lecture 13

Computation

ALAN TURING, 1912 - 1954
course outlook

Sections I485/H400

- 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)
      - Due: April 1st
Readings until now

- **Class Book**
    - Chapters 1, 2, 7.1-7.5, 8.1-8.2, 8.3.10

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

- **Other materials**
    - Chapters 10, 11, 14
Projects

- Due by May 4th 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 **due by April 1st**!

- Individual or group
  - With very definite tasks assigned per member of group
Many systems biology models operate in the ordered regime.

Dynamical systems capable of computation exist well before the edge of chaos:
- A much wider transition? A “band” of chaos.

Most important information transmission and computation in Biology an altogether different process than self-organization:
- Turing/Von Neumann Tape
where do numbers come from?

- **Number Perception**
  - Recognition of a discrete quantity of objects distinct from a continuous quantity
    - Exists even in animals, birds, and insects

- **Counting**
  - A measurement process from a physical system to a symbol
    - E.g. notches on a bone
    - First symbols were probably numbers

- **Lebombo bone**
  - Oldest counting tool is a piece of baboon fibula with 29 notches from 35,000 BC, discovered in the mountains between South Africa and Swaziland
    - Probably representing the number of days in a Moon Cycle
  - “Wolf Bone” from Czech Republic
    - with 55 notches in groups of 5, from 30,000 BC.
The *Ishango Bone*

- Oldest Mathematical Artefact?
  - 20,000 BC, border of Zaire and Uganda
- Used as a counting tool?
  - 9, 11, 13, 17, 19, 21: odd numbers
  - 11, 13, 17, 19: prime numbers
  - 60 and 48 are multiples of 12
from counting to computation

abstracting symbol mappings

- **Counting**
  - A measurement process from a physical system to a symbol
    - A mapping between discrete objects and symbols
    - First numbers were not completely abstract
      - Specific attributes of concrete objects

- **Computation**
  - Abstract concept of one-to-one pairing of symbols
  - Mathematical concept of *function*

- **Formalization**
  - To completely abstract away the significance of measuring observables from real objects

“When you can measure what you are speaking of and express it in numbers you know that on which you are discoursing. But if you cannot measure it and express it in numbers. your knowledge is of a very meagre and unsatisfactory kind”. Lord Kelvin
“The most direct and in a sense the most important problem which our conscious knowledge of nature should enable us to solve is the *anticipation of future events*, so that we may arrange our present affairs in accordance with such anticipation”. (Hertz, 1894)
producing symbols from symbols

\[ f : X \rightarrow Y \]

**Function**: a complete and unambiguous mapping between sets of symbols

\[ y = f(x) \]

Leibniz introduced the word in 1694

**Computation**: automatic process or method of implementing a function
from counting to computation

abstracting symbol mappings

- **Formal Mathematics**
  - **Axiomatic System**
    - Finite set of symbols
      - Numbers, letters
    - Strings of symbols
      - expressions
    - Unambiguous rules to produce strings
      - axioms
    - Unambiguous rules to re-write strings
      - deductions, productions
  - **Semantic Independence from Syntax**
    - All strings and properties (theorems) derived entirely from axioms

“Insofar as the propositions of mathematics are certain they do not refer to reality; and insofar as they refer to reality, they are not certain”. Albert Einstein
Computing with numbers

- It is always possible to encode any symbol string into a sequence of integers
- A sequence of integers can be mapped into a single natural number
  - Gödelization (prime factorization)
- Computer scientists can concentrate on functions that take a single number as input and output
  - Computation as a mapping of numbers to other numbers

Models of Computation

- How to construct number mappings
  - Turing machine, general recursive functions, λ-calculus
Alan Turing (1912-1954)

relevant contributions to biocomplexity

- “The chemical basis of morphogenesis”
  - Reaction-diffusion systems

- “Computing machinery and intelligence”
  - The “Turing Test”

- “On computable numbers with an application to the Entscheidungsproblem”
  - Turing machine, universal computation, decision problem

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 a program, while data for program is on limitless 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)

“The fundamental, indivisible unit of information is the bit. The fundamental, indivisible unit of digital computation is the transformation of a bit between its two possible forms of existence: as [memory] or as [code]. George Dyson, 2012.
At every discrete time instance the machine is in a single state.

Control containing an algorithm / program that specifies the required computation.

Program is a state transition table:

<table>
<thead>
<tr>
<th>state</th>
<th>Read symbol</th>
<th>Next state</th>
<th>Write symbol</th>
<th>Tape move</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-</td>
<td>left</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>0</td>
<td>1</td>
<td>right</td>
</tr>
</tbody>
</table>
Turing machines beyond the decision problem

“‘Words’ coding the orders are handled in the memory just like numbers” --- distinction between numbers that mean things and numbers that do things.

- realizing the power of Turing’s tape
  - physical (electronic) computers
  - emphasized the importance of the stored-program concept (the external tape)
    - EDVAC
  - allows machine to modify its own program
    - von Neumann architecture: The separation of storage from the processing unit.
      - programs can exist as data (two roles)
      - Converts tape to fixed-address memory (random-access memory)

- prolific scientist
  - Father of game theory, cellular automata, artificial life, quantum mechanics, cybernetics, artificial intelligence,…
  - saw Turing’s tape as a fundamental principle for generating open-ended complexity

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

- **Process of rewriting strings in a formal system according to a program of rules**
  - Operations and states are syntactic
  - Symbols follow syntactical rules
  - **Rate of computation is irrelevant**
    - Program determines result, not speed of machine
  - Physical implementation is irrelevant for result

- **Computer**
  - **Physical device** that can reliably execute/approximate a formal computation
    - Errors always exist
    - Design aims to make rate and dynamics irrelevant

“[… ] essential elements in the machine are of a binary […] nature. Those whose state is determined by their history and are time-stable are **memory elements**. Elements of which the state is determined essentially by the existing amplitude of a voltage or signal are called ‘gates’”. Bigelow et al, 1947
Next lectures

readings

- **Class Book**
    - Chapter 2, 7, 8
    - Appendix B.3.2-3 - Turing Machines, Computational complexity
    - Chapter 3, sections 3.1 to 3.4

- **Lecture notes**
  - Chapter 1: What is Life?
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- **Papers and other materials**
  - Optional
      - Chapters 1-4 – Computation