of life come from the “external tape” in biology.

- DNA transfer from bacteria to the fly [Dunning Hotopp, 2007] and Human.
- Importance of non-coding RNA in life.
  - Exploiting “automaton C”
    - Eukaryotic complexity [Taft et al, 2007]
    - Patterning [Martello et al, 2007]
    - Essential gene regulation and development [Mattick, 2005, 2007]
    - Epigenetic neural development and modulation [Mehler and Mattick, 2007]
    - Non-transcribed RNA involved in extra-genomic inheritance

Evidence for the importance of the external symbolic tape:

Acinetobacter-like integrations into the genome of acute myeloid leukemia samples.
Evidence for the importance of the external symbolic tape

- Exciting and strange discoveries about design principles of life come from the “external tape” in biology
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U-insertion and A-to-I substitution

RNA Editing

General principle for Genome recoding

Mechanism of receptor diversity

**V(D)J or Somatic Recombination:**
randomish generation of gene segments (variable, diverse, and Joining)

**TdT:** Terminal deoxynucleotidyl transferase, adds nucleotides (without a template) to VDJ exons

**Controlled, private Natural Selection**

Goldman & Prabhakar. Immunology Overview.
indirect gene effects and other genomic tape challenges to autonomy

- Focus on autonomy prevents understanding the role of genes in horizontal control
  - Assuming that the genetic component of a particular trait is a) for vertical transmission and b) confined to genes in a cell
- Storage of genes in environment (extended regulatory genome)
  - Control of gene expression from without
    - Wolbachia confers Drosophila differential virus protection
    - Plant genes control neighbors and pollinators behavior
  - Bacterial metagenome
    - Ubiquitous regulatory transfer is major factor of phenotypic plasticity
- Origin of life
  - Focus of autonomous self-replication prevents study of open, horizontal interactions
    - Collective evolution of the genetic code via HGT
  - Genetic control as open network (semiopoiesis, computation)
    - Autonomy an emergent property for robustness

Indirect gene effects and other genomic tape challenges to autonomy

- Focus on autonomy prevents understanding the role of genes in horizontal control
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    - Wolbachia confers Drosophila differential virus protection
    - Plant genes control neighbors and pollinators behavior

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

M.A. Genung et al., *PLOS ONE*, 8:e53718, 2013..
The fruit of 40 fruit

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Next lectures

readings

- **Class Book**
    - Chapter 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