UNIVERSITY OF LOUISVILLE
J. B. SPEED SCHOOL OF ENGINEERING
Computer Engineering and Computer Science Department

CECS545-Artificial Intelligence: Artificial Life, CA

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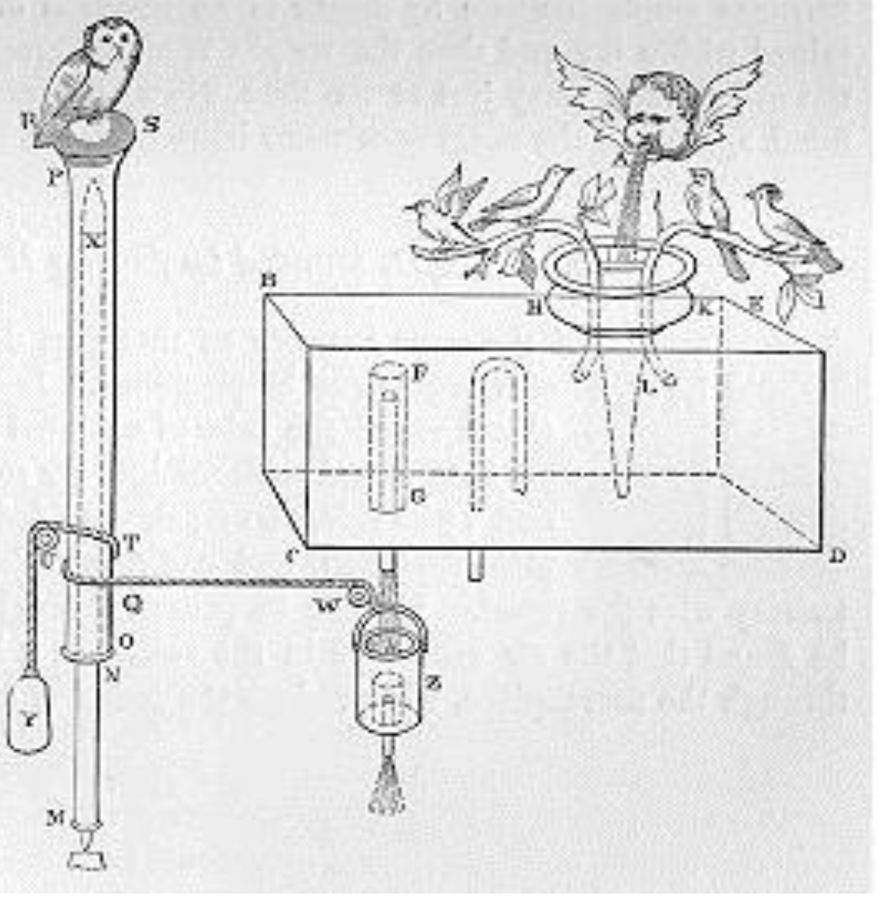
Slides by: Leigh Tesfatsion, Martijn Schut, Lubomir Ivanov, Inman Harvey And http://cellular-automata.um.ac.id/wp-content/uploads/2009/10/nature-inspired-ca1.ppt

Early Artificial Life

Automata

Started with the Ancient Greeks.

1st century AD, Hero of Alexandria described working models of animals and humans, using hydraulics and pneumatics.



Middle Ages

From around 14th Century AD, development of clocks allowed more sophisticated automata.

Early Alife quote:
"For seeing life is but a motion of Limbs, the beginning whereof is in the principal part within; why may we not say that all *Automata* (Engines that move themselves by springs and wheeles as doth a watch) have an **artificiall life**?"

Thomas Hobbes in *Leviathan* (1651)

Jump to 20 C

2nd World War – **Cybernetics** "the study of control and communication in the animal and machine" N Wiener.
Aiming of anti-aircraft fire -- notion of **Feedback**

A lot of important early work in Cybernetics in 1940/50s that got rather forgotten in the rise of **Computing**.

And Computing

Then came computing ... ... the classical AI approach
... disembodied abstract reasoning.

Computing has been enormously successful for abstract problem solving, but led to this insidious popular view that humans and animals think and behave like problem-solving computers.

Embodied behaviour before abstract rationality

From several directions, particularly in the last decade, has come the realisation that humans are the product of 4 billion years of evolution, and only the last tiny fraction of this period has involved language and reasoning.

If we don't understand the capacities of simple organisms, how can we hope to understand human capacities?

This is **one motive** for doing A-life.

OK, so what is Artificial Life?

"Artificial Life is the study of man-made systems that exhibit behaviours characteristic of natural living systems. It complements the traditional biological sciences concerned with the *analysis* of living organisms by attempting to *synthesize* life-like behaviours within computers and other artificial media. By extending the empirical foundation upon which biology is based *beyond* the carbon-chain life that has evolved on Earth, Artificial Life can contribute to theoretical biology by locating *life-as-we-know-it* within the larger picture of *life-as-it-could-be."*

Chris Langton (in Proc. of first Alife conference)

Alife Strong and Weak

Note 2 meanings of 'Artificial':
(1) = fake (ex. artificial snow)
(2) = made by artifice, an artefact, but not fake (ex. artificial light)

Two positions you will come across:
Weak Alife: computer programs as useful simulations of real life
Strong Alife: ditto as **actually living**

Is A-life more than Theoretical Biology?

“This paper examines A-Life as theoretical biology, as a set of computer simulation methods that may prove useful to biologists given their native concerns. I will not address A-life as engineering, entertainment, pedagogy, philosophy of biology, or runaway post-modern cult."

*** Geoffrey Miller in 'Artificial Life as Theoretical Biology: How to do real science with computer simulation'

Yes it is more!

✓Alife **can** be used for theoretical biology
--- but then make sure you are working on a problem biologists are interested in.

First explicit Alife paper in Nature v400 12 Aug 1999. Lenski et al. pp. 661-664 And others since

Such as …

But Also Alife can and should cover
✓engineering,
✓entertainment,
✓pedagogy,
✓philosophy of biology,
✓Etc.

There are many strong differences of views in this field.

Alife Related Topics …

- ✓ Cellular Automata, 'Game of Life‘ (today)
- ✓ Search spaces (Genetic Algorithms)
- ✓ Swarm Intelligence (Ants, Bees, Flocks)
- ✓ Humans (Wisdom of Crowds)

More AL topics if you are interested:

- ✓Digital organisms
- ✓Evolutionary Robotics
- ✓Evolvable Hardware
- ✓Neutral Networks

Universal Machines – Cellular Automata

Stanislaw Ulam (1909 - 1984)

Universal Machines – Cellular Automata

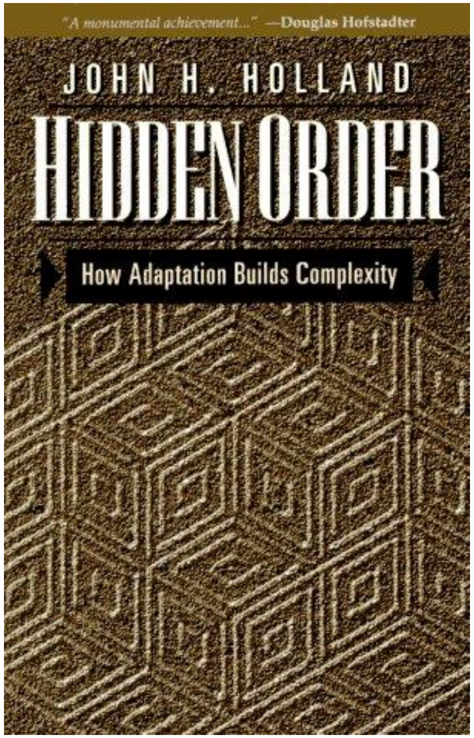
- conceived in the 1940s

- Stanislaw Ulam - evolution of graphic constructions generated by simple rules
    -

- Ulam asked two questions:

    - can recursive mechanisms explain the complexity of the real?

    - Is complexity then only apparent, the rules themselves being simple?



Stanislaw Ulam Memorial Lectures

Universal Machines – Neumann Machines

John von Neumann (1903- 1957)

Universal Machines – Neumann Machines

- John von Neumann interests himself on theory of self-reproductive automata

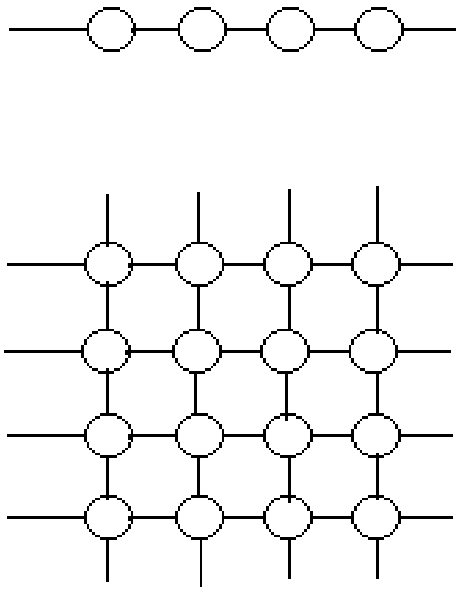
- Ulam suggested von Neumann to use “cellular spaces”

- extremely simplified universe

Cellular Automata

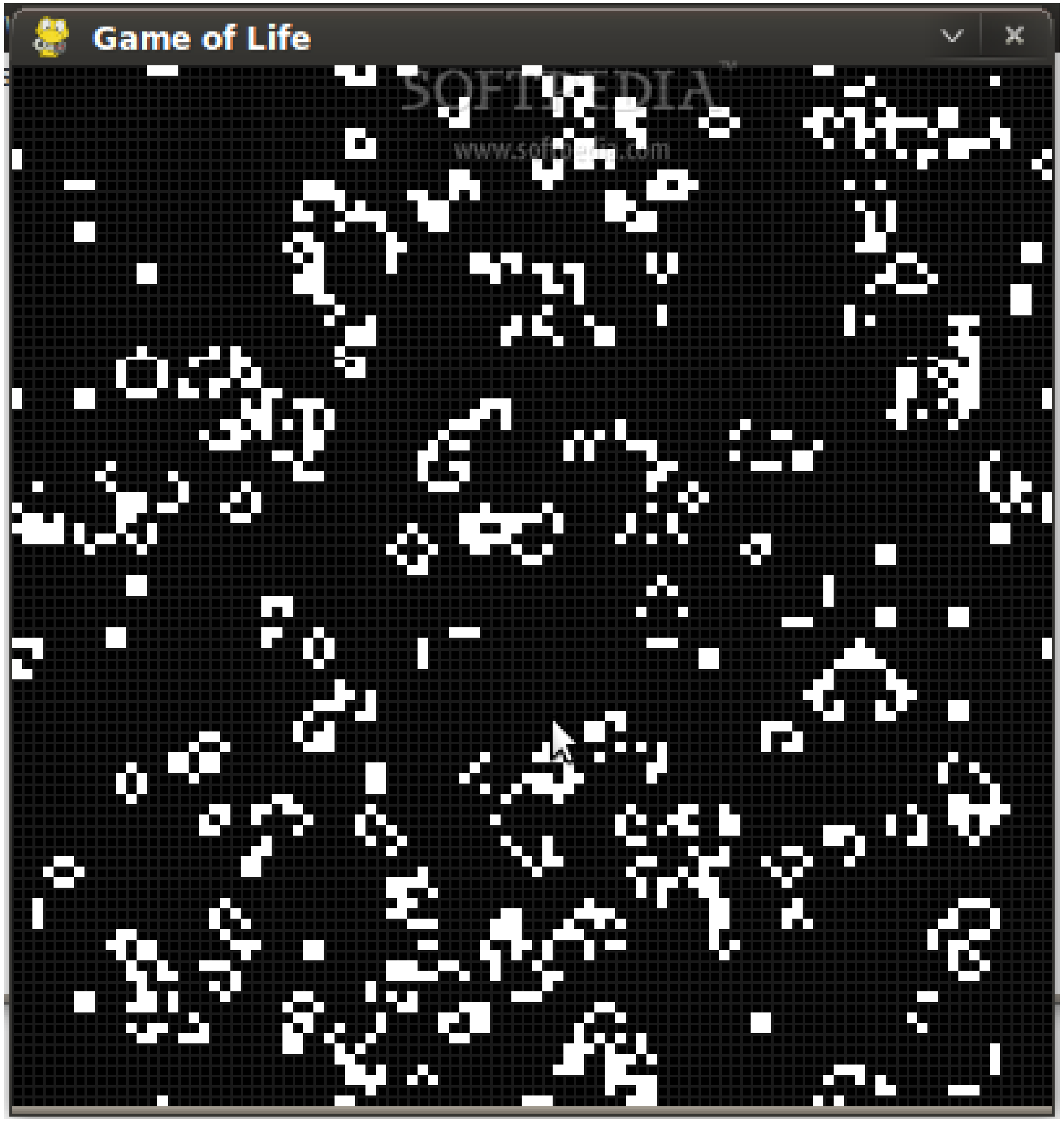
- A Cellular Automaton is a model of a parallel computer
- A CA consists of processors (cells), connected usually in an n-dimensional grid

1-D CA



2-D CA

EXAMPLE: Life – The Game



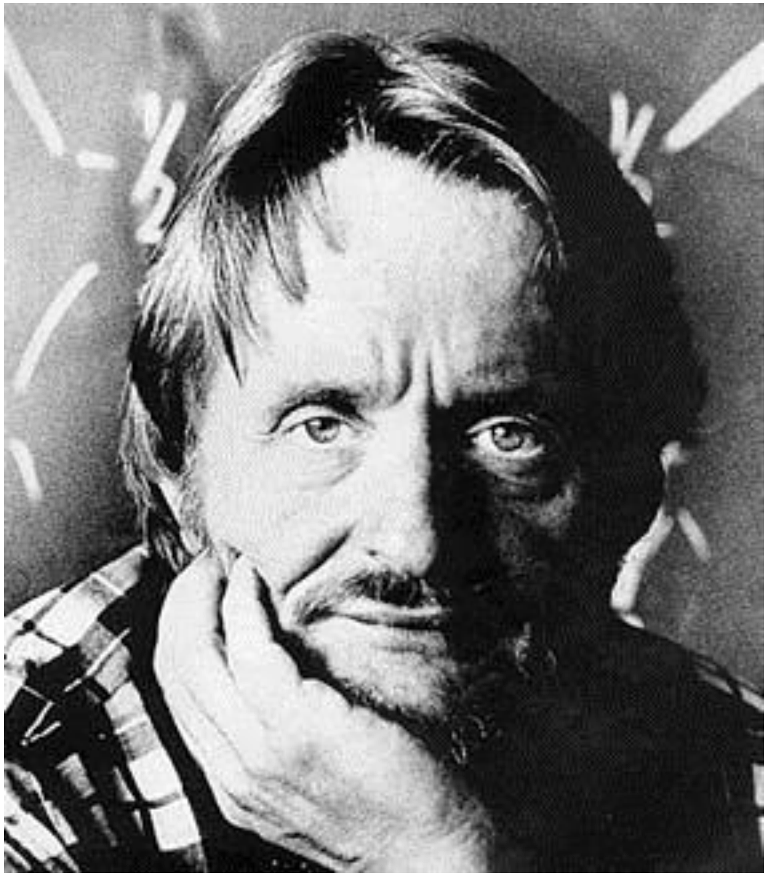
Movement of patterns on grid matrix

History of Cellular Automata

- Original experiment created to see if simple rule system could create "universal computer"

- Universal Computer (Turing): a machine capable of emulating any kind of information processing through simple rule system
  - Von Neumann and Stan Ulam
- late 1960's: John Conway invents "Game of Life"

Life - Conway's Game of Life



John H. Conway

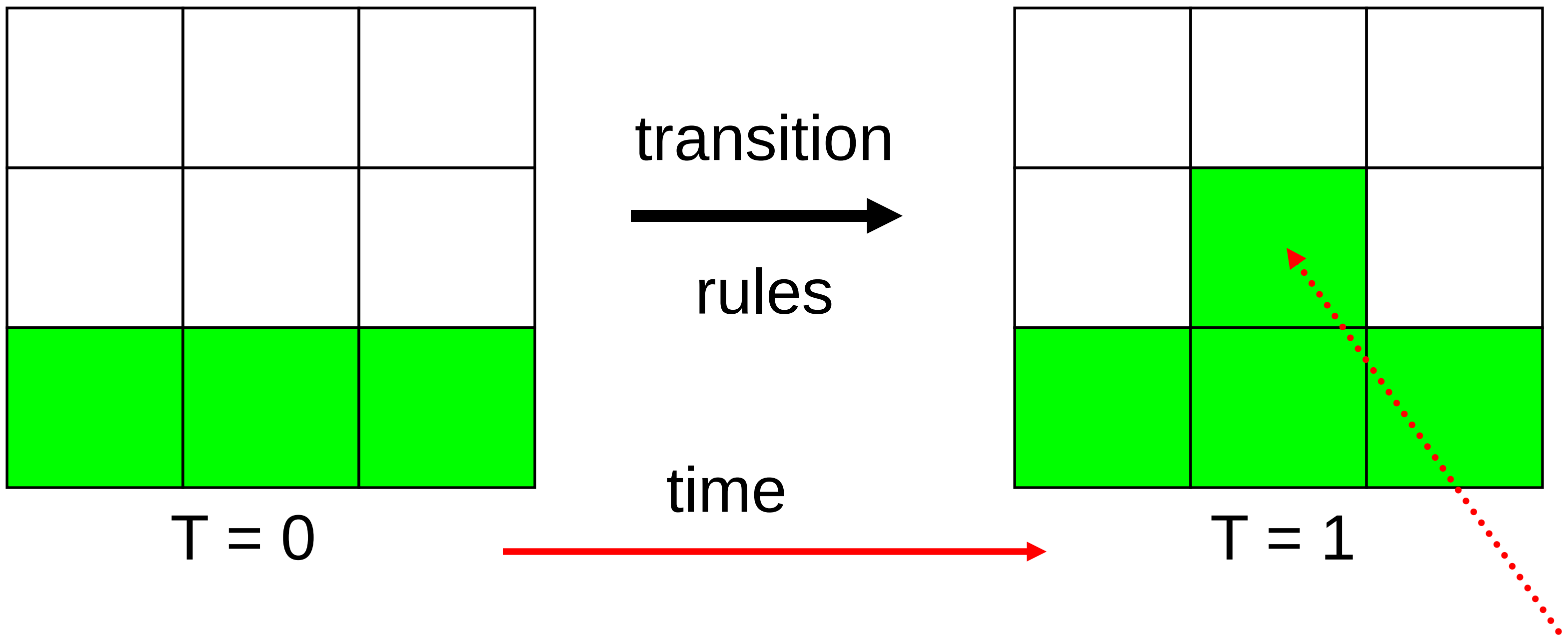
Life - Conway's Game of Life

- Simplest possible universe capable of computation
- **Basic design:** rectangular grid of "living" (on) and "dead" (off) cells

- Complex patterns result from simple structures
- In each generation, cells are governed by three simple rules
- Which patterns lead to stability? To chaos?

Life - Conway's Game of Life

- A cell dies or lives according to some *transition rule*



Here we are interested in rules for the middle cell only

Life - Conway's Game of Life

Three simple rules

- dies if number of alive neighbor cells =< 2 (*loneliness*)
- dies if number of alive neighbor cells >= 5 (*overcrowding*)
- lives is number of alive neighbor cells = 3 (*procreation*)

This means that in original "Game of Life" when the cell has 4 alive neighbors, then its state remains as it was.

Life - Conway's Game of Life

Another variant of Conway's Rules

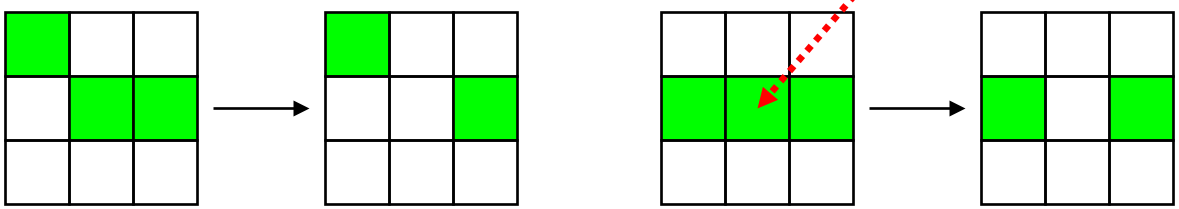
- Death: if the number of surrounding cells is less than 2 or greater than 3, the current cell dies
- Survival: if the number of living cells is exactly 2, or if the number of living cells is 3 (including the current cell), maintain status quo
- Birth: if the current cell is dead, but has three living cells surrounding it, it will come to life

Life - The Game

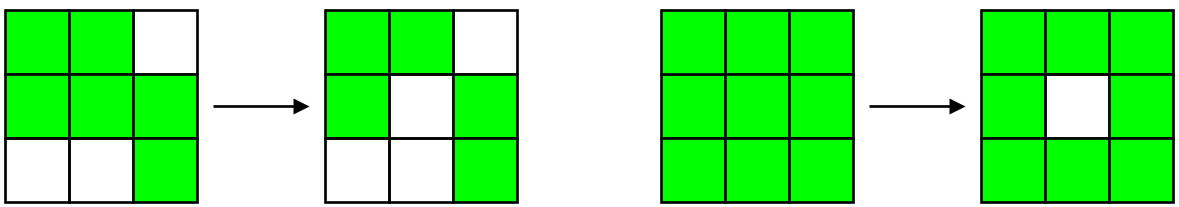
Here the rules are applied only to the cell in the middle

Examples of the rules

- **loneliness** (dies if #alive =< 2)

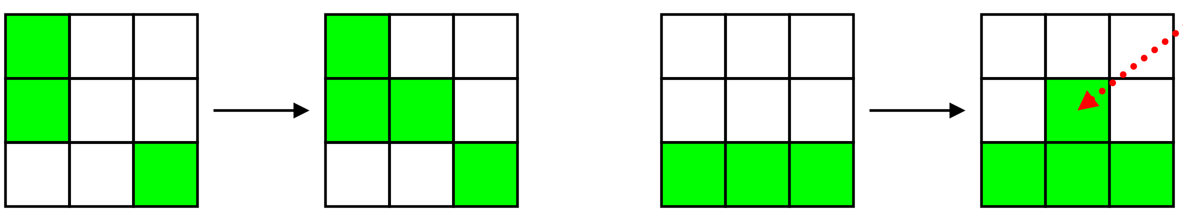


- **overcrowding** (dies if #alive >= 5)



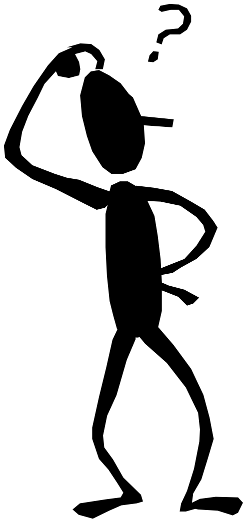
- **procreation** (lives if #alive = 3)

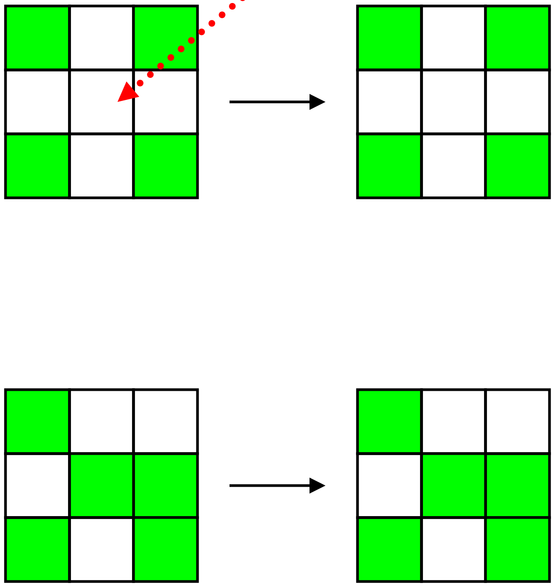
New cell is born

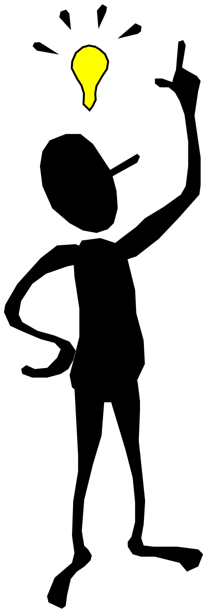


Life - The Game

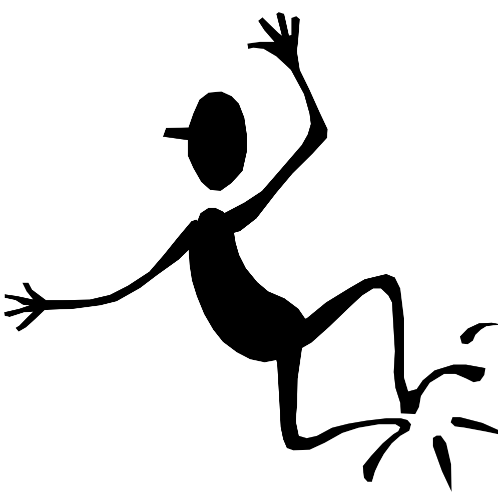
Here the rules are applied only to the cell in the middle







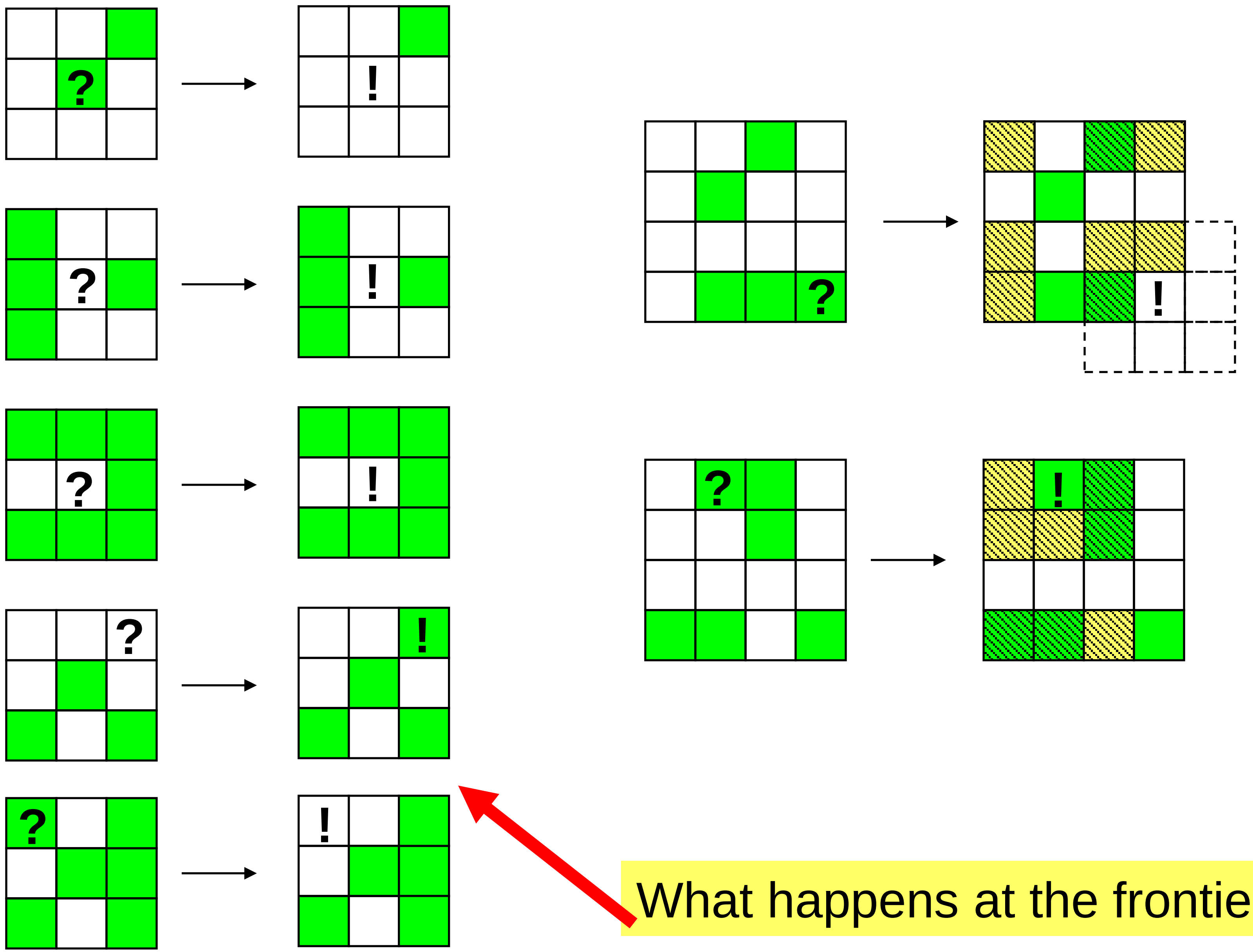
Cell has four alive neighbors so its state is preserved



Life – The Game

Rap-around the east and west

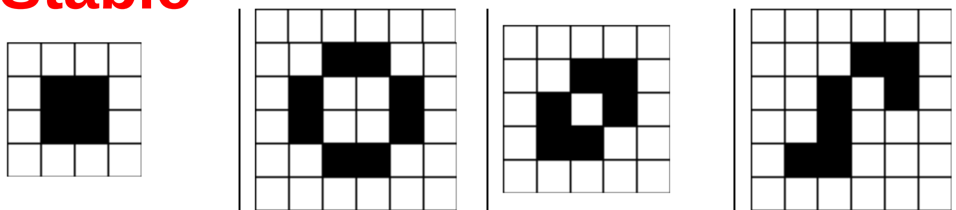
and the north and south (this is only in some variants)



What happens at the frontiers?

Life - Patterns

Stable

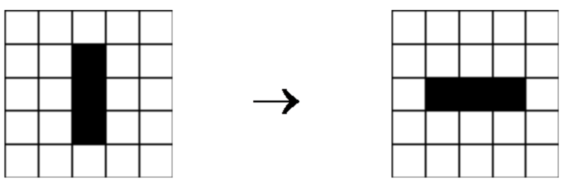


block | pond | ship | eater

If you start from such patterns, they will remain

If such separated pattern is ever created, it remains.

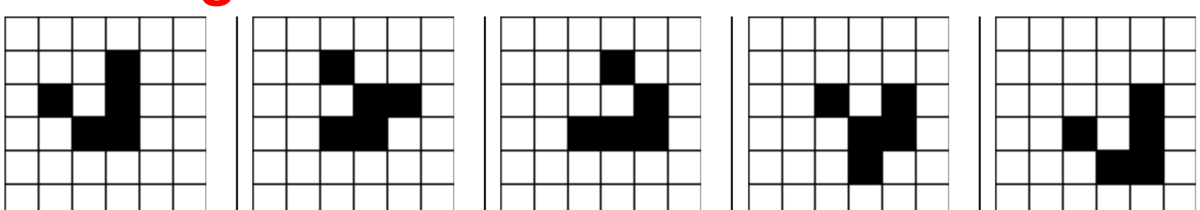
Periodic



time = 1 | time = 2

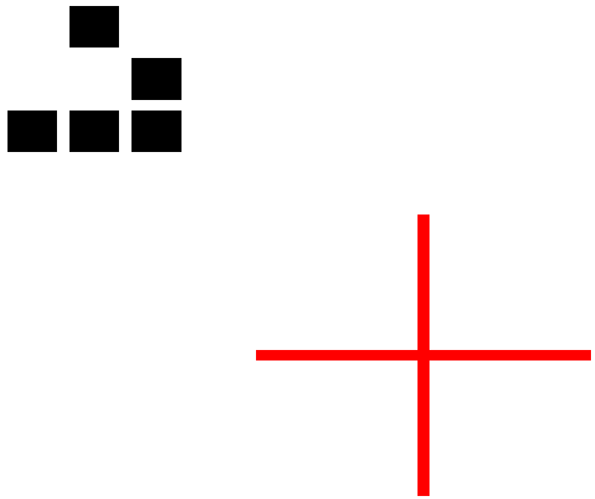
These patterns oscillate with certain periods, here the period is two.

Moving

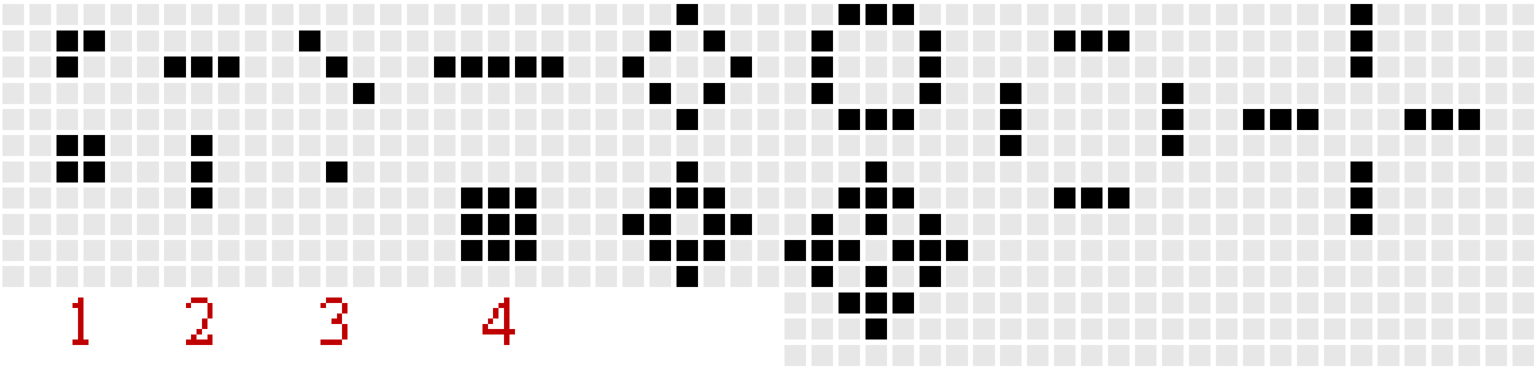


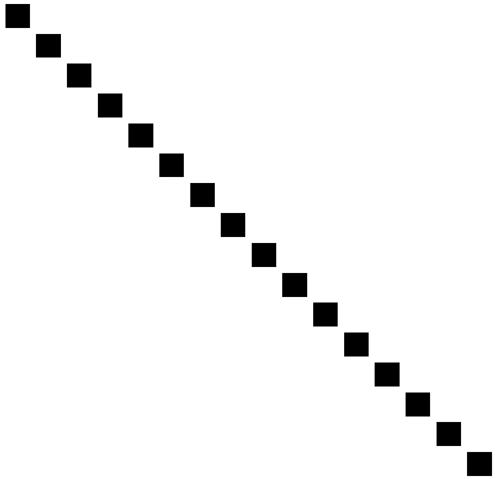
Time = 1 | time = 2 | time = 3 | time = 4 | time = 5

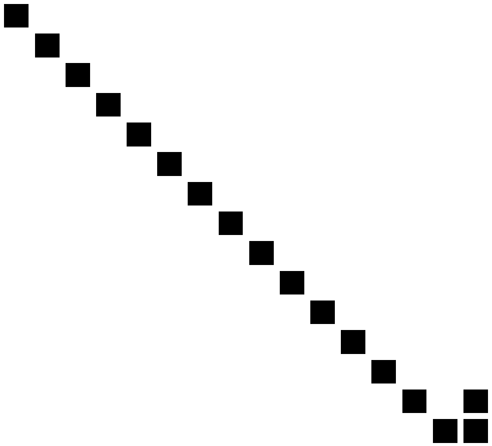
Glider



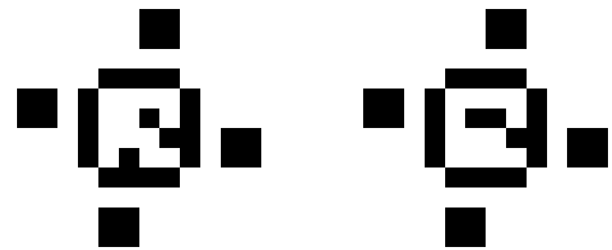
Sequences







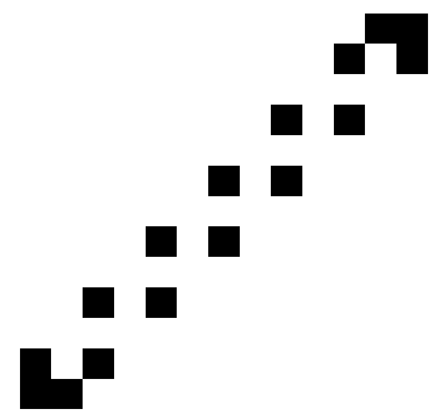
More



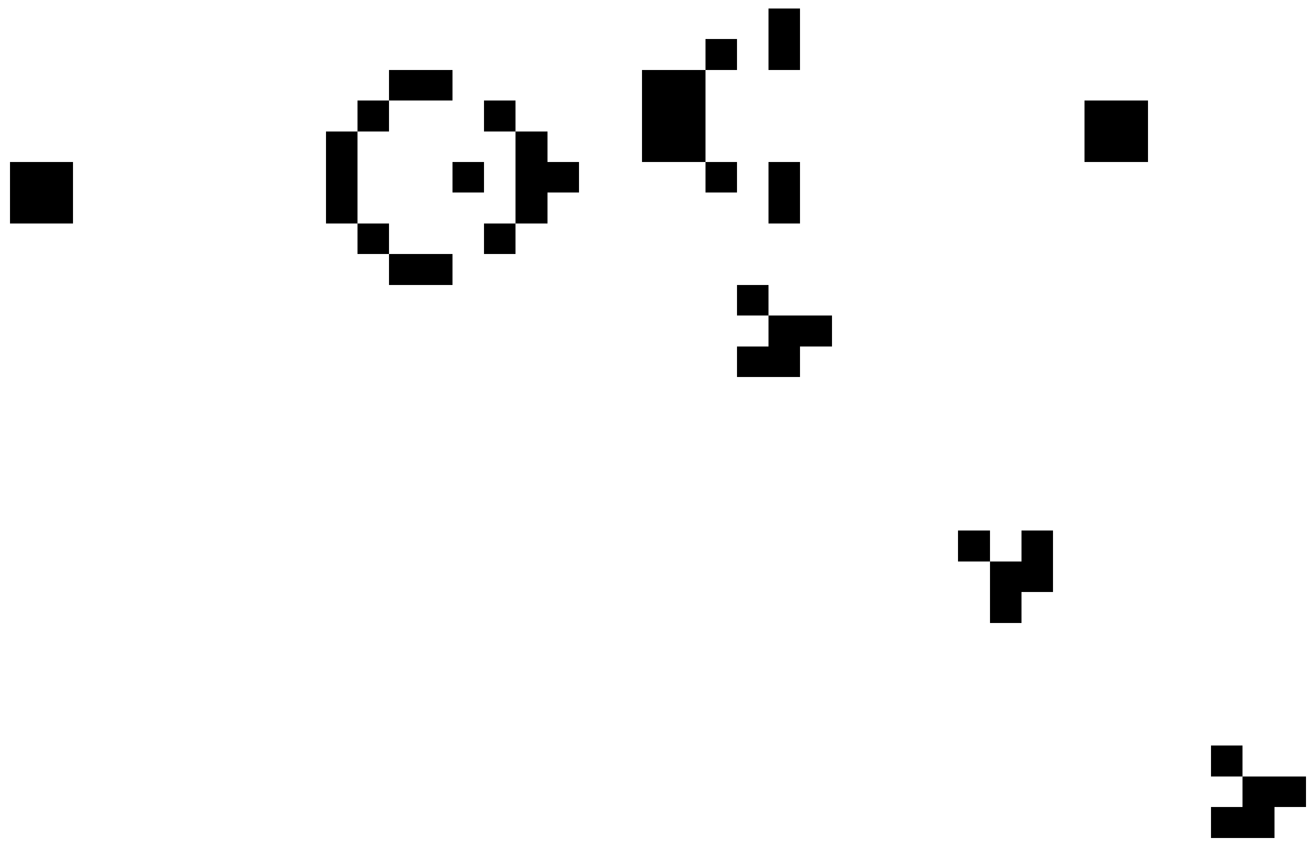
Sequence leading to Blinkers

Clock

Barber's pole

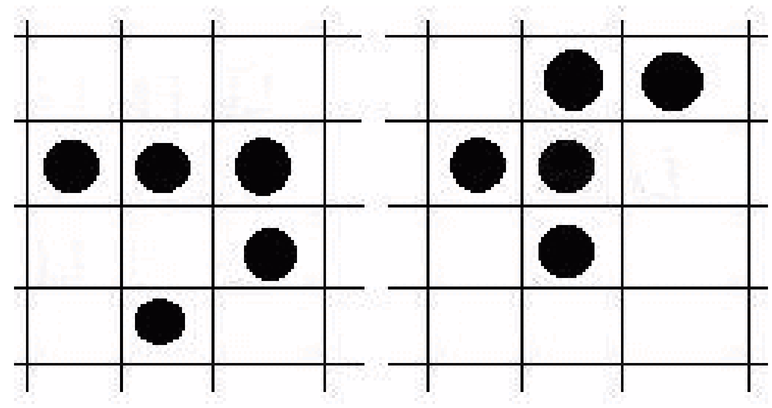


A Glider Gun



Gliders and pentominoes

On the left: a **'Glider'**
On a clear background, this shape will 'move' to the NorthEast one cell diagonally after 4 timesteps.



Each cell does not 'move', but the 'pattern of cells' can be seen by an observer as a glider travelling across the background.

Emergence

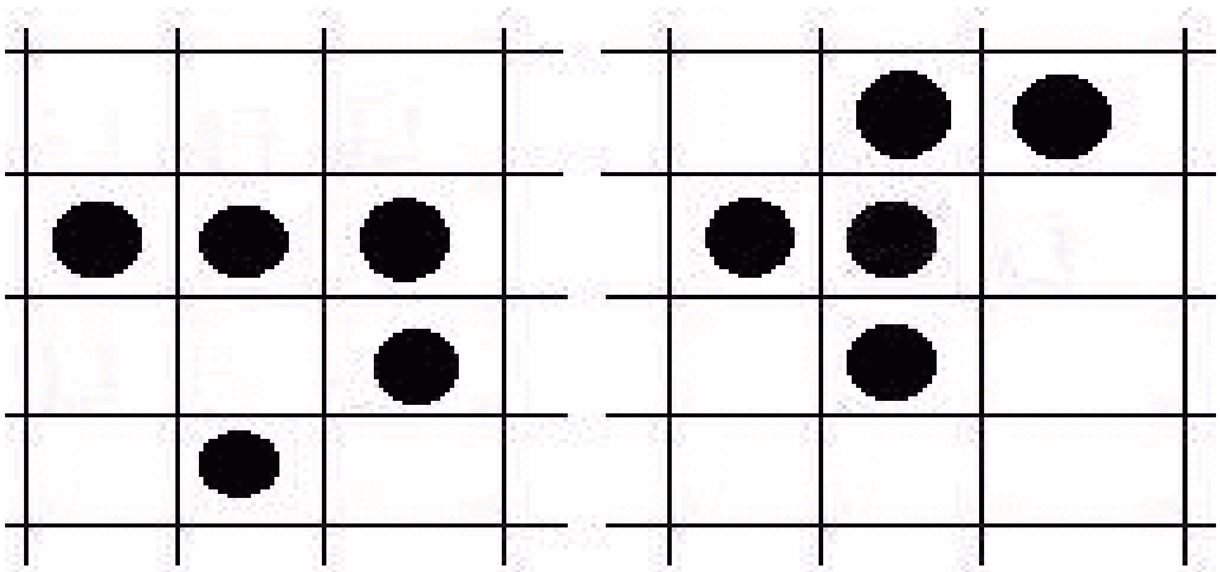
This behaviour can be observed as ‘the movement of a glider’, even though no glider was mentioned in the rules.

'Emergent' behaviour at a higher level of description, emerging from simple low-level rules.

Emergence = emergence-in-the-eye-of-the-beholder (dangerous word, controversial)

Pentominoes

a 'pentomino'. Simple starting state on a blank background => immense complexity, over 1000 steps before it settles.



Game of Life - implications

Typical Alife computational paradigm:

✓bottom-up

✓parallel

✓locally-determined

Complex behaviour from (... emergent from ...) simple rules.

Gliders, blocks, traffic lights, blinkers, glider-guns, eaters...

Game of Life as a Computer ?

Higher-level units in GoL can in principle be assembled into complex 'machines' -- even into a full computer, or Universal Turing Machine.

'Computer memory' held as 'bits' denoted by 'blocks‘ laid out in a row stretching out as a potentially infinite 'tape'. Bits can be turned on/off by well-aimed gliders.

Beyond Life - Cellular Automata

"A CA is an array of identically programmed automata, or cells, which interact with one another in a neighborhood and have definite state"

Let us analyze every component of the definition

In essence, what are Cellular Automata?

- 1. Computer simulations which emulate the laws of nature
- 2. Discrete time/space logical universes
- 3. Complexity from simple rule set: reductionist approach
- 4. Deterministic local physical model
- 5. Rough estimation of nature: no precision
- 6. This model does not reflect 'closed sphere' life: can achieve same end results given rules and initial conditions

Simulation Goals using CA

- Avoid extremes: patterns that grow too quickly (unlimited) or patterns that die quickly

- Desirable behaviors:
  - No initial patterns where unlimited growth is obvious through simple proof
  - Should discover initial patterns for which this occurs
  - Simple initial patterns should grow and change before ending by:
    - fading away completely
    - stabilizing the configuration
    - oscillating between 2 or more stable configurations
  - Behavior of population should be relatively unpredictable

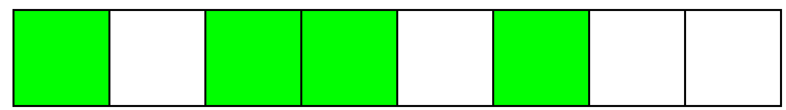
Cellular Automata – Various types of Arrays

"A CA is an array of identically programmed automata, or cells, which interact with one another in a neighborhood and have definite state"

1	45	34	12	90	4	27	7

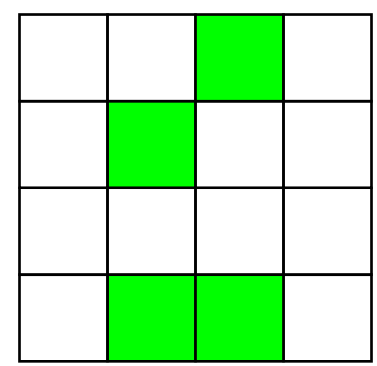
H	Q	M	S	W	E	T	G

1	0	1	1	0	1	0	0



- 1 dimensional
- 2 dimensional

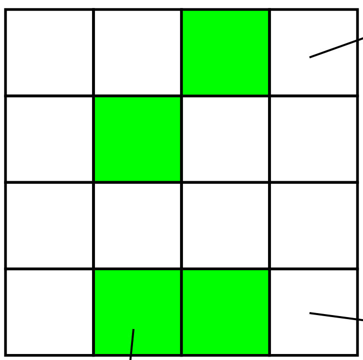
G	O	M	R
A	W	J	D
X	R	E	P
N	I	Z	T



Cellular Automata – rules for Cells

“A CA is an array of identically programmed automata, or cells, which interact with one another in a neighborhood and have definite state”

- **if #alive =< 2, then die**
- **if #alive = 3, then live**
- **if #alive >= 5, then die**



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Identically programmable?

Cellular Automata – Interaction is local

"A CA is an array of identically programmed automata, or cells, which interact with one another in a neighborhood and have definite state"

the rules

if #alive =< 2, then die

if #alive = 3, then live

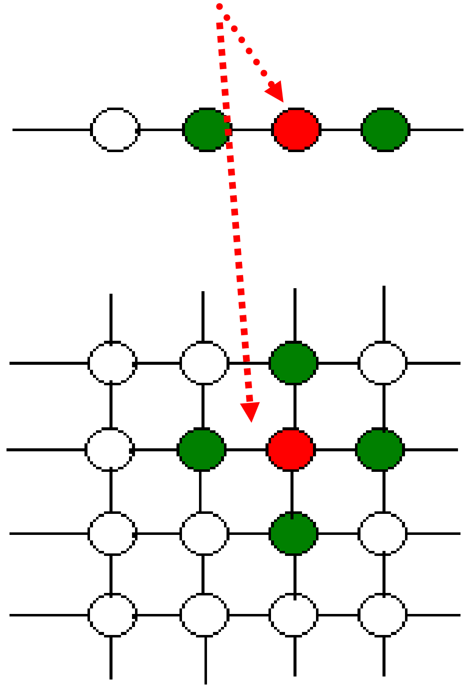
if #alive >= 5, then die

The role of local interaction in (nano) technologies

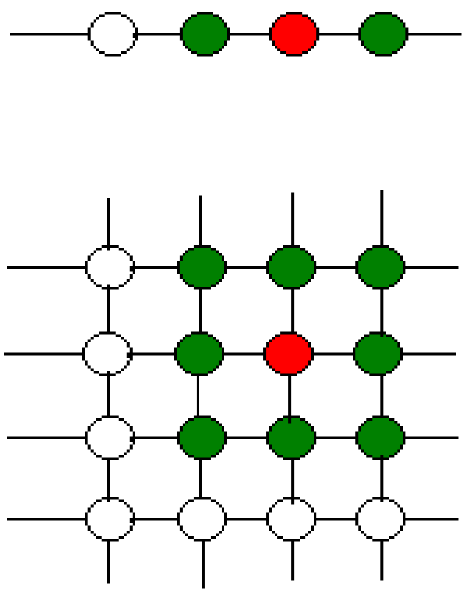
Cellular Automata – Neighbourhood

- Classic examples of cell neighborhoods:

Von Neumann Neighborhood

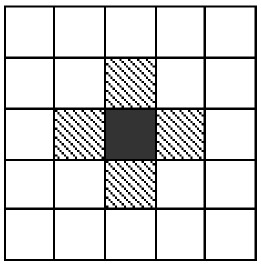


Moore Neighborhood

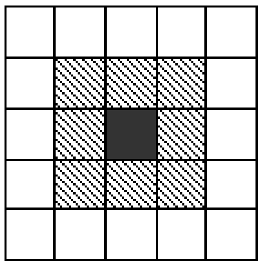


Cellular Automata – Neighbourhood

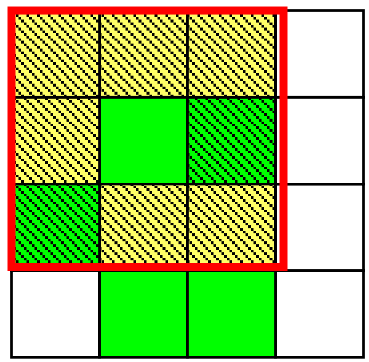
"A CA is an array of identically programmed automata, or cells, which interact with one another in a neighborhood and have definite state"



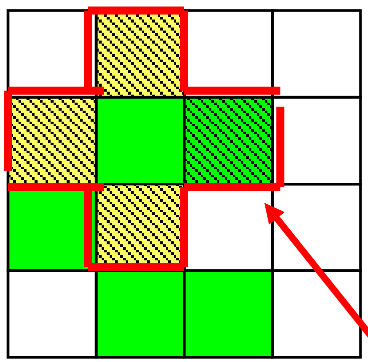
von Neumann Neighbourhood



Moore Neighbourhood



Moore neighborhood



Neumann neighborhood

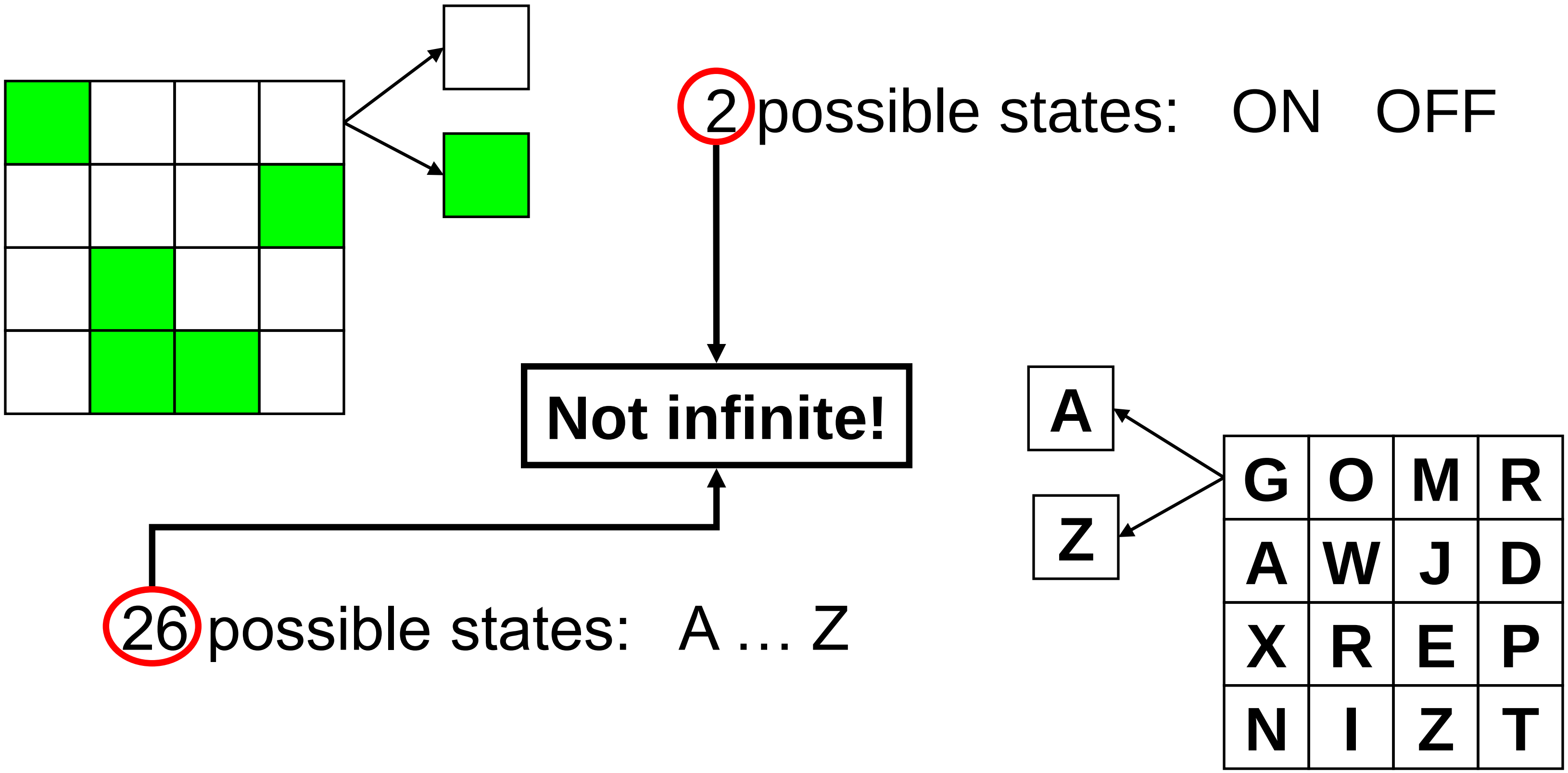
8 neighbors in Moore neighborhood

4 neighbors in Von Neumann neighborhood

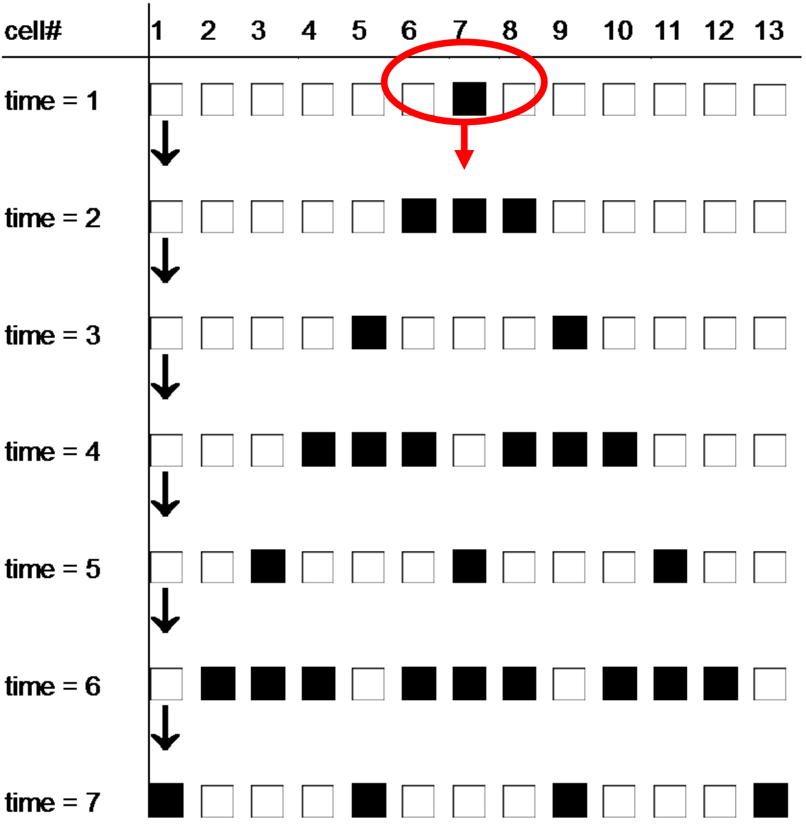
Margolus, Wolfram and other neighborhoods

Cellular Automata - States

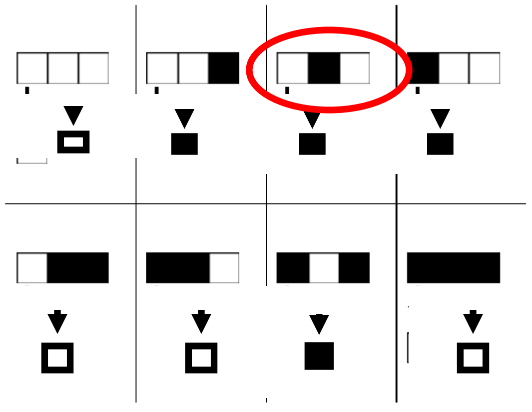
"A CA is an array of identically programmed automata, or cells, which interact with one another in a neighborhood and have definite state"



Cellular Automata - Simple 1D Example

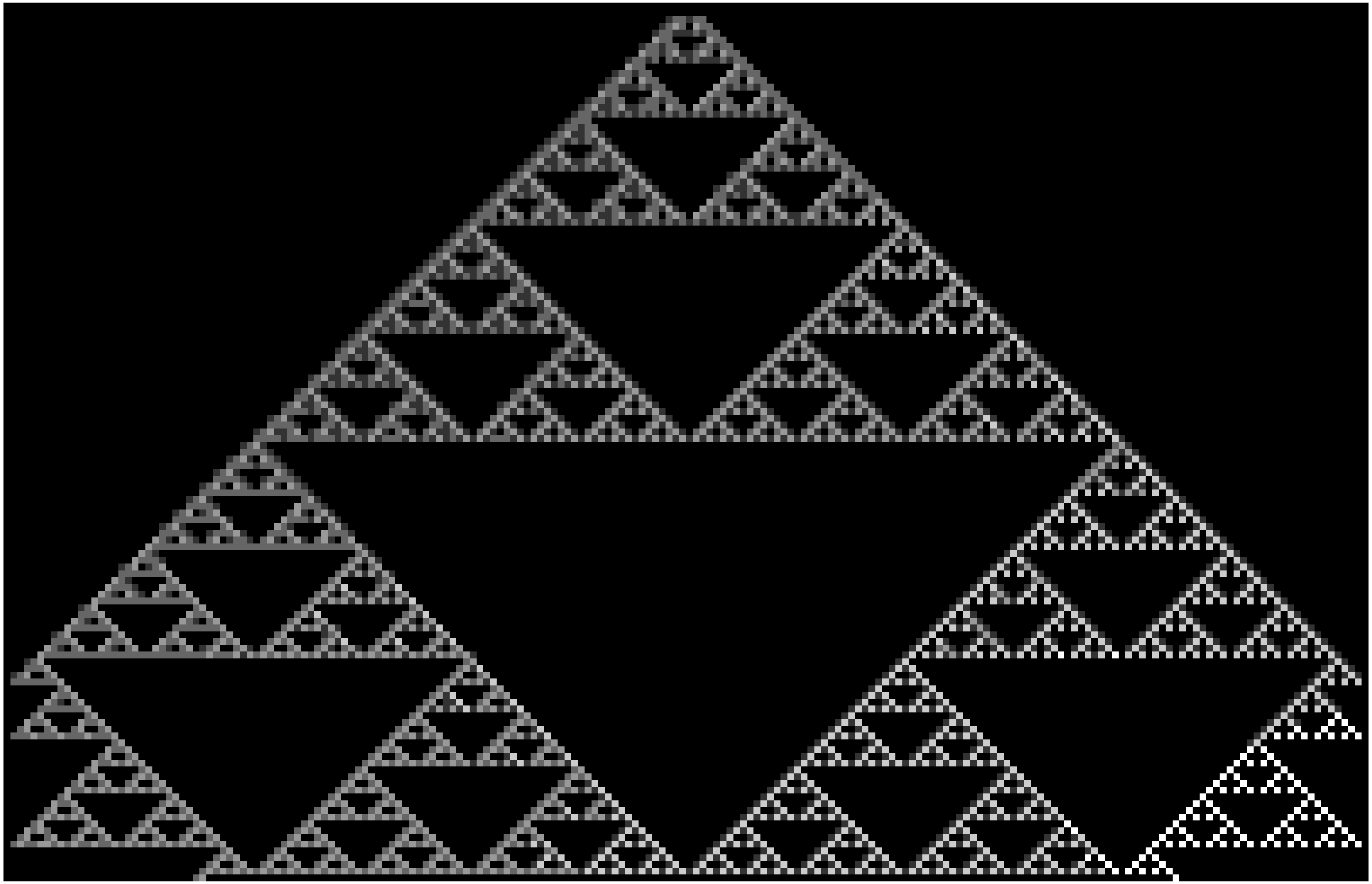


The rules



Observe the recursive property of the pattern

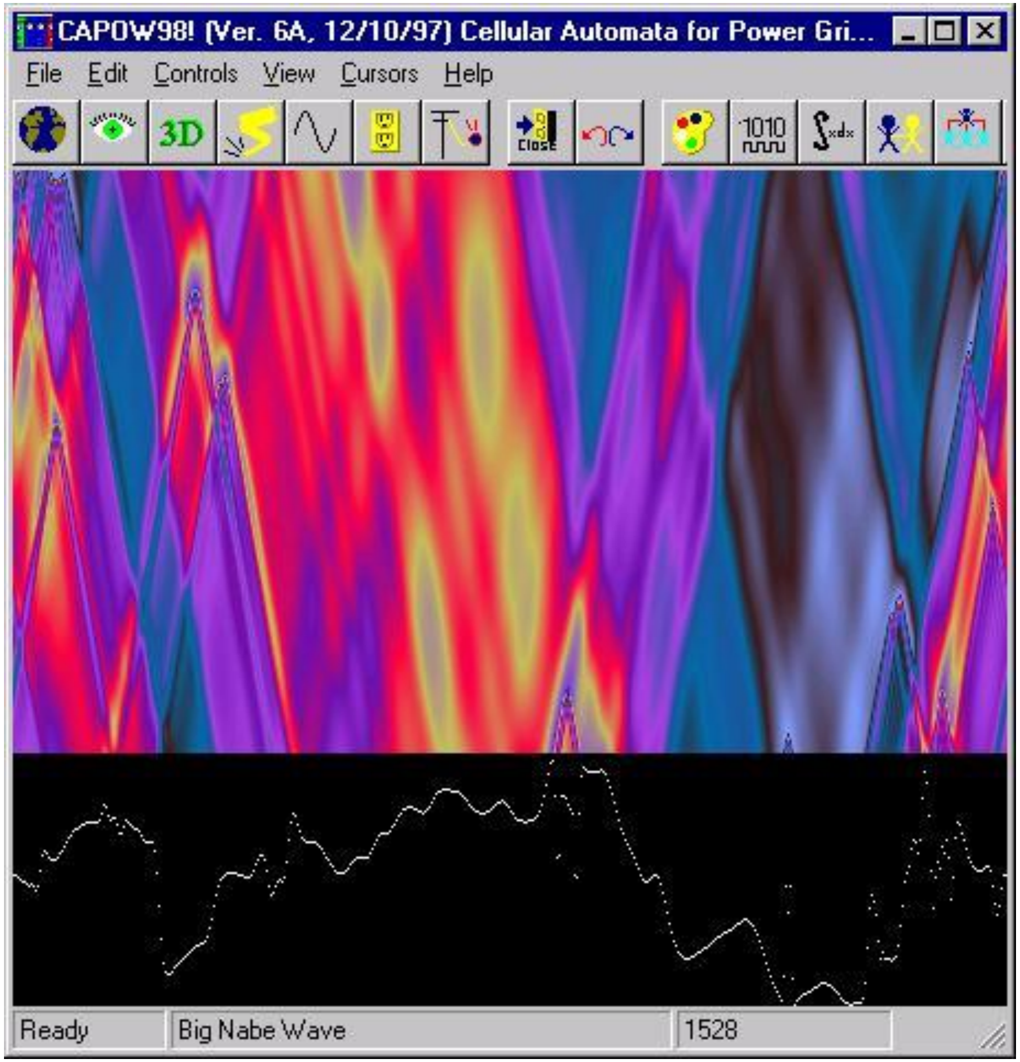
Cellular Automata – Pascal's Triangle

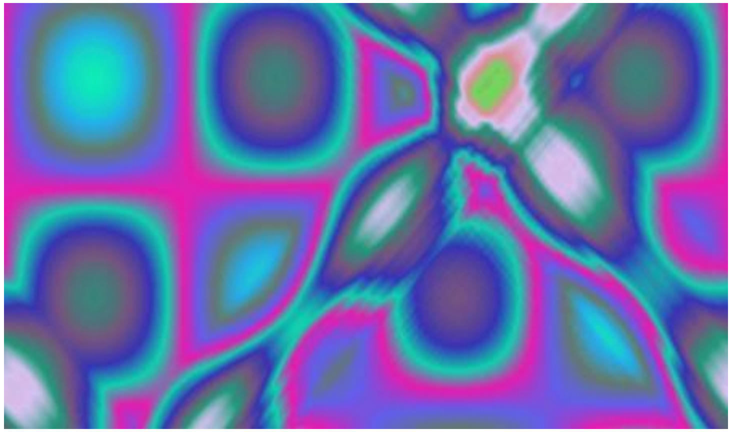


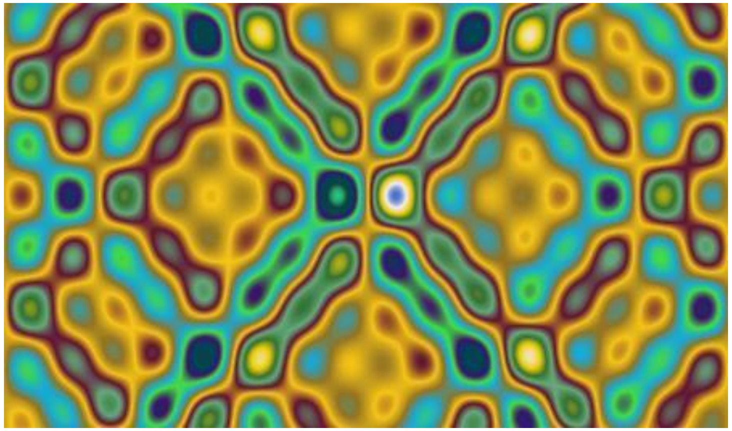
Cellular Automata – Classification

- *dimension* 1D, 2D … nD
- *neighborhood* Neumann, Moore for 1D
- *number of states* 1,2,…, n

Cellular Automata - Wow! examples







Cellular Automata - Wolfram

What are the possible “behaviors” of CA?

There are four possibilities:

I. Always reaches a state in which all cells are dead or alive

II. Periodic behavior

III. Everything occurs randomly

IV. Unstructured but complex behavior

Cellular Automata – Complexity of rules

- What is the total number of possibilities with CAs?
- Let's look at total number of possible rules
- For 1D CA:

  $2^3 = 8$ possible "neighborhoods" (for 3 cells)

  $2^8 = 256$ possible rules
- For 2D CA:

  $2^9 = 512$ possible "neighborhoods"

  2^{512} possible rules (!!)

This is dramatic!

Cellular Automata – Alive or not?

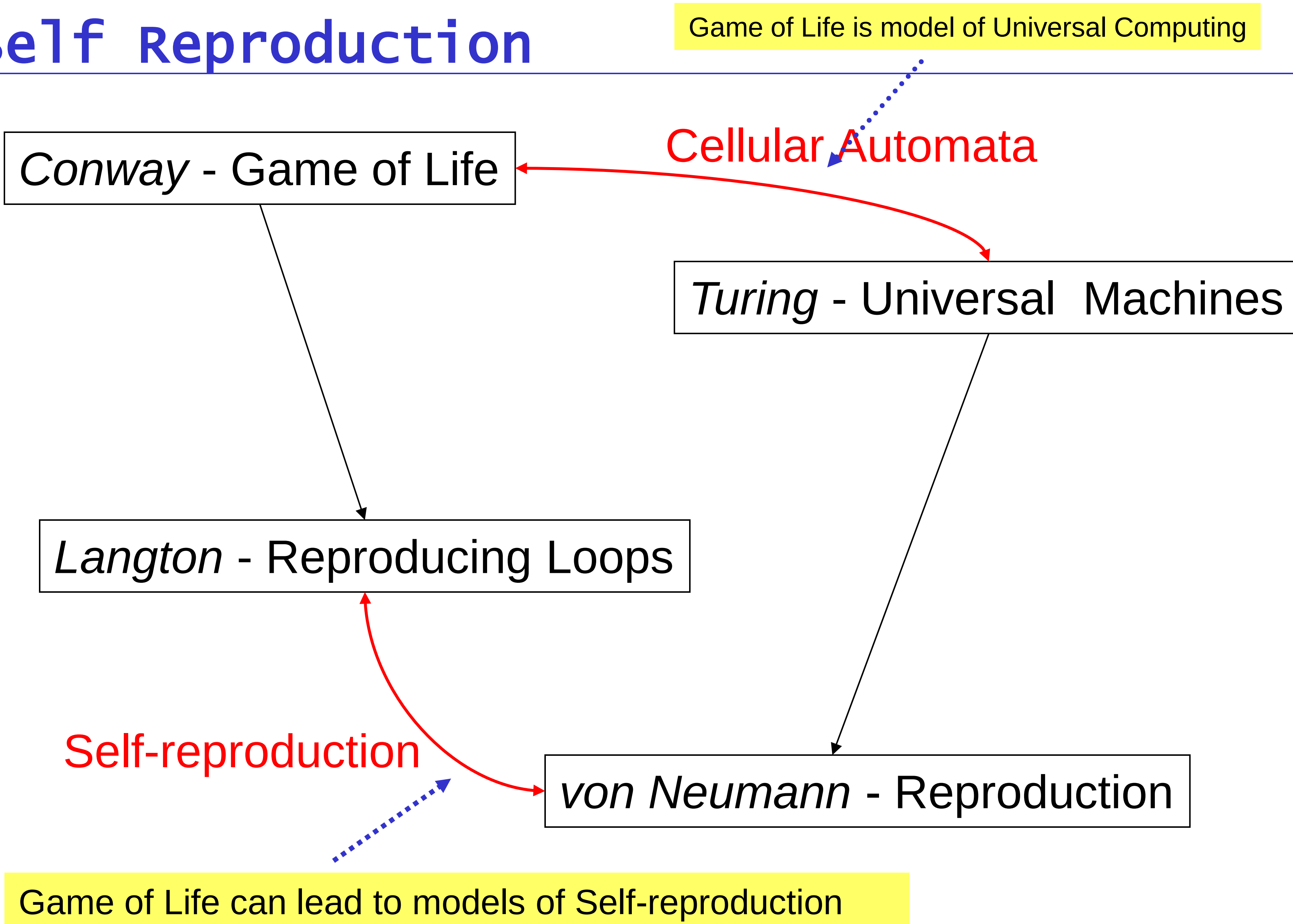
- Can CA or Game of Life represent life as we know it?

- A computer can be simulated in Game of Life

- Building blocks of a computer (wires, gates, registers) can be simulated in Game of Life as patterns (gliders, eaters etcetera)

- Is it possible to build a computer based on this game model?
  - YES
- Is it possible to build life based on this model?
  - ??

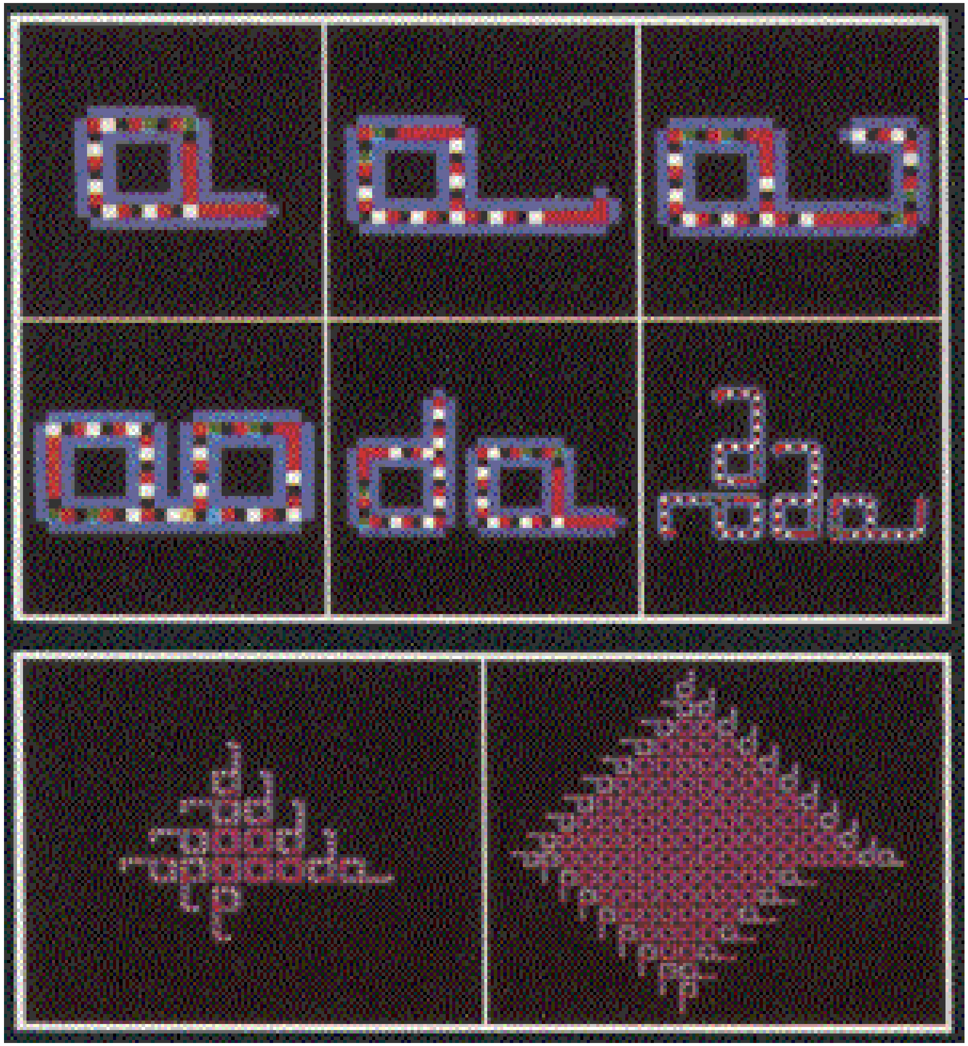
Self Reproduction



See next slide

Self Reproduction

	2	2	2	2	2	2	2	2					
2	1	7	0	1	4	0	1	4	2				
2	0	2	2	2	2	2	2	0	2				
2	7	2					2	1	2				
2	1	2					2	1	2				
2	0	2					2	1	2				
2	7	2					2	1	2				
2	1	2	2	2	2	2	2	1	2	2	2	2	2
2	0	7	1	0	7	1	0	7	1	1	1	1	1
	2	2	2	2	2	2	2	2	2	2	2	2	2



Langton Loop's

- 8 states
- 29 rules

Is life that simple?

Another Famous 2D CA Example: The Schelling Segregation Model

- An interesting and important puzzle:
  - after 1964 housing discrimination was illegal
  - since 1950 racial prejudice has declined
  - yet neighborhoods remain highly segregated
- T. C. Schelling (1978) hypothesized that segregation:
  - does not need to be imposed (top-down)
  - does not reflect preferences (bottom-up)
  - self-organizes through dynamic interaction
- Schelling was a co-recipient of the 2005 Nobel Prize in Economics. He is considered a "father" of agent-based modeling.

The Schelling Segregation Model

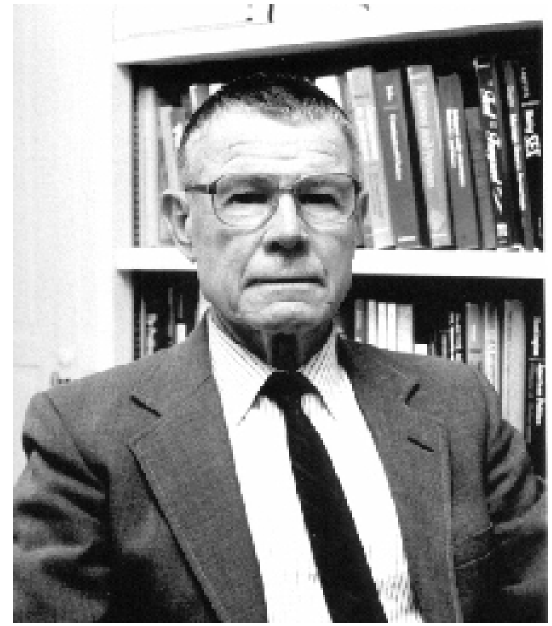
Micro-level rules of the game

Stay if **more than one third** of your neighbors are “kin”

$> 1/3$

$\leq 1/3$

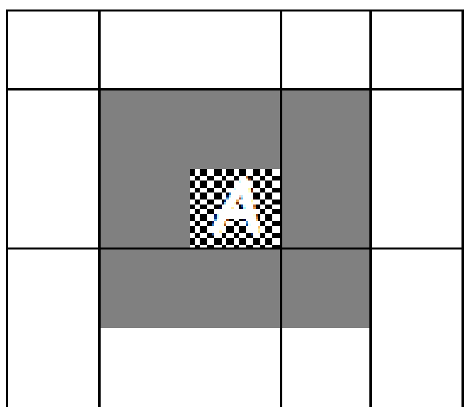
Move to random vacant location otherwise



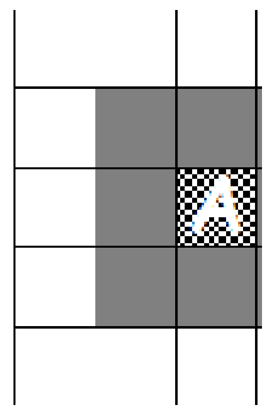
Thomas C. Schelling

***Micromotives and Macrobehavior*, 1978**

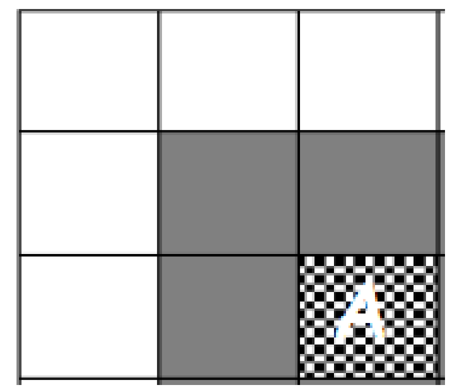
Counting "Neighbors" for the Schelling Segregation Model



Interior agent A
up to 8 neighbors



Border agent A
up to 5 neighbors



Corner agent A
up to 3 neighbors

Illustrative “Happiness Rule” for the Schelling Segregation Model

- Each agent is “happy” (no need to move) if **more than 1/3** of its neighbors are of same type.
- Boxes below give number of neighbors that must be “same type” for happiness given the total neighbors an agent has, from 0 to 8.

0	1	2	3	4	5	6	7	8	Total Neighbors
0	1	1	2	2	2	3	3	3	

Starting Pattern for the Schelling Segregation Model

	o	x	o	x	o	x	
o	x	o	x	o	x	o	x
x	o	x	o	x	o	x	o
o	x	o	x	o	x	o	x
x	o	x	o	x	o	x	o
o	x	o	x	o	x	o	x
x	o	x	o	x	o	x	o
	x	o	x	o	x	o	

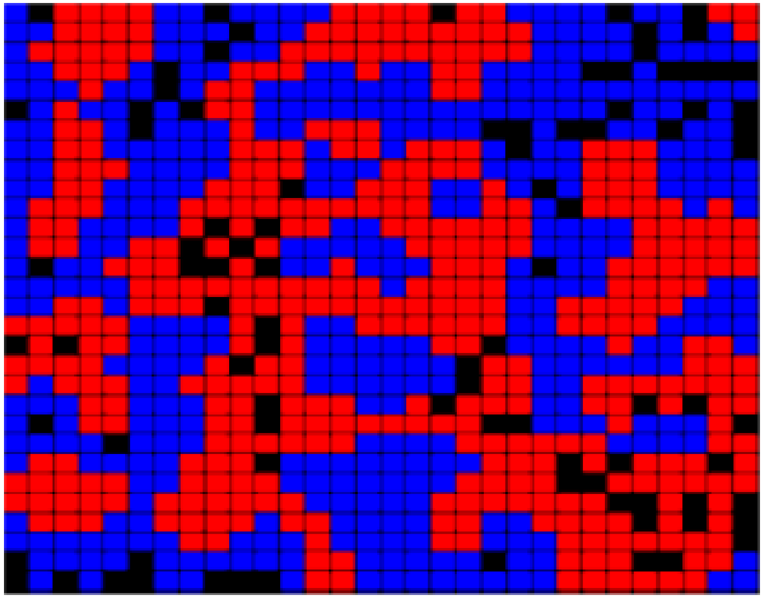
Now "Play the Game" !!

- Given the pattern on previous slide, everyone is happy and no one moves. Now **remove 10** randomly selected agents from the board.
- Starting from the top row, moving from left to right, row by row, **check for unhappy agents**.
- Every time you encounter an unhappy agent, **if possible move him** to a "tolerable" vacant square where he is happy; **otherwise remove him**.
- Keep going until there are no unhappy agents left on the board. What degree of segregation does the **resulting pattern** display?

Illustrative Segregation Pattern

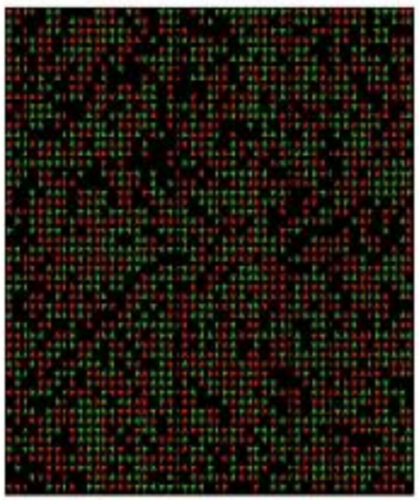
Two classes of households = blue and red cells

Empty lots = black cells

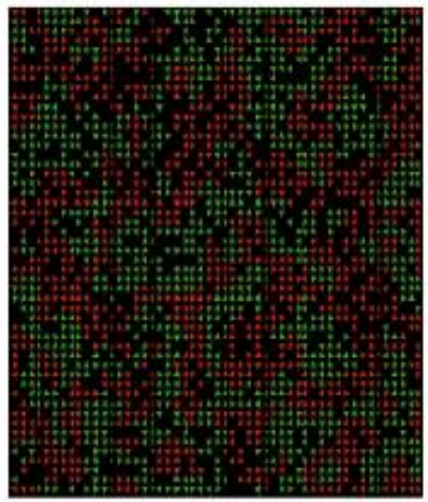


Illustrative Segregation Patterns with Different Levels of Tolerance for Un-Like Types

Two classes of households = green and red cells
Empty lots = black cells



(a) Initial (random) pattern. The average share of racially similar neighbours is roughly 50%. With a tolerance level of 70% (40%), less than 20% (more than 80%) of the individuals are not satisfied.



(b) Final pattern. The average share of racially similar neighbours is 72.1%. Everyone is satisfied

(70% tolerance)

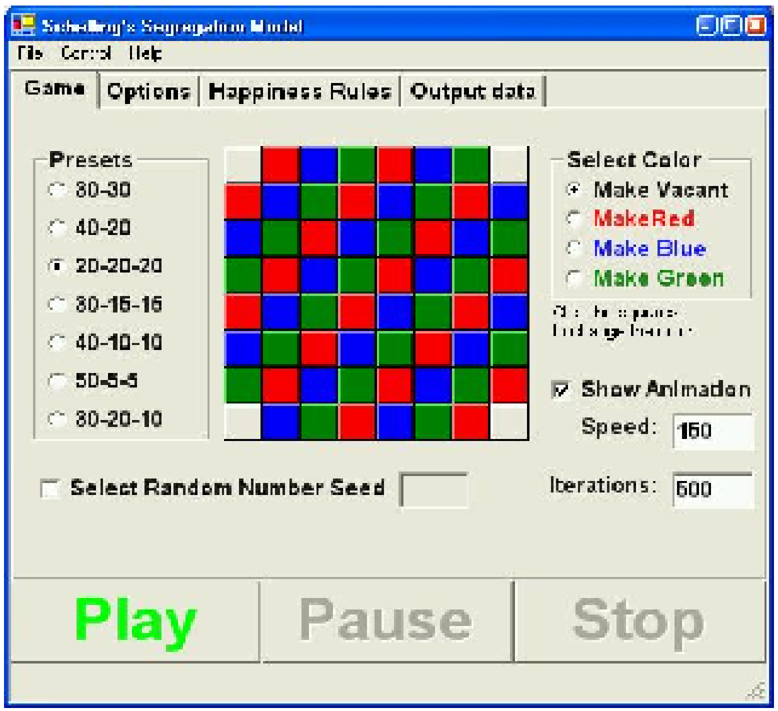
(c) Final pattern. The average share of racially similar neighbours is 99.7%. Everyone is satisfied

(20% tolerance)

Extended Schelling Segregation Demo

Basic Model by T. Schelling; Demo developed by C. Cook

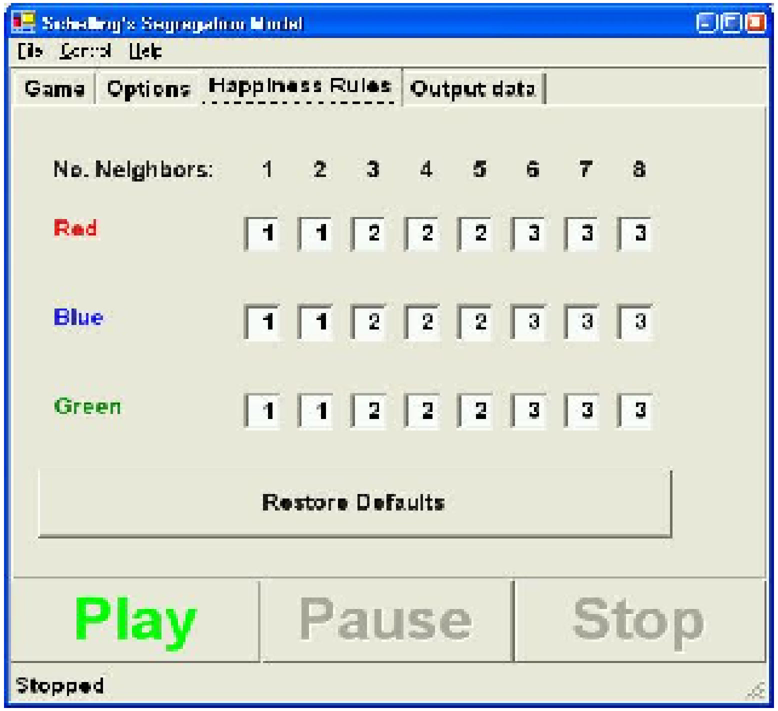
http://www.econ.iastate.edu/tesfatsi/acedemos.htm



- Checkerboard city model
- Three classes of agents (red, blue, green) + vacant cells
- Agents satisfied with their location if "enough" of their neighbors are of their own type; otherwise they move.
- **KEY FINDING:** City can "tip" into high segregation even if agents have only mild preferences for living with agents of their own type!

Schelling Segregation Demo … Continued

(Agent Happiness Rules)



- User specifies a happiness rule for each agent type
- Given n neighbors, how many have to be of my type in order for me to be happy at my current location?
- Unhappy agents attempt to move to vacant spots at which they would be happy.
- Does this cause city to "tip" into a segregated pattern?

The End!