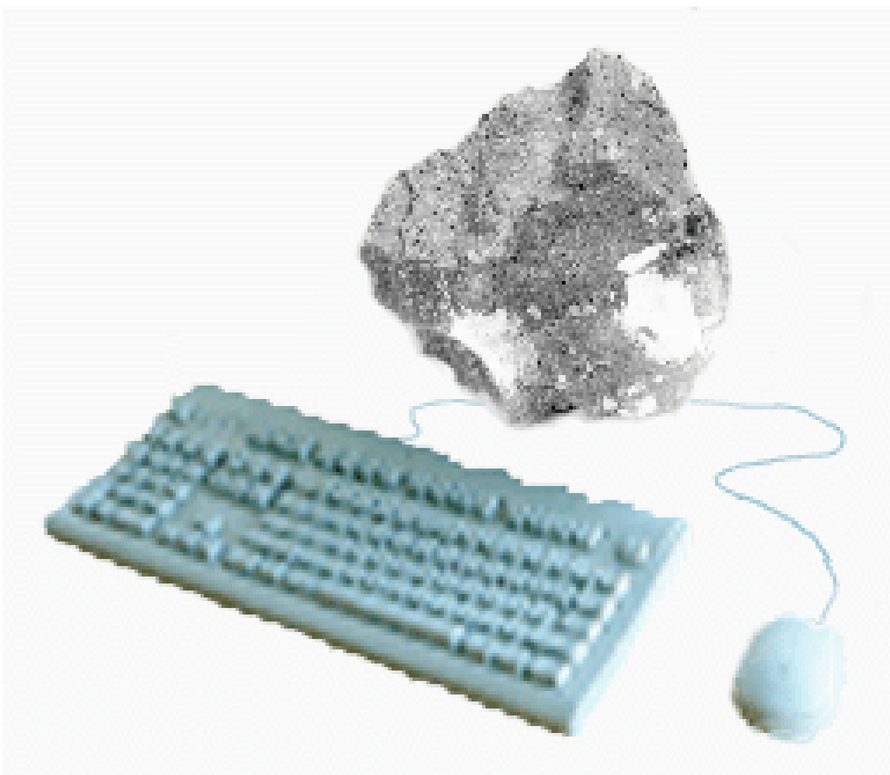
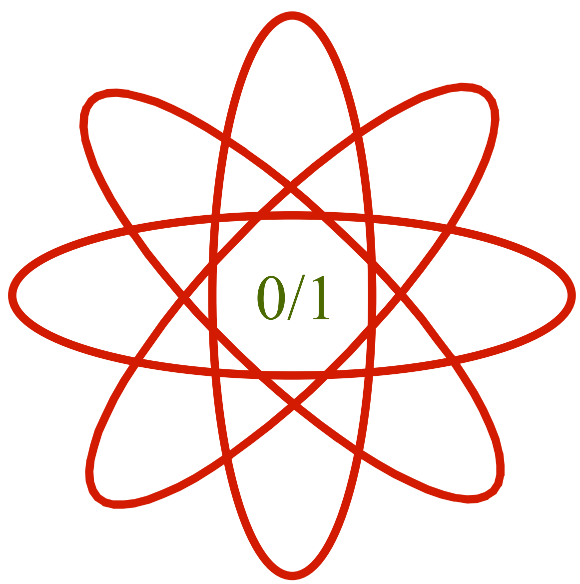
Computing Beyond Silicon Summer School

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*

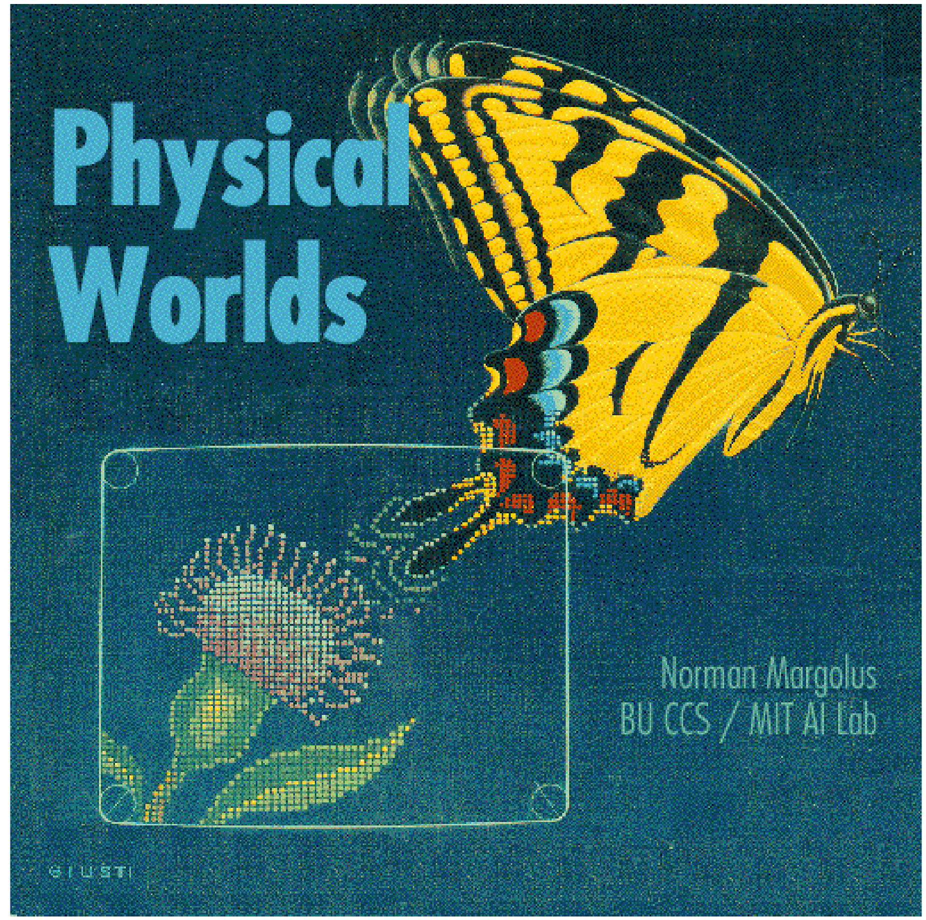
Spatial Computers
- » *Architectures and algorithms for large-scale spatial computations*

Nature as Computer
- » *Physical concepts enter CS and computer concepts enter Physics*

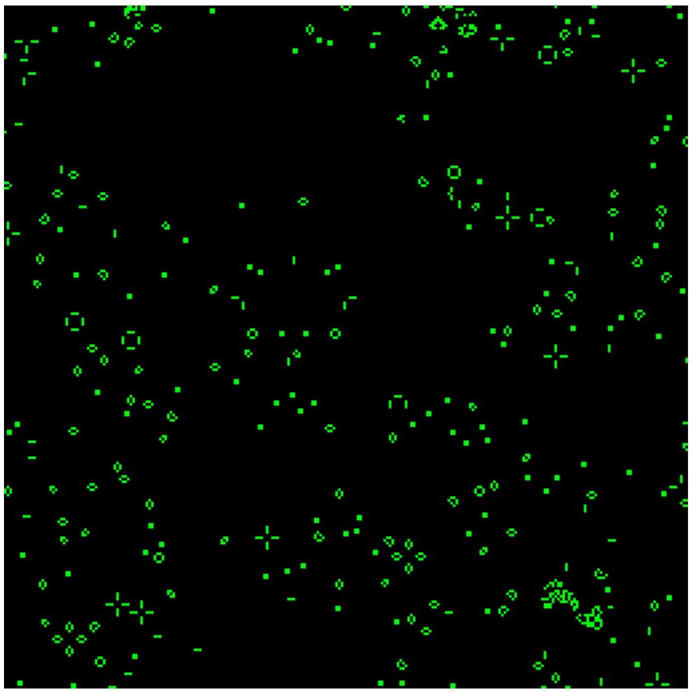
Review: Why emulate physics?

- Comp must adapt to microscopic physics
- Comp models may help us understand nature
- Rich dynamics

- Started with locality (*Cellular Automata*).



Review: Conway's "Life"



256x256 region of a larger grid. Activity has mostly died off.

- 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

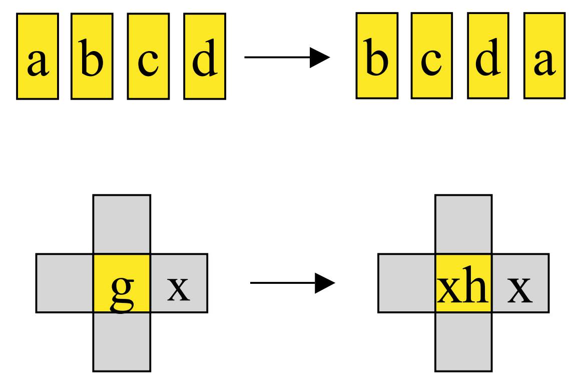
Observation:

- It's hard to create (or discover) conservations in conventional CA's.

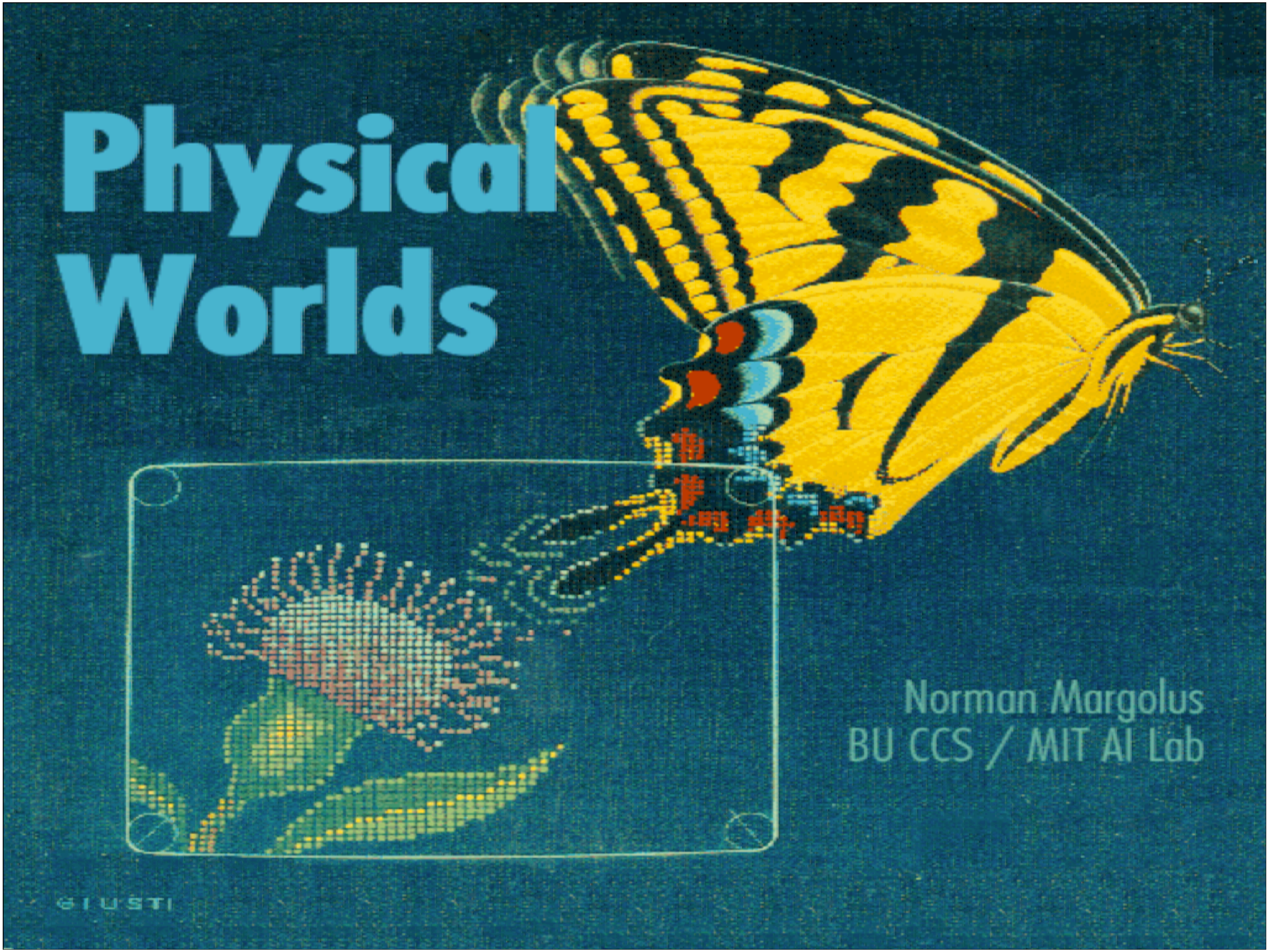
Review: CA's with conservations

To make reversibility and other conservations manifest, we employ a multi-step update, in each step 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. *Such CA's have hardly been studied.*

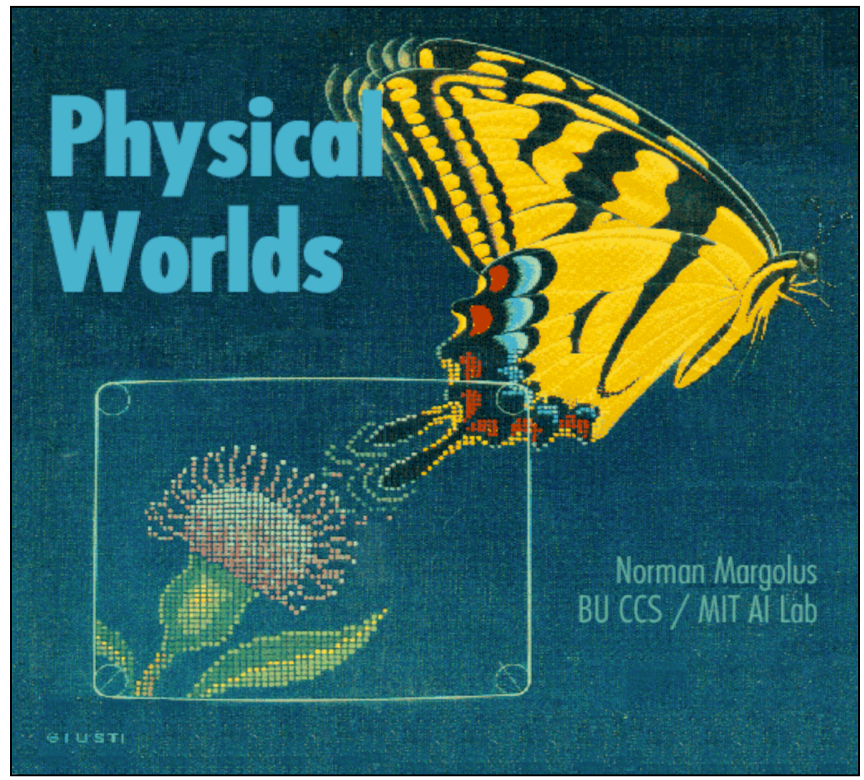

Physical
Worlds
Norman Margolus
BU CCS / MIT AI Lab
GIUSTI

Physical Worlds

Some regular spatial systems:

1. Programmable gate arrays at the atomic scale
2. Fundamental finite-state models of physics
3. Rich "toy universes"

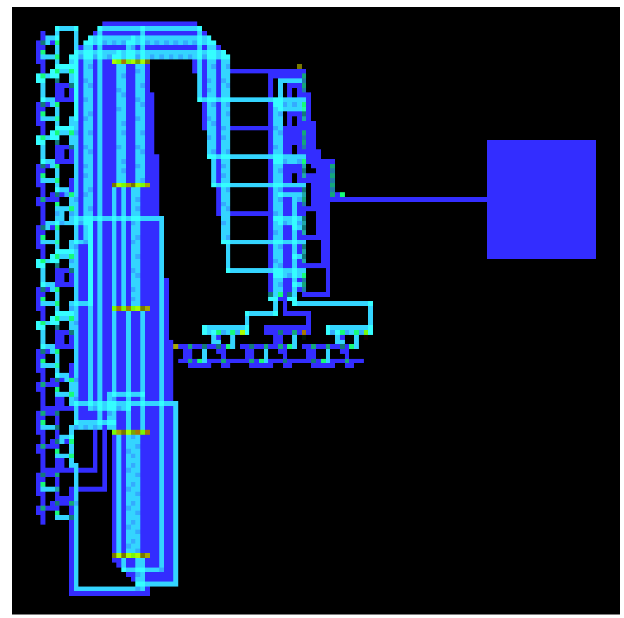
- *All of these systems must be computation universal*



Computation Universality

If you can build basic logic elements and connect them together, then you can construct any logic function -- your system can do anything that any other digital system can do!

- It doesn't take much.
- Can construct CA that support logic.
- Can discover logic in existing CAs (eg. Life)
- Universal CA can simulate any other



Logic circuit in gate-array-like CA

Computation Universality

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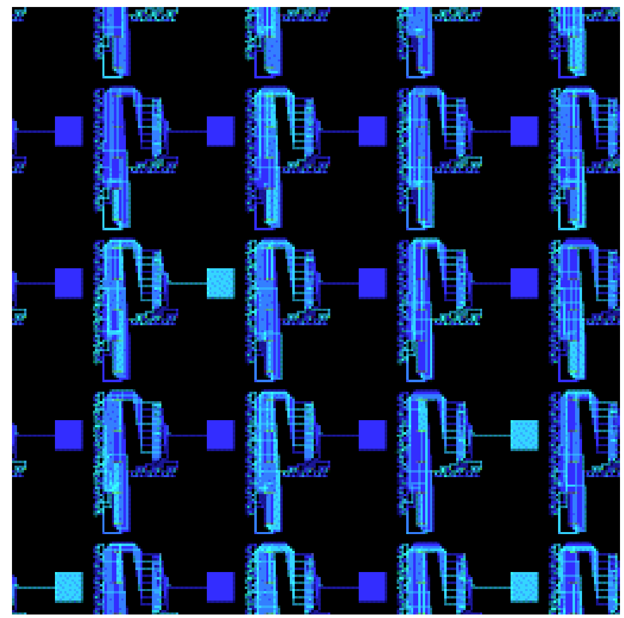
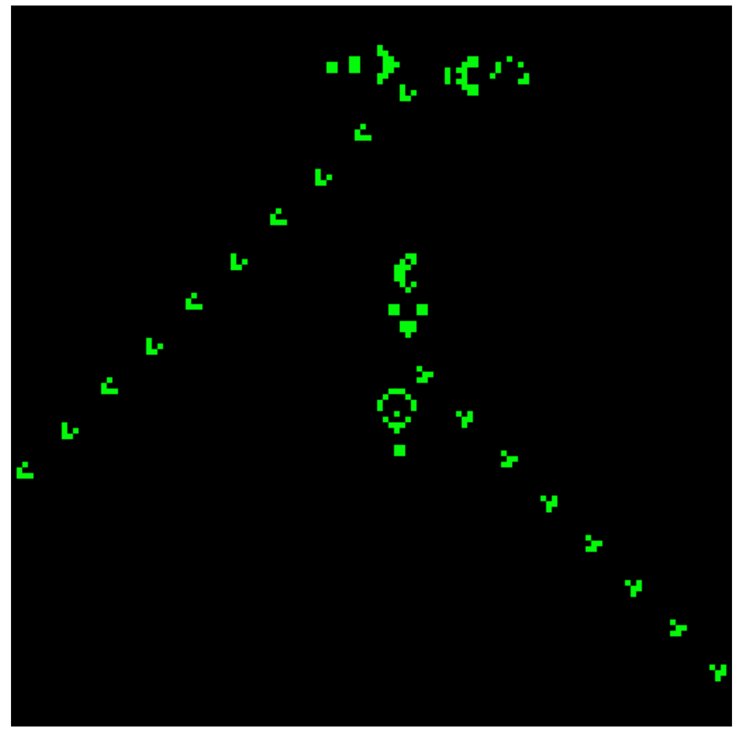


Logic circuit in gate-array-like CA

What's wrong with Life?

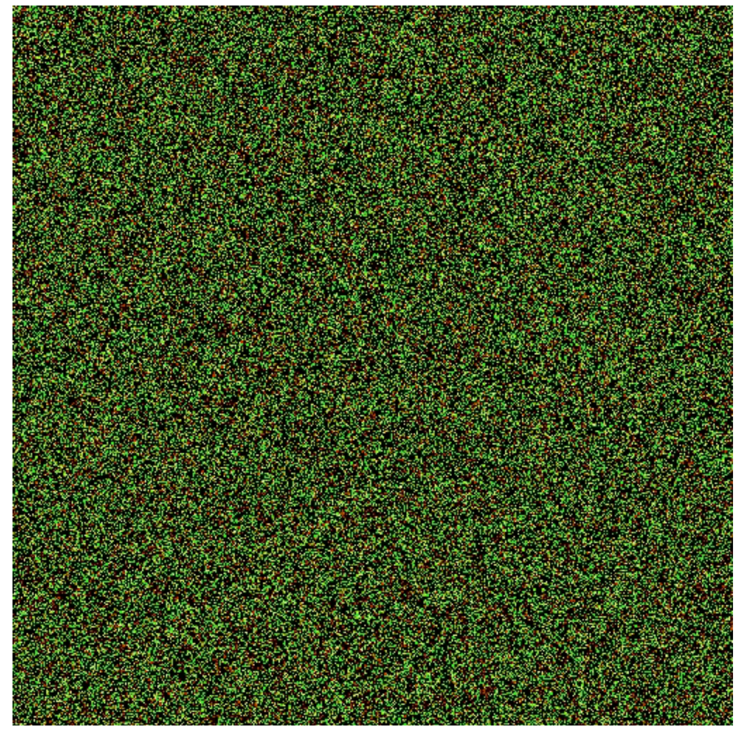
- One can build signals, wires, and logic out of patterns of bits in the Life CA



Glider guns in Conway's "Game of Life" CA. Streams of gliders can be used as signals in Life logic circuits.

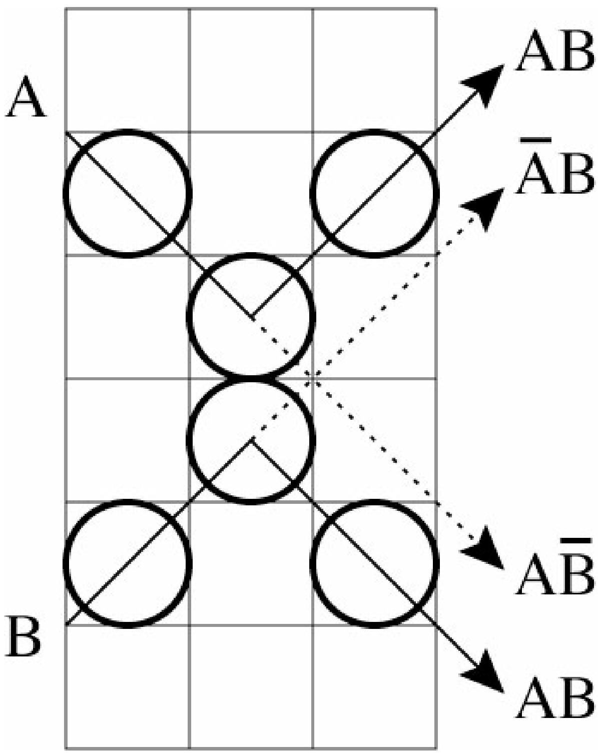
What's wrong with Life?

- One can build signals, wires, and logic out of patterns of bits in the Life CA
- Life is short!
- Life is microscopic
- Can we do better with a more physical CA?



Life on a 2Kx2K space, run from a random initial pattern. All activity dies out after about 16,000 steps.

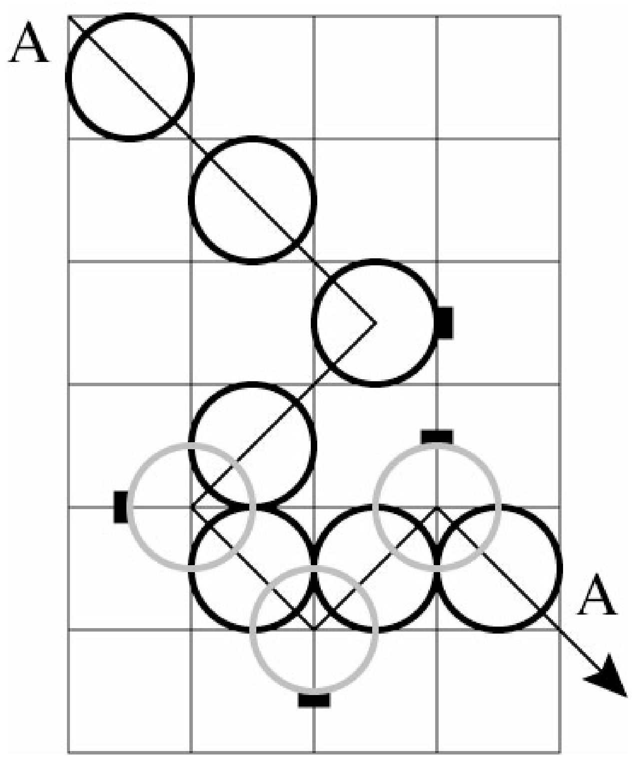
Billiard Ball Logic



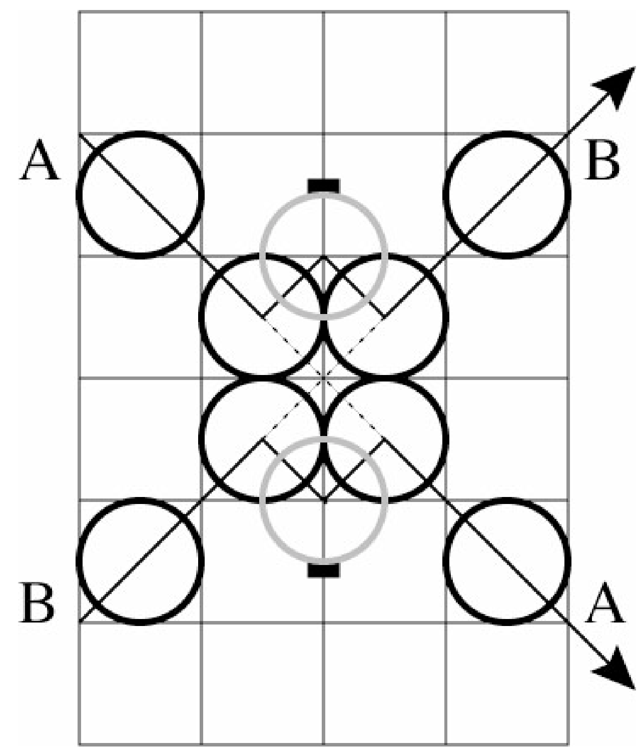
Fredkin's reversible Billiard Ball Logic Gate

- Simple reversible logic gates can be universal
- Turn continuous model into digital at discrete times!
- (A,B)□ AND(A,B) isn't reversible by itself
- Can do better than just throw away extra outputs
- Need to also show that you can *compose* gates

Billiard Ball Logic

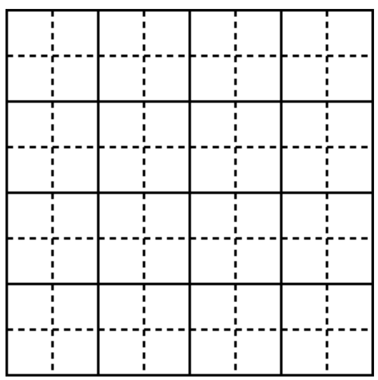


Fixed mirrors allow signals to be routed around.

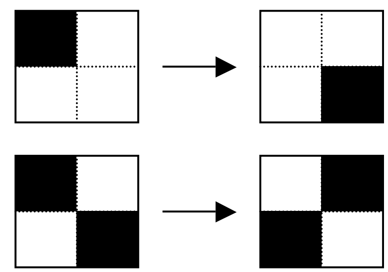


Mirrors allow signals to cross without interaction.

A BBM CA rule

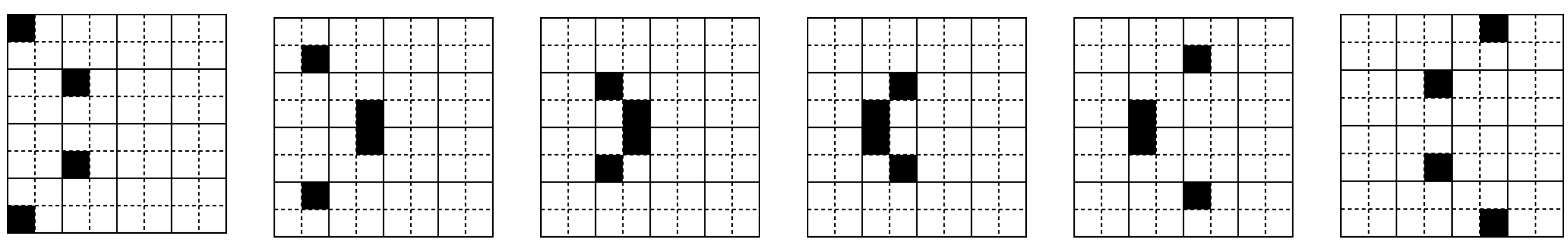


2x2 blockings.
The solid blocks are used at even time steps, the dotted blocks at odd steps.

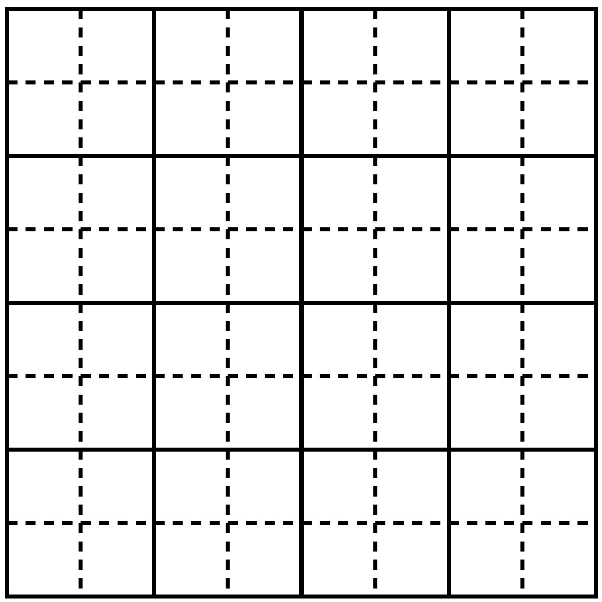


BBMCA rule.
Single one goes to opposite corner, 2 ones on diagonal go to other diag, no other cases change.

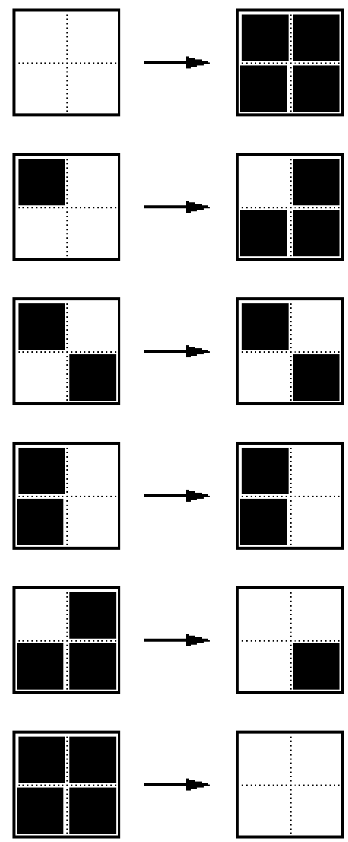
A BBMCA collision:



The “Critters” rule



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

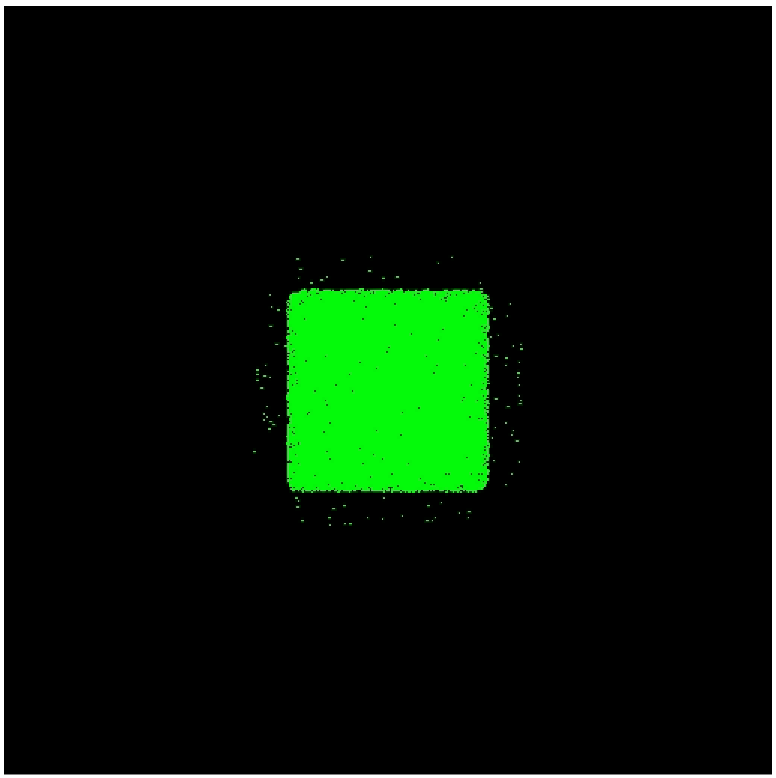


This rule is applied both to the even and the odd blockings.

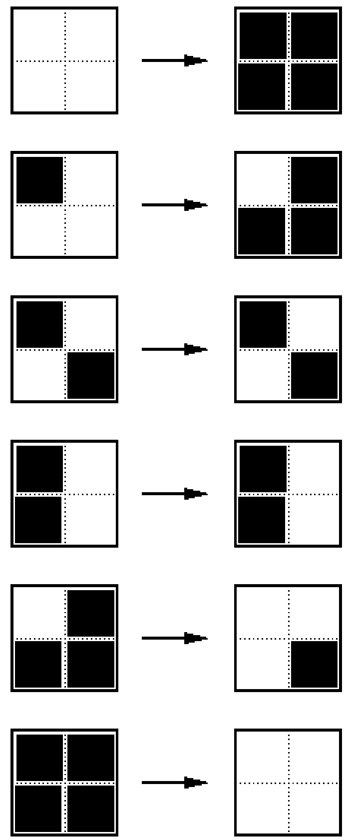
We show all cases: each rotation of a case on the left maps to the corresponding rotation of the case on the right.

Note that the number of ones in one step equals the number of zeros in the next step.

The “Critters” rule



Reversible “Critters” rule, started from a low-entropy initial state (2Kx2K).



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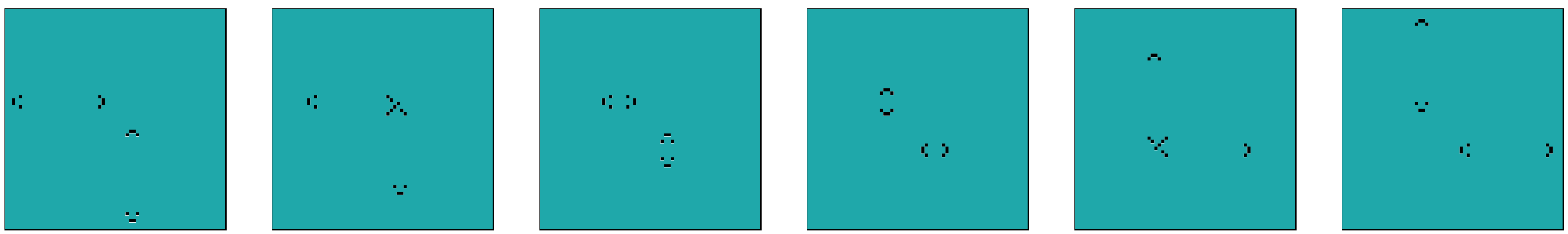
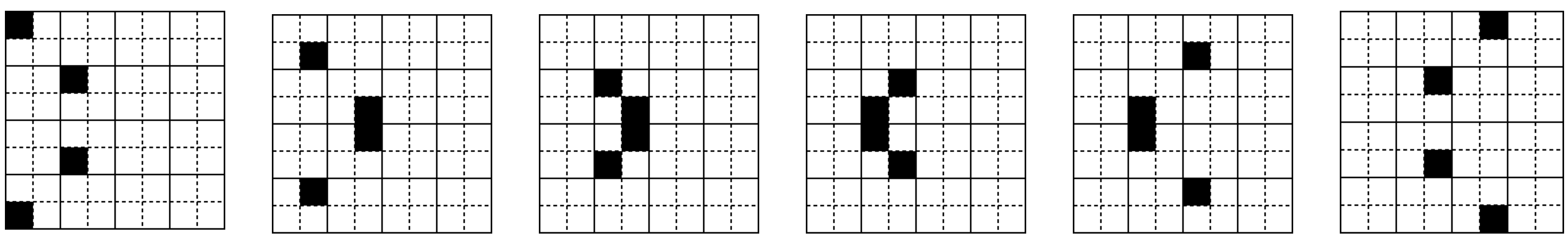
“Critters” is universal

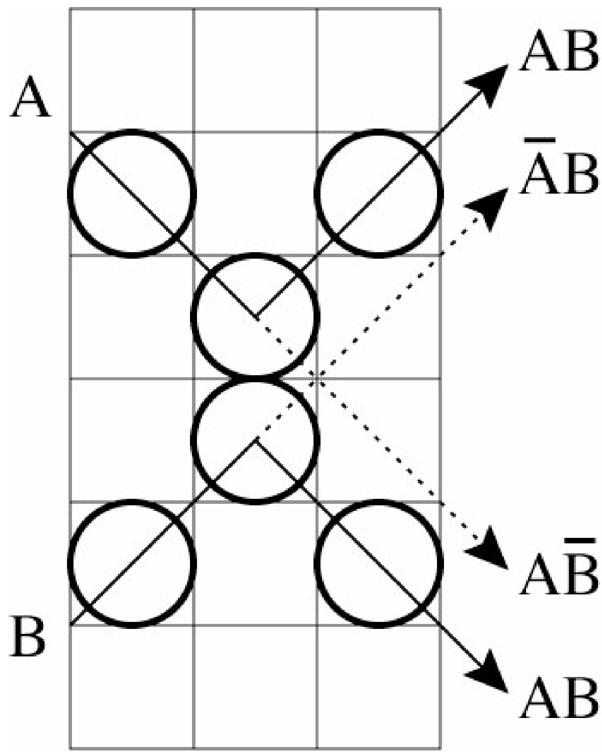
Critters “glider” collision:



A BBMCA collision:



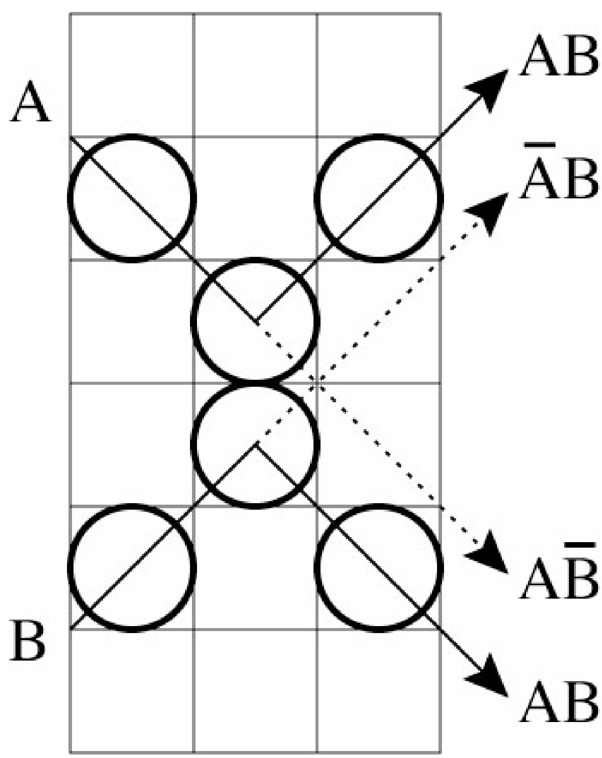
UCA with momentum conservation



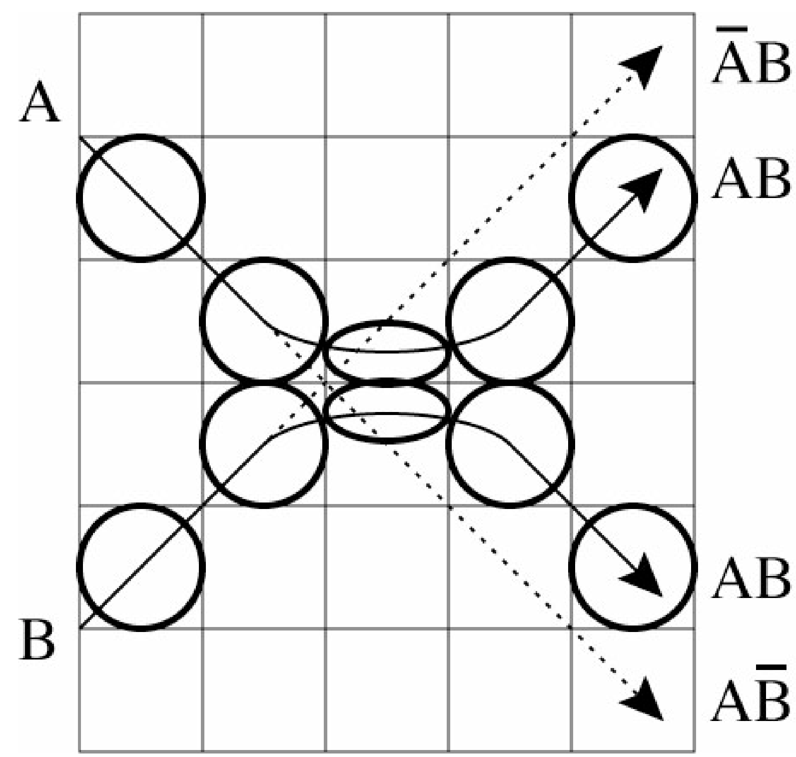
Hard sphere collision

- Hard-sphere collision conserves momentum
- Can’t make simple CA out of this that does
- *Problem:* finite impact parameter required
- *Suggestion:* find a new physical model!

UCA with momentum conservation

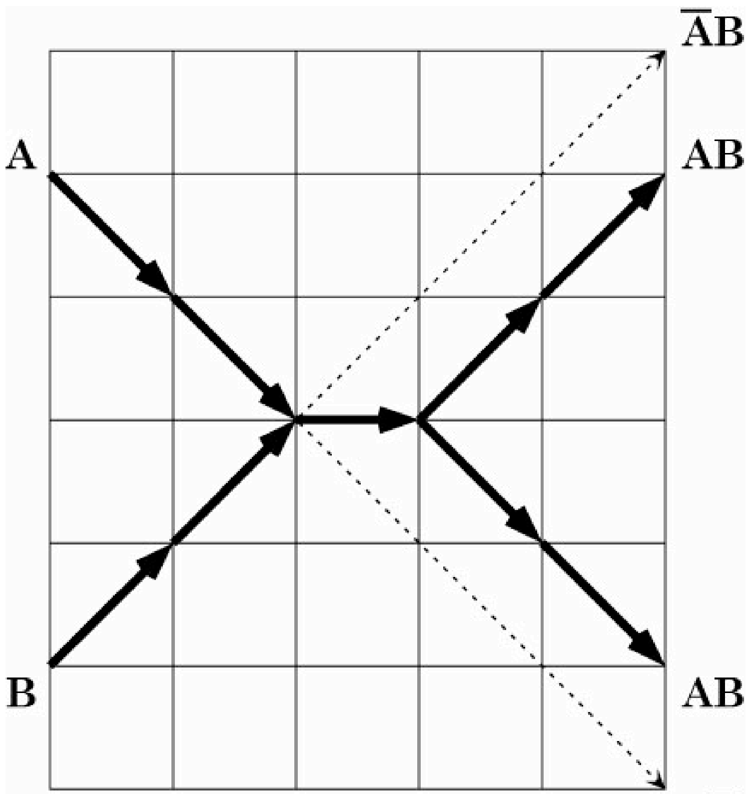


Hard sphere collision

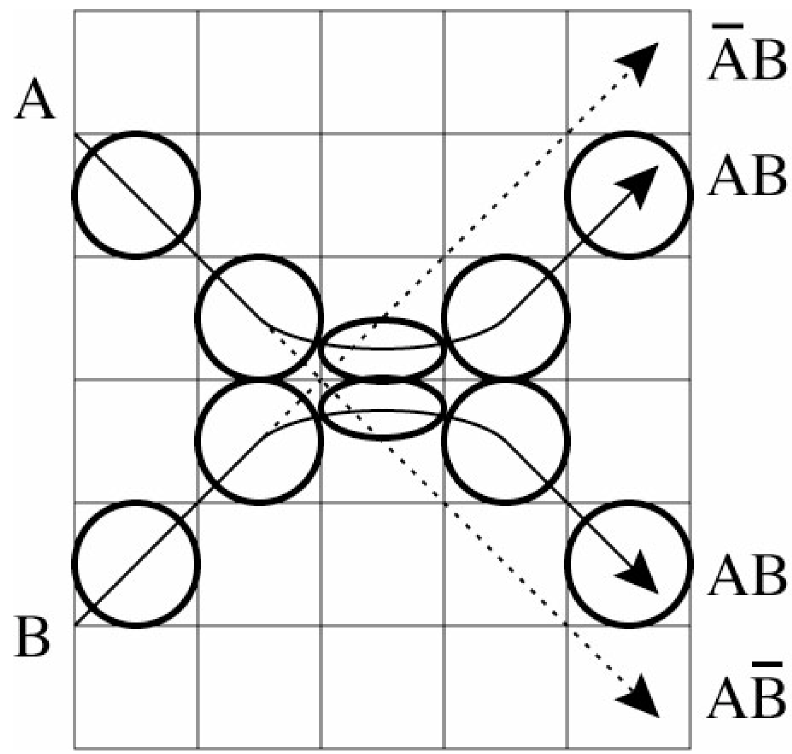


Soft sphere collision

UCA with momentum conservation



Can shrink balls to points!



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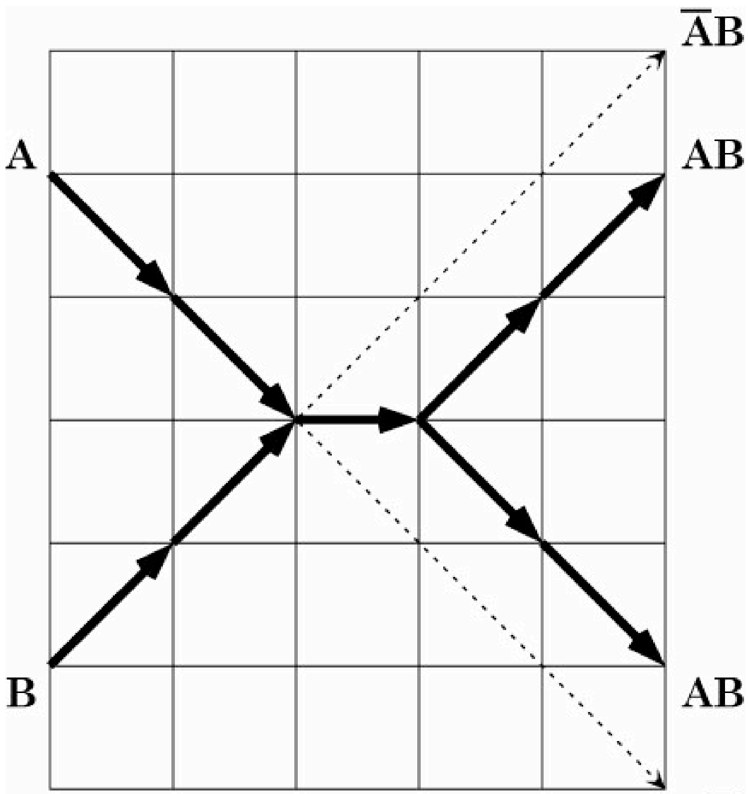

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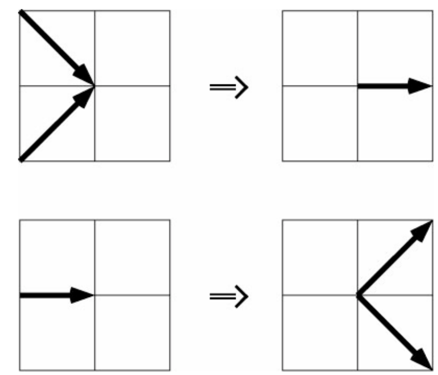
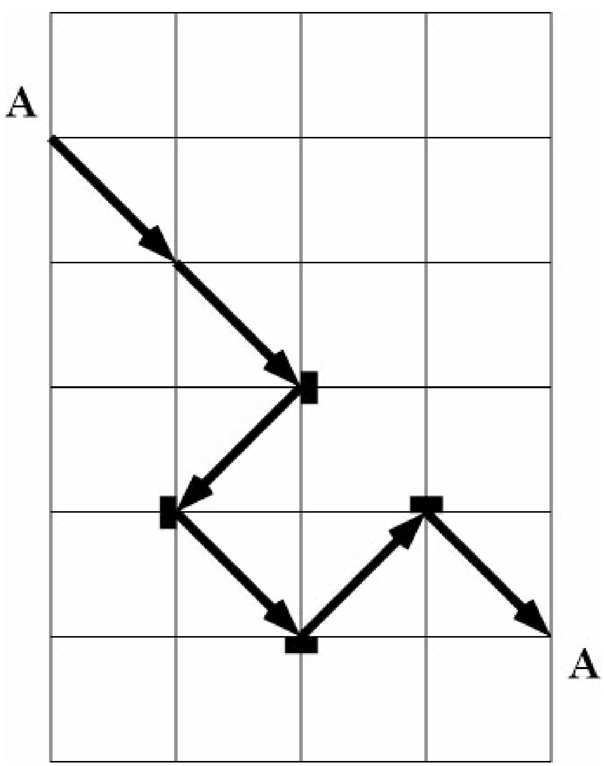
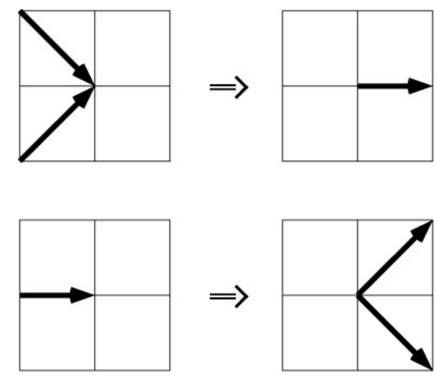


SSM rule: rotations also act like this. All other cases remain unchanged. This is a ***Lattice Gas****:* ***movement*** *and* ***interaction*** *steps alternate.*

UCA with momentum conservation



Add mirrors at lattice points to guide balls.



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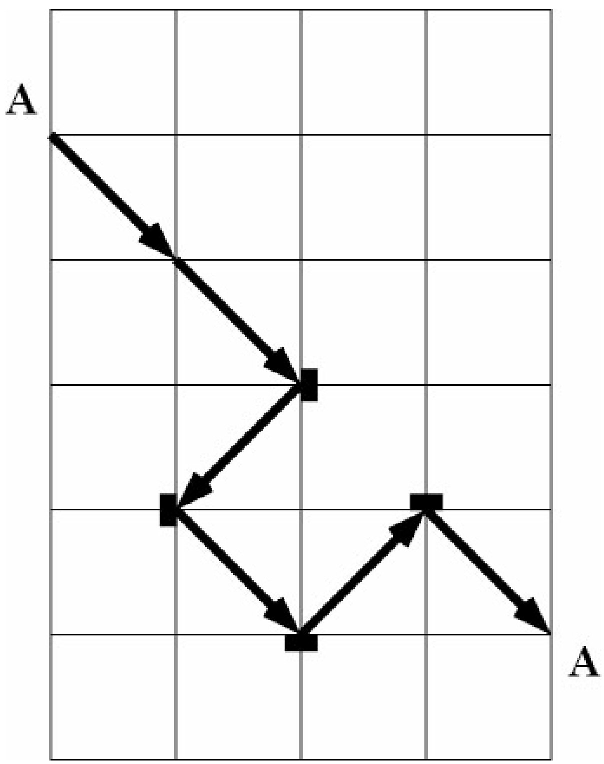
UCA with momentum conservation



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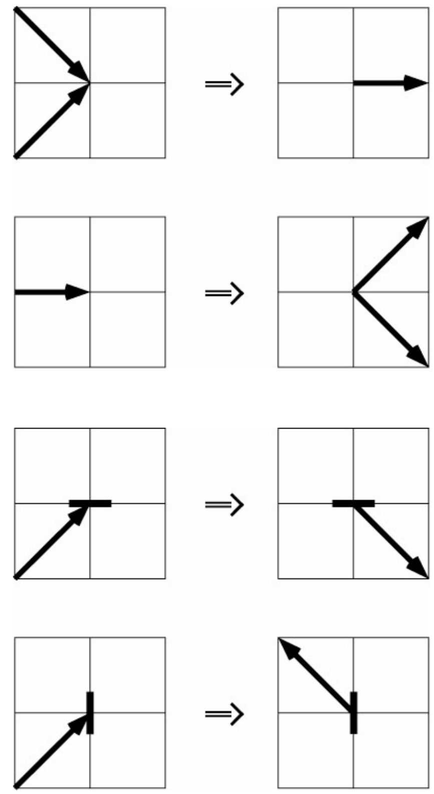
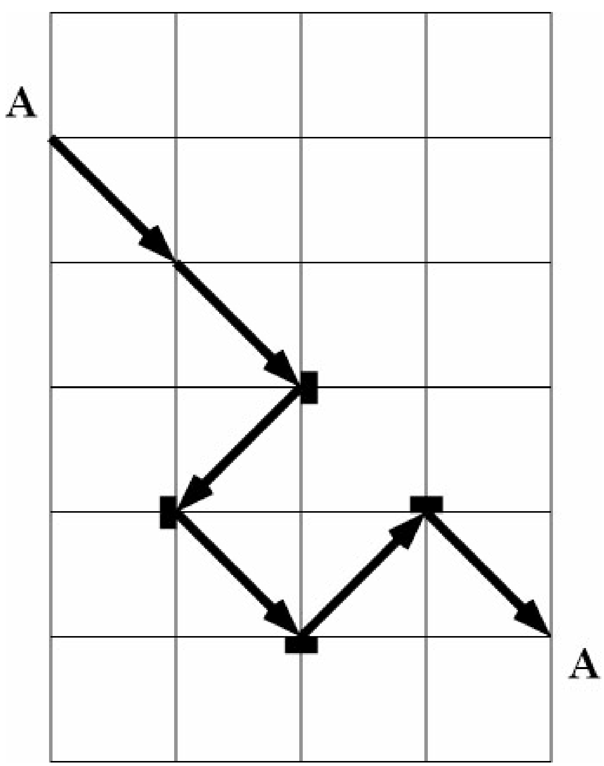


SSM rule with mirrors

UCA with momentum conservation



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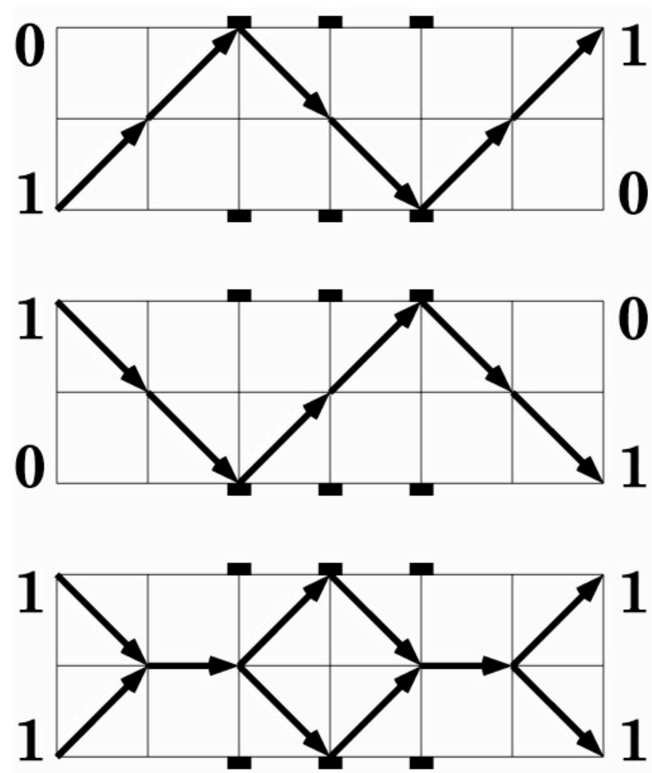
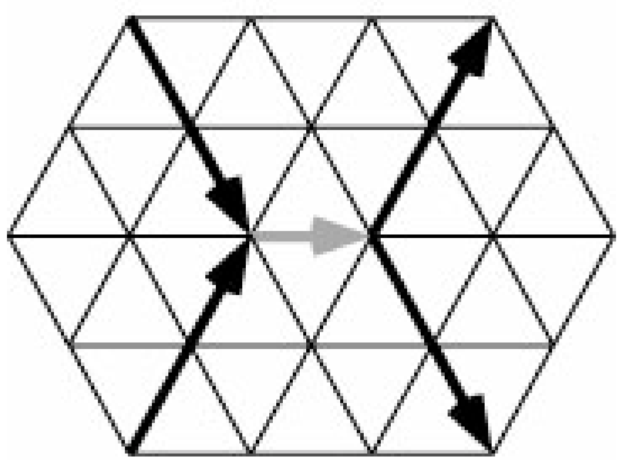
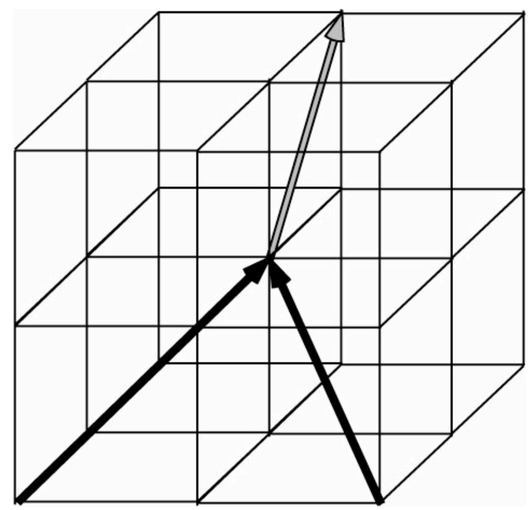


Mirrors allow signals to cross without interacting.

SSM collisions on other lattices

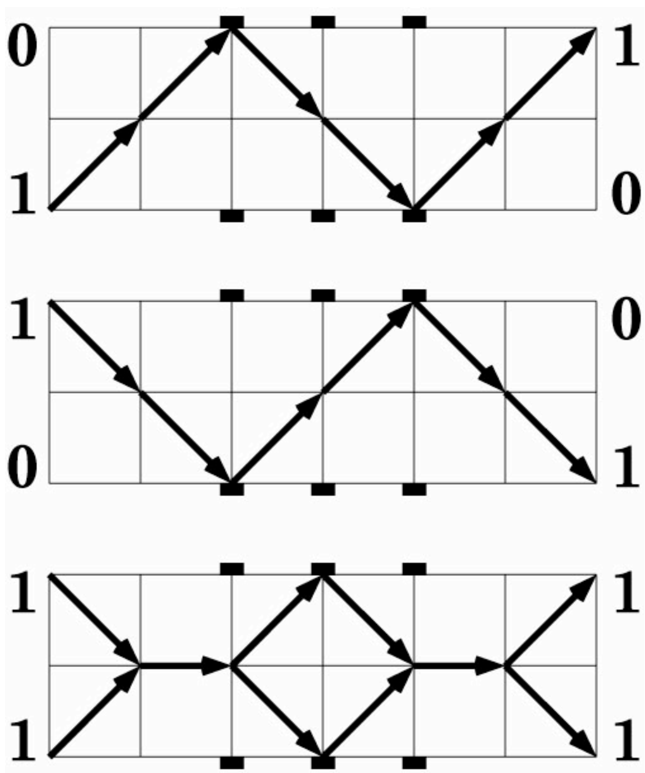


Triangular lattice



3D Cubic lattice

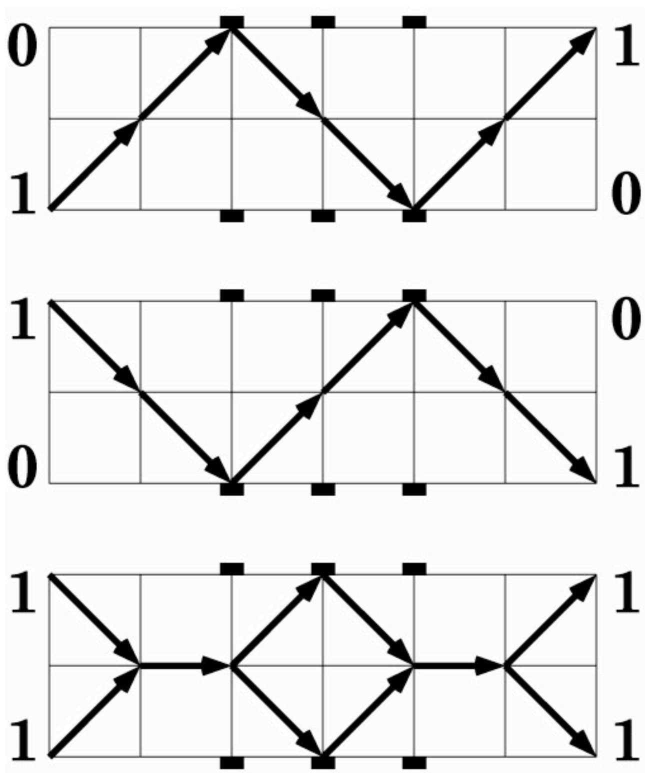
Getting rid of mirrors



Mirrors allow signals to cross without interacting.

- SSM with mirrors does *not* conserve momentum
- Mirrors must have infinite mass
- Want both universality and mom conservation
- Can do this with just the SSM collision!

Getting rid of mirrors



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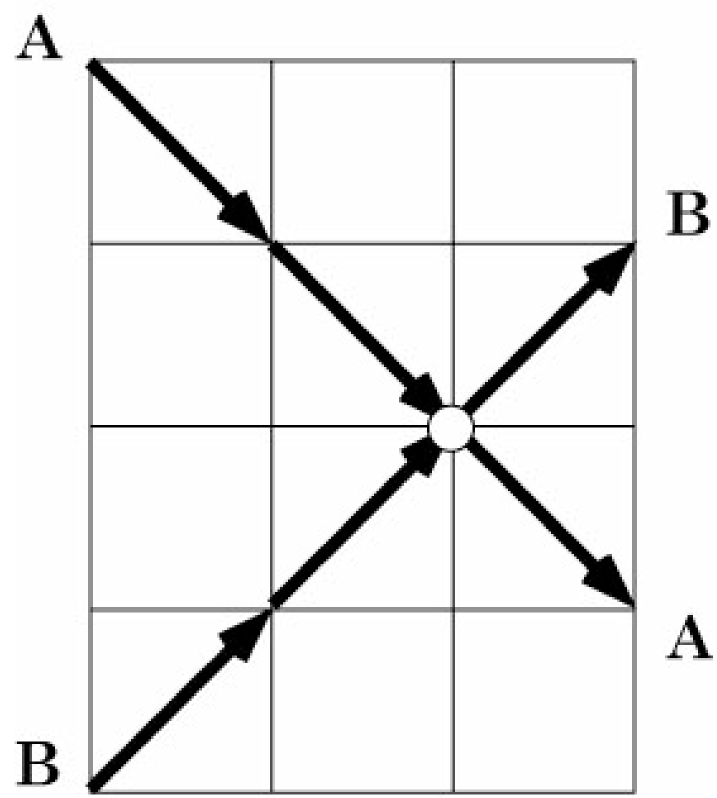
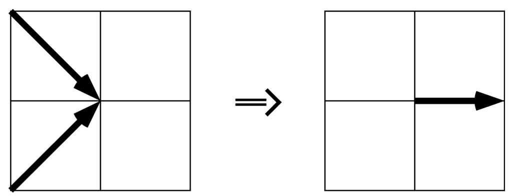
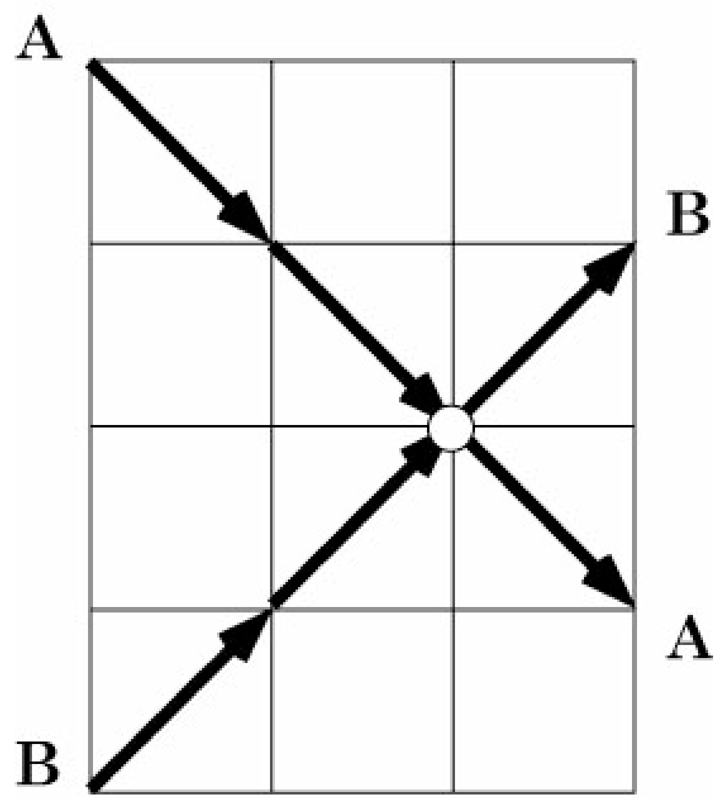


Adding a rest particle allows signals to cross.

Getting rid of mirrors



- The rule is very simple without mirrors: just one collision and it’s inverse.
- All other cases, including the rest particle case, go straight through.



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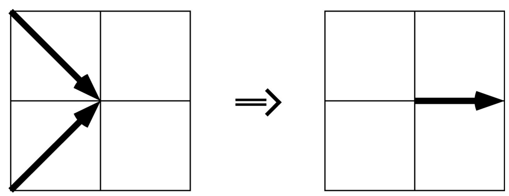
Getting rid of mirrors



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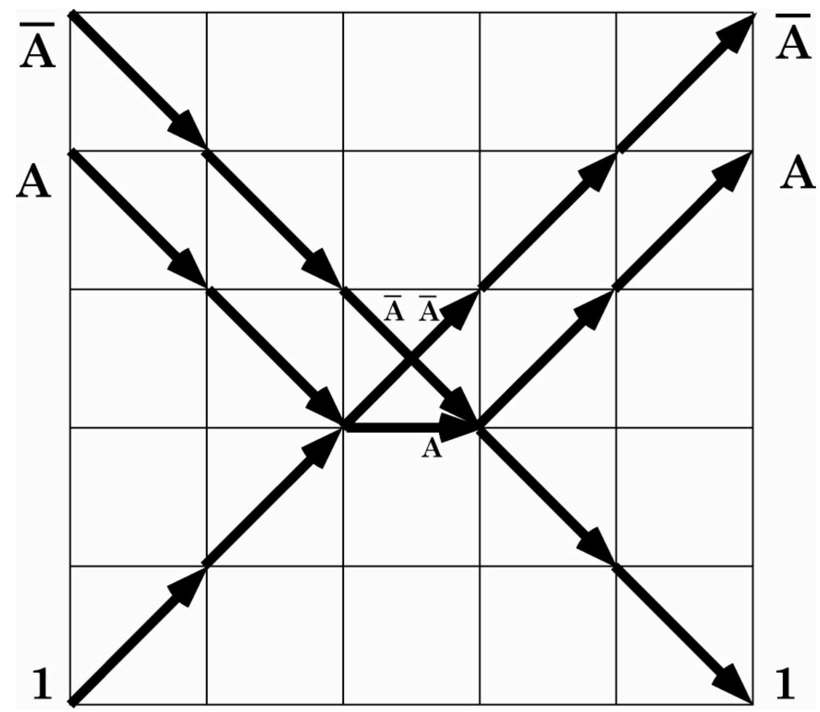
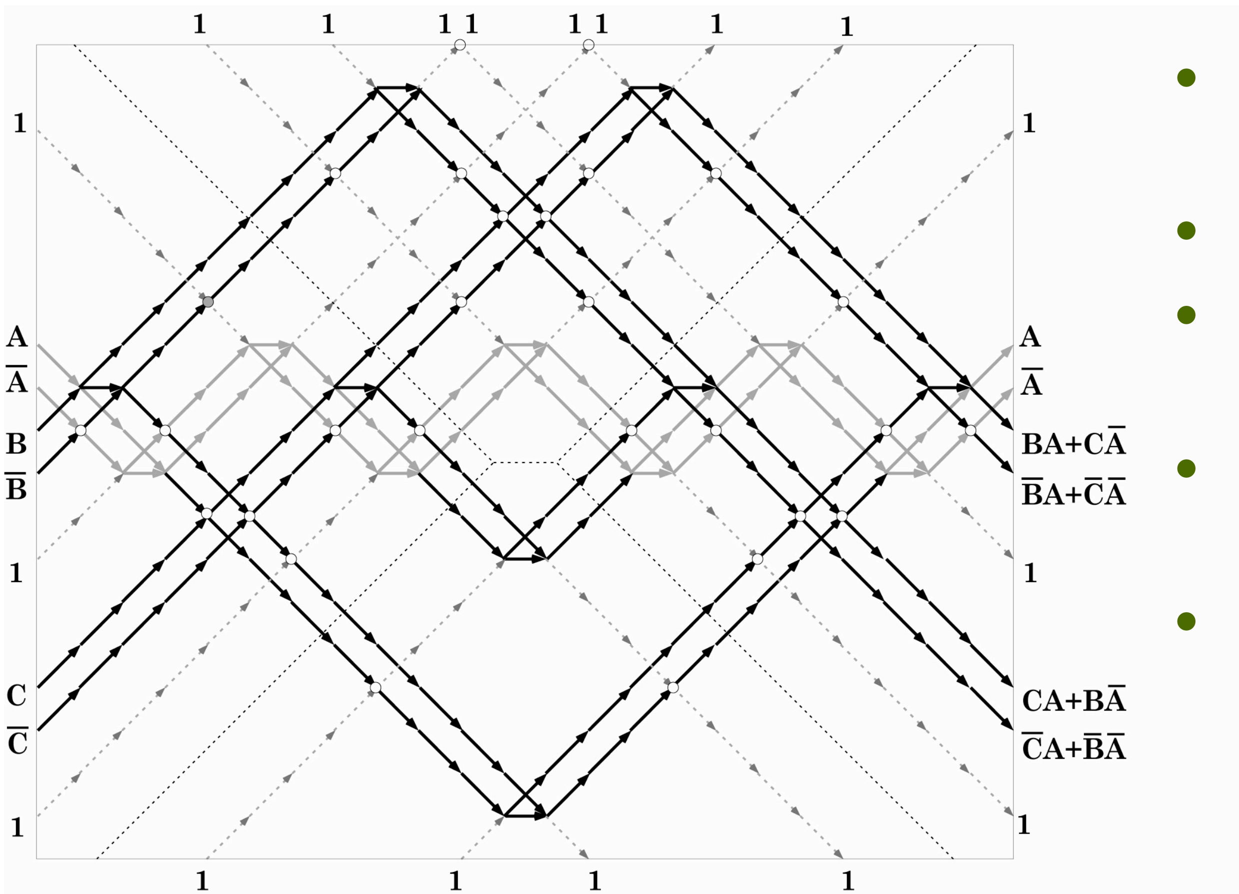


Pairing every signal with its complement allows constant streams of 1's to act like mirrors

Getting rid of mirrors



- Fredkin Gate, built in SSM
- No mirrors
- Constants of 1 act as mirrors
- Dual-rail pairs used as signals
- Can show that 1's can be reused by building BBMCA in SSM

Macroscopic universality

*With exact **microscopic** control of every bit, the SSM model lets us compute reversibly and with momentum conservation, but*

- an interesting world should have **macroscopic** complexity!
- **Relativistic invariance** would allow large-scale structures to move: *laws of physics same in motion*
- This would allow a robust Darwinian evolution
- Requires us to reconcile forces and conservations with invertibility and universality.

Relativistic conservation

Non-relativistic:

$$\sum \tfrac{1}{2} m_i v^2 = \sum \tfrac{1}{2} m_i v_i'^2 \quad \text{(energy)}$$

$$\sum m_i = \sum m_i' \quad \text{(mass)}$$

$$\sum m_i \vec{v}_i = \sum m_i \vec{v}_i' \quad \text{(mom)}$$

Relativistic:

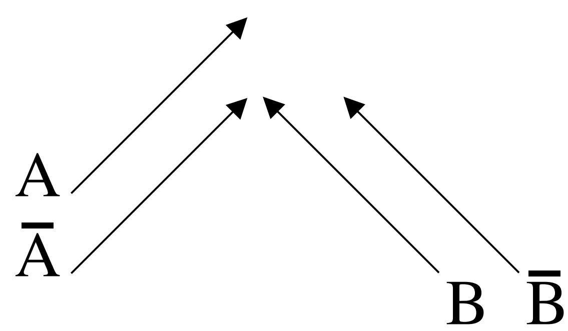
$$\sum E = \sum E' \quad \text{(energy)}$$

$$\sum E_i \vec{v}_i = \sum E_i' \vec{v}_i' \quad \text{(mom)}$$

(since $\vec{p} = \gamma m \vec{v} = \gamma m c^2 \cdot \vec{v} / c^2$)

- Non-relativistically, mass and energy are conserved separately
- Simple lattice gasses that conserve only *m* and *mv* are more like rel than non-rel systems!

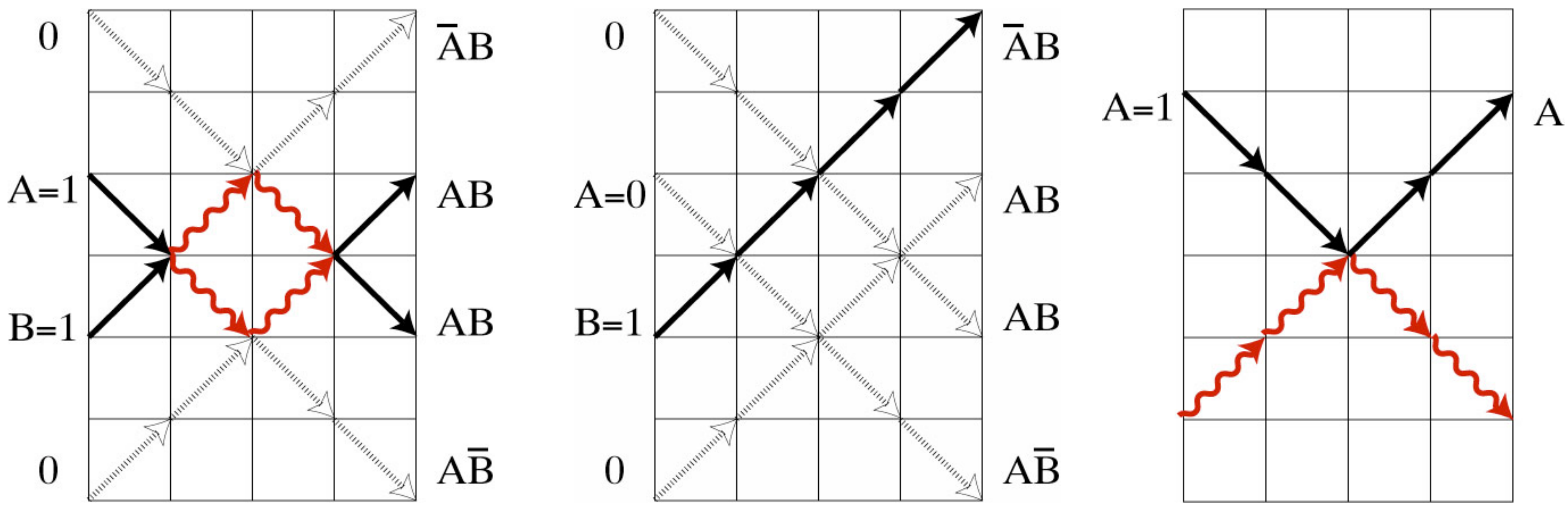
Relativistic conservation



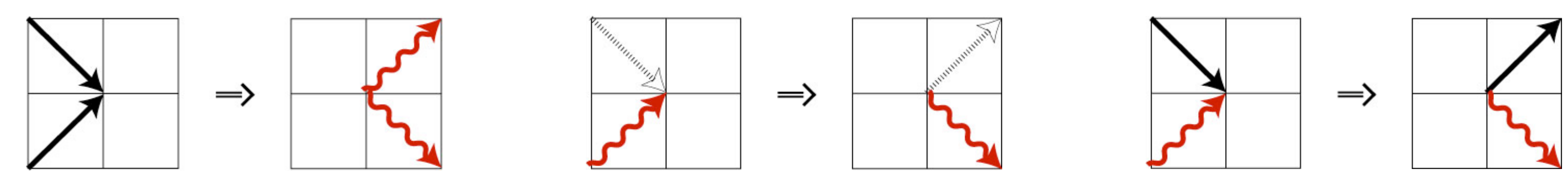
Dual-rail signals have a defect when it comes to allowing rotated signals to interact with each other.

- We used dual-rail signalling to allow constant 1's to act as mirrors
- Dual rail signals don't rotate very easily
- Suggestion: make an LGA in which you don't need dual-rail

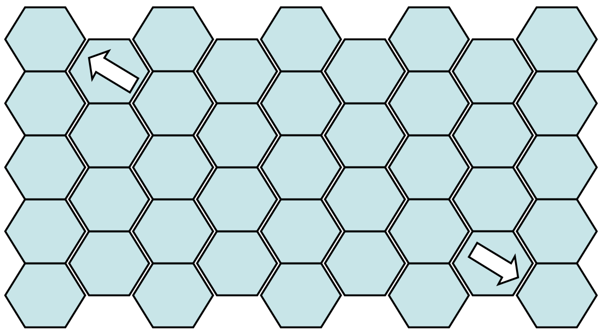
Relativistic conservation



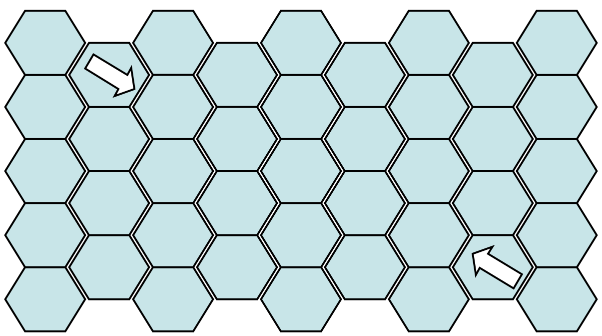
The rule we infer from this is:



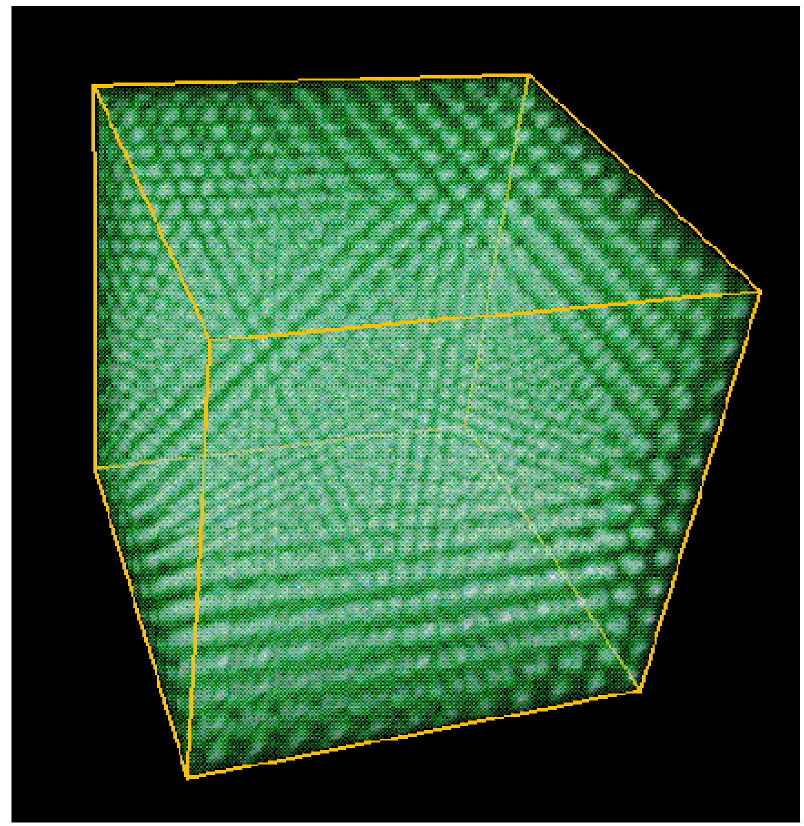
Can we add macroscopic forces?



becomes:

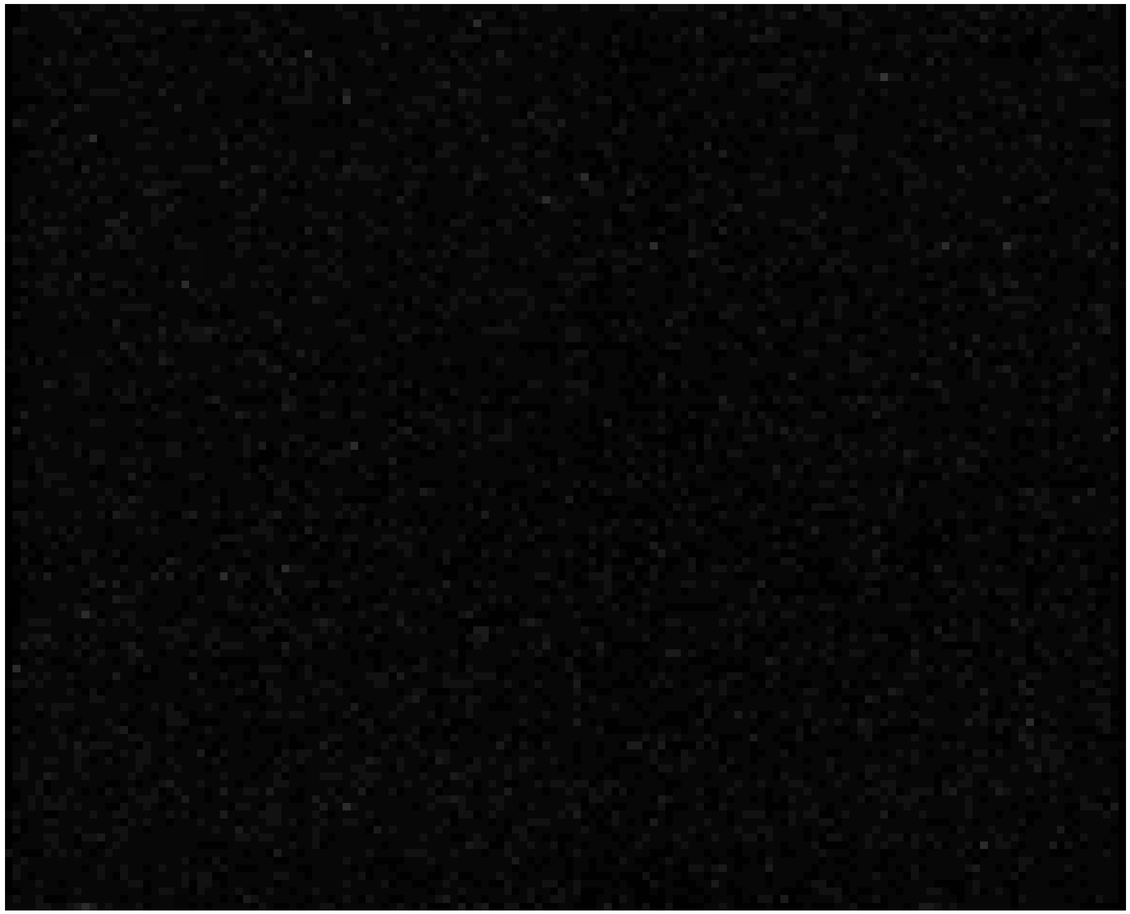


Particles six sites apart along the lattice attract each other.



3D momentum conserving crystallization.

Can we add macroscopic forces?

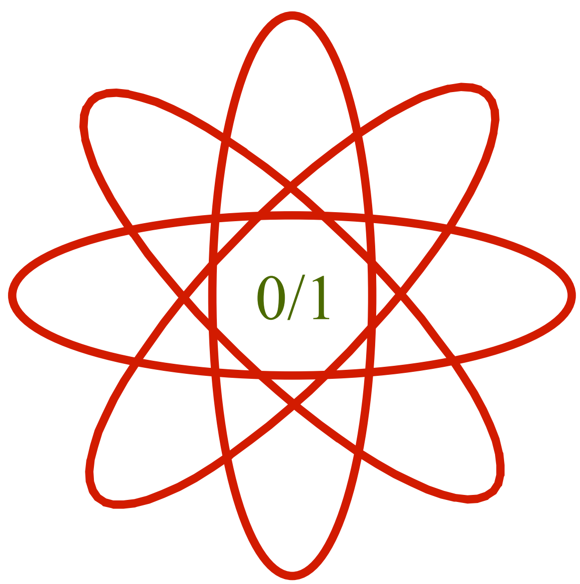


Crystallization using irreversible forces (Jeff Yepez, AFOSR)

Summary

- Universality is a low threshold that separates triviality from arbitrary complexity
- More of the richness of physical dynamics can be captured by adding physical properties:
  - » Reversible systems last longer, and have a realistic thermodynamics.
  - » Reversibility plus conservations leads to robust "gliders" and interesting macroscopic properties & symmetries.
- We know how to reconcile universality with reversibility and relativistic conservations

Physics becomes the computer



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Physical Worlds

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Spatial Computers

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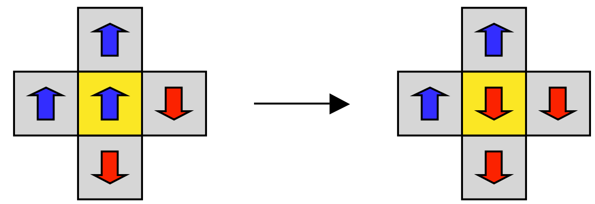
Nature as Computer

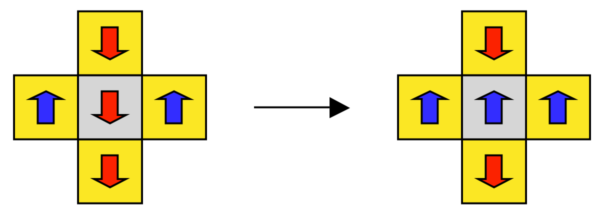
- » *Physical concepts enter CS and computer concepts enter Physics*

Problem from last lecture: 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.

Problem from last lecture: Dynamical Ising rule

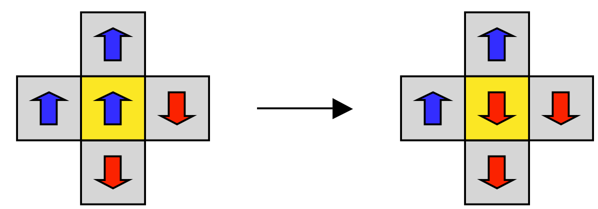
Problem:

- Show that the waves running along the boundary obey the wave equation exactly

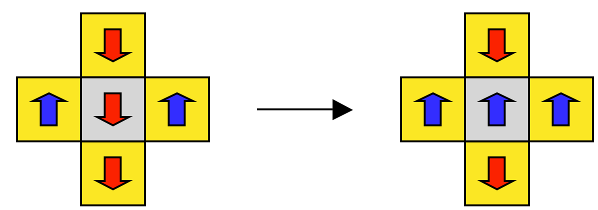
Hint:

- The wave equation's solutions consist of a superposition of right- and left-going waves

Even steps: update gold sublattice



Odd steps: update silver sublattice



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