Physics becomes the computer

Norm Margolus

Computing Beyond Silicon Summer School
Physics becomes the computer

Emulating Physics

Physical concepts enter Physics

Physical concepts enter CS and

Nature as Computer

Large-scale spatial computations

Architectures and algorithms for

Spatial Computers

at small and large scales

Incorporating comp-universality

Physical Worlds

and conservation laws

Finite-state, locality, invertibility,

Emulating Physics
Emulating Physics
Why emulate physics?

- Start with locality:
  - Cellular Automata

- Rich dynamics allow us to understand nature
- Comp models may help microscopics physics
- Comp must adapt to...
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

256x256 region of a larger grid.
Glider gun inserted near middle.
Conway's "Game of Life"

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

But, 256x256 region of a larger grid.

About 1500 steps later.
Reversibility & other conservations

- Reversibility is conservation of information
- Why does exact conservation seem hard?
- Reversibility is conservation of information
- Reversibility vs other conservations

For rev, one nth of the neighbor info must be left at the center at multiple positions. The same information is visible.
With traditional CA’s, conservations are a non-local property of the dynamics. The simplest solution: redefine CA’s so that non-local properties of the dynamics are manifestly local properties. Regular computation in space & time is redefined: regular in space: repeated structure; regular in time: repeated sequence of steps.

Adding conservations •

CA ≡ \text{regular computation in space \& time}
Diffusion rule

Even steps: rotate cw or ccw
Odd steps: rotate cw or ccw

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

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

Even steps: rotate cw or ccw

Odd steps: rotate cw or ccw

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

Odd steps:
rotate cw or ccw

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

Odd steps: rotate ccw

Except: 2 ones on diag, nc

Use 2x2 blockings. Use solid blocks on even time steps, use dotted blocks on odd steps.
Even steps:
- Rotate cw

Odd steps:
- Rotate ccw

Except: 2 ones on diag, nc

Solid blocks:

**TM Gas Rule**
Odd step: update dotted blocks

Even steps: rotate cw
Odd steps: rotate ccw
Except: 2 ones on diag, nc

TM Gas rule

dotted blocks
Even steps: rotate cw
Odd steps: rotate ccw

Except: 2 ones on diag, nc

Even step: update solid blocks

Tm Gas Rule
TM Gas rule

Even steps: rotate cw
Odd steps: rotate ccw

Except: 2 ones on diag, nc

Odd step: update dotted blocks
Even steps: rotate cw

Odd steps: rotate ccw

Except: 2 ones on diag, nc

Solid blocks: update solid blocks
Even steps:
rotate cw

Odd steps:
rotate ccw

Except:
2 ones on diag, nc

dotted blocks

Odd step: update dotted blocks

TM Gas Rule
Even steps: rotate cw
Odd steps: rotate ccw

Except: 2 ones on diag, nc

TM Gas rule
TM Gas rule

Even steps: rotate cw

Odd steps: rotate ccw

Except: 2 ones on diag, nc
TM Gas rule
CBSS 6/24/02

Half the time: HPP gas

ID rule inside (no change).

ID rule outside of blue region,

 Except: two ones on diag flip

Even & odd: swap along diags

Rule everywhere:

Half the time: HPP gas

Lattice gas reflection
Lattice gas hydrodynamics
A spin is flipped if exactly 2 of its 4 neighbors are parallel. After the flip, exactly 2 neighbors are still parallel.

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

**Dynamical Ising rule**

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

Odd steps: update silver sublattice
Even steps: update gold sublattice

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 still parallel. After the flip, exactly 2 neighbors are parallel to it.
Bennett’s 1D Rule

A spin is flipped if exactly 2 of its 4 neighbors are parallel. After the flip, exactly 2 neighbors are parallel to it. At each site in a 1D space, we put 2 bits of state. We’ll call one the “gold” bit, and the other the “silver” bit. We update the gold bits on even steps, and the silver on odd steps.

Even steps: update gold sublattice

Odd steps: update silver sublattice
Even steps: update gold sublattice

Odd steps: update silver sublattice

A spin is flipped if exactly 2 of its 4 neighbors are parallel. After the flip, exactly 2 neighbors are parallel to it. After two updates, the system returns to the initial configuration.)

Bennett's 1D rule
If the heat bath is initially much cooler than the spin system, then domains grow as the spins cool.
A spin is flipped if all 4 of its neighbors are the same. Otherwise it is left unchanged.

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

Even steps: update gold sublattice

Odd steps: update silver sublattice

2D "Same" rule
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.

Odd steps: update silver sublattice

Even steps: update gold sublattice

2D “Same” rule
3D “Same” rule
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. We update the gold lattice, then let gas and heat diffuse, then update the silver lattice, and diffuse.

For more info, see cond-mat/9810258
Reversible aggregation rule

For more info, see cond-mat/9810258

Odd steps: update silver sublattice

Even steps: update gold sublattice

When a gas particle diffuses next to exactly one crystal particle, it crystallizes and emits a heat particle. The reverse also happens.
Adding forces irreversibly makes the lattice attract each other. Particles six sites apart along becoming: 3D momentum conserving crystallization.
Crystallization using irreversible forces (Jeff Yepez, AFOSR)
Conservations allow computations to map efficiently onto microscopic physics, and also allow them to have interesting macroscopic behavior. Conservations allow computations to map efficiently onto microscopic physics, and also allow them to have interesting macroscopic behavior.

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

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

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

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

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

Conservations allow computations to map efficiently onto microscopic physics, and also allow them to have interesting macroscopic behavior. Conservations allow computations to map efficiently onto microscopic physics, and also allow them to have interesting macroscopic behavior.
Physics becomes the computer

Emulating Physics

Physical concepts enter CS and computer concepts enter Physics

Nature as Computer

Large-scale spatial computations

Architectures and algorithms for Spatial Computers

Architectures and algorithms for Spatial Computers

Incorporating comp-universality at small and large scales

Physical Worlds

and conservation laws

Finite-state, locality, invertibility

Emulating Physics

Physics becomes the computer