Artificial Life
Summer 2025

Cellular Automata 2D
Conway's Game of Life

Master Computer Science [MA-INF 4201]
Mon 14c.t. – 15:45, HS-2

Dr. Nils Goerke, Autonomous Intelligent Systems,
Department of Computer Science, University of Bonn

Overview:

- Cellular Automata in 2 dimensions
- Examples and Applications of CAs
- Conway's Game of Life
- Computational Universality
- Is Information == Structure ?

Cellular Automata in 2 dimensions

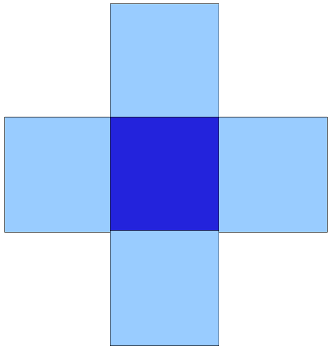
Although S.Wolfram has investigated the 1-dim Cellular Automata very intensively, the original idea from Stanislav Ulam (1940) and J. von Neumann was a 2 dimensional Cellular Automaton.

In the 50ies and 60ies the idea of Cellular Automata were the basis for a series of analogue computers.

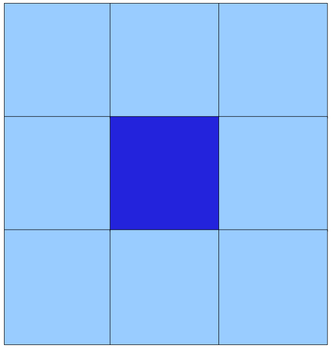
The famous German computer scientist Konrad Zuse published in 1969 an idea (from the 40ies) „*Rechnender Raum*" where he supposed that the law of natures are discrete, working like a CA.

Neighborhood in 2 dimensions

For a 2 dimensional rectangular grid there are two variants to define the neighborhood with r=1:



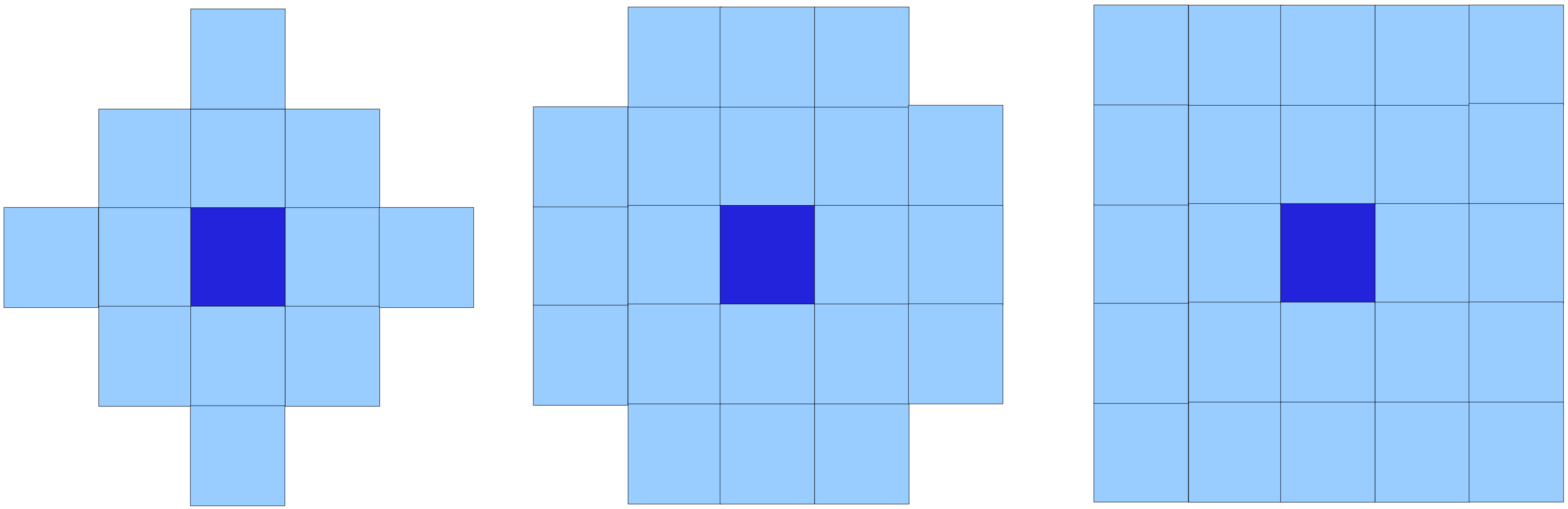
r =1, von Neumann



r =1, Moore

Neighborhood in 2 dimensions

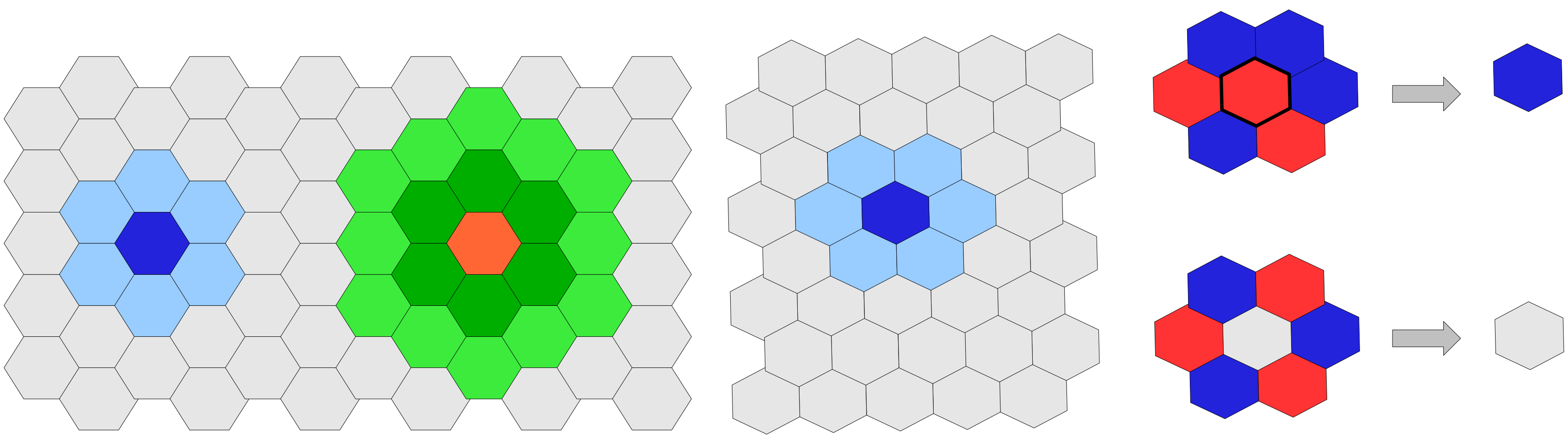
A larger neighborhood radius ***r*** requires a more precise definition of the neighboring cells:



r = 2

Cellular Automata extended

Cellular Automata can be easily extended to higher dimensions, (e.g. 3-dim) to a different tiling of the workspace (e.g. triangles or hexagons in 2-dim) or even to a non-uniform neighborhood (e.g. graph). Only the definition of the neighborhood and the rule has to be adjusted accordingly.



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- Cellular Automata in 2 dimensions
- **Examples and Applications of CAs**
- Conway's Game of Life
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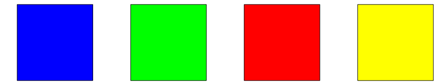
Examples and Applications of CAs

- Growth of crystals
- Population dynamics
- Modeling, and predicting traffic situations
- Modeling urban city development
- Modeling diffusion process
- Generation of „close to real“ patterns
- Modeling forest fires
- ...

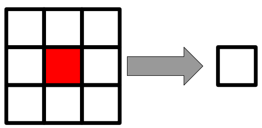
Cellular Automata in 2 Dimensions

Majority-Voting CA

d=2, rectangular grid, r=1, Moore, k=4,



The state of the cell is changing to the majority of states present in the neighborhood.



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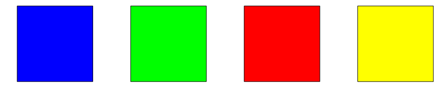

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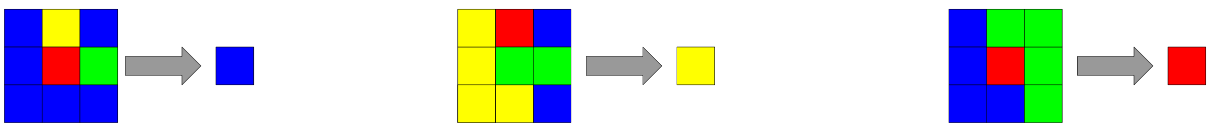

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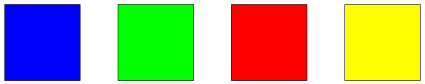

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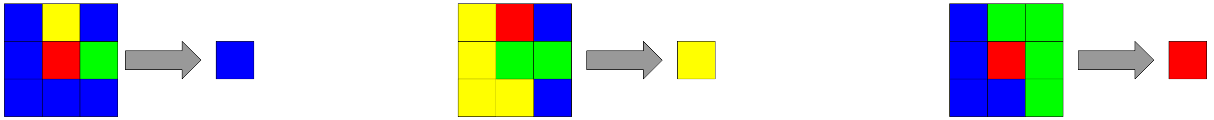

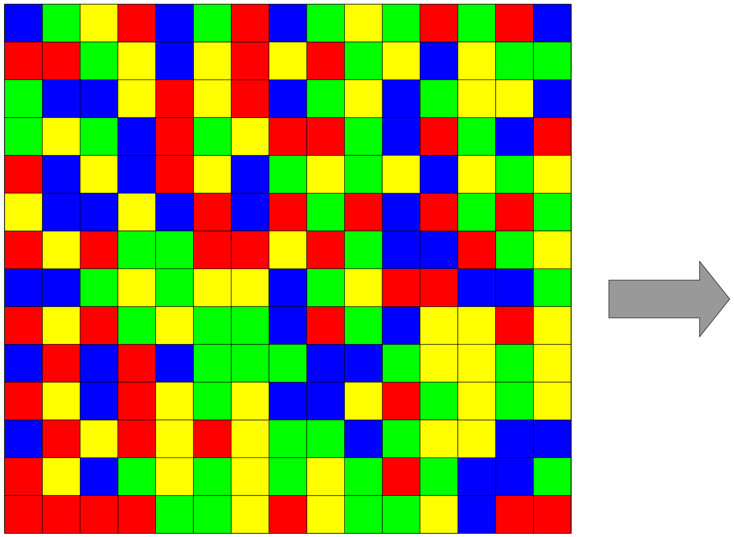

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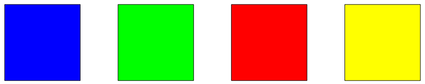

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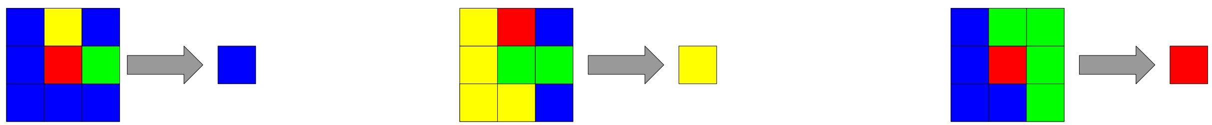

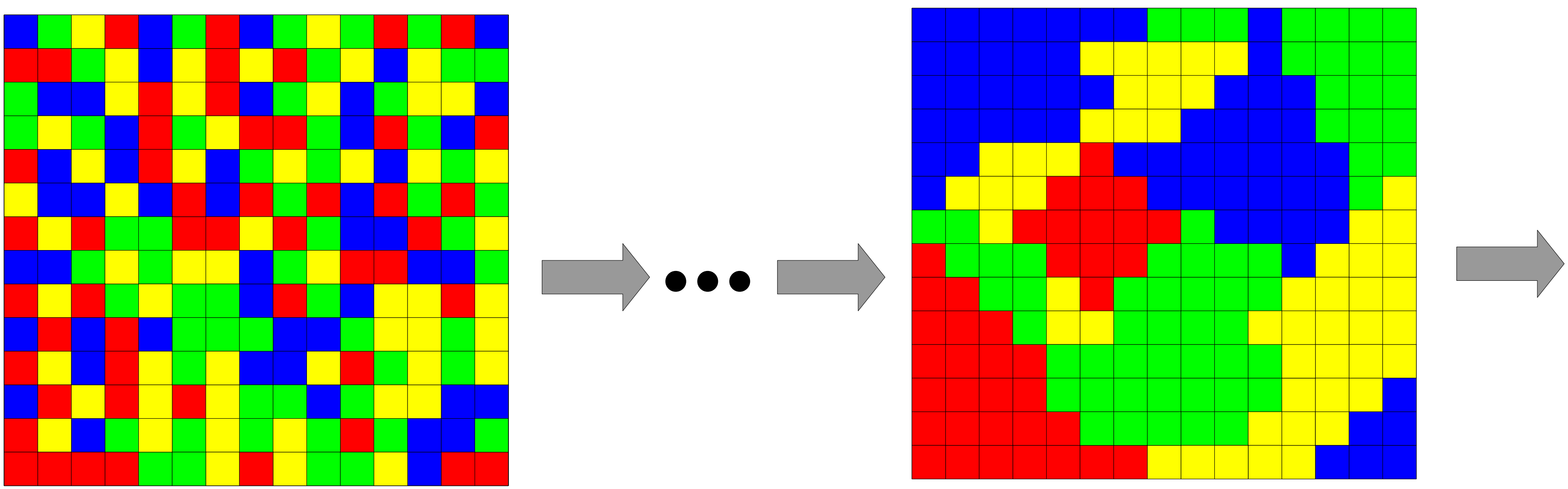

Cellular Automata in 2 Dimensions

Non Deterministic Cellular Automata

As an extension to the deterministic rule of a classically defined Cellular Automaton, the transition from one state to the next state can have a stochastic component.

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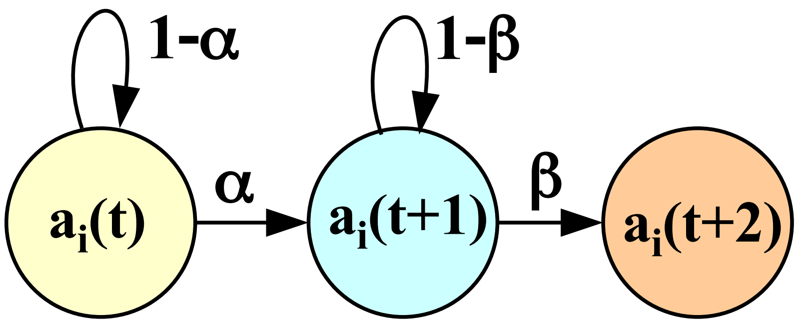

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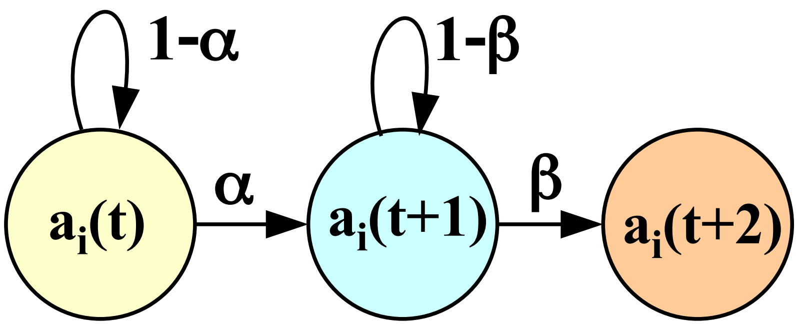

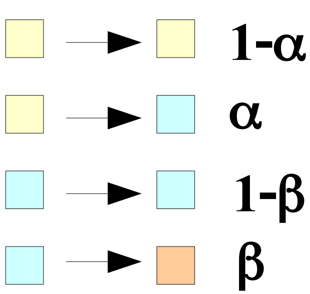

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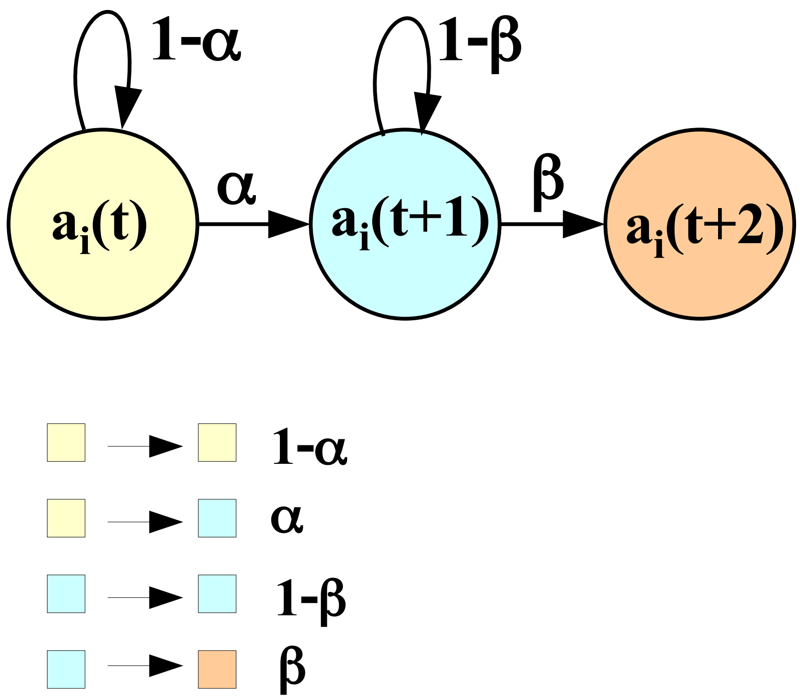

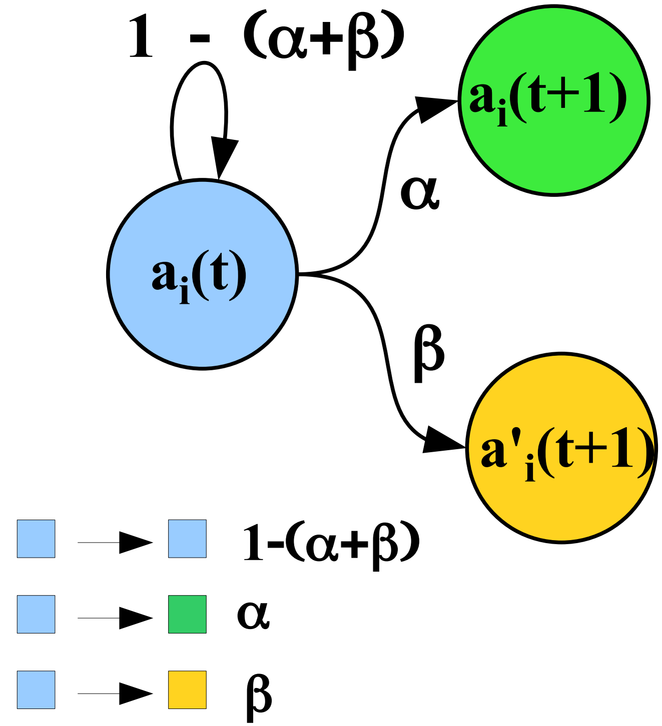

Cellular Automata in 2 Dimensions

Forest Fire CA

d=2, rectangular grid, r=1, von Neumann, k=3

non deterministic cellular automaton,

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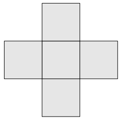
A empty / **A**shes

T **T**ree

F burning tree / **F**ire



von Neumann

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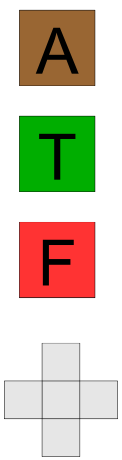
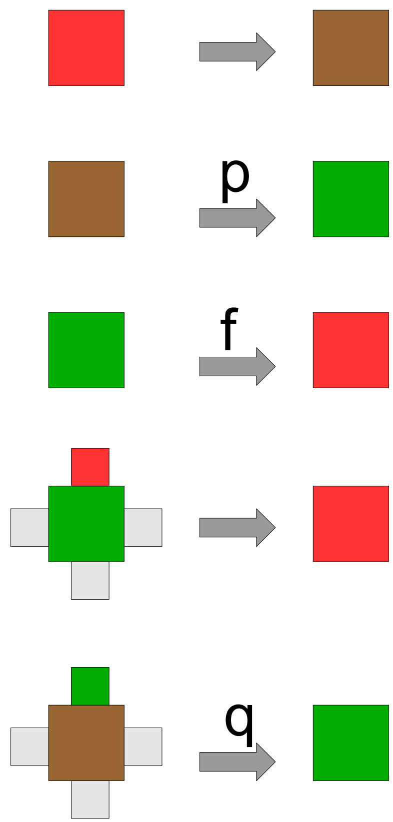


empty / **A**shes

Tree

burning tree / **F**ire

von Neumann



Fire turns into ashes

Spontaneous growth

Spontaneous fire

Induced fire: a tree burns if at least one neighbor burns

Induced growth:
a tree grows if at least one neighbor is a tree

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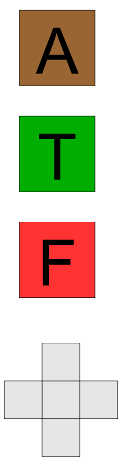
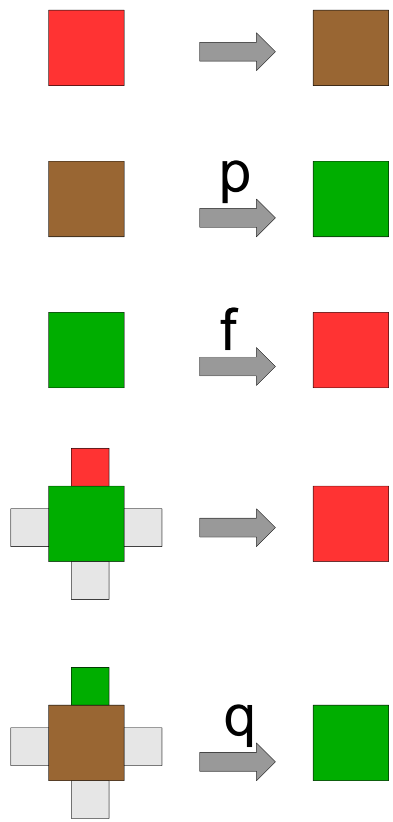


- empty / **A**shes
- **T**ree
- burning tree / **F**ire
- von Neumann



- Fire turns into ashes
- Spontaneous growth
- Spontaneous fire
- Induced fire: a tree burns if at least one neighbor burns
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Chen, K., Bak, P. and Jensen, M. H. (1990), "A deterministic critical forest-fire model. Phys. Lett. A 149, 207–210.

Drossel, B. and Schwabl, F. (1992) *"Self-organized critical forest-fire model*." Phys. Rev. Lett. 69, 1629–1632.

Cellular Automata in 2 Dimensions

Forest Fire CA

d=2, rectangular grid, r=1, von Neumann, k=3

non deterministic cellular automaton,

The behavior of the complete system is determined by the underlying mircro-behavior of the cells.

The control parameters are:

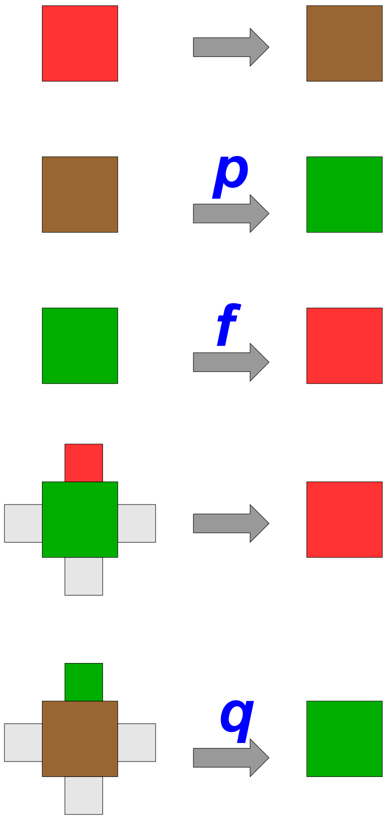
p rate of spontaneous growth

f rate of spontaneous fire

q rate of induced growth

A setting of *q=0* (no induced growth) is a good setting to start from.

Interesting (fractal) behavior arises when $f << p$ (e.g. p/f = 100).



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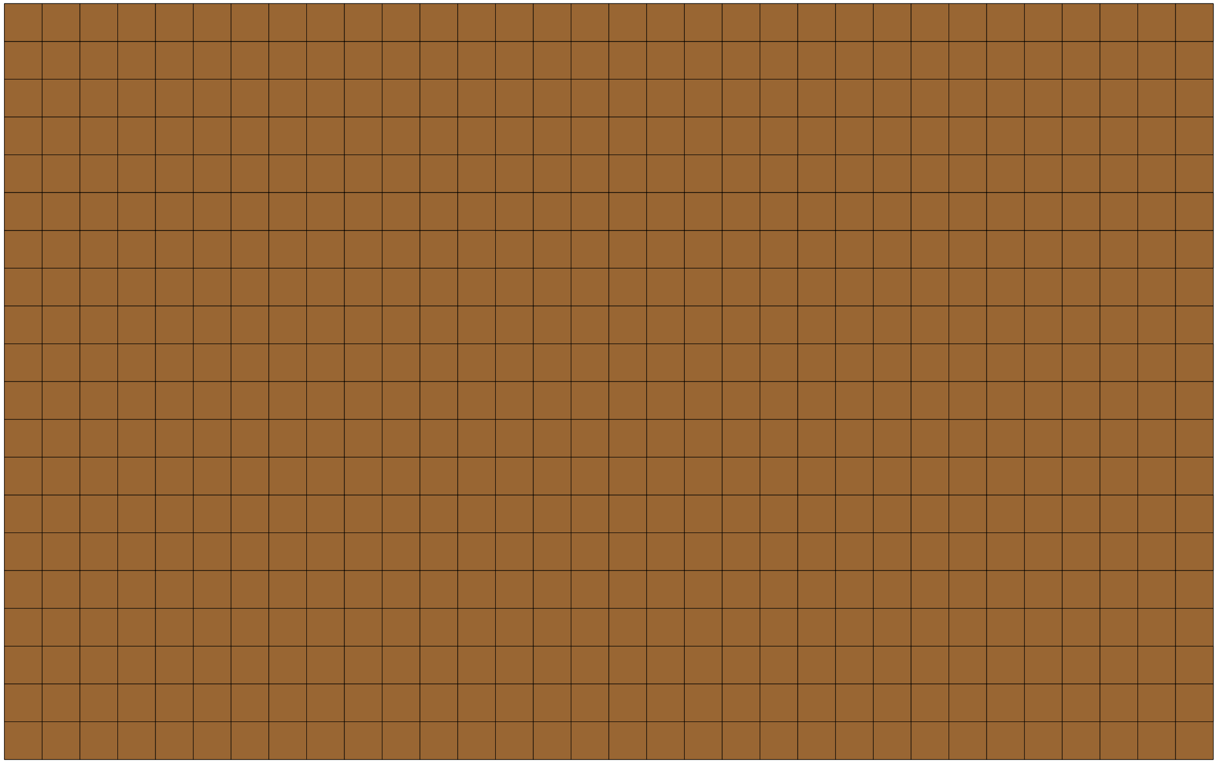

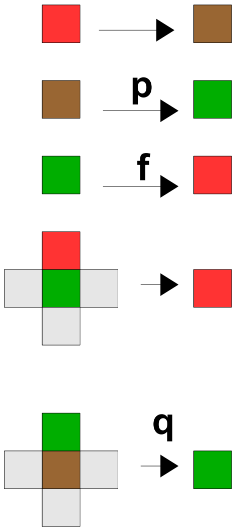

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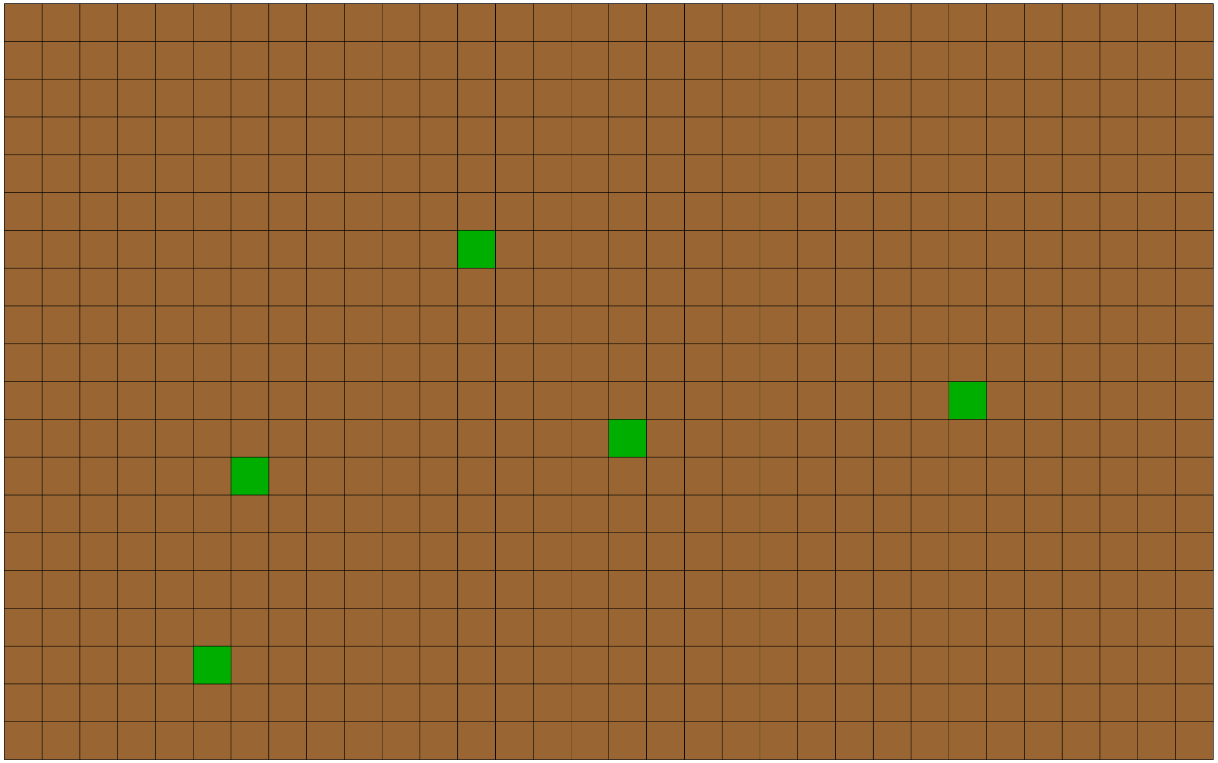

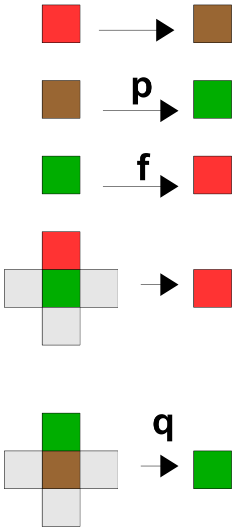

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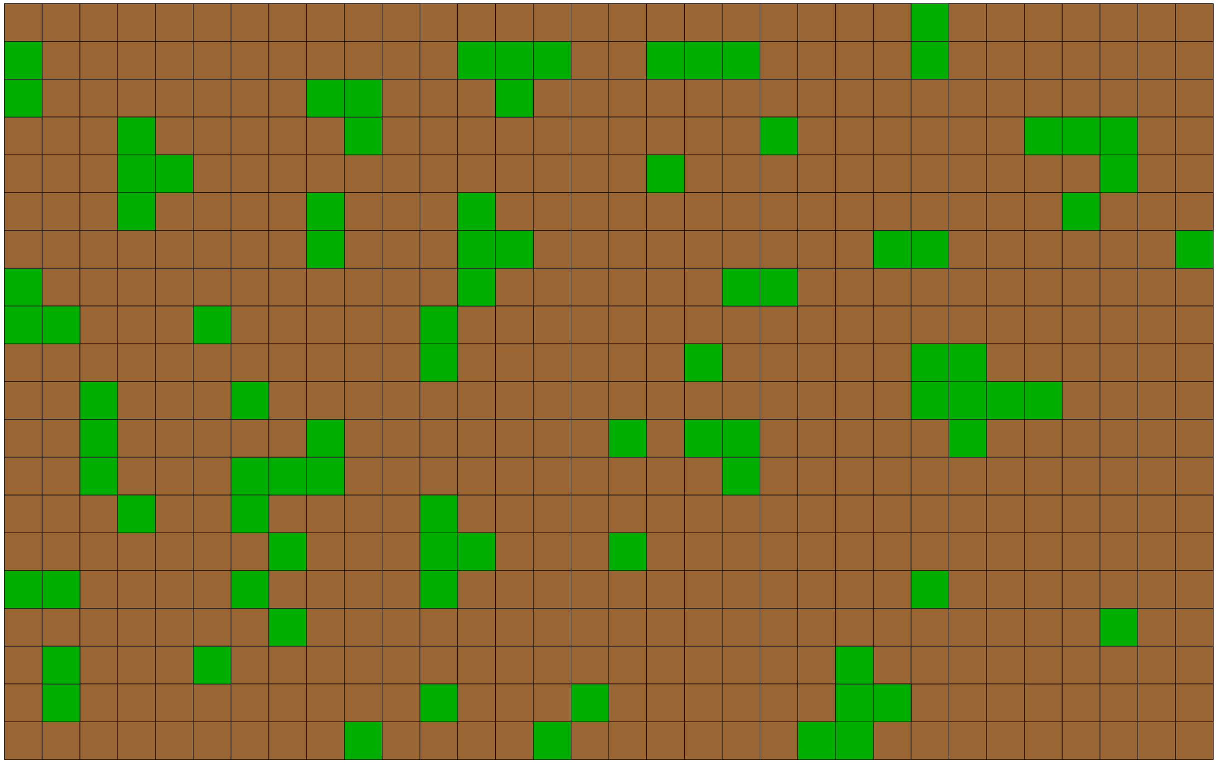

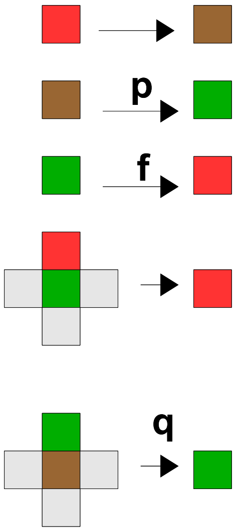

q = 0,
no induced growth

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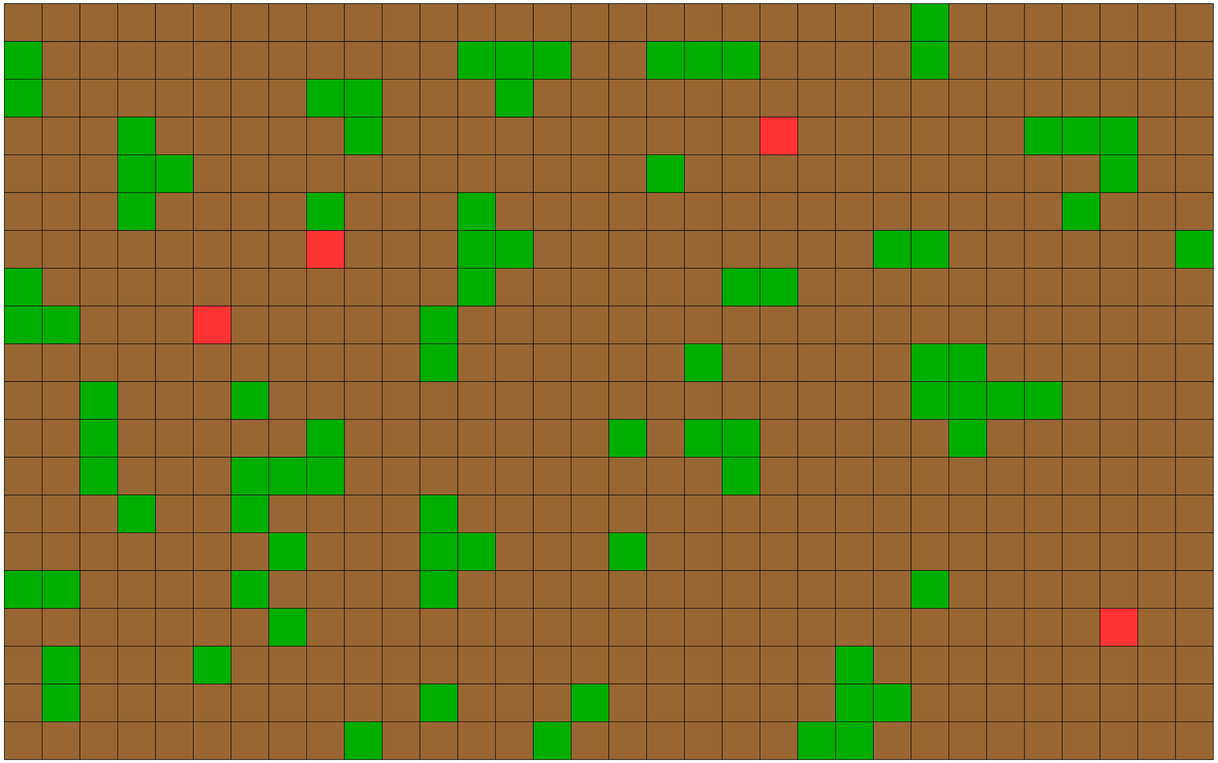

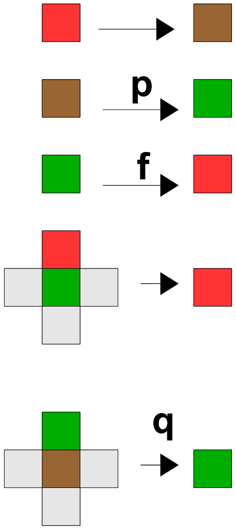

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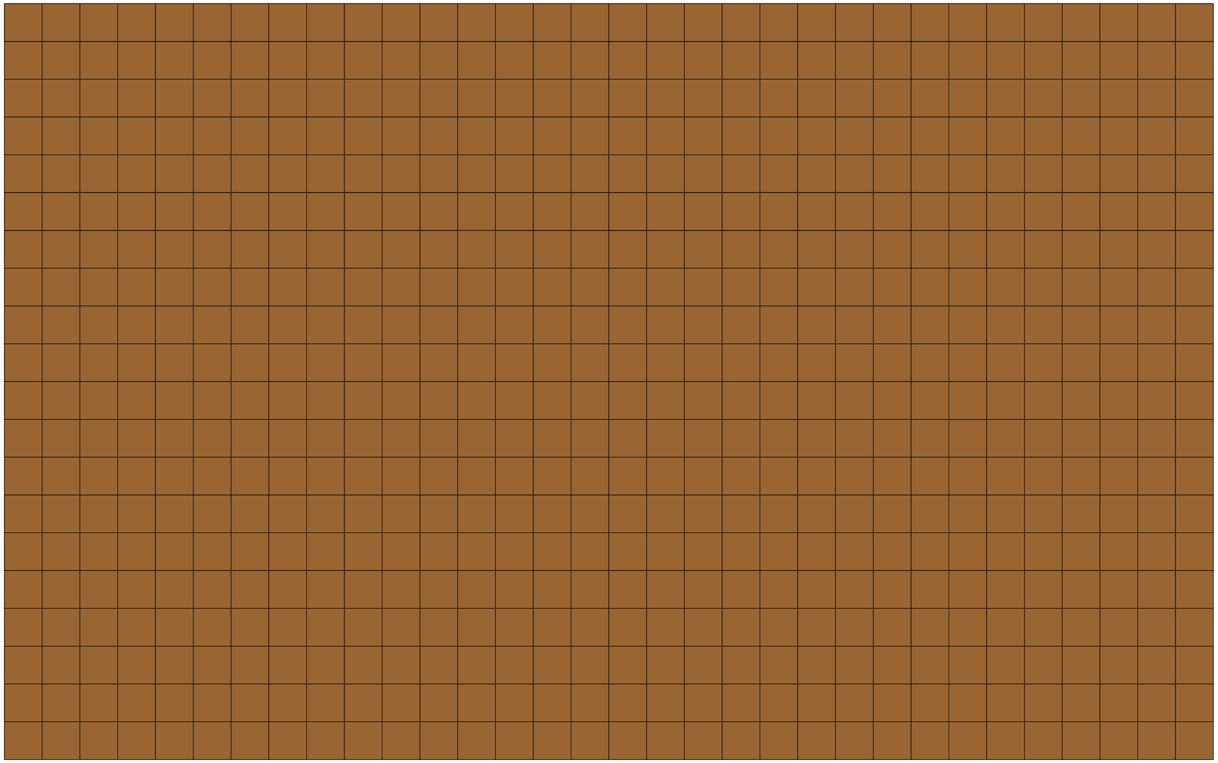
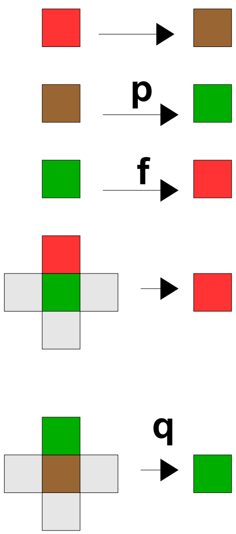


step i-1



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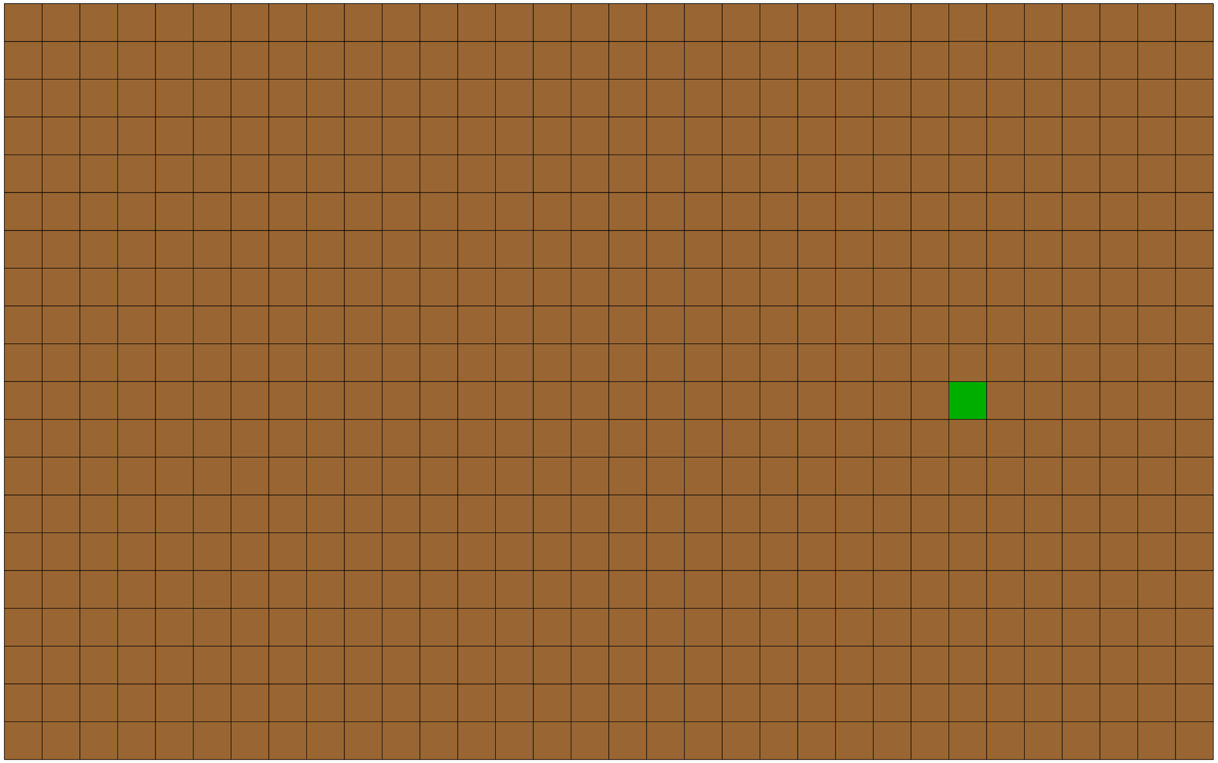
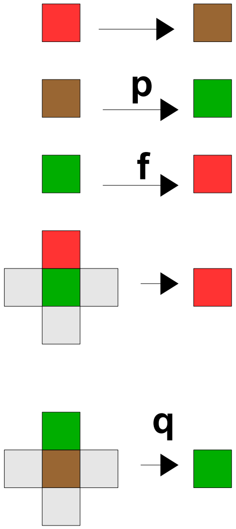

step i



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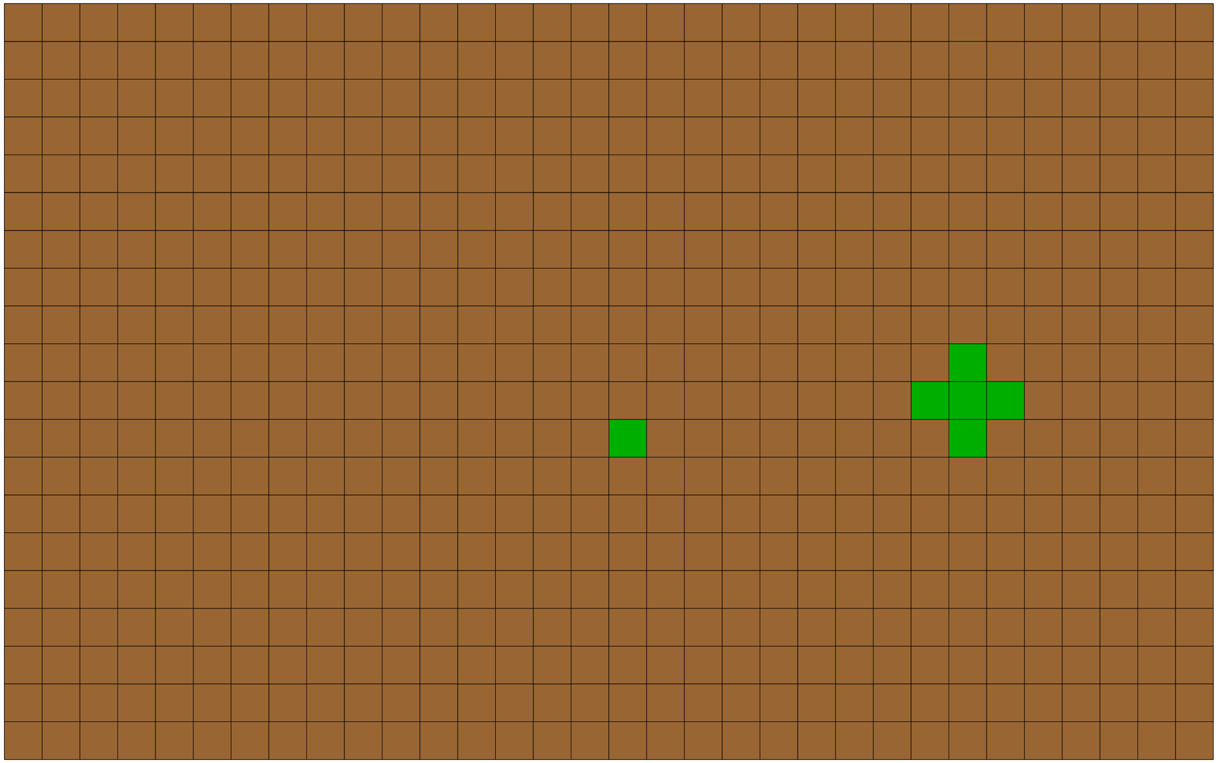
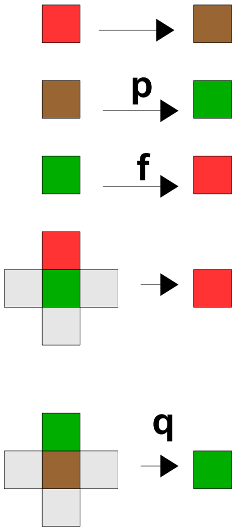


step i+1



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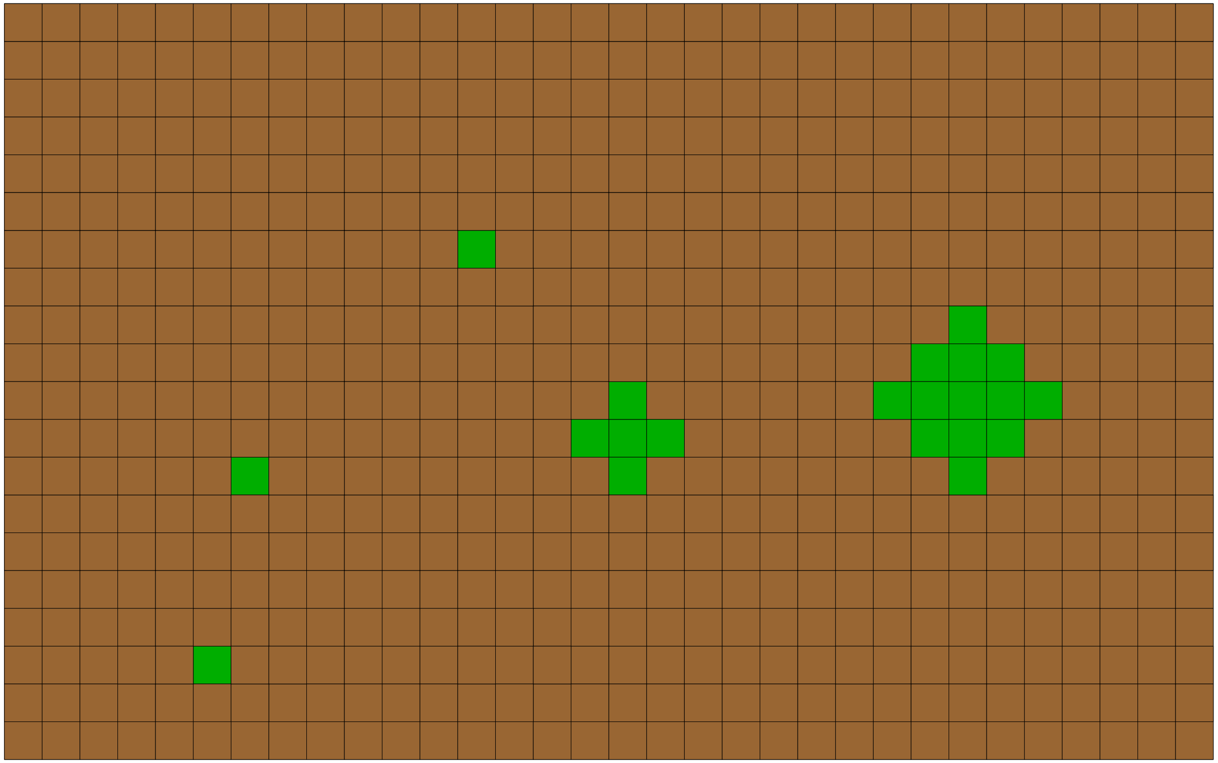
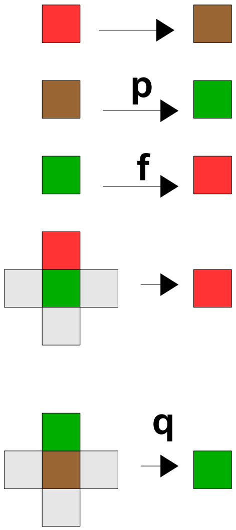


step i+2



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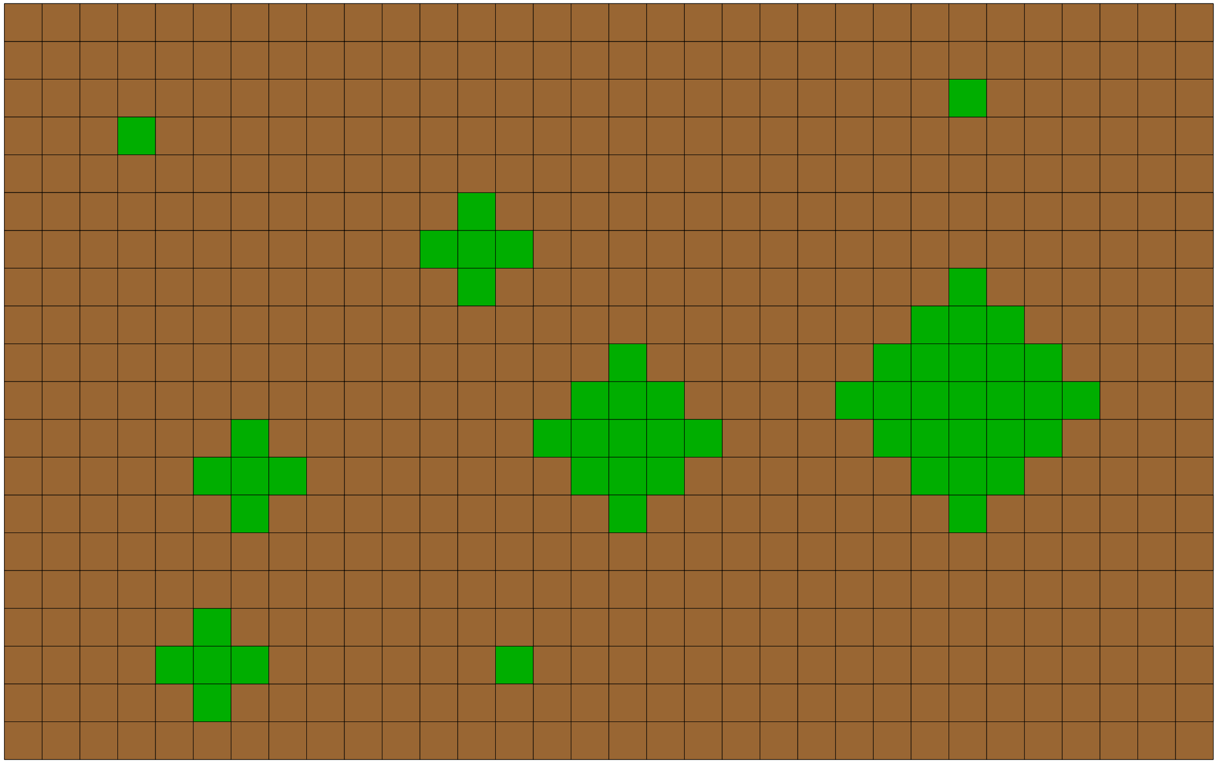
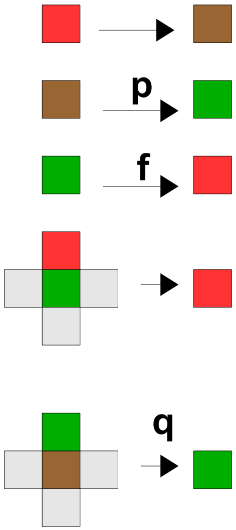


step i+3



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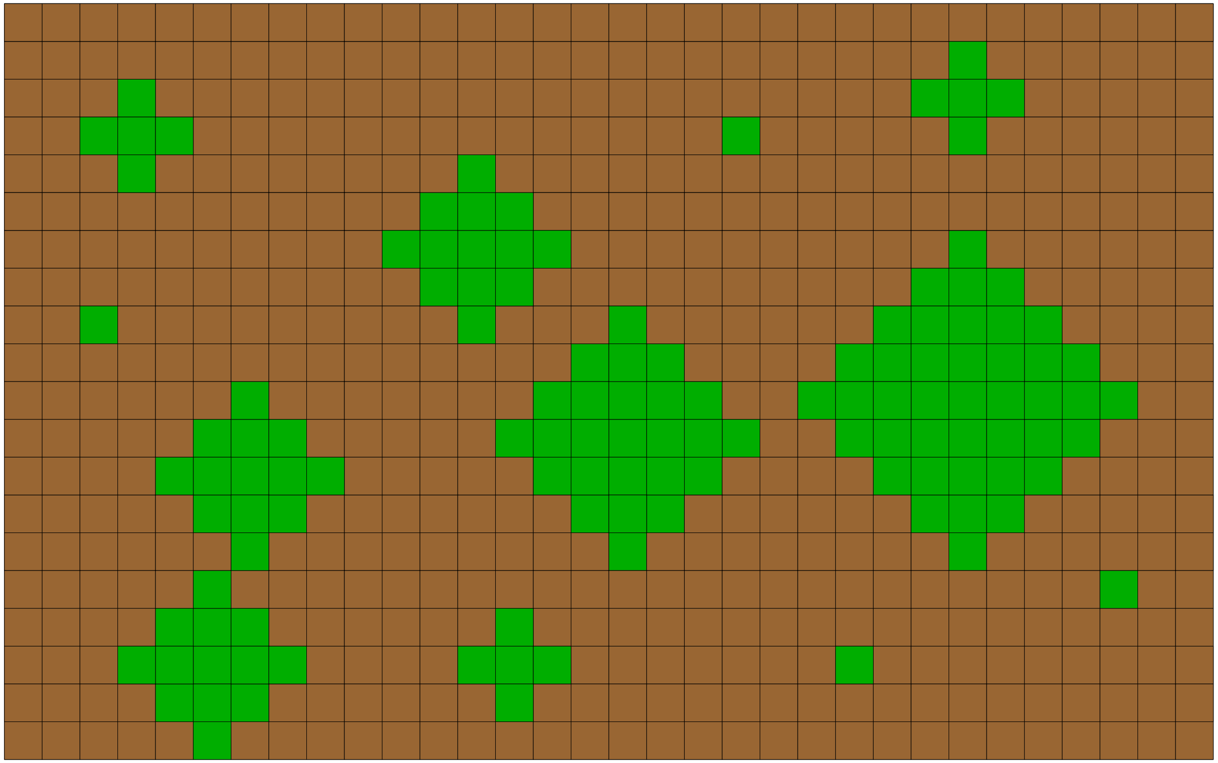
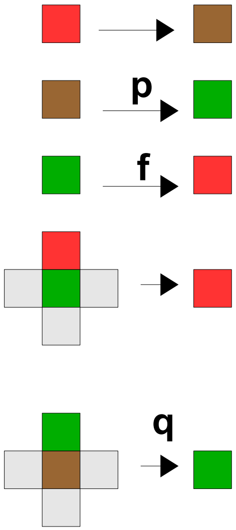


step i+4



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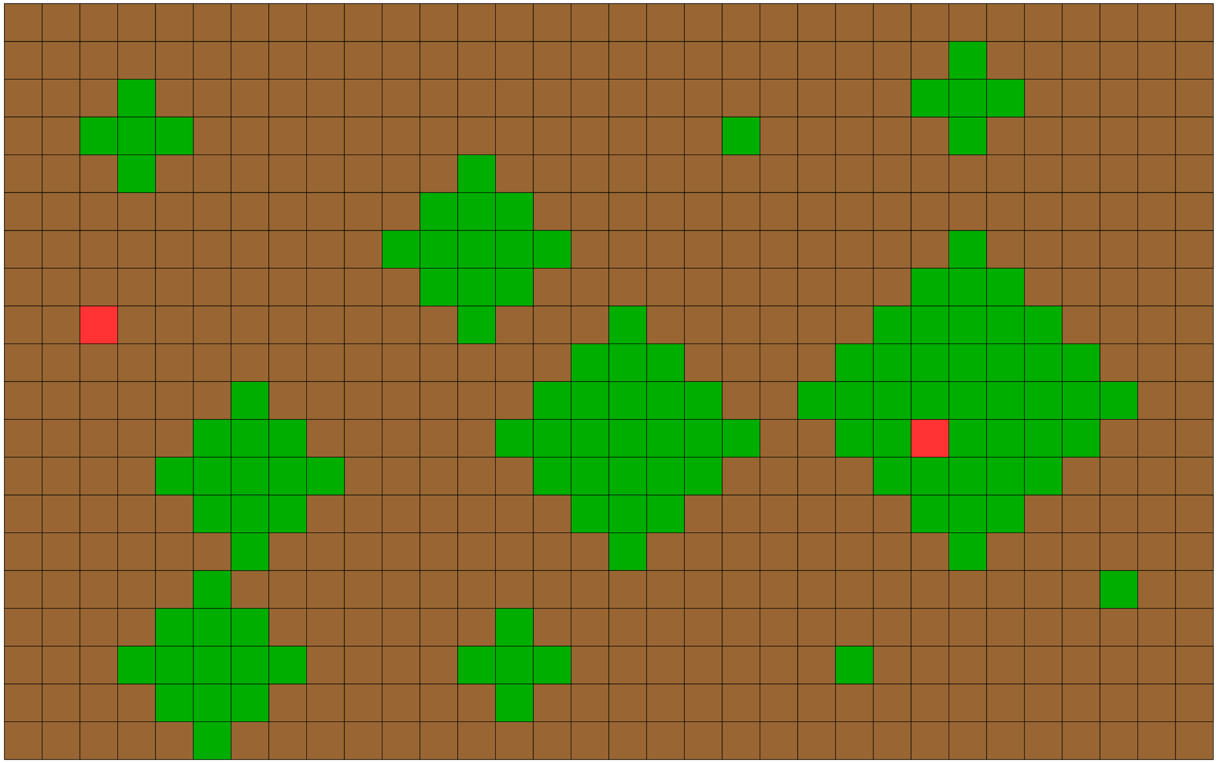
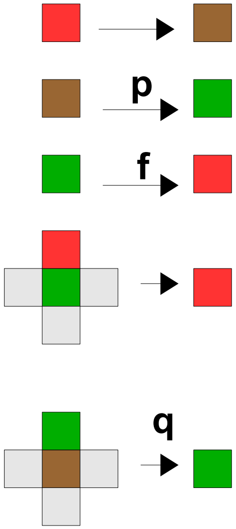


step i+j



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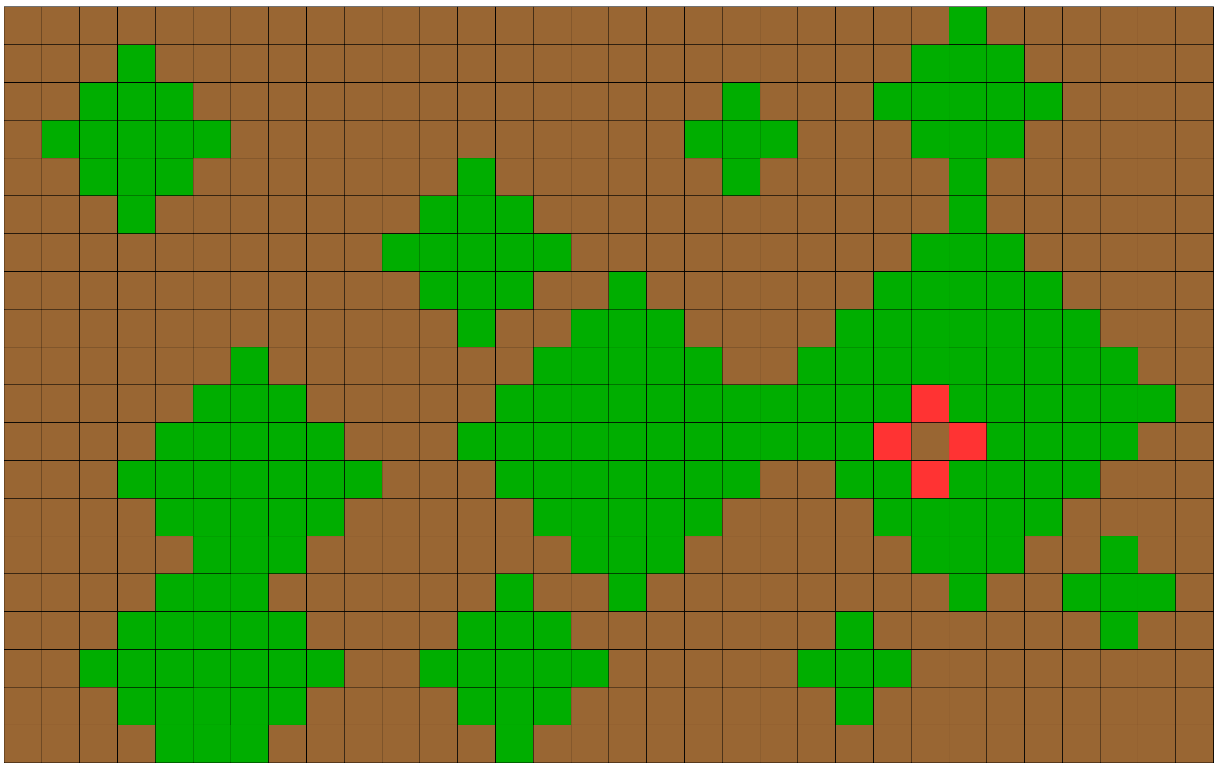
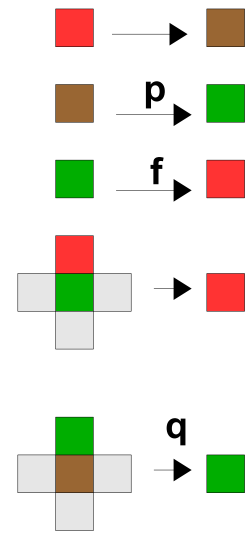


step i+j+1



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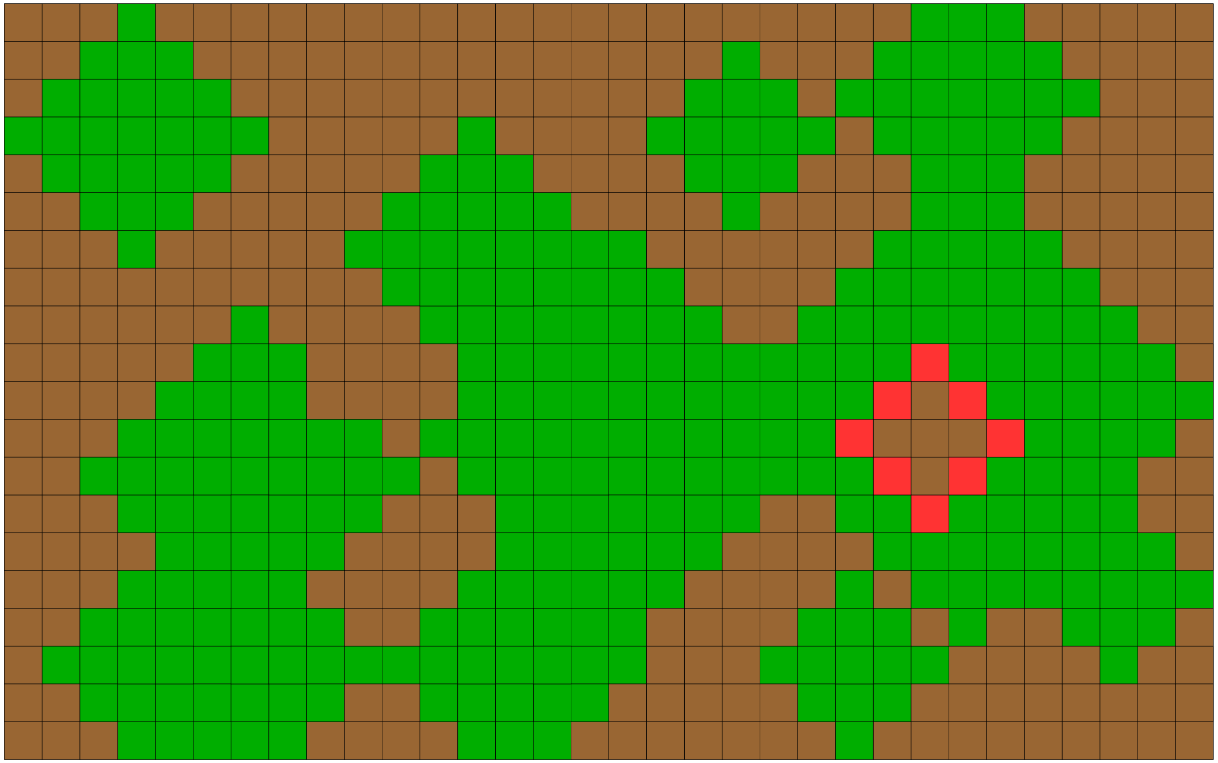
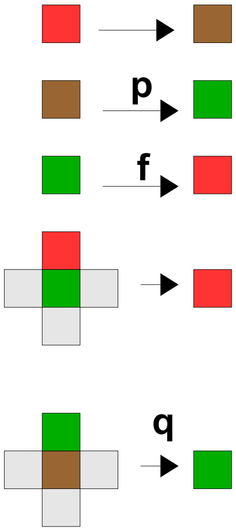


step i+j+2



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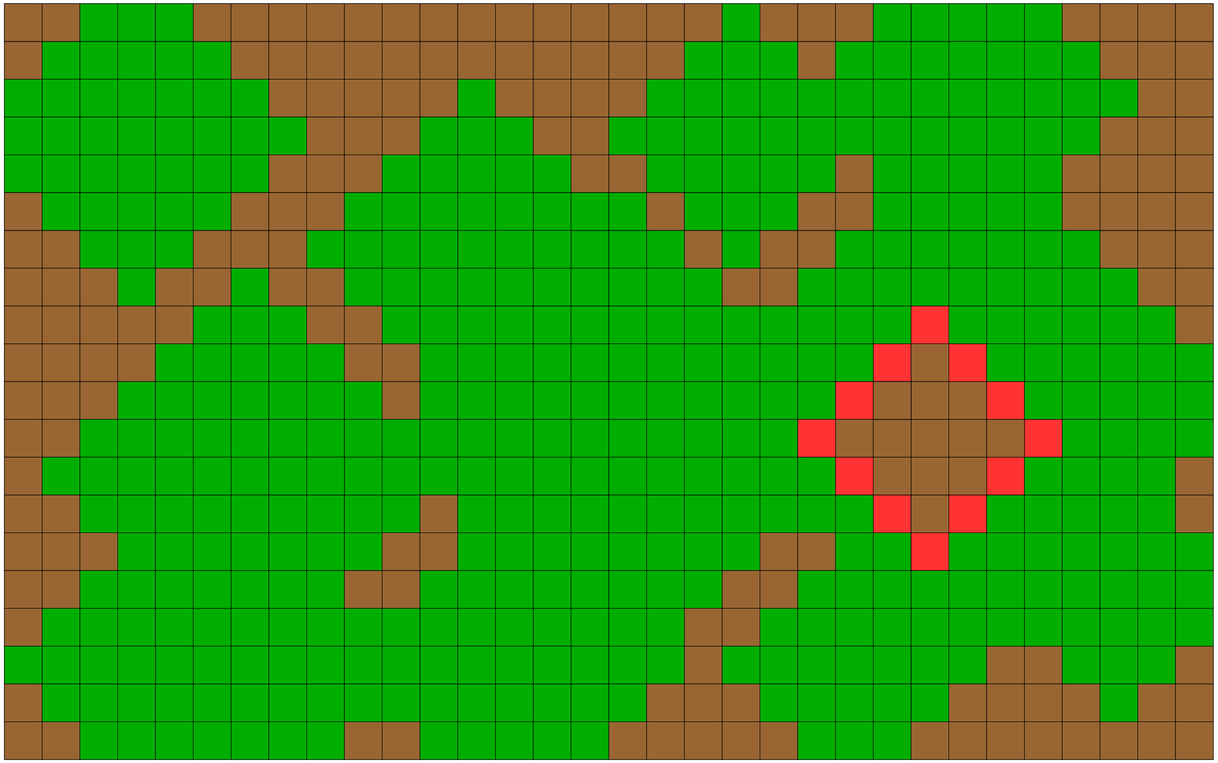
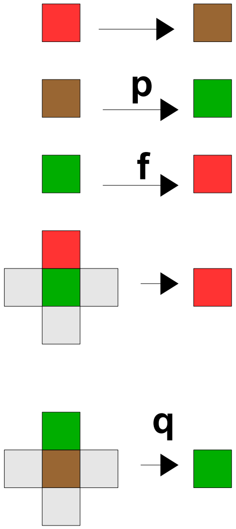


step i+j+3



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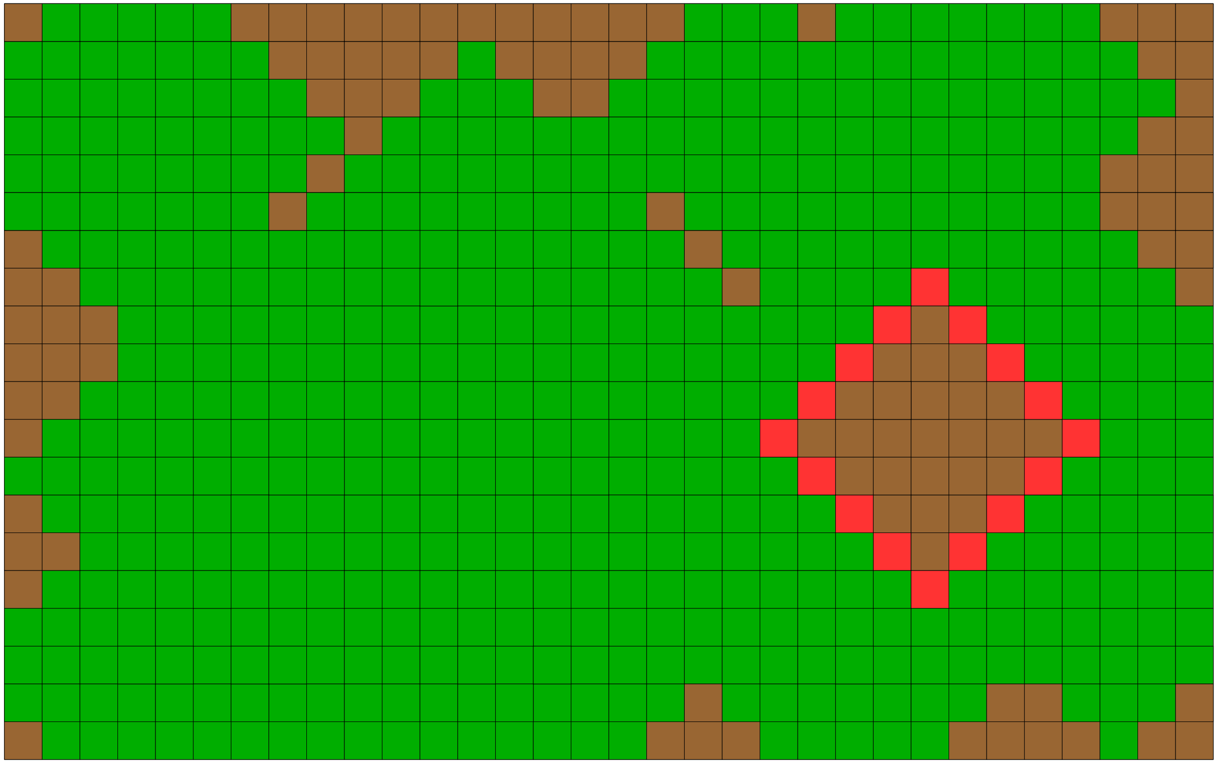
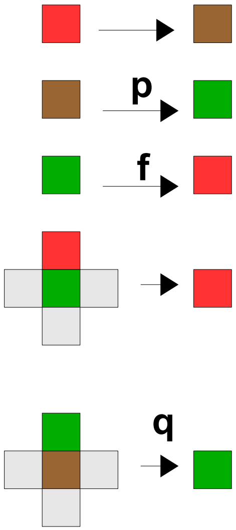


step i+j+4



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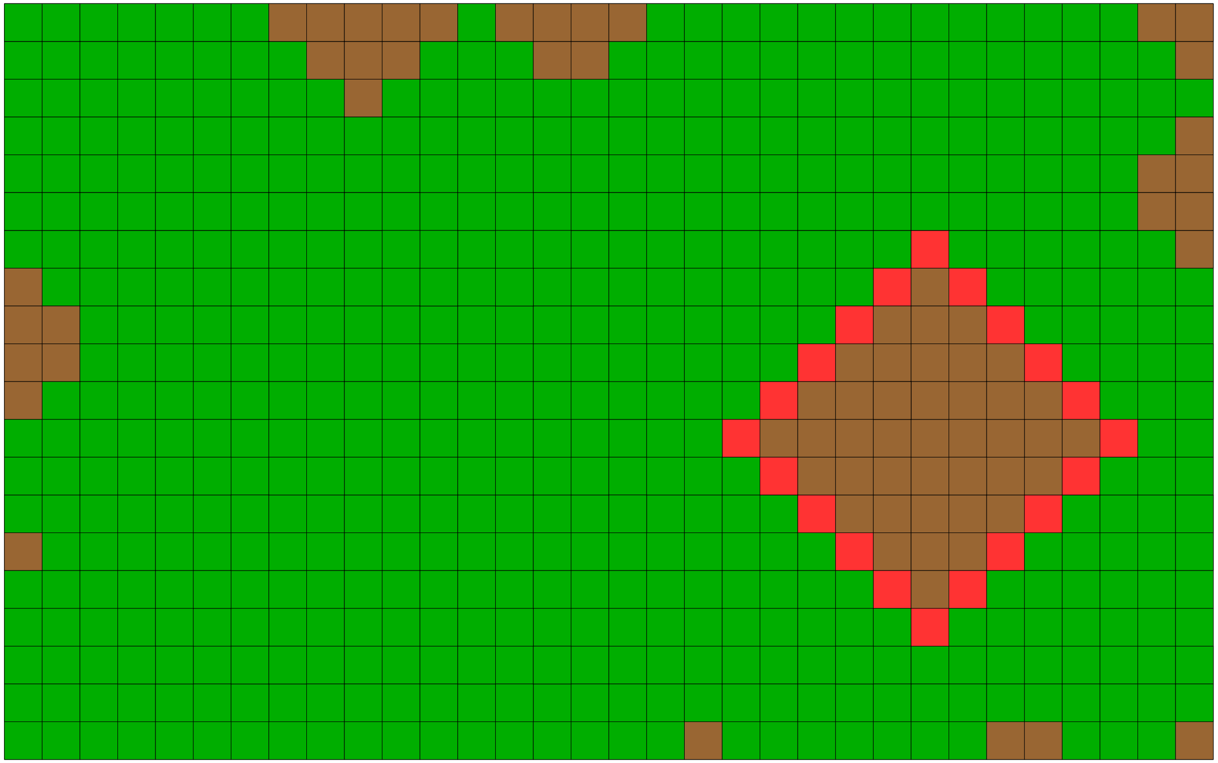
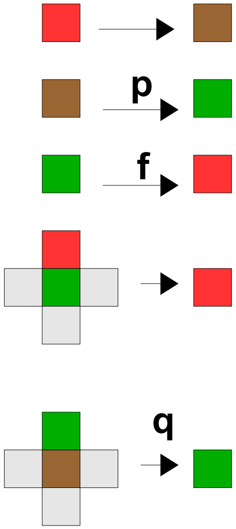
non deterministic cellular automaton,



step i+j+5



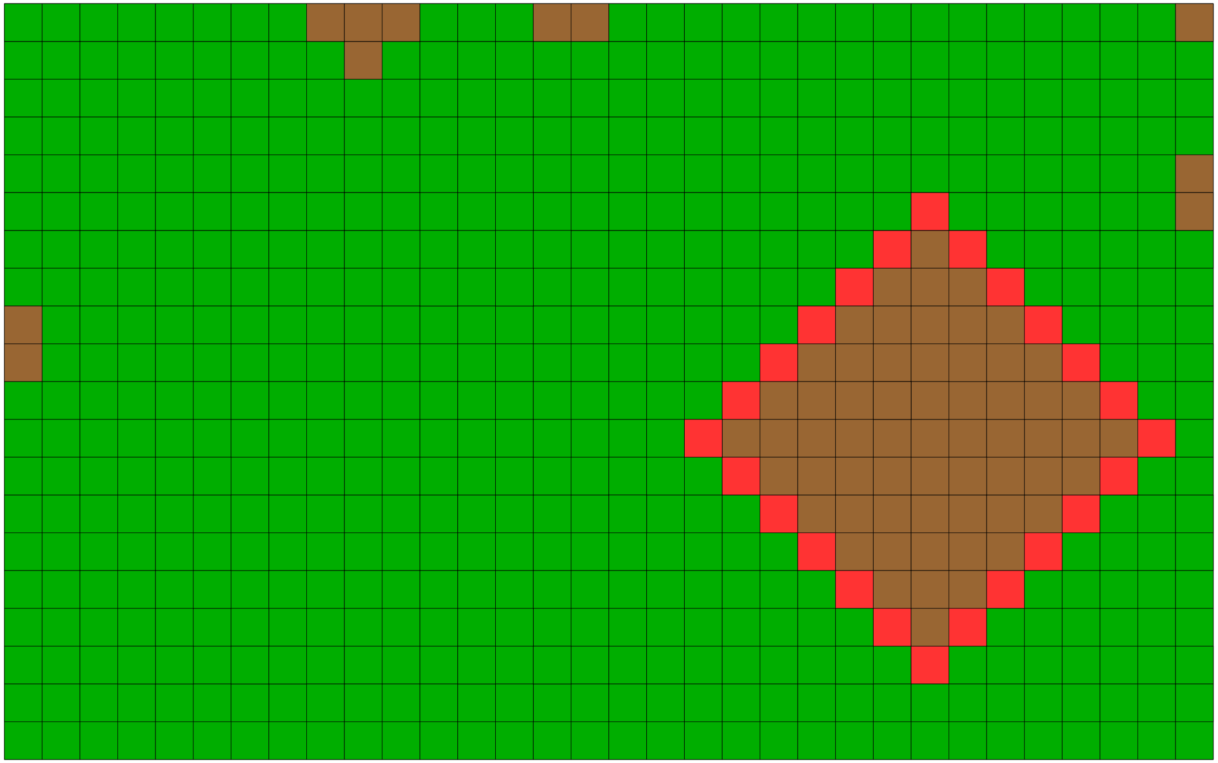
q = 1.0

Cellular Automata in 2 Dimensions

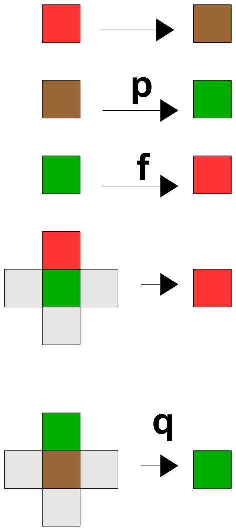
Forest Fire CA

d=2, rectangular grid, r=1, von Neumann, k=3

non deterministic cellular automaton,



step i+j+6



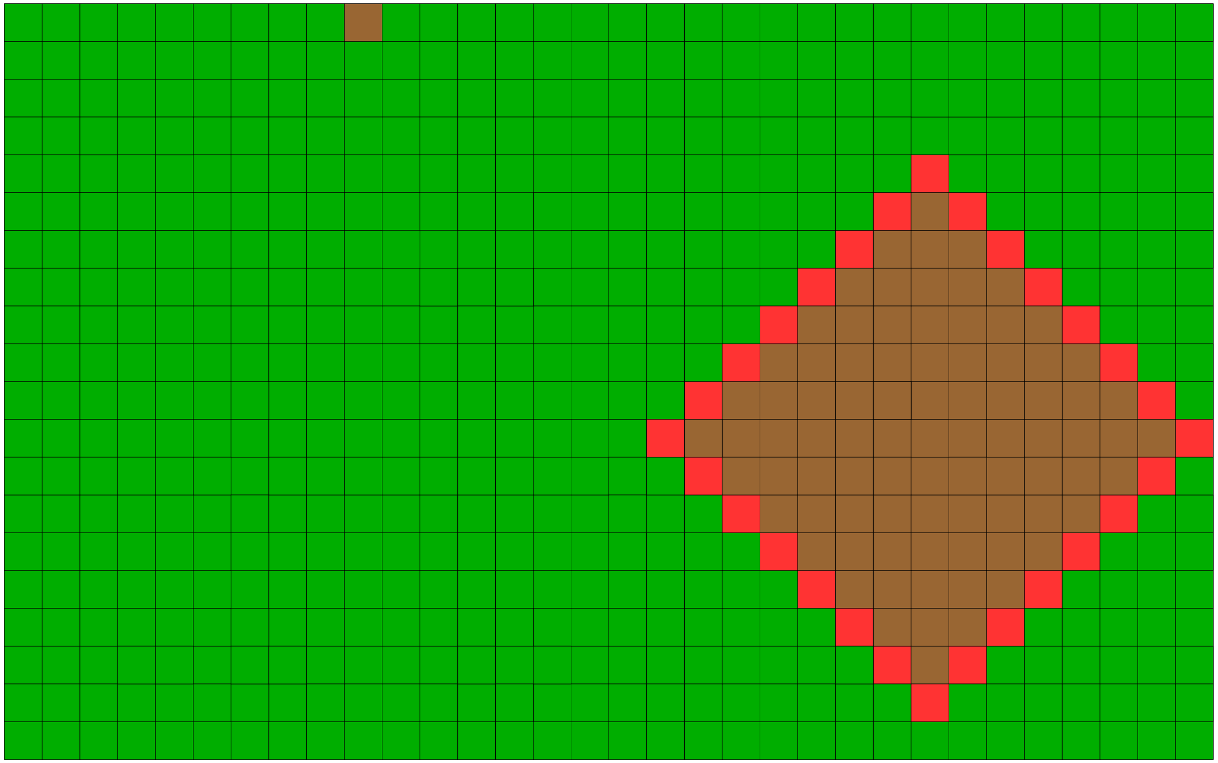
q = 1.0

Cellular Automata in 2 Dimensions

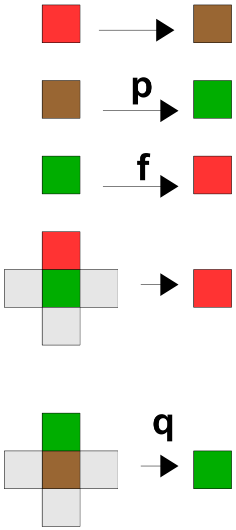
Forest Fire CA

d=2, rectangular grid, r=1, von Neumann, k=3

non deterministic cellular automaton,



step i+j+7



q = 1.0

Overview:

- Cellular Automata in 2 dimensions
- Examples and Applications of CAs
- **Conway's Game of Life**
- Computational Universality
- Is Information == Structure ?

Special Cellular Automaton in 2 dim

In 1970 the British professor for mathematics John H. Conway proposed a 2 dim cellular automaton:

Game of Life

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Conway's Game of Life

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or

Conway's Game of Life

Conway's Game of Life

In 1970 the British professor for mathematics John H. Conway proposed a 2 dim cellular automaton:

Game of Life

or

Conway's Game of Life

Conway's Game of Life is probably the most popular 2-dimensional cellular automaton.

Special Cellular Automaton in 2 dim

John Horton Conway (26 December 1937 – 11 April 2020) was an English mathematician active in the theory of finite groups, knot theory, number theory, combinatorial game theory and coding theory.
He also made contributions to many branches of recreational mathematics, most notably the invention of the **cellular automaton** called the **Game of Life**.

Born and raised in Liverpool, Conway spent the first half of his career at the University of Cambridge before moving to the United States, where he held the John von Neumann Professorship at Princeton University for the rest of his career.

On 11 April 2020, at age 82, he died of complications from COVID-19.

From https://en.wikipedia.org/wiki/John_Horton_Conway (29.4.2020)

Conway's Game of Life

Conway's Game of Live:
is a Cellular Automaton defined on a

d=2, 2-dimensional rectangular grid, using a

r=1, Moore-Neighborhood,**Moore-periphery** and has

k=2, binary states for each cell: **O** dead, **I** alive.

The rule is legal.

The rule is implementing concepts from population dynamics:
birth, *survival*, death from *overcrowding* or from *loneliness*.

Conway's Game of Life: 23/3 rule

The rule for Conway's Game of Live was inspired by observations from population dynamics.

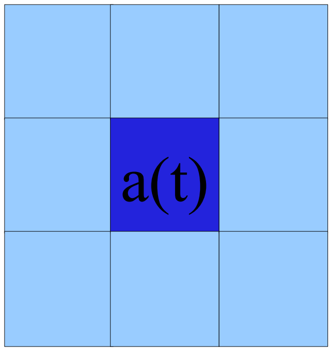
Survival:
A living cell survives if 2 or 3 neighboring cells are alive.

Birth:
A cell is born if exactly 3 neighboring cells are alive.

Death:
A living cell dies
from overcrowding if more than 3 neighboring cells are alive
or from loneliness if less than 2 neighboring cells are alive.

Conway's Game of Life: 23/3 rule

If cell *a(t)* is **alive**



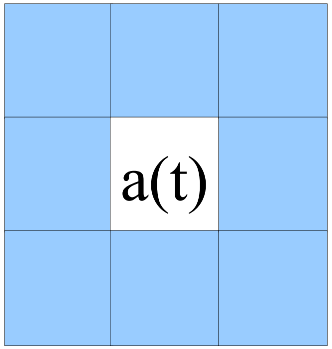
Σ ap(t)		8	7	6	5	4	**3**	**2**	1	0
a(t+1)		O	O	O	O	O	**I**	**I**	O	O

overcrowded

survival

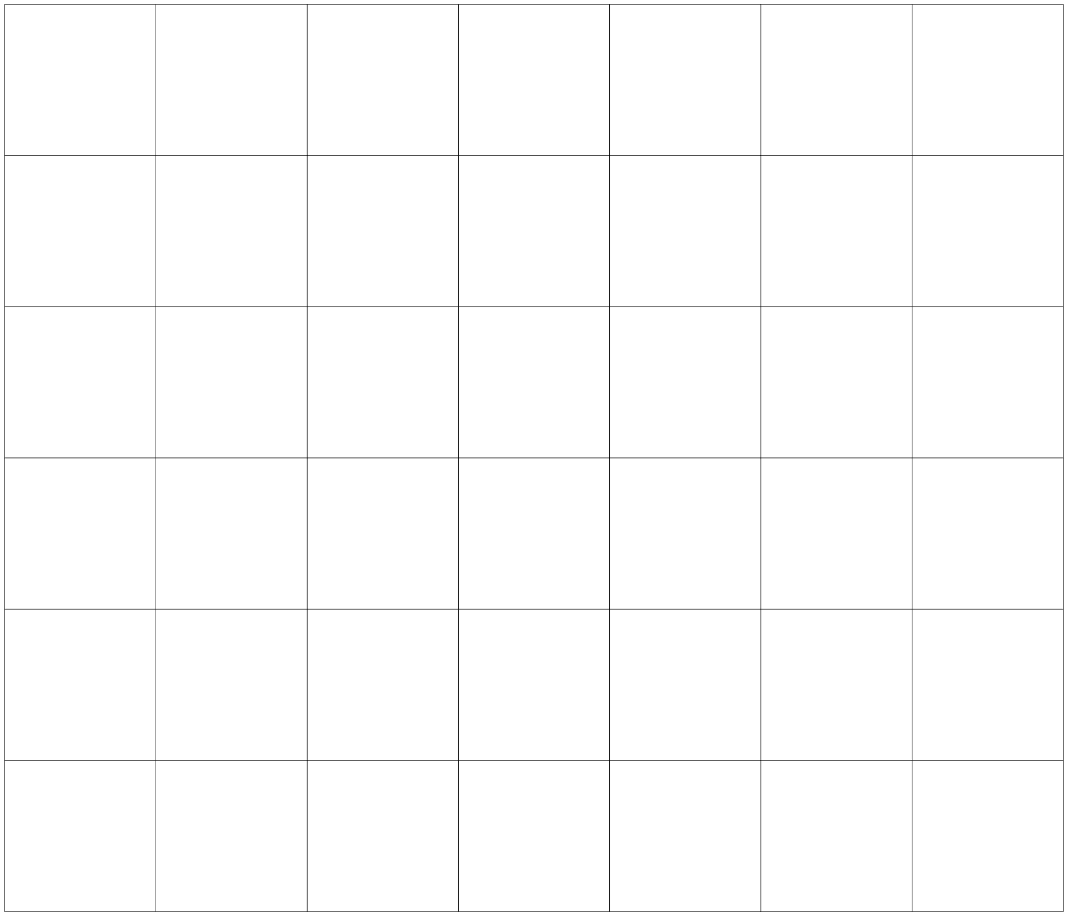
loneliness

If cell *a(t)* is **dead**



Σ ap(t)		8	7	6	5	4	**3**	2	1	0
a(t+1)		O	O	O	O	O	**I** birth	O	O	O

Conway's Game of Life

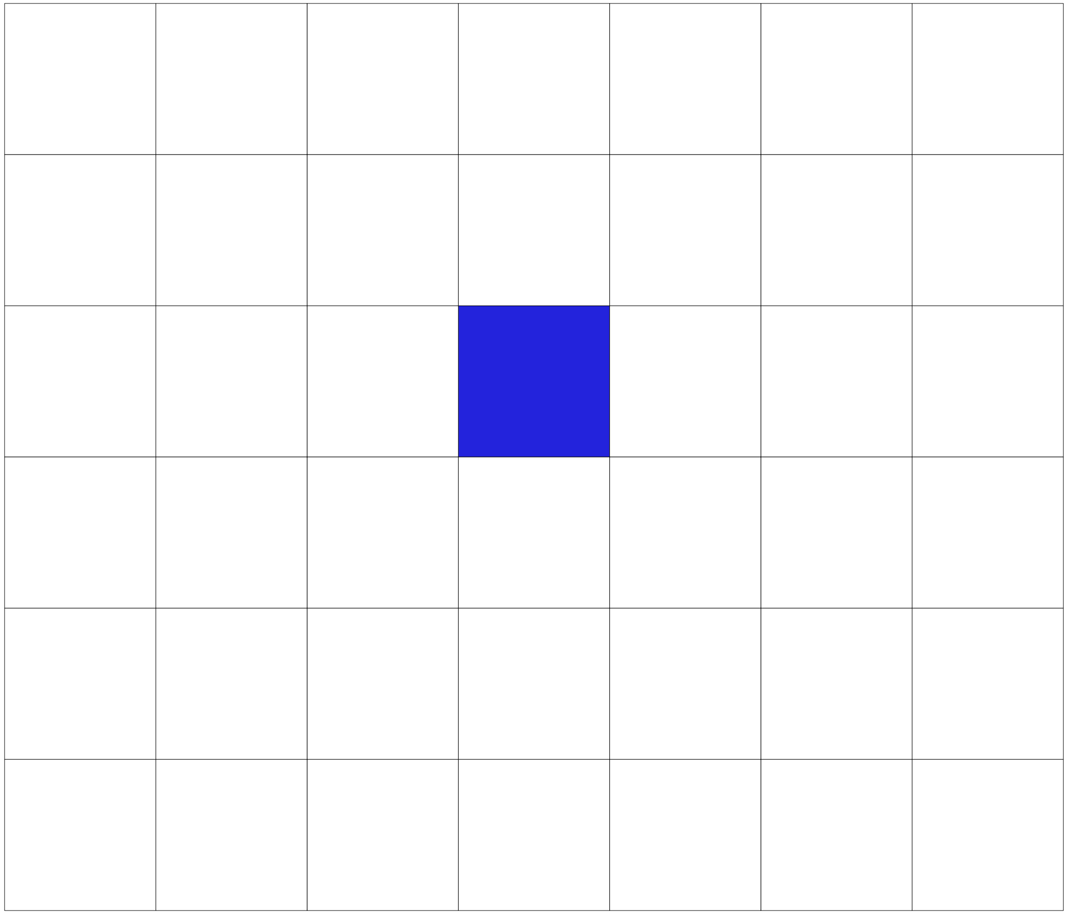


Rule: 23/3

A cell survives with 2 or 3 neighbors.

A cell is born if it has 3 neighbors.

Conway's Game of Life



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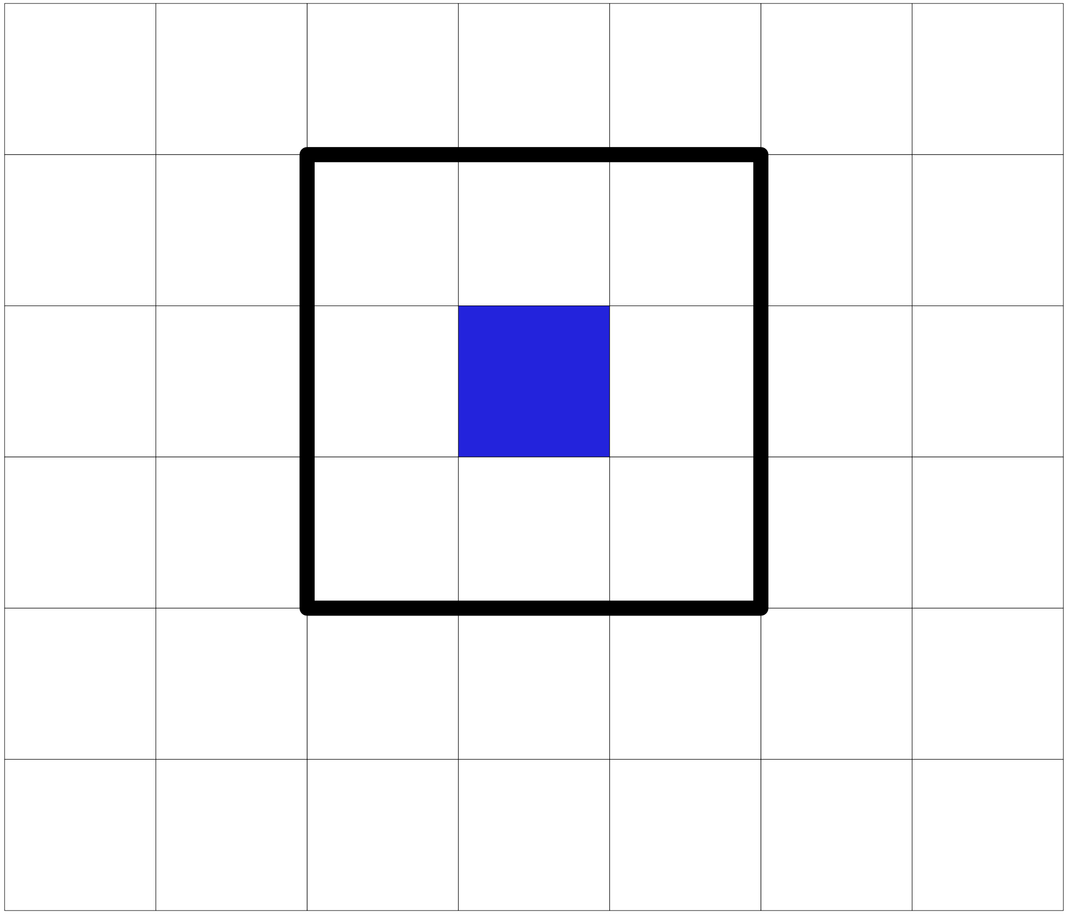

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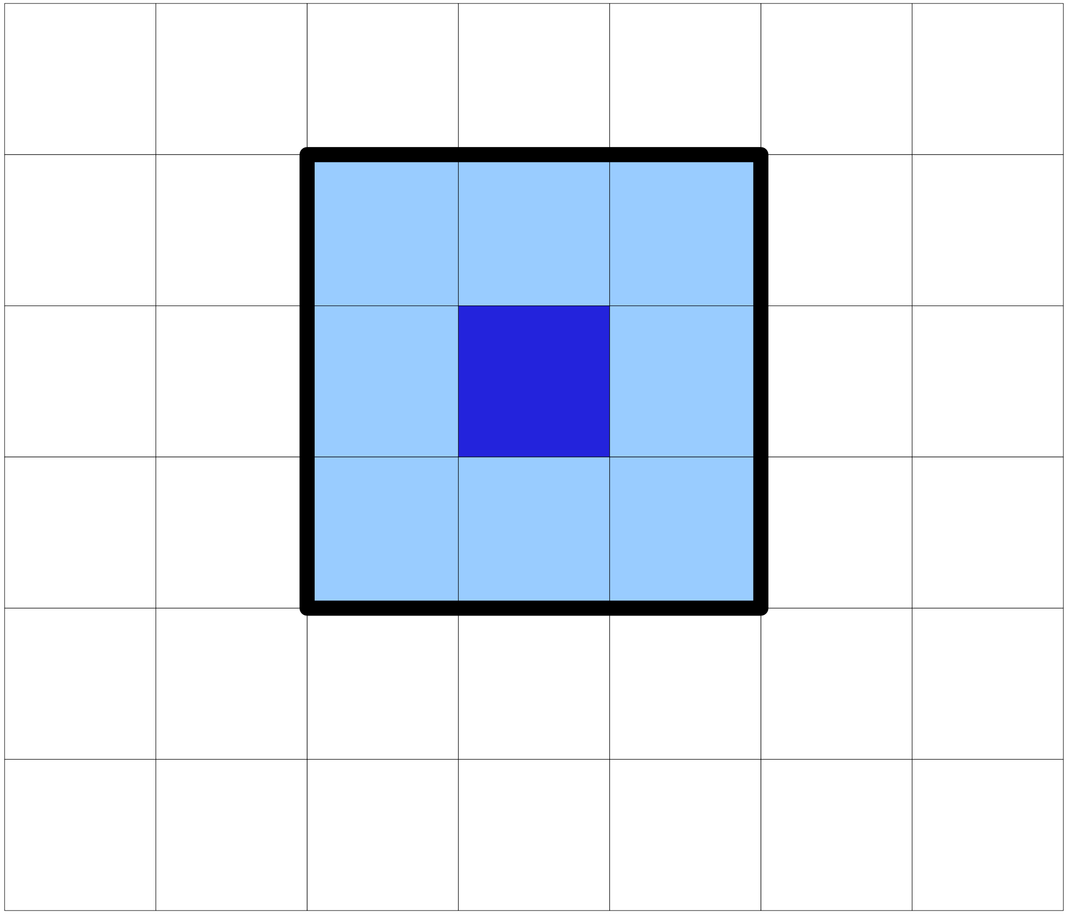

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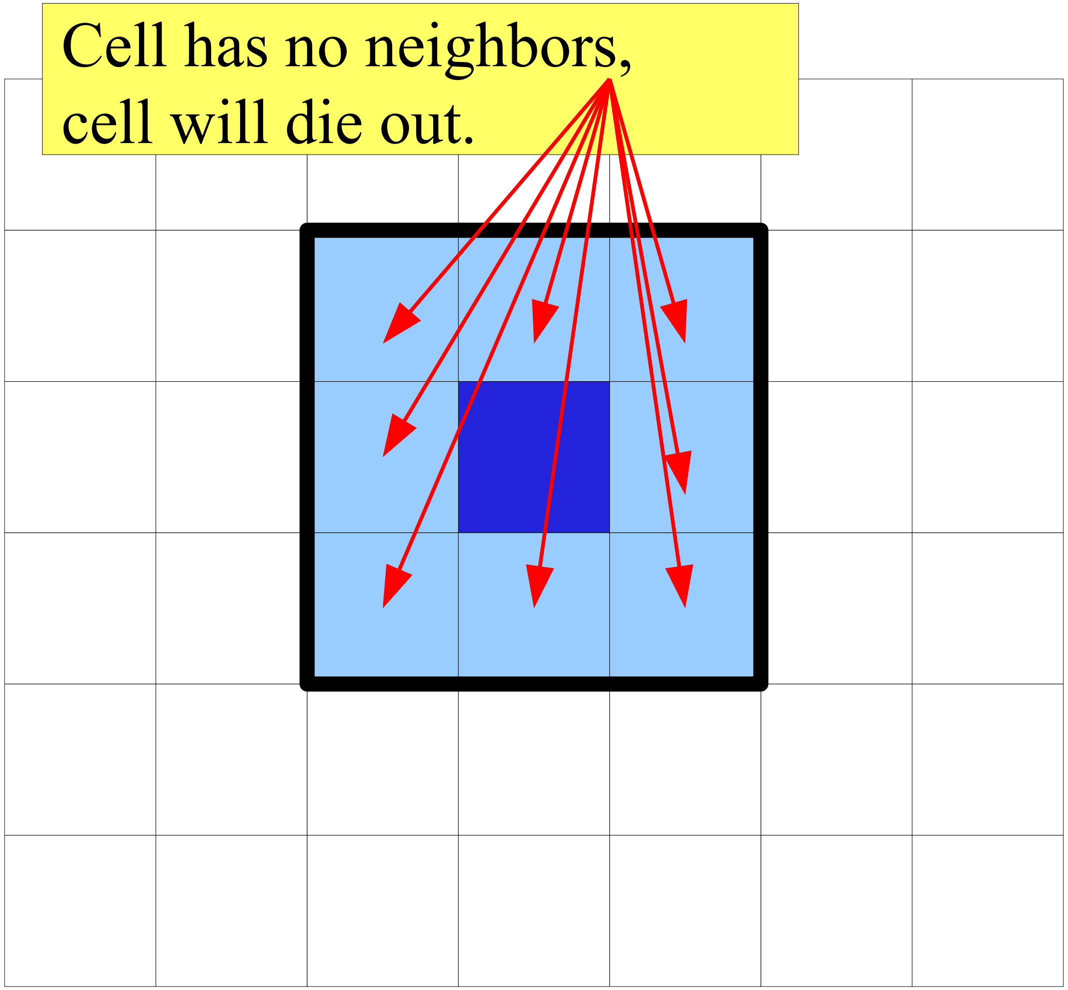
Conway's Game of Life



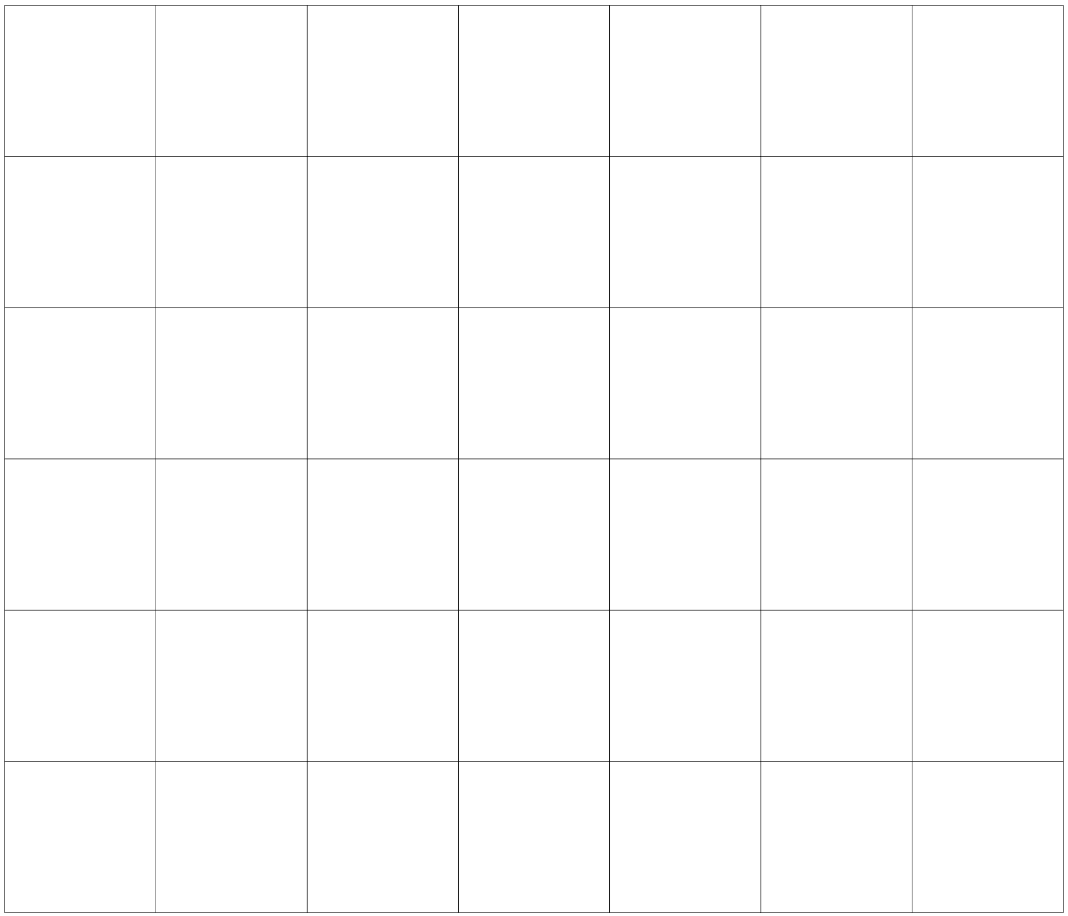
Rule: 23/3

A cell survives with 2 or 3 neighbors.

A cell is born if it has 3 neighbors.

Cell dies out.

Conway's Game of Life



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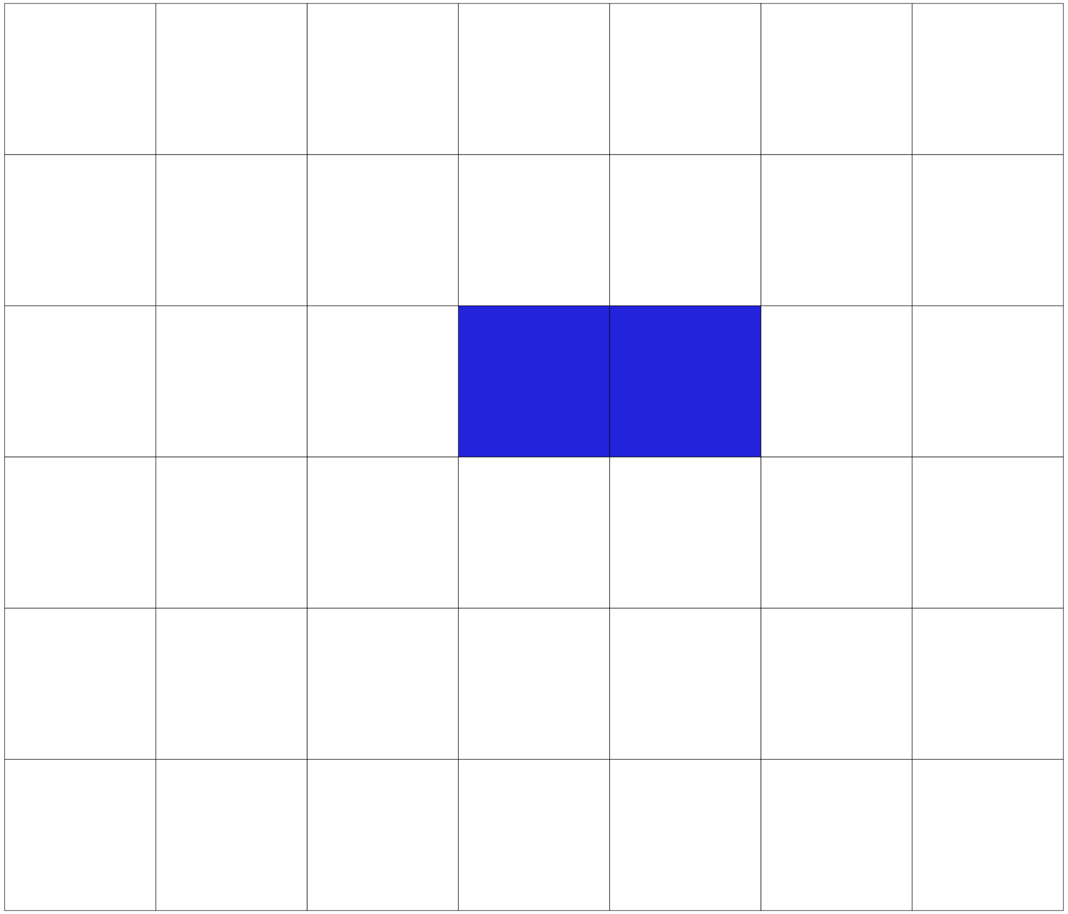
Conway's Game of Life



Rule: 23/3

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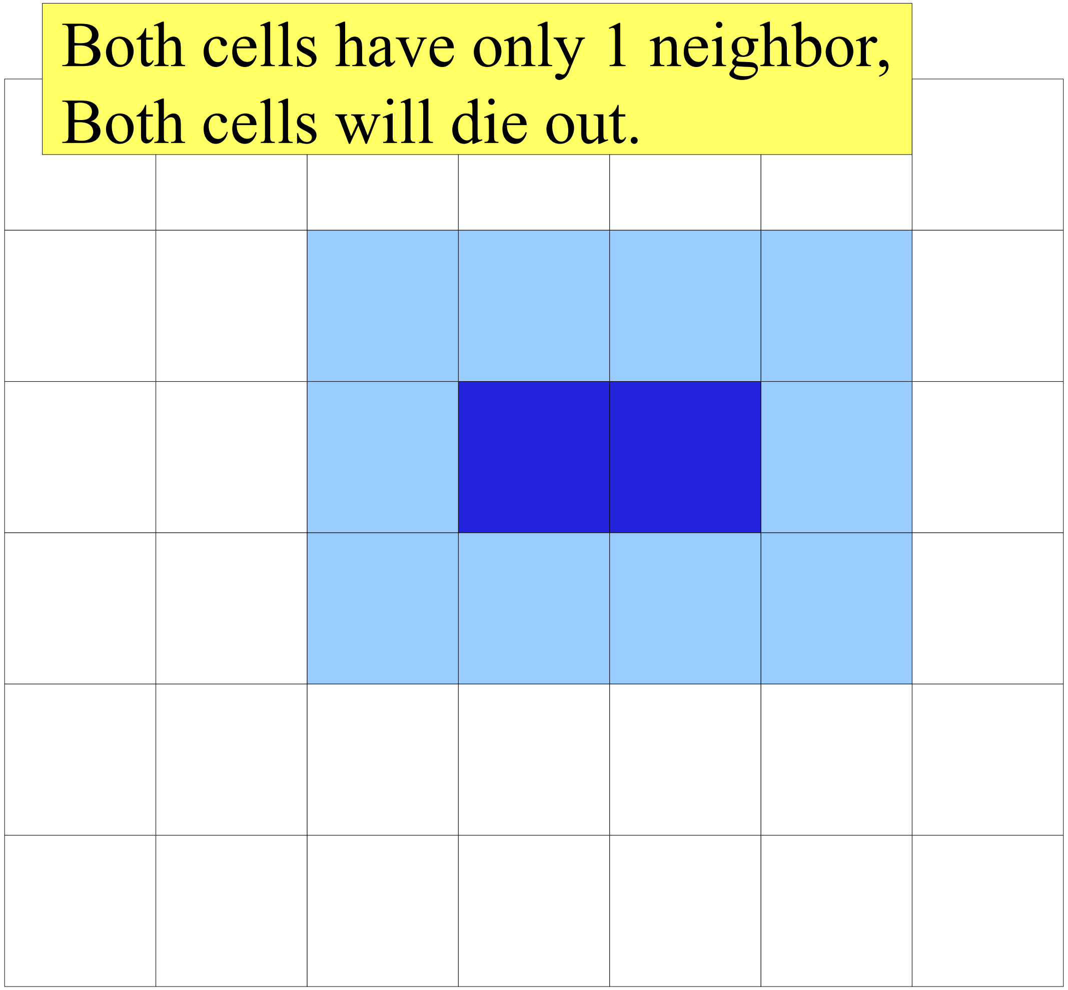
Conway's Game of Life



Rule: 23/3

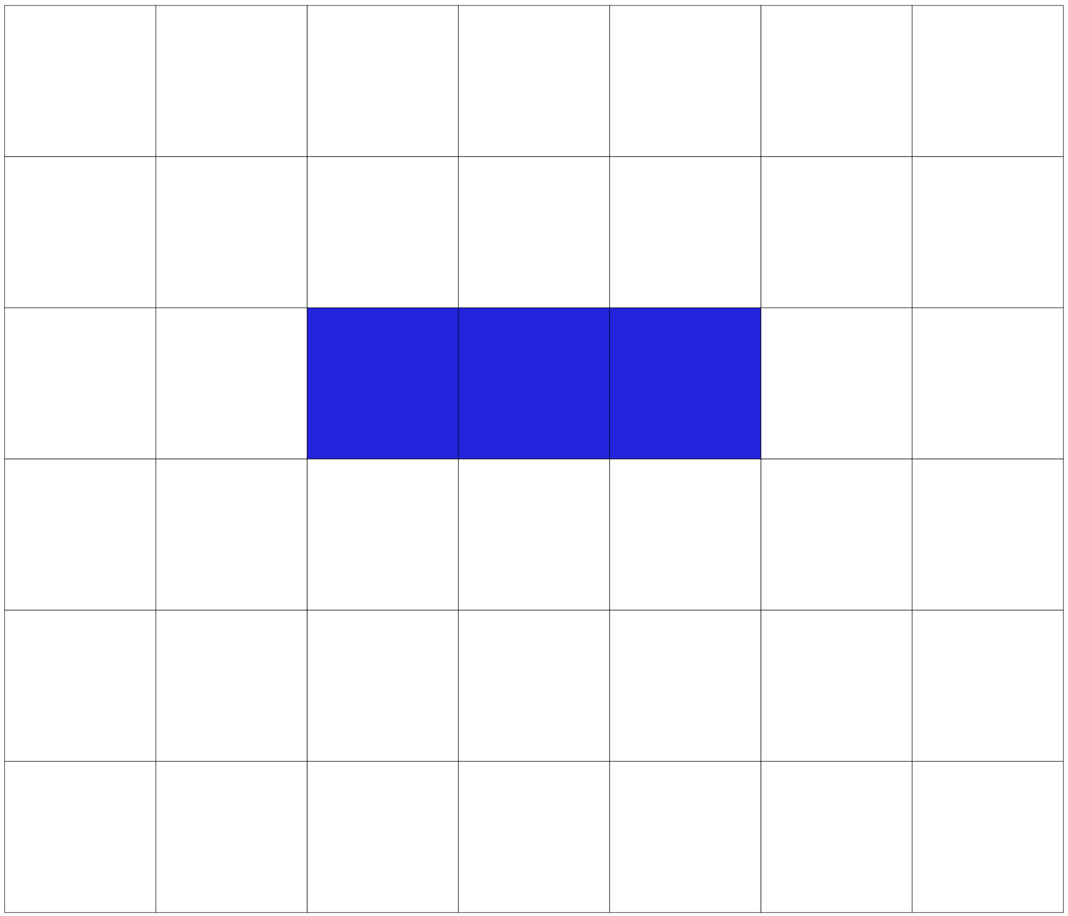
A cell survives with 2 or 3 neighbors.

A cell is born if it has 3 neighbors.

Both cells die out.

Conway's Game of Life

time step t

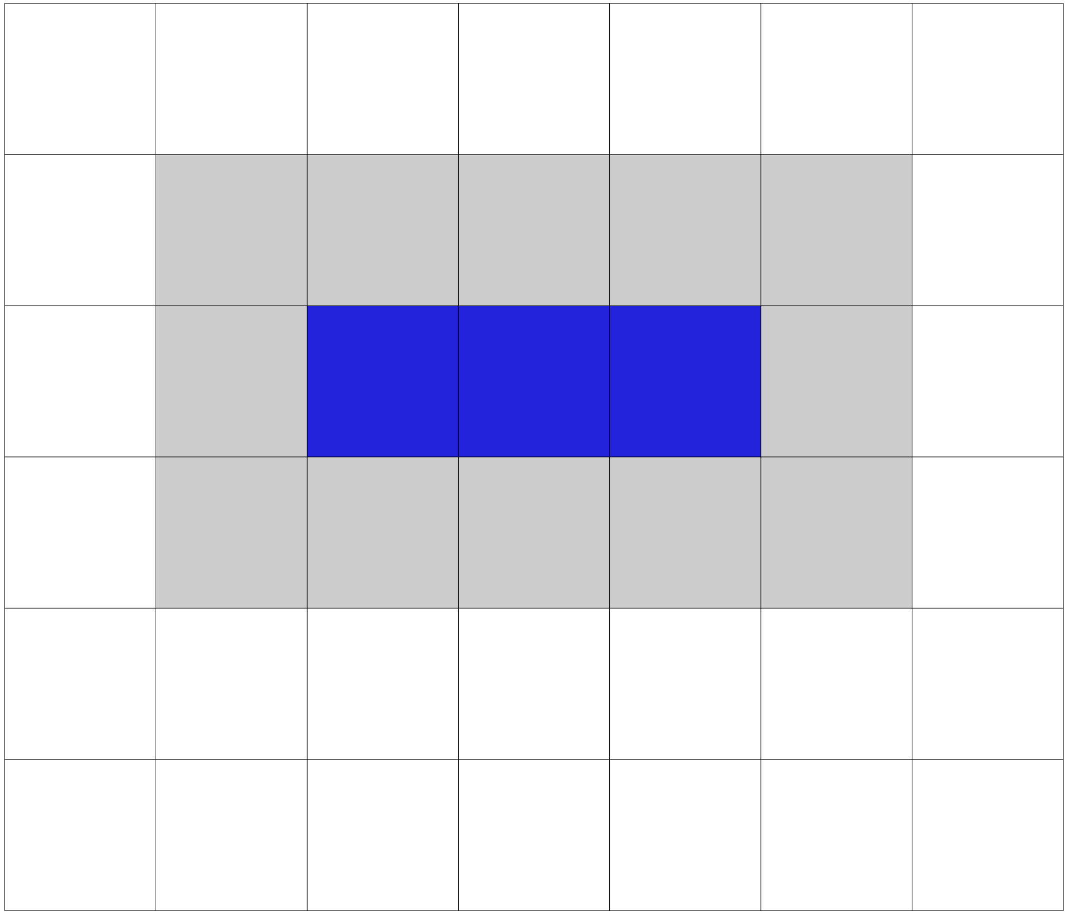


Rule: 23/3

A cell survives with
2 or 3 neighbors.

A cell is born if it has 3
neighbors.

Conway's Game of Life



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A cell survives with
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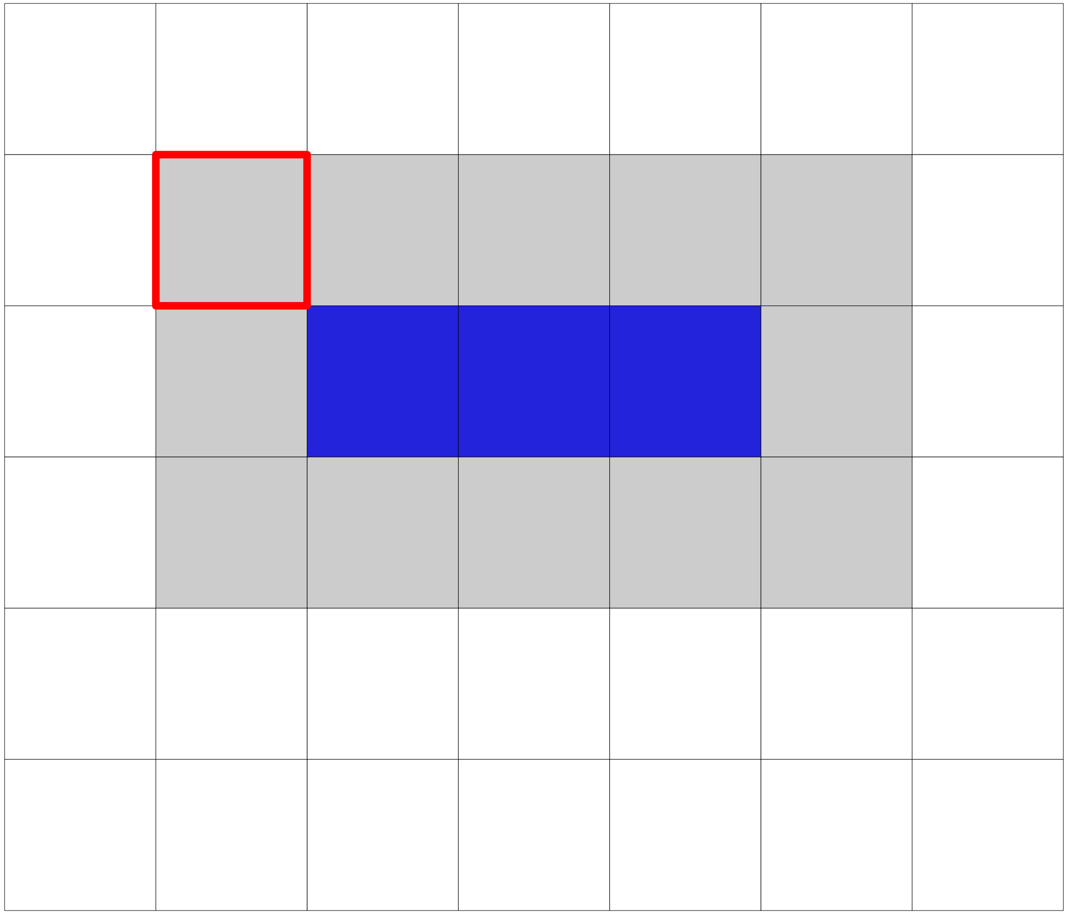
Conway's Game of Life



Rule: 23/3

A cell survives with
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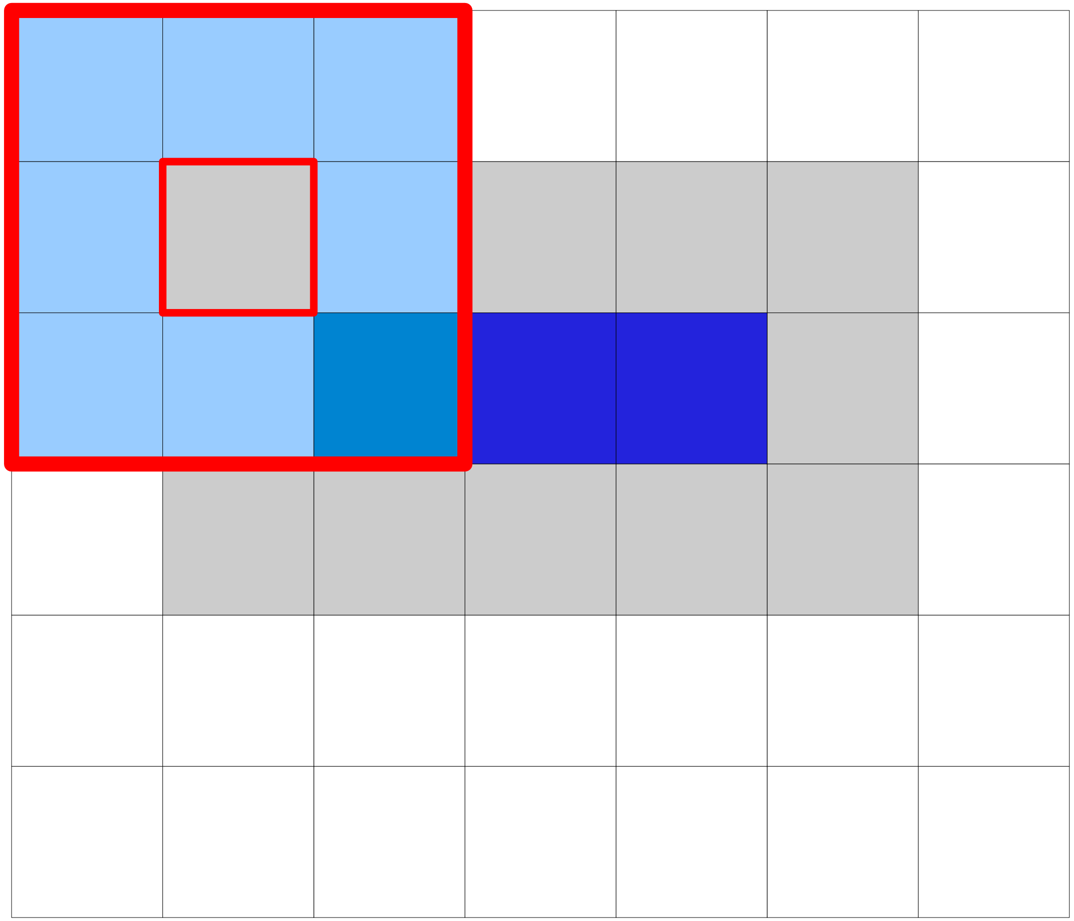
A cell is born if it has 3 neighbors.

Conway's Game of Life



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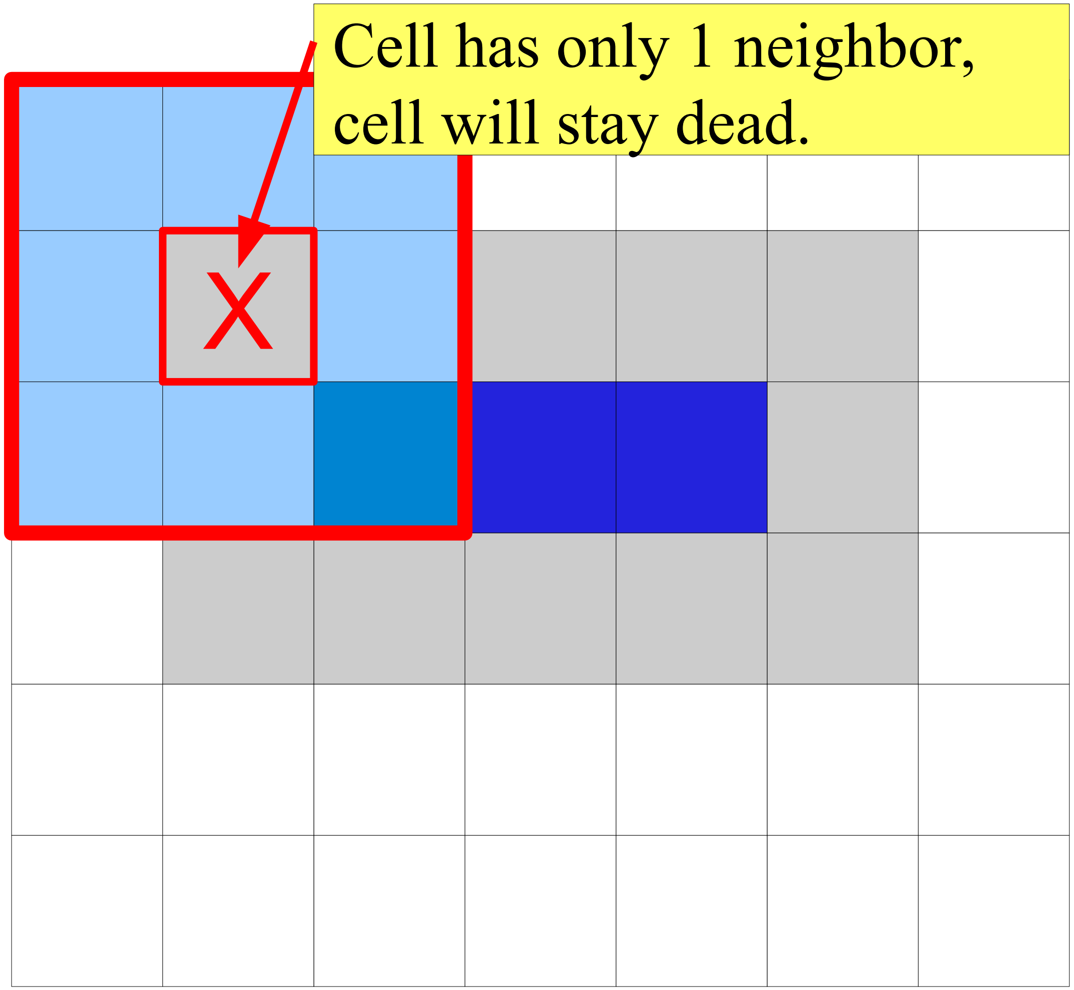
A cell is born if it has 3 neighbors.

Conway's Game of Life



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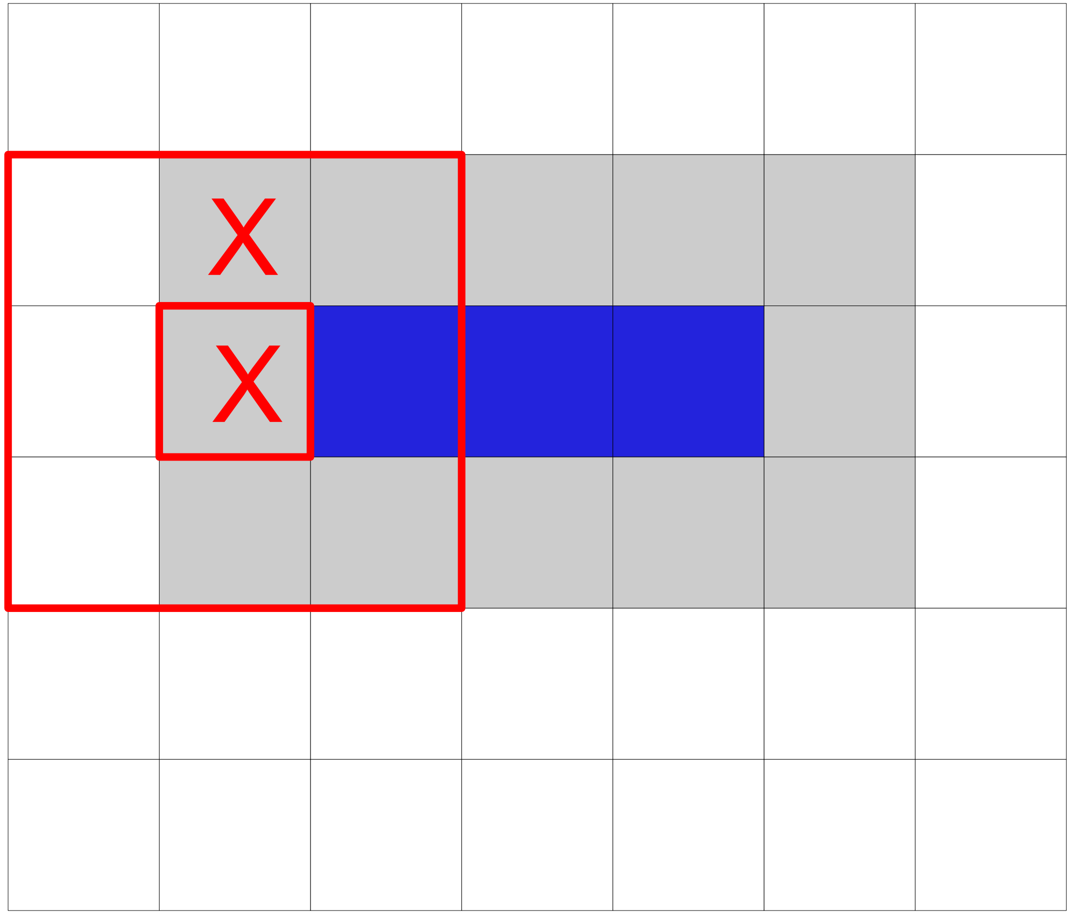
A cell is born if it has 3 neighbors.

Conway's Game of Life



Rule: 23/3

A cell survives with
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A cell is born if it has 3
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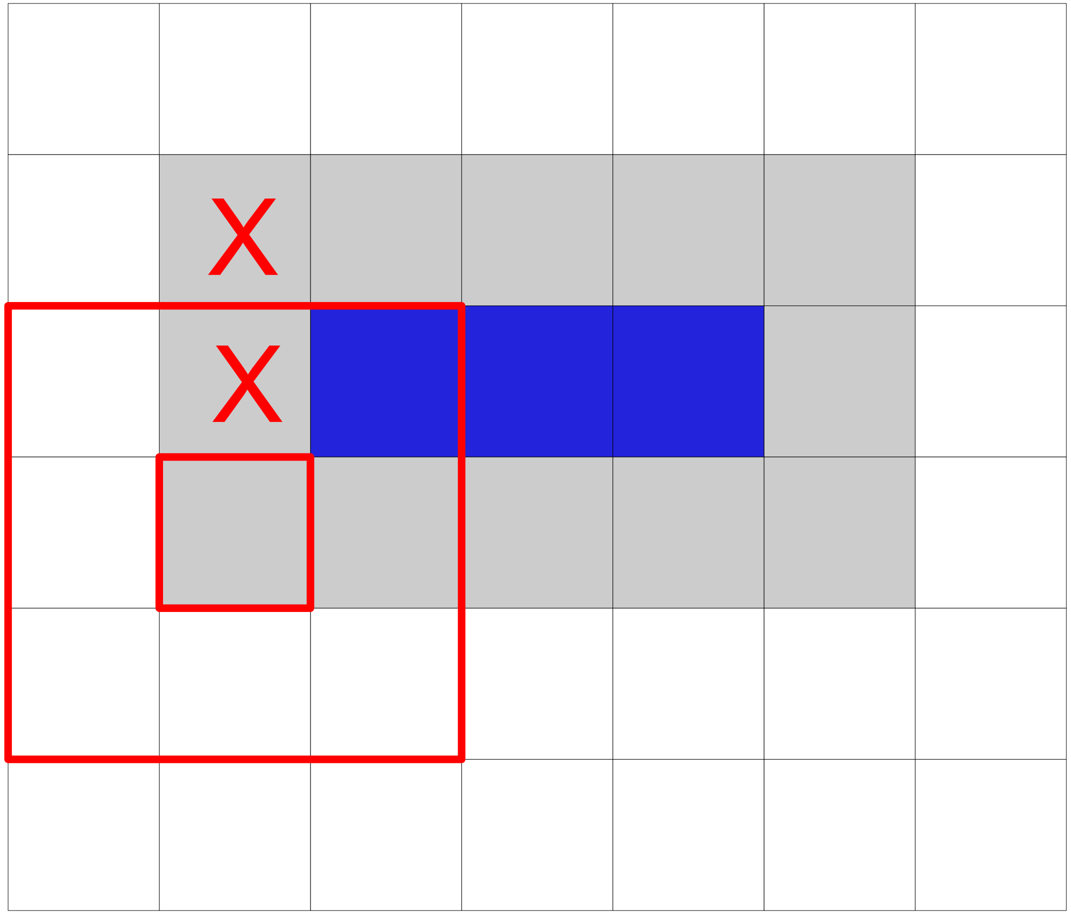
Conway's Game of Life



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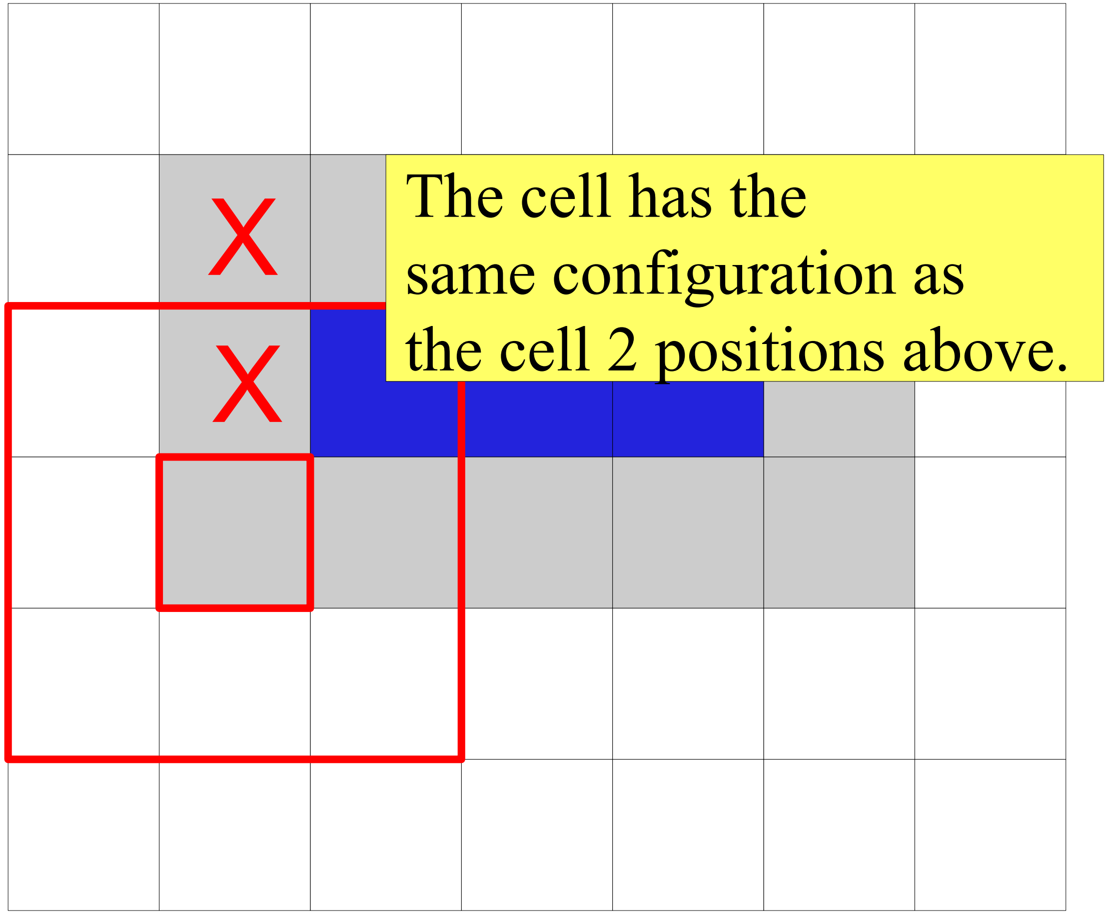
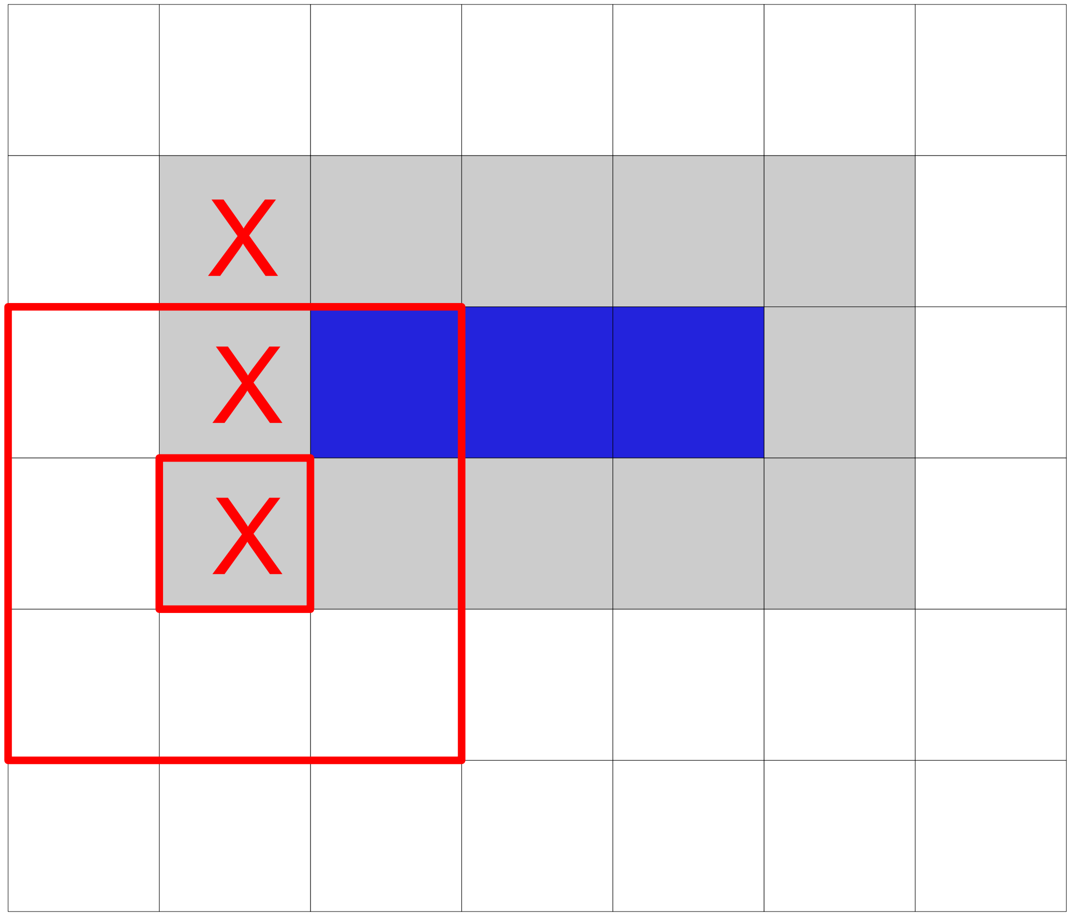


Rule: 23/3

A cell survives with 2 or 3 neighbors.

A cell is born if it has 3 neighbors.

Conway's Game of Life

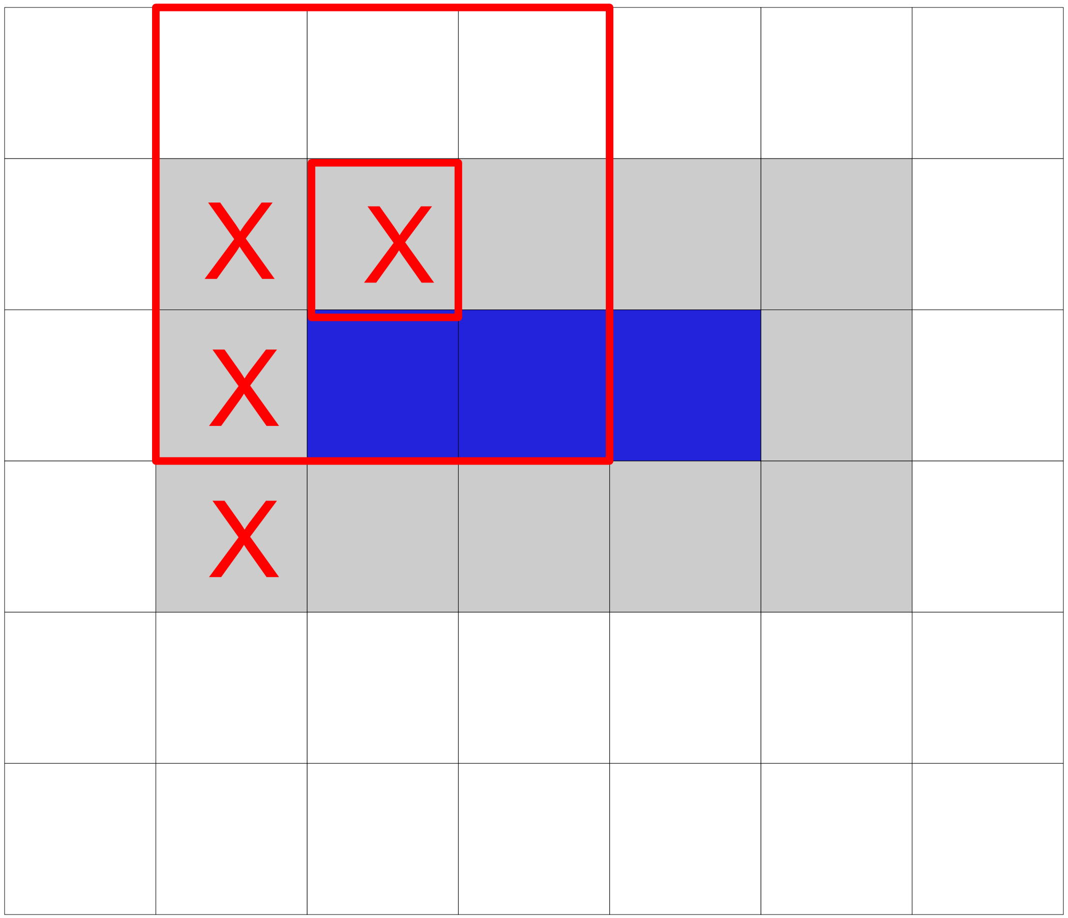


Rule: 23/3

A cell survives with 2 or 3 neighbors.

A cell is born if it has 3 neighbors.

Conway's Game of Life



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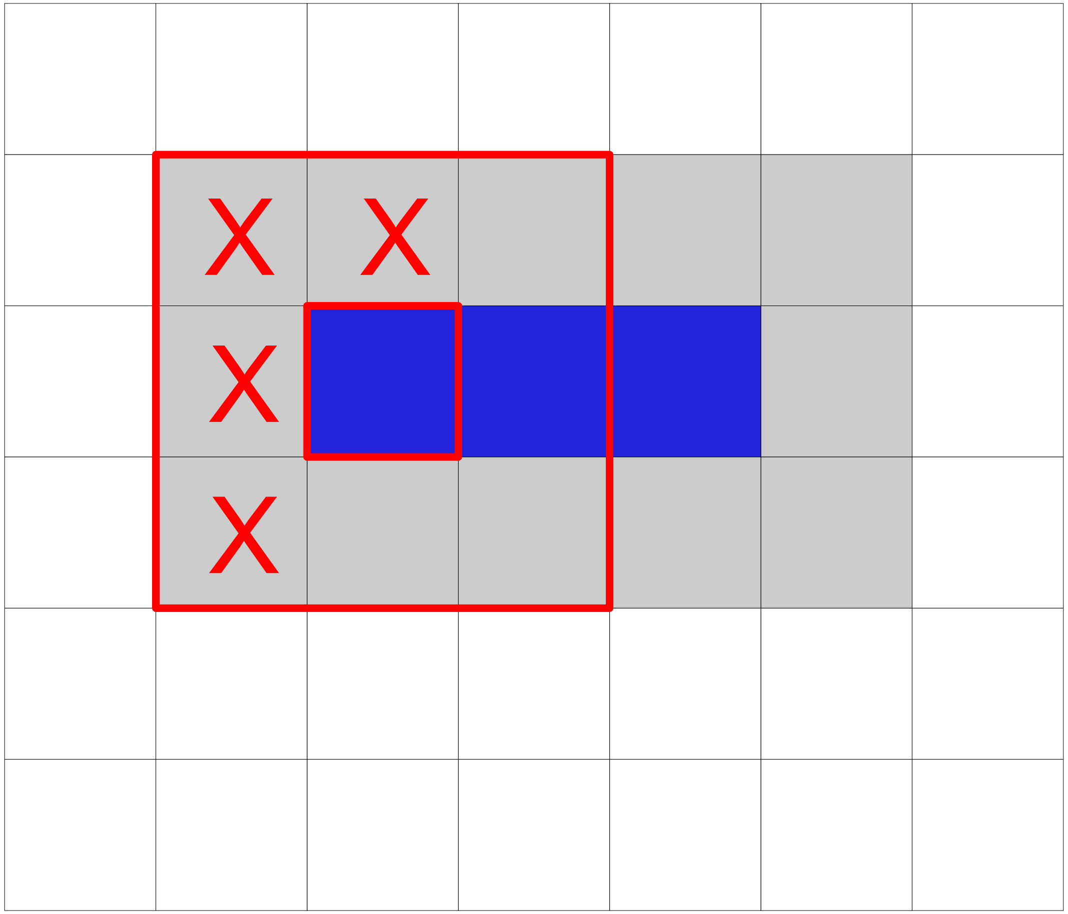

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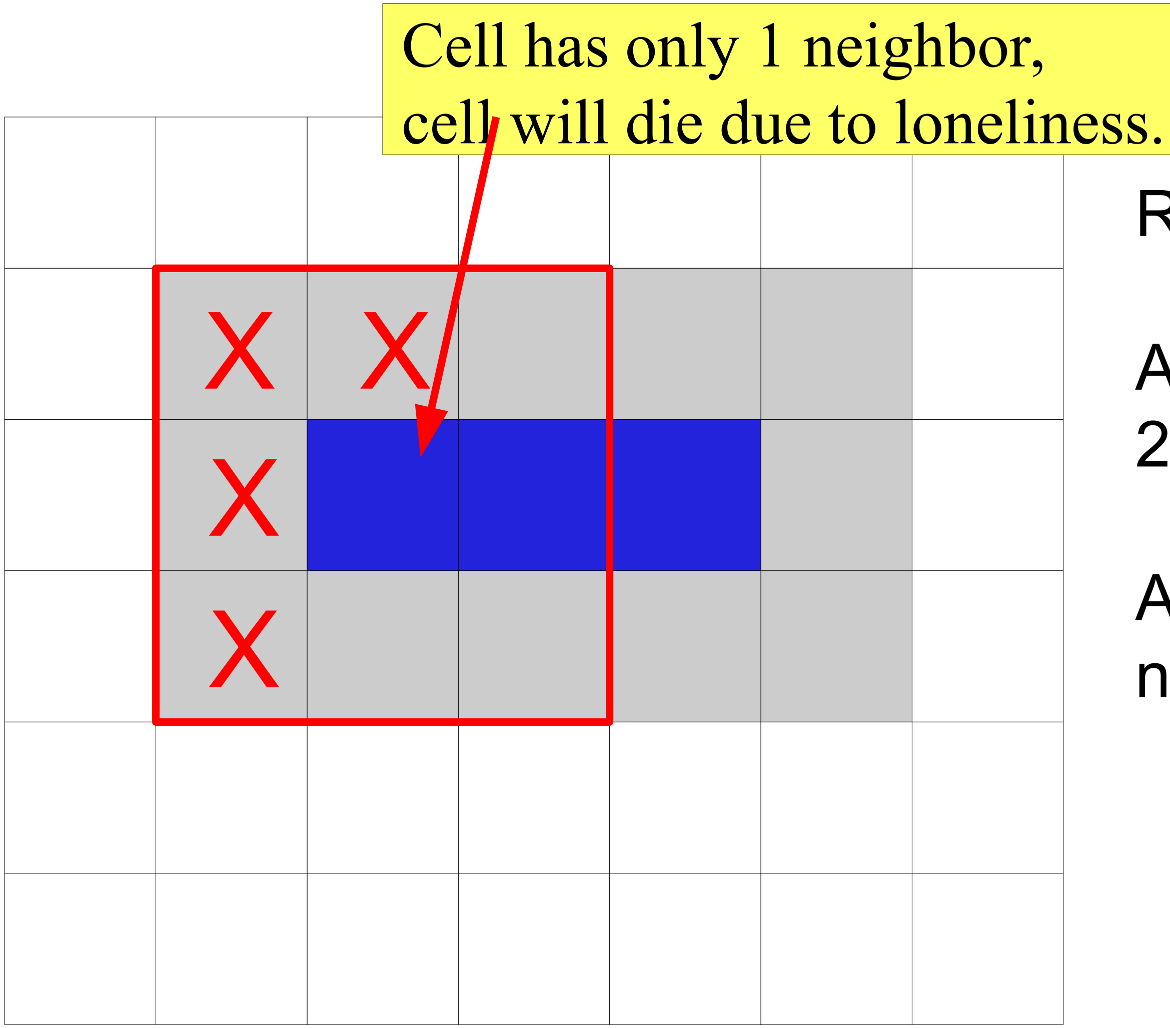

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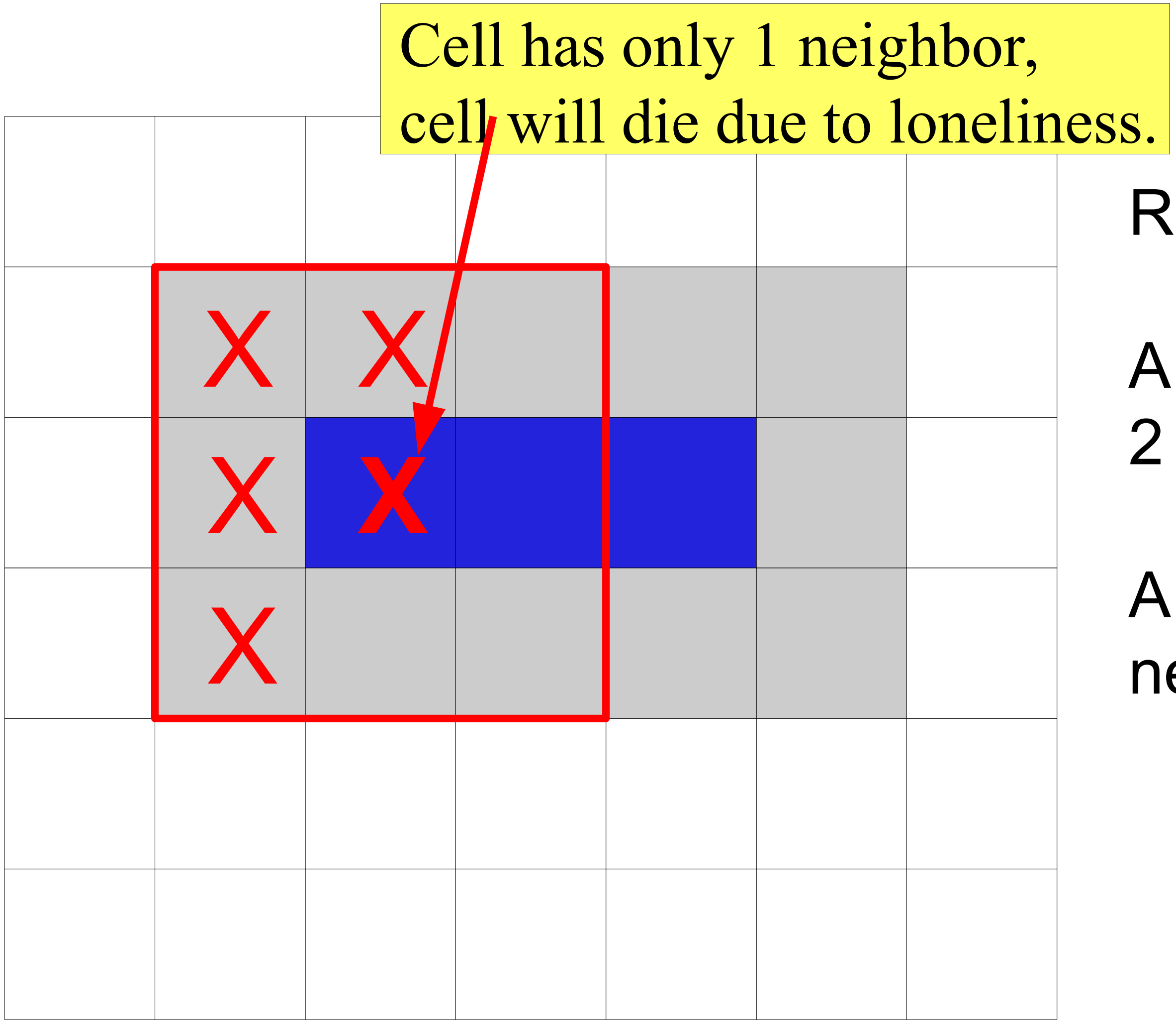
Conway's Game of Life



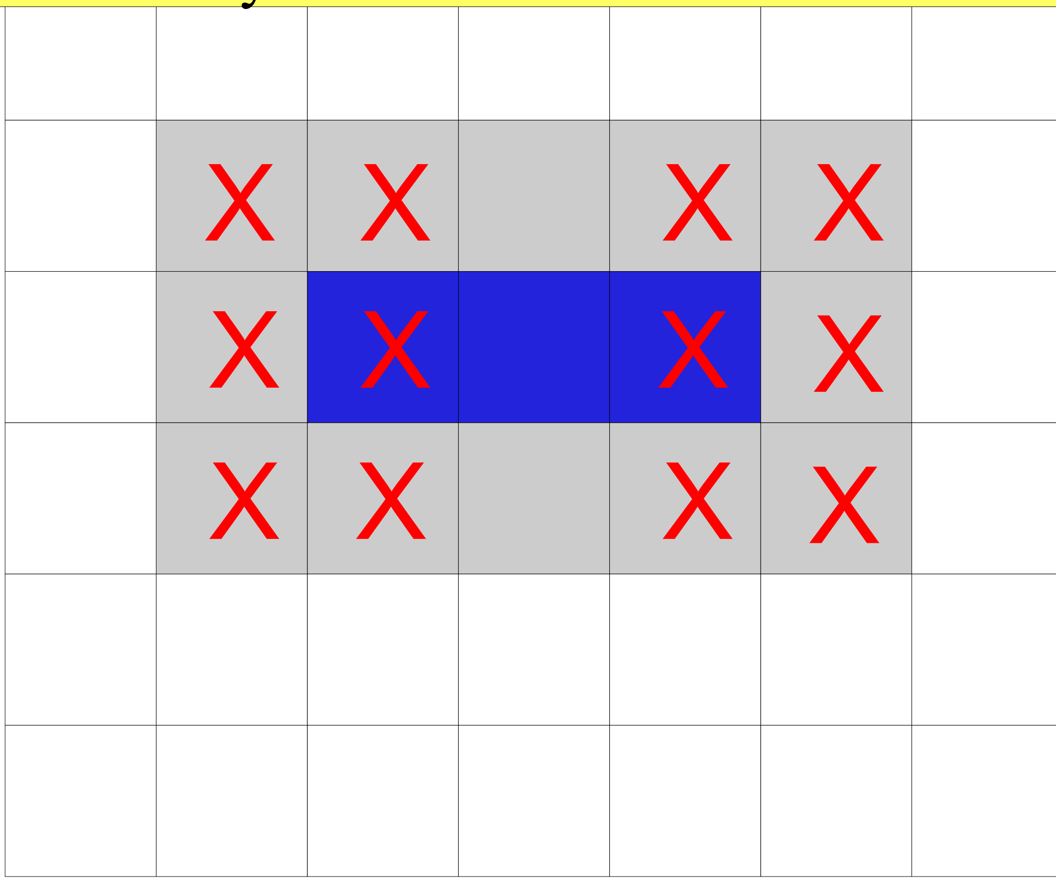
Rule: 23/3

A cell survives with 2 or 3 neighbors.

A cell is born if it has 3 neighbors.

Conway's Game of Life

Since the rule is symmetric,
we directly have the state of these other cells.



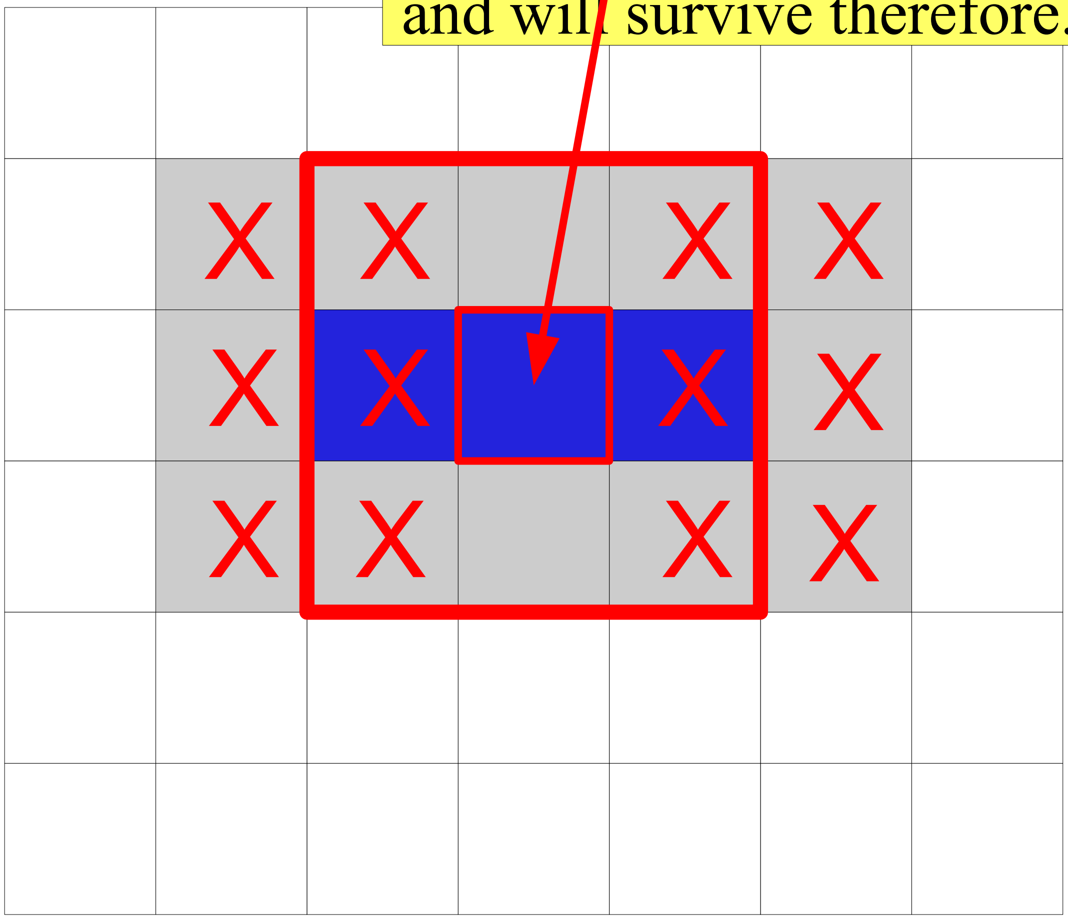
Rule: 23/3

A cell survives with 2 or 3 neighbors.

A cell is born if it has 3 neighbors.

Conway's Game of Life

The central cell has 2 neighbors,
and will survive therefore.

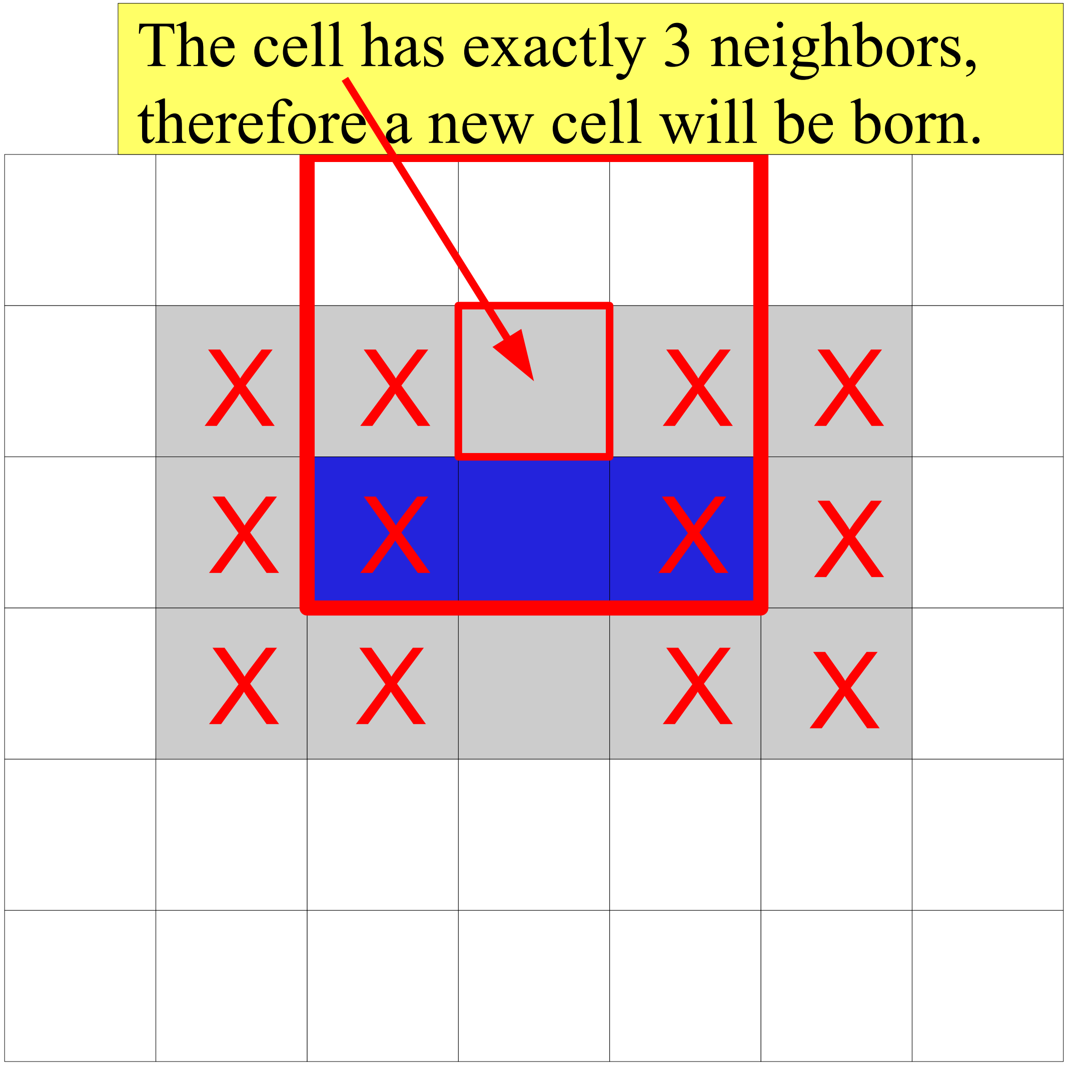


Rule: **2**3/3

A cell **survives** with
2 or 3 neighbors.

A cell is born if it has 3 neighbors.

Conway's Game of Life

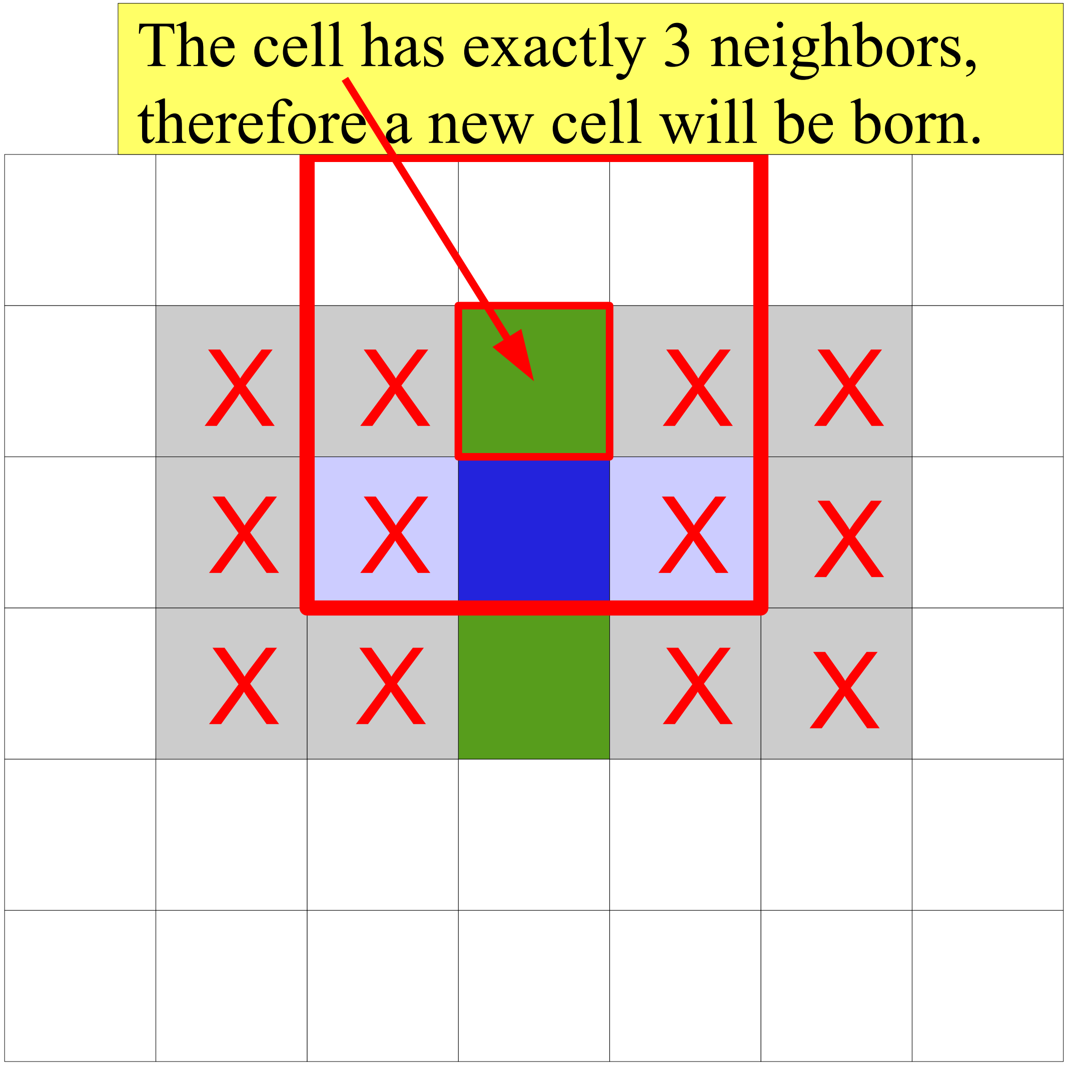


Rule: 23/**3**

A cell survives with 2 or 3 neighbors.

A cell is **born** if it has **3** neighbors.

Conway's Game of Life



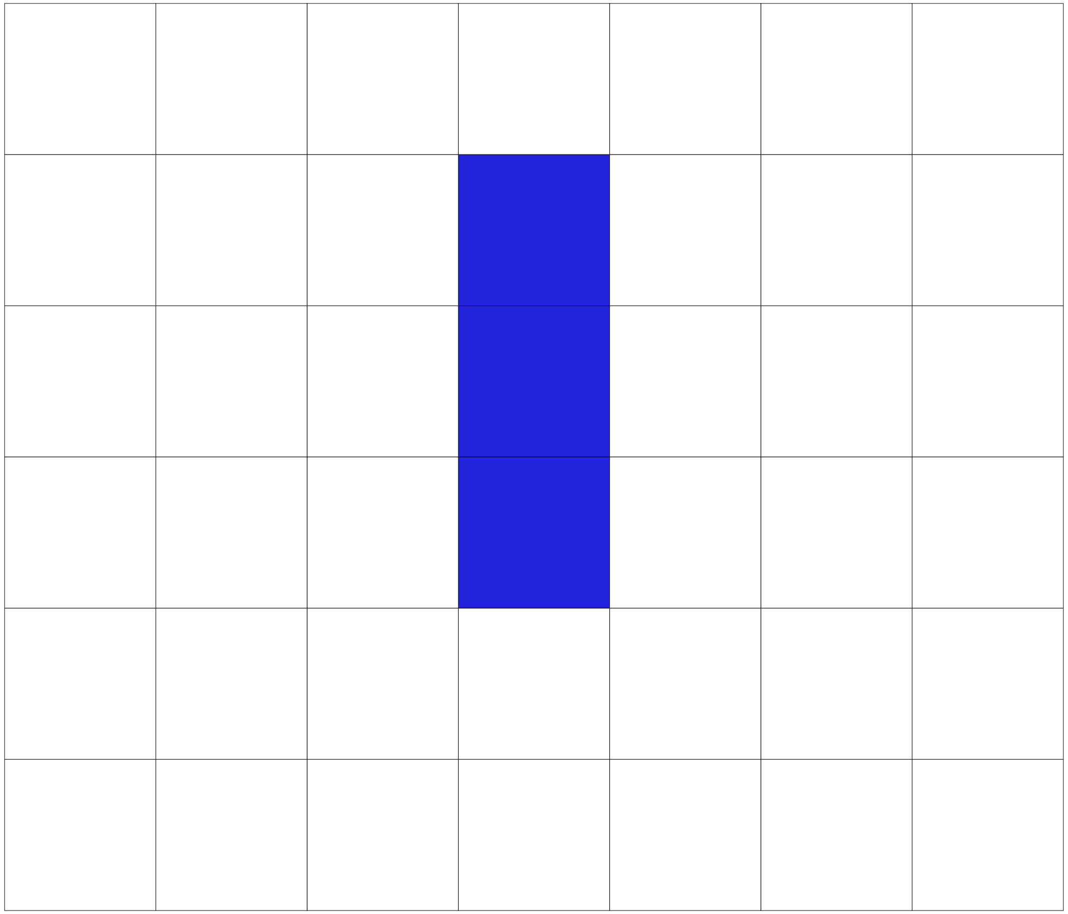
Rule: 23/**3**

A cell survives with
2 or 3 neighbors.

A cell is **born** if it has **3** neighbors.

Conway's Game of Life

time step t+1



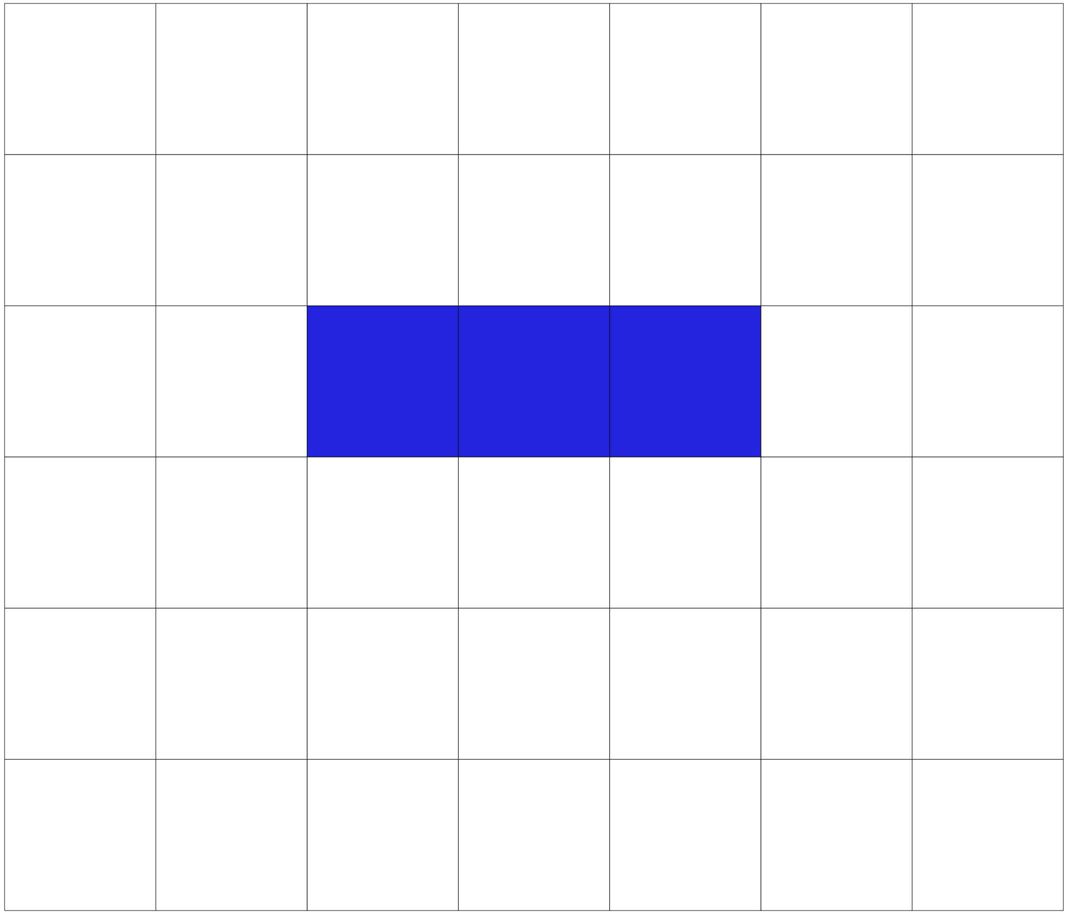
Rule: 23/3

A cell survives with
2 or 3 neighbors.

A cell is born if it has 3
neighbors.

Conway's Game of Life

time step t+2 has the same pattern as time step t



Rule: 23/3

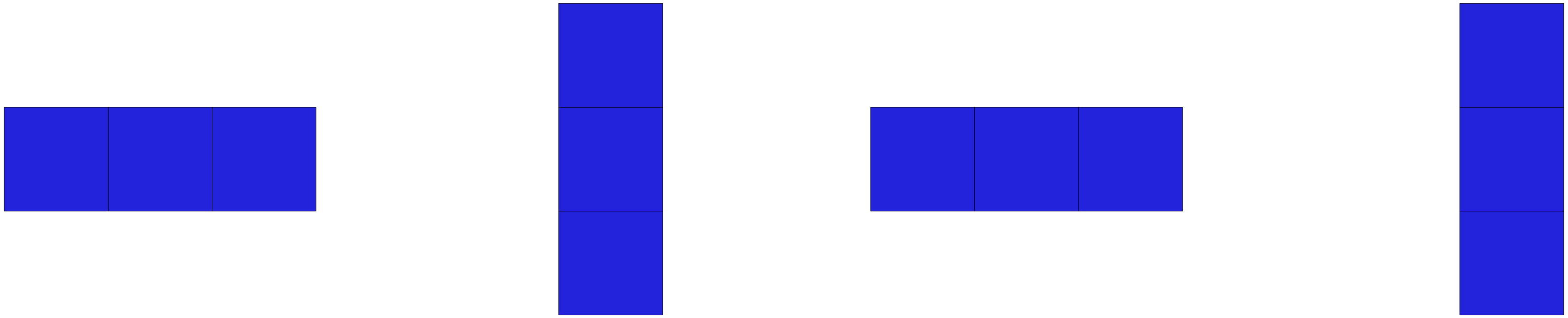
A cell survives with
2 or 3 neighbors.

A cell is born if it has 3
neighbors.

Conway's Game of Life

Three cells in a row, in Conway's Game of Life yield a periodic structure, oscillating with period 2, called: **Blinker**

It is the archetype of a ***periodic class II*** behavior.

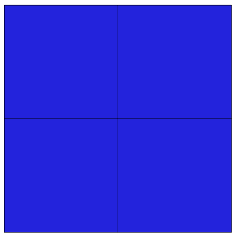


time step t t+1 t+2 t+3

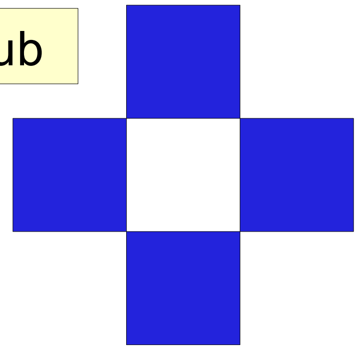
Conway's Game of Life

Examples of stationary **class II** patterns:

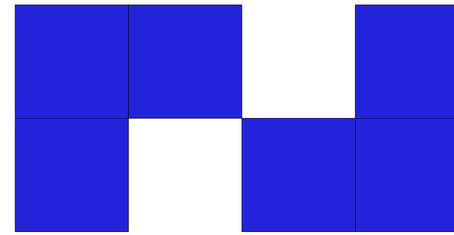
Block



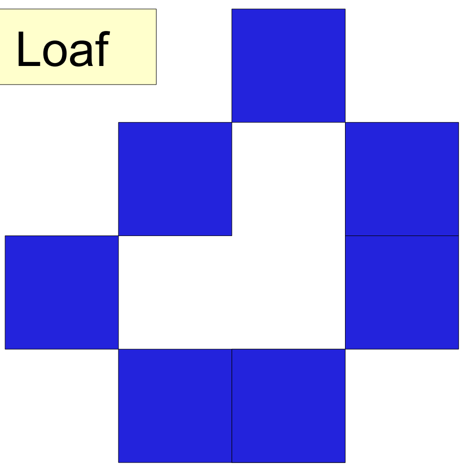
Tub



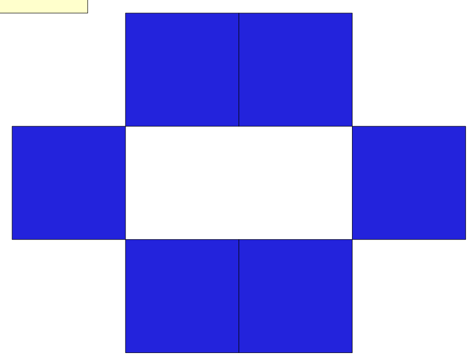
Snake



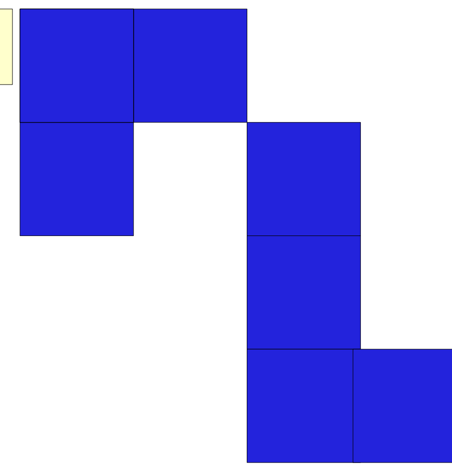
Loaf



Hive

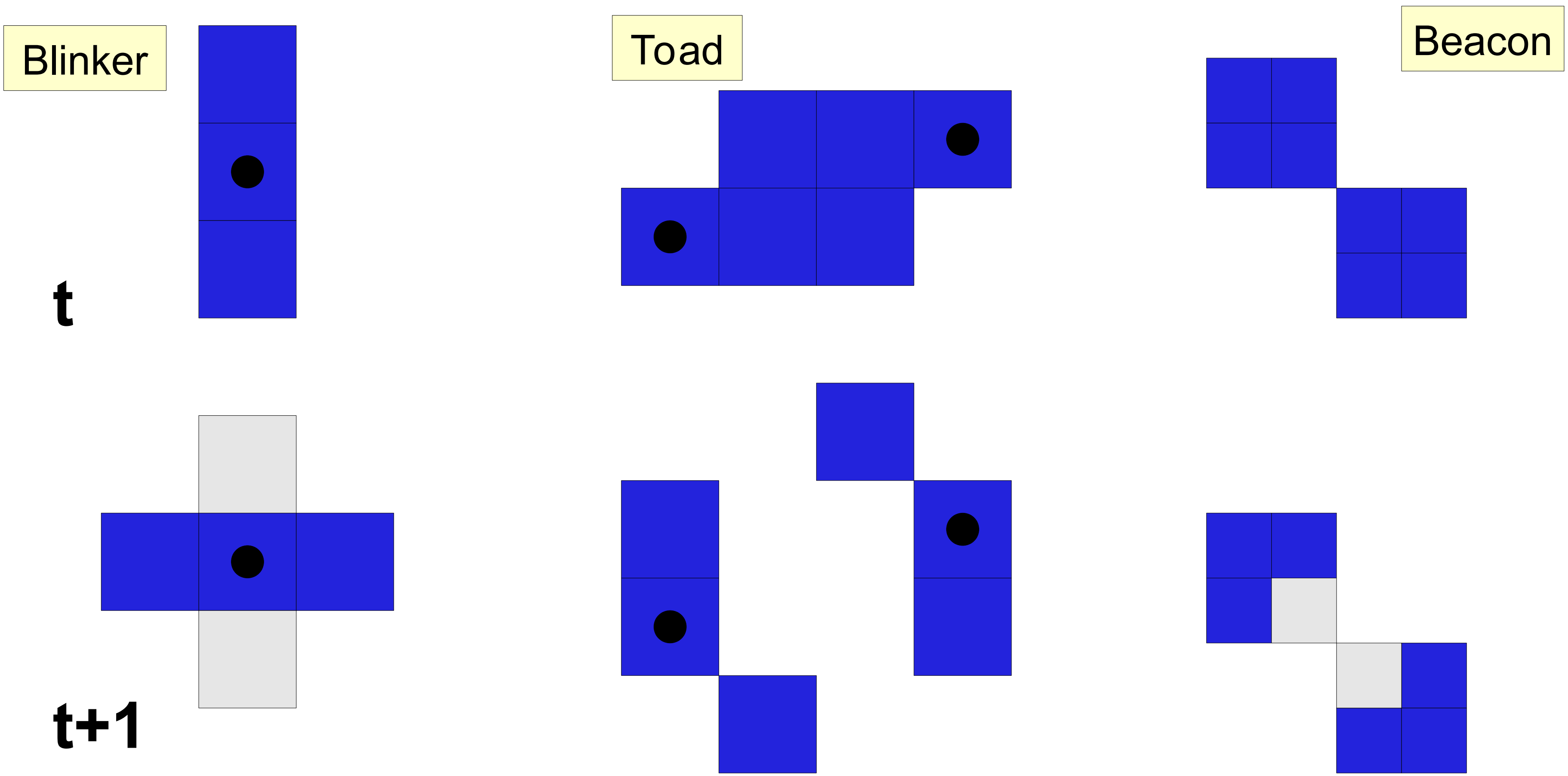


Hook



Conway's Game of Life

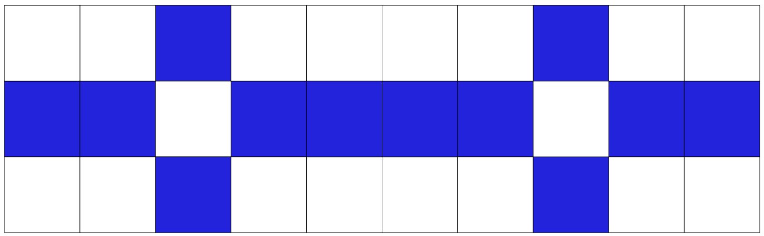
Examples of oscillating **class II** patterns,   period 2

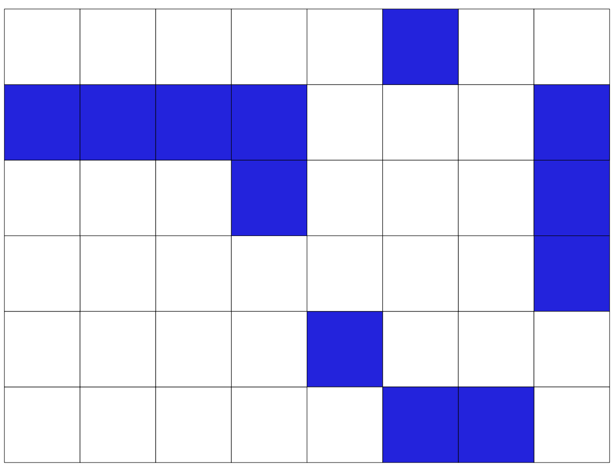


Conway's Game of Life

Examples of **class II** oscillators.

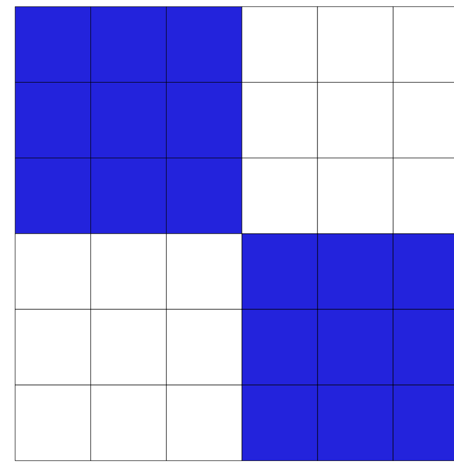
Pentadecathlon (p15)





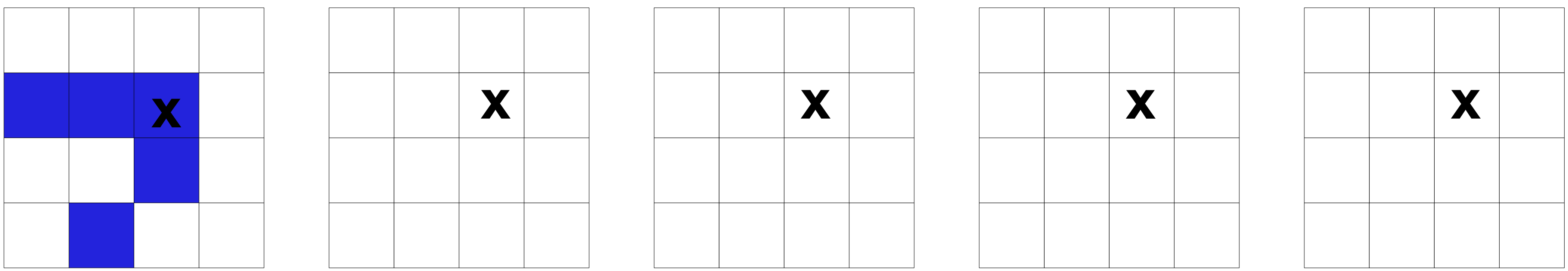
Caterer (p3)
smallest oscillator known
that has period 3

Eight (p8)



Conway's Game of Life

A special Game of Life pattern became very famous:
it is reproducing it's shape in 4 steps.



t t +1 t +2 t +3 t +4

Conway's Game of Life

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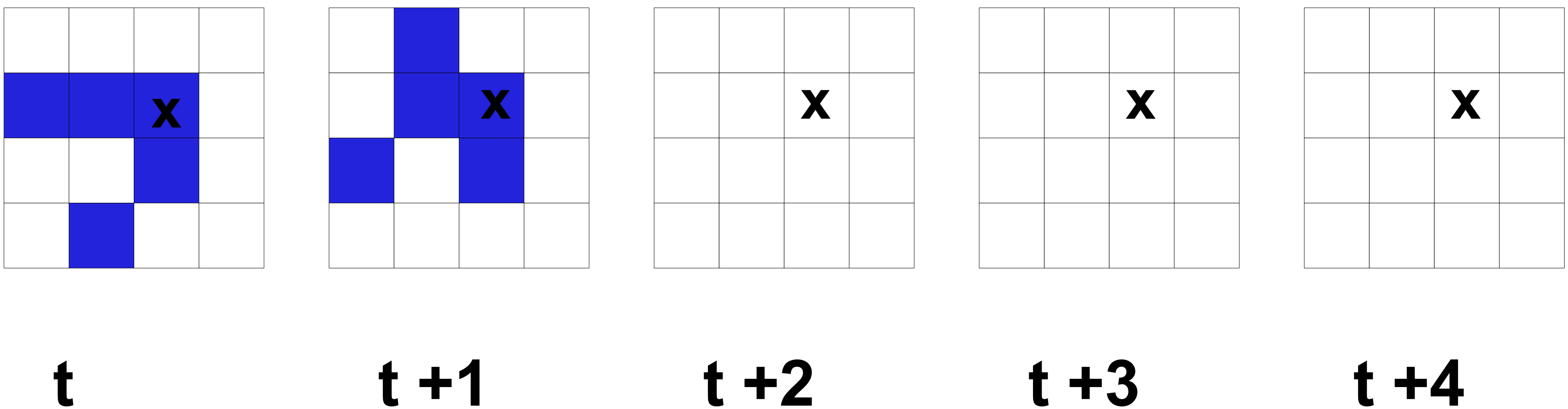

Conway's Game of Life

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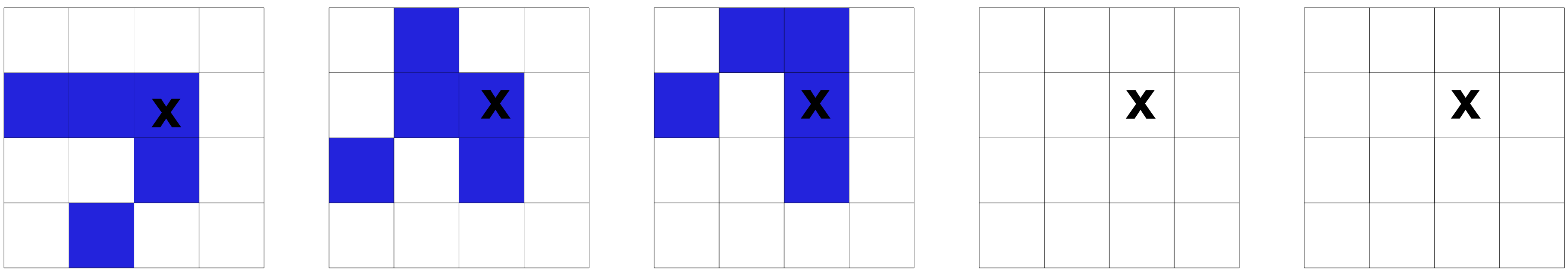

t   t +1   t +2   t +3   t +4

Conway's Game of Life

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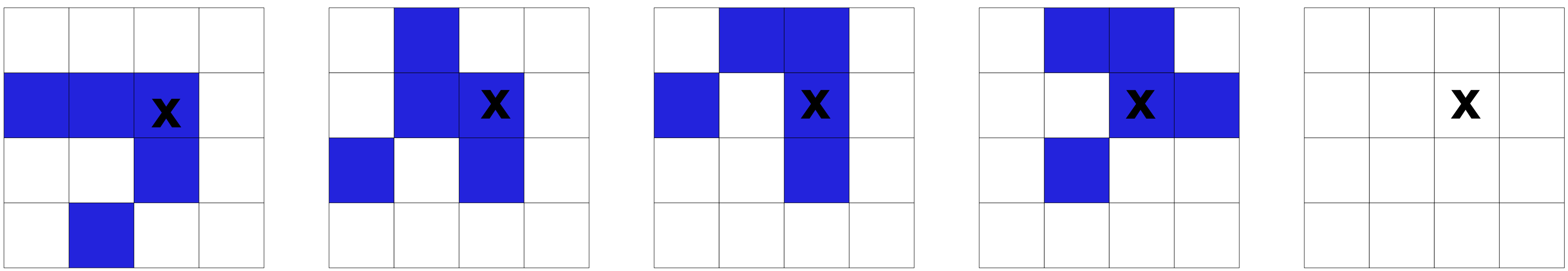

t **t +1** **t +2** **t +3** **t +4**

Conway's Game of Life

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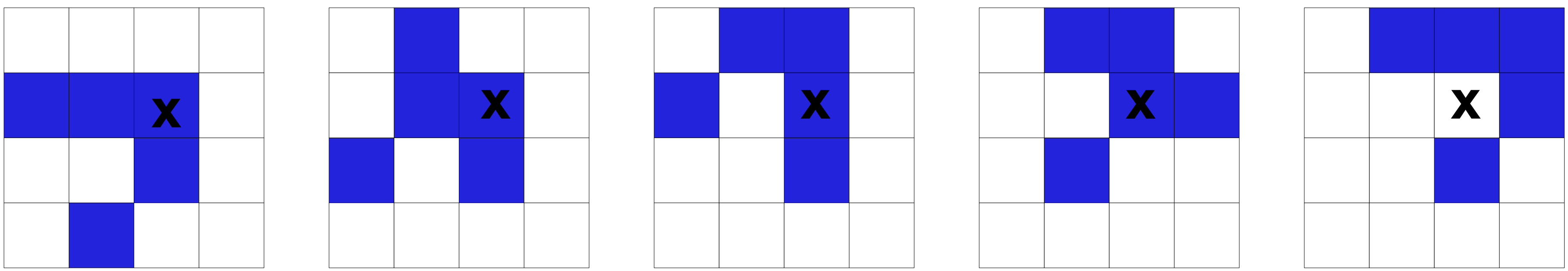
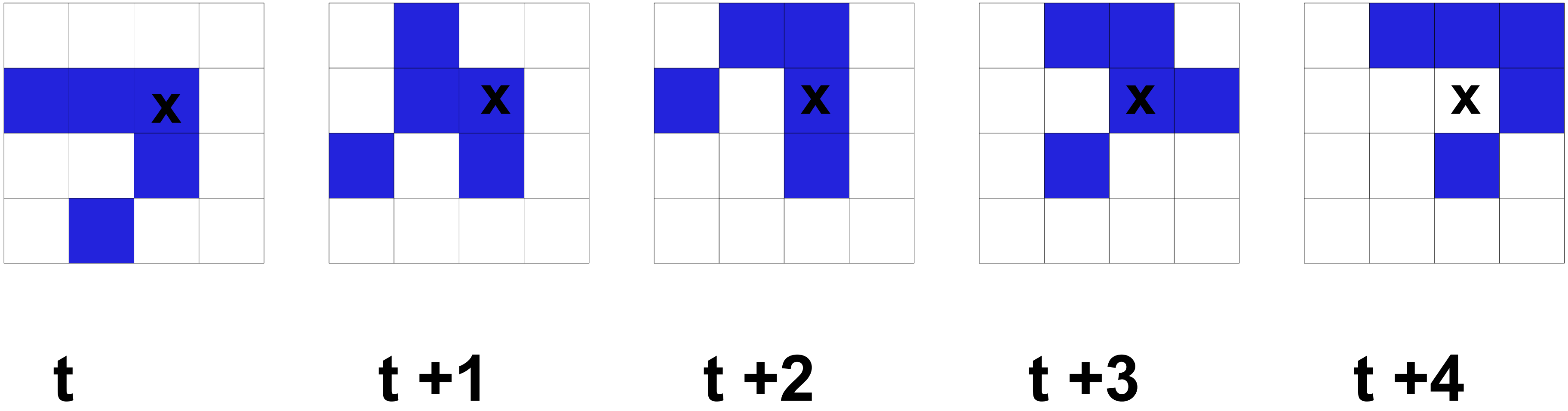


t **t +1** **t +2** **t +3** **t +4**

Conway's Game of Life

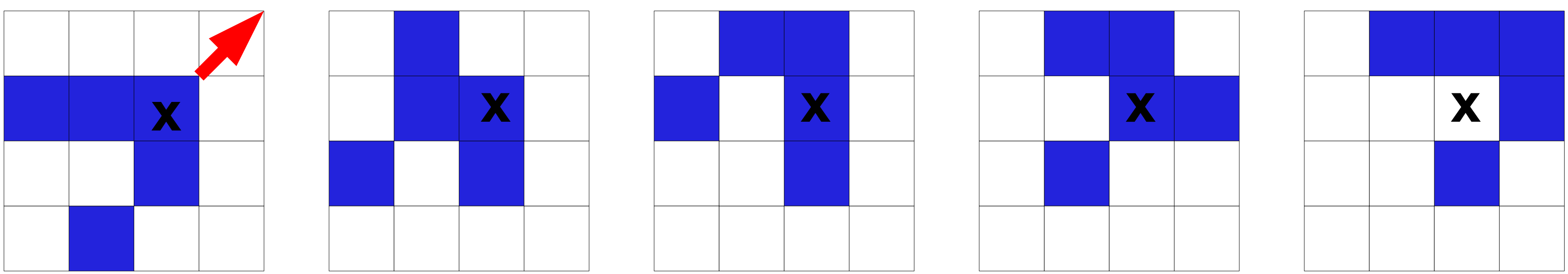
A special Game of Life pattern became very famous:
it is reproducing it's shape in 4 steps.
Please notice: although the exact shape is reproduced, the pattern is **NOT** periodic.



Conway's Game of Life: *Glider*

This pattern is called ***Glider***:

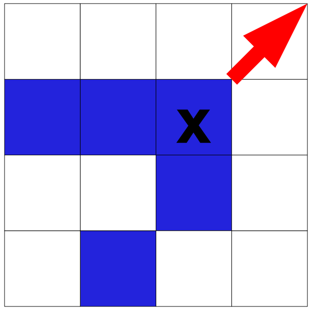
- the ***Glider*** is a prototypic **class IV** pattern
- a ***Glider*** consists of 5 living cells
- in 4 steps it moves one cell in diagonal direction.

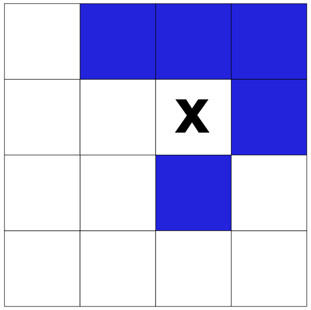


Conway's Game of Life: *Glider*

A ***Glider*** is moving over the underlying grid.
After 4 time steps the original shape is reconstructed in an adjacent position and all five cells have changed their state meanwhile.

*Would you consider it to be the **same** Glider ?*





Conway's Game of Life

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In 1970, Bill Gospers (a MIT mathematician) found such a pattern, and was rewarded by Conway with 50$.

Bill Gospers pattern is an oscillator, constantly changing it's shape, with a cycle length of 30 steps.
During each cycle, a 5 cell sub-structure is remaining.
The nice thing is, that this left over is a Glider.
Thus, every cycle a Glider is produced.

Conway's Game of Life: *Glidergun*

This structure is called: ***Glidergun***
It is composed by 4 elements, consisting of 36 cells in a 36X9 bounding box, cycle length 30 time steps.

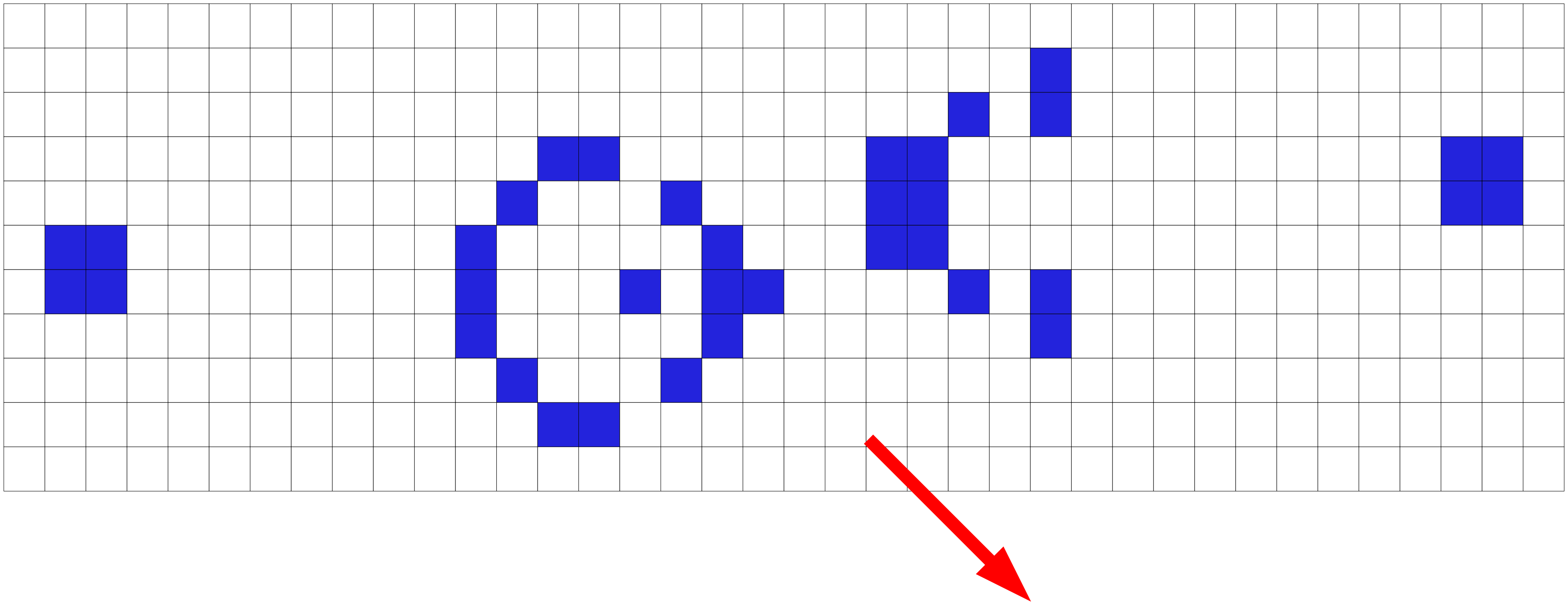
Two blocks, one on the left side, one on the right implement two stoppers, limiting the structure.

The two other elements approach each other, collide, turn around, and separate again. When they reach the stoppers they are reflected and the cycle starts over.

The collision produces the 5 cell remainder which is shaped like a glider. This ***Glider*** starts to move, and leaves the ***Glidergun.***

Conway's Game of Life: *Glidergun*

Glidergun by Bill Gosper, 36 cells, 36 x 9 bounding box.



This, Gosper Glidergun, is producing a glider leaving to the lower right every cycle (30 time steps).

Conway's Game of Life: *Glidergun*

Meanwhile, a wide variety of other ***Gliderguns*** have been found, invented or constructed with different characteristics like periodicity, size or type of gliders.
Research and development is still ongoing today.

A smart combination of simple Game of Life elements can be used to construct complex machineries.

Gliderguns are the *motors* of complex Game of Life constructions.
Streams of Gliders are the *information carriers* and the *tools* of Game of Life machineries.

Conway's Game of Life

Streams of Gliders can be regarded as information streams, a single Glider would be a single bit.

Gliders can interfere when they collide with other Gliders and with specially shaped structures.
Depending on the individual phase during the collision they can be erased, delayed, reflected or doubled.

By this means, it is possible to construct Game of Live structures that act as *Boolean gates*,
AND, OR, NOT, NAND, NOR, XOR, ...

Conway's Game of Life

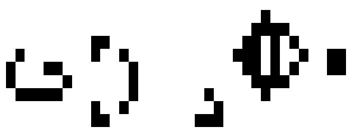
Whenever a Glider collides with an other Glider or with an other structure an intermediate cell structure arises.
This intermediate structure is of course undergoing further changes following the Game of Life rule.
The final result is typically hard to predict.

With a lot of effort and a lot of Game of Life experience it is possible to influence the shape of the remainder. Carefully arranged, the collision can yield a structure that is useful for further processing.

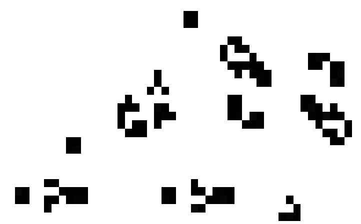
Colliding Gliders are the universal tools to construct and destroy other structures in Game of Life.

Conway's Game of Life: *Gliderguns*

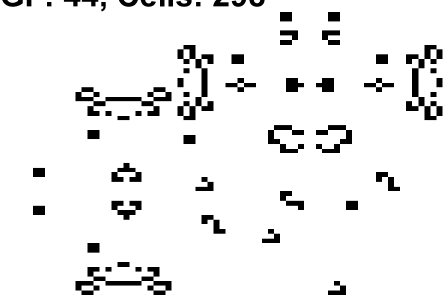
GF: 30, Cells: 54



GF: 144, *Cells: 132*



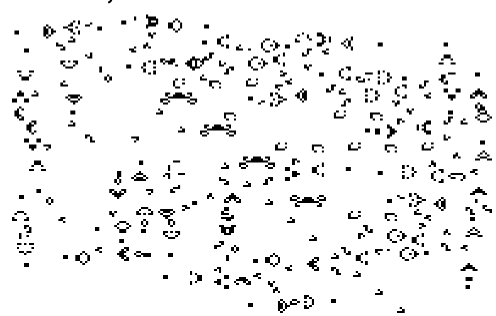
GF: 44, Cells: 298



GF: 570, Cells: 260

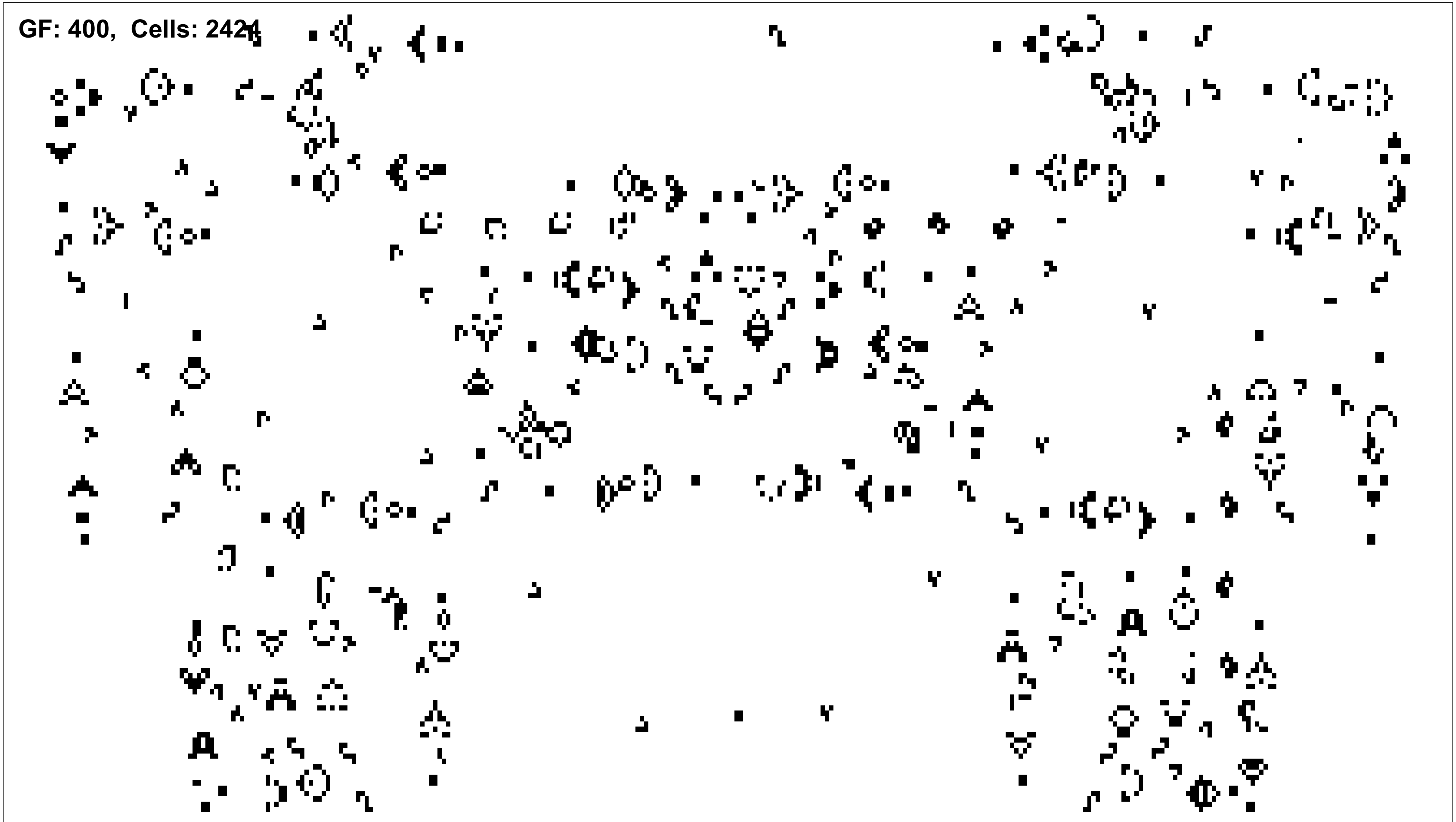
GF: 9990, Cells: 339

GF: 36, Cells: 1973



From: *http://www.radicaleye.com/lifepage/patterns/gunprev.html*

Conway's Game of Life: *Gliderguns*



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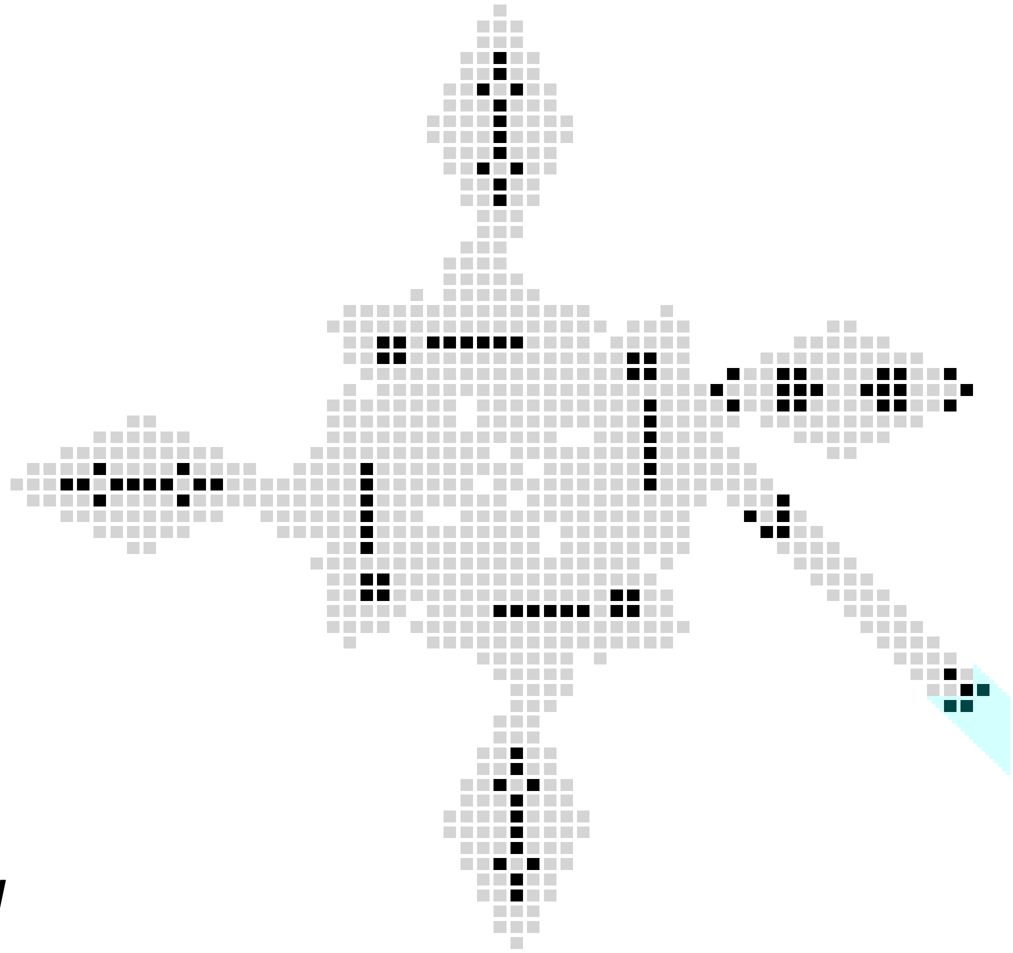
Conway's Game of Life: *Gliderguns*

The research on Game of Life structures is still ongoing:
e.g. in 29-April-2010 a new Glidergun has been published, with a 45 time step cycle.



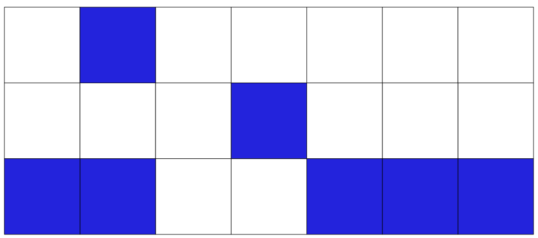
„Period 45 is currently the shortest known odd period for a true-period gun."

From: http://pentadecathlon.com/lifeNews/index.php

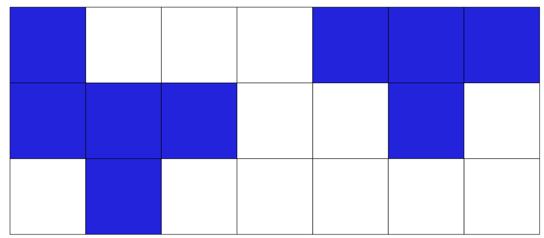
Conway's Game of Life

Long lasting patterns (Methuselah patterns)

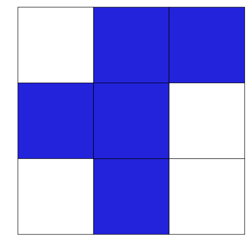
Acorn



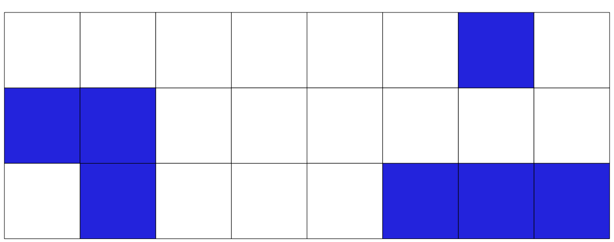
Rabbits



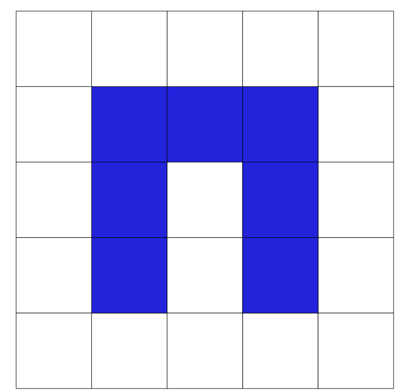
r-pentomino



Diehard



Pi-heptomino



Other Game of Life rules

Conway's Game of Live has the rule **23/3** or (**S23/B3**) with a cell **S**urviving if it has **2** or **3** neighbors, and a new cell is **B**orn having **3** neighbors.

There are other rules, that lead to interesting behavior:

2 / 3
3 / 3
13 / 3
23 / 3
34 / 3
35 / 3
236 / 3
135 / 35
1357 / 1357

Game of Life Simulators

A wide variety of simulation tools for Conway's Game of Life exist today for all typical computing architectures and operating systems, and most of them are freely available.

Some of them are accompanied with a large library of patterns.

Some of them are designed to simulate cellular automata, and “just” include Conways Game of Life.

The list on the next page is is neither complete, nor should it be considered as being a judgment;
these are just some of my personal favorites.

Game of Life Simulators

The list is neither complete, nor should it be considered as being a judgment; these are just my personal favorites.

Mirek's Cellebration, MCell 4.20
1D and 2D Cellular Automata explorer by Mirek Wojtowicz
http://psoup.math.wisc.edu/mcell/

Winlife32, Version 2.3
A system for manipulating Conway's Game of Life
http://www.winlife32.com/

Golly, Version 4.2 for Windows / Mac / Linux / Android / Web
An open source, cross-platform Game of Life Simulator
https://sourceforge.net/projects/golly/files/latest/download
http://www.macupdate.com/info.php/id/19622/golly

Overview:

- Cellular Automata in 2 dimensions
- Examples and Applications of CAs
- Conway's Game of Life
- **Computational Universality**
- Is Information == Structure ?

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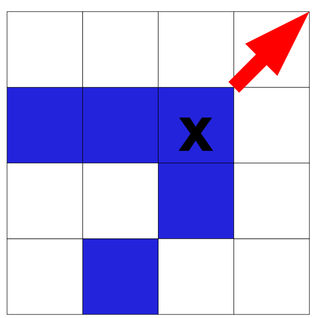

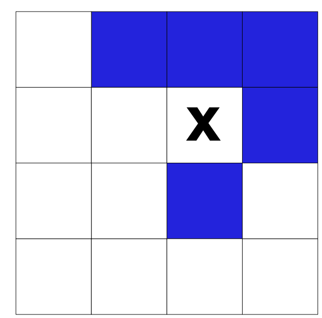

Next Thursday is 1st of May

Next Thursday is May 1st ,
which is a public holiday in Germany,
Thus, the shops will be closed,
restaurants will be open,
University will be closed (no lectures, seminars, labs).

There might be festivities or parties in the night from April 30 to May 1st .

And thus, **no Artificial Life exercise groups 1.5.25**.

Artificial Life
Summer 2025

Cellular Automata 2D
Conway's Game of Life

Master Computer Science [MA-INF 4201]
Mon 14c.t. – 15:45, HS-2

Dr. Nils Goerke, Autonomous Intelligent Systems,
Department of Computer Science, University of Bonn

Artificial Life
Summer 2025

Cellular Automata 2D
Conway's Game of Life

Thank you for your listening

Dr. Nils Goerke, Autonomous Intelligent Systems,
Department of Computer Science, University of Bonn