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Computing Beyond Silicon Summer School

Physics becomes the computer
Physics becomes the computer

Emulating Physics

Physical concepts enter CS and computer concepts enter Physics

Nature as Computer

Incorporating comp-universality

Spatial Computers

Architectures and algorithms for large-scale spatial computations

Physical Worlds

and conservation laws

Finite-state, locality, invertibility

Emulating 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”

- Captures physical locality and finite state
- Not reversible (does not map well onto microscopic physics)
- No conservation laws (nothing like momentum or energy)
- No interesting large-scale behavior
- It’s hard to create (or discover)

Observation:

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

256x256 region of a larger grid.
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.

I. 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.
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.
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.

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

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.

**Computation Universality**

- Universal CA can simulate any other
- Existing CAs (eg. Life)
- Can discover logic in support logic
- Can construct CA that
doesn’t take much.
Life CA patterns of bits in the wires, and logic out of
glider guns in Conway’s “Game of Life”

• What’s wrong with Life?
What's wrong with Life?

- One can build signals, wires, and logic out of wires, and logic out of bits in the Life CA patterns of bits in the space.
- Life is microscopic
- Life is short!
- 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.
Fredkin's reversible Billiard Ball Logic Gate

- Simple reversible logic gates can be universal
- Can do better than just throw away extra outputs
- Need to also show that you can compose gates
- (A,C) ≠ (A,D)(A,C) isn't reversible by itself
- Digital at discrete times;
- Turn continuous model into can be universal
- Simple reversible logic gates

Billiard Ball Logic
Fixed mirrors allow signals to cross without interaction.

Billiard Ball Logic
A BBMCA rule

A BBMCA collision:

other cases change,
no go to other diag.
2 ones on diagonal
opposite corner,
single one goes
BBMCA rule.
The "Critters" rule

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

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

We show all cases:
- the even blockings,
- the odd blockings.

The number of ones in one step equals the number of zeros in the next step.

Each rotation of a case on the left maps to the corresponding rotation on the right.

This rule is applied.
The “Critters” rule

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

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

This rule is applied to both the even and odd blockings of the case. Each rotation of a case on the left maps to the corresponding rotation of the case on the right. We show all cases.
"Critters" is universal

A BBMCA collision:

"Critters" glider collision:

"Critters" is universal
Hard-sphere collision

- Hard-sphere collision conserves momentum.
- Can't make simple CA out of this.
- Finite impact parameter required.

Problem: Finite impact parameter.

Suggestion: Find a new physical model!
UCA with momentum conservation

Soft sphere collision

Hard sphere collision
CBSS 6/25/02

UCA With momentum conservation

Can shrink balls to points!

Soft sphere collision
This is a Lattice Gas: movement and interaction steps alternate. All other cases remain unchanged. All other act like this. All other SSM rule: Rotations also can shrink balls to points.

UCA with momentum conservation
This is a Lattice Gas: movement and interaction steps alternate. All other cases remain unchanged. SSM rule: rotations also act like this. Add mirrors at lattice points to guide balls.

UCA with momentum conservation
SSM rule with mirrors

UCM with momentum conservation

Add mirrors at lattice points to guide balls.
Add mirrors at lattice points to guide balls.

UCA with momentum conservation.
SSM collisions on other lattices

3D Cubic Lattice

Triangular Lattice
Getting rid of mirrors

SSL collision

- Can do this with just the SSM collaboration
- Want both universality and mom conserv.
- Mirrors must have infinite mass
- Mirrors allow signals to cross without interacting.

Getting rid of mirrors
Getting rid of mirrors

Adding a rest particle allows signals to cross.

Mirrors allow signals to cross without interacting.

Getting rid of mirrors
Getting rid of mirrors

• The rule is very simple: without mirrors, just one collision and its inverse:

• Adding a rest particle allows signals to cross.

All other cases, including the rest particle case, go straight through.
Pairing every signal with its complement allows constant streams of 1's to act like 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.

Getting rid of mirrors.
Getting rid of mirrors

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

BBMCA in SSM
Macroscopic universality

With invertibility and universality.

Requires us to recognize forces and conservation laws of physics same in motion.

This would allow a robust Darwinian evolution.

Relativistic invariance would allow large-scale structures to move.

This would allow a robust Darwinian evolution.

Requires us to reconcile forces and conservation with invertibility and universality.

An interesting world should have macroscopic complexity but invertible and universality.

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

- Non-relativistically, mass and energy are conserved separately.
- Simple lattice gases that conserve only $m$ and $m v$ are more like real systems than non-relativistic systems.

**Relativistic:**

\[ \begin{align*}
\text{(energy)} & : \quad m \quad \frac{v}{c} = \gamma m_c \\
\text{(mass)} & : \quad m = \gamma m_c \\
\text{(momentum)} & : \quad \frac{p}{mc} = \gamma \frac{p_c}{c} \\
\end{align*} \]
Relativistic conservation

We used dual-rail LGA in which you don’t need dual-rail.

Dual-rail signals don’t act as mirrors constant 1’s to act as signaling to allow dual-rail signals to interact with each other.

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

Suggestion: make an LGA in which you don’t rotate very easily.
The rule we infer from this is:

Relativistic conservation
Can we add macroscopic forces?

3D momentum conserving crystallization becomes:

Particles six sites apart along the lattice attract each other.

Can we add macroscopic forces?
Can we add macroscopic forces?
Summary

We know how to reconcile universality with reversibility

Reversibility plus conservations leads to robust "gliders" and interesting microscopic properties & symmetries.

Reversible systems last longer, and have a realistic thermodynamics.

More of the richness of physical dynamics can be captured by adding physical properties.

Universality is a low threshold that separates triviality from arbitrary complexity.
Physics becomes the computer

Nature as Computer

Large-scale spatial computations
Architectures and algorithms for spatial computers

Architectures and algorithms for

Incorporating comp-universality

Physical Worlds

and conservation laws
Finite-state, local, invertible

Emulating Physics

Physical concepts enter CS and

Physical concepts enter Physics
Problem from last lecture:

Dynamical Ising rule

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

Even steps: update gold sublattice

Odd steps: update silver sublattice
Problem from last lecture:

Dynamic Ising rule

Odd steps: update silver sublattice

Even steps: update gold sublattice

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

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.

• Show that the waves running along the boundary obey the wave equation exactly.