What is "Computing"?

Herbert Jaeger

Jacobs University Bremen

Overview

Part 1: Create Confusion:	*Is that Computing?*
Part 2: Call to Order:	*That is Computing!*
Part 3: Seed Doubt:	*Thinking of Matter*
Part 4: Beyond Computing:	*Thinking Matter*

Part 1: Is that Computing?

Note. Sources of pictures and videos are given in separate hidden slides, visible in online version of this talk.

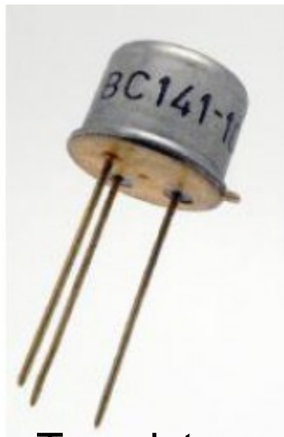
Things that compute (- - really?), selection the first

IBM PS 2

HP-35

Internet (Google server farm)

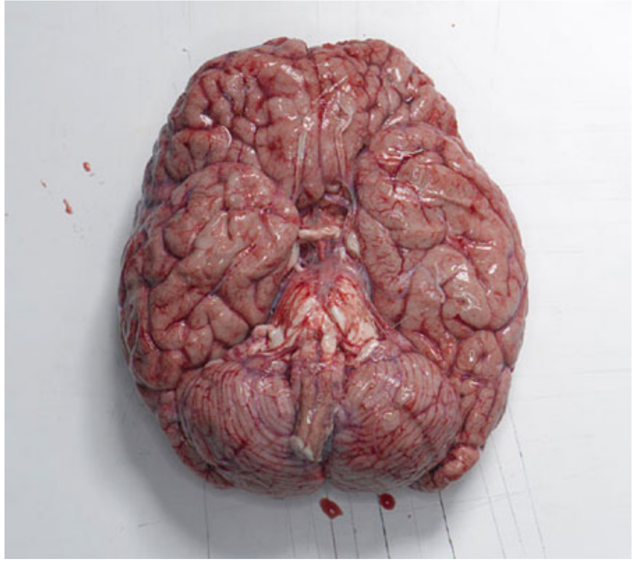
Swatch

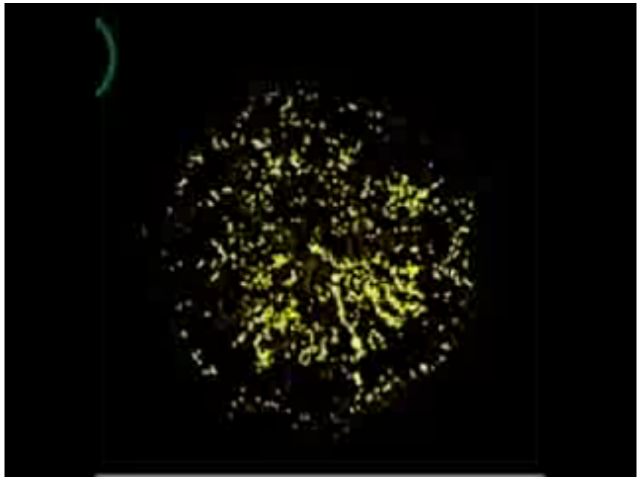


Transistor

Things that compute (or what?), selection the second

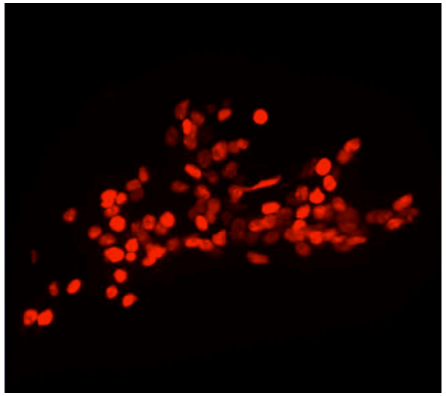
human brain





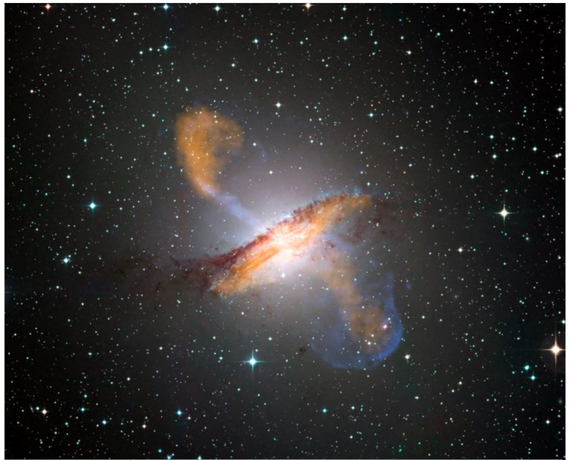
physarum polycephalum

English parliament

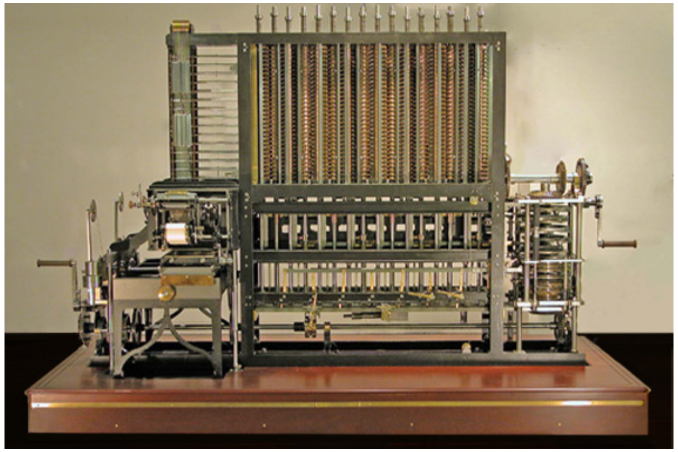


C. elegans brain

Things that compute (- - eh?), selection the third



the universe and everything



Babbage's *difference engine 2*

pendulum

Clock

Tingueley's *meta-matic 17* drawing machine

Big questions asked by serious people

- Are "computing", "calculating", "rational reasoning", "information processing", "signal processing" the same?
- Does "intuition", "feeling", "experiencing", "consciousness" give humans some ultimate extra over machines?
- Can physics at the (sub)quantum level be explained in terms of "computing"?

Part 2: *That* is Computing!

The answer is...

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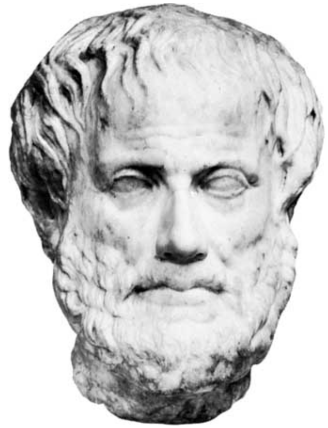
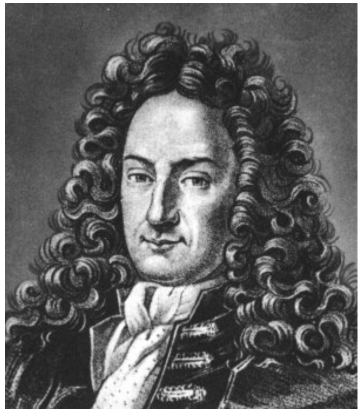
Deep historical roots

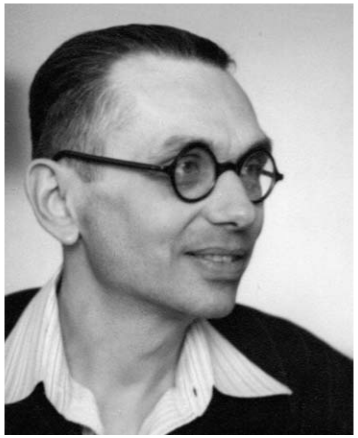
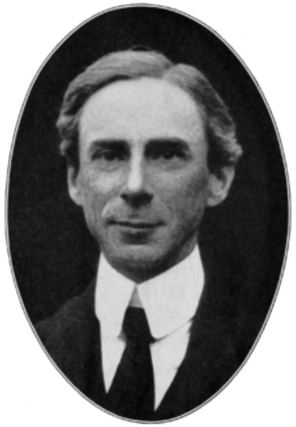
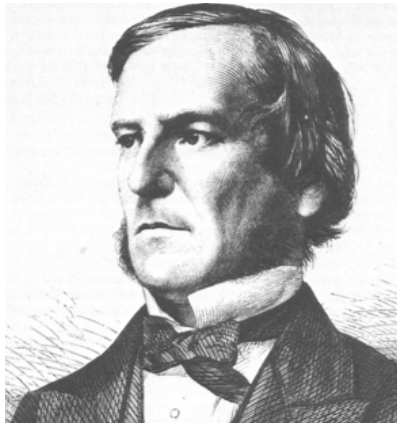


Aristotle (384-322 BC) *"All men are mortal. All Greeks are men. Hence, all Greeks are mortal"* – Syllogistic logic reasoning as basis of irrefutable reasoning from truth to truth.



Leibniz (1646-1716) *Characteristica Universalis* and *Calculus Ratiocinator* – Vision of a universal logical language and mechanical rules of argumentation

Boole, Frege, Hilbert, Russell, Gödel (~1850'ies to 1930'ies) *mathematical logic systems* – dream of mechanically deciding all mathematical questions

THE question answered by Turing with Turing machines: Hilbert's *Entscheidungsproblem*

Is there an effective procedure for deciding every mathematical concecture?

Axioms $\overset{?}{\Rightarrow}$ Claimed Theorem

$$\{a_1, ..., a_n\} \overset{?}{\Rightarrow} c$$

$$a_1\#...\#a_n\#c \mapsto \{yes, no\}$$

$$< codeNr\ of\ a_1\#...\#a_n\#c > \mapsto \{0, 1\}$$

a function $f: \mathbb{N} \mapsto \mathbb{N}$ that can be specified by a finite text

Is there an effective procedure for computing every finitely definable function on the natural numbers?

Is there an effective procedure for computing every finitely definable function on the natural numbers?

- Turings approach: investigate and formalize what a *human* "computer" can and cannot do with the aid of his [!] brain and paper and pencil

- Quotes on next slides are from Turing's groundbraking 1936 paper

ON COMPUTABLE NUMBERS, WITH AN APPLICATION TO THE ENTSCHEIDUNGSPROBLEM

"Computing is normally done by writing certain symbols on paper. [...] I shall also suppose that the number of symbols which may be printed is finite. If we were to allow an infinity of symbols, then there would be symbols differing to an arbitrarily small extent j . The effect of this restriction of the number of symbols is not very serious. It is always possible to use sequences of symbols in the place of single symbols."

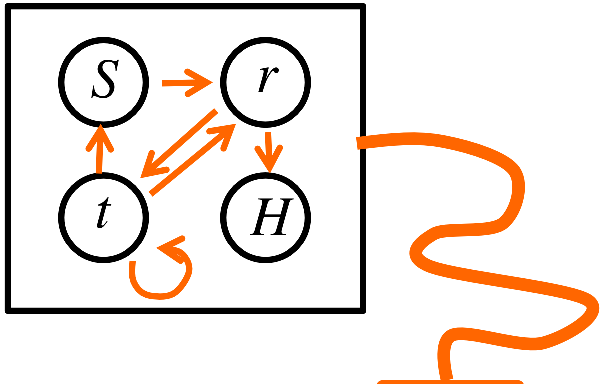
- An "effective procedure" uses finite set of identifiable symbols (an *alphabet*).
- There must be an unlimited supply of "paper" (*computer memory*) for storing arbitrarily long symbol sequences

"The behaviour of the computer at any moment is determined by the symbols which he is observing, and his " state of mind " at that moment. [...] We will also suppose that the number of states of mind which need be taken into account is finite. The reasons for this are of the same character as those which restrict the number of symbols. If we admitted an infinity of states of mind, some of them will be "arbitrarily close" and will be confused."

- The apparatus ("mind") which processes symbolic information is a finite state-switching system.

The Turing Machine (TM)

Is there a finite state-switching machine commanding on an unbounded symbol-sequence memory, which can compute every finitely definable function on the natural numbers?



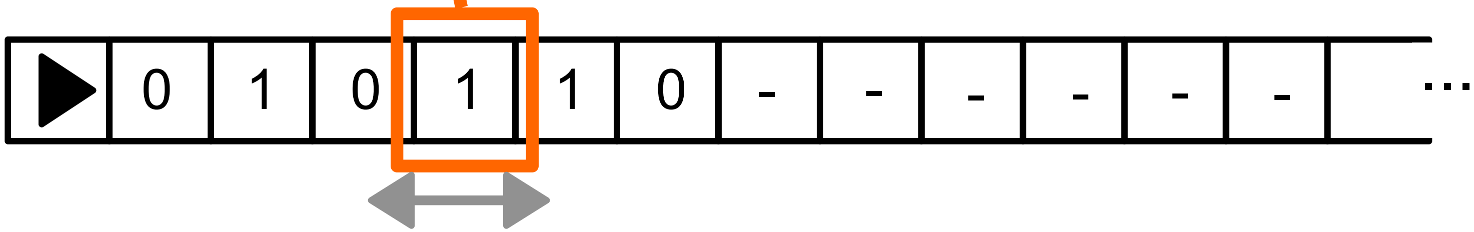
transition rule table:

$(S, \blacktriangleright) \rightarrow (r, \blacktriangleright, \rightarrow)$

$(r, 0) \rightarrow (t, 1, -)$

...

$(t, 1) \rightarrow (H, 1, \rightarrow)$



tape alphabet: {▶, 0, 1, -}

finite state set, including start and halt state: $\{S, r, t, H\}$

Demo: compute function $f(n) = 2n$

S	$\boxed{\blacktriangleright}$	1	0	1	-	…	**Start:** input $n = 5$ (binary)
r	▶	$\boxed{1}$	0	1	-	…	rule: $(S, \blacktriangleright) \rightarrow (r, \blacktriangleright, \rightarrow)$
r	▶	1	$\boxed{0}$	1	-	…	rule: $(r, 1) \rightarrow (r, 1, \rightarrow)$
r	▶	1	0	$\boxed{1}$	-	…	rule: $(r, 0) \rightarrow (r, 0, \rightarrow)$
r	▶	1	0	1	$\boxed{-}$	…	rule: $(r, 1) \rightarrow (r, 1, \rightarrow)$
H	▶	1	0	1	$\boxed{0}$	…	rule: $(r, \text{-}) \rightarrow (H, 0, \text{-})$, **halt!**

Turing Machines, comments

- TMs can compute all functions that your PC can compute
- Church-Turing (-Rosser) hypothesis: *Every function that can be computed by whatever "effective" mechanism can also be TM-computed*
- Two main arguments in favor of this hypothesis:
  1. so far, no counterexample
  2. many other formalizations of "effective computing mechanism" proven equivalent to TMs
- Turing found a finitely definable function f that he proved is not TM-computable: the *halting problem*
- This gives a negative answer to Hilbert's Entscheidungsproblem: *there is no effective procedure to decide all mathematical conjectures*

Cellular automata (CA),
another model of universal computation

1-dimensional CA, by example

…	0	1	0	0	1	0	1	0	0	…	$t = 0$
…	0	0	1	1	0	0	0	1	1	…	$t = 1$
…	0	1	1	1	1	0	1	1	0	…	$t = 2$
…	1	1	0	0	1	0	1	1	0	…	$t = 3$

…

0	0	0	0	0	1
	0			1	
0	1	0	0	1	1
	0			1	
1	0	0	1	0	1
	1			0	
1	1	0	1	1	1
	1			0	

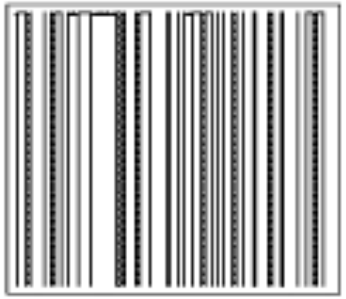
Cellular automata, core properties

- Like TMs:
  - finite symbol set (memory symbols and state symbols coincide)
  - discrete time "computing steps"
  - update rules in finite table
  - unbounded memory
- CA first introduced by von Neumann (and others, 1950'ies) as model for biology-inspired self-reproducing systems
  - maybe first appearance of theme "life =? computing"
- CA can compute exactly the same functions $f: \mathbb{N} \mapsto \mathbb{N}$ as TMs
- Use in Computer Science: basic model of parallel computing

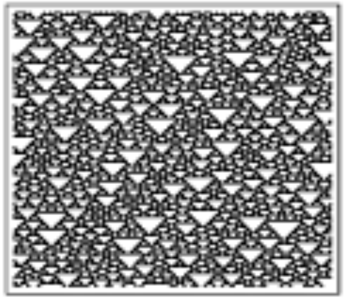
CAs for modeling nature

- for 1-dim, 2-dim, ... systems
- model for spatio-temporal dynamics
- PDE models can be approximated by CAs via discretization
- Popular to model pattern formation
- Popular to analyze self-organization classes in spatiotemporal systems

Wolfram Class 1



Class 2



Class 3

Class 4

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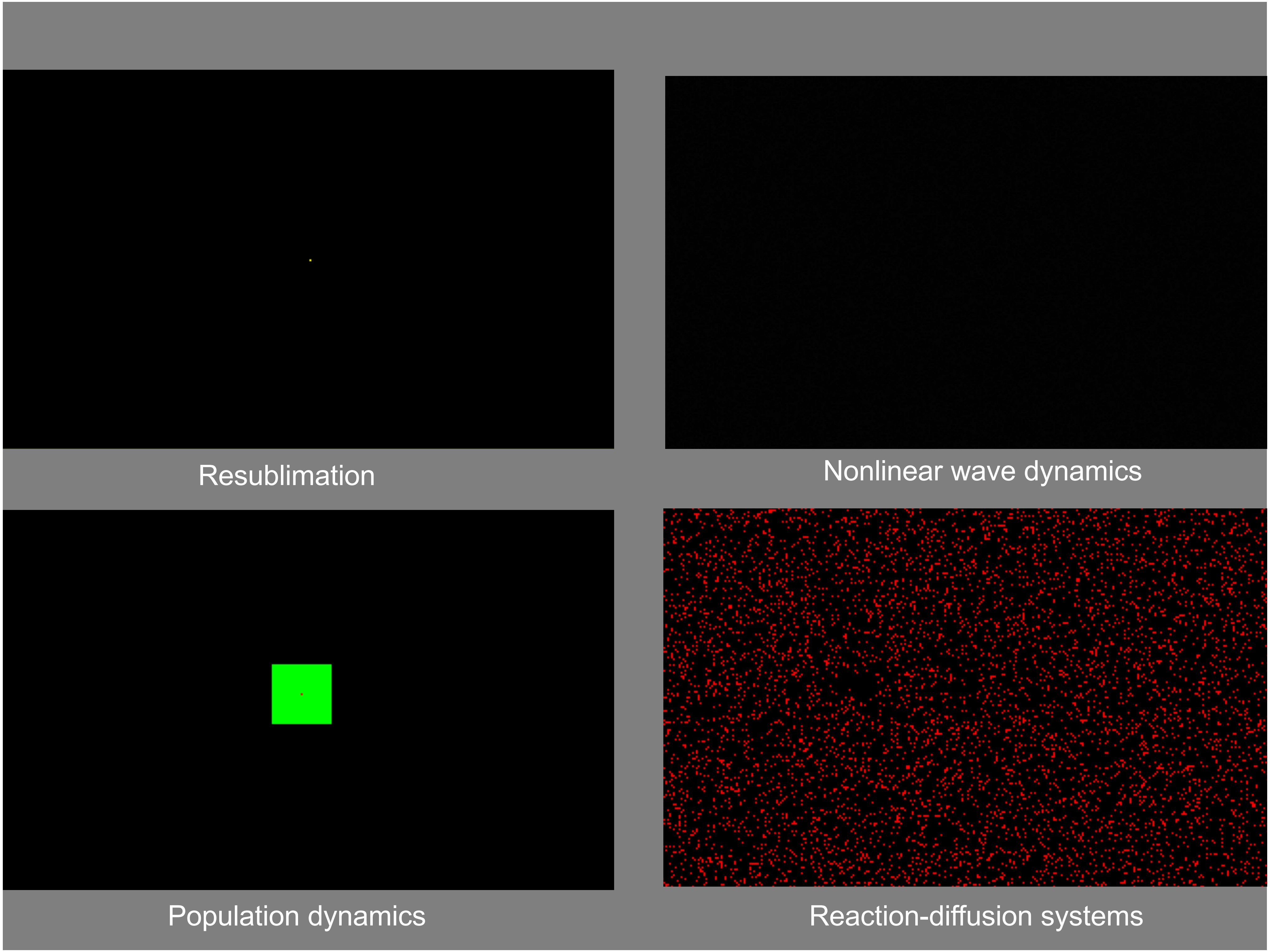

Resublimation
Nonlinear wave dynamics
Population dynamics
Reaction-diffusion systems

What the Turing Machine is and is not

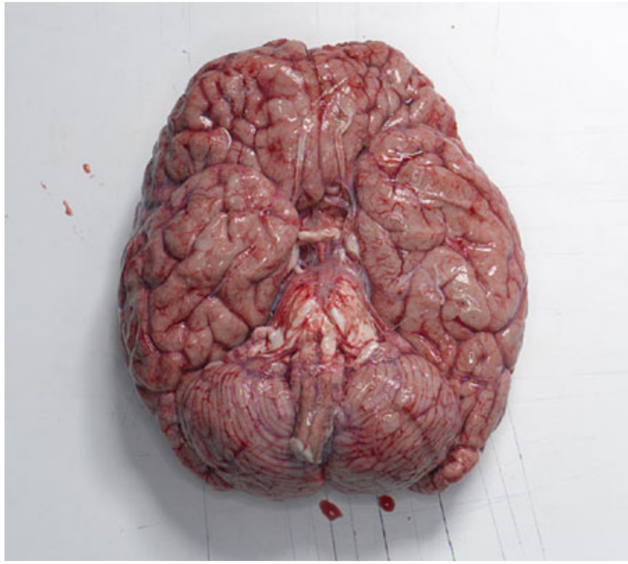
- It IS: A formal definition of a class of numerical functions
- It IS: an intuitive summary of what gives *effective* computation:
  - finite symbol set
  - finite state set
  - coding information in finite but arbitrarily long symbol strings,
  - finite set of symbol string manipulation rule
- It is NOT: a practical device or engineered "machine"

Part 3: Thinking of Matter

Riddle

- What general-purpose computer came before Turing Machines?

- What computer is hosting the theory of computing?



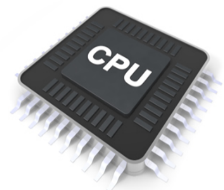
- What computer can do more and do less than TMs, at the same time?

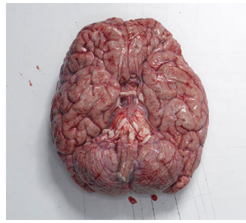
- What singular computing system receives the largest public research funding?

Two worlds of computing

WHEREIN is computing realized? – the material substrates

transistors, copper wires, solder, batteries

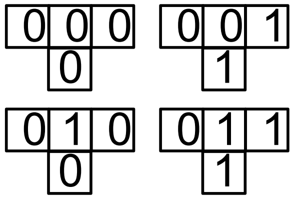


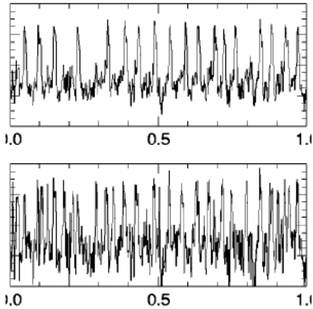


nerve cells, glia cells, vessels, neuro-transmitters, hormones

HOW is it computed? – the "algorithmic" procedures

symbol pattern matching, table lookup, symbol replacement

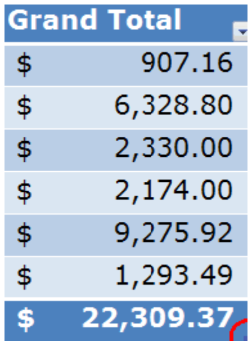




spike pulses, neurotransmitter chemistry, nonlinear neural field dynamics

WHAT is computed? – the tasks

functions, simula-tions, visualizations, digital signals, inter-net host connections, ... *everything*?



Grand Total	
$	907.16
$	6,328.80
$	2,330.00
$	2,174.00
$	9,275.92
$	1,293.49
$	22,309.37

Let me not to the marriage of true minds admit impediments

sonnets, breathing, walking, jokes, tears, tax declarations, nonsense, dreams..., *everything*?

Is it the same?

Q: Can human, brain-based intelligence be explained by / reduced to Turing computation?

A: Yes and no.

The YES IT IS THE SAME faction

"A physical symbol system has the necessary and sufficient means for general intelligent action. [...] By "general intelligent action" we wish to indicate the same scope of intelligence as we see in human action: that in any real situation behavior approprate to the ends of the system and adaptive to the demands of the environment can occur, within some limits of speed and complexity." (From the Turing Award Lecture of Allen Newell and Herbert A. Simon, 1975)

- Explicitly construed as equivalent to universal TMs
- Claimed evidence for *sufficient*: progress in AI
- Claimed evidence for *necessary*: progress in cognitive psychology

Some NO IT'S NOT THE SAME factions

Epistemology

- Scattering of the *same* concept ("explain", "reduce", "functional equivalence", "ontological identity")

Philosophy of mind

- Consciousness, experience of qualia, mental attitudes not captured by symbolic computation

Connectionism

- Information representation and processing in parallel, distributed systems (neural networks) is not symbolic

Behavior-based robotics, "New AI"

- Biological intelligence is situated and embodied

Evolutionary theories of intelligence

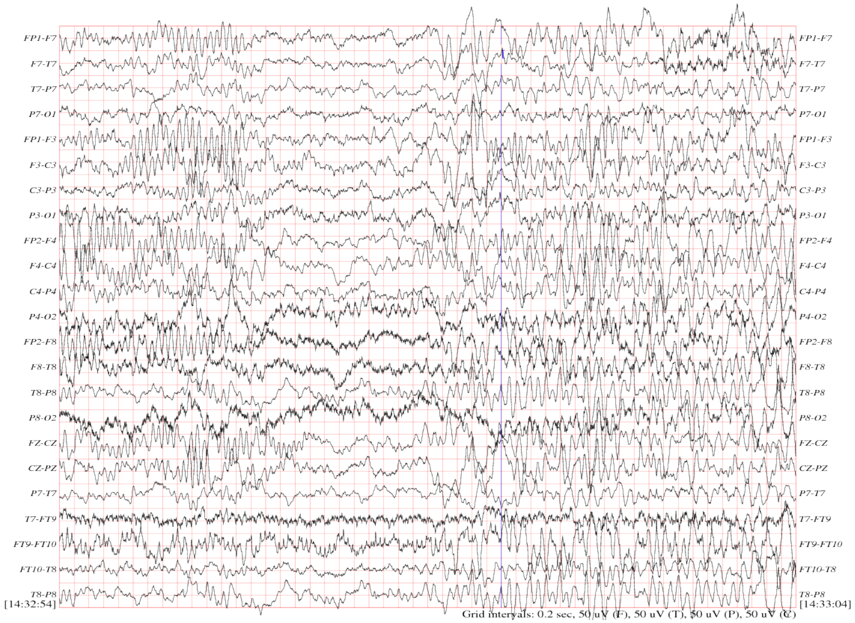
- Rational reasoning and symbolic language emerged from pre-rational intelligence

Clean symbols in messy brains, part 1: analog/quantitative $\leftrightarrow$ digital/symbolic conversions

Representing analog quantities by discrete symbols

- Standard method: Approximate real numbers by (arbitrarily long but finite) digit strings
  - $\pi \approx 3$, - 3.1, -- 3.14, --- 3.141, ...
  - the basis of physics simulations on digital computers
- Alternative method: probabilistic logic
  - proposed by von Neumann 1956
  - represent real numbers by random bit streams
  - $1/3 = 010100101010010...$ (fraction of 1's = $1/3$)
  - elegant: multiplication effected by AND gate
  - biologically more appealing

Representing discrete symbols by analog quantities



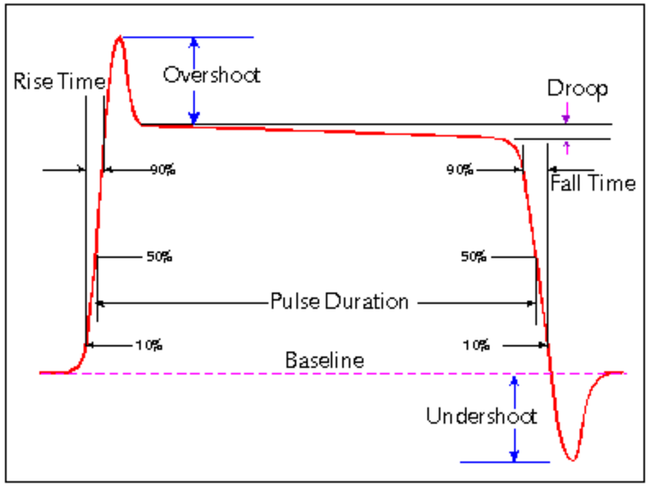
?

$1 + 1 = 2$

- Core question for Physical Symbol System hypothesis
- Important question for unconventional computing / unconventional substrates

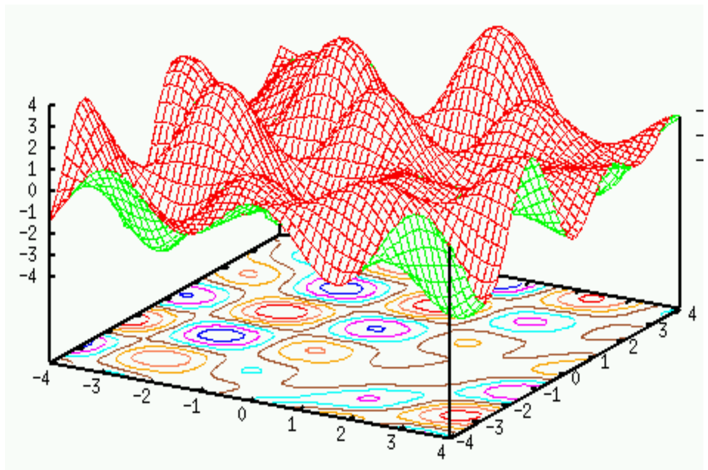
Symbols in dynamical systems, examples

- Bistability
  - digital circuits are analog at heart
  - bistable neurons suspected in prefrontal cortex, associated with working memory



representative pulse waveform

- Multistable systems
  - THE classical model of neural memory: Hopfield networks
  - combined with stochastic sampling dynamics: Boltzmann machines – historical (2006) quickstarter of deep learning



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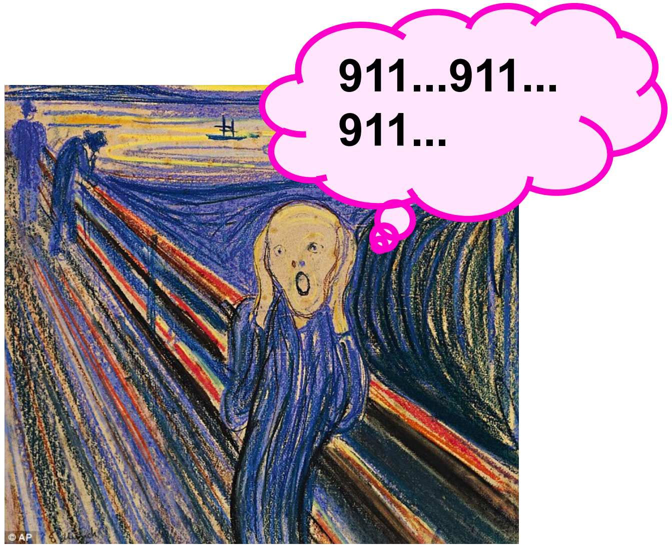
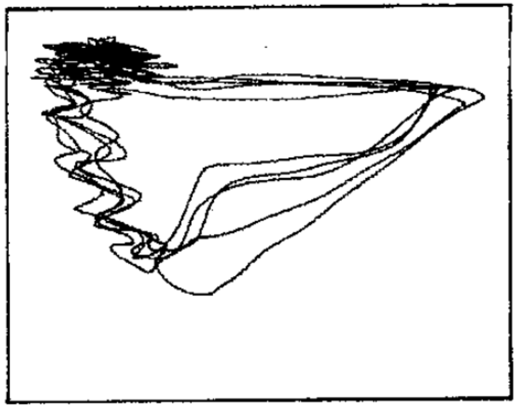
Symbols in dynamical systems, more examples

- Periodic attractors
  - cyclic rehearsal: Baddeley model of working memory
  - rich theory: coupled oscillator systems
  - options to couple together symbolic items



- Chaotic attractors
  - Freeman model of representing odors in olfactory bulb
  - options for representing hierarchical symbolic structures



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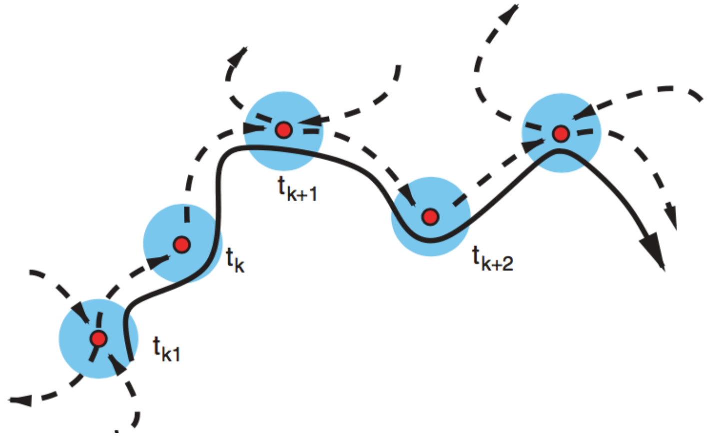
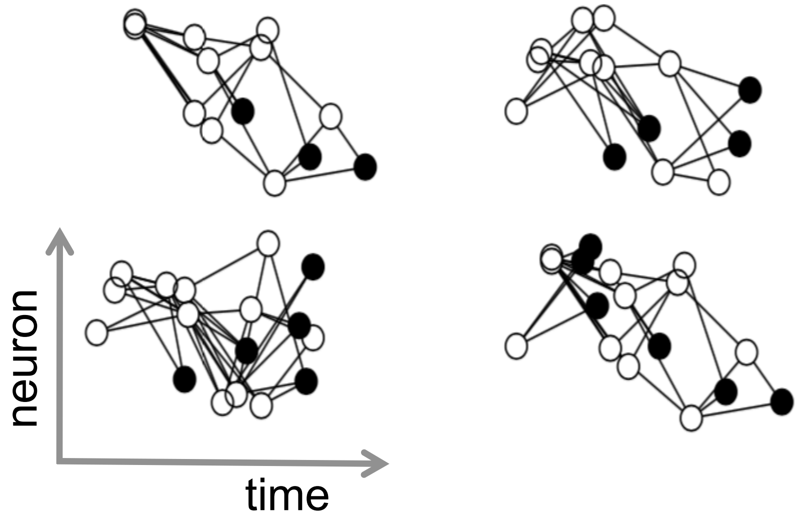
Symbols in dynamical systems, even more examples

- Saddle note dynamics
  - heteroclinic channel model of cognitive dynamics (Rabinovich 2008)
  - option to explain transient stability

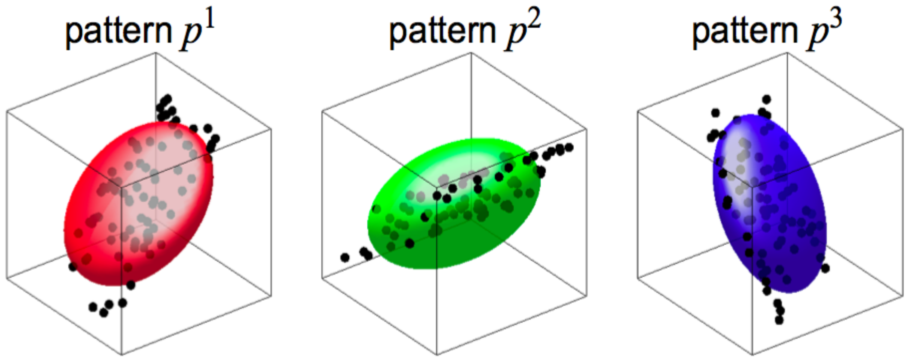


- Spike time patterns
  - e.g. *polychronicity* model of Izhikevich (2006)
  - options to exploit fine-grained neural information

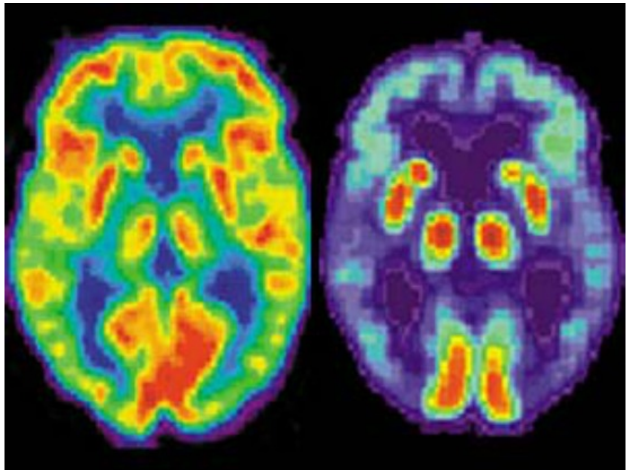


Symbols in dynamical systems, ever more examples

- Conceptors
  - switchable dynamical modes of recurrent neural networks
  - temporal long term memory model for dynamical patterns
  - options for neural coding of conceptual structures



- Spatial coding
  - the grand alternative to attractor-like phenomena
  - "grandmother cells"
  - what you see in neural imaging



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Mind, math and matter: summary comments

- Symbols in neural dynamics?
  - too many candidates for single definite answer
  - hence, unclear whether / in what sense brains "compute"

- Impact on engineering!
  - novel materials share core properties with brain wetware:
    - ✸ analog
    - ✸ unclocked
    - ✸ parallel
    - ✸ stochastic
    - ✸ (very) low precision
    - ✸ drift, aging, irreproducibility

hardly compatible with TM model

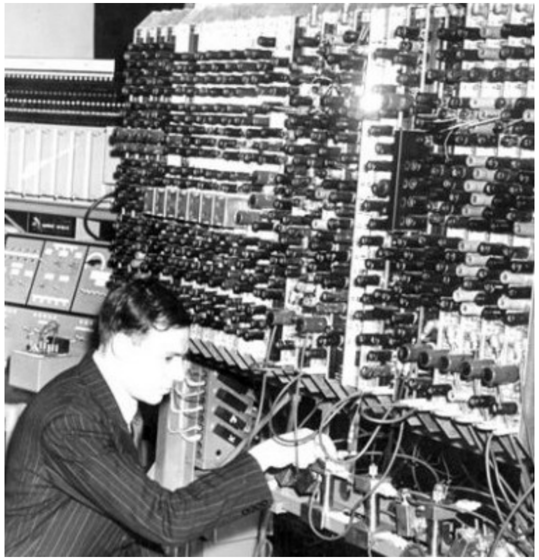
My opinion

Essence of TM computing

Combine few "atomic", static symbols into arbitrarily large, arbitrarily complex data structures

Essence of brain computing

Combine limited small number (7 ± 2) of very complex, dynamical concept instantiations into "organic" states of mind



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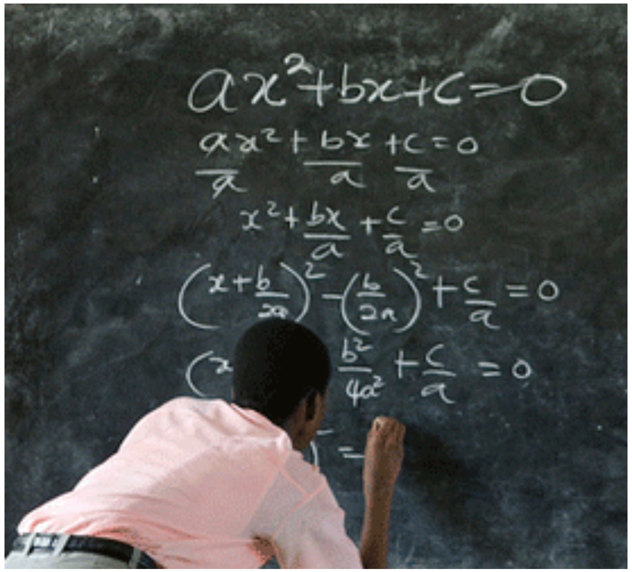

Part 4: Thinking Matter

In the Whirlpool

soft computing
next-generation computing
reservoir computing
cognitive computing
non-von Neumann computing
DNA computing
intelligent materials
morphological computing
physical computing
computational neuroscience
chaos computing
computing zero-energy computing
natural computing
computing materials
evolutionary computation
neuro-symbolic computing
neuromorphic computing
unconventional computing
non-standard computing
non-classical computing

Where to go from here

Where we stand:

- TM model only partially suitable for capturing the brain's information processing (IP)
- unconventional computing and substrates are similar to brains in important ways

What we wish to have:

- insightful guidance for practical unconventional IP engineering

How to move on:

- take stock of existing alternative scientific IP paradigms
- delineate natural task types for unconventional IP
- identify key design coordinates for unconventional IP machines

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Alternative paradigms with promises for brainlike IP

Signal processing and control

Where: engineering, neuroscience ● **Objects**: time series data, sensor signals, motor commands ● **Math**: linear systems, information theory ● **Why brainlike**: ... cybernetics!

Nonlinear optimization, stochastic search

Operations research, theoretical CS, theoretical physics ● Complex optimization problems ● Variational calculus, sampling techniques, statistical thermodynamics, unsupervised and reinforcement learning ● Free energy model of autonomous agent (Friston); stochastic parallel dynamics

Self-organizing dynamical systems, pattern formation

Theoretical physics, theoretical biology ● Spatiotemporal nonlinear systems ● PDEs, field dynamics, coupled oscillators, phase transitions ● Neural field theories; attractor models of concept representations

Naturally suited task types, examples

Stochastic search / online anytime optimization

Why bad for von Neumann computing: parallel, stochastic, graded ● **Inhowfar suited for brainlike systems**: parallel and stochastic; global optima and repeatability often not required; anytime interim solutions in online processing

Intelligent sensing / immersive brain-machine interfaces

digital processing too slow; undefined-multimodal input hard to pre-meditate in programs ● exploiting any kind of nonlinear physics for generating sensor response; low energy; on-chip learnt / self-organized signal extraction

Situated adaptive natural language understanding

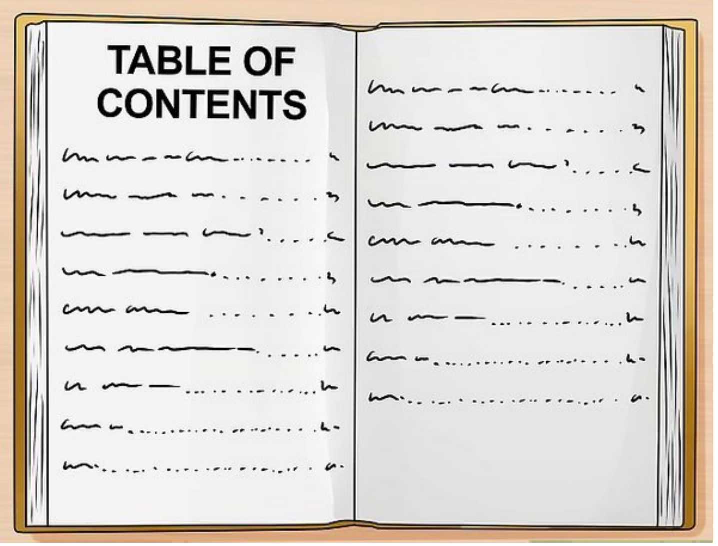
formal semantics algorithms are slow, brittle, and hardly adaptive; deep learning too data-expensive and non-adaptive ● may accept super-high-dimensional multimodal input; "correct" understanding neither defined nor needed; immediate responsiveness

Brainlike IP (ahem... how's that work?) – design coordinates

- We perceive some "negative" global characteristics
  - like, *stochastic*, *analog*, *unclocked*, *low-precision*, ...

- (Computational) neuroscience doesn't give many exploitable hints
  - no system blueprint
  - some local mechanisms, like STDP, cochlear model for acoustic processing, ...

What would be sections in a brainlike IP engineering textbook?



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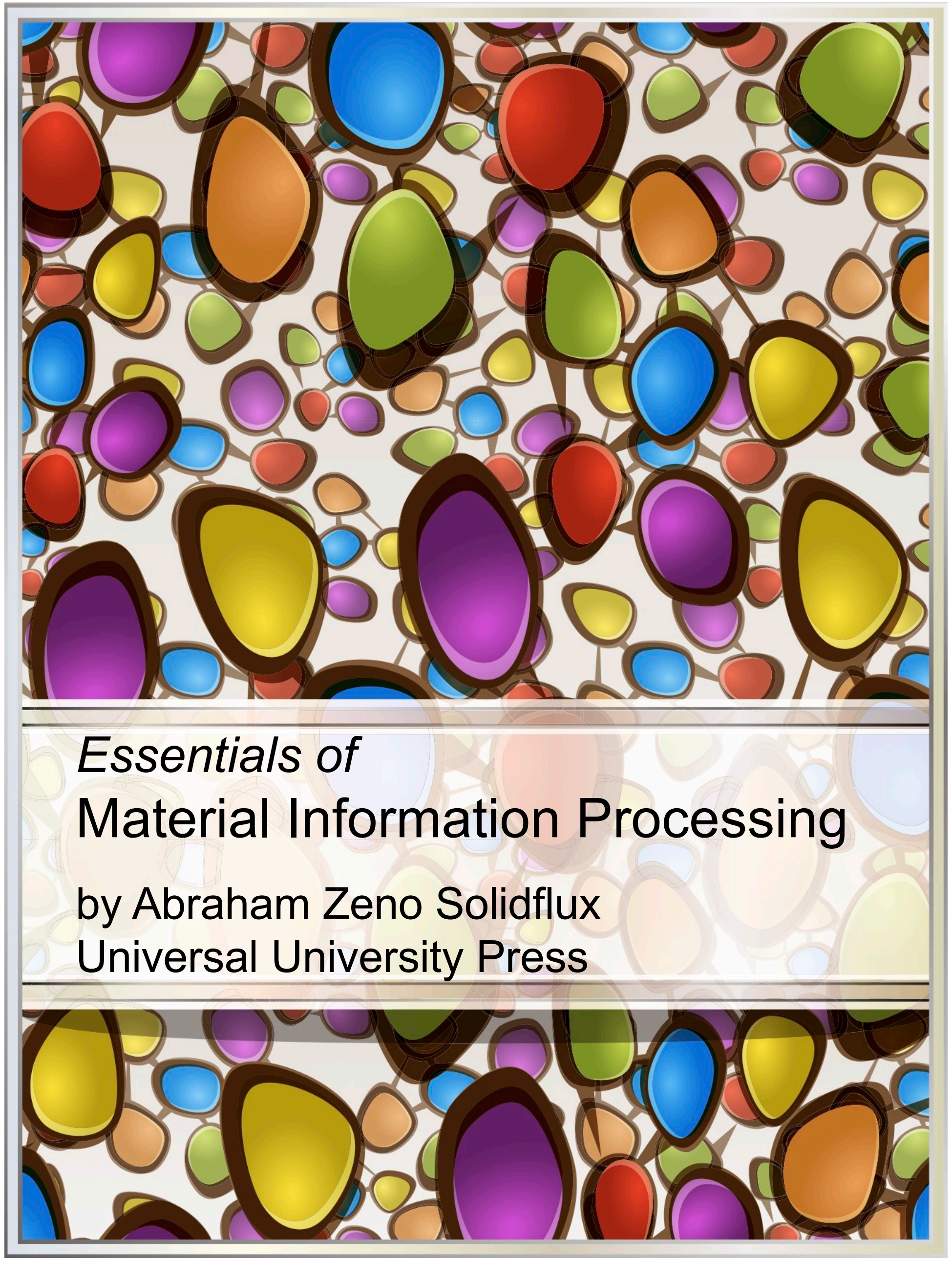
The project



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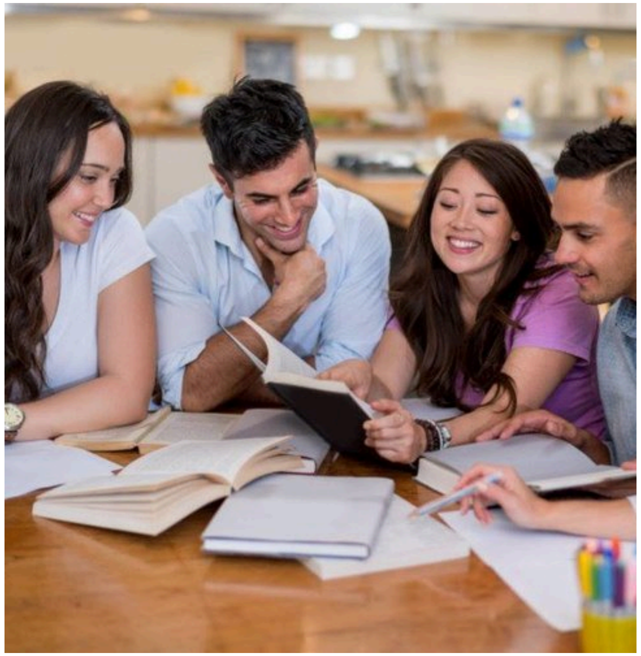
3 Timing



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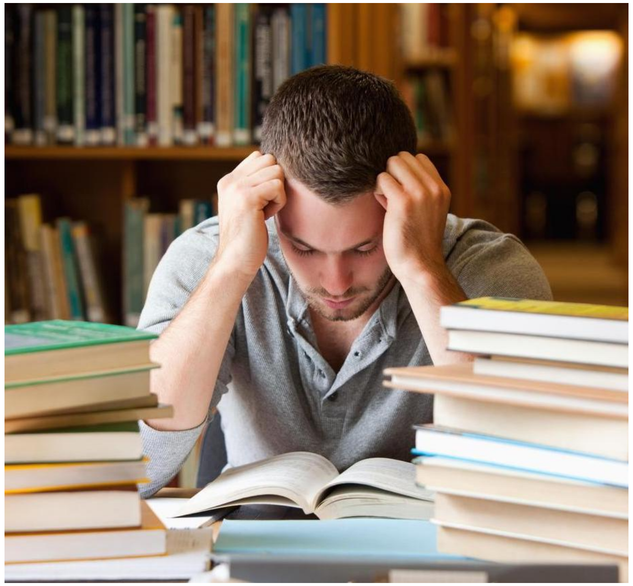
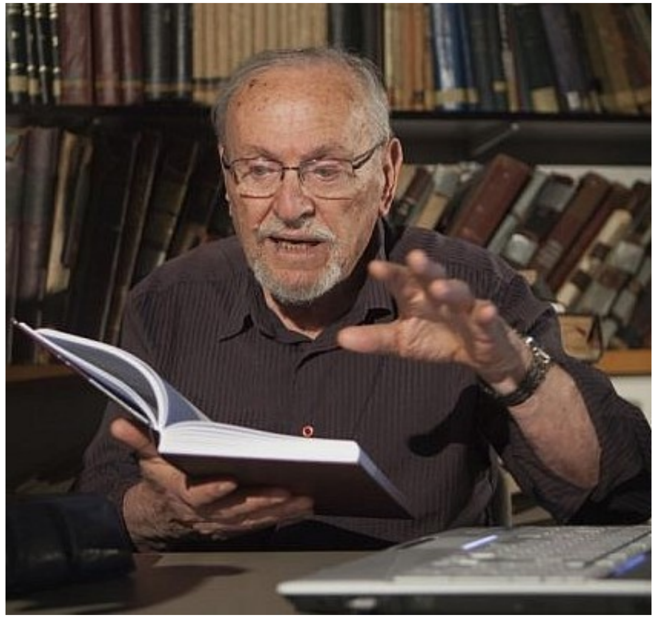
4 Persistent Memory



5 Transient Memory



6 Energy

7 Information Coding

8 Robustness

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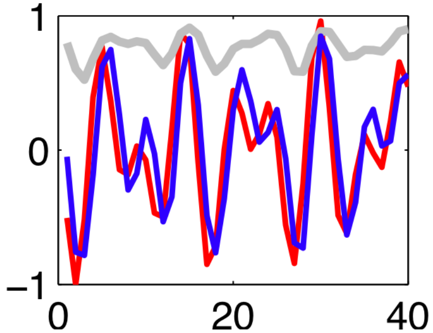
Functional stabilization – done by a real brain

Ivo Kohler and Theodor Erismann at the University of Innsbruck, Austria, ~1950

Functional stabilization with conceptors: demo

Task specification



Given: transform signal $F(s(n))$ obtained from passing reference signal $s(n)$ through some filter F.

Wanted: equalizing RNN H which transforms $F(s(n))$ back to $s(n)$: $H(F(s(n))) \approx s(n)$

We want much more!

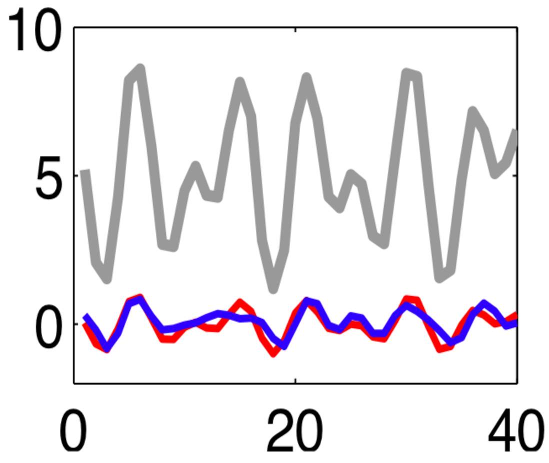
- The same equalizing RNN H should work for *any* transform F !
- This generic equalizer H should be trained single-shot on the reference $s(n)$ as *only* training data!

Idea

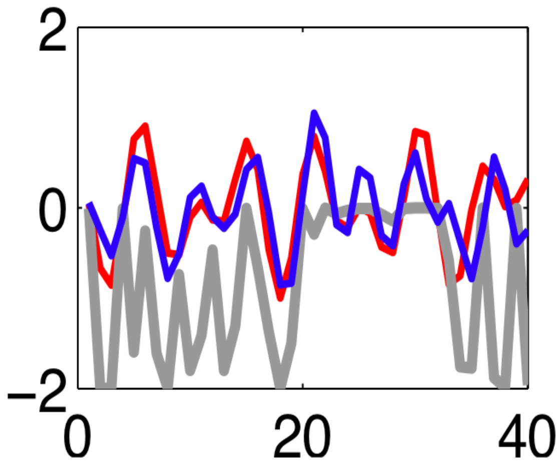
- The equalizing RNN H has *homeostatic dynamics*: it tries to self-regulate to attain a reference RNN dynamics envelope (shape of state space described by reference conceptor C^{ref})
- A self-regulation mechanism inside H tries to pull the state space geometry toward C^{ref}.

Results

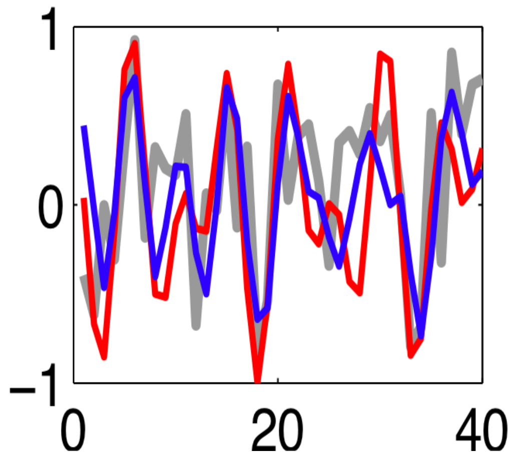
- Reference $s(n)$ is sum of two incommensurable sines
- Neural homeodynamics H: 5-stage cascade, each stage with 50 + 200 neurons



F: shift and upscaling



F: nonlinear autoregression



F: additive noise, SNR = 1

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Summary

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