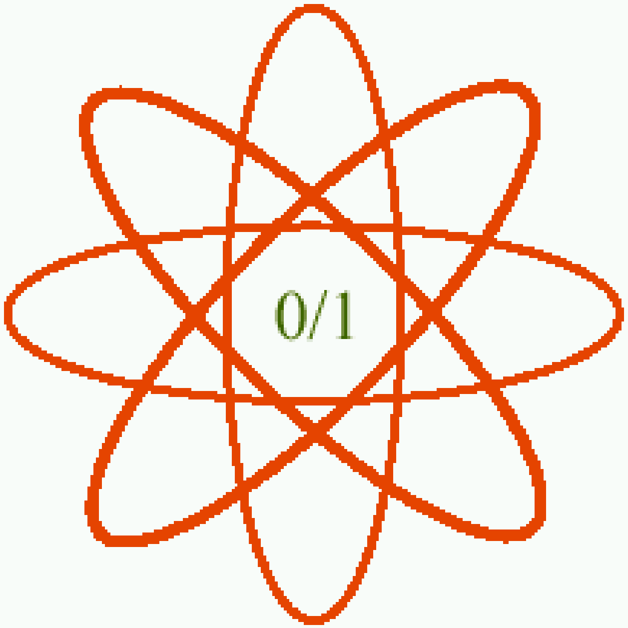
Lecture of Norm Margolus

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*

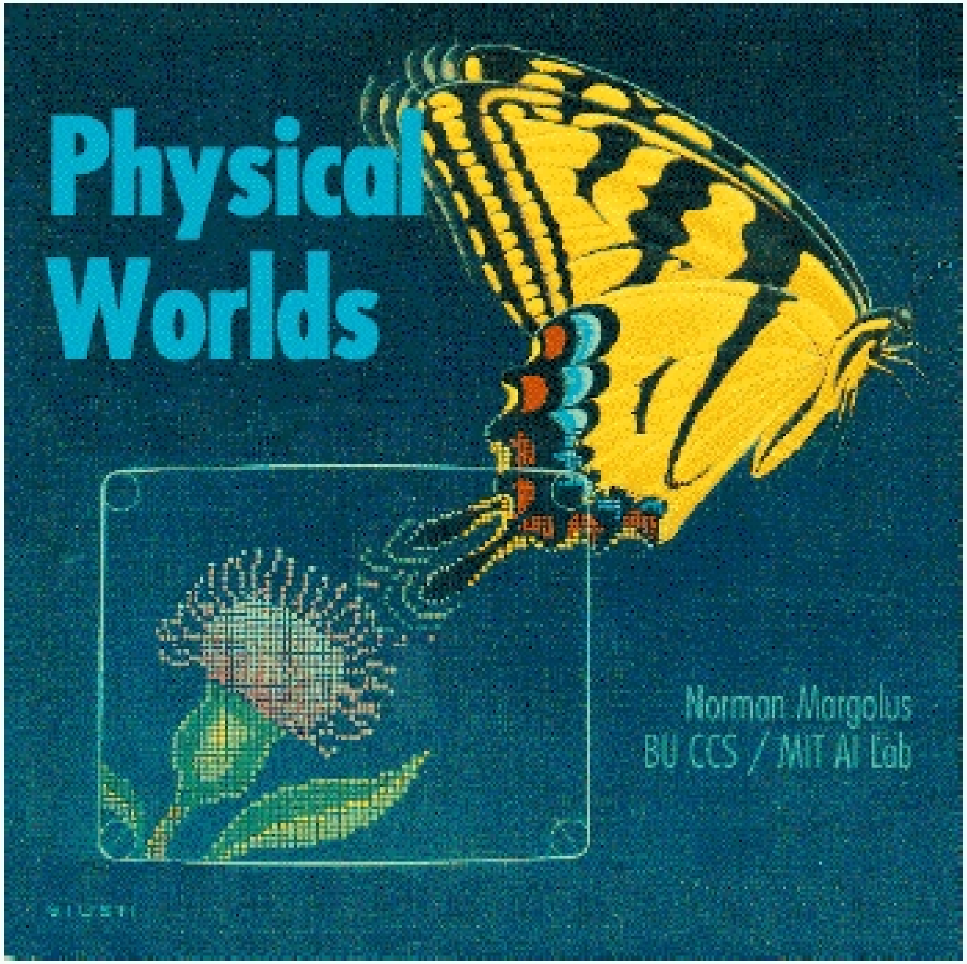
Nature as Computer

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

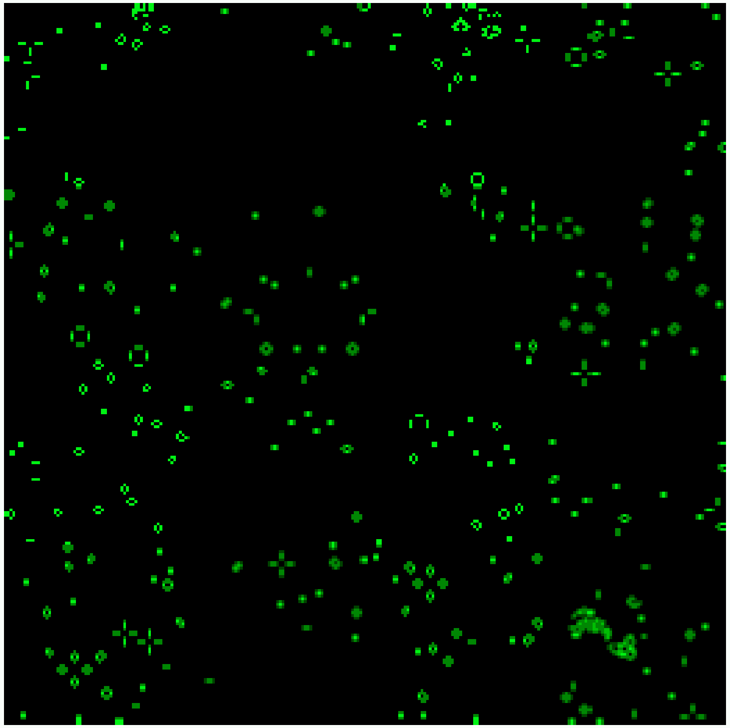
Review: Why emulate physics?

- 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

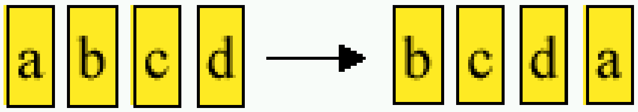
Observation:

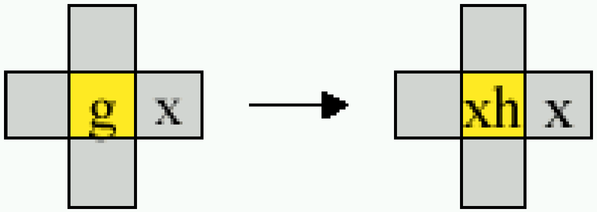
- It's hard to create (or discover) conservations in conventional CA's.

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.*





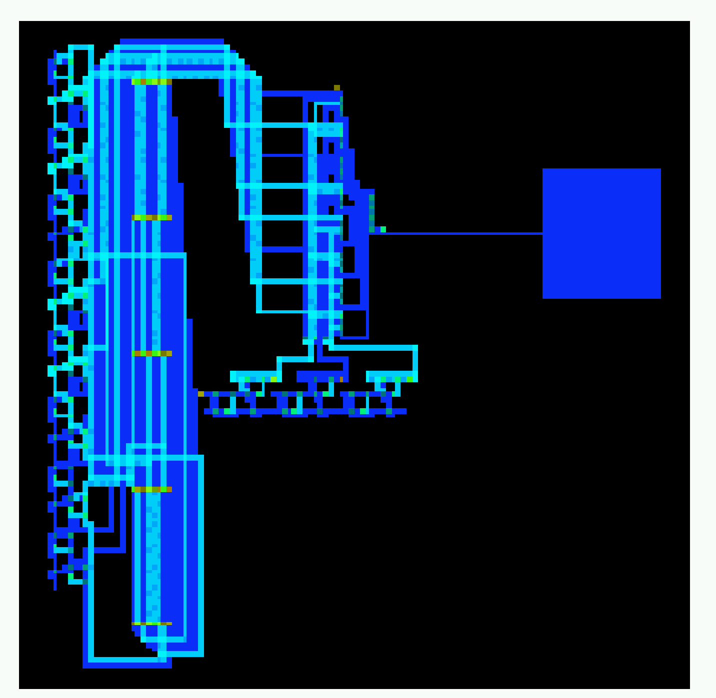
Conservations allow computations to map efficiently onto microscopic physics, and also allow them to have interesting macroscopic behavior. *Such CA's have hardly been studied.*

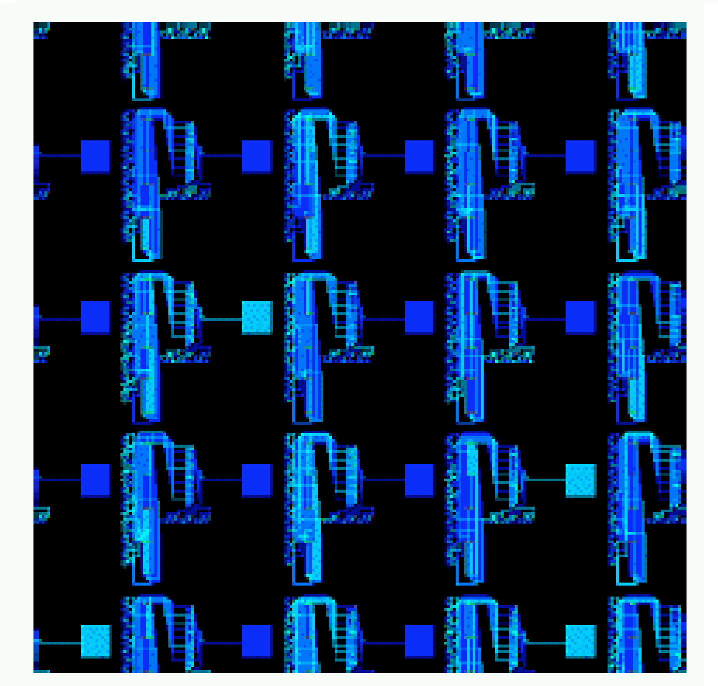
Physical Worlds

- ***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 "material".
  - Can construct CA that support logic.
  - Can discover logic in existing CAs (eg. Life)
  - Universal CA can simulate any other

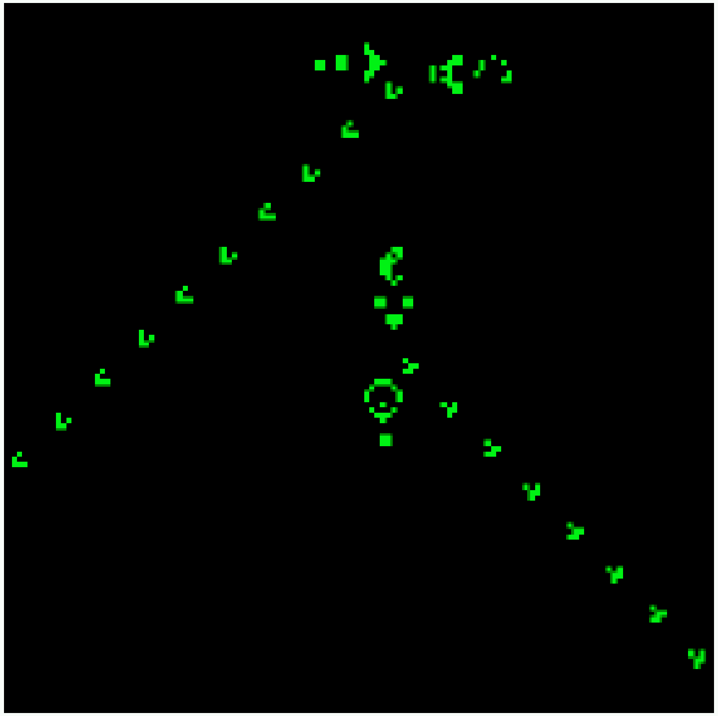




Logic circuit in gate-array-like CA

What's wrong with Life?

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

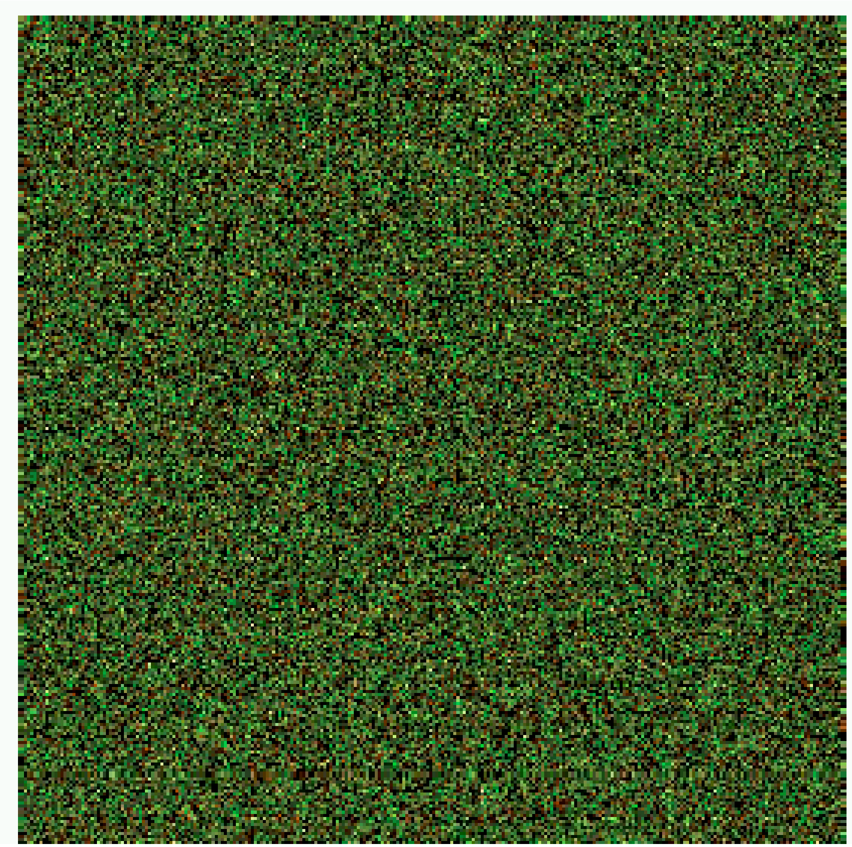


- *Glider guns in Conway's "Game of Life" CA.*
- *Streams of gliders can be used as signals in* ***Life logic circuits***.

What’s wrong with Life?

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

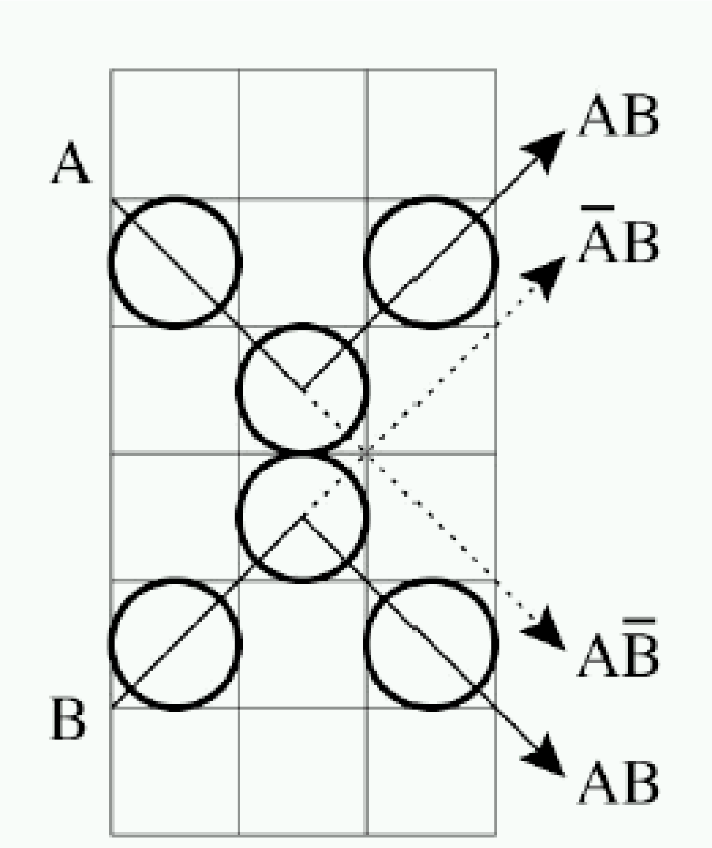
- **BUT:**
  - **Life is short!**
  - **Life is microscopic**
  - **Can we do better with a more physical CA?**



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

Billiard Ball Logic reminder.

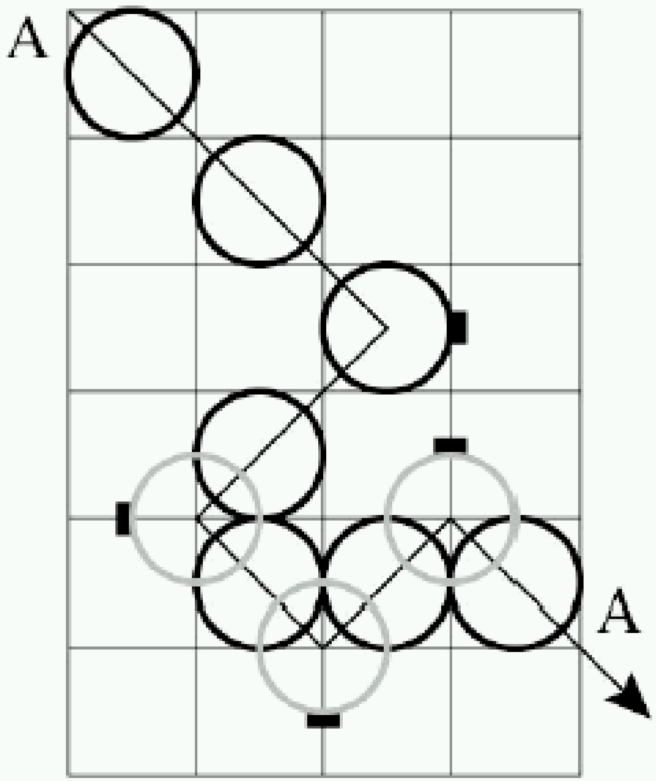
- Simple reversible logic gates can be **universal**
  - Turn continuous model into digital at discrete times!
  - (A,B) --> AND(A,B) isn't reversible by itself
  - Can do better than just throw away extra outputs
  - Need to also show that you can *compose* gates



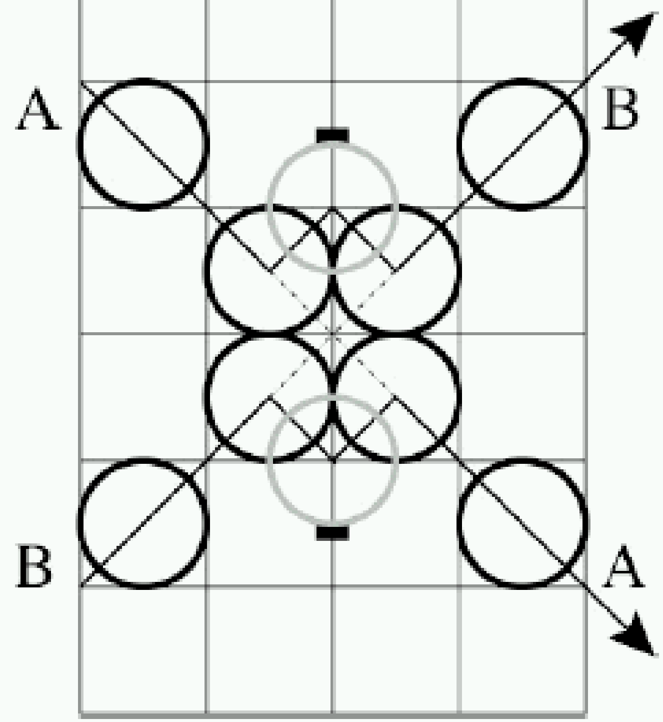
Fredkin's reversible Billiard Ball Logic Gate. Interaction gate.

This is NOT the Fredkin Gate that you know from class. He invented many gates!

Billiard Ball Logic review



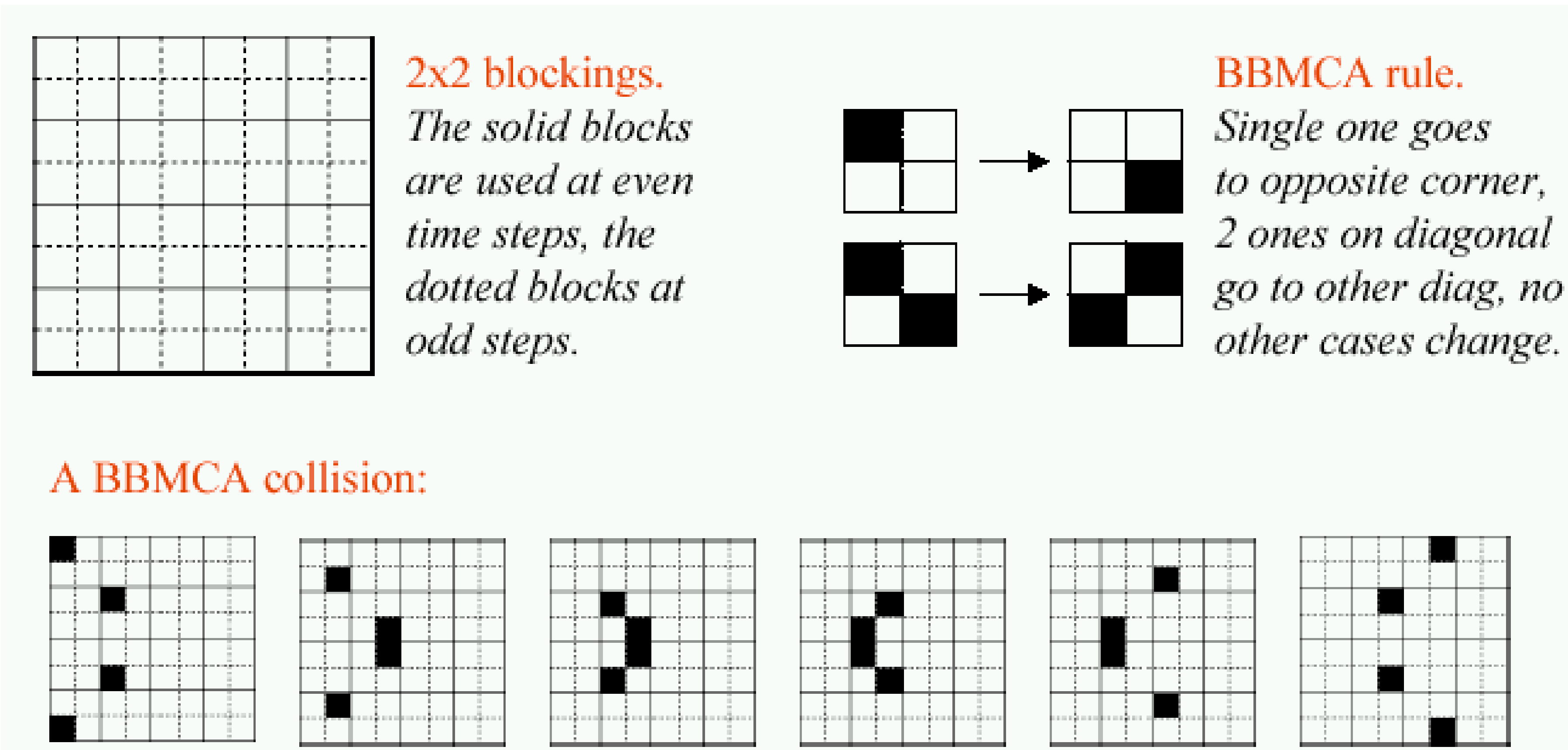
Fixed mirrors allow signals to be routed around.



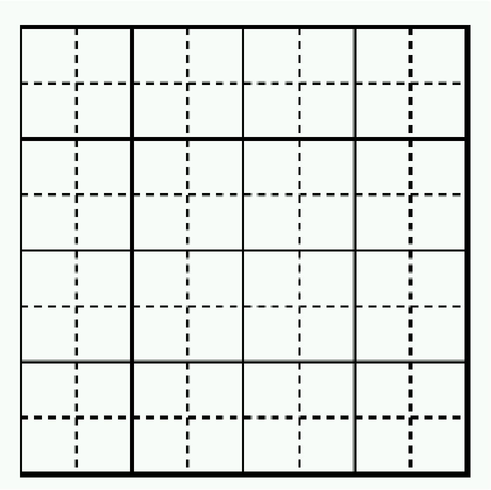
Mirrors allow signals to cross without interaction.

A BBM CA rule

- Now we map these BB behaviors not to gates as before but to CA rules.

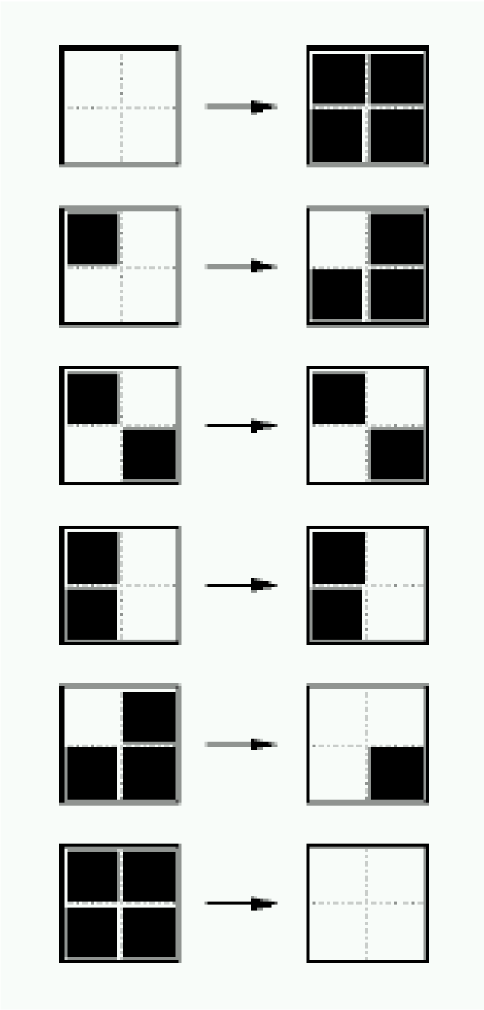


The “Critters” rule



Use 2x2 blockings.

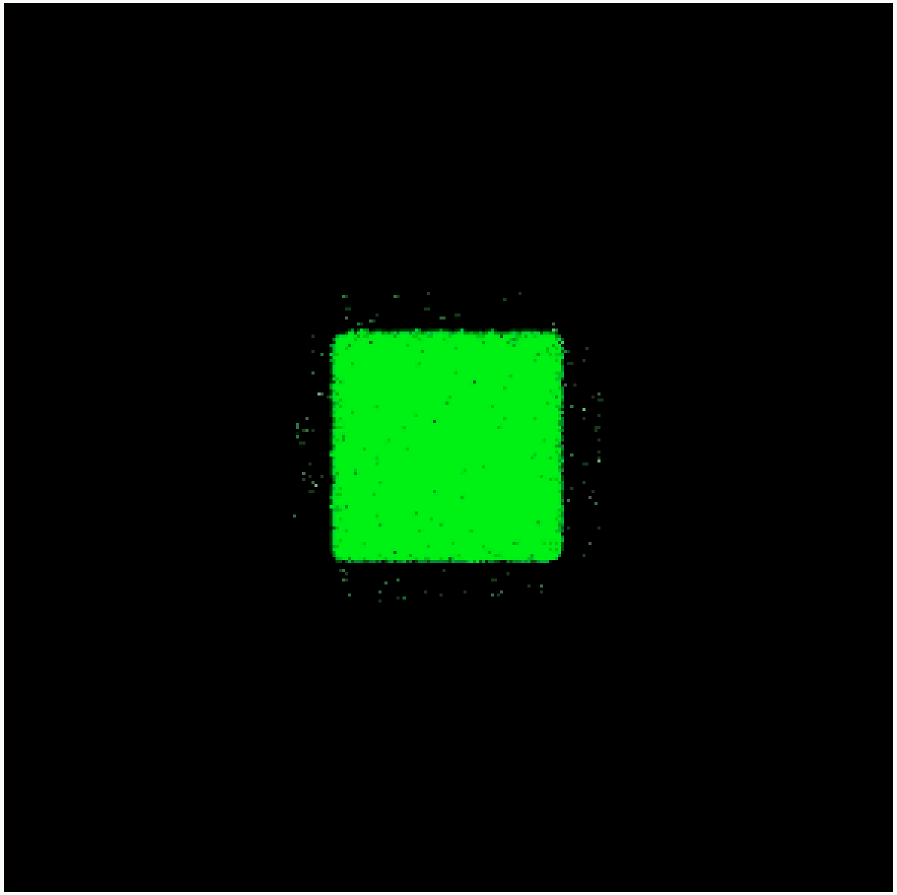
Use solid blocks on even time steps, use dotted blocks on odd steps.



- *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.*

These rules are not the same as shown in an earlier lecture.

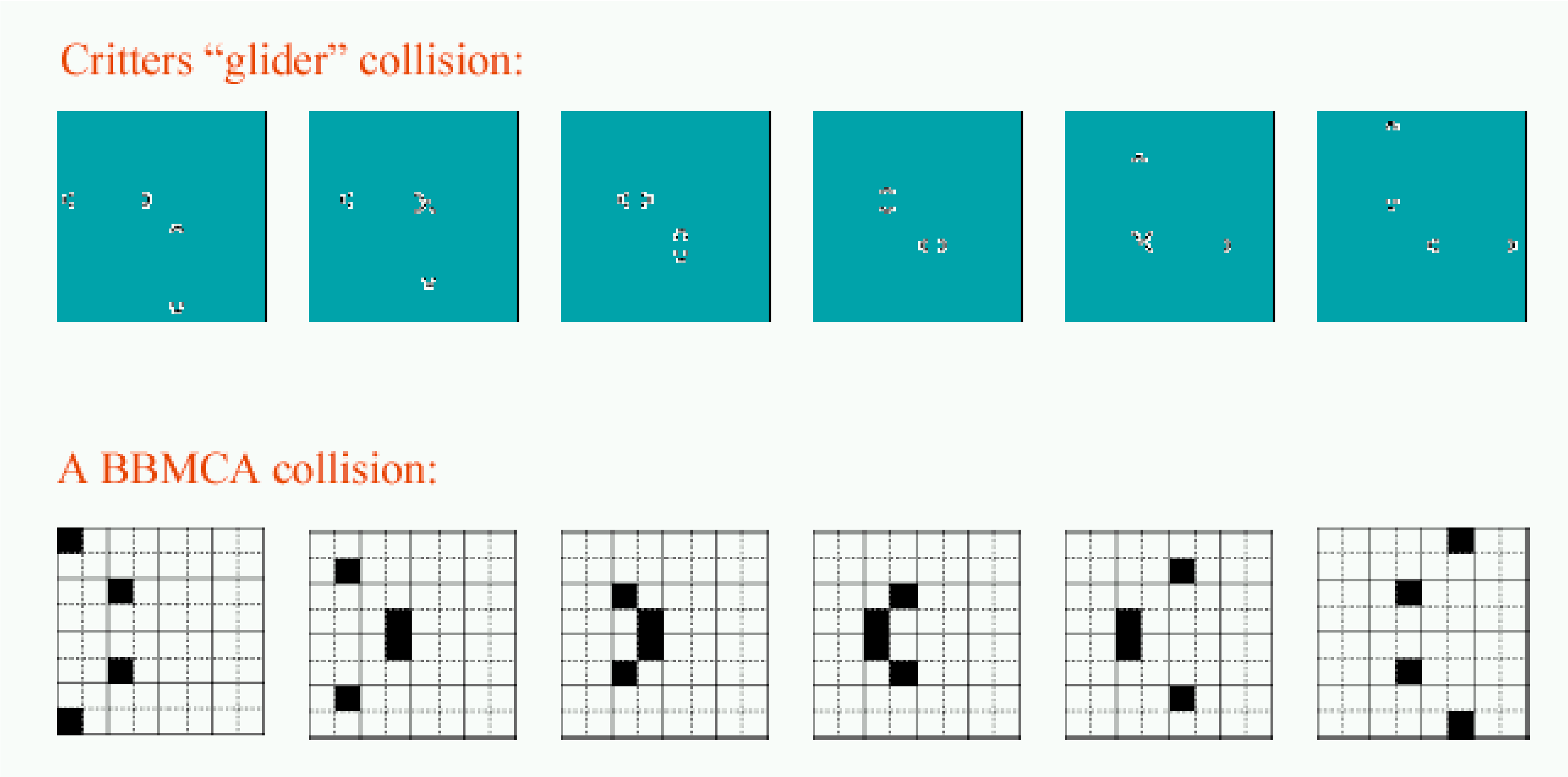
The “Critters” rule



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

- Standard question: what will happen after N generations.
- Predict the dynamics.

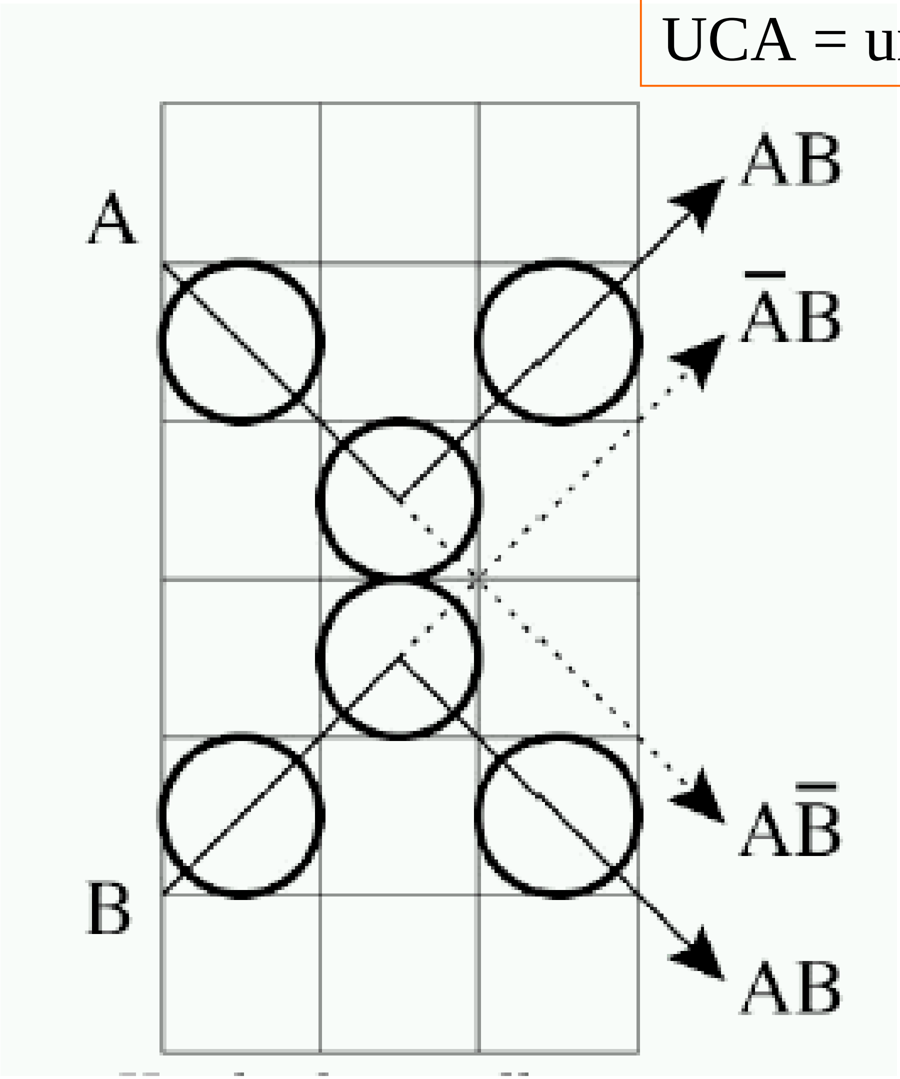
“Critters” is universal



Comparison of collisions in Critter and BBMCA models

UCA with momentum conservation

UCA = universal CA

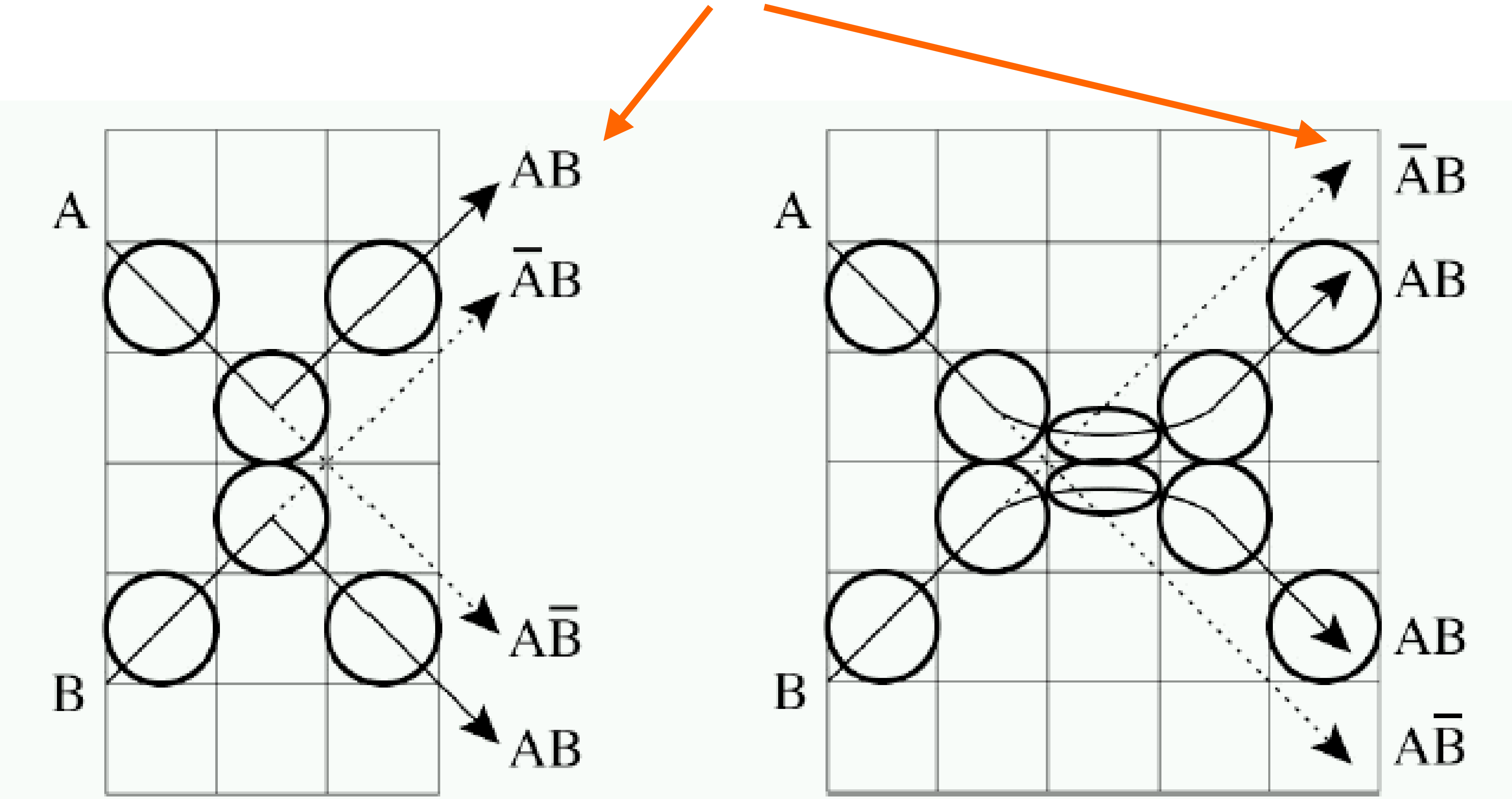


Hard sphere collision

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

UCA with momentum conservation

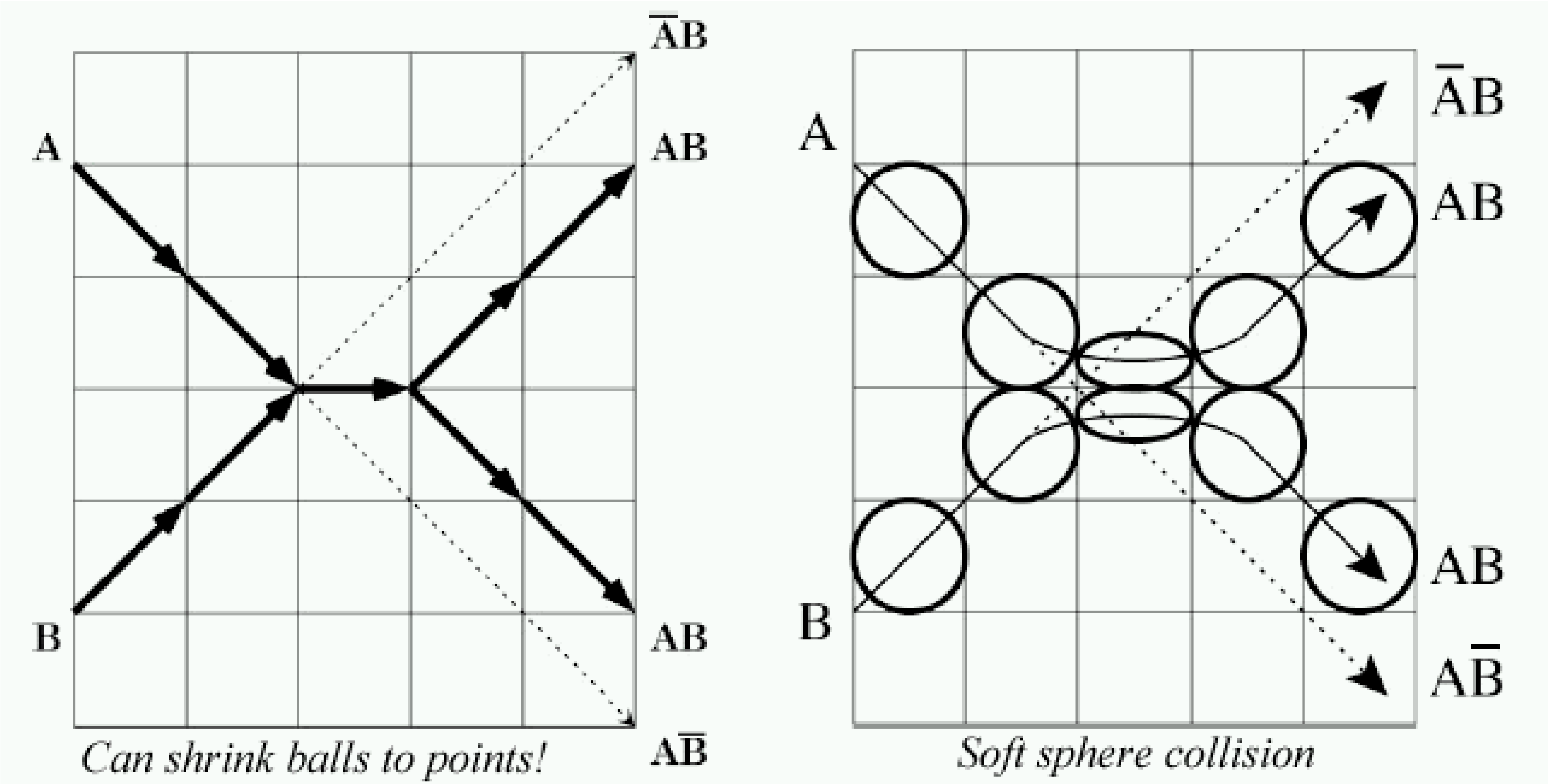
Compare orders



Hard sphere collision

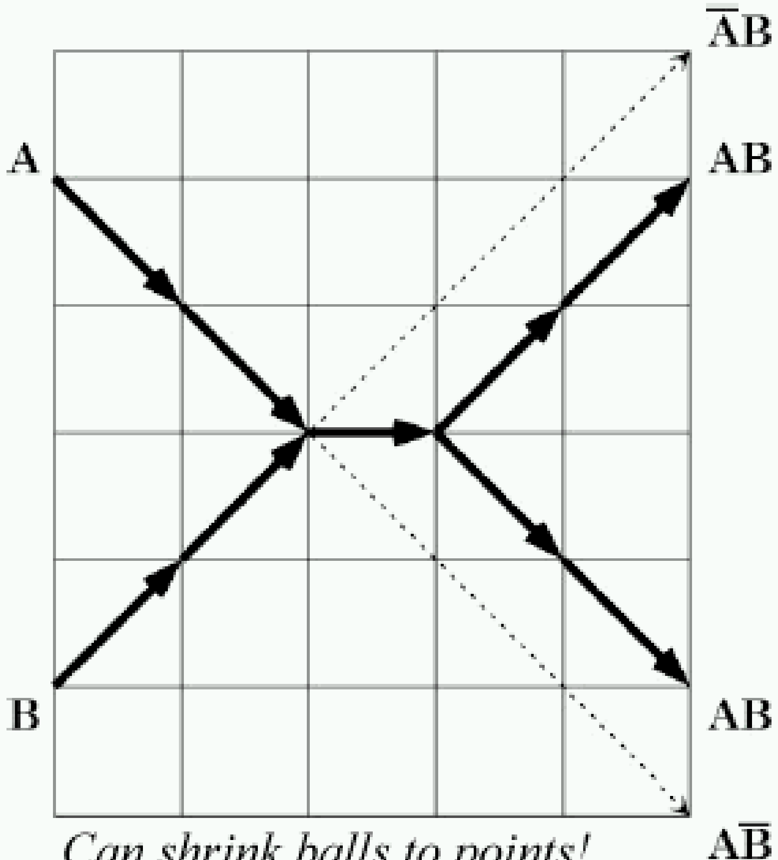
Soft sphere collision

UCA with momentum conservation

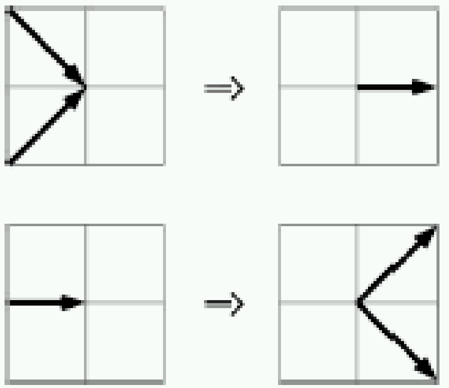


SSM = Soft sphere Model

UCA with momentum conservation

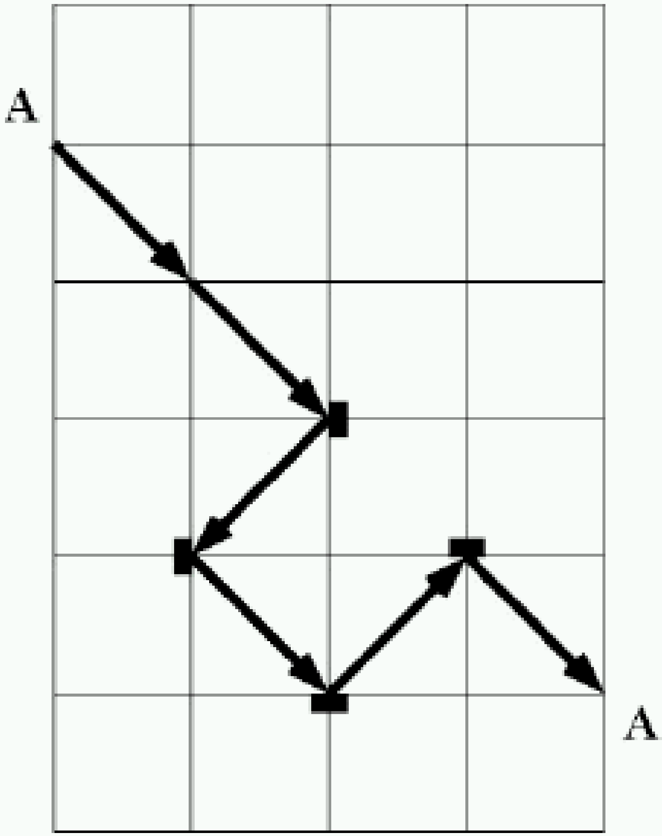


Can shrink balls to points!

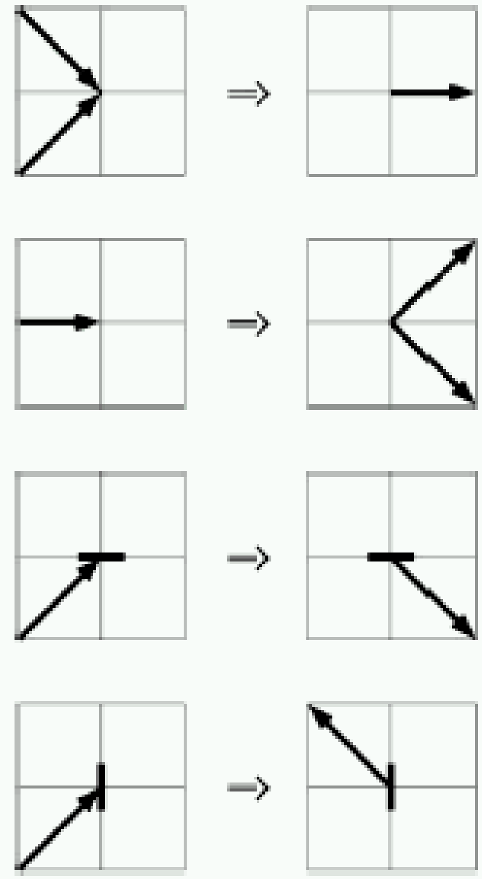


SSM rule: rotations also act like this. All other cases remain unchanged. This is a ***Lattice Gas****:* ***movement*** *and* ***interaction*** *steps alternate.*

UCA with momentum conservation

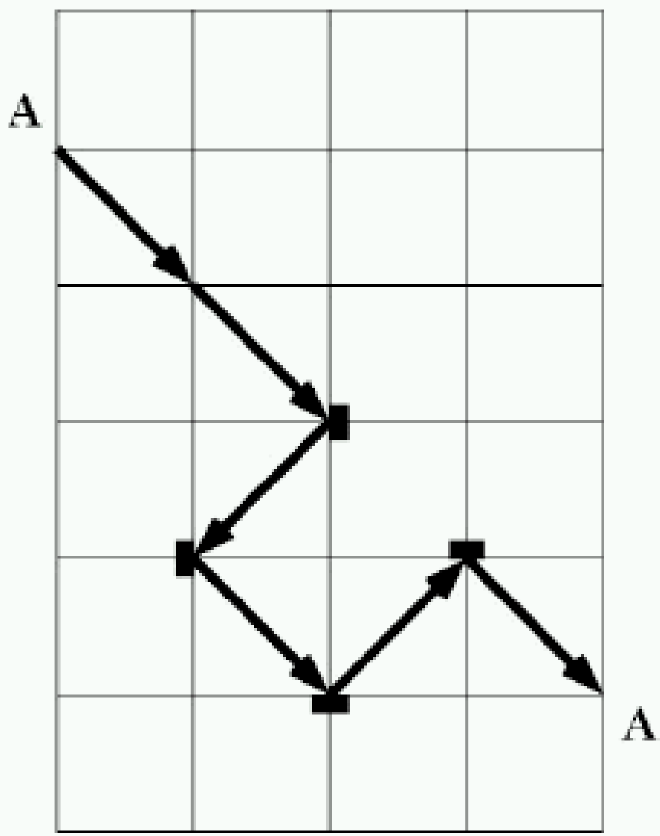


Add mirrors at lattice points to guide balls.



SSM rule with mirrors

UCA with momentum conservation



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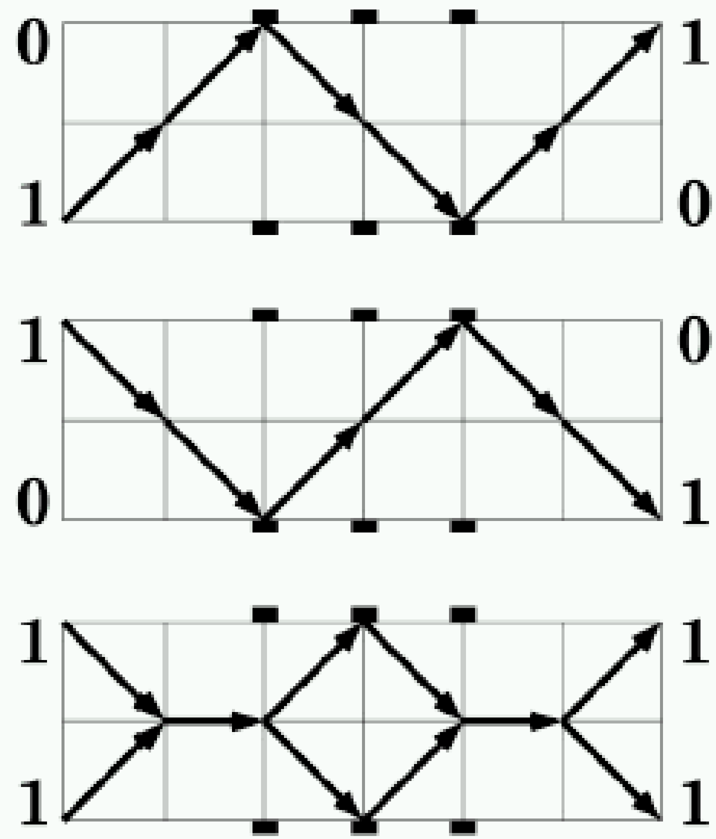
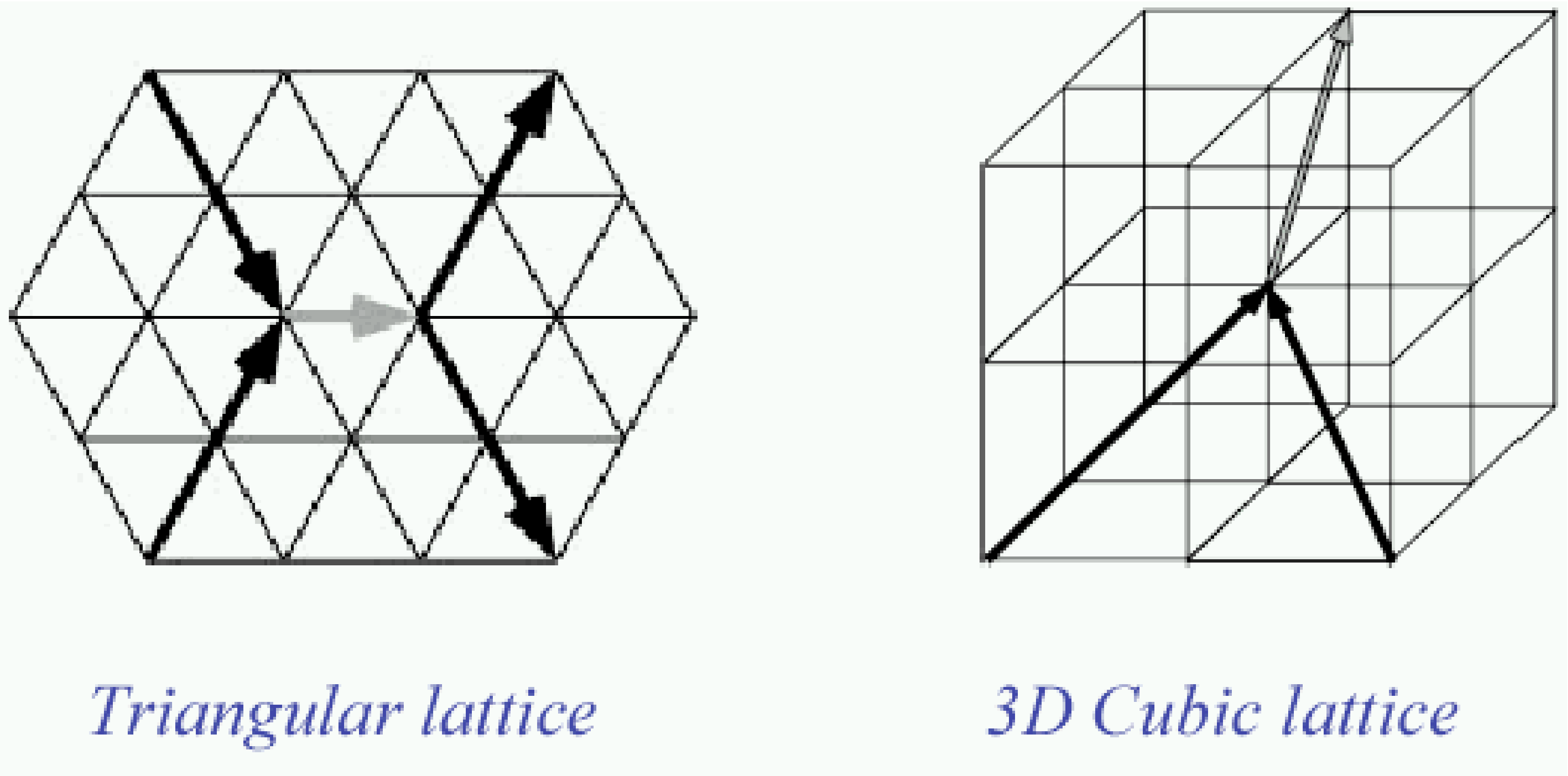


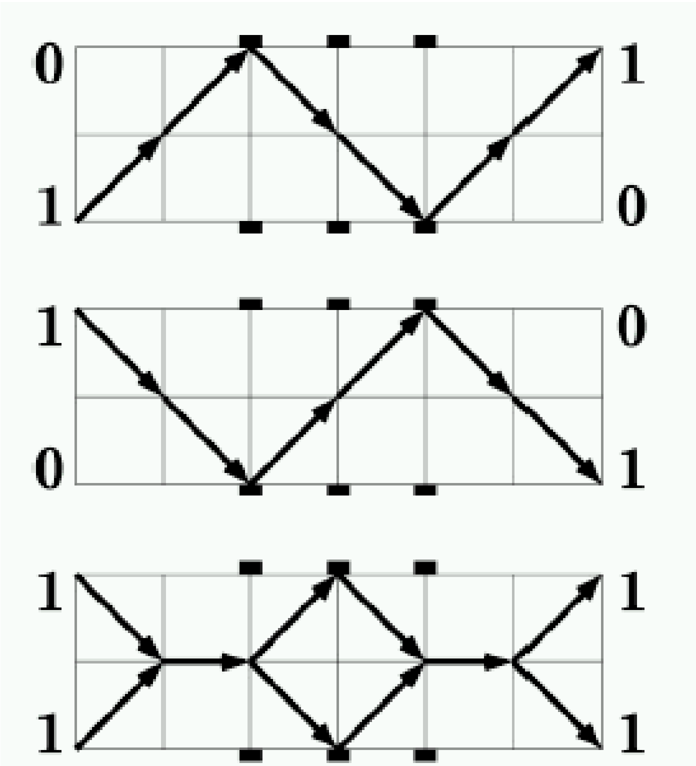
Mirrors allow signals to cross without interacting.

Swap gate realization

SSM collisions on other lattices



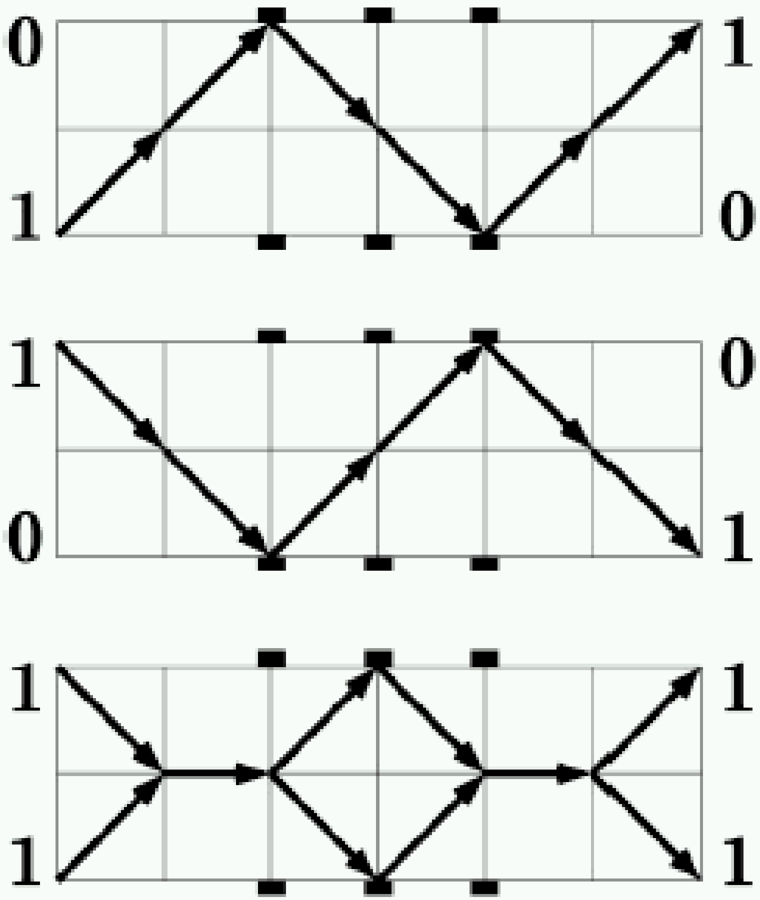
Getting rid of mirrors



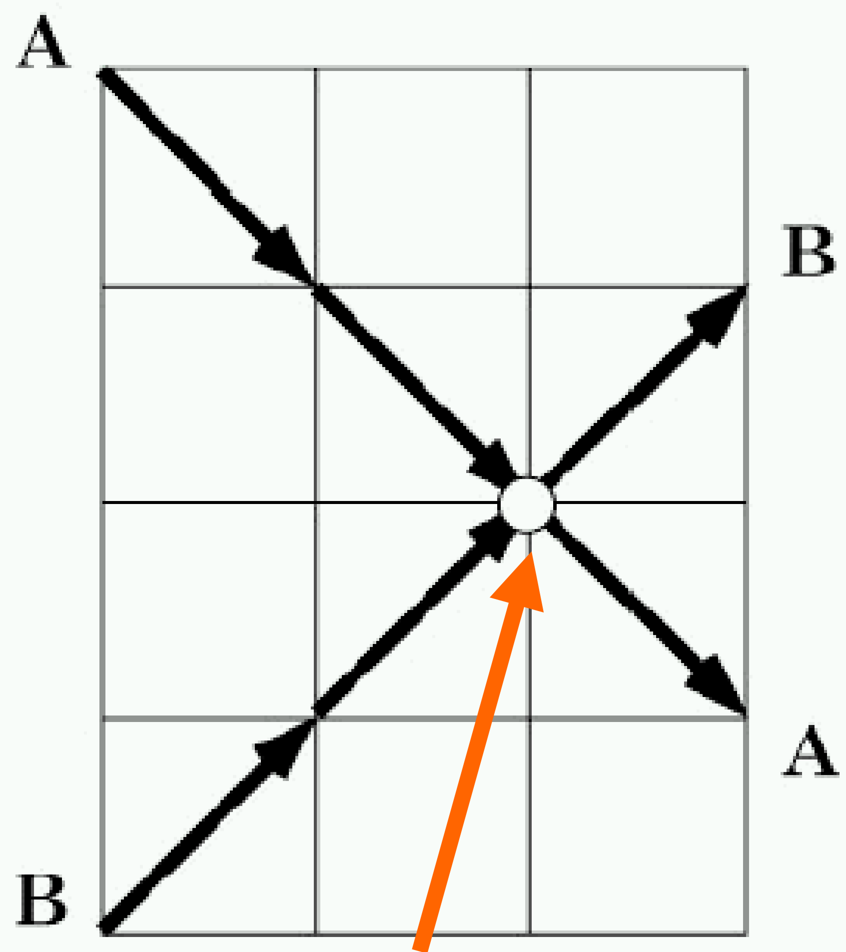
- SSM with mirrors does *not* conserve momentum
- Mirrors must have infinite mass
- Want both universality and mom conservation
- Can do this with just the SSM collision!

Mirrors allow signals to cross without interacting.

Getting rid of mirrors - the rest particle

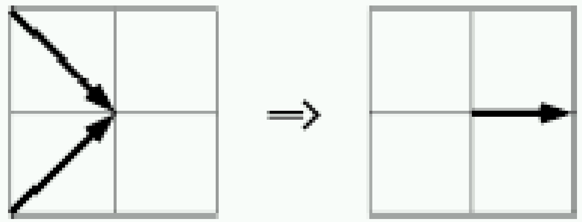


Mirrors allow signals to cross without interacting.

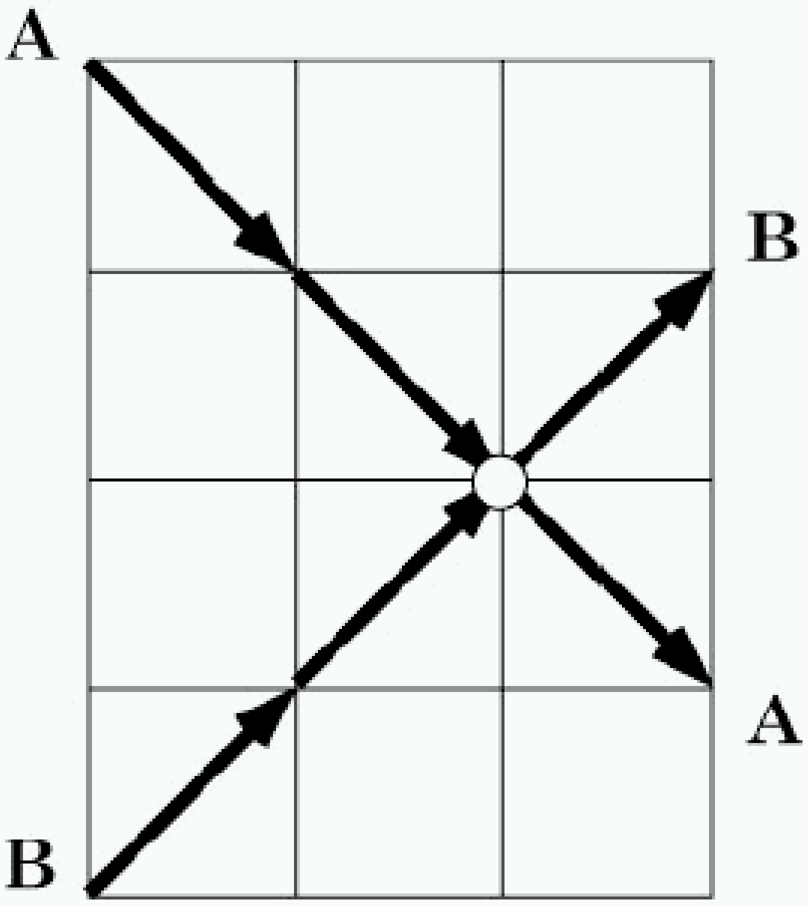


Adding a rest particle allows signals to cross.

Getting rid of mirrors

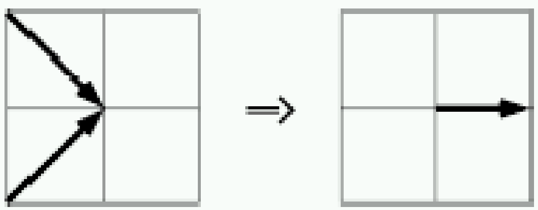


- The rule is very simple without mirrors: just one collision and it's inverse.
- All other cases, including the rest particle case, go straight through.



Adding a rest particle allows signals to cross.

Getting rid of mirrors - signal and its complement



- The rule is very simple without mirrors: just one collision and it's inverse.
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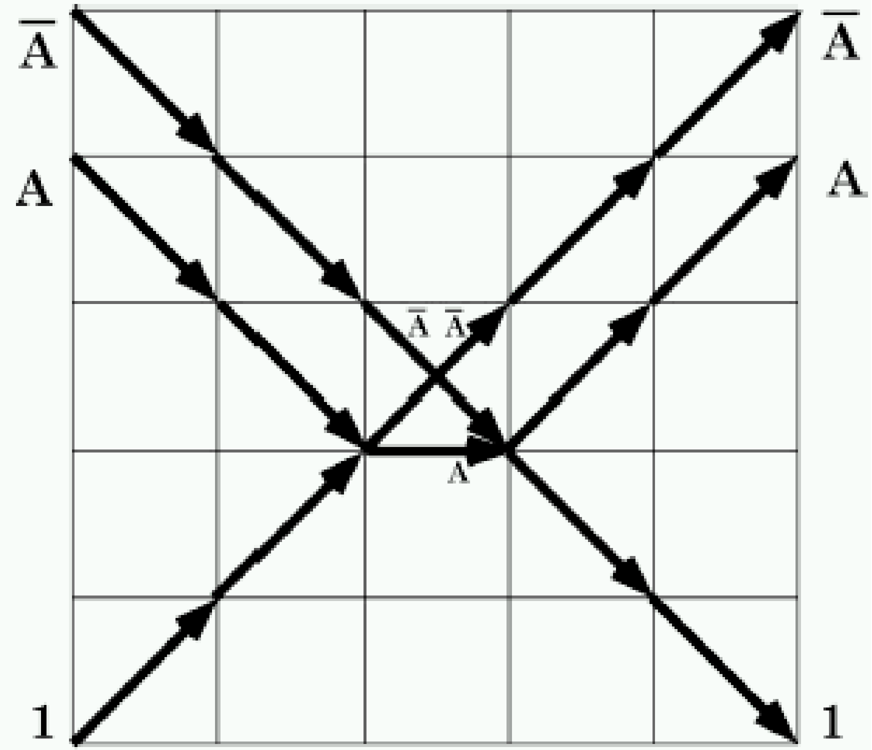
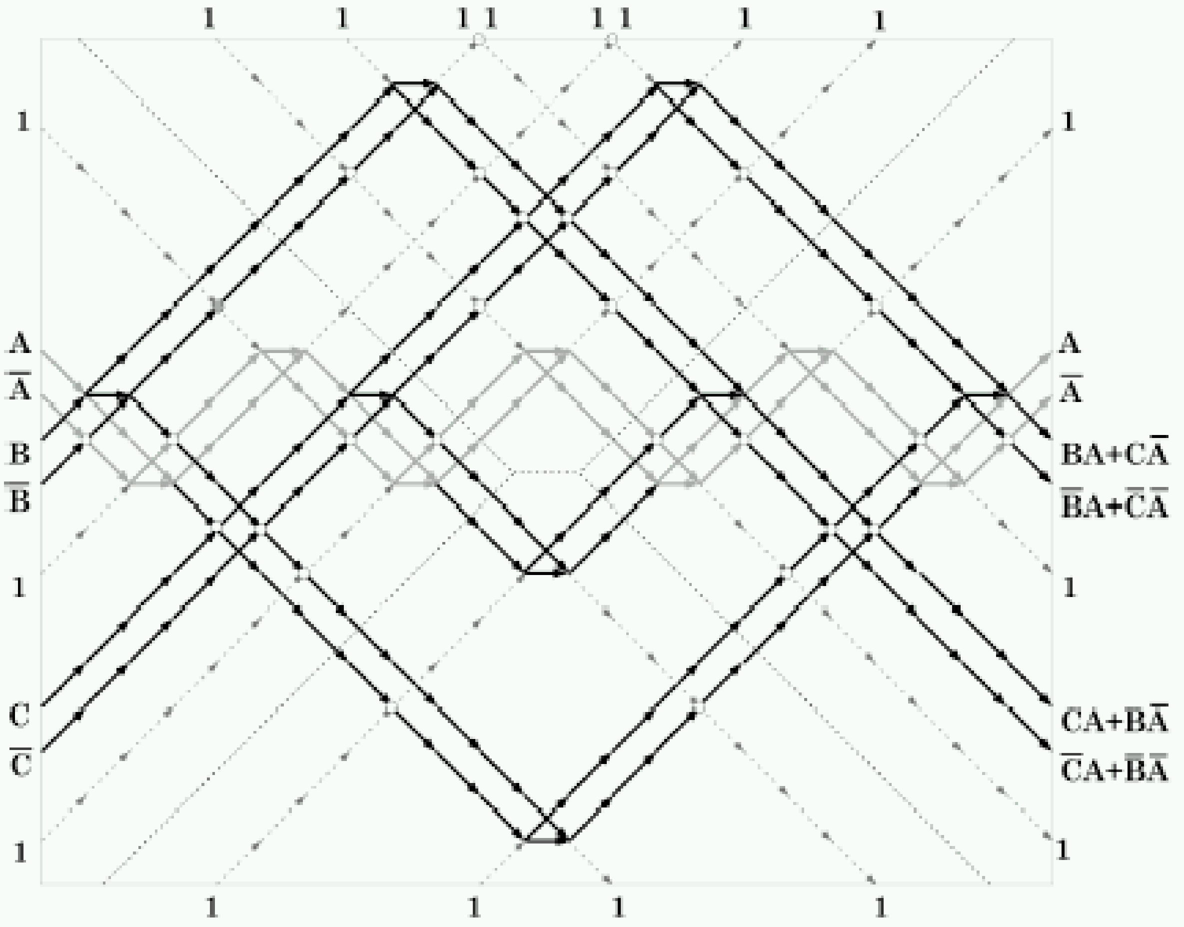


Pairing every signal with its complement allows constant streams of 1's to act like mirrors

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

The concept of dual-rail logic is important also in asynchronous, reversible, low power and self-assembly circuits. No negations necessary or possible.

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.

SSM = Soft sphere Model

Relativistic conservation

Non-relativistic:

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

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

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

Relativistic:

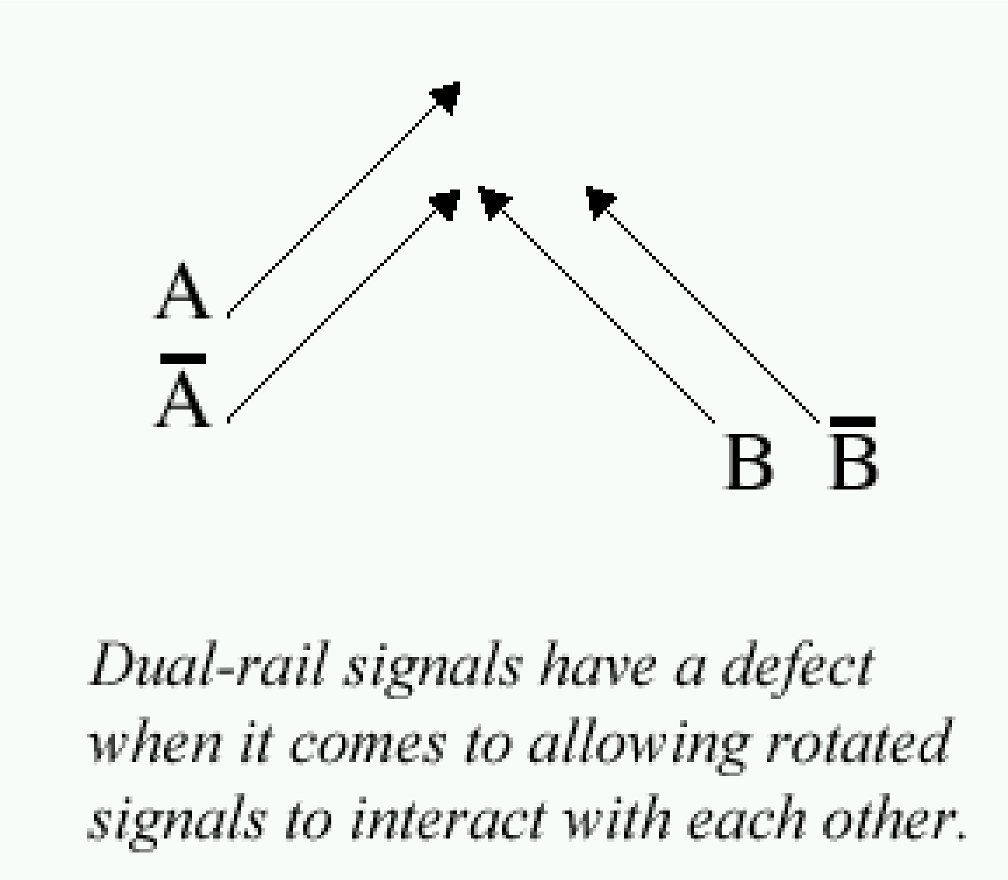
$$\sum E = \sum E' \qquad \text{(energy)}$$

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

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

- <== 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!

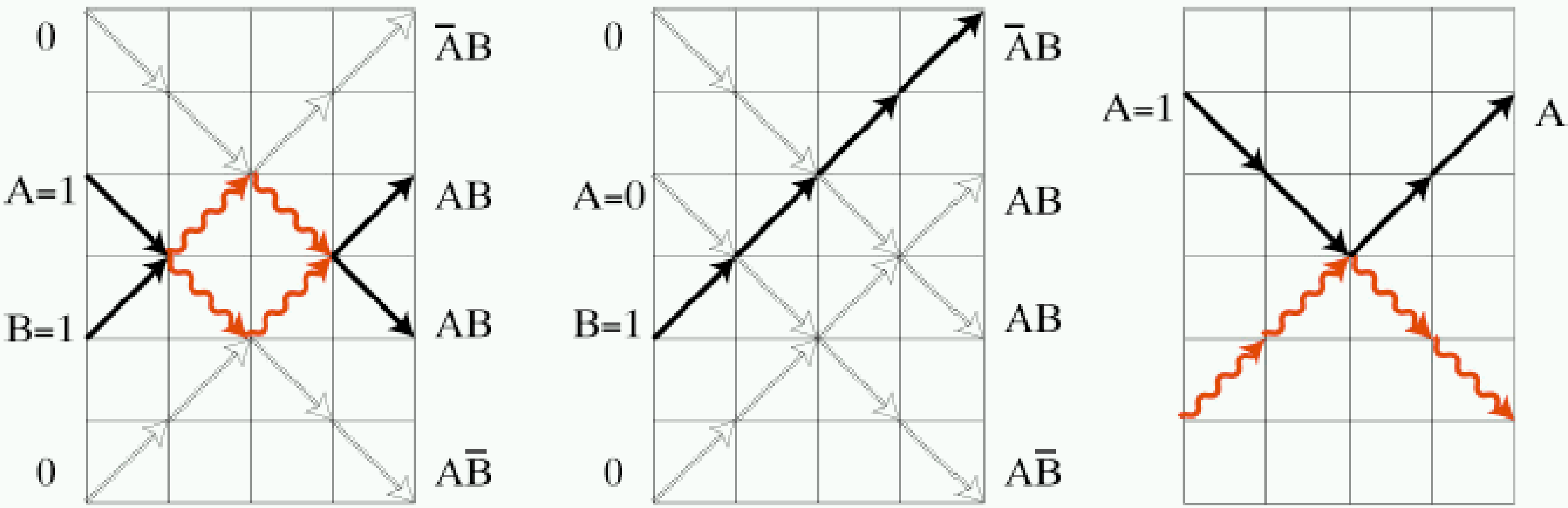
Relativistic conservation



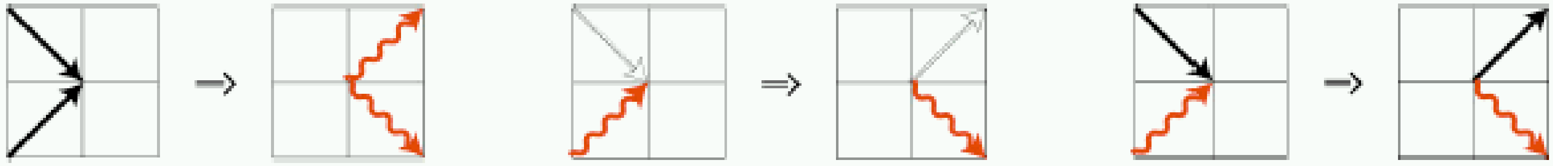
LGA = lattice gas

- 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

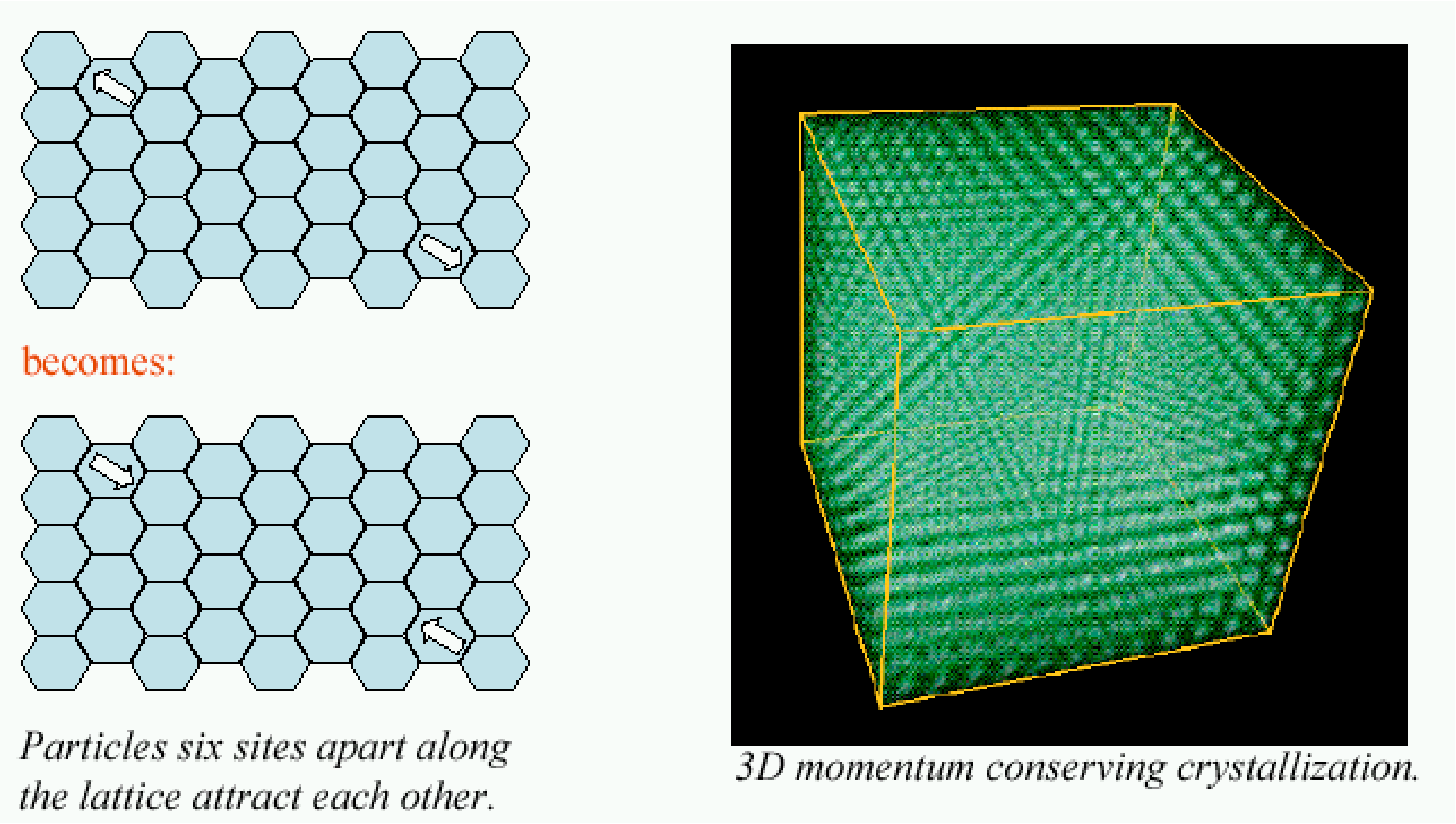
Relativistic conservation



The rule we infer from this is:



Can we add ***macroscopic*** forces?



Particles six sites apart along the lattice attract each other.

3D momentum conserving crystallization.

- *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**