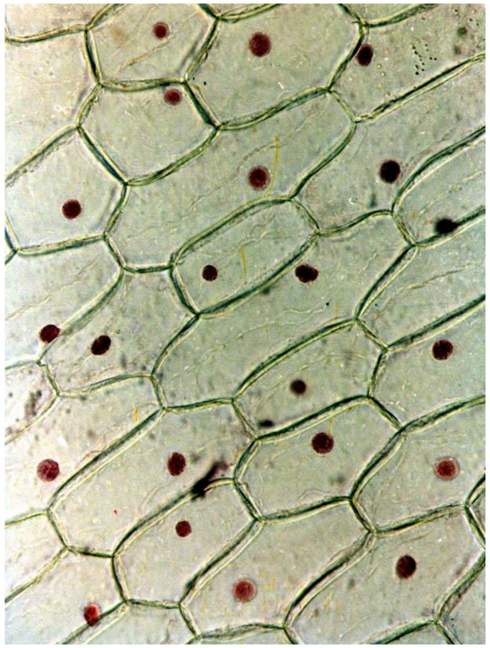
Bio-Inspired Artificial Intelligence

Lecture 2: Cellular Systems

http://www.informatik.uni-hamburg.de/WTM/

Motivation

- Evolution has rediscovered ***multicellularity*** several times as a way to build complex living systems



- ***Multicellular systems*** are composed by copies of a unique basic unit - the cell
- Local interaction between cells influences fate and behavior of each cell
- Result: A heterogeneous system composed by differentiated cells that act as specialized units, even if they all contain the same genetic material and have essentially the same structure

- Slides based on: *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies* by Floreano & Mattiussi, MIT 2008.

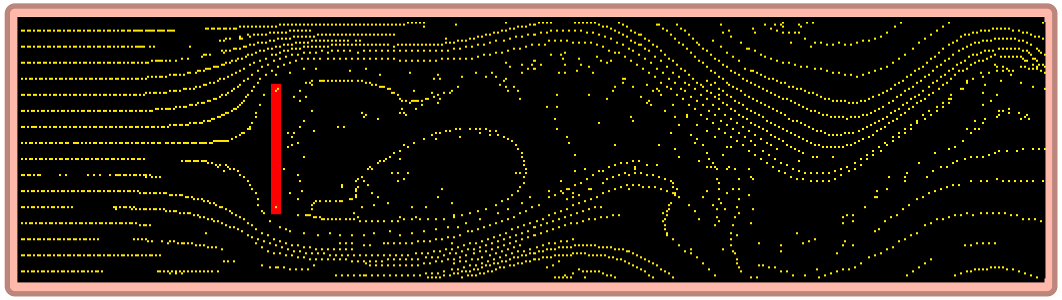
Fields of Application

The concept of “many simple systems with (geometrically structured) local interaction” is relevant to:

- ***Artificial Life*** and ***Evolutionary Experiments***, where it allows definition of arbitrary “synthetic universes”.
- ***Computer Science*** and ***Technology*** for implementation of parallel computing engines and study of rules of emergent computation.
- ***Physics***, ***Biology***, and other sciences, for modeling and simulation of complex biological, natural, and physical systems and phenomena, and research on rules of structure and pattern formation.
  - More generally, the study of ***complex systems***, i.e., systems composed by many simple units that interact non-linearly
- ***Mathematics***, for the definition and exploration of complex space-time dynamics and of the behavior of dynamical systems

Modelling complex phenomena

- Many complex phenomena are the result of the collective dynamics of a very large number of parts obeying simple rules.



from: http://cui.unige.ch/~chopard/

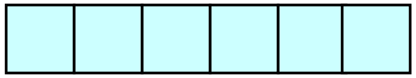
Unexpected global behaviors emerge from the interaction of many systems that "communicate" only locally.

Modeling cellular systems

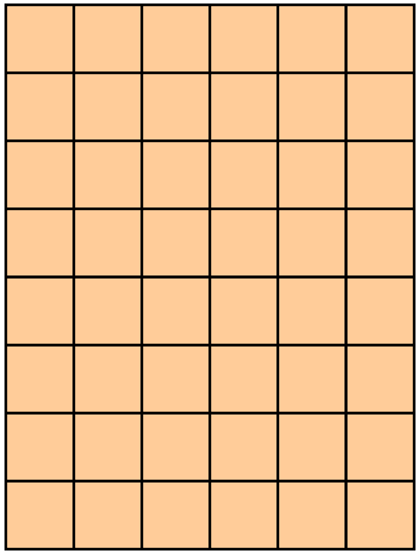
- We want to define simplest nontrivial model of a cellular system. We base our model on the following ***concepts***:
  - Cell and cellular space
  - Neighborhood (local interaction)
  - Cell state
  - Transition rule
- We do not model all details and characteristics of biological multicellular organisms but we obtain ***simple models*** where many interesting phenomena can still be observed
  - There are many kinds of cellular system models based on these concepts
  - The simplest model is called ***Cellular Automaton*** (CA)

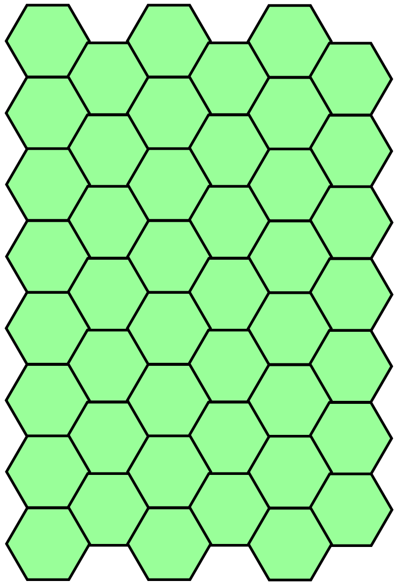
Cellular space

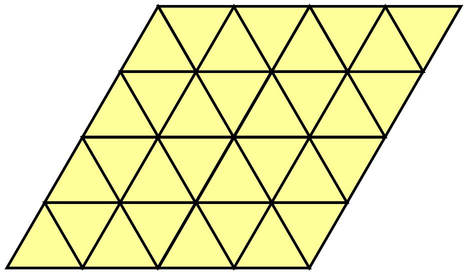
1D



2D







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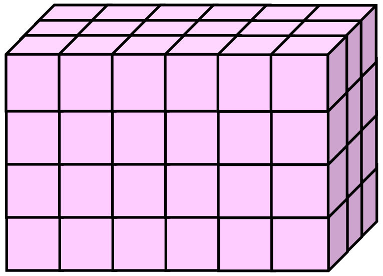
3D



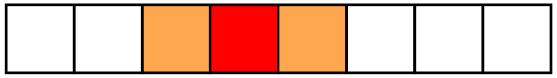
...

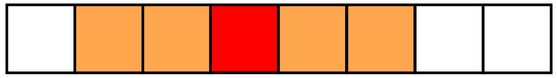
and beyond...

Neighbourhood and Radius

- Informally, it is the set of cells that can influence a given cell directly
- In homogeneous cellular models it has the same shape for all cells

1D





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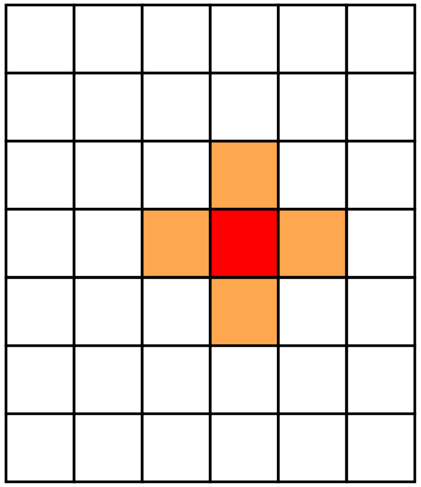
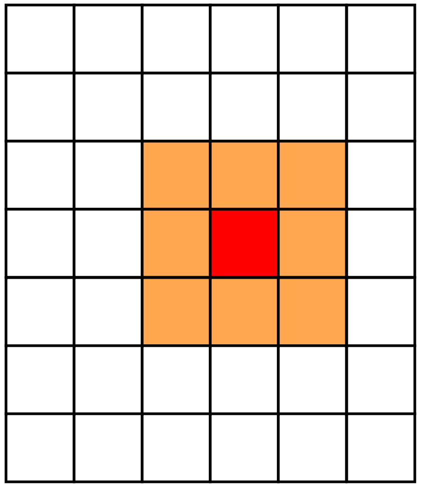
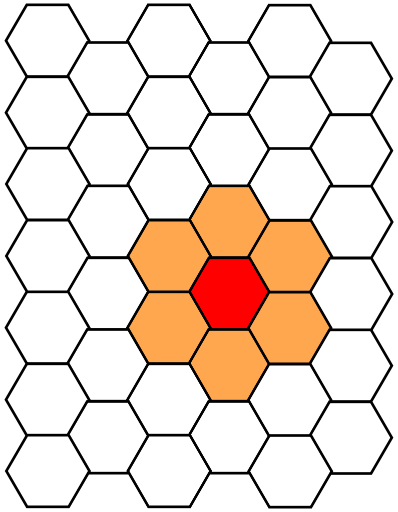
2D



von Neumann



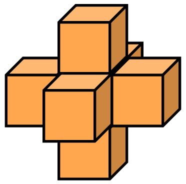
Moore



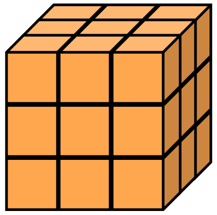
Hexagonal

...

3D



most common



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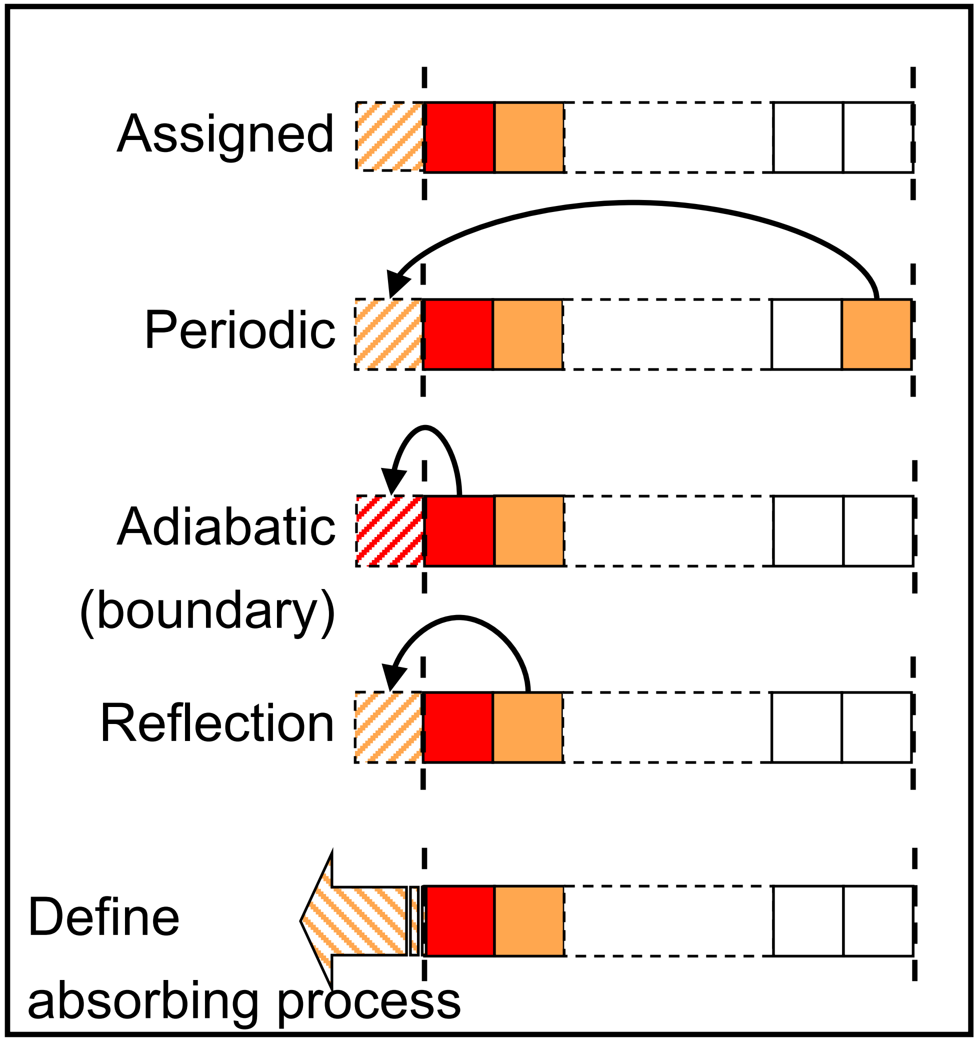
Boundary Conditions

- If the cellular space has a boundary, cells on the boundary may lack the cells required to form the prescribed neighborhood
- ***Boundary conditions*** specify how to build a “virtual” neighborhood for boundary cells

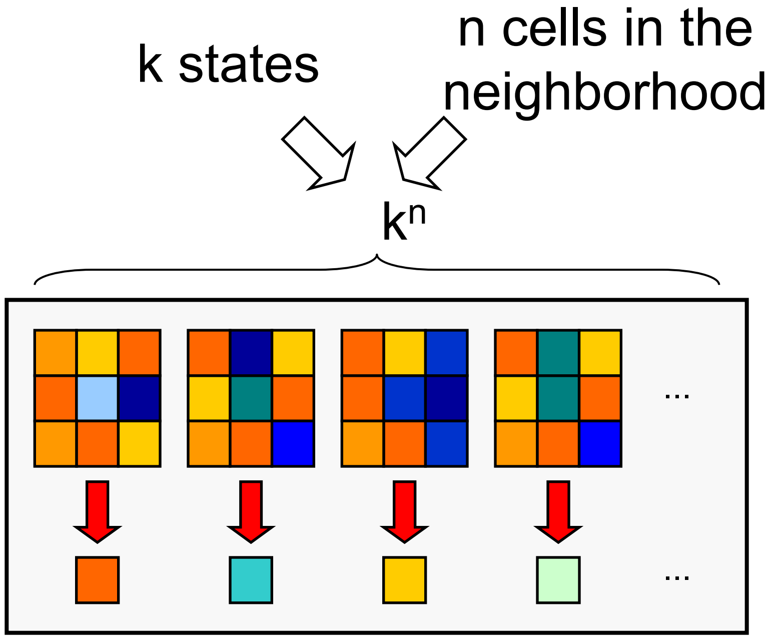
Some common kinds of boundary conditions



State Set and Transition Rule

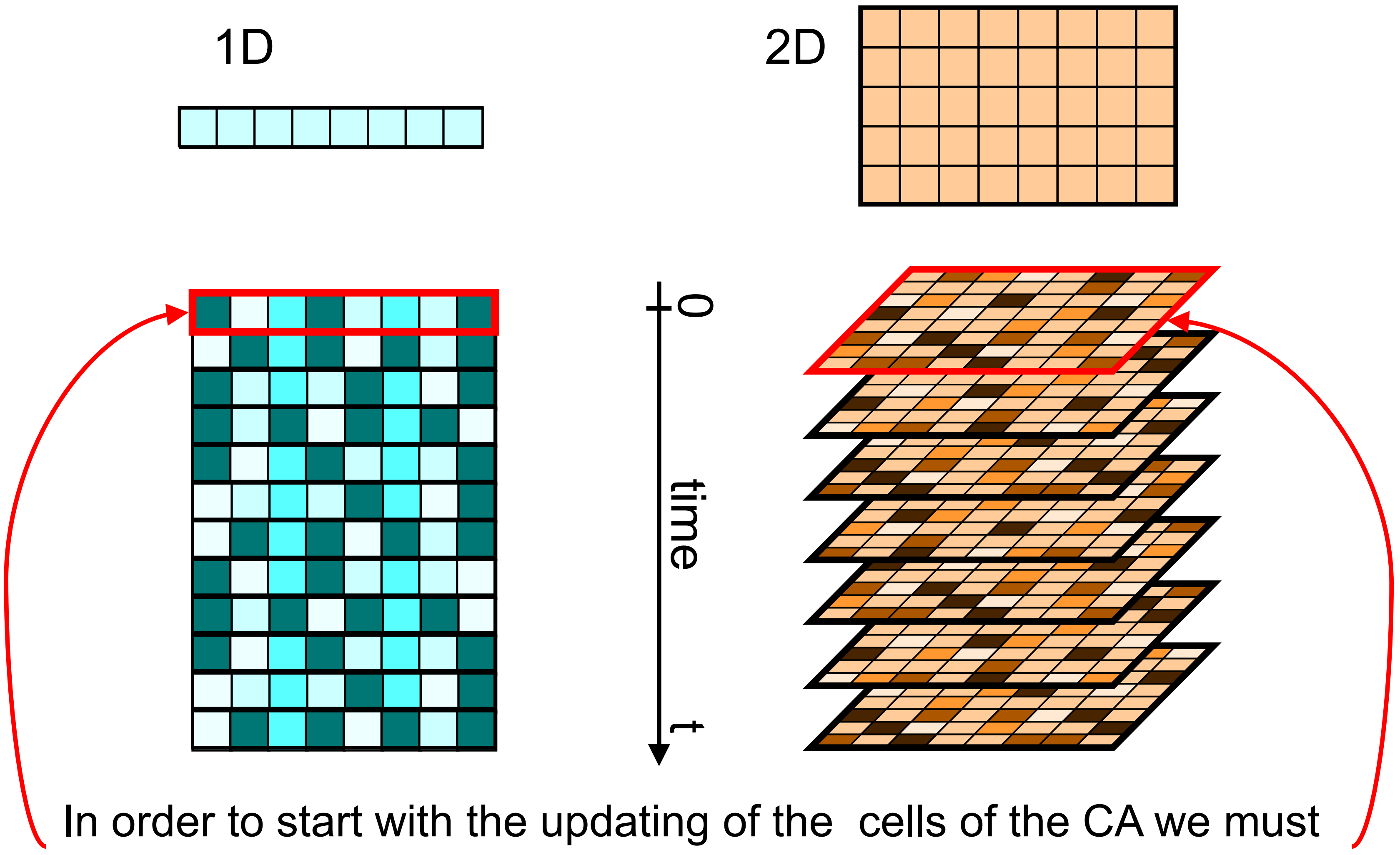
- The value of the ***state*** of each cell belongs to a finite set, whose elements we can assume as being ***numbers***. The value of the state is often represented by cell colors. There can be a special ***quiescent state*** s_0.
- The ***transition rule*** is the fundamental element of the CA. It must specify the new state corresponding to each possible configuration of states of the cells in the neighborhood.
- The transition rule can be represented as a ***transition table***, although this becomes rapidly impractical.

$$S = \{s_0, \dots, s_{k-1}\}$$
$$= \{0, \dots, k-1\}$$
$$= \{●, \dots, ●\}$$



transition table

Initial Conditions

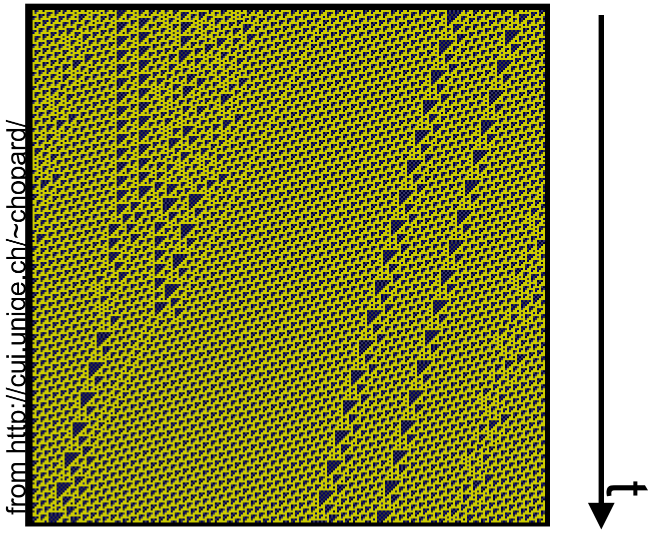


In order to start with the updating of the cells of the CA we must specify the initial state of the cells (**initial conditions** or **seed**)

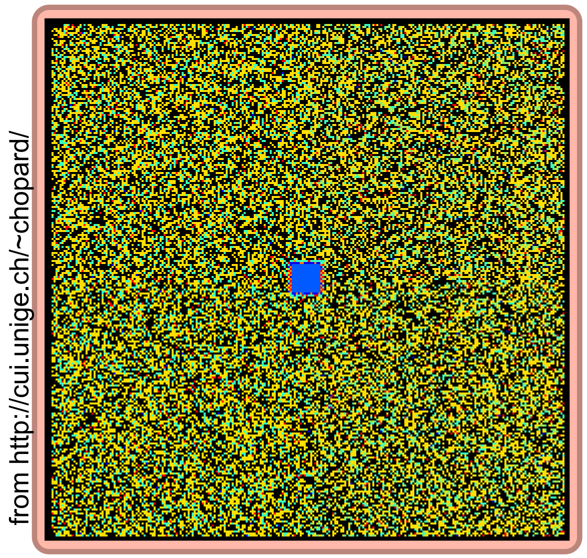
Displaying CA dynamics

1D

Space-time animation
(or static plot)

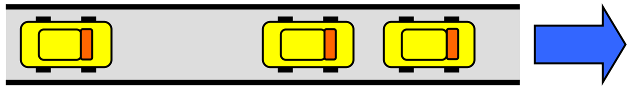


2D

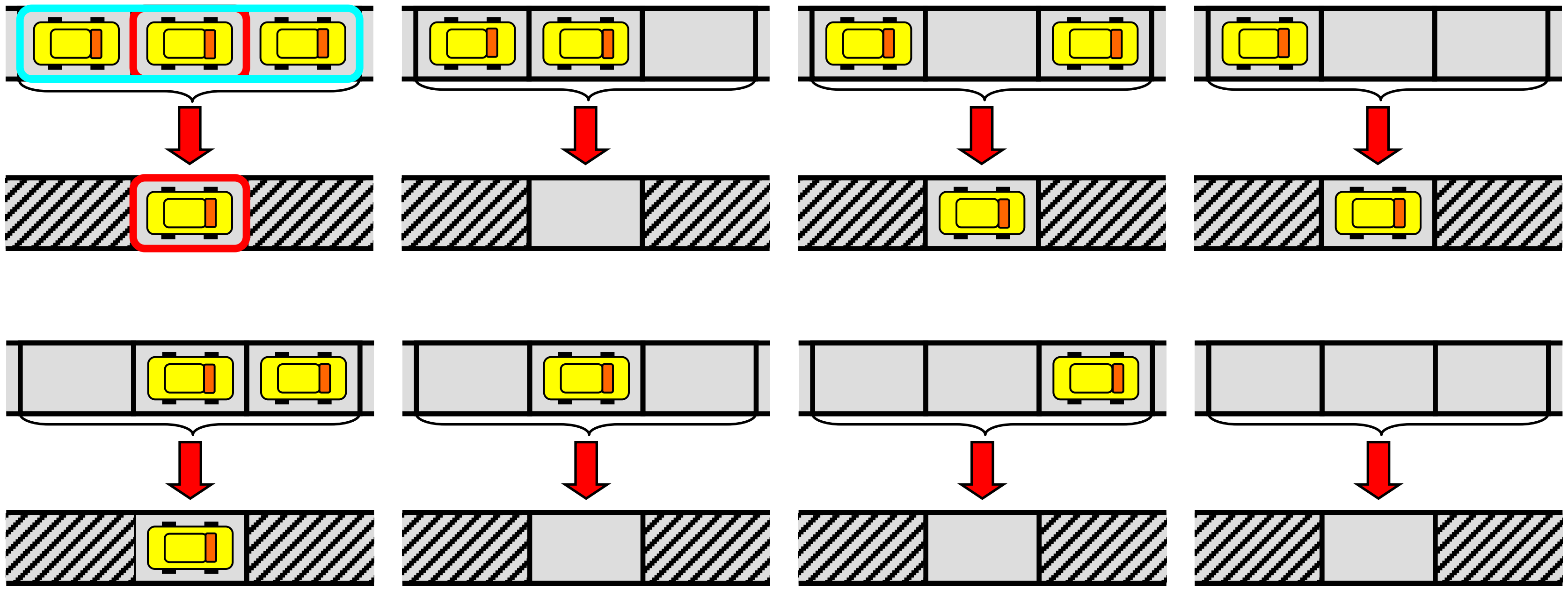


animation of spatial plot

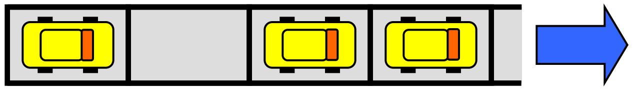
Example: Modelling Traffic



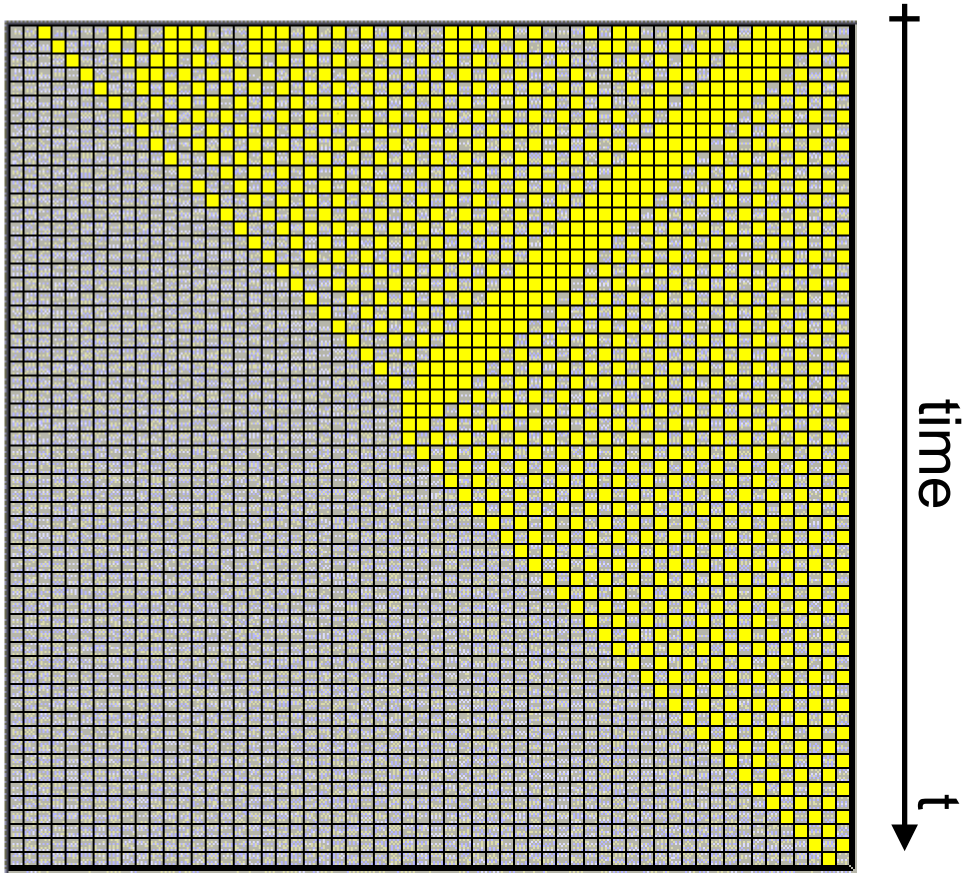
We construct an elementary model of car motion in a single lane, based only on the ***local*** traffic conditions. The cars advance at ***discrete time*** steps and at ***discrete space*** intervals. A car can advance (and must advance) only if the destination interval is free. ***Transition table*** shown:



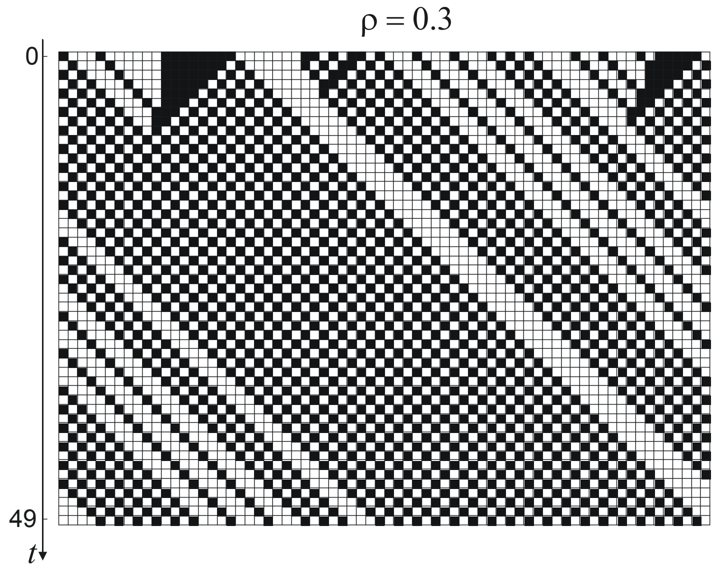
Example: Traffic Jam

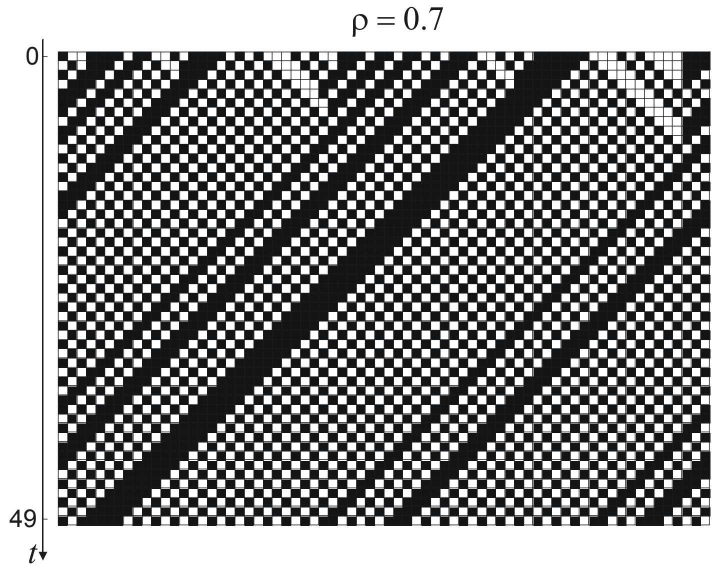


Running the *traffic CA* with a ***high-density random initial distribution*** of cars we observe a phenomenon of ***backward propagation of a region*** of extreme traffic congestion (traffic jam).

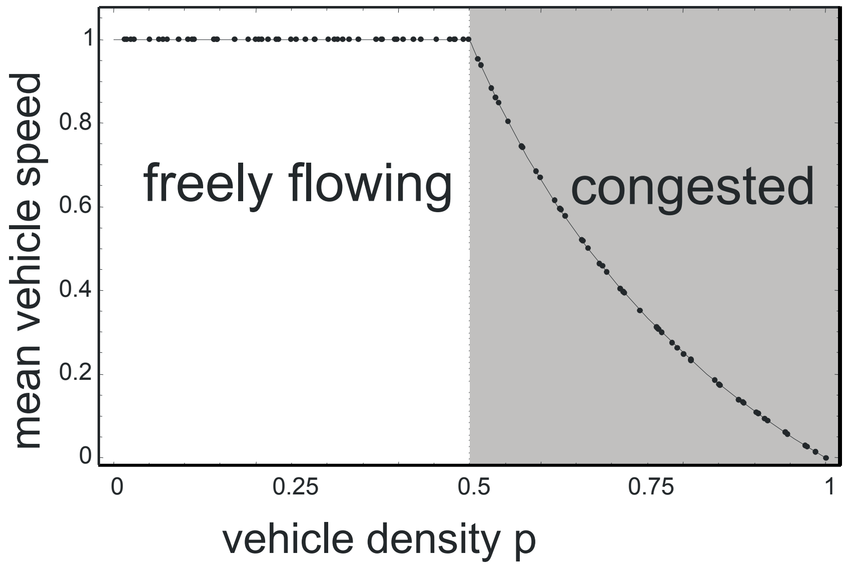


Emergent phenomena differ by density





There is a qualitative change of behavior for vehicle density *ρ* = 0.5. In the language of physics there is a *phase transition* between the two regimes at the *critical density ρ* = 0.5



mean vehicle speed: number of cells traveled per time step

In practice...

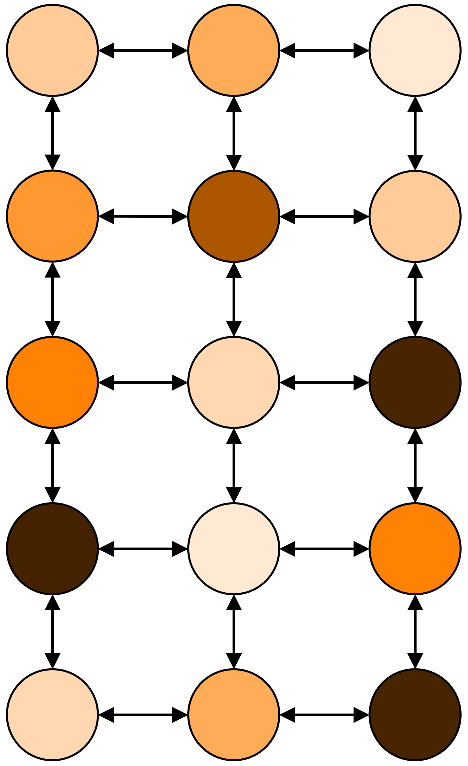
To implement and run a CA experiment

1. Assign the geometry of the CA space
2. Assign the geometry of the neighborhood
3. Define the set of states of the cells
4. Assign the transition rule
5. Assign the boundary conditions
6. Assign the initial conditions of the CA
7. Repeatedly update all cells of CA, until some stopping condition is met (for example, a pre-assigned number of steps is attained, or CA is in a quiescent state, or cycles in a loop,...).

Informal definition of CA

A Cellular Automaton is

- a ***geometrically structured*** and
- ***discrete*** collection of
- ***identical*** (simple) systems called cells
- that ***interact*** only ***locally***
- with each cell having a local ***state*** (memory) that can take a ***finite*** number of values
- and a (simple) ***rule*** used to ***update*** the state of all cells
- at ***discrete time*** steps
- and ***synchronously*** for all the cells of the automaton (global "signal")

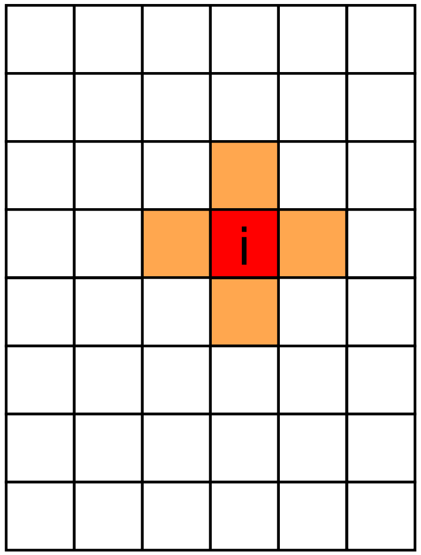


More formal definition of CA

A Cellular Automaton is

- an ***n-dimensional lattice*** of
- identical and synchronous finite state machines
- whose state s is updated (synchronously) following a ***transition function*** (or transition rule) ϕ
- that takes into account the state of the machines belonging to a ***neighbourhood*** *N* of the machine, and whose geometry is the same for all machines

$$s_i(t+1) = \phi(s_j(t)\ ;\ j \in N_i)$$



Special Rules

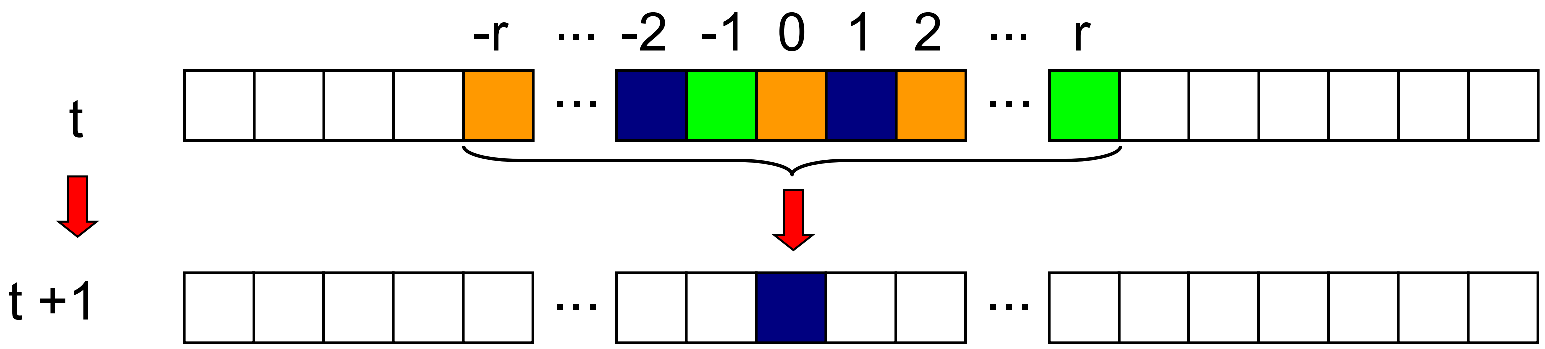
- The transition table of a generic CA can have an enormous number of entries. Special rules can have more compact definitions.
- A rule is ***totalistic*** if the new value of the state depends only on the sum of the values of the states of the cells in the neighborhood

$$s_i(t+1) = \phi(\Sigma_j \, s_j(t) \; ; j \in N_i)$$

- A rule is ***outer totalistic*** if the new value of the state depends only on the value of the state of the updated cell and on the sum of the values of the states of the other cells in the neighborhood

$$s_i(t+1) = \phi(s_i(t) \, , \Sigma_j \, s_j(t) \; ; j \in N_i \, , j \neq i)$$

Rules for 1D CA



k states (colors ● , ● , ● , ...), range (or radius) r

$k^{k^{2r+1}}$ possible rules

e.g.: k=2 , r=1$\rightarrow$ 256

k=3 , r=1$\rightarrow \approx 8 \cdot 10^{12}$

$k^{(2r+1)(k-1)+1}$ totalistic rules

e.g.: k=2 , r=1$\rightarrow$ 16 totalistic

k=3 , r=1$\rightarrow$ 2187 totalistic

The number of possible rules grows very rapidly with k and r

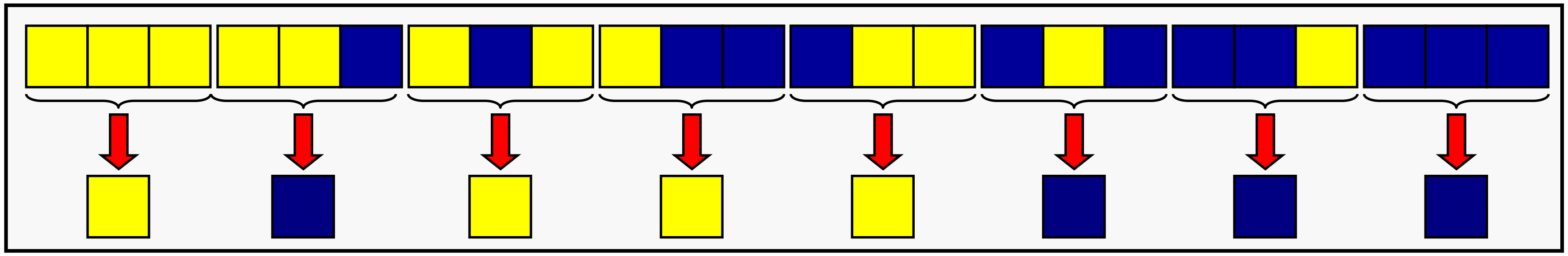
Rule Code for Elementary CA

Elementary CA

256 1D binary CA (k=2) with minimal range (r=1)

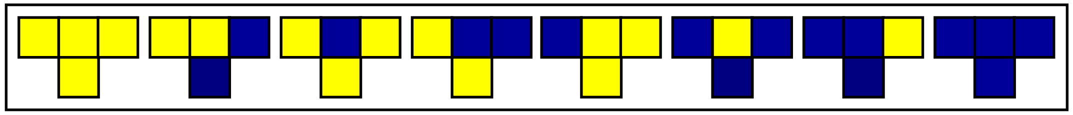
Wolfram's Rule Code (here, 🟦 = 0 , 🟨 = 1)

111_2 110_2 ... ... 010_2 001_2 000_2



1 0 1 1 1 0 0 0

$10111000_2 = 1 \cdot 2^7 + 0 \cdot 2^6 + \ldots + 0 \cdot 2^0 = 184_{10}$ $\Rightarrow$ Rule 184

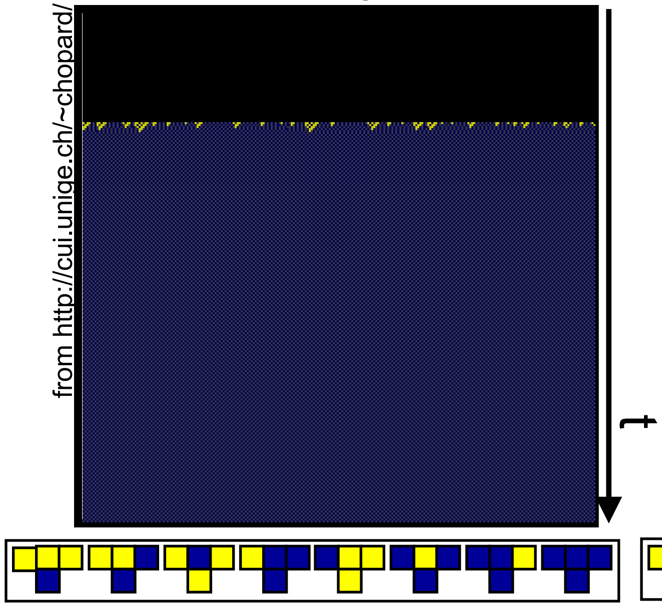


(the "car traffic" rule!)

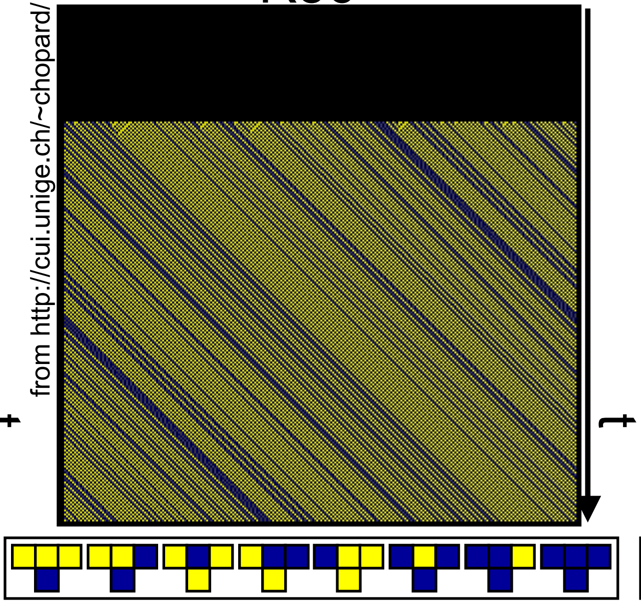
Wolframs code associates an integer from 0 to 255 with each elementary CA

Examples of Elementary CA

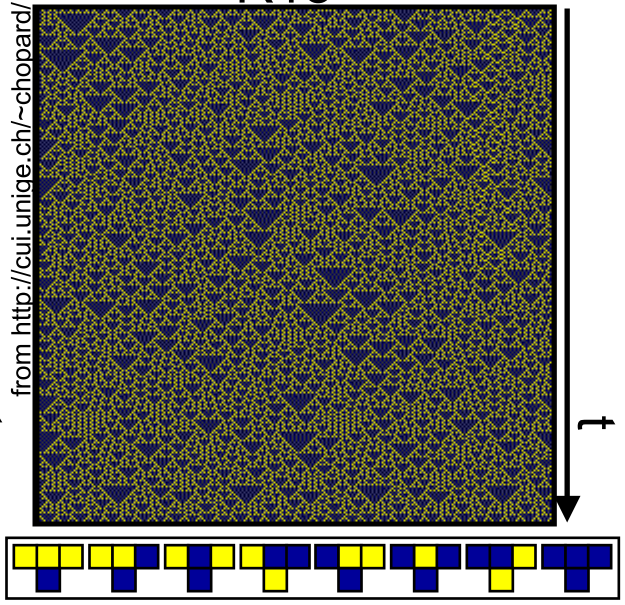
R40



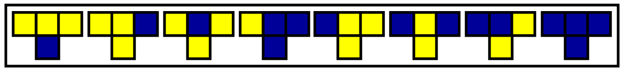
R56

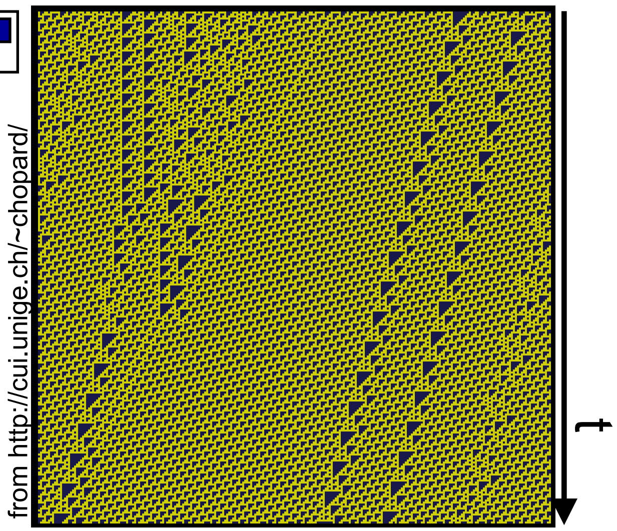


R18



R110



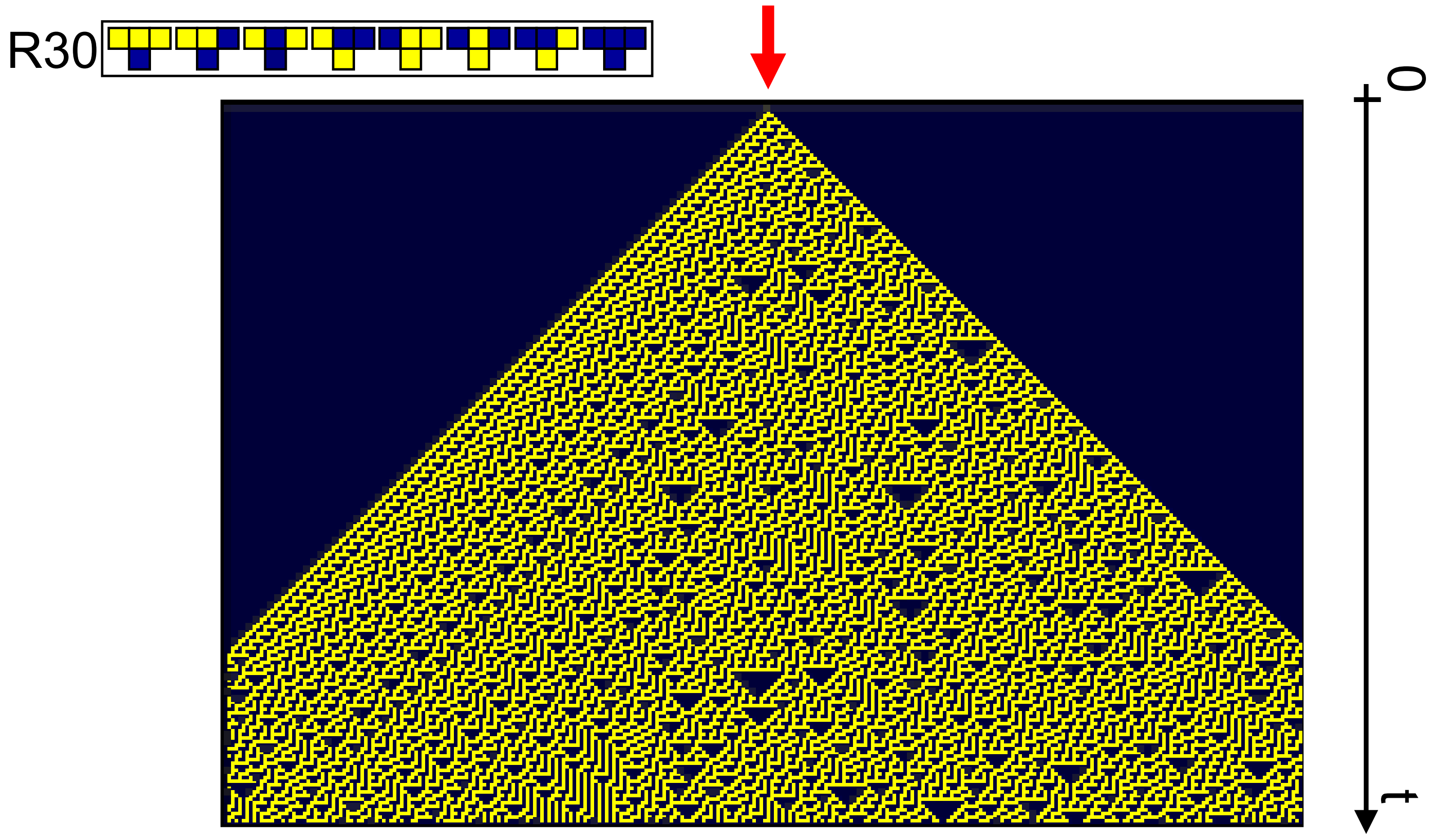


There are four *qualitative* behavioral classes:

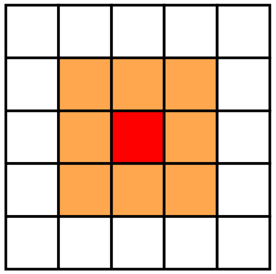
1. Uniform final state
2. Simple stable or periodic final state
3. Chaotic, random, nonperiodic patterns
4. Complex, localized, propagating structures

Example of application: RNG

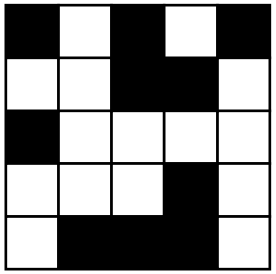
- Rule 30 is used by Mathematica as its Random Number Generator (RNG are ubiquitous in bio-inspired experiments).



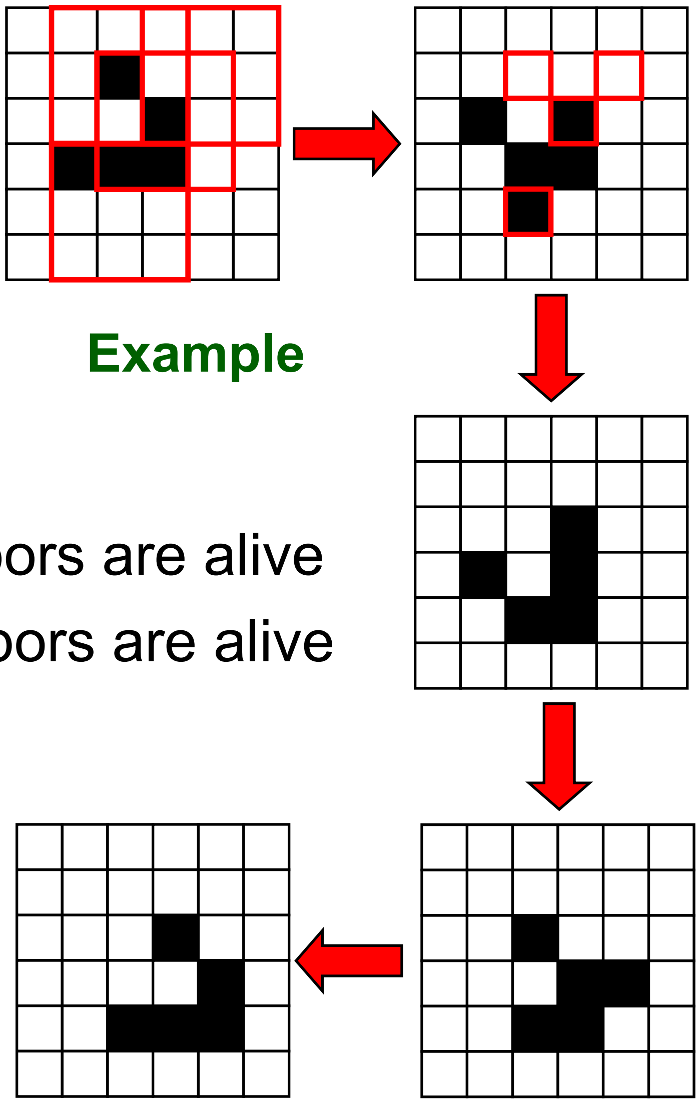
The classical 2D CA: Life



Moore
neighborhood



two states
dead □ alive ■



Example

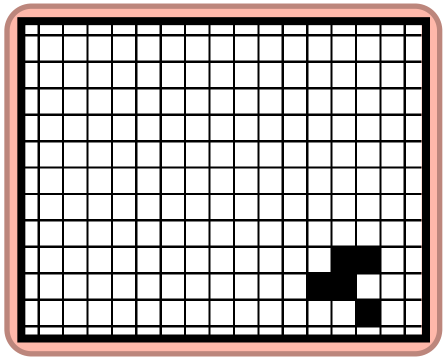
Outer totalistic rule (John Conway)

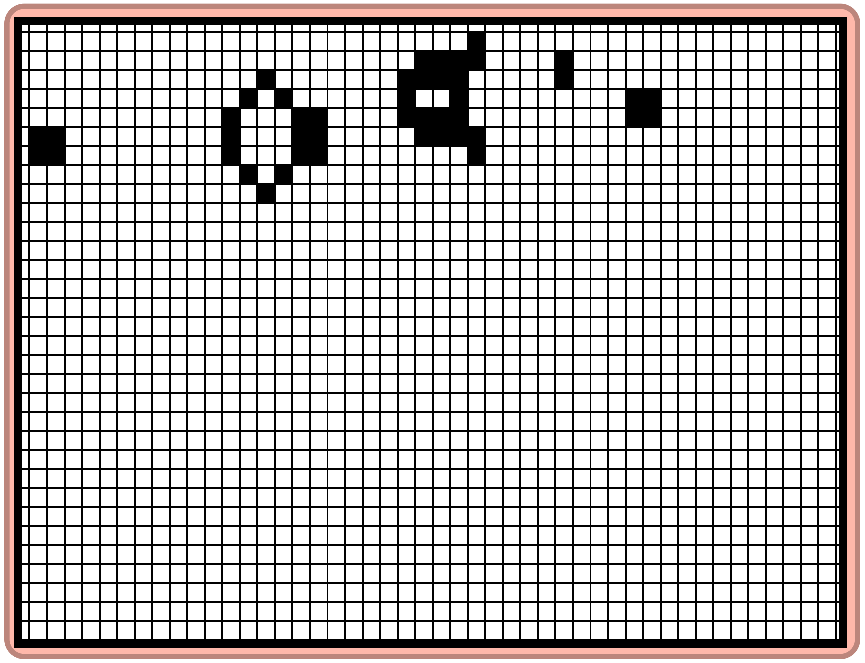
- ***Birth*** □ → ■ if exactly 3 neighbors are alive
- ***Survival*** ■ → ■ if 2 or 3 neighbors are alive
- ***Death*** ■ → □

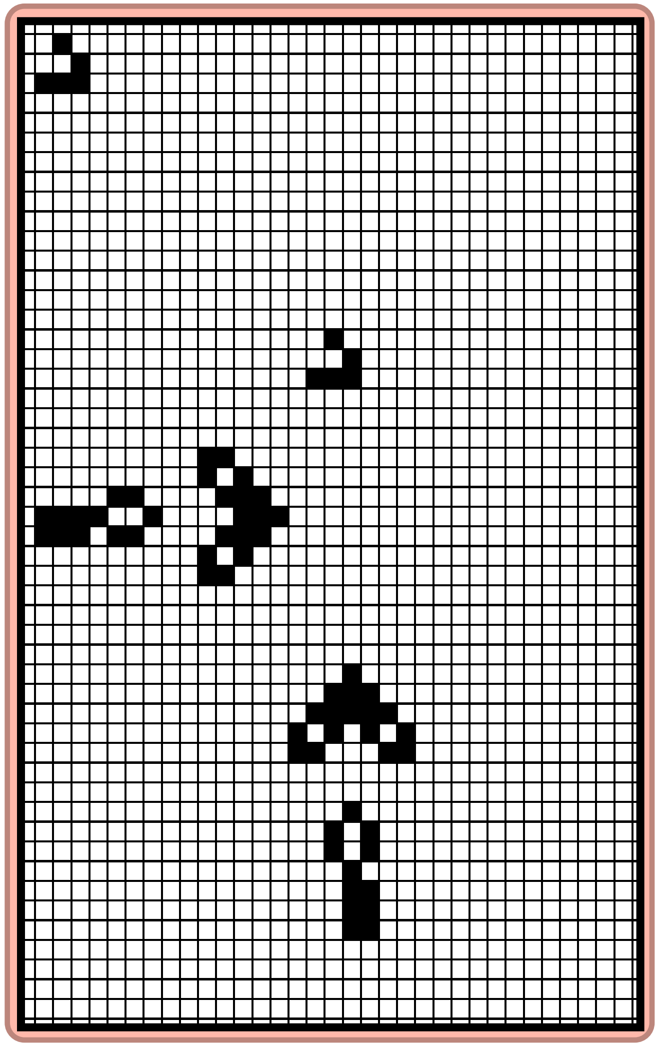
  from “isolation” if 0 or 1 n. a. aut.

  from “overcrowding” if more
  than 3 neighbors are alive

Computation in *Life*





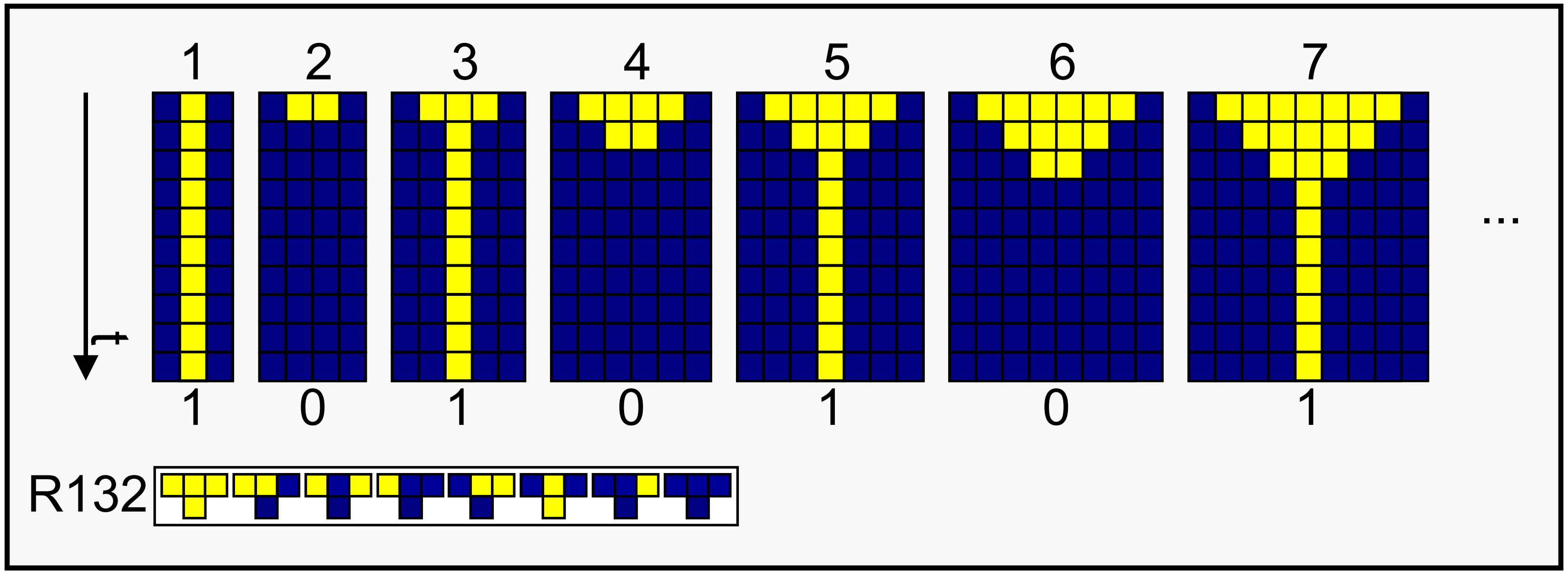


Glider gun produces a new glider every 30 time steps

Computation with CA

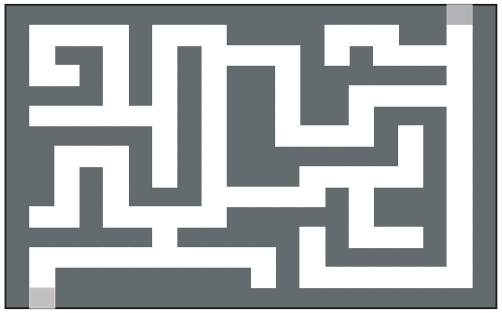
- CA used as input-output devices. The initial state is the input. The CA should go to a quiescent state (fixed point), which is the output.

  Example: Remainder after division by 2

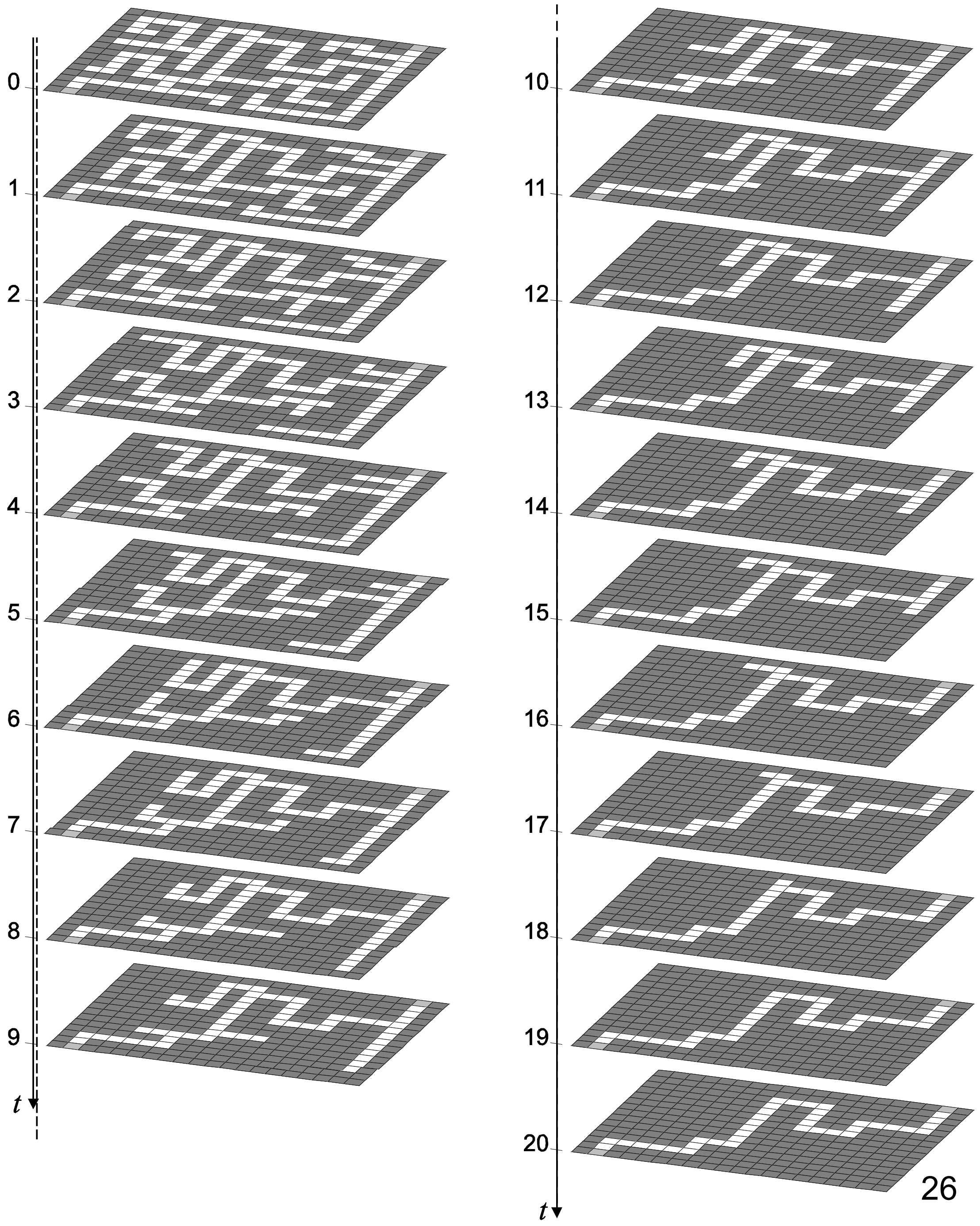


- The difficulty stems from the fact that we use a local rule to evaluate a property that depends on information distributed globally.

Example: CA maze solver

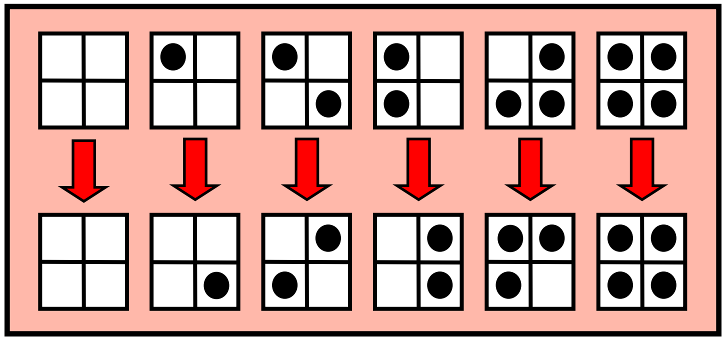


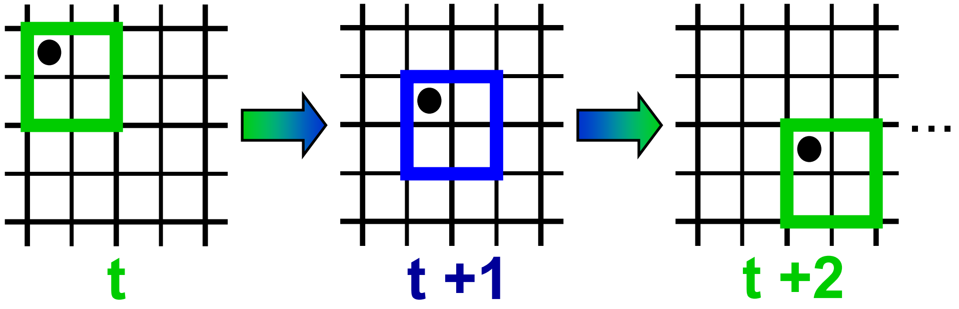
- Given a maze the problem consists in finding a path from the entrance to the exit.
- The conventional approach marks blind alleys sequentially
- The CA solver removes blind alleys in parallel

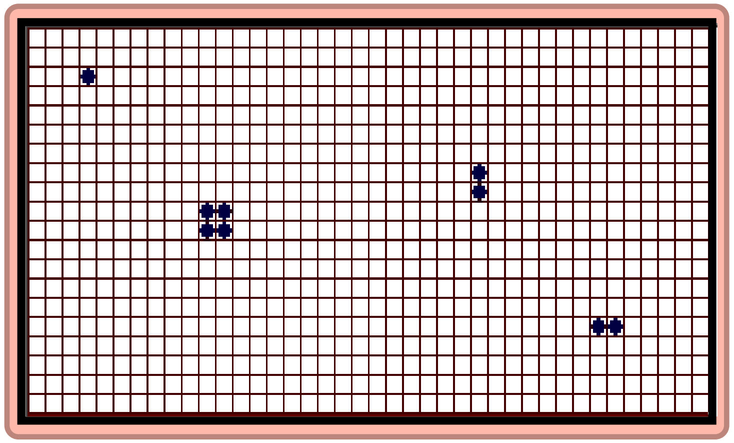


Particle CA

- CA can be used to model phenomena that involve particles. The transition rule can be specified in terms of the motion of particles within ***blocks*** of two by two cells (block rules).
- The automaton space is ***partitioned*** in non-overlapping blocks
- To allow the propagation of information the position of the blocks alternates between an odd and an even partition of the space (Margolus neighborhood).





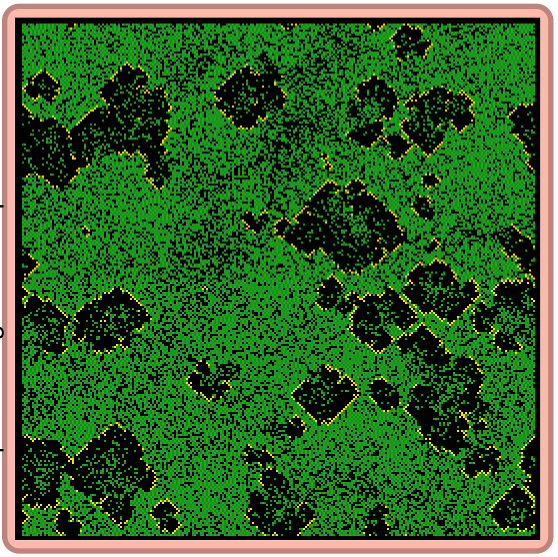


Probabilistic CA

- So far we have considered only ***deterministic*** CA.
- To model many phenomena it is useful to have transition rules depending on some externally assigned probability

  Example: The ***forest fire model***

  - Each cell contains a green tree 🟩, a burning tree 🟨, or is empty ⬛
  - A burning tree becomes an empty cell
  - A green tree with at least a burning neighbor becomes a burning tree
  - A green tree without burning neighbors becomes a burning tree with probability *f* (probability of lightning)
  - An empty cell grows a green tree with probability g (probability of growth)

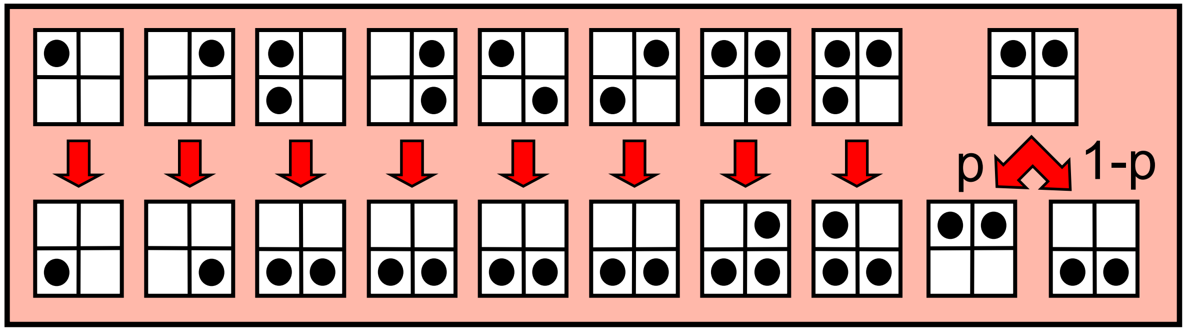

from http://cui.unige.ch/~chopard/

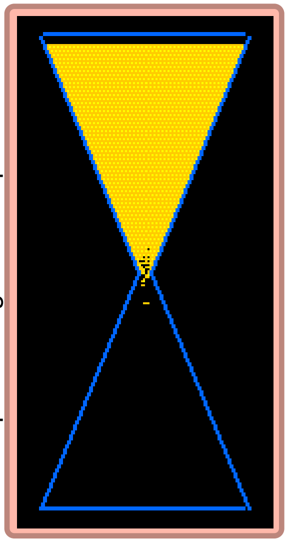
- The parameters can be varied in a continuous range and introduce some "continuity" in the discrete world of CA models

Complex Systems

- Cellular systems allow the modeling and simulation of phenomena that are difficult to describe with conventional mathematical techniques

  Example: The sand rule with friction

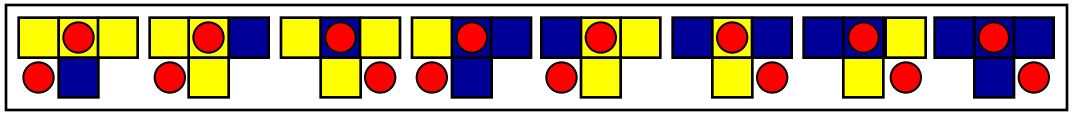




- This kind of model permits the exploration of the behavior of *granular media*, which is difficult with conventional tools

Variants and Extensions

- The basic CA is discrete in space, time and state; updates all its cells synchronously; uses the same neighborhood geometry and transition rule for all cells.
- We can relinquish some of these prescriptions and obtain:
  - ***Asynchronous*** CA (for example, mobile automata, where only one cell is active at each time step, and the transition rule specifies the fate of the activation)



  - ***Non-homogenous*** (or non-uniform) CA
  - Continuous-state CA (***Coupled Map Lattices***)
  - Continuous-state and time CA (***Cellular Neural Networks***)

Summary

- We have given an overview of cellular systems world: Cellular systems can be used at least as:
  - Synthetic universes creators in Evolutionary and Artificial Life experiments
  - Models and simulators of simple and complex, biological, natural, and physical systems and phenomena
  - Computation engines
  - Testers of hypotheses about emergent physical and computational global properties and the nature of the underlying local mechanisms