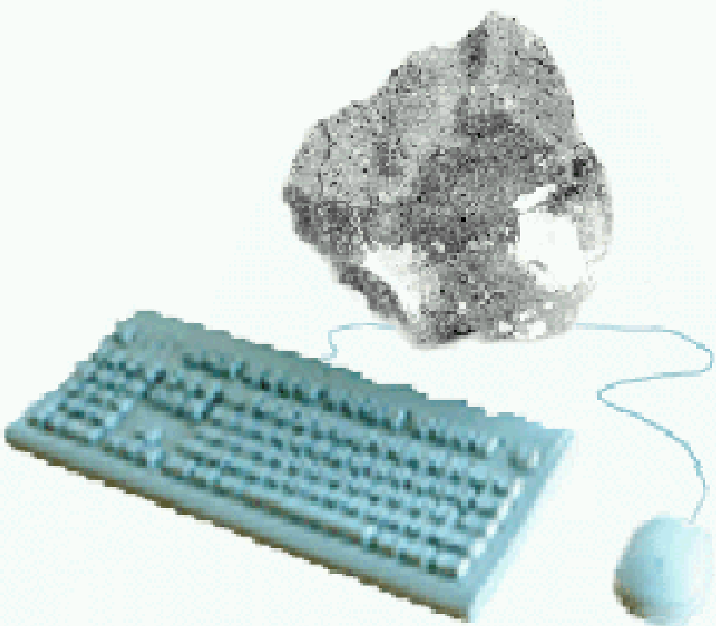
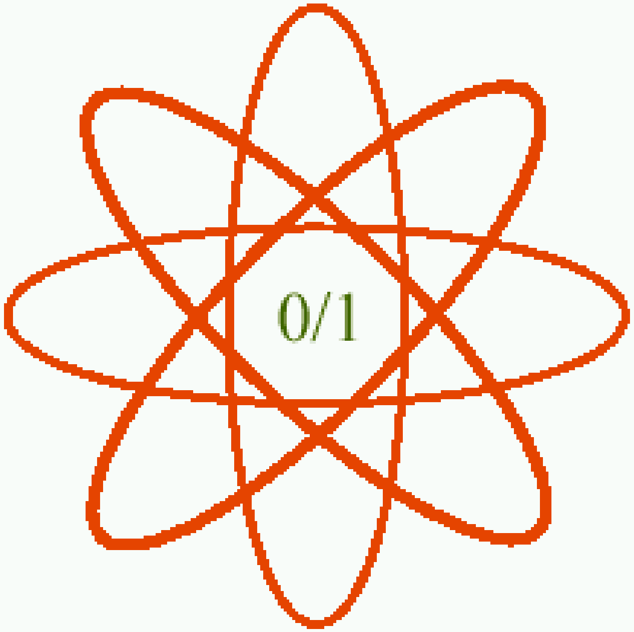
Computing Beyond Silicon Summer School

Physics becomes the computer



Norm Margolus

Physics becomes the computer



Emulating Physics

- » *Finite-state, locality, invertibility, and conservation laws*

Physical Worlds

- » *Incorporating comp-universality at small and large scales*

Spatial Computers

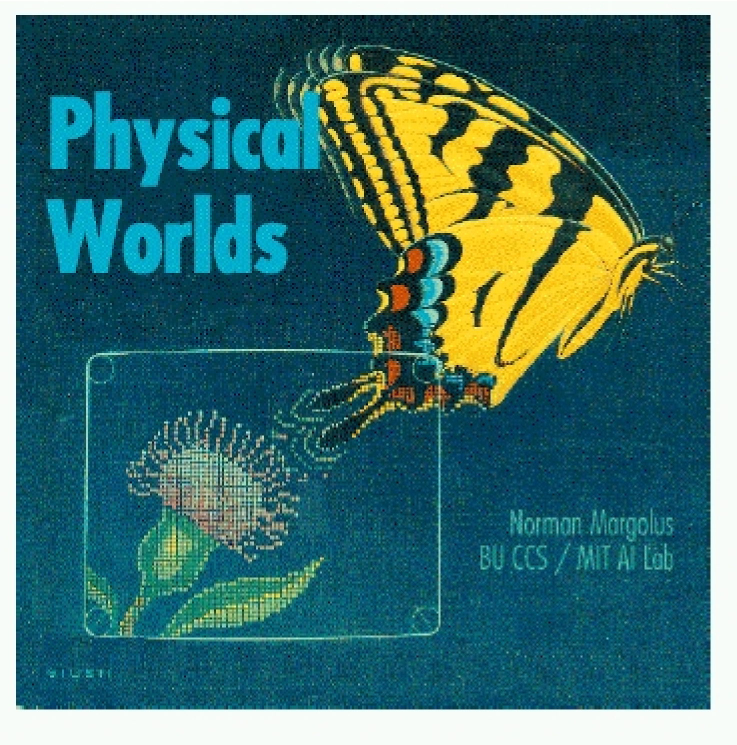
- » *Architectures and algorithms for large-scale spatial computations*

Nature as Computer

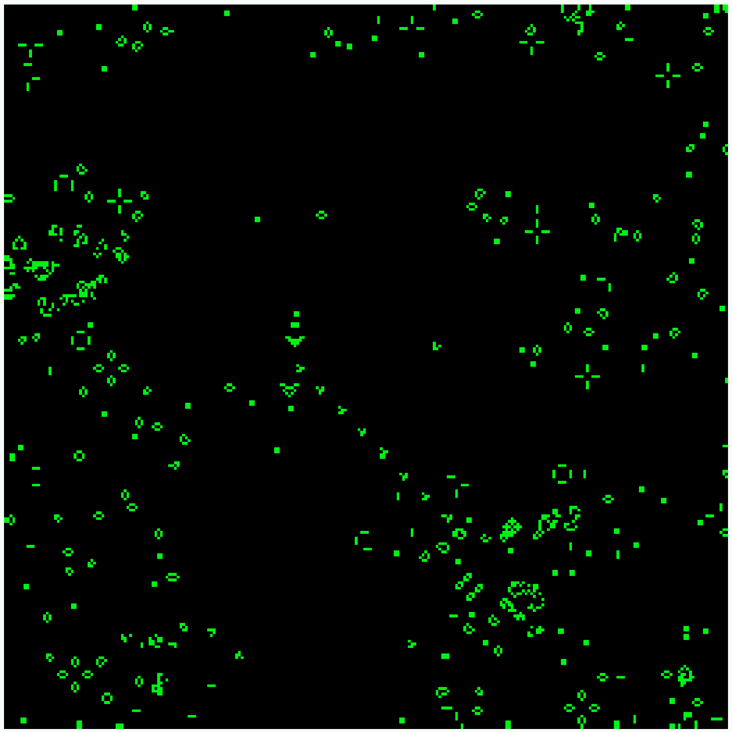
- » *Physical concepts enter CS and computer concepts enter Physics*

Emulating Physics

- **Why emulate physics?**
  - Computation models must adapt to microscopic physics
  - Computation models may help us understand nature
- Rich dynamics
- Start with locality:
  - *Cellular Automata*

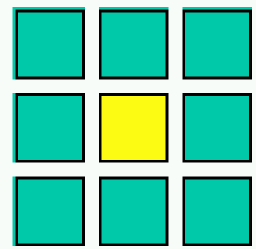


Conway's "Game of Life"



256x256 region of a larger grid. Glider gun inserted near middle.

In each 3x3 neighborhood, count the ones, not including the center:

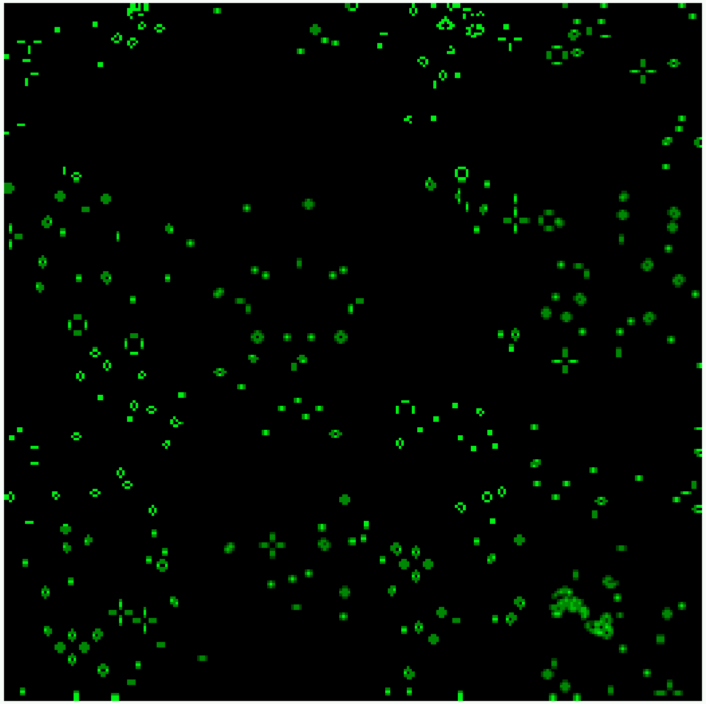


If total = 2: center unchanged

If total = 3: center becomes 1

Else: center becomes 0

Conway's "Game of Life"



256x256 region of a larger grid. About 1500 steps later.

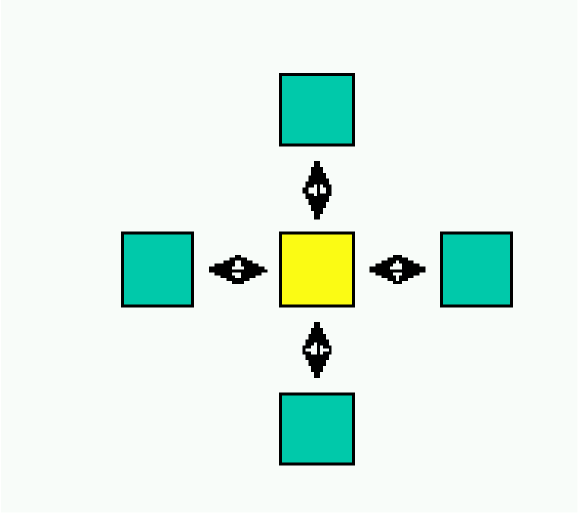
- Captures physical locality and finite-state

But,

- Not reversible (doesn't map well onto microscopic physics)
- No conservation laws (nothing like momentum or energy)
- No interesting large-scale behavior

Reversibility & other conservations

- Reversibility is **conservation of information**
- Why does exact conservation seem hard?



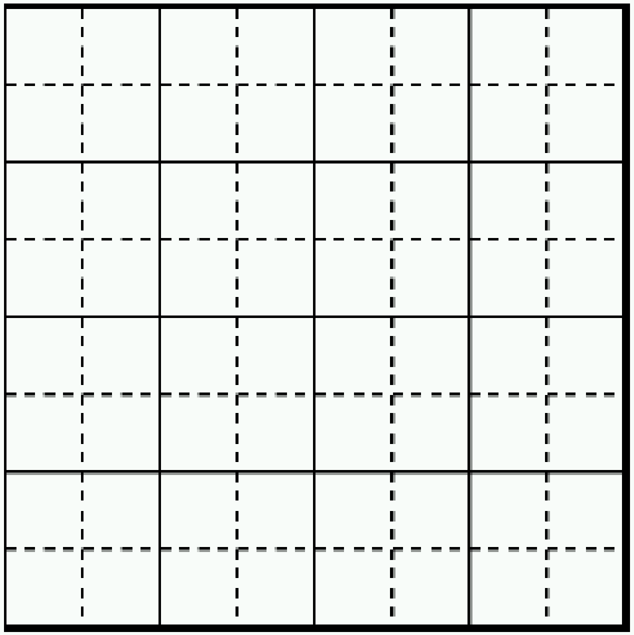
•The same information is visible at multiple positions

•For reversibility, **one *n*** **th** of the neighbor information must be left at the center

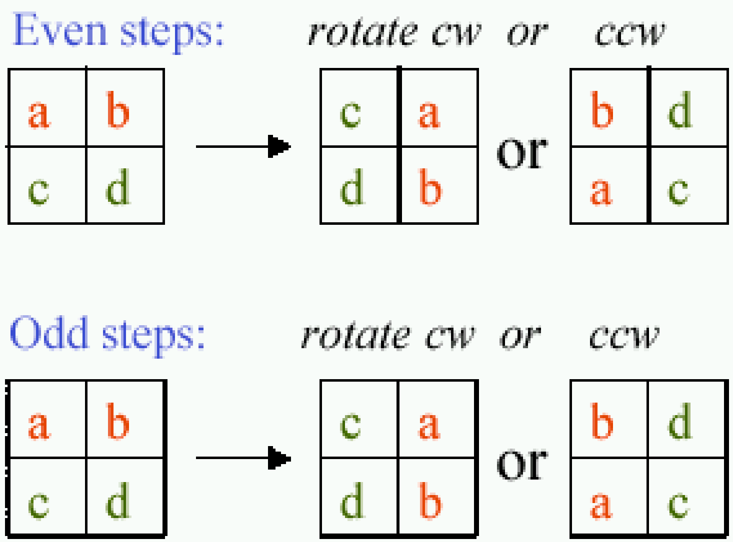
Adding conservations

- With traditional CA's, conservations are a ***non-local* property** of the dynamics.
- **Simplest solution**: redefine CA's so that ***conservation*** is a *manifestly local* property
- *CA* = ***regular computation in space & time***
  - » Regular in space: repeated structure
  - » Regular in time: repeated sequence of steps

Diffusion rule



Use 2x2 blockings. Use solid blocks on even time steps, use dotted blocks on odd steps.

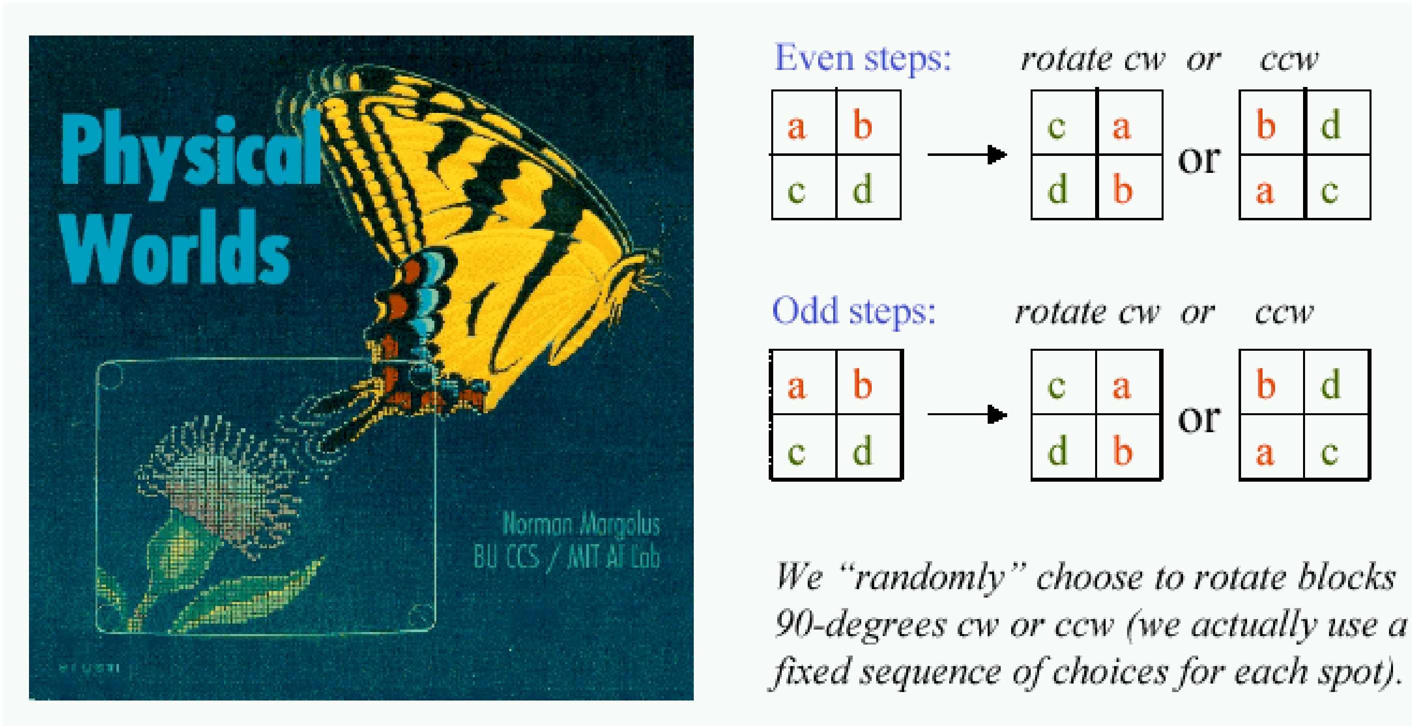


We "randomly" choose to rotate blocks 90-degrees cw or ccw (we actually use a fixed sequence of choices for each spot).

cw = clockwise

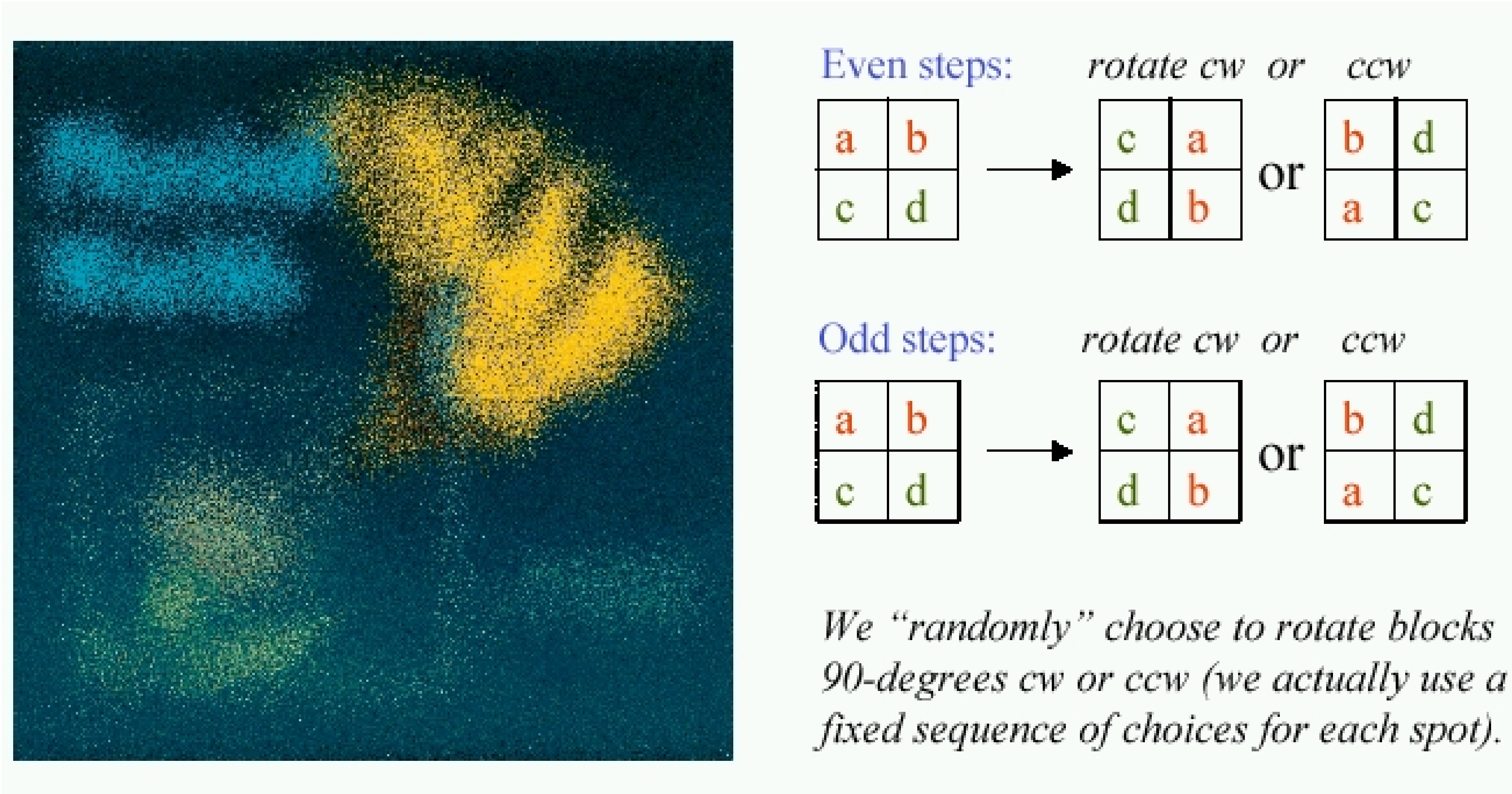
ccw = counter-clockwise

Diffusion rule



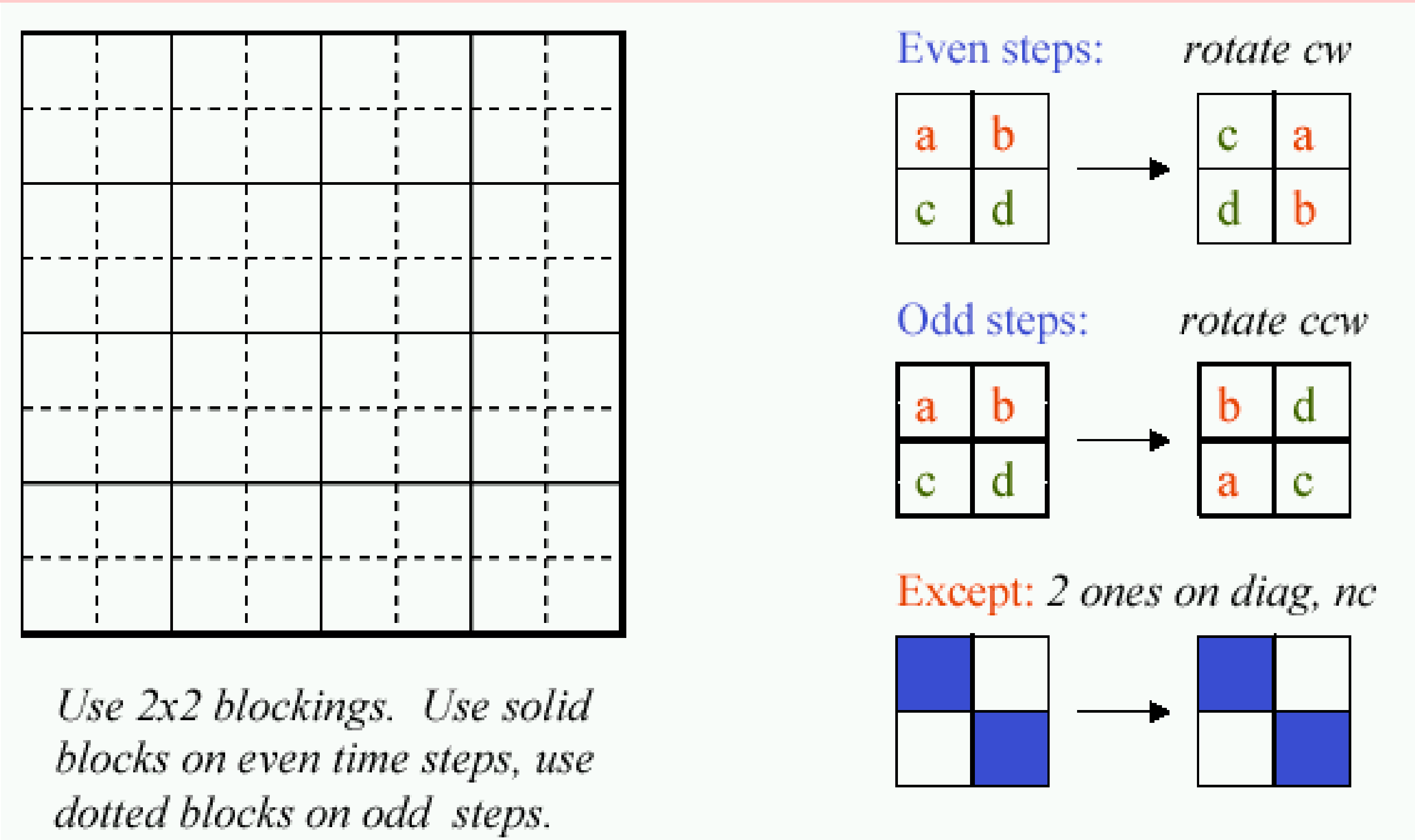
- Take this image as our working environment

Diffusion rule



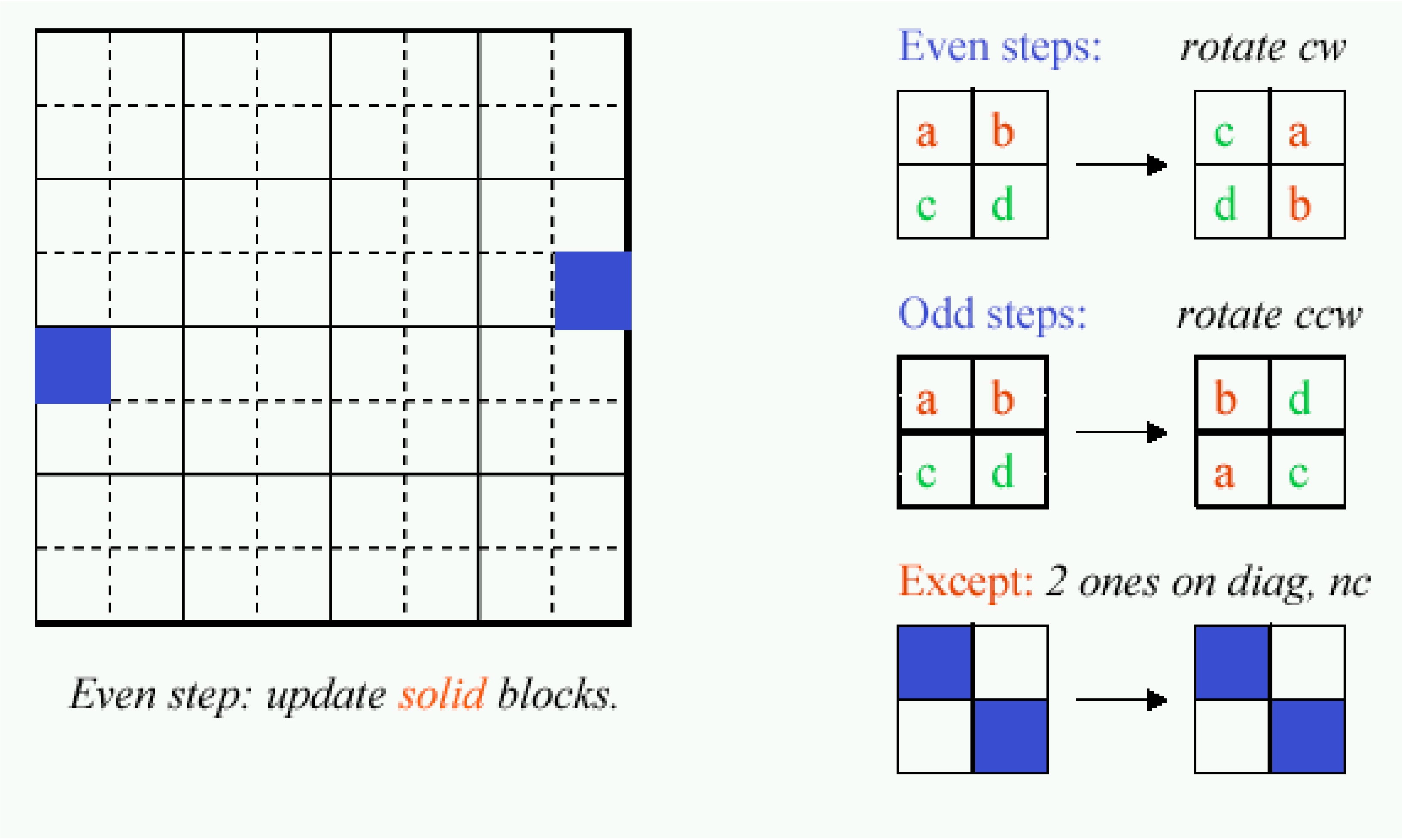
… and this is [what is created]() after some number of generations

TM Gas rule

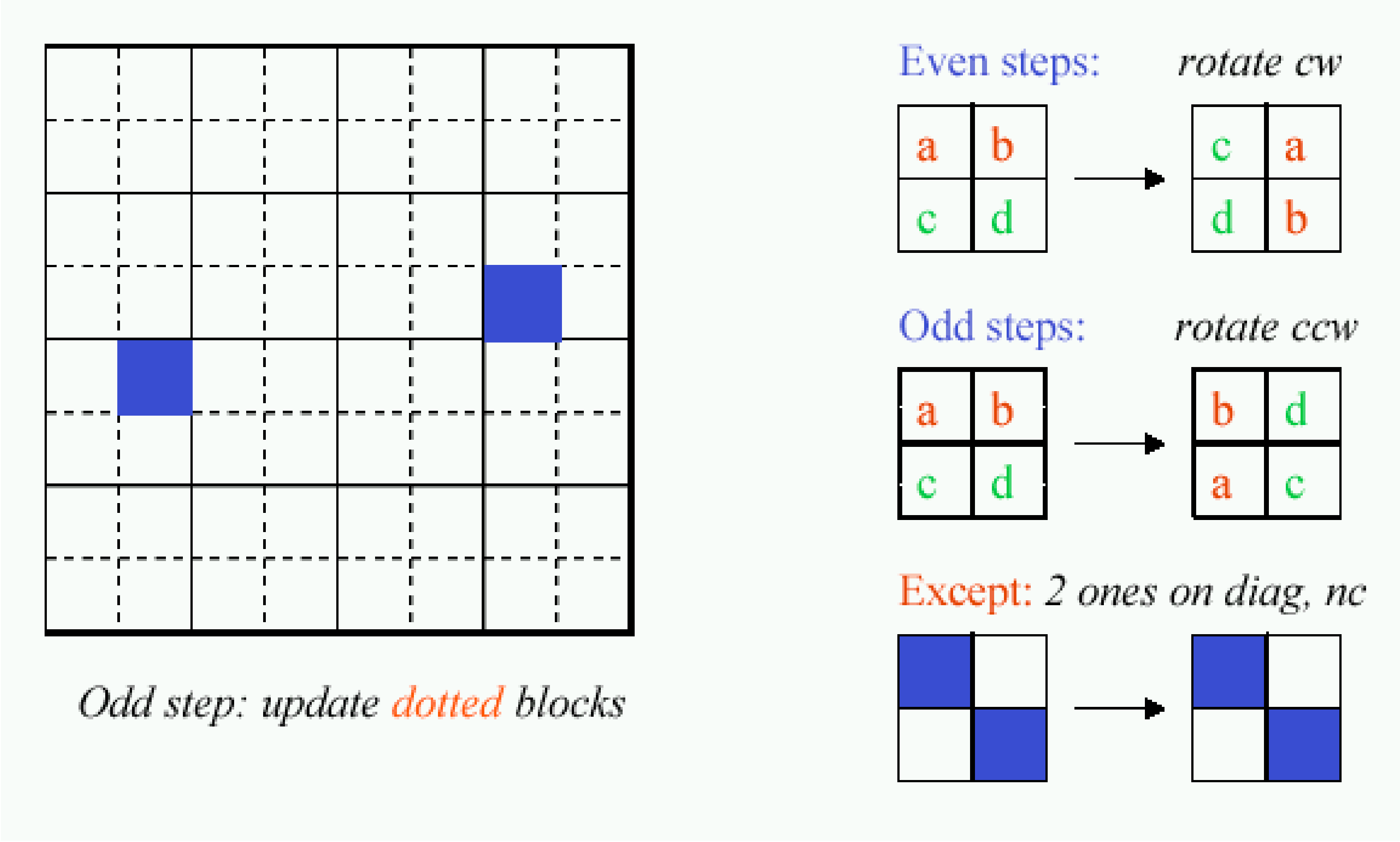


- TM = Toffoli/Margolus

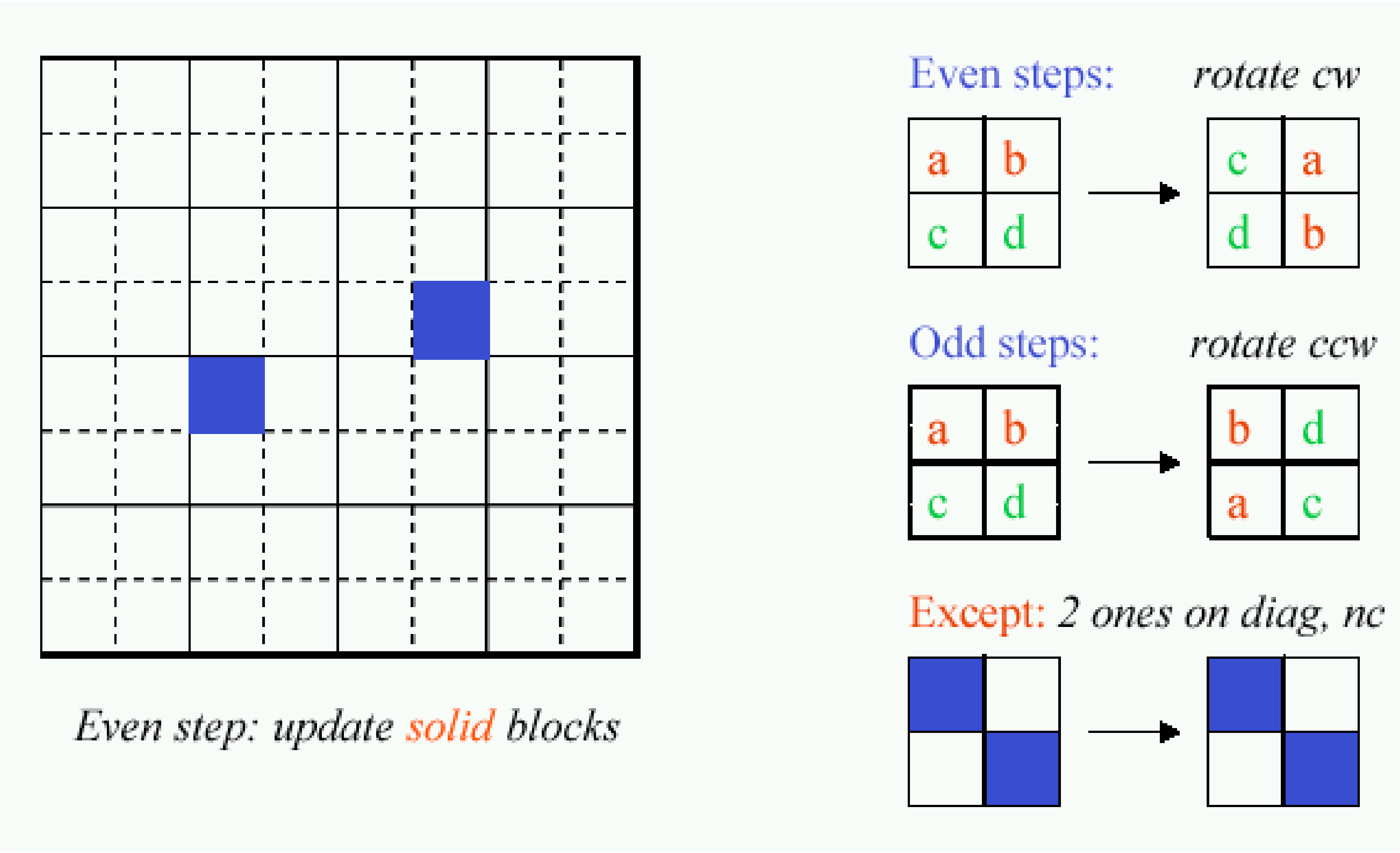
TM Gas rule


Even step: update solid blocks.
Even steps: rotate cw
a b
c d
c a
d b
Odd steps: rotate ccw
a b
c d
b d
a c
Except: 2 ones on diag, nc

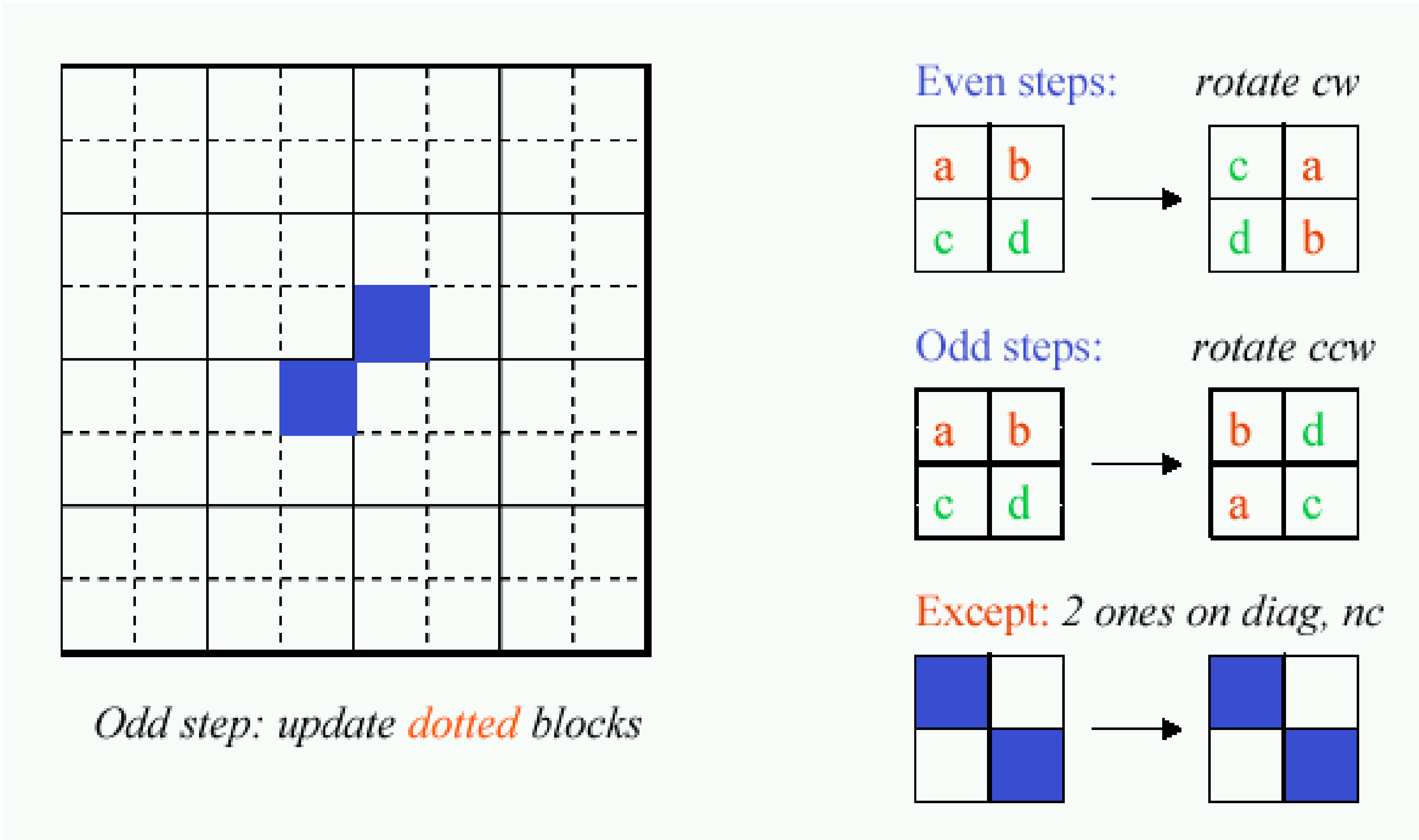
TM Gas rule


Even steps:
rotate cw
a b c d
c a d b
Odd steps:
rotate ccw
a b c d
b d a c
Except: 2 ones on diag, nc
Odd step: update dotted blocks

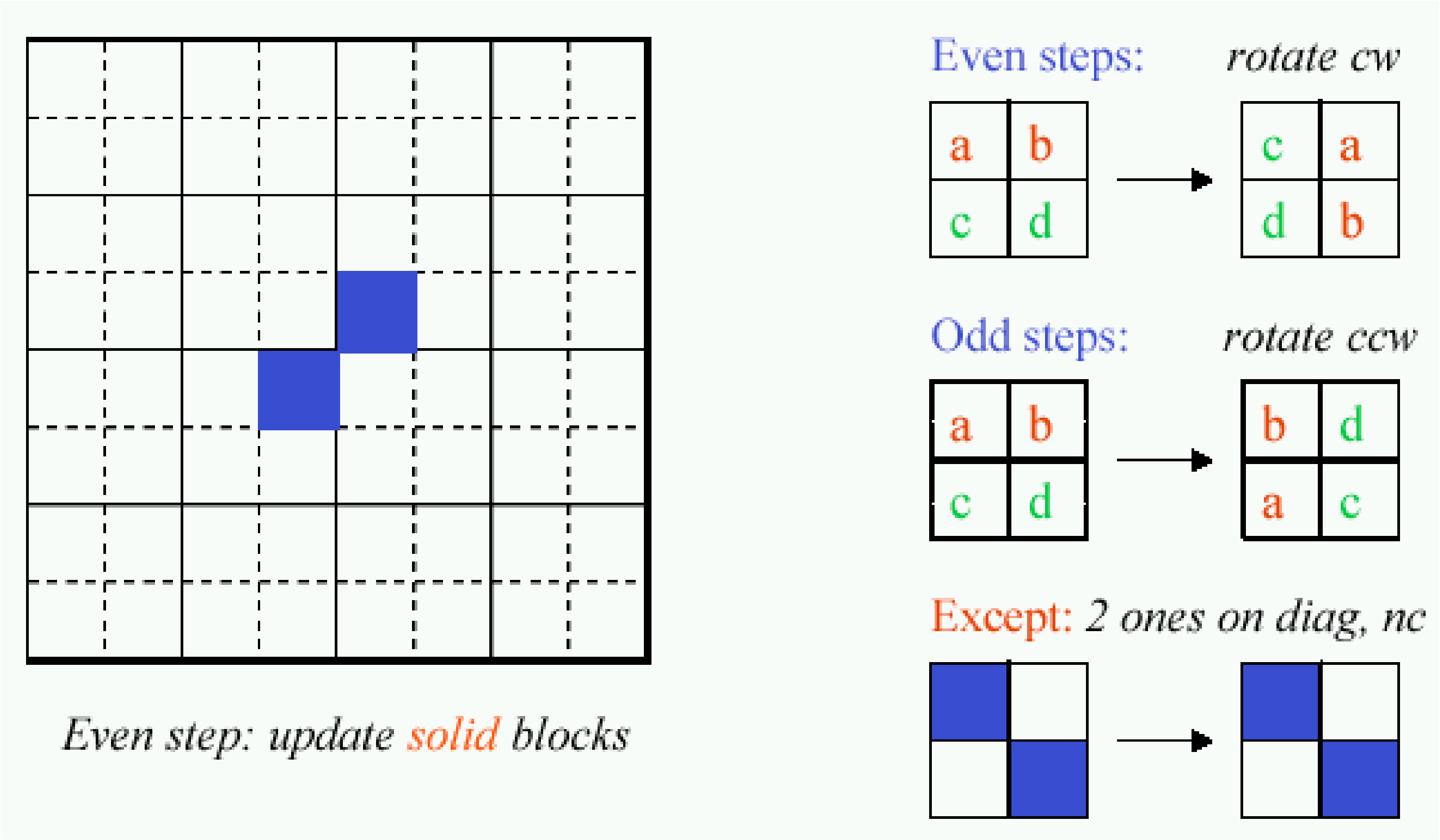
TM Gas rule


Even steps:
rotate cw
a
b
c
d
c
a
d
b
Odd steps:
rotate ccw
a
b
c
d
b
d
a
c
Except: 2 ones on diag, nc
Even step: update solid blocks

TM Gas rule

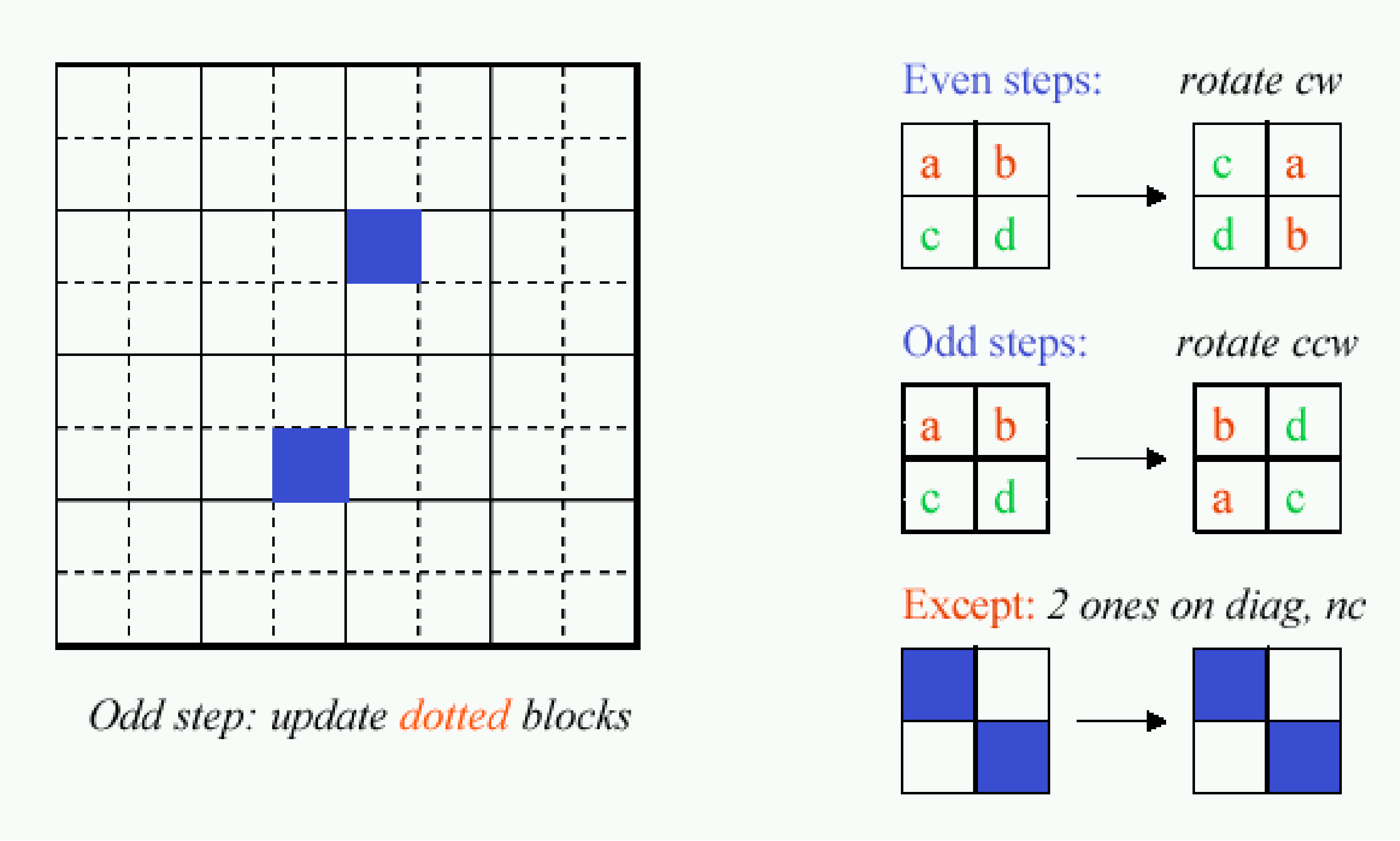

Odd step: update dotted blocks
Even steps:
rotate cw
a
b
c
d
c
a
d
b
Odd steps:
rotate ccw
a
b
c
d
b
d
a
c
Except: 2 ones on diag, nc

TM Gas rule

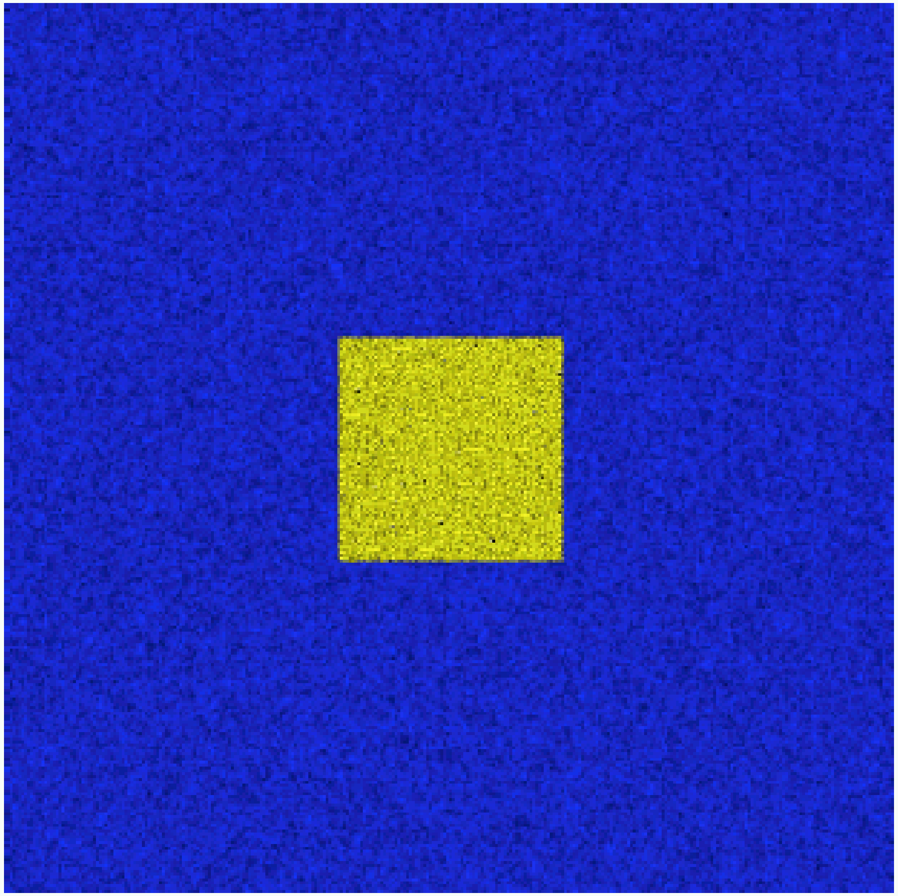


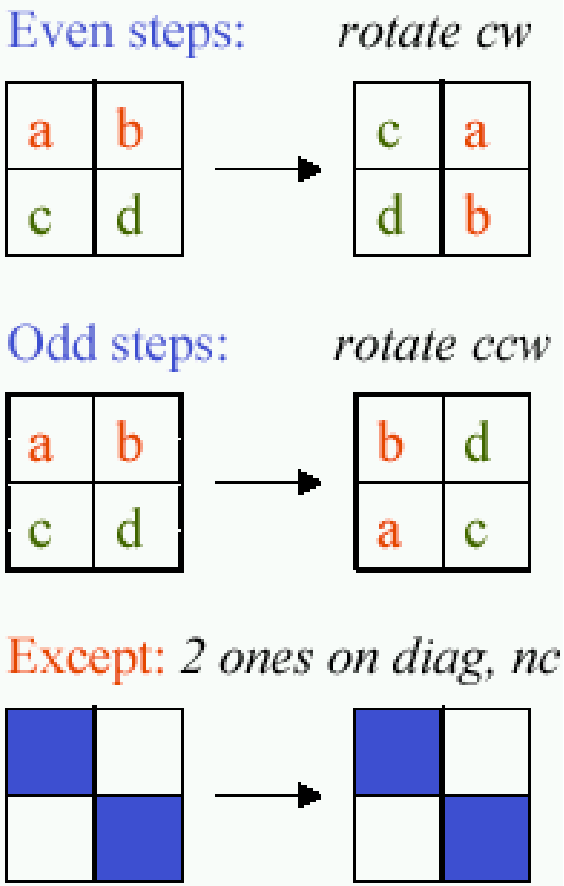
Even step: update solid blocks
Even steps:
rotate cw
a b
c d
c a
d b
Odd steps:
rotate ccw
a b
c d
b d
a c
Except: 2 ones on diag, nc

TM Gas rule


Odd step: update dotted blocks
Even steps:
rotate cw
a
b
c
d
c
a
d
b
Odd steps:
rotate ccw
a
b
c
d
b
d
a
c
Except: 2 ones on diag, nc

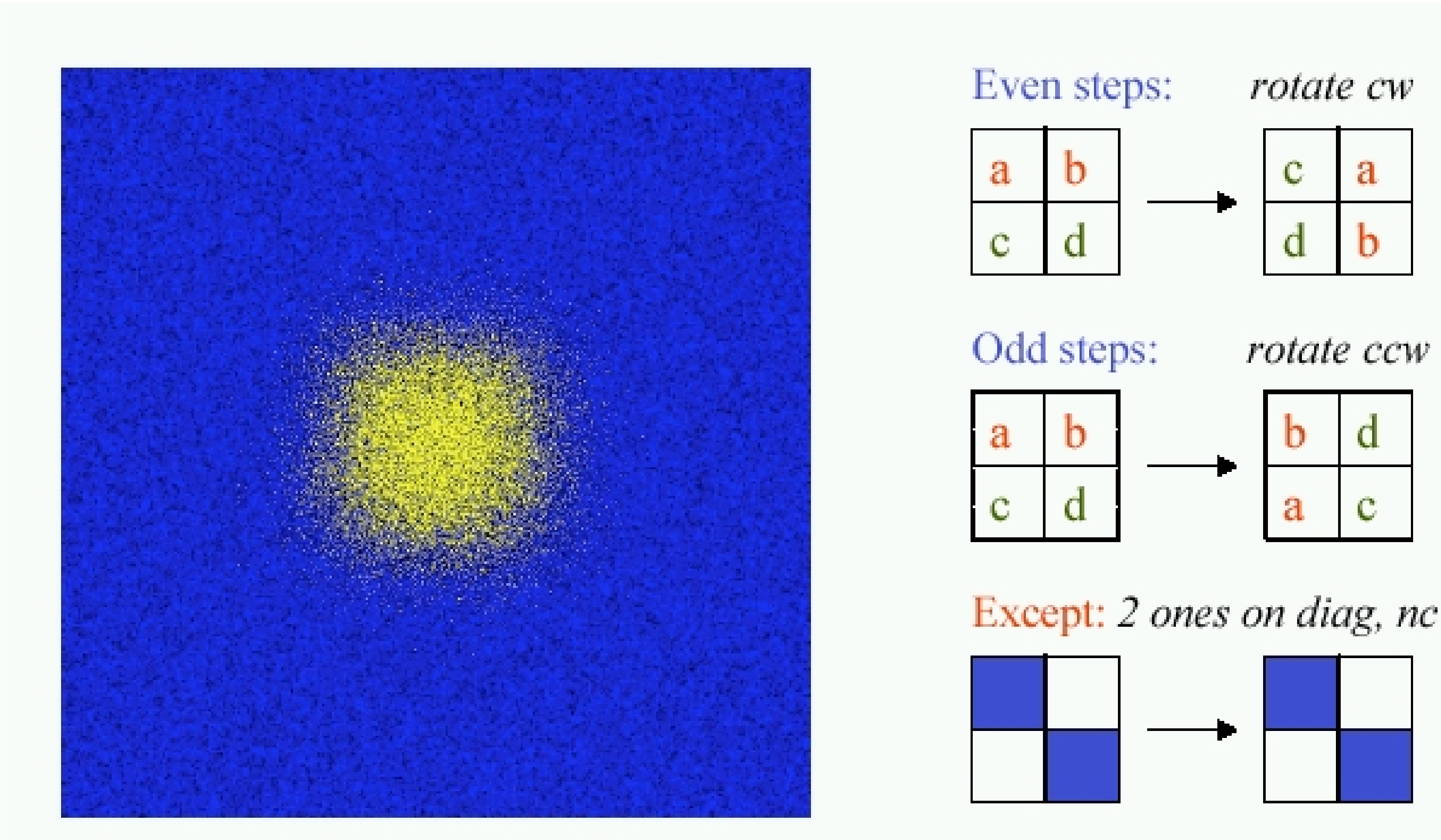
TM Gas rule



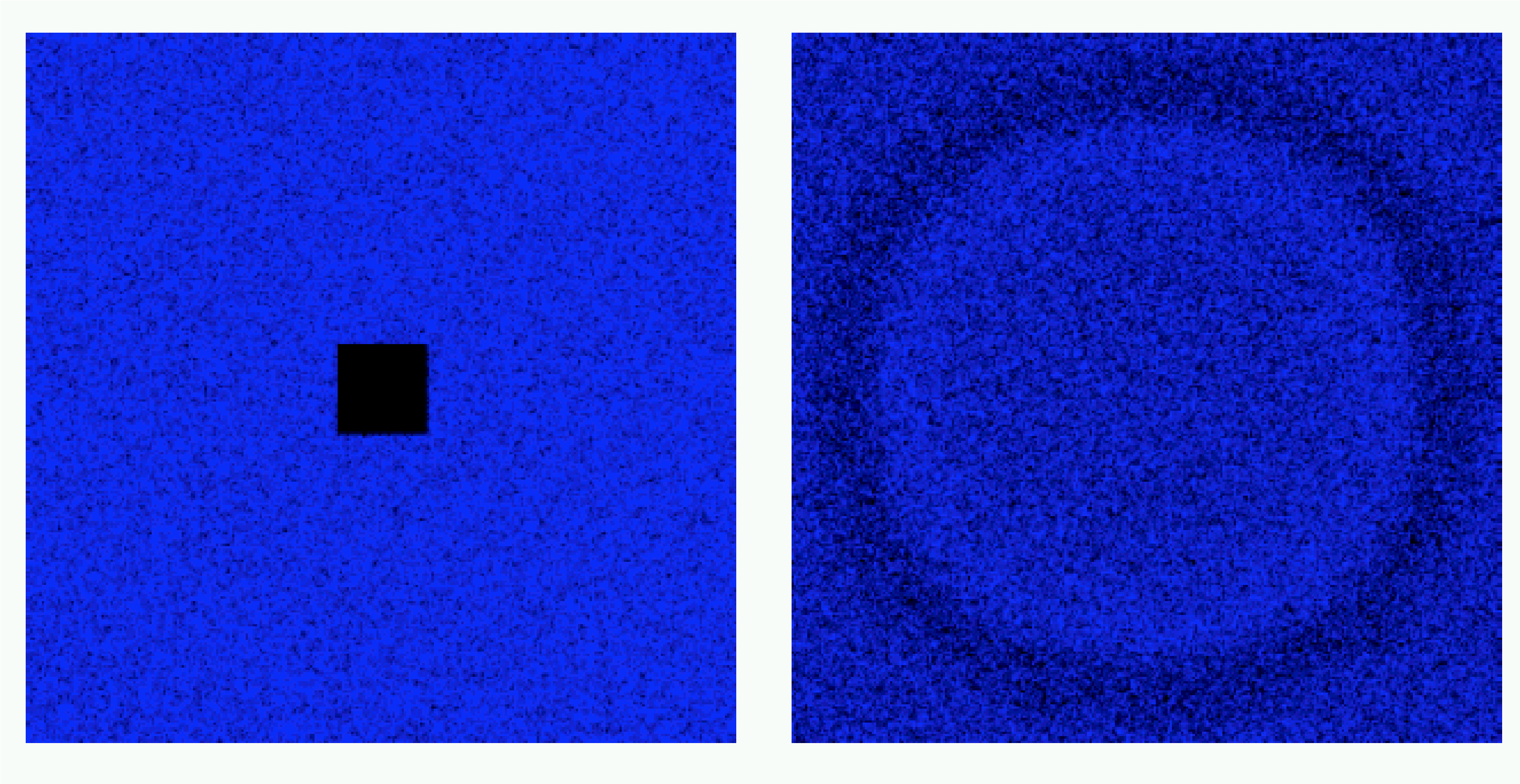


Now we analyze how it works on a larger example and for more generations

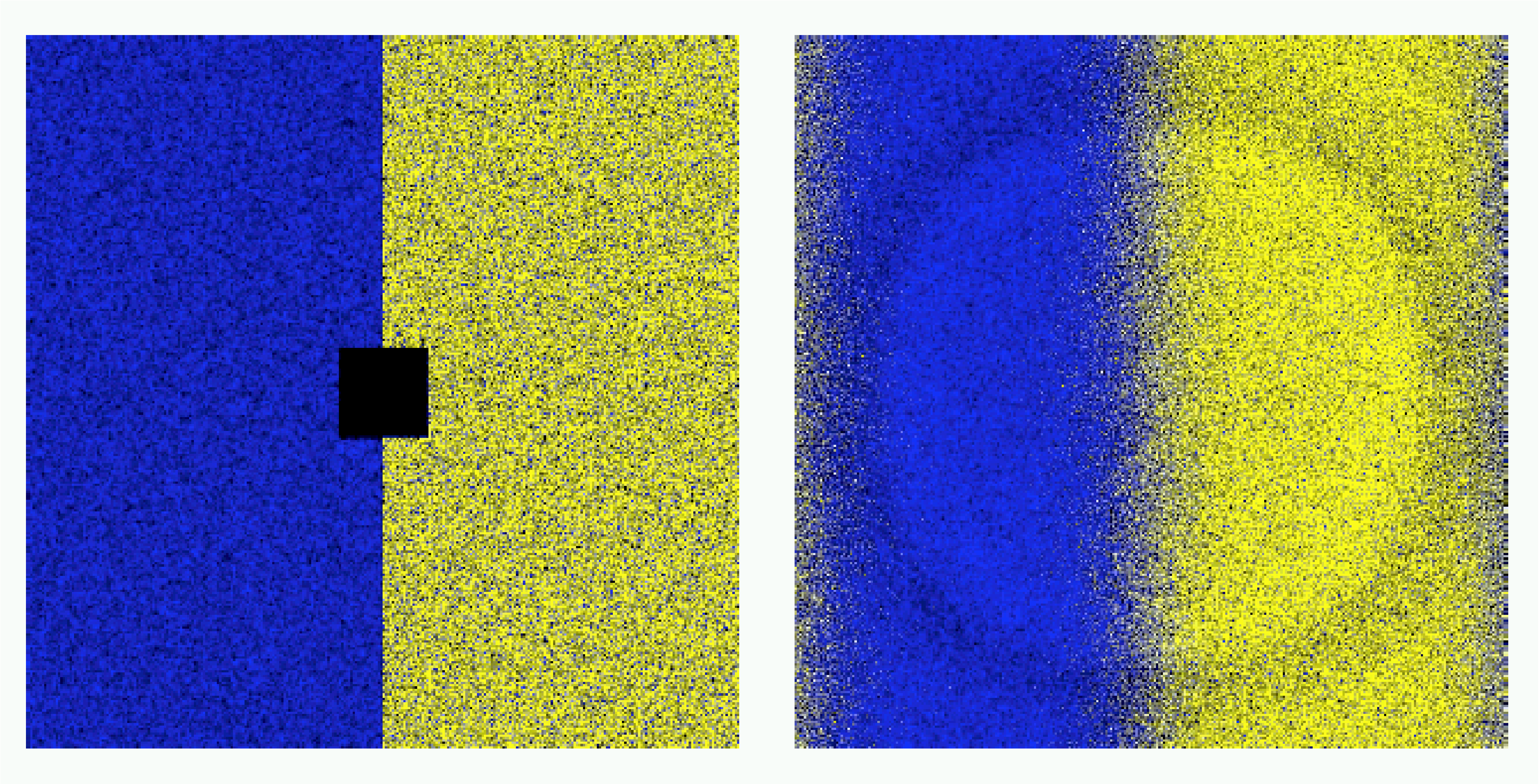
TM Gas rule


Even steps:
rotate cw
a b
c d
c a
d b
Odd steps:
rotate ccw
a b
c d
b d
a c
Except: 2 ones on diag, nc

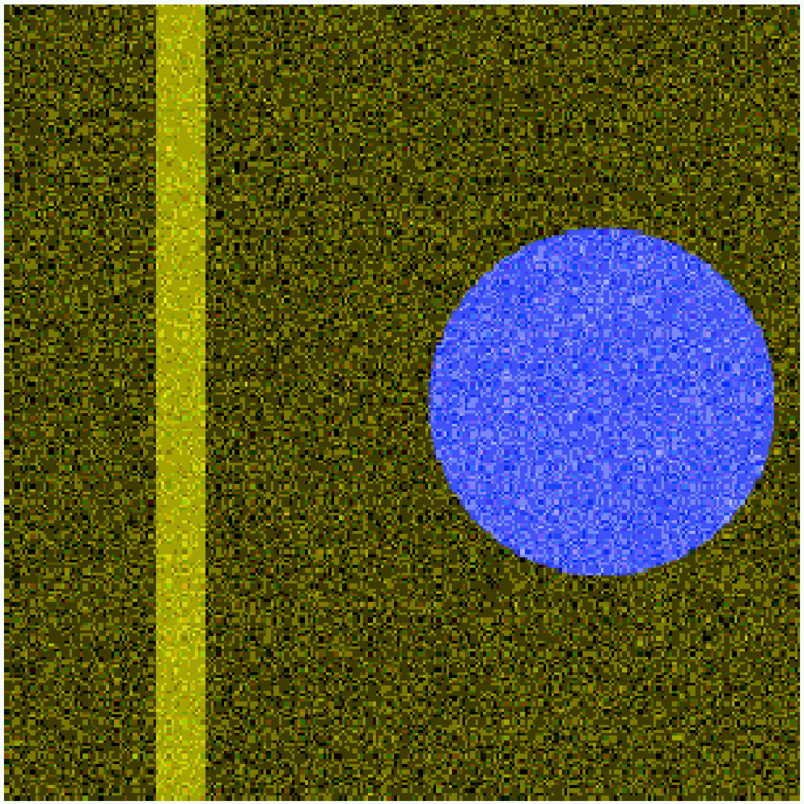
TM Gas rule



TM Gas rule

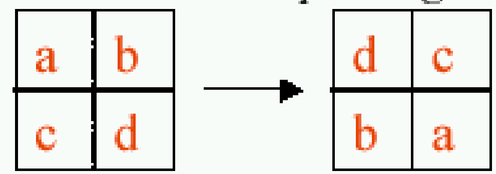


Lattice gas refraction

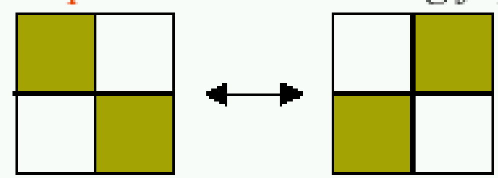


- *Half the time:* HPP gas rule everywhere:

  Even & odd: *swap along diags*

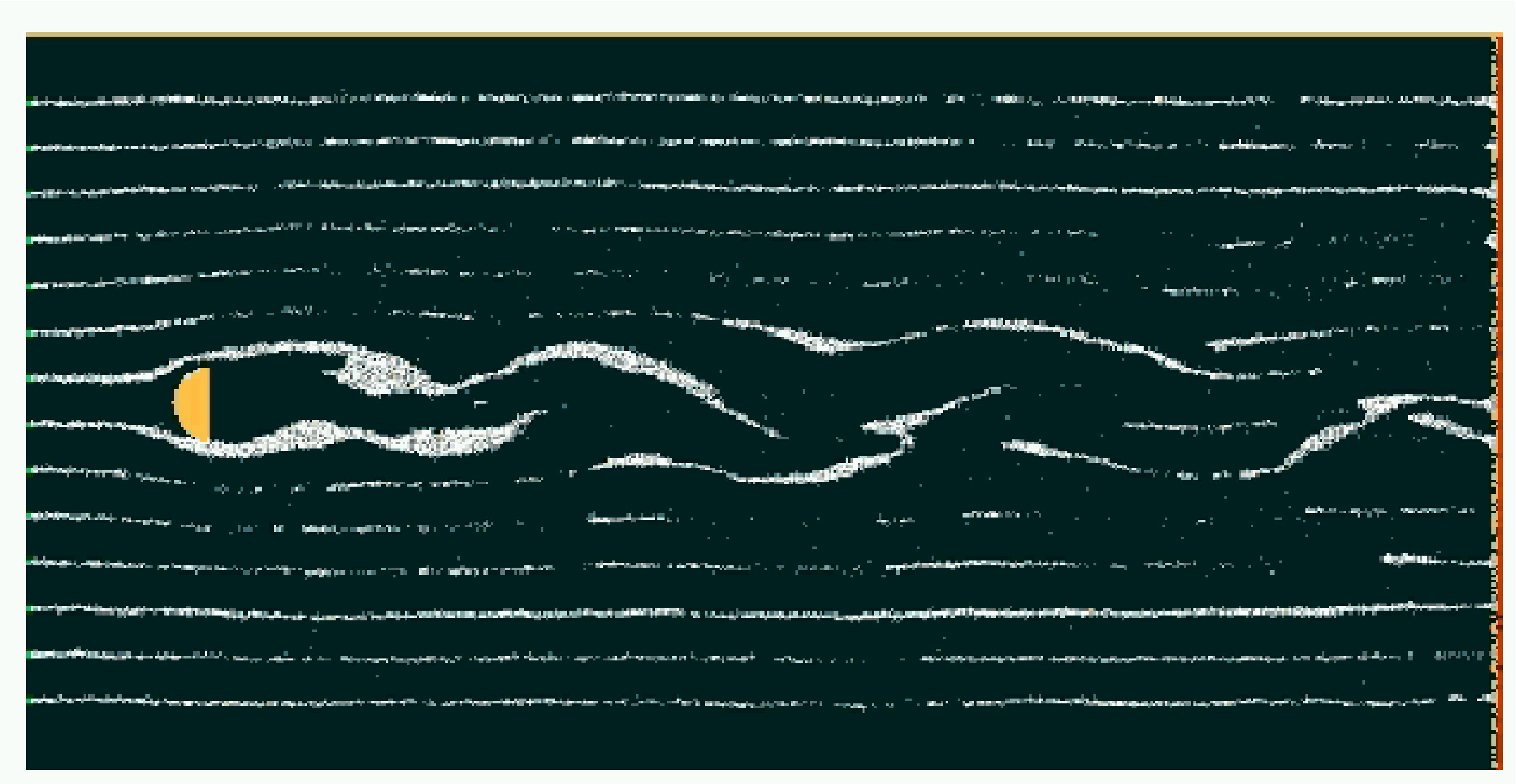


  Except: *two ones on diag flip*



- *Half the time:* HPP gas rule outside of blue region, *ID rule* inside (no change).

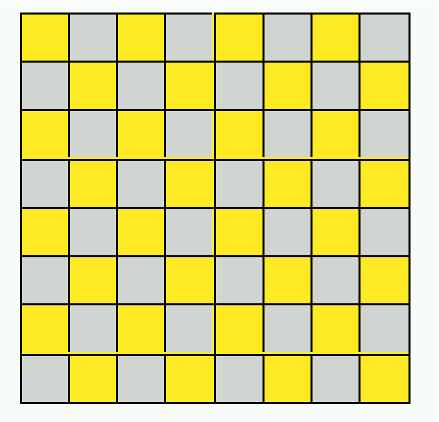
Lattice gas hydrodynamics



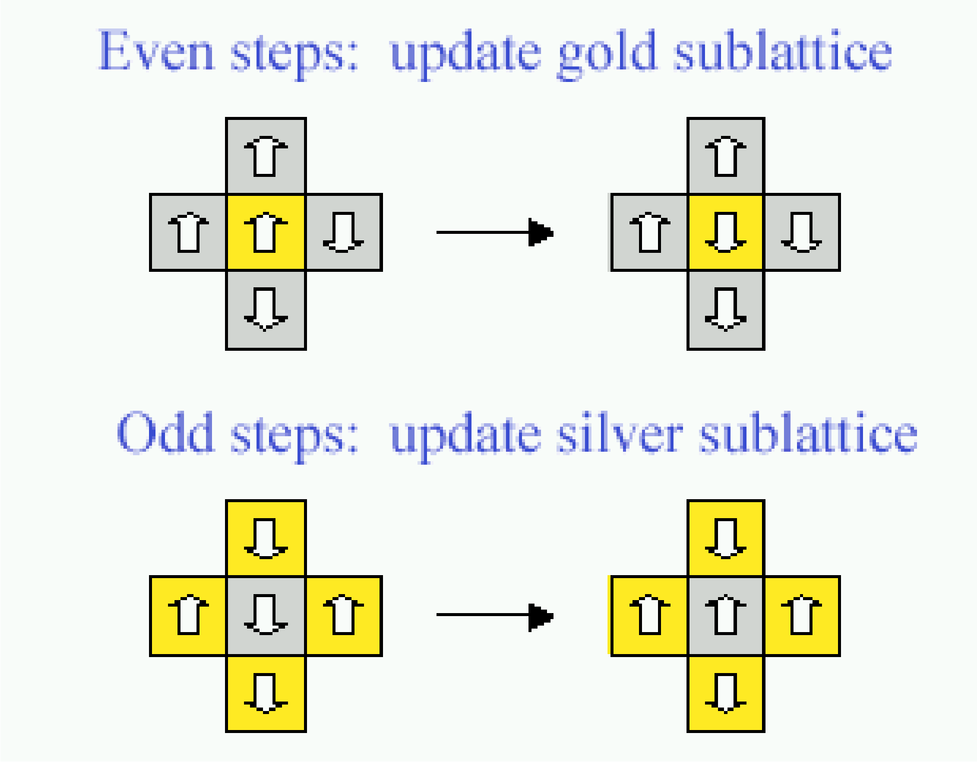
Six direction LGA flow past a half-cylinder, with vortex shedding. System is 2Kx1K.

Dynamical Ising rule

Gold/silver checkerboard

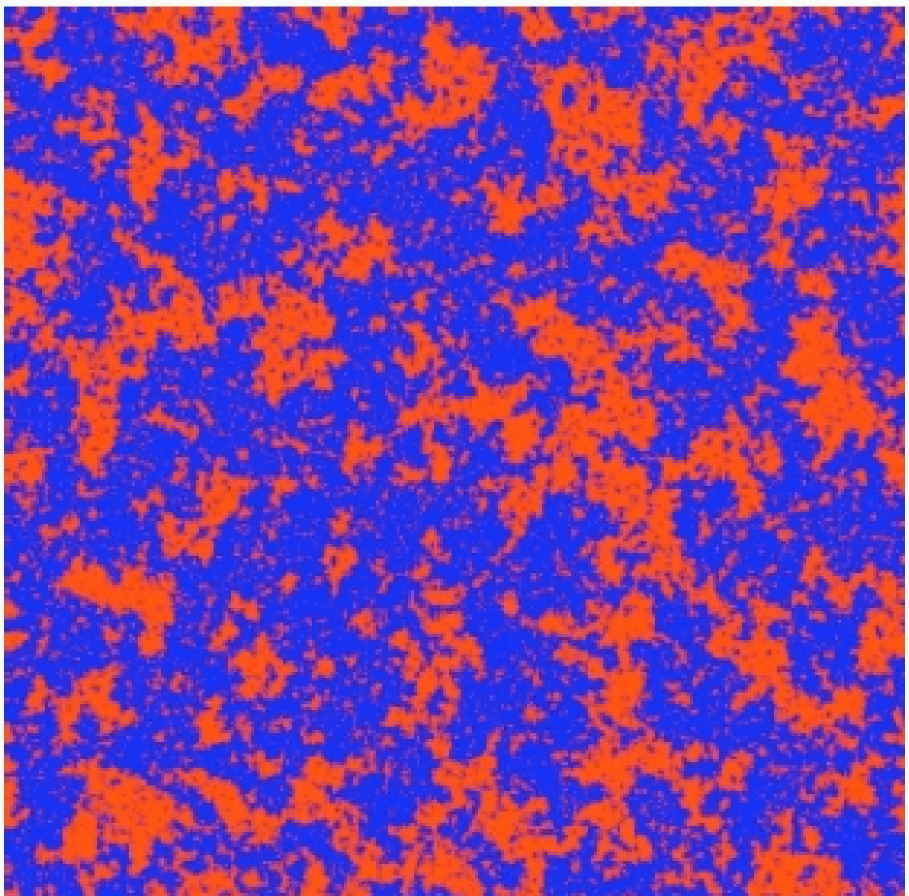


We divide the space into two sublattices, updating the gold on even steps, silver on odd.

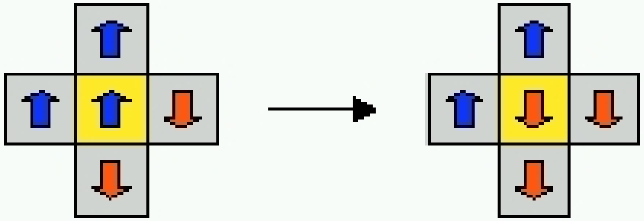


A spin is flipped if exactly 2 of its 4 neighbors are parallel to it.
After the flip, *<u>exactly 2 neighbors are still parallel.</u>*

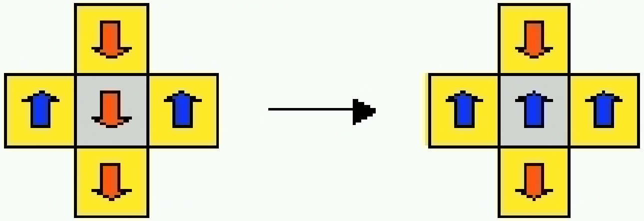
Dynamical Ising rule



Even steps: update gold sublattice

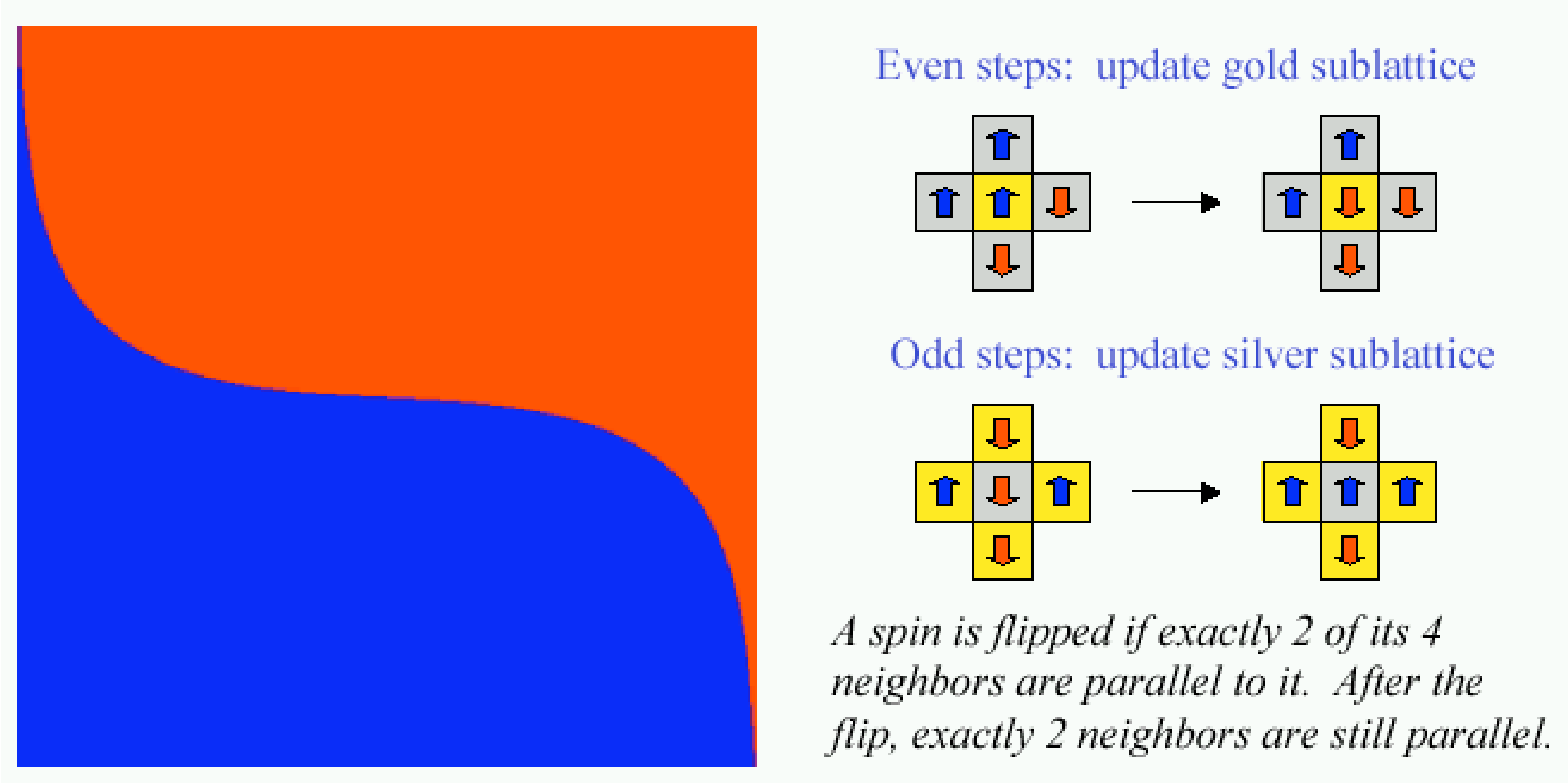


Odd steps: update silver sublattice



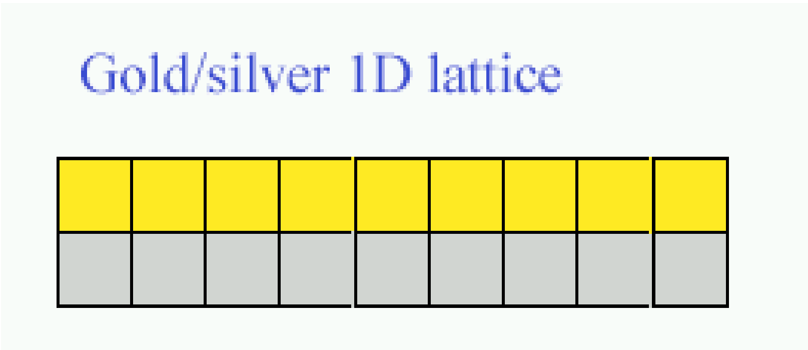
A spin is flipped if exactly 2 of its 4 neighbors are parallel to it. After the flip, exactly 2 neighbors are still parallel.

Dynamical Ising rule

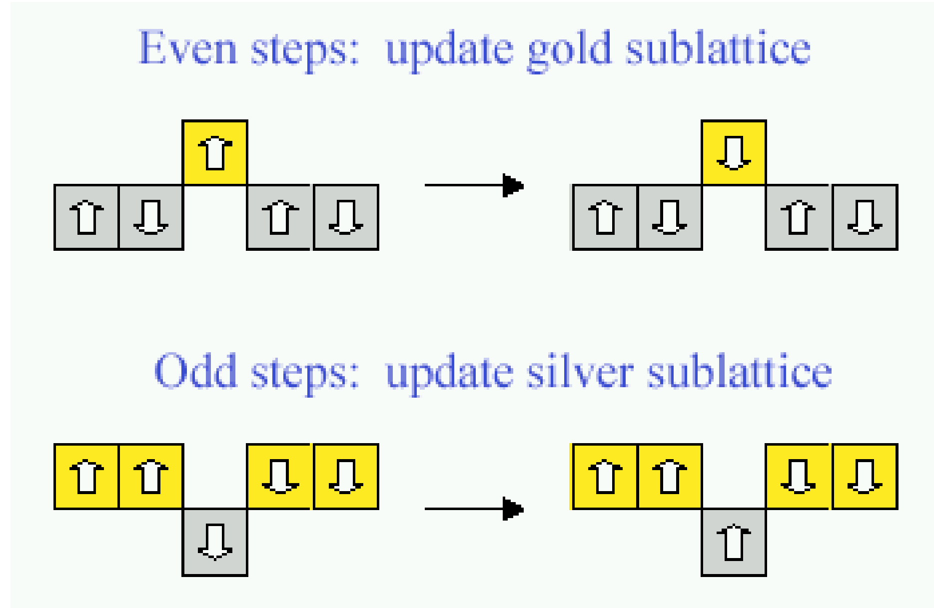


Question: What will be the state in 100 generations, if he picture above is the initial state? What in 10,000 generations?

Bennett's 1D rule



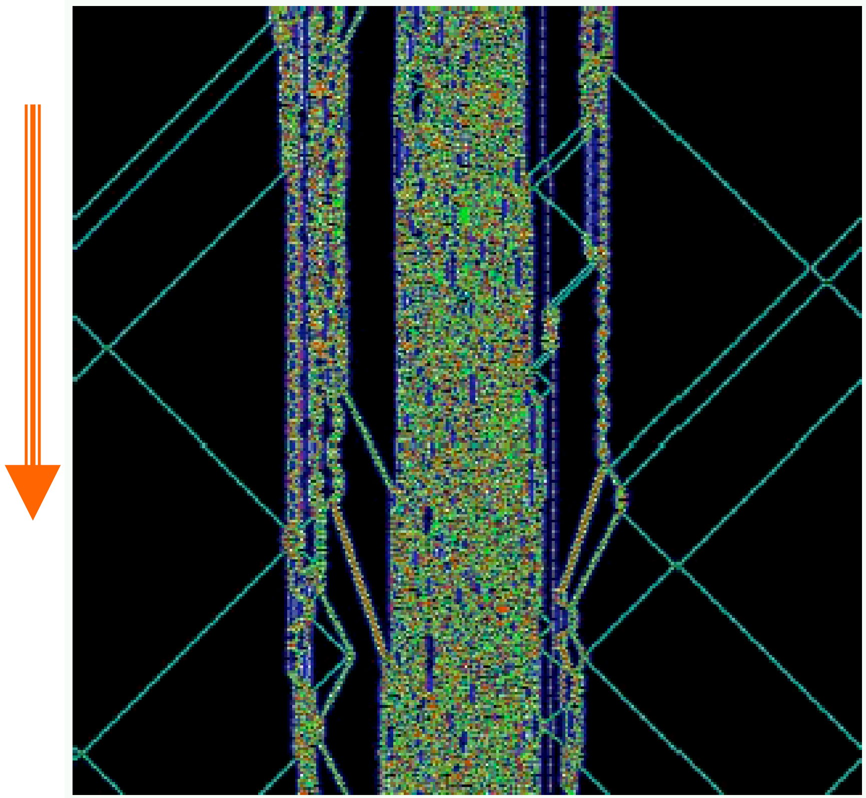
- *At each site in a 1D space, we put 2 bits of state.*
- *We'll call one the "gold" bit and one the "silver" bit.*
- *We update the gold bits on even steps, and the silver on odd steps.*



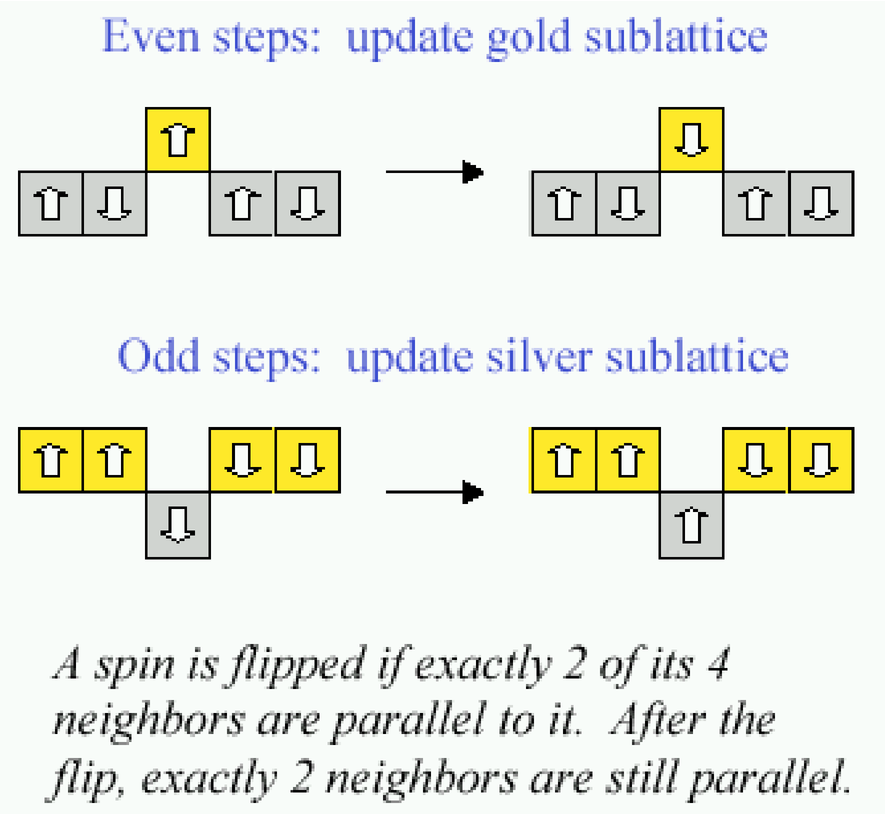
- *A spin is flipped if exactly 2 of its 4 neighbors are parallel to it.*
- *After the flip, exactly 2 neighbors are still parallel.*

Bennett’s 1D rule

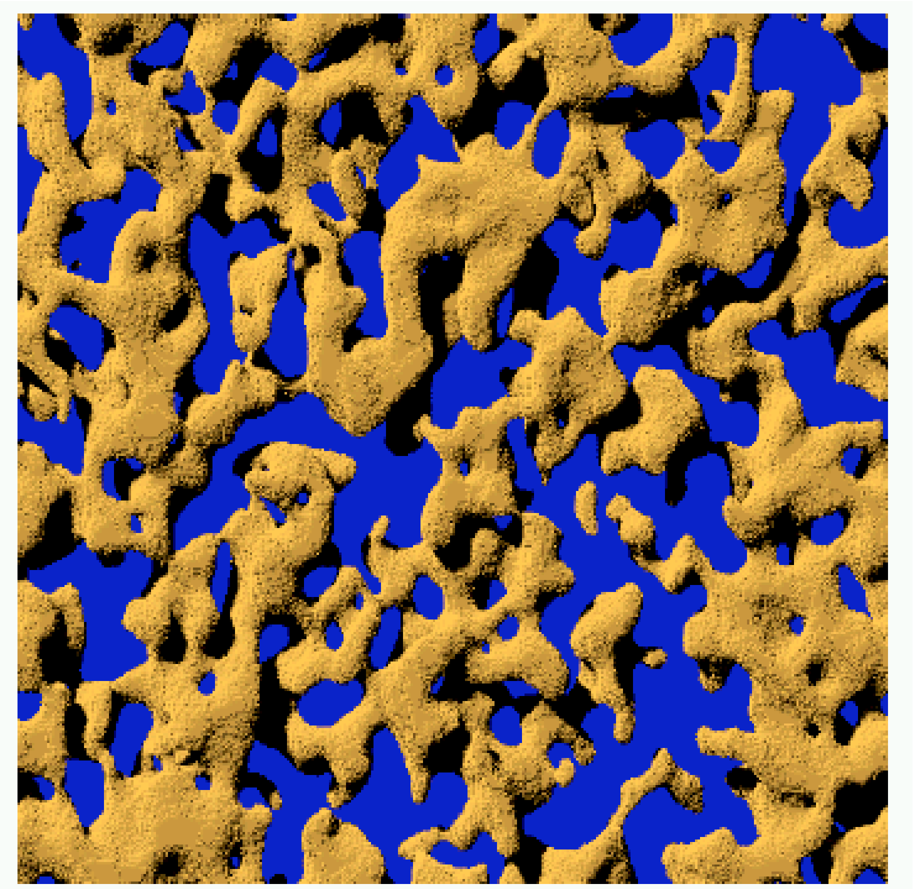
<u>Bennett’s rules creation:</u>
<u>2D picture from 1D rules</u>



<u>Bennett’s rules:</u>

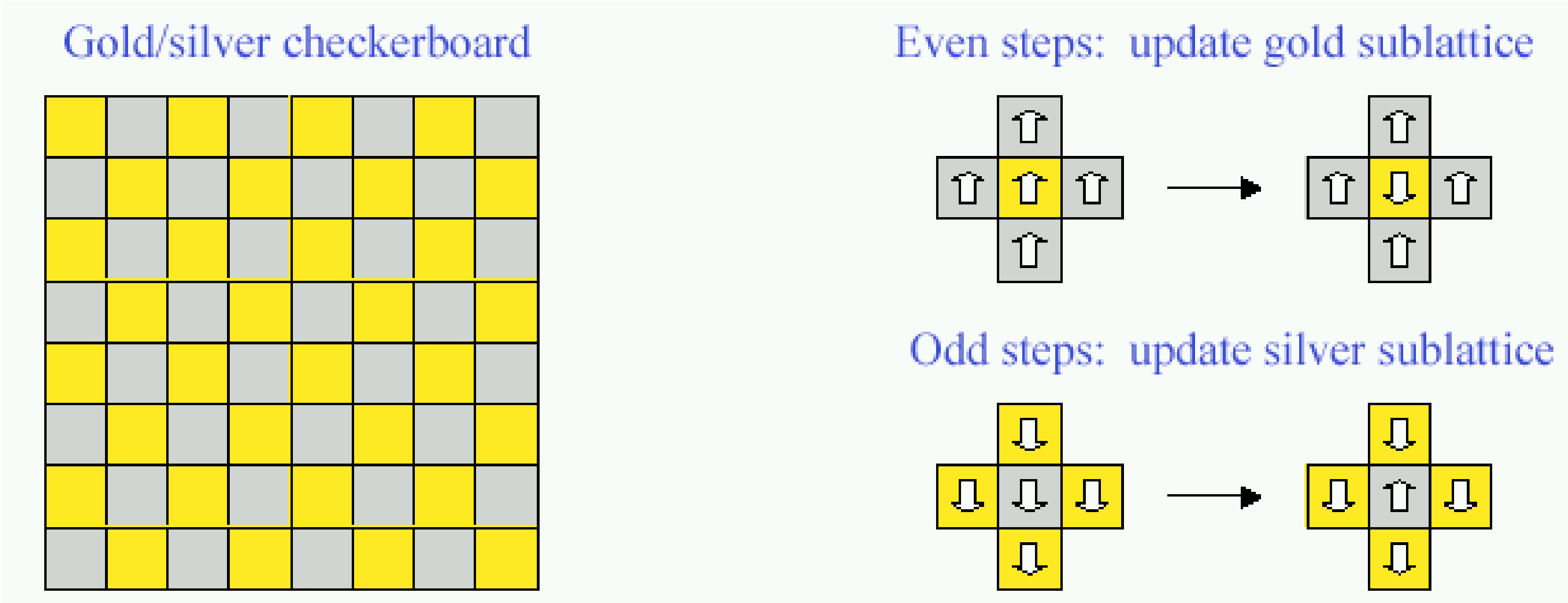


3D Ising with heat bath



If the heat bath is initially much cooler than the spin system, then domains grow as the spins cool.

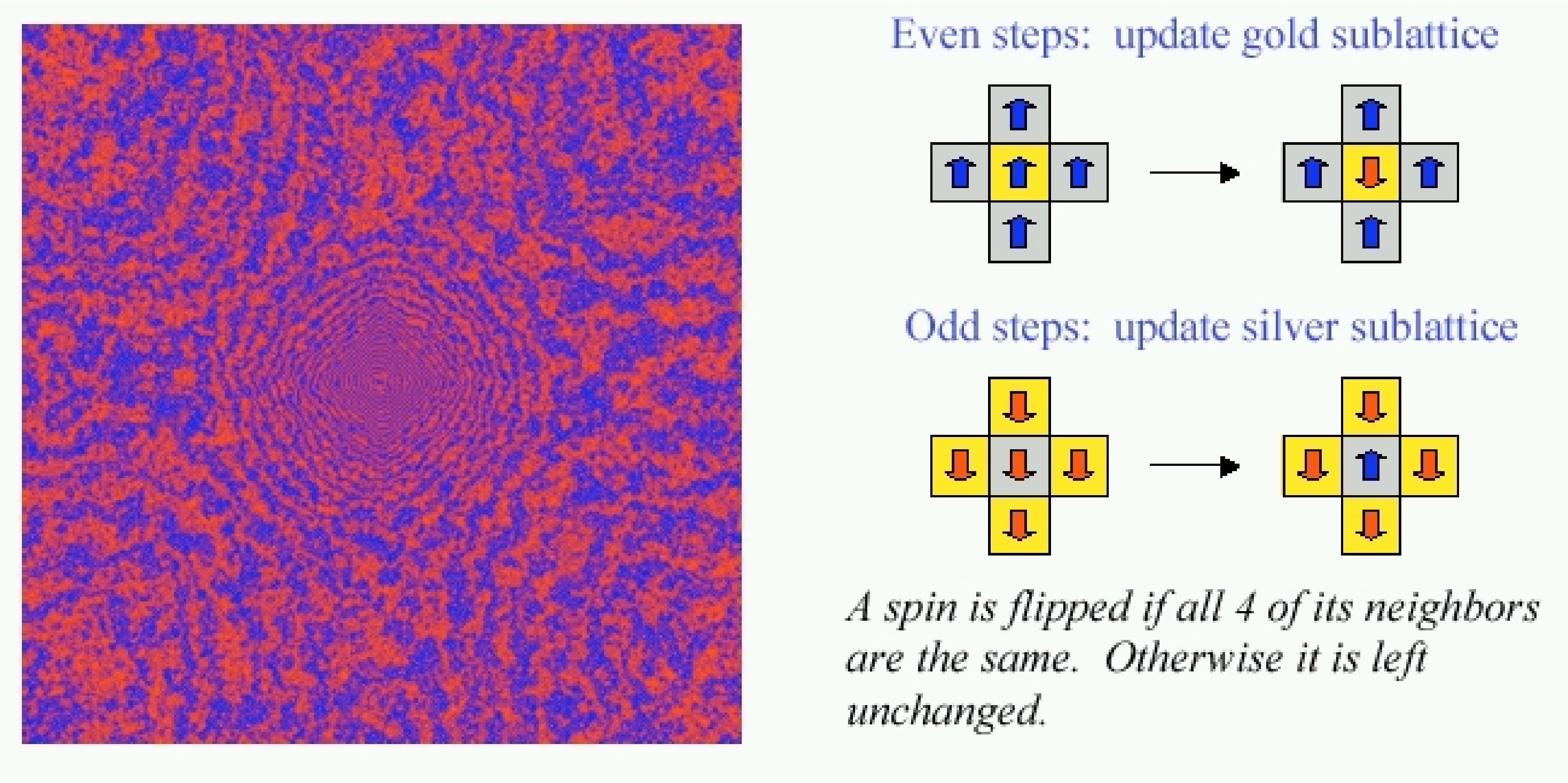
2D "Same" rule



- ***We divide the space into two sublattices**, updating the gold on even steps, silver on odd.*

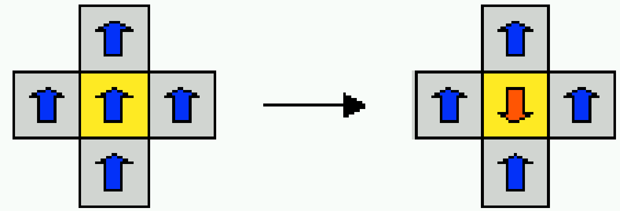
- *A spin is flipped if all 4 of its neighbors are the same.*
- *Otherwise it is left unchanged.*

2D “Same” rule

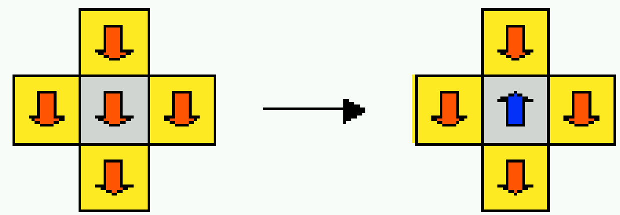

Even steps: update gold sublattice
Odd steps: update silver sublattice
A spin is flipped if all 4 of its neighbors are the same. Otherwise it is left unchanged.

2D "Same" rule

Even steps: update gold sublattice

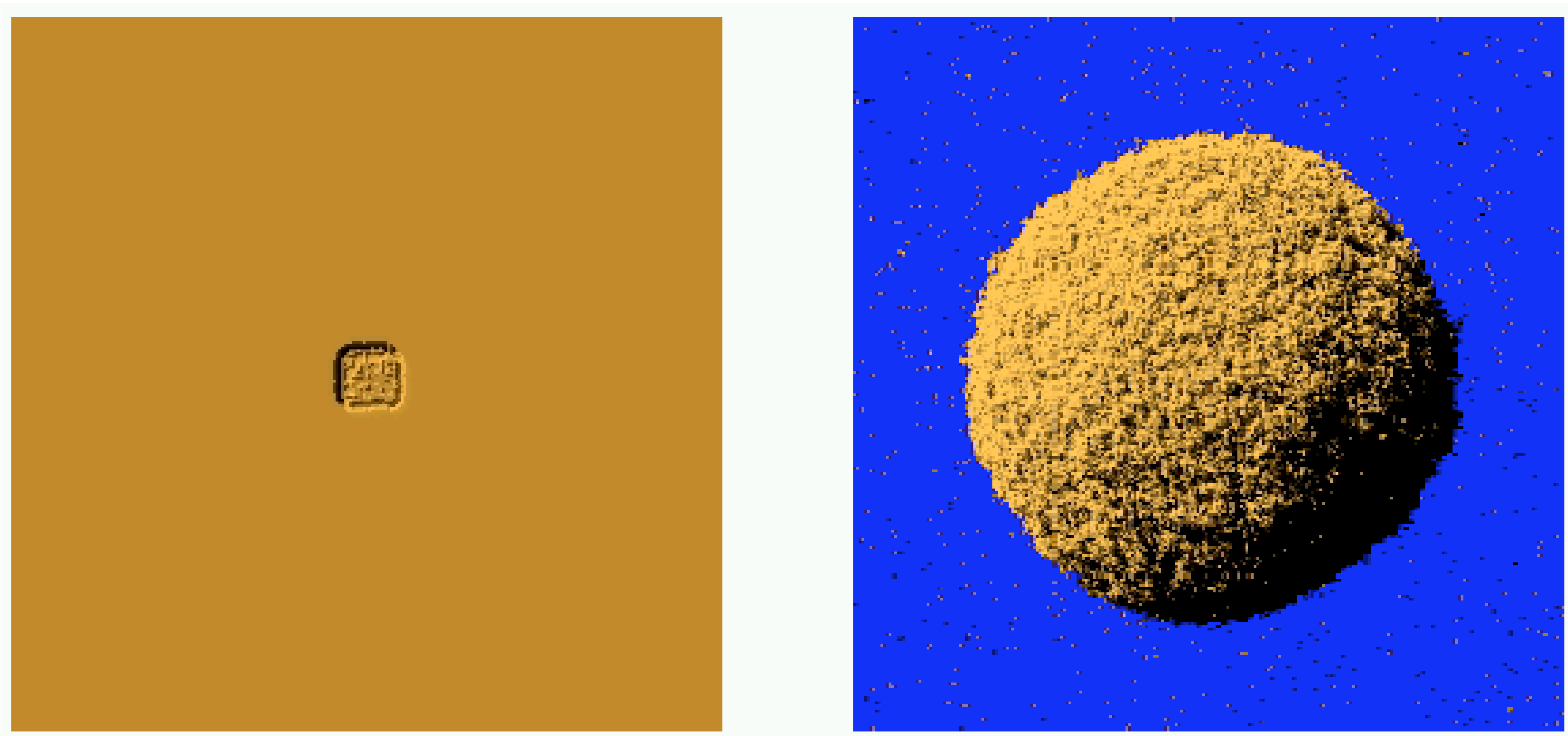


Odd steps: update silver sublattice

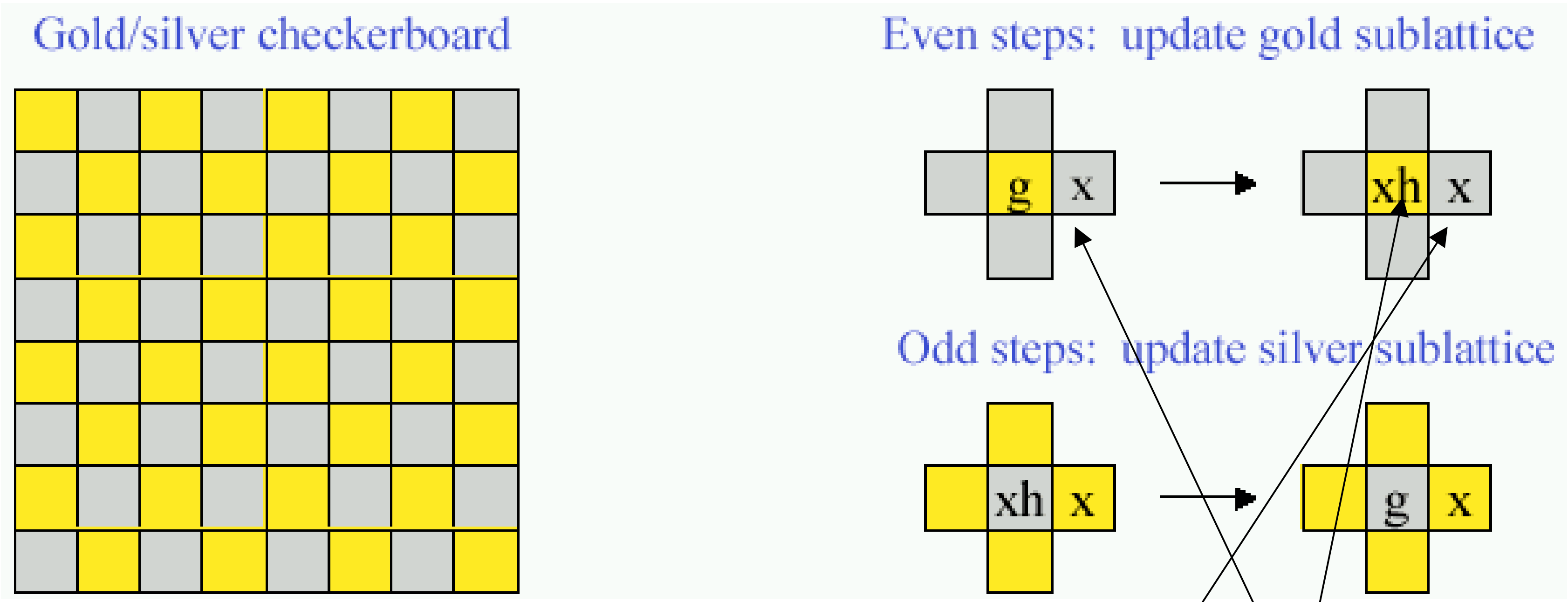


A spin is flipped if all 4 of its neighbors are the same. Otherwise it is left unchanged.

3D “Same” rule



Reversible aggregation rule

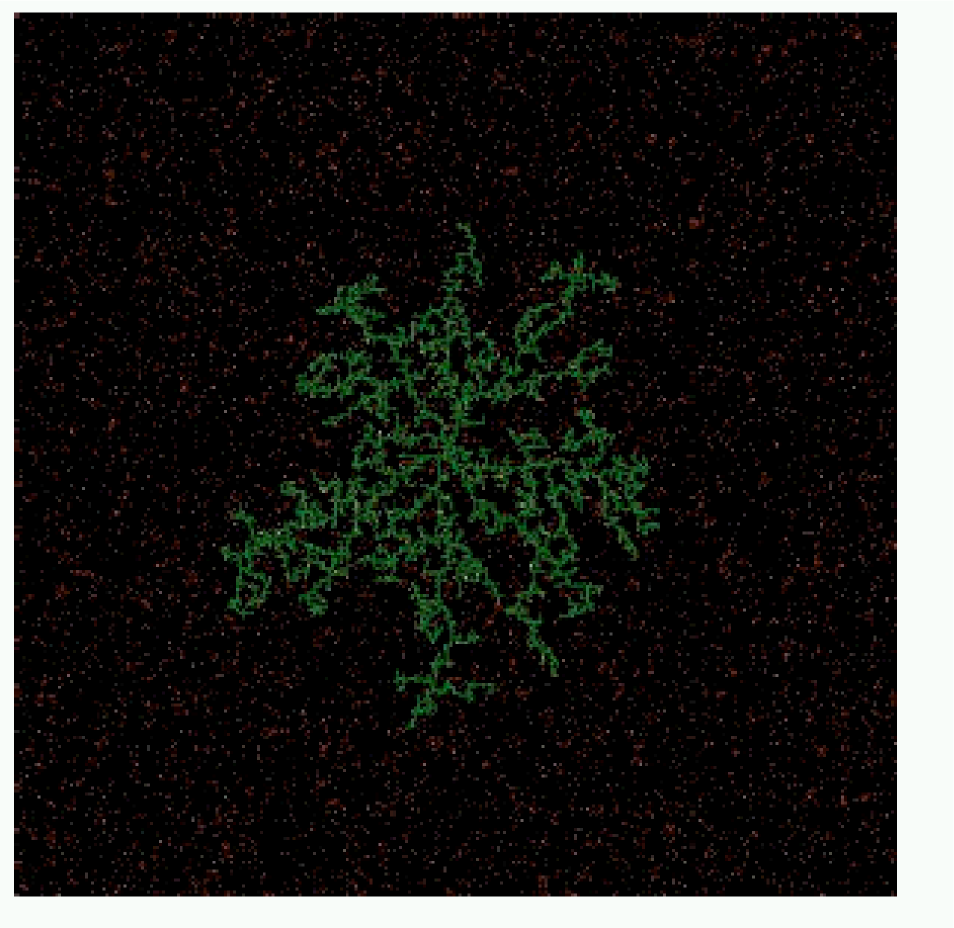


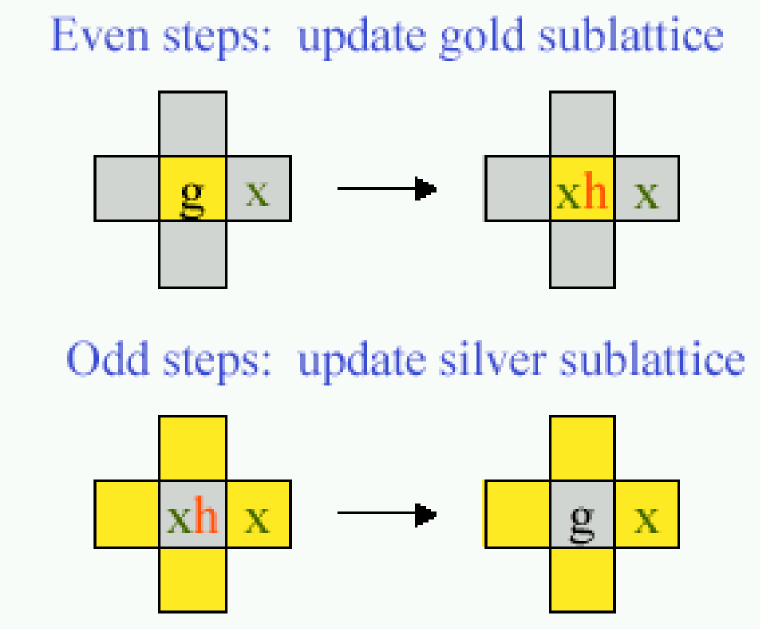
- *We* *update* *the gold sublattice, then let gas and heat diffuse, then* *update* *silver and* *<u>diffuse</u>*.

- *When a gas particle diffuses next to exactly one crystal particle, it crystallizes and emits a heat particle.*
- *The reverse also happens.*

for more info, see cond-mat/9810258

Reversible aggregation rule

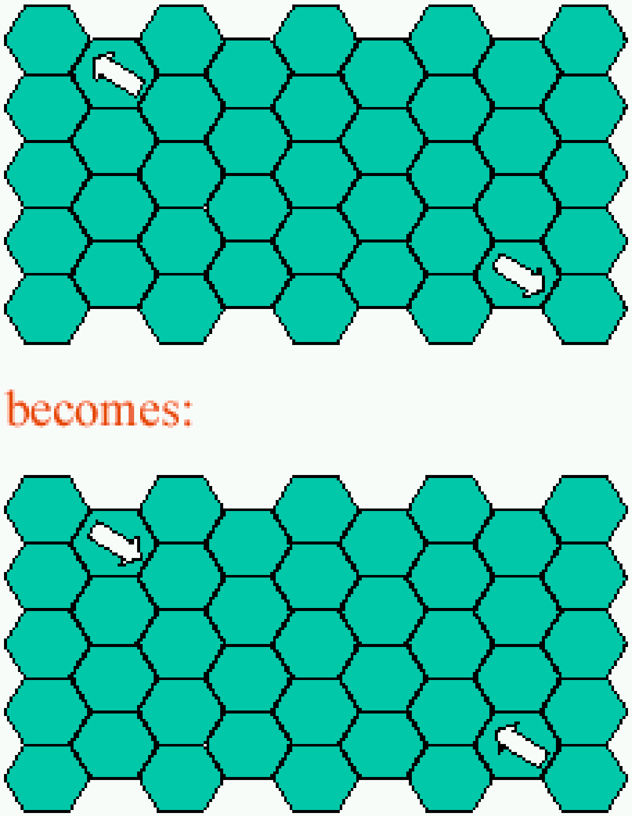




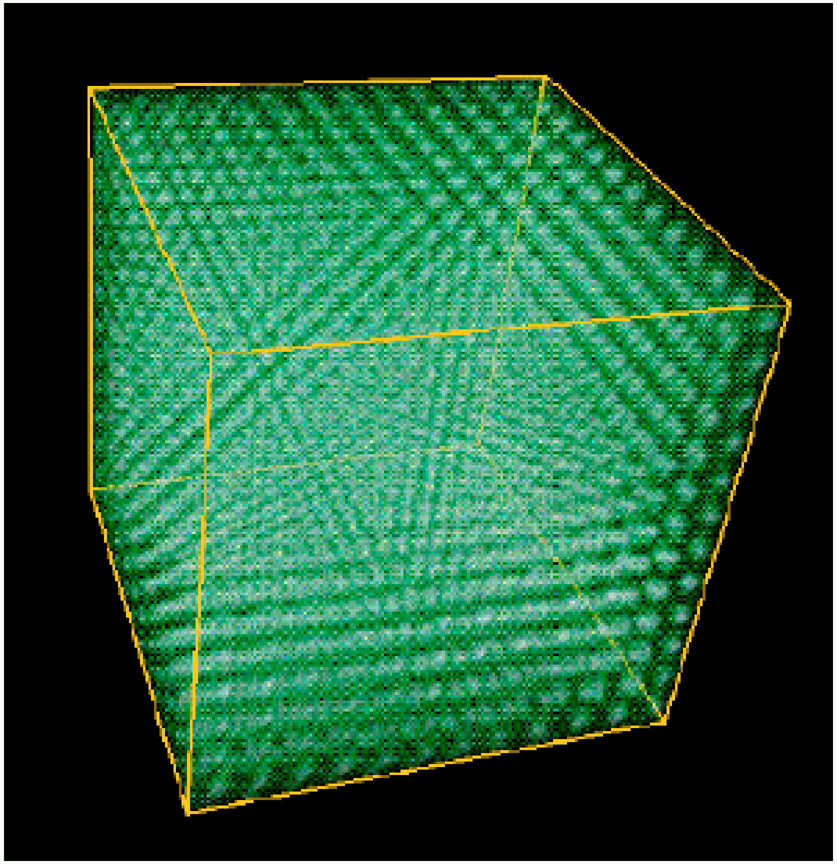
- *When a gas particle diffuses next to exactly one crystal particle, it crystallizes and emits a heat particle.*
- *The reverse also happens.*

for more info, see cond-mat/9810258

Adding forces irreversibly

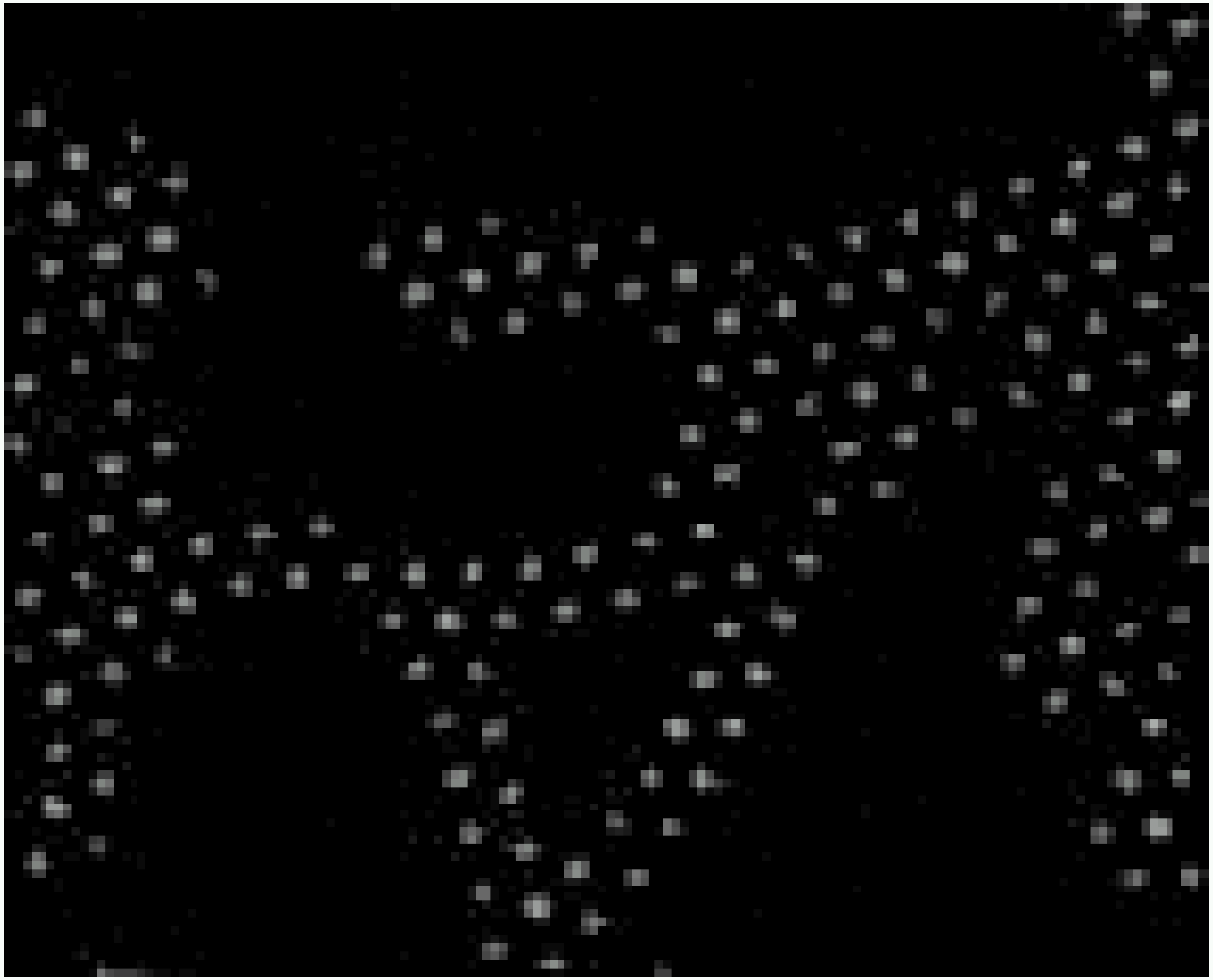


Particles six sites apart along the lattice attract each other.



3D momentum conserving crystallization.

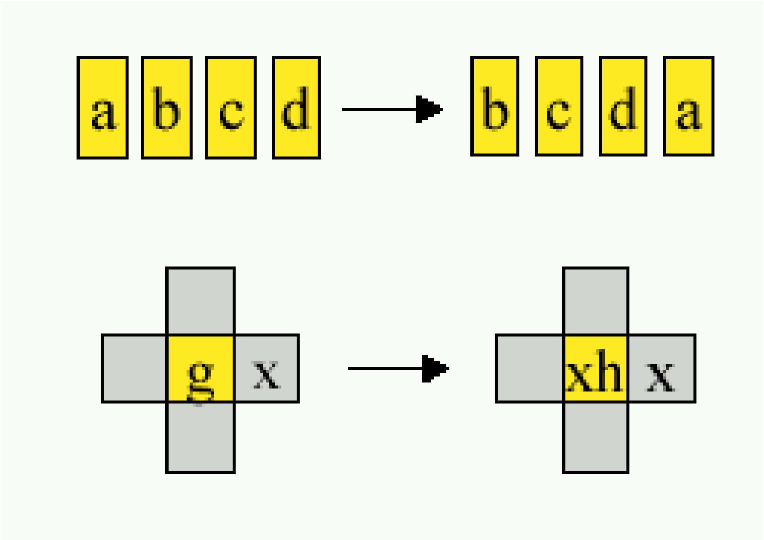
Adding forces irreversibly



Crystallization using irreversible forces (Jeff Yepez, AFOSR)

Conservations summary

- To make conservations manifest, we employ a sequence of steps, in each of which either
  - *1. the data are rearranged without any interaction*, or
  - *2. the data are partitioned into disjoint groups of bits that change as a unit.*
- *Data that affect more than one such group don't change.*



- Conservations allow computations to map efficiently onto microscopic physics, and also allow them to have **interesting macroscopic behavior**.