Turing’s Tape And The Design principle of Computation
By Erik Stolterman

- Towards problem solving
- Beyond computing
- Into the natural and social
- Synthesis of information technology
- **Two-dimensional science of systems?**
- **Empirical, computer-aided study/modeling of organization**

**Informatics**

- X-Informatics or Computational X
- Health-
- HCID
- Security
- Geo-
- Data Mining
- Music-
- Geo-
- Complex Systems
- Social Informatics
- Data & Search
- Computer Science

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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
    - **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."
A fundamental principle of computation

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  - Turing, A. M.
  - Turing machine, universal computation, decision problem
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A fundamental principle of computation

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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
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)
Charles Babbage (1791 – 1871) and Ada Lovelace (1815-1852)
The external tape as a general principle (system) of universal computing

- **Analytical engine**
  - “Since Babbage’s machine was not electrical, and since all digital computers are in a sense equivalent, we see that this use of electricity cannot be of theoretical importance…. The feature of using electricity is thus seen to be only a very superficial similarity.” (Alan Turing)

- **Programmable**
  - instructions on punched cards
  - Inspired by the Jacquard Loom
  - Ada Lovelace: the science of operations
    - Set of (recursive) rules for producing Bernoulli numbers (a program)
    - Separation of variable and operational (data) cards
    - would punch out cards for later use
      - “the Engine eating its own tail.” (Babbage)

  distinction between numbers that mean things and numbers that do things.
design principles of computation

Babbage/Lovelace first to try to build it (before Turing)

distinction between *numbers that mean things* and *numbers that do things (move matter)*
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
Von Neumann’s generalization of Turing’s tape as a general principle (system) of self-replication

universal constructor (TM)

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

Description (Tape)

operations  universal copier

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

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

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

semiotic closure

- symbolic memory
- nonlinear dynamics
- code

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

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

Von Neumann’s generalization of Turing’s tape
genesis, computers and the cybernetics of biocomplexity

“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
Leads to open-ended evolution
Informatics as a science
modeling and analysis of physical (semiotic) 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.)

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

history

- 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)

2 different strains of pneumococcus bacteria
initially not well accepted
(No auto-catalysis with DNA)
importance of the “external tape”

in biology

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)

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


Orlando, L. et al. [2013] *Nature* doi.org/10.1038/nature12323

Meyer et al. [2013]. *Nature*. doi:10.1038/nature12788
fundamental principle of biocomplexity as informatics
autonomy and semiotic closure

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

semiotic closure

symbolic memory

nonlinear dynamics

code

symbolic memory

nonlinear dynamics

code

symbolic memory

nonlinear dynamics

code

symbolic memory

nonlinear dynamics

code

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decoupling and externalization enable collective behavior
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. Weiss & Stoye [2013]. “Our Viral Inheritance.” Science.340 (6134): 820-821.
biology in the last 20 years
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
  - 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]

"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
biology in the last 20 years

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Acinetobacter-like integrations into the genome of acute myeloid leukemia samples

Schrodinger vs. Von Neumann

autonomous self-replication vs. decoupled, encoded information


“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

data/program (Turing)
description/construction (Von Neumann)
genotype/phenotype (Biology)

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

fundamental principle of organized complexity

Leads to open-ended evolution

General principle that includes *Natural Selection*

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

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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)
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
  - Memes as crystals are a throwback to Schrödinger
    - Dawkins’ gene/meme is not the von Neumann/Turing code nor the molecular biology gene

- Semiotic closure
  - requires code, dynamics, embodiment

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

- **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

**two roles** of information
- data/program
- description/construction
- genotype/phenotype
- language/brain
- symbol/society-mind-body

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"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?

In the presence of semiotic closure
- Details of cells, brains, and culture can easily become irrelevant
- Borges’ garden of forking paths
external messages

collective behavior via the external tape

- In the presence of semiotic closure
  - Details of cells, brains, and culture can easily become irrelevant
  - Borges’ garden of forking paths
    - All the knowledge on the labyrinth, but Albert is just a symbol
    - Not only is most of the library of Babel meaningless, but things that have meaning, can easily become irrelevant in the intertwined semiotic closures of collective behavior (the garden of forking paths)

If only my mouth, before a bullet shattered it, could cry out that secret name so it could be heard in Germany.... My human voice was very weak. How might I make it carry to the ear of the Chief?

I have won out abominably; I have communicated to Berlin the secret name of the city they must attack. They bombed it yesterday; I read it in the same papers that offered to England the mystery of the learned Sinologist Stephen Albert who was murdered by a stranger, one Yu Tsun. The Chief had deciphered this mystery. He knew my problem was to indicate (through the uproar of the war) the city called Albert, and that I had found no other means to do so than to kill a man of that name. He does not know (no one can know) my innumerable contrition and weariness.