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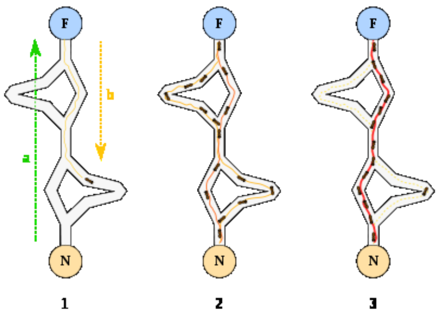
Cellular Automata and Evolution-in-Materio

Guest Lecture, Sub-symbolic AI Methods 2016

Stefano Nichele, PhD
http://www.nichele.eu



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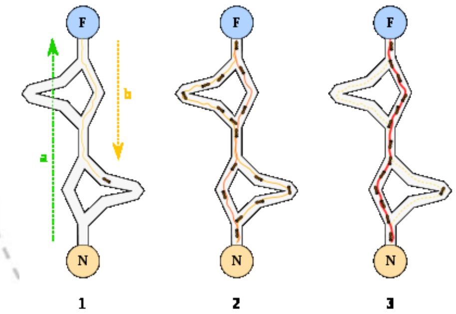
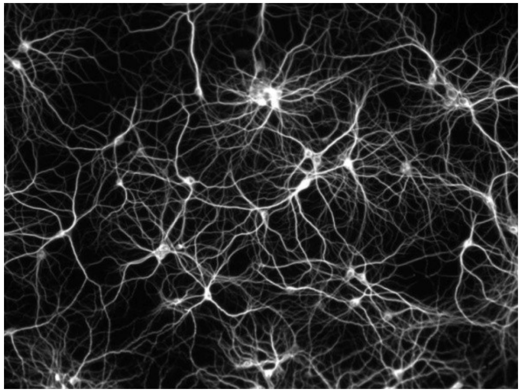


Complex systems



- Small ”simple” components
- Local interactions
- Self-organization (over time)
- Emergence (over scale)
- “The whole is more than the sum of its parts”
  Aristotle

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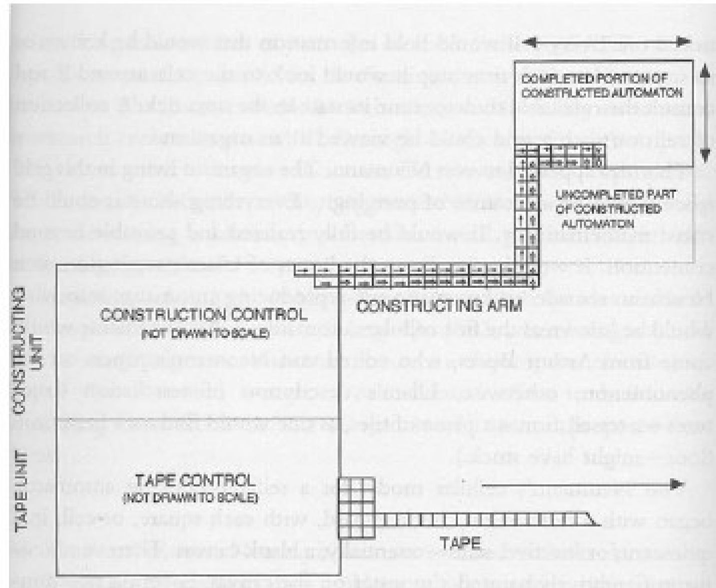
Part 1: Cellular Automata

Cellular automata modeling two species of gastropod
Chris King, University of Auckland - MATHS 745 2009

What are Cellular Automata?

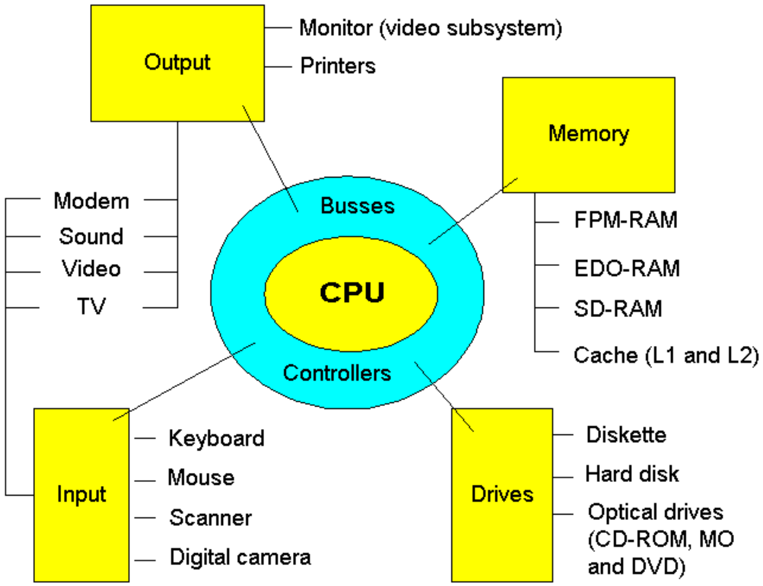
Cellular automata are discrete dynamical systems that model complex behavior based on simple, local rules animating cells on a lattice



Invented by John von Neumann

Study of biological self-replication in machines, universal computer with simple rules

Theory of Self-Reproducing Automata, completed in 1966 by Arthur W. Burks (based on von Neumann's work in 1940s)



© Michael B. Karbo 1997

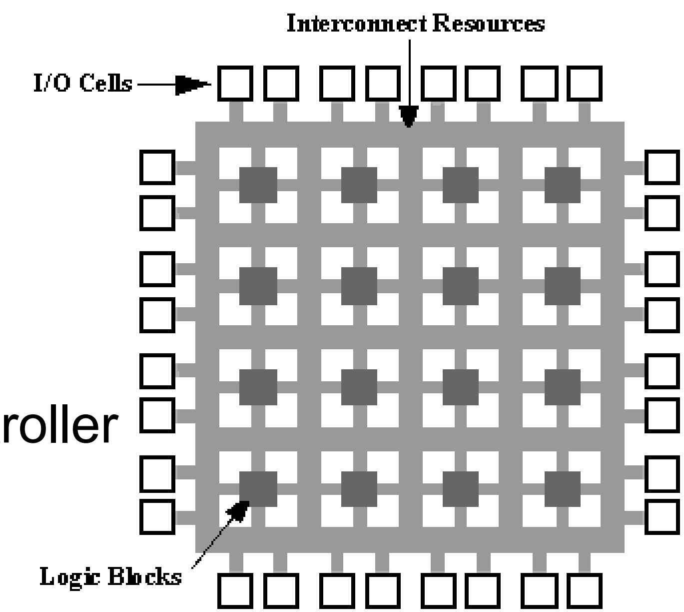
von Neumann architecture

- 1 complex processor
- tasks executed sequentially

Engineering (top-down)
vs.
Nature (bottom-up)

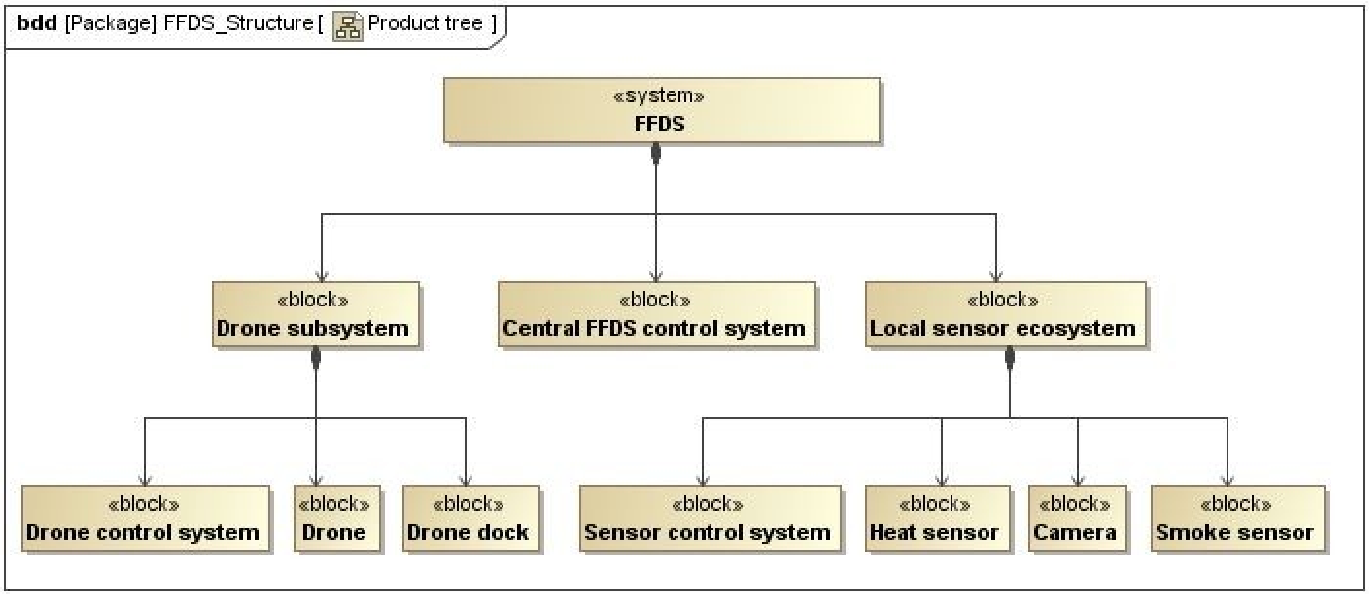
cellular computing

- myriad of small and unreliable parts: cells
- simple elements governed by local rules
- cells have no global view – no central controller
- local interactions with neighbours
- global behavior: emergent

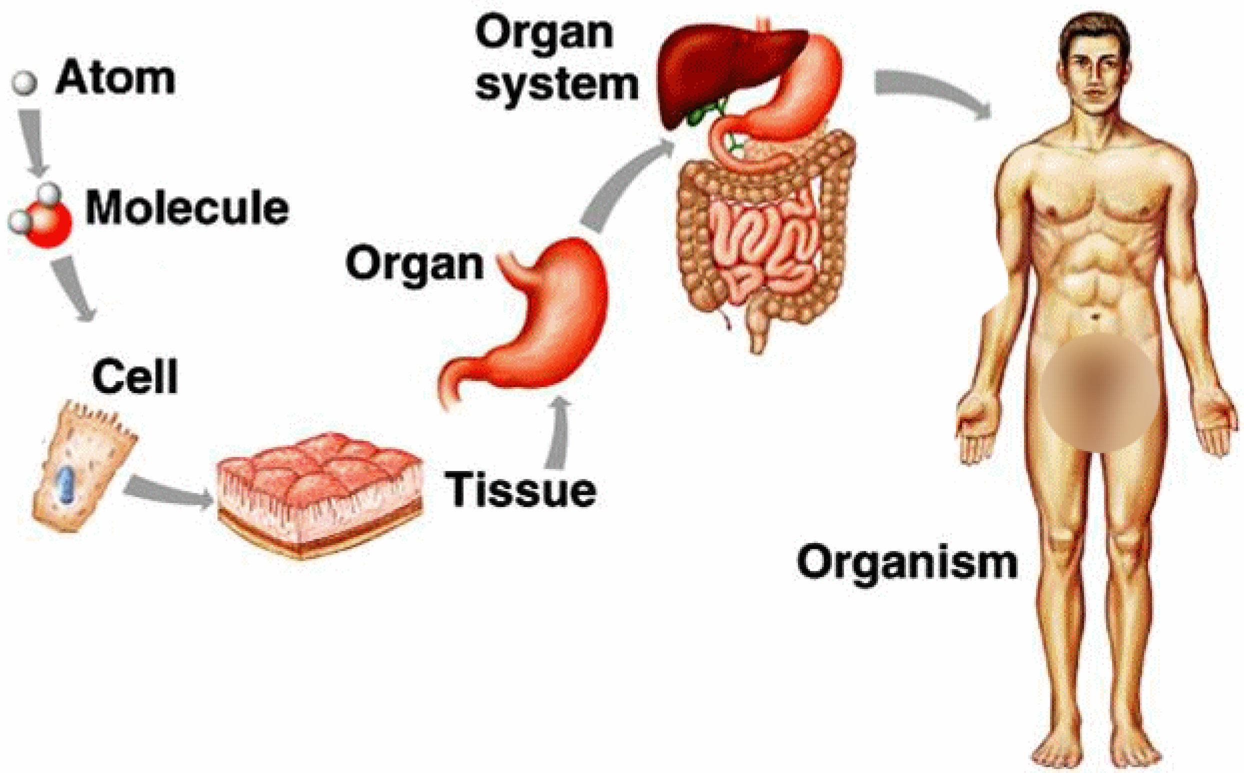


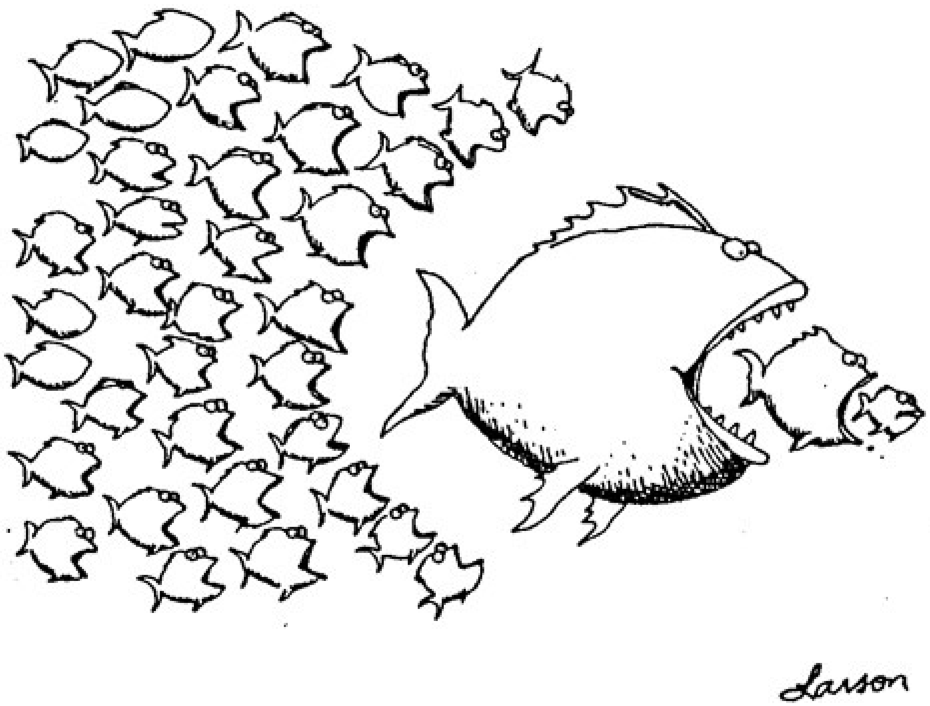
Szedő Gábor, MBE_MIT, 2000

Engineering: top-down

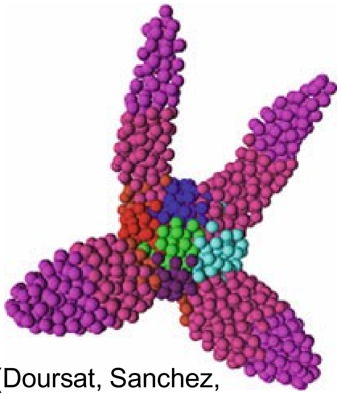


Nature: bottom-up

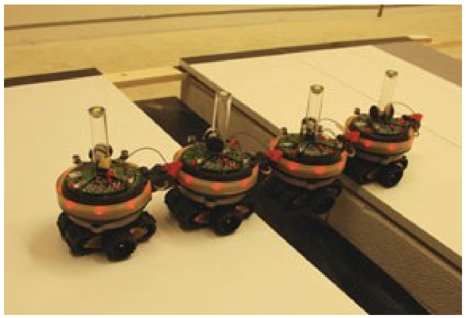



Larson

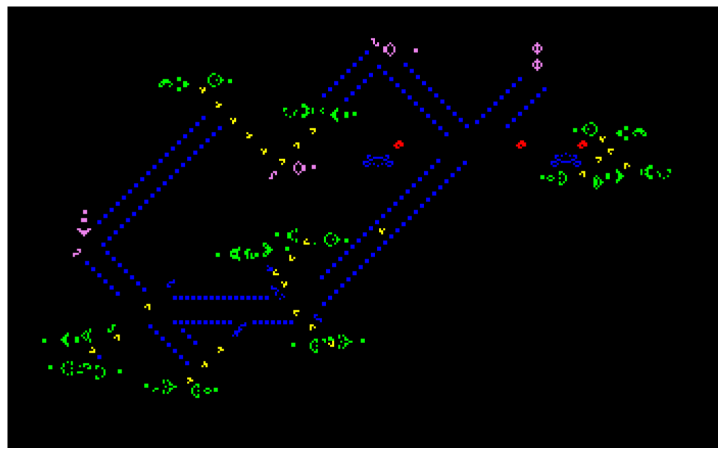
Examples



(Doursat, Sanchez, Dordea, Fourquet, Kowaliw 2014)

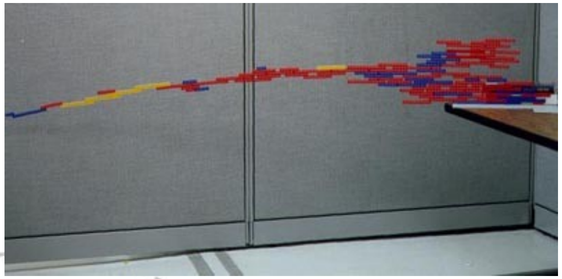


(Christensen, Grady, Dorigo 2009)



(Conway 1970)

(Hornby, Al Globus, Linden, Lohn 2006)



(Funes 1997)

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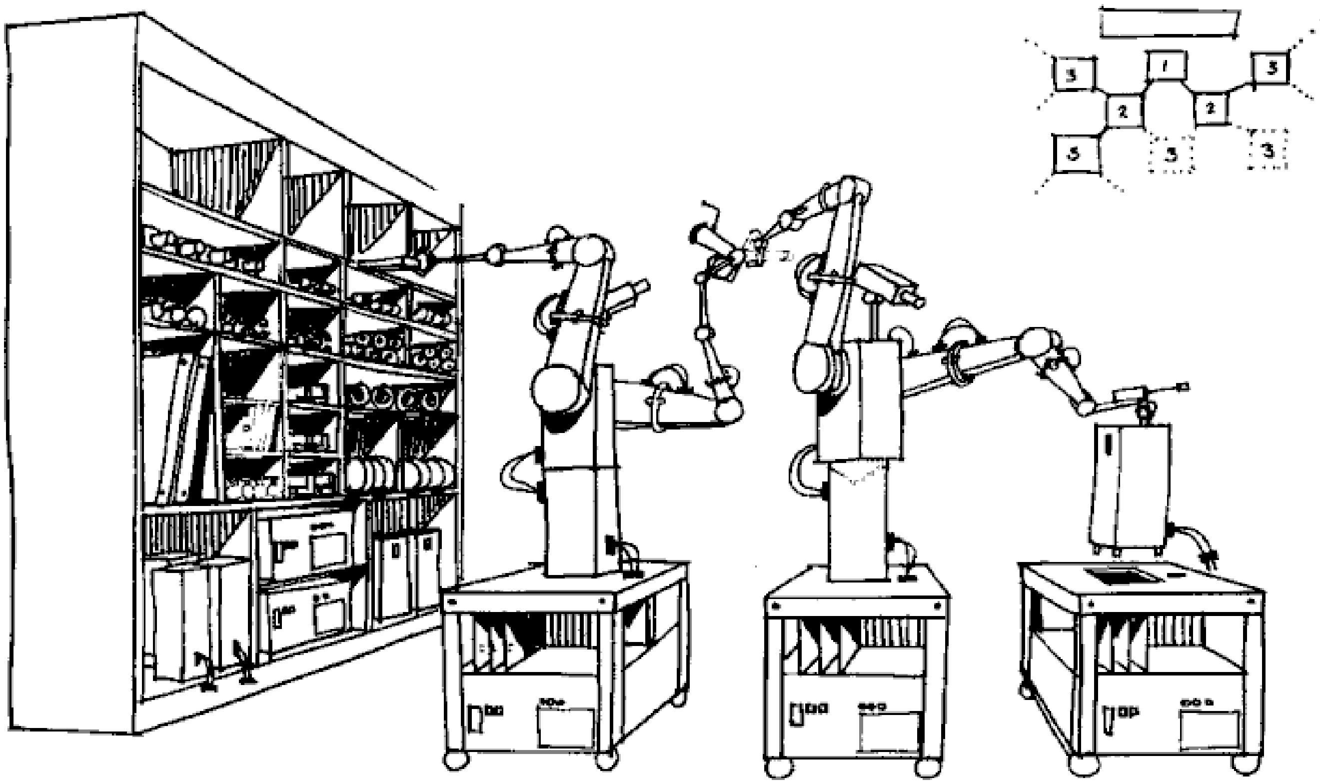
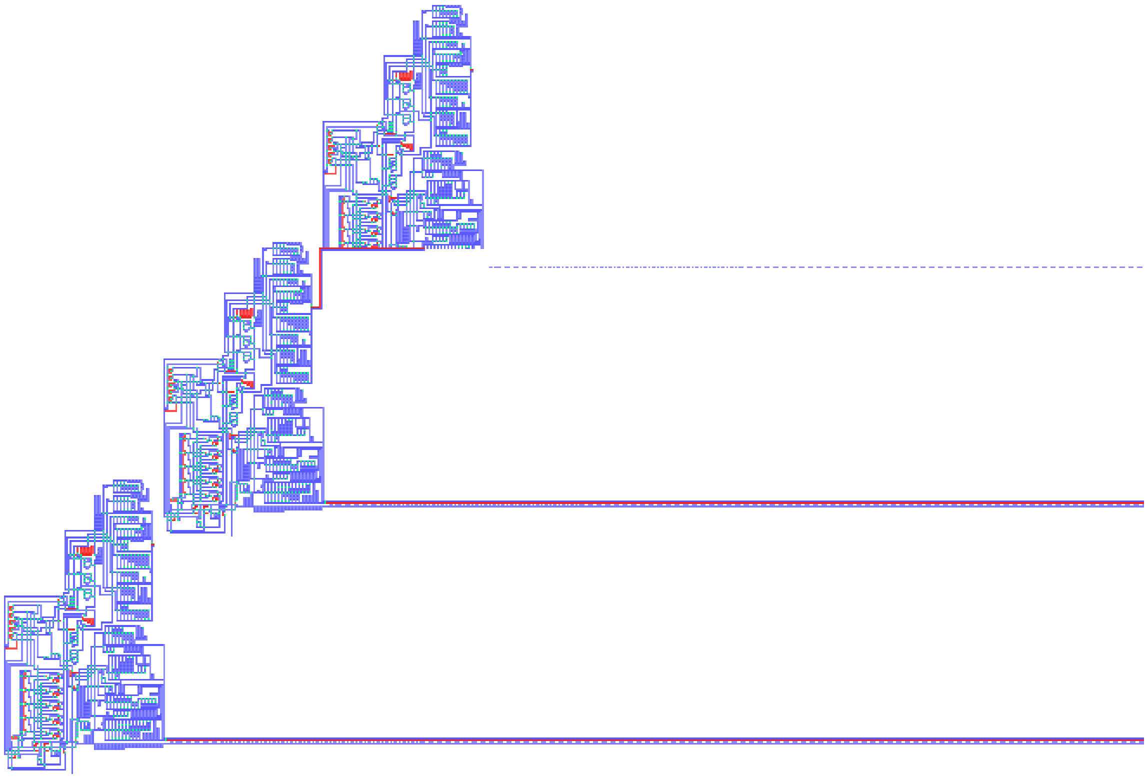
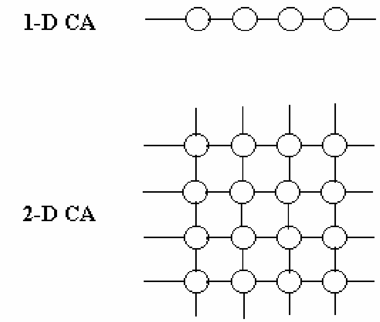


von Neumann universal constructor



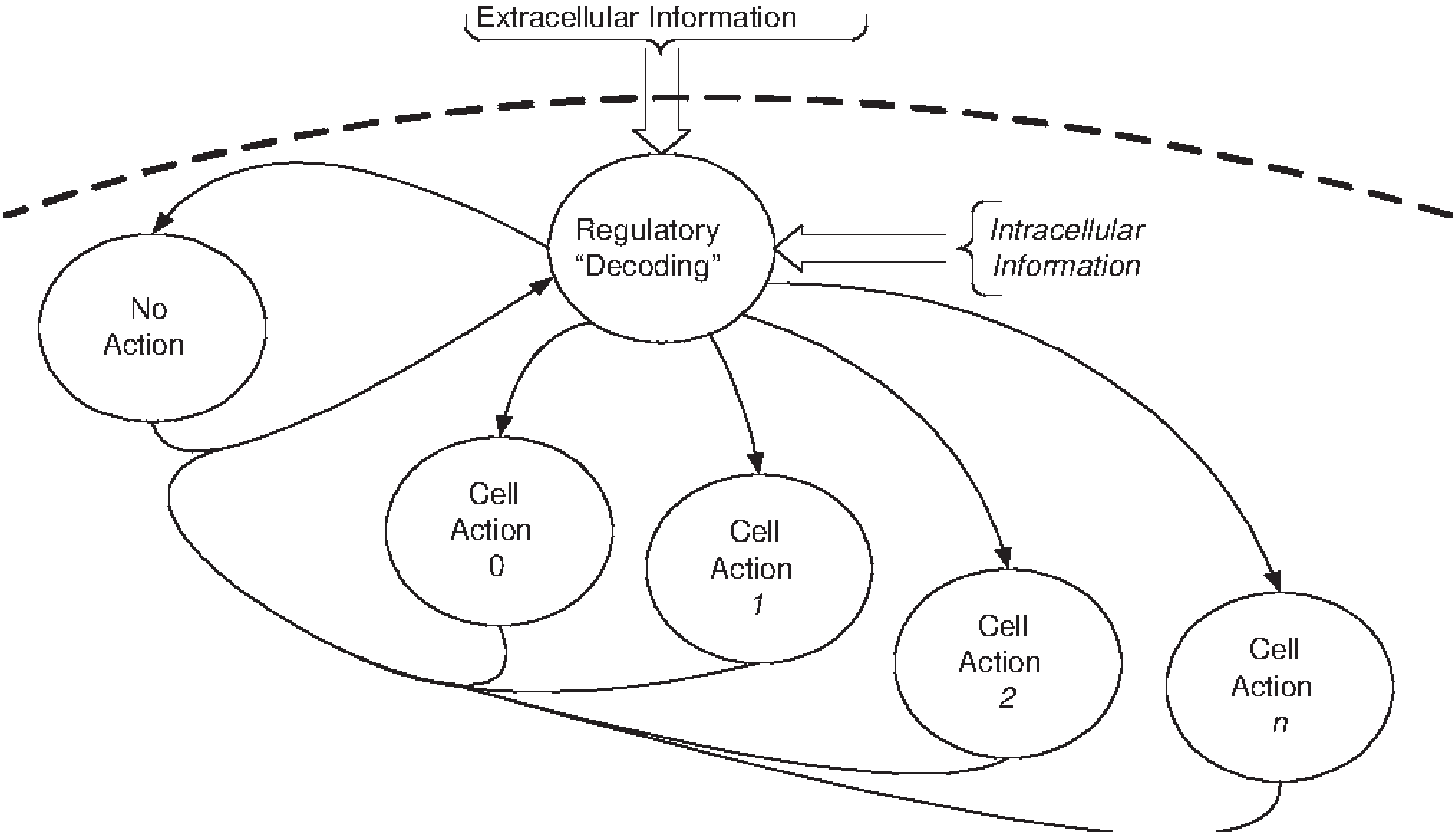
Nobili & Pasavento (1995) 32 state CA (original version by von Neumann had 29 states)



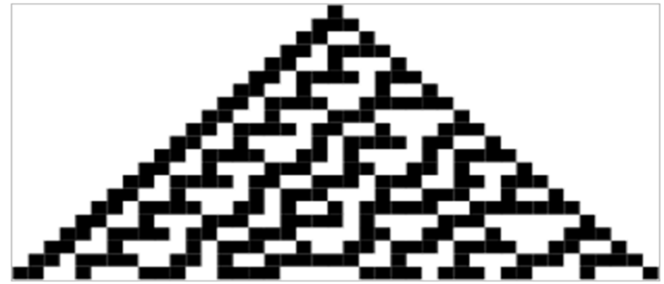
- CA is a ”simplified” universe
  (simplest possible universe capable of computation)

- Space is represented by a uniform N-dimensional grid of cells (N=1, N=2, ...), with each cell containing some data

- Time advances in discrete steps and the laws of the ”universe” (the physics) are expressed through a set of rules (or FSM = finite state machine), defining how, at each time step, each cell computes its new state given its old state and the state of its K closest neighbors


Extracellular Information
Regulatory "Decoding"
Intracellular Information
No Action
Cell Action 0
Cell Action 1
Cell Action 2
Cell Action n

Formally

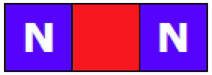


Neighboorhood	111	110	101	100	011	010	001	000	$\sigma^{i-1}_t\ \sigma^i_t\ \sigma^{i+1}_t$
Next cell value	0	0	0	1	1	1	1	0	σ^i_{t+1}

- Countable array of discrete cells *i*
- Discrete-time update rule Φ (operating in parallel on local neighborhoods of a given radius *r)*
- Alphabet: $\sigma^i_t \in \{0, 1, \ldots, k-1\} \equiv A$
- Update function: $\sigma^i_{t+1} = \Phi(\sigma^{i-r}_t, \ldots, \sigma^{i+r}_t)$
- *State of CA at time t:* $s_t \in A^N$ *(N=number of cells)*
- Global update Φ: $A^N \rightarrow A^N$
- $s_t = \Phi\, s_{t-1}$

Examples of 1-Dimensional (1D) CA

- 1D CA: Each cell has at most two neighbors

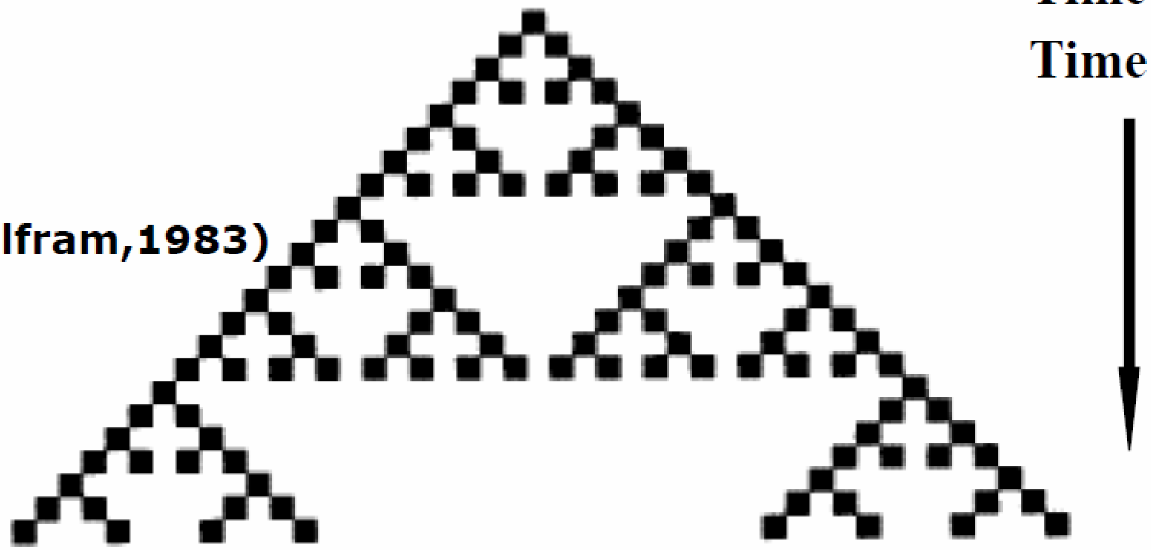


- Example: 1D CA operating through time under "Rule 90"

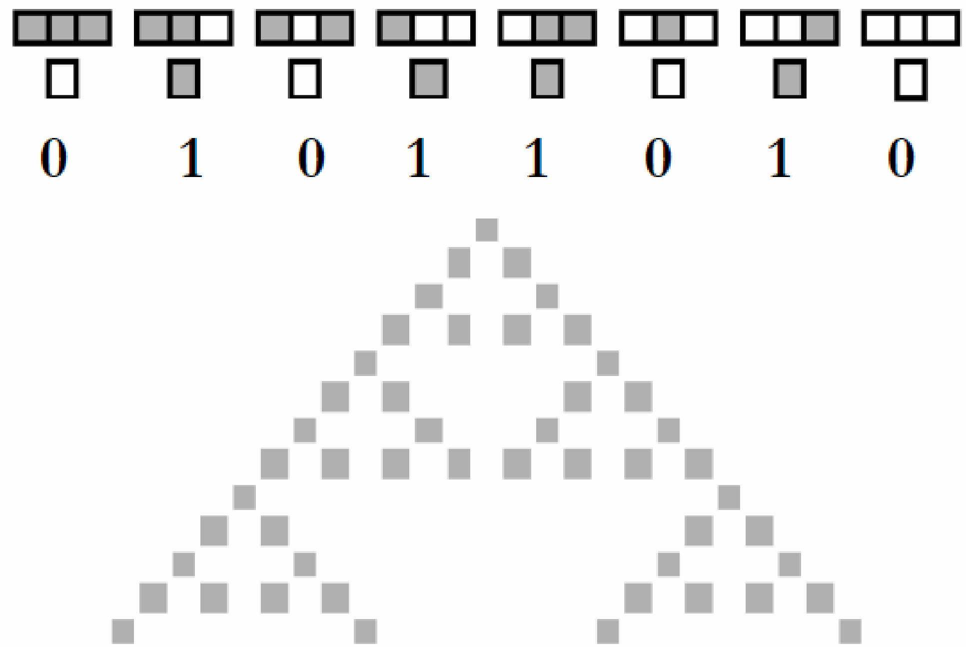
Time T=1

Time T=2

(Wolfram,1983)



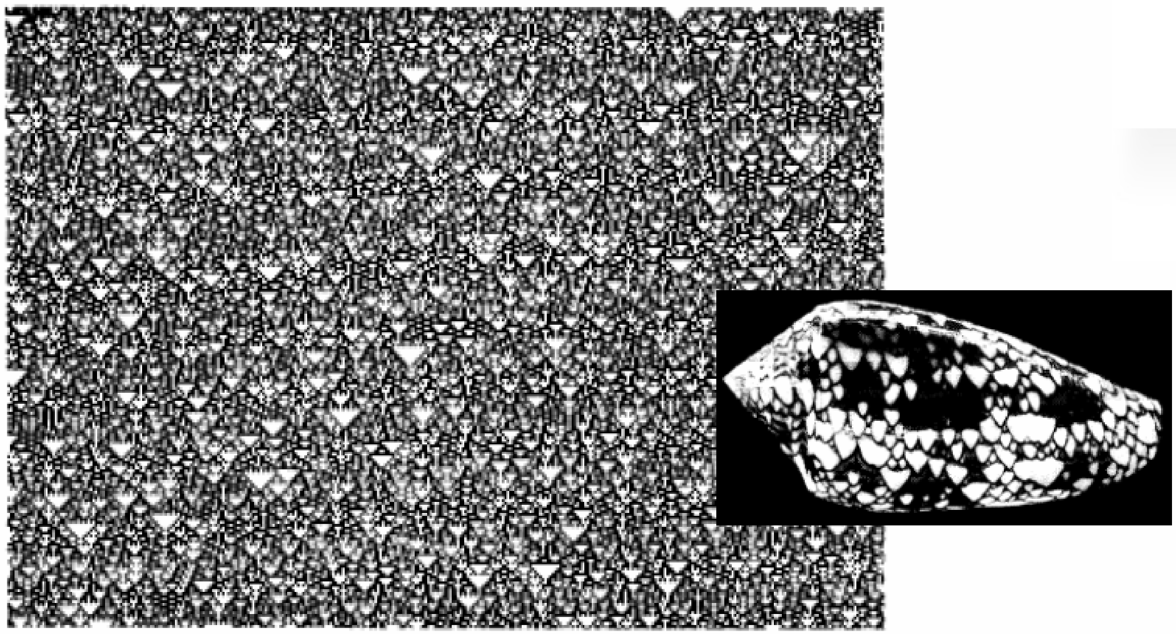
“Rule 90” = One of 2^8 Elementary 1D CA

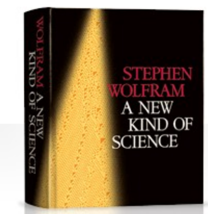


90 =(01011010)_base 2 = $0*2^7+1*2^6+0*2^5+1*2^4+1*2^3+0*2^2+1*2^1+0*2^0$

1D CA in Nature?

1D CA shell patterns (Wolfram, 1983)

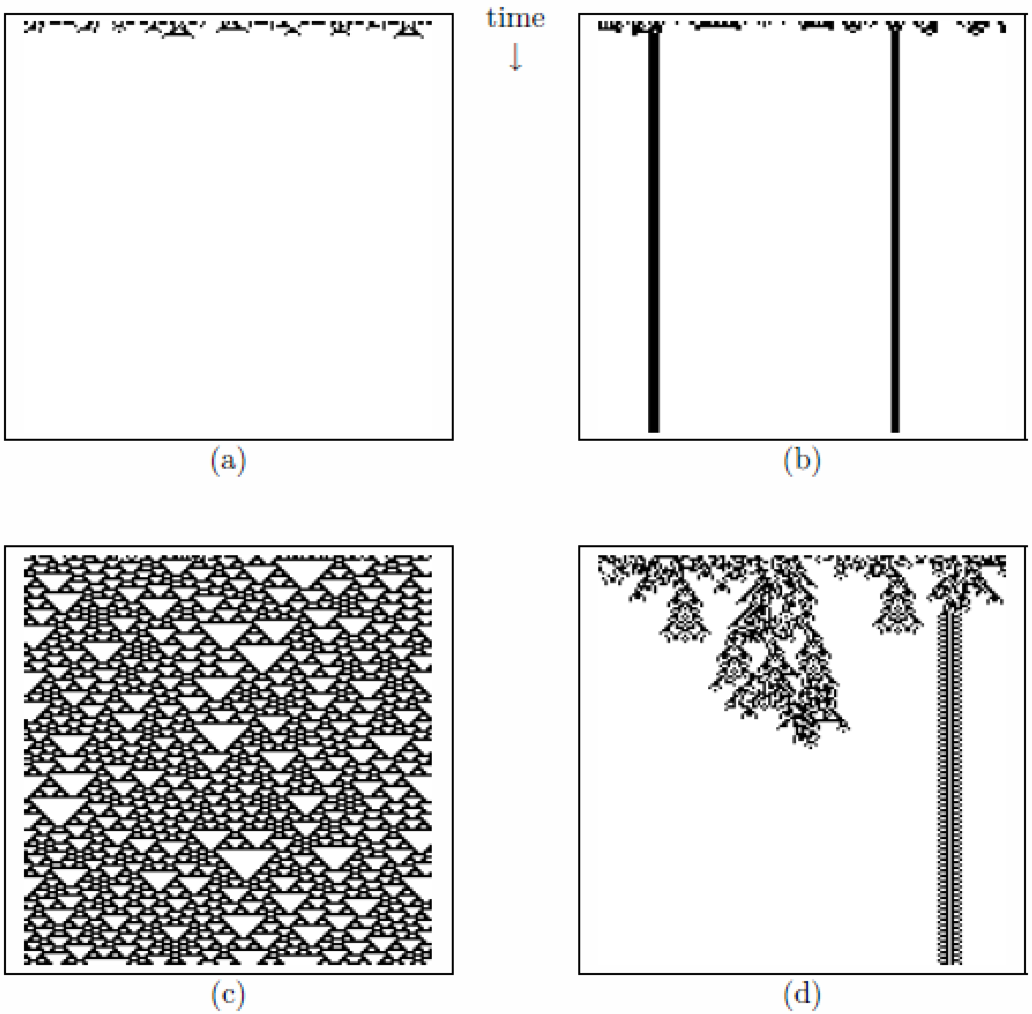


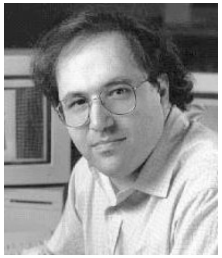


Wolfram Mathematica

WolframAlpha

CA Classes





Wolfram, 1984

a) Ordered class 1
b) Periodic class 2
c) Chaotic class 3
d) Complex class 4

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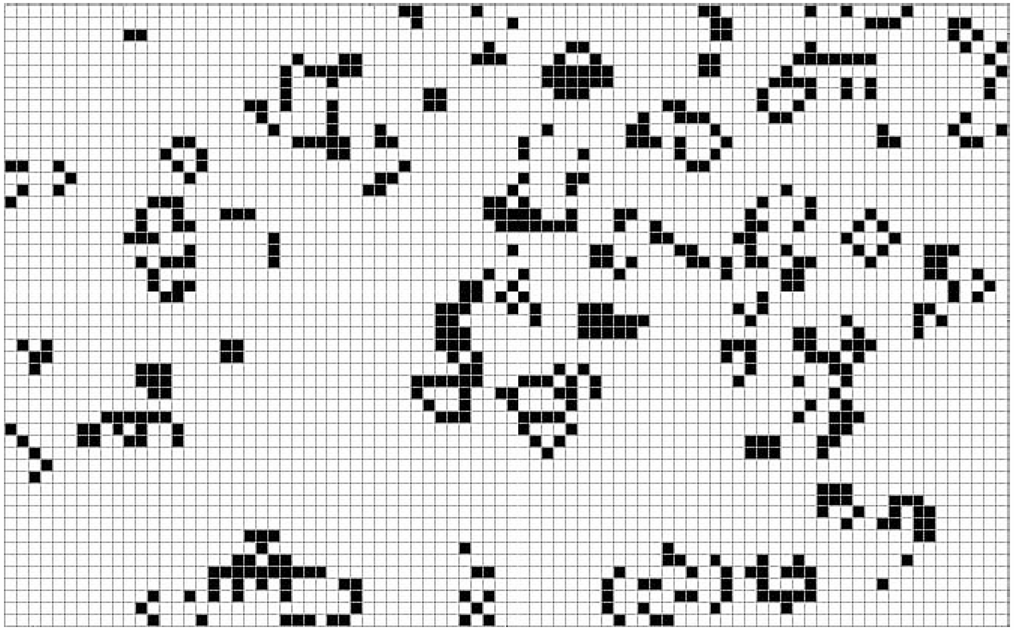
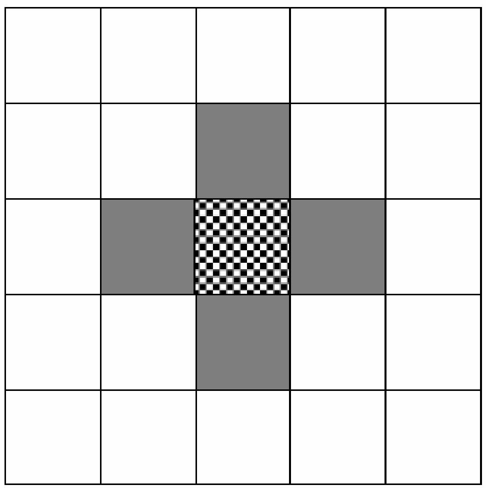
Examples of 2D CA

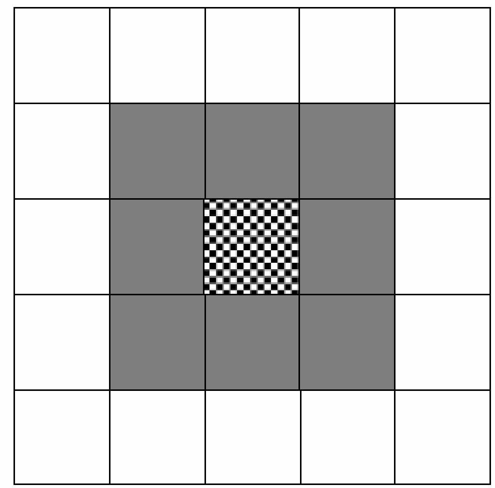
- 2D image entirely replaced each time step.



Possible Neighborhoods for 2D CA



Von Neumann Neighborhood

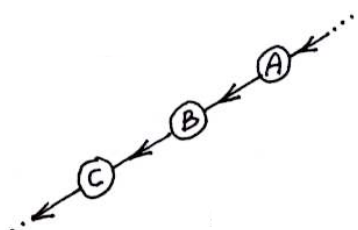


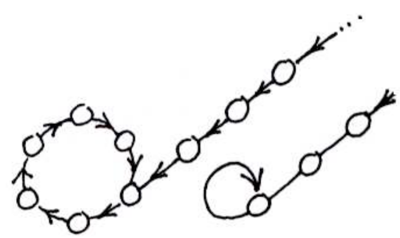
Moore Neighborhood

CA types

- Uniform / Non-uniform
- Boundary conditions
- Dimensions
- Neighborhood
- State space (K^N, K states, N cells)
- Attractor

with 3 states:
9 cells = 3^9 = 19 683
36 cells = 3^{36} = $1,5 \times 10^{17}$





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Complexity

- What is the total number of CA rules?

- For Boolean 1D CA:
  2^3 = 8 possible ”neighborhoods” (for 3 cells)
  2^8 = 256 possible rules

- For Boolean 2D CA:
  2^9 = 512 possible ”neighbohoods”
  2^{512} possible rules (!!!)

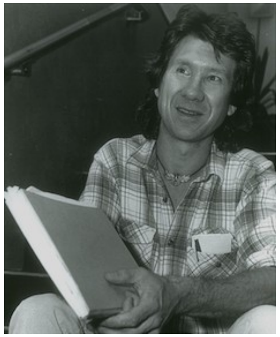
CA computation

1. Computer
2. Universe in which the computer is embedded

- Properties: emergent behavior, self-organization

- Some are universal (=universal Turing machine)
- Game of Life, Elementary Rule 110
- von Neumann self replicating automata

Study Artificial Life with CA



C. Langton

Emergent computation

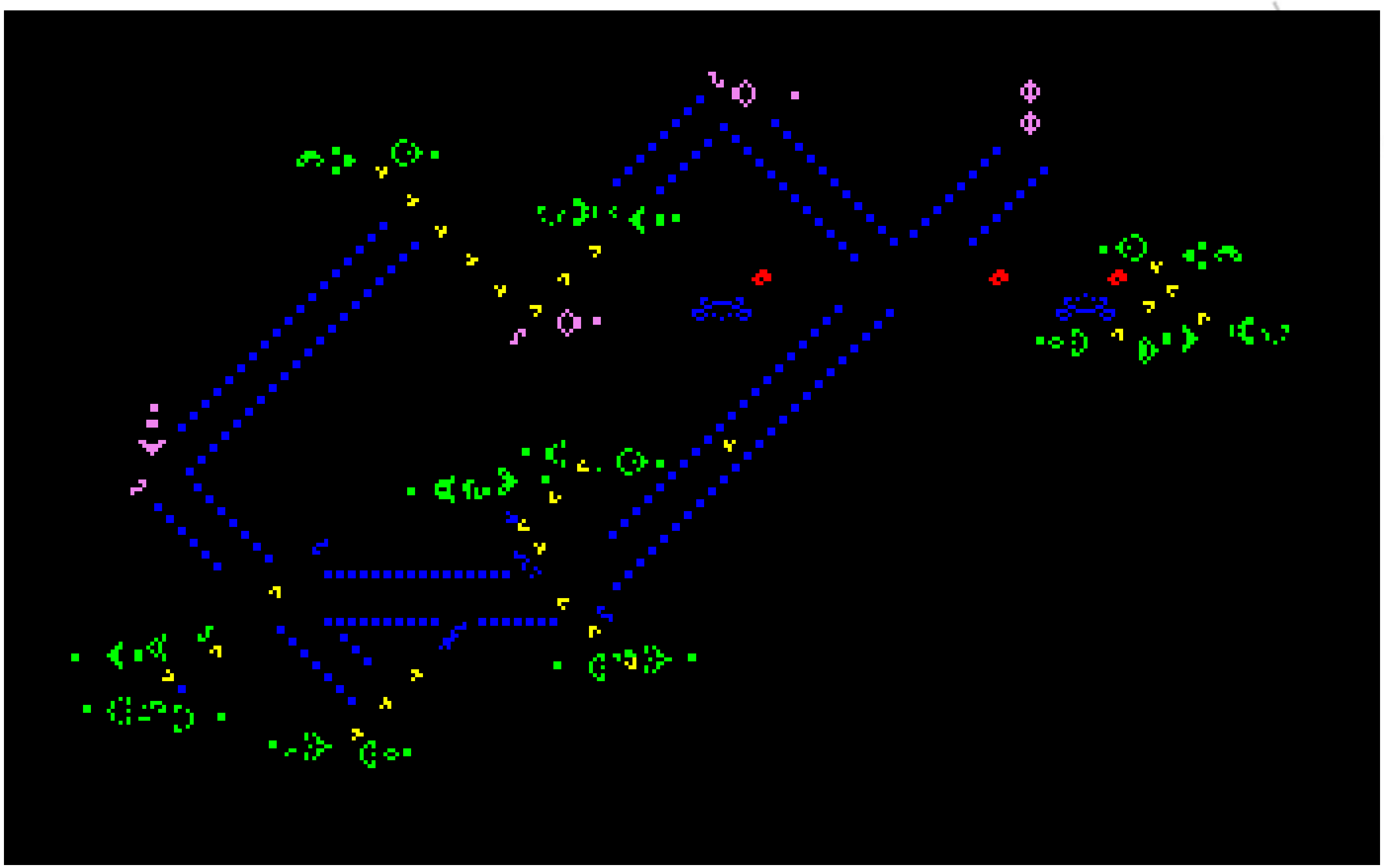
- *”Under what conditions will physical systems support the basic operations of information transmission, storage, and modification constituting the capacity to support computation?”*

Abstraction of a physical systems -> CA

- *”Under what conditions will cellular automata support the basic opeartions of information transmission, storage, and modification?”*

Example - Conway's Game of Life

John Conway



Wikipedia, Conway's Game of Life

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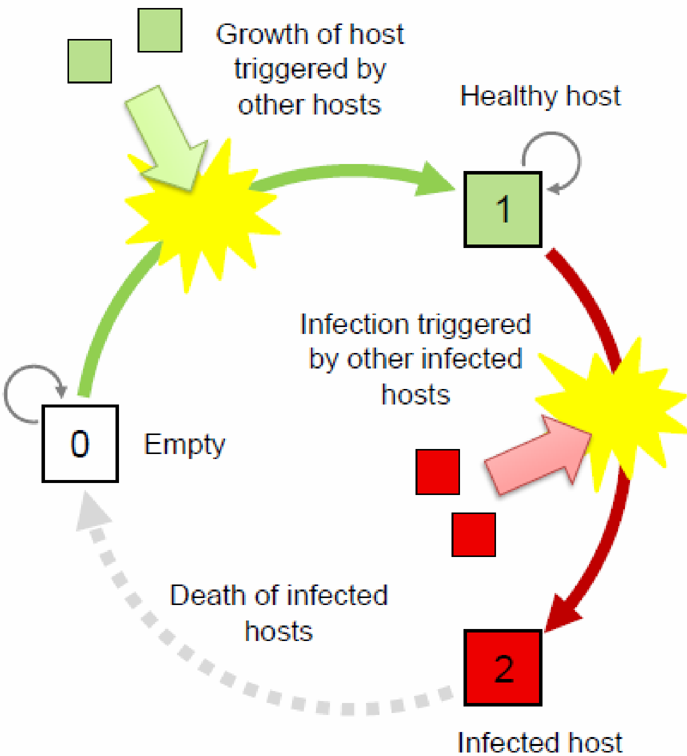
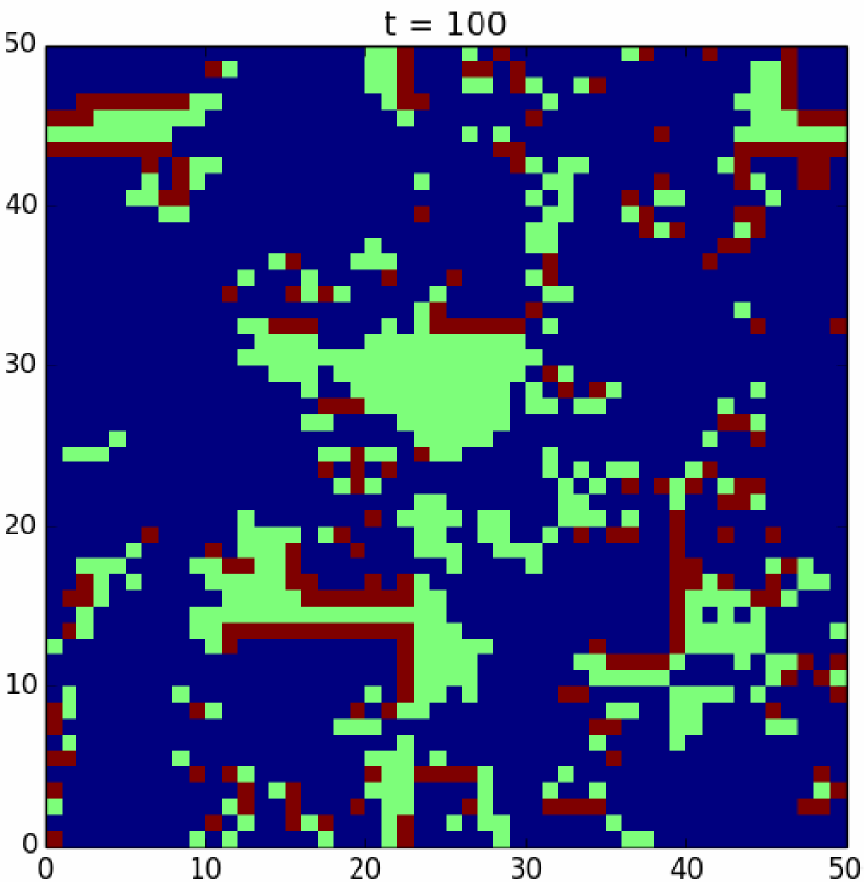
The "Rules of Life"

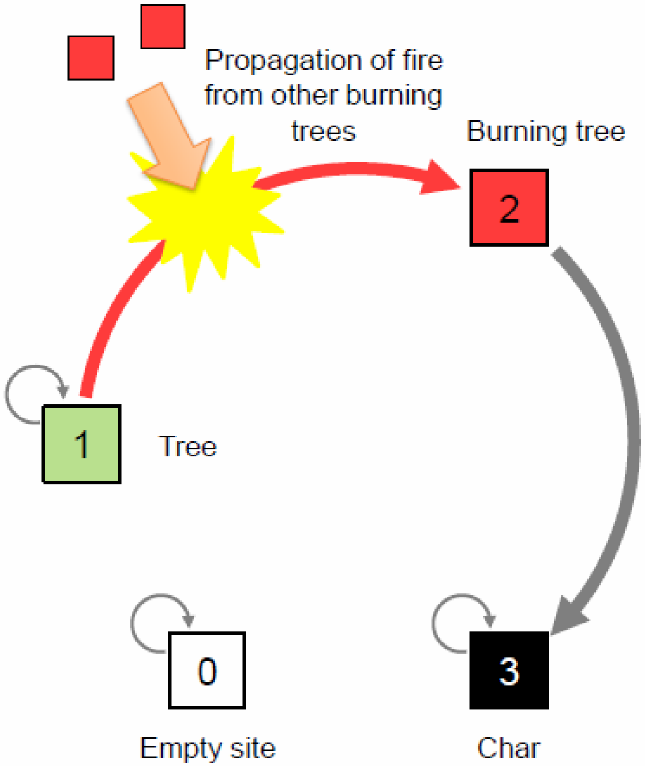
- If an alive (black) cell has fewer than 2 alive neighbors, it dies (turns white) -- **loneliness**
- If an alive cell has more than 3 alive neighbors, it dies – **overcrowding**
- If an alive cell has either 2 or 3 alive neighbors, it goes on living (stays black) -- **happiness**
- If a dead cell has exactly 3 alive neighbors, it comes alive -- **reproduction**. Otherwise it stays dead.

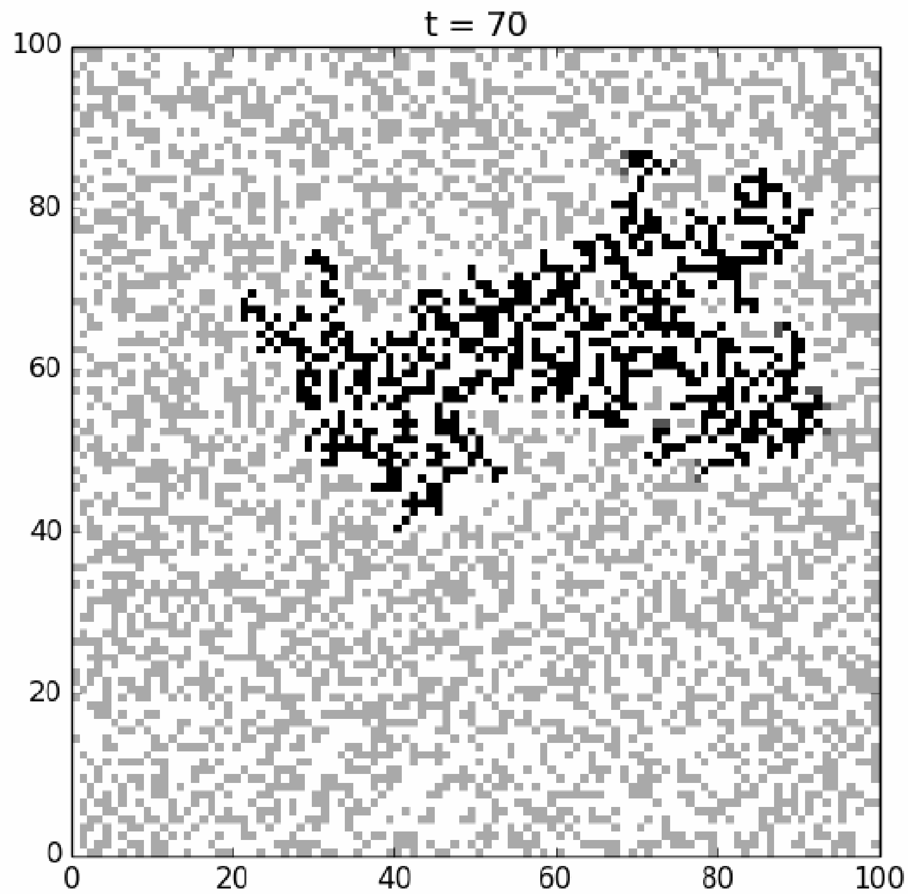
Other CA models

- Host pathogen models
- Waves in excitable media
- Turing patterns
- Epidemic spread
- Forest fire models
- Artificial organisms
- Panic spread, criminality spread
- Random numbers (Mathematica)
- ……….

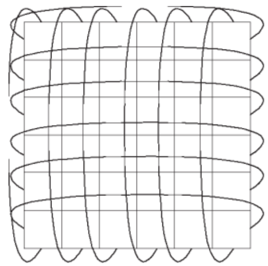

Growth of host
triggered by
other hosts
Healthy host
1
Infection triggered
by other infected
hosts
0
Empty
Death of infected
hosts
2
Infected host

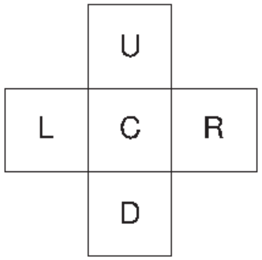

t = 100
50
40
30
20
10
0
0
10
20
30
40
50

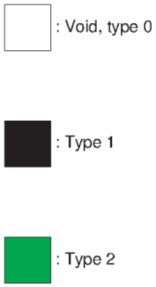

Propagation of fire
from other burning
trees
Burning tree
2
1
Tree
0
Empty site
3
Char


t = 70
100
80
60
40
20
0
0
20
40
60
80
100

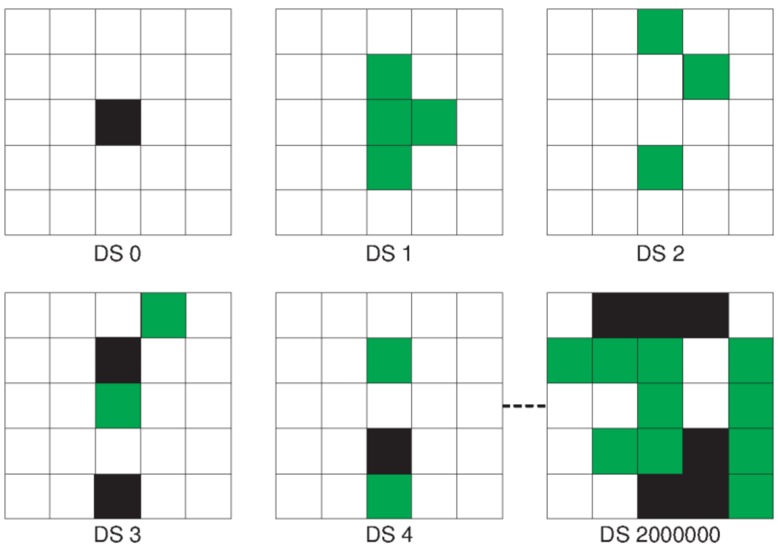
Example model

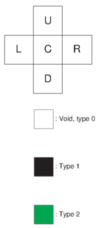






L	R	U	D	C	$C_{(t+1)}$
0	0	0	0	0	0
0	0	0	0	1	{0,1,2}
0	0	0	1	0	{0,1,2}
0	0	0	1	1	{0,1,2}
0	0	1	0	0	{0,1,2}
		:			:
1	1	1	1	1	{0,1,2}
0	0	0	0	2	{0,1,2}
0	0	0	2	0	{0,1,2}
0	0	0	2	1	{0,1,2}
0	0	0	2	2	{0,1,2}
		:			:
2	2	2	2	2	{0,1,2}



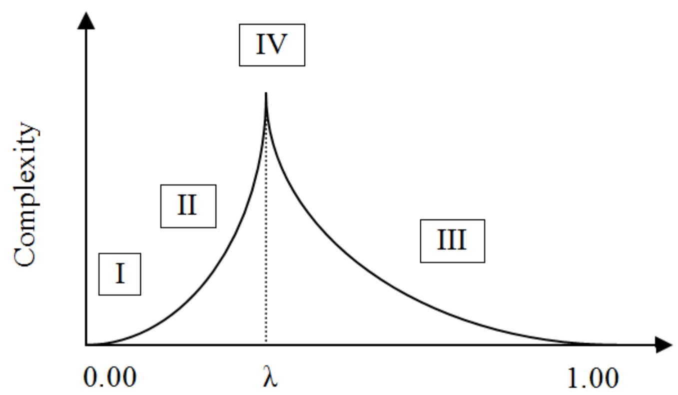


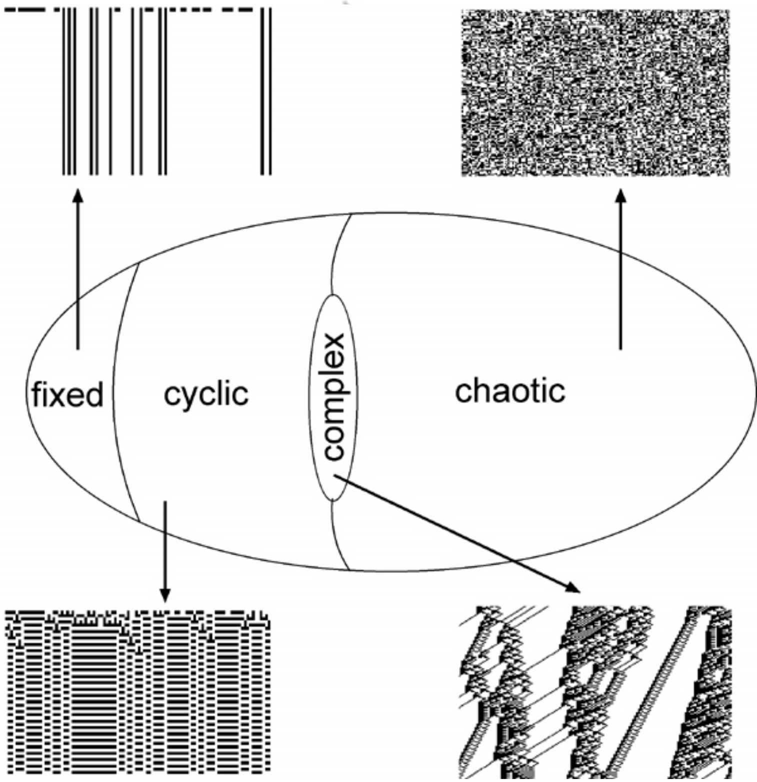
L	R	U	D	C	$C_{(t+1)}$
0	0	0	0	0	0
0	0	0	0	1	{0,1,2}
0	0	0	1	0	{0,1,2}
0	0	0	1	1	{0,1,2}
0	0	1	0	0	{0,1,2}
		:			:
1	1	1	1	1	{0,1,2}
0	0	0	0	2	{0,1,2}
0	0	0	2	0	{0,1,2}
0	0	0	2	1	{0,1,2}
0	0	0	2	2	{0,1,2}
		:			:
2	2	2	2	2	{0,1,2}

Lambda Parameter

$$\lambda = \frac{K^N - n}{K^N}$$

- n = # transitions to the quiescent state
- K = number of cells types
- N = neighborhood size





A region in the CA rule space where there is a phase transition between ordered and chaotic behavioral regimes (Langton, 1990)

Comments on Lambda

Claims

- There is a phase transition between periodic and chaoic behavior. Most complex behavior is in the vicinity of the transition (edge of chaos)
- CA near the transition point correspond to Wolfram's class IV
- CA capable of complex computation have long transient (near the transition point)
- E.g., Game of Life has Lambda = 0.273 (in the transition region for k=2, N=9 2D CAs)

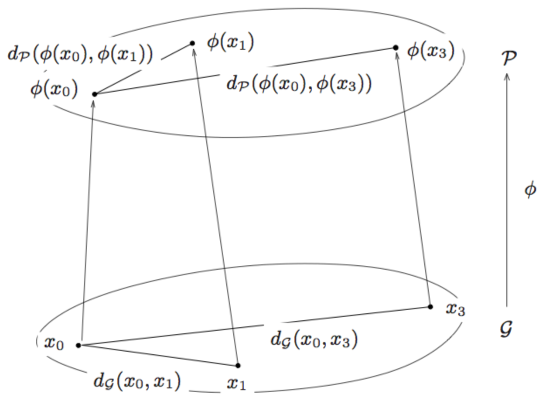
Criticism

- CAs with high Lambda value can still have simple behavior (Lambda describes "average" behavior)
- Does not take initial state into account.

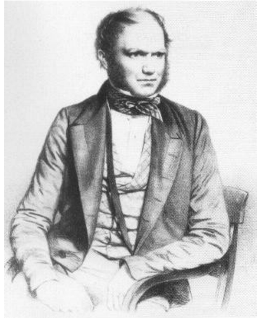
DNA ~ 22000 – 25000 genes
Human body ~3.72x10^{13} cells

Genotype - Phenotype

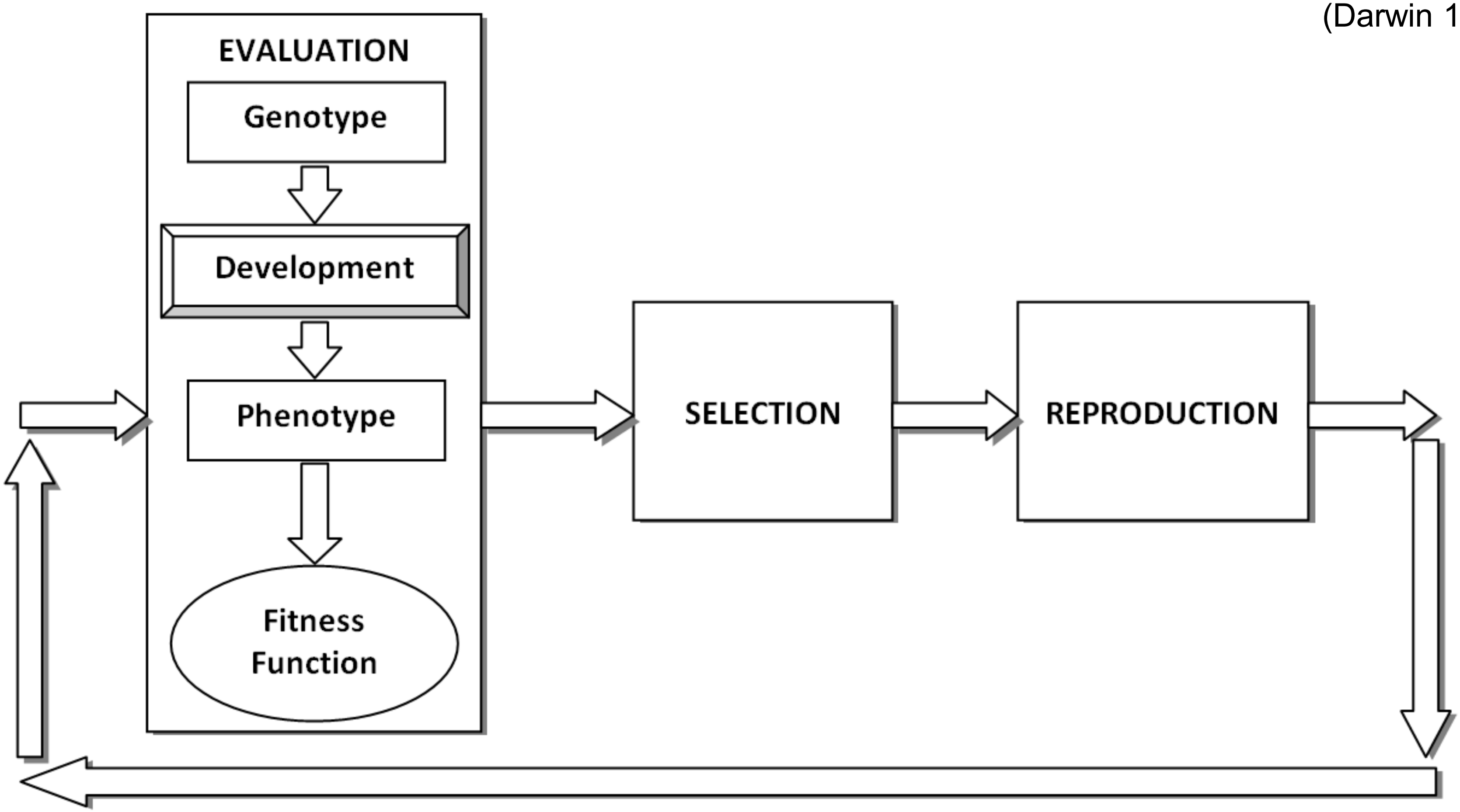
- A CA can be considered as a developmental system, in which an organism can develop (e.g. grow) from a zygote to a multi-cellular organism (phenotype) according to specific local rules, represented by a genome (genotype).



EvoDevo

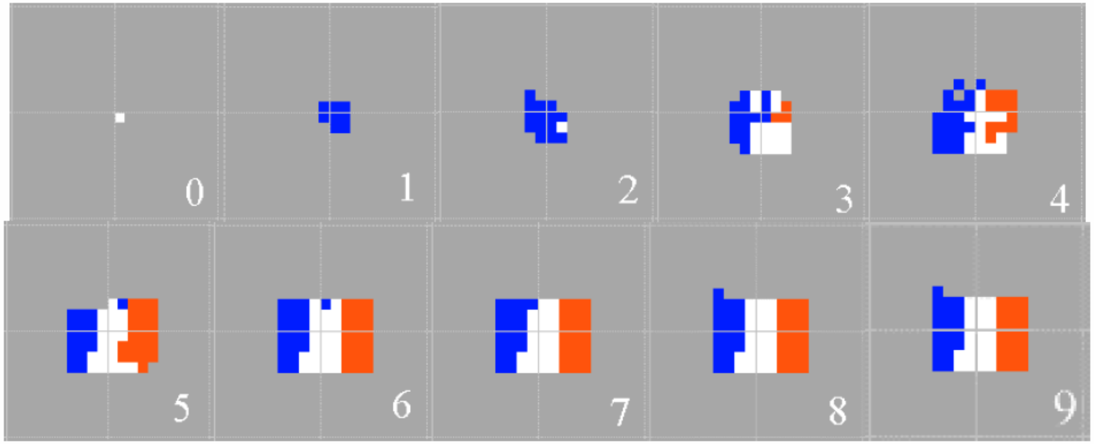


(Darwin 1859)



Evolving a Self-Repairing, Self-Regulating French Flag Organism

- cells can grow, die, change colour or release chemicals
- grow until a certain size and remain stable afterwards
- chemicals are responsible for the type of action that each cell will perform at every time-step
- self-repair and self-regulation was much faster with chemicals



(Miller and Banzhaf, 2004)

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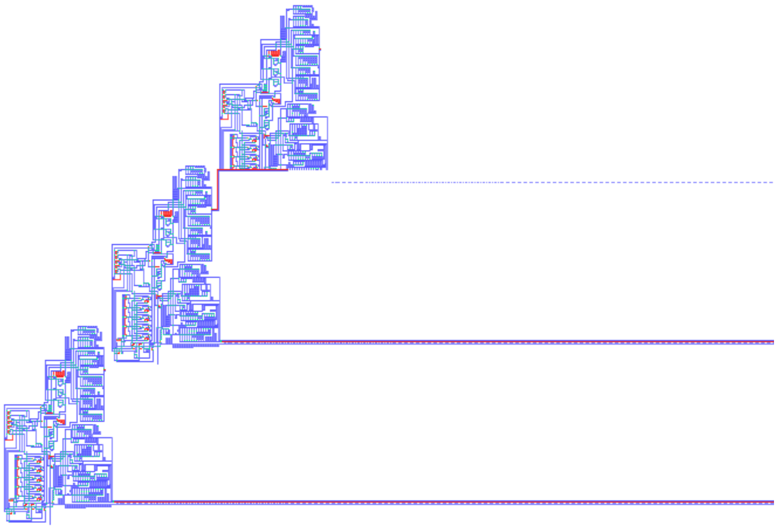
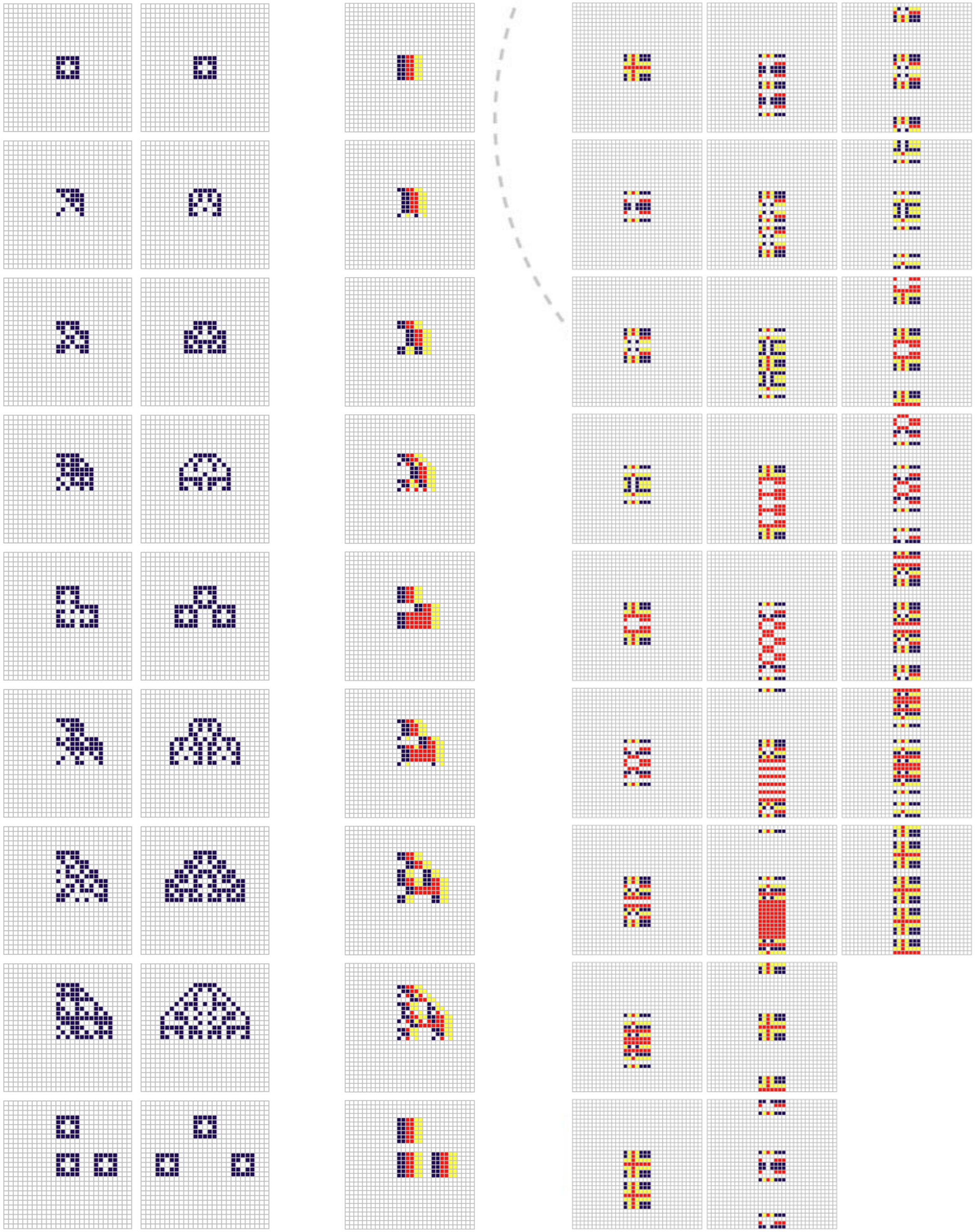
Cellular Automata Replication



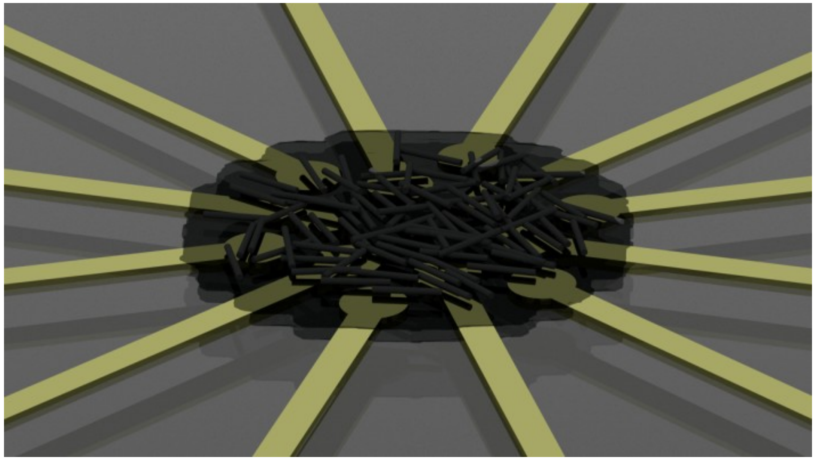


(Nichele et al., 2015)

CA summary (speculative)

- Emergent computation (and possibly life) at the Edge of Chaos
- Class 4: complex (possibly universal)
- Information transmission, storage and modification
- Provide capacity for emergent (spontaneous) computation
- Life: a kind of “computation” that emerges at the Edge of Chaos (between order and disorder)

Part 2: Evolution-in-Materio

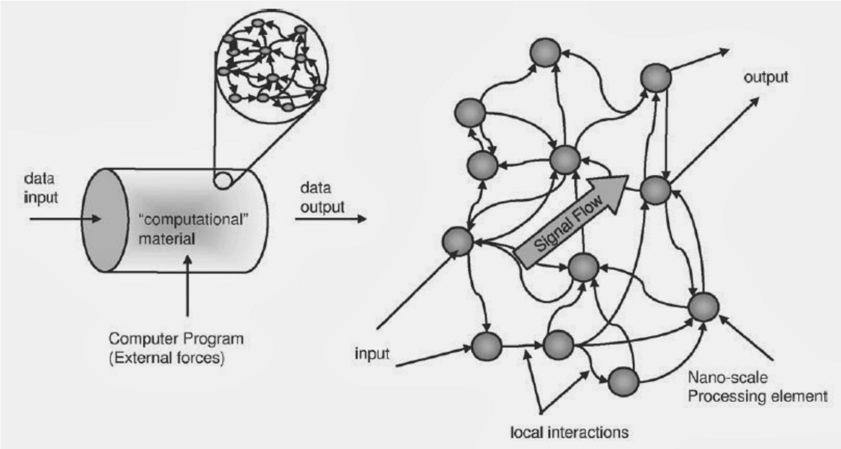


Carbon nanotubes deposited on a microelectrode array.
EU project NASCENCE (2015)

- **Evolution-in-materio**: ”...the manipulation of a physical system using computer controlled evolution (CCE)”

Miller, Julian F., and Downing, Keith. "Evolution in materio: Looking beyond the silicon box." *Evolvable Hardware, 2002. Proceedings. NASA/DoD Conference on*. IEEE, 2002.

- ”...a kind of unconstrained evolution in which, by the application of physical signals, various intrinsic properties of a material can be configured so that a useful computation function is achieved”



Miller J., Harding S., and Tufte G., Evolution-in-materio: evolving computation in materials. Evolutionary Intelligence, vol. 7, no. 1, 2014, pp. 49-67.

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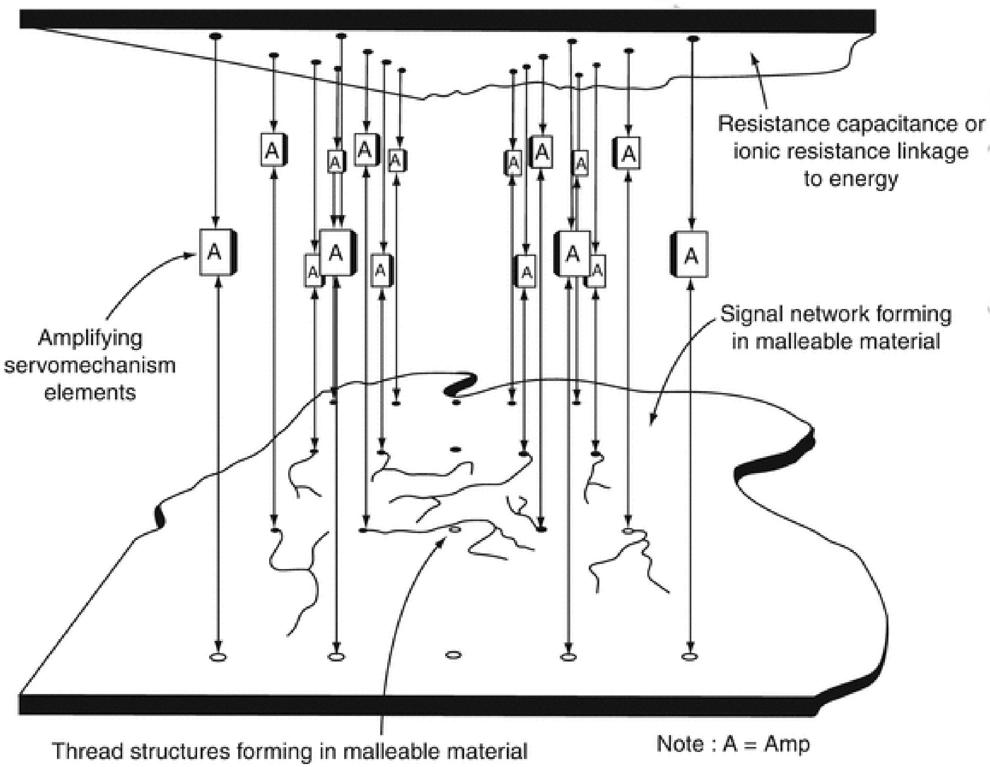
Gordon Pask (1958)

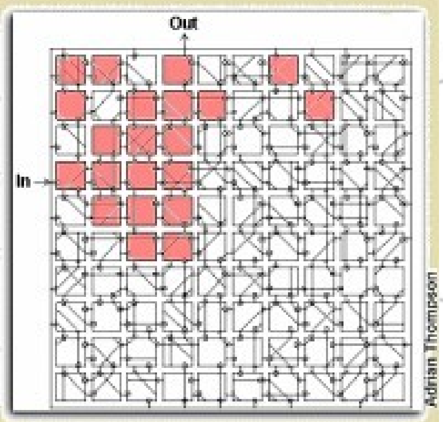
- Grow neural structures in Ferrous Sulphate
- Self-assembly of thread like structures
- Changing current would alter structure
- Frequency discriminator



Pask, G., Physical analogues to the growth of a concept. In: Mechanisation of Thought Processes, no. 10in National Physical Laboratory Symposium, pp. 877-922 (1958)

Adrian Thompson (1996)

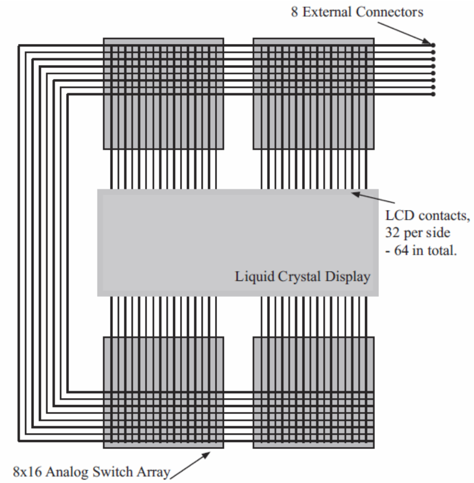
- Artificial evolution to configure a field programmable gate array (FPGA)
- Frequency discriminator: 1kHz and 10kHz
- Computation relied on physical properties of the FPGA chip itself, outside the discrete logical domain
- Much larger space of configurations than top-down engineering
- Exploit natural physical properties of the underlying substrate

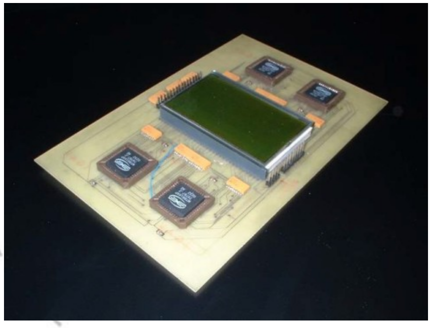


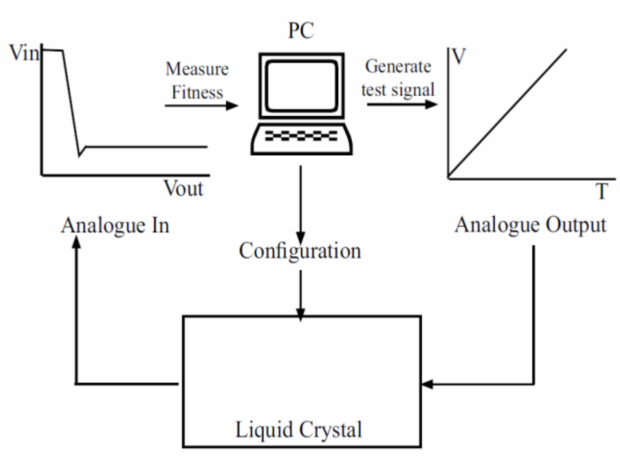
A 10x10 FPGA Array

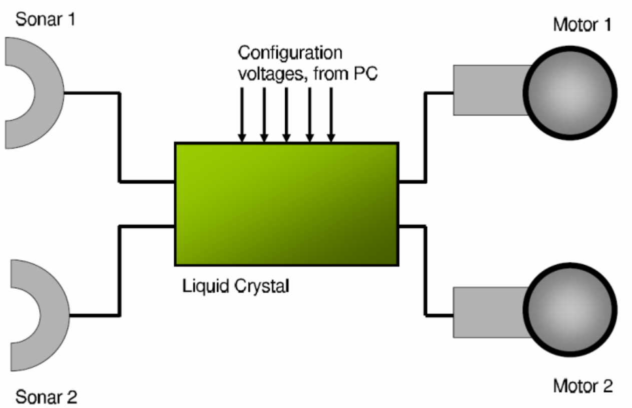
Thompson A., An evolved circuit, intrinsic in silicon, entwined with physics. In: Proc. 1st Int. Conf. on Evolvable Systems (ICES96), pp. 390-405, Berlin, 1997, Springer-Verlag.

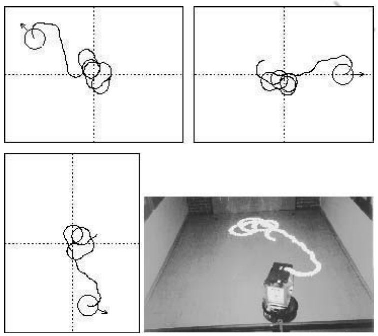
Liquid crystal







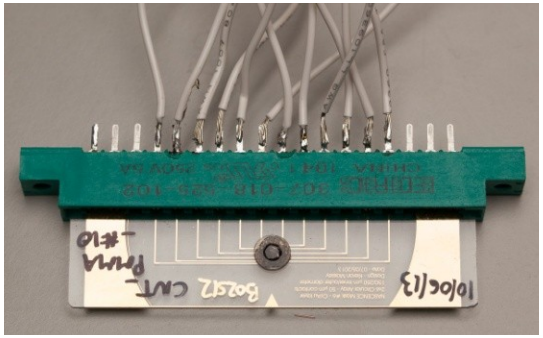


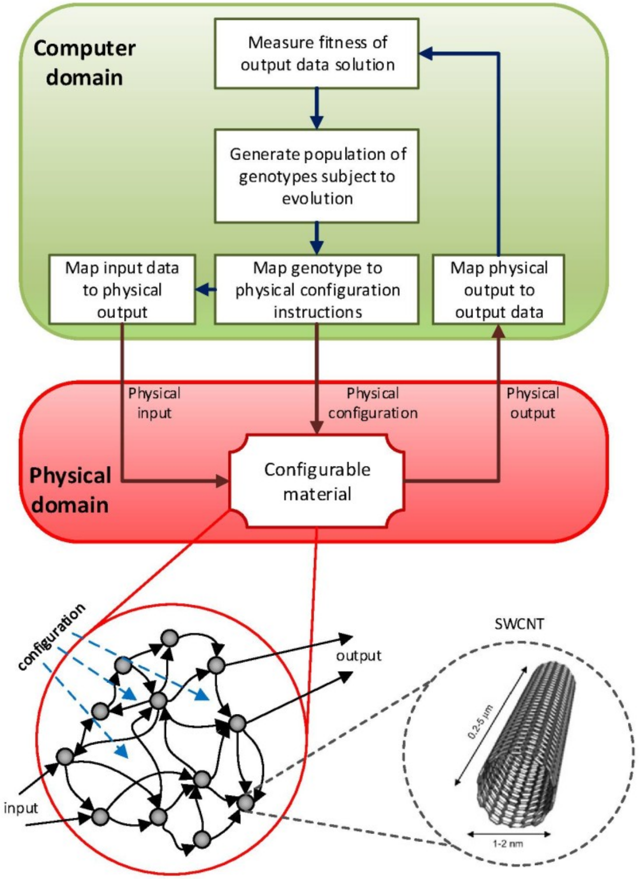


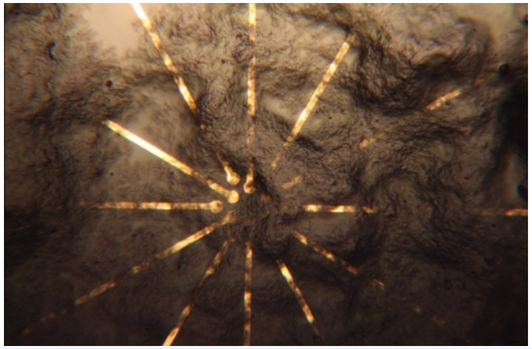
Harding S. and Miller J., Evolution in materio: A real-time robot controller in liquid crystal. In:Proceedings of the 2005 NASA/DoD Conference on Evolvable Hardware, pages 229--238, Washington, DC, USA, 29 June-1 July 2005. IEEE Press.

NASCENCE

SEVENTH FRAMEWORK PROGRAMME

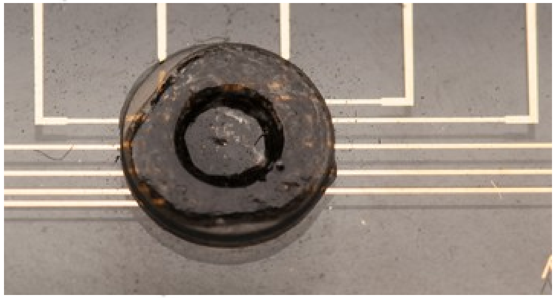




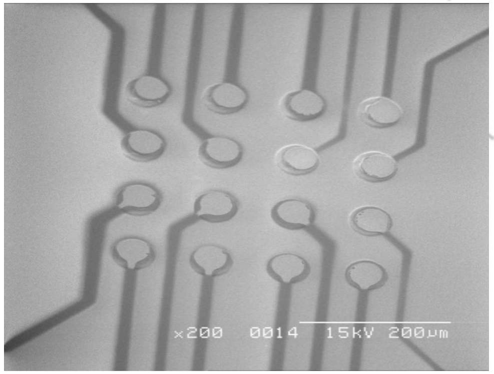


“The aim of this project is to model, understand and exploit the behaviour of evolving nanosystems (e.g. networks of nanoparticles, carbon nanotubes or films of graphene) with the long term goal to build information processing devices exploiting these architectures without reproducing individual components”.

Investigated material



- 20 µL material:
  - Single-wall carbon nanotubes (SWCNT) – 0.53% of weight
    - 30% metallic
    - 70% semi-conducting
  - Polybutyl methacrylate (PBMA)



- 4x4 grid of gold microelectrode array
- ”Baked” for 30 min at 90°C ->thick film
- Variable distribution of nanotubes across electrodes

- Materials supplied by Durham University

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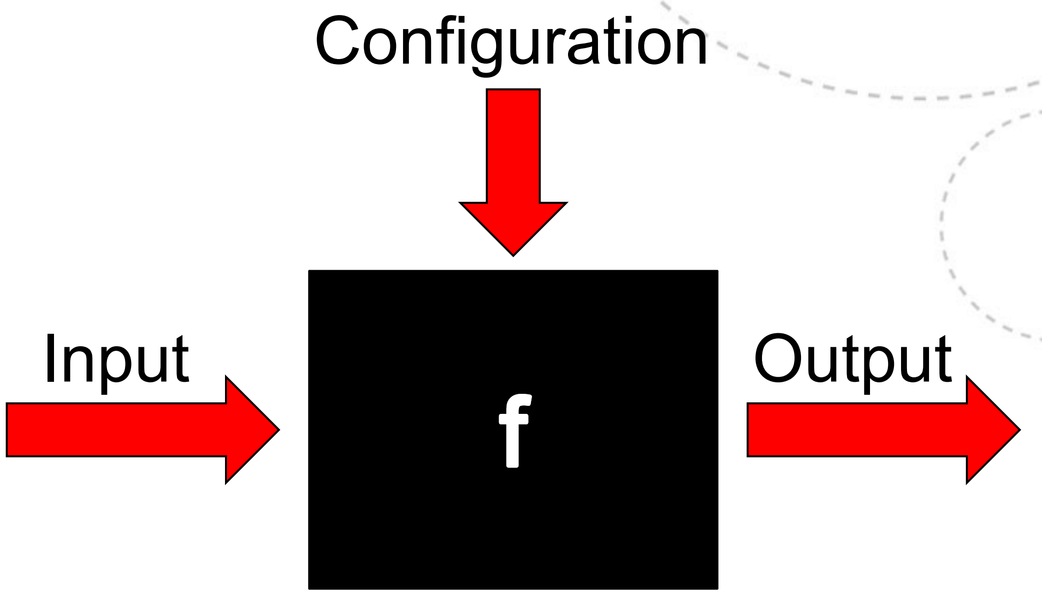
Black box approach

Solved problems in-materio:

- Traveling Salesman
- Logic gates
- Bin packing
- Machine learning classification
- Frequency classification
- Function optimization
- Graph coloring
- Robot controllers



- What are the exploited physical properties?

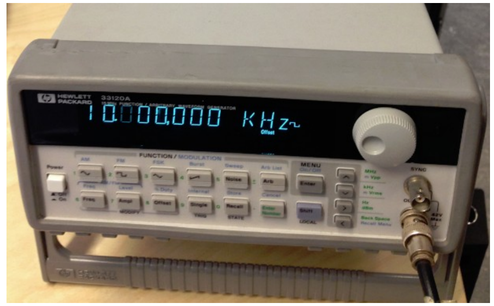
  Electrical (capacitance, resistance)...material dependent.
- What is the best way to exploit them?
- Which signals/configurations?
- How many electrodes?
- ...

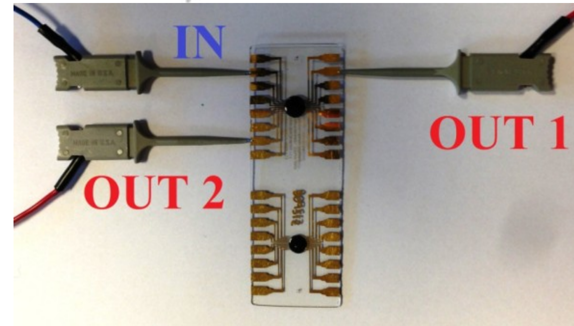
- Important for solving bigger instances of the investigated problems
- Number and type of parameters impact on search space / evolvability / computational power

Nano-materials as complex systems

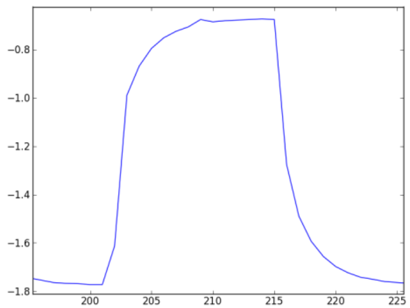
- Randomly dispersed carbon nanotubes in polymer solution
- Complex system with huge number of tiny elements interacting at local level -> emergent dynamics
- Connected with notion of Edge of Chaos (maximum complexity / computational power)
- Computation may occur in the vicinity of phase transition between
  - Order: little dynamics / information processing and high memory / structure preservation
  - Chaos: no memory and plenty of dynamics.
- Computation at molecular level (evo-in-materio) -> may produce very rich dynamics as the very essence of the material physics is exploited -> needs a balance between order and chaos to compute

Setup

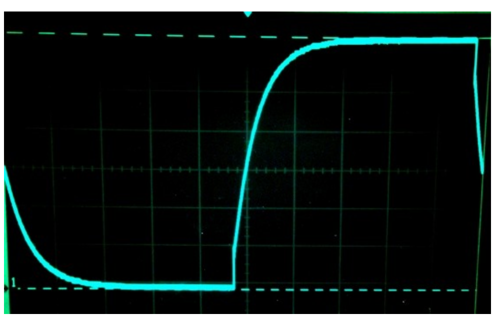


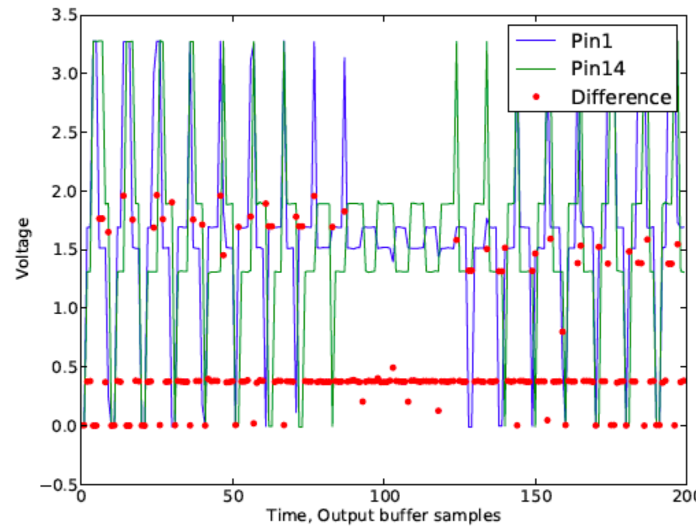


Mecobo Board



Oscilloscope





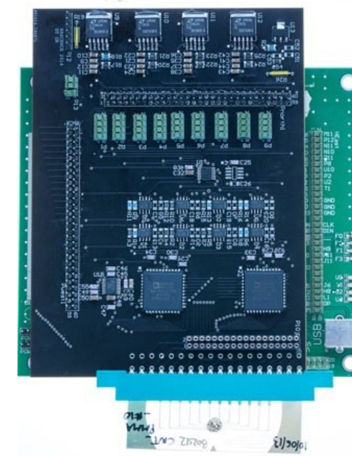
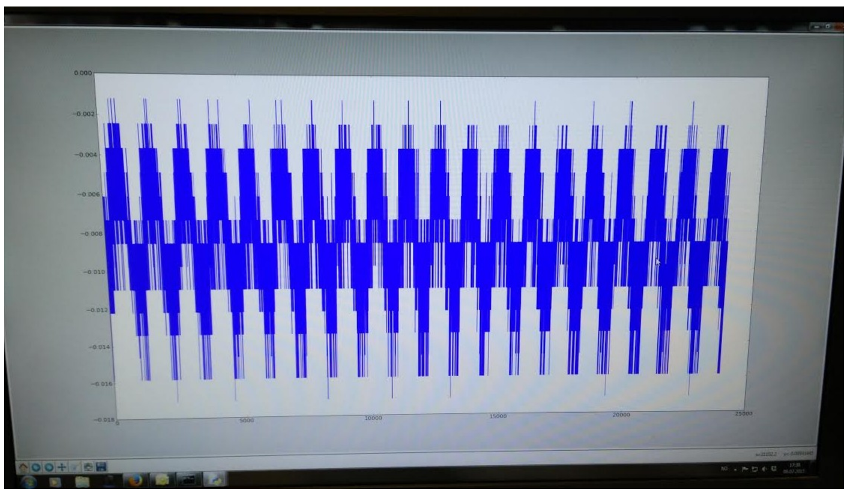
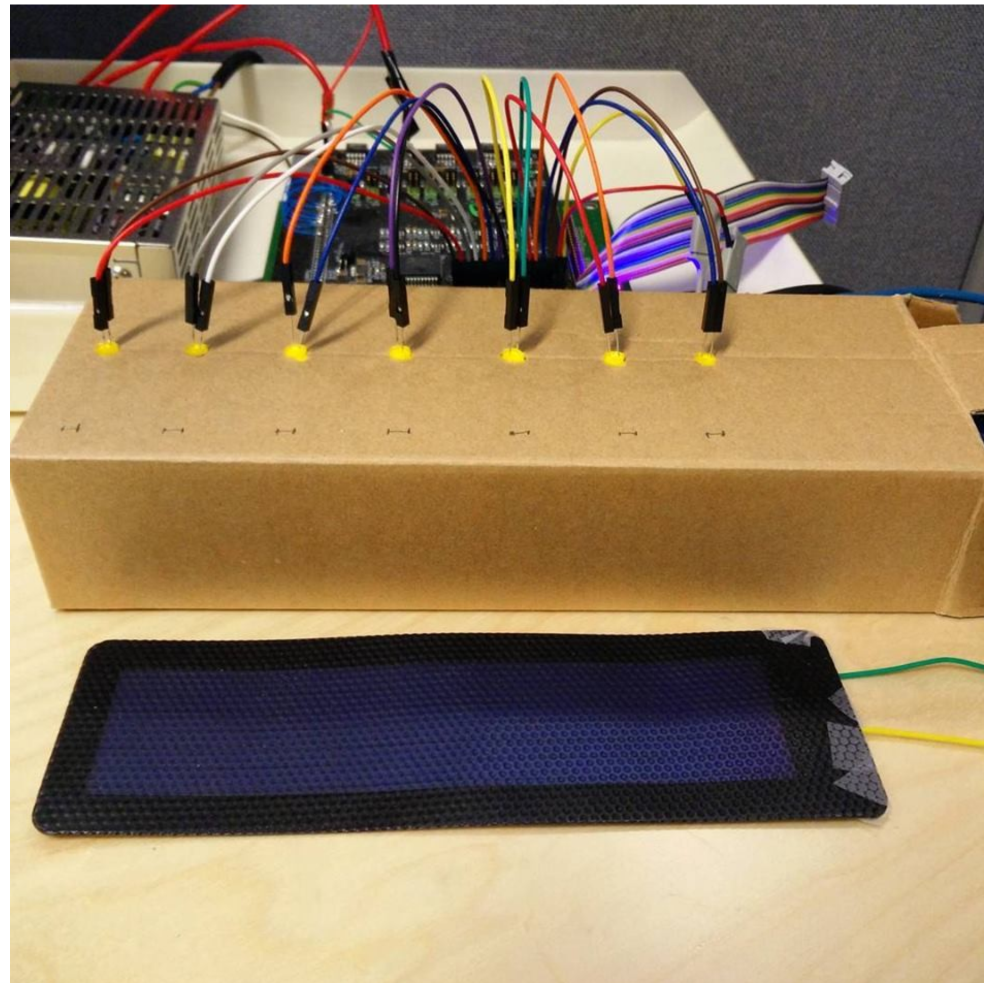


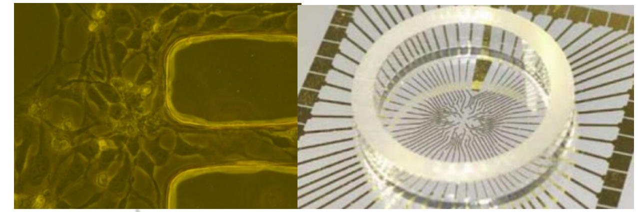
Fig. 24: 5,00% nanotubes, example with 2 inputs, evolve max difference. Input pin 13: 23945 Hz, duty cycle 27%; Input pin 2: 24576 Hz, Duty cycle 96%, Output pins: 1, 4.

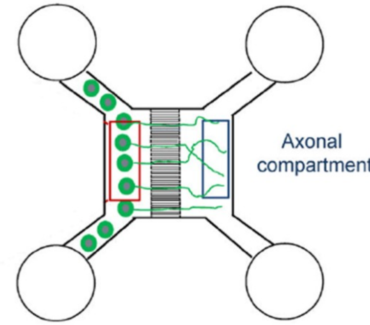
Computation-in-materio with light in solar panels



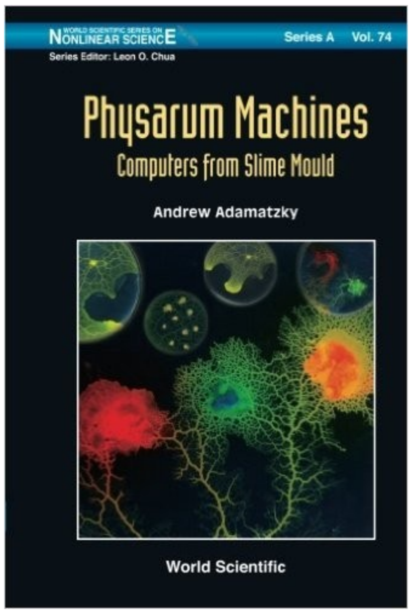


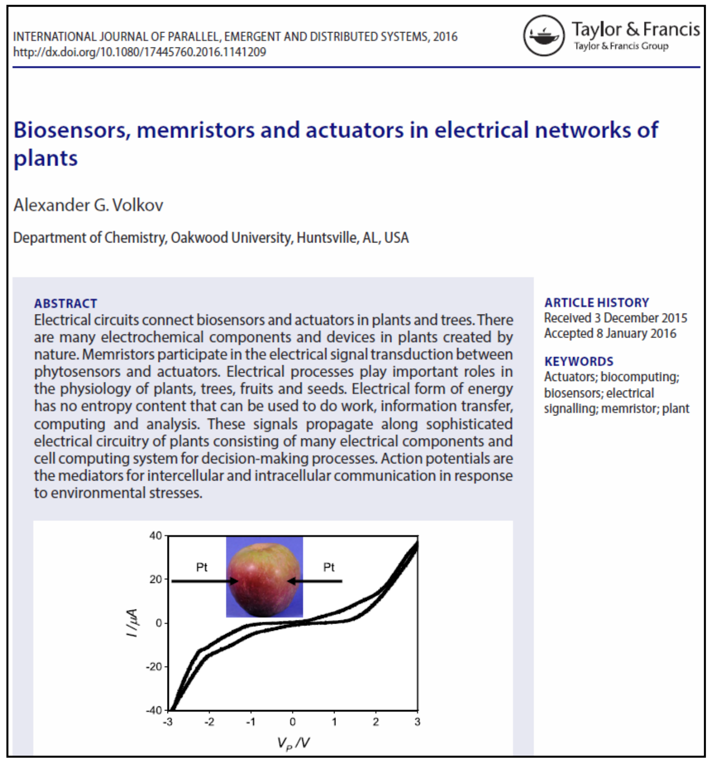
Organic materials?





https://www.ntnu.edu/cyborg





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Biosensors, memristors and actuators in electrical networks of plants

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ABSTRACT
Electrical circuits connect biosensors and actuators in plants and trees. There are many electrochemical components and devices in plants created by nature. Memristors participate in the electrical signal transduction between phytosensors and actuators. Electrical processes play important roles in the physiology of plants, trees, fruits and seeds. Electrical form of energy has no entropy content that can be used to do work, information transfer, computing and analysis. These signals propagate along sophisticated electrical circuitry of plants consisting of many electrical components and cell computing system for decision-making processes. Action potentials are the mediators for intercellular and intracellular communication in response to environmental stresses.

ARTICLE HISTORY
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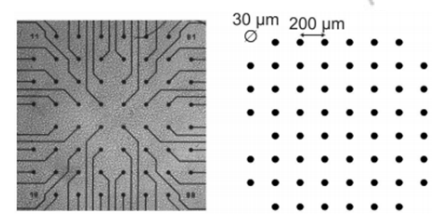
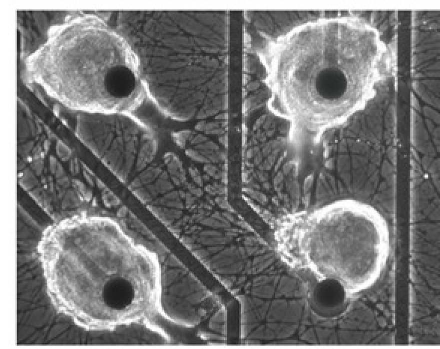
KEYWORDS
Actuators; biocomputing; biosensors; electrical signalling; memristor; plant





50 μm

Interested in specialization project / master thesis?

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