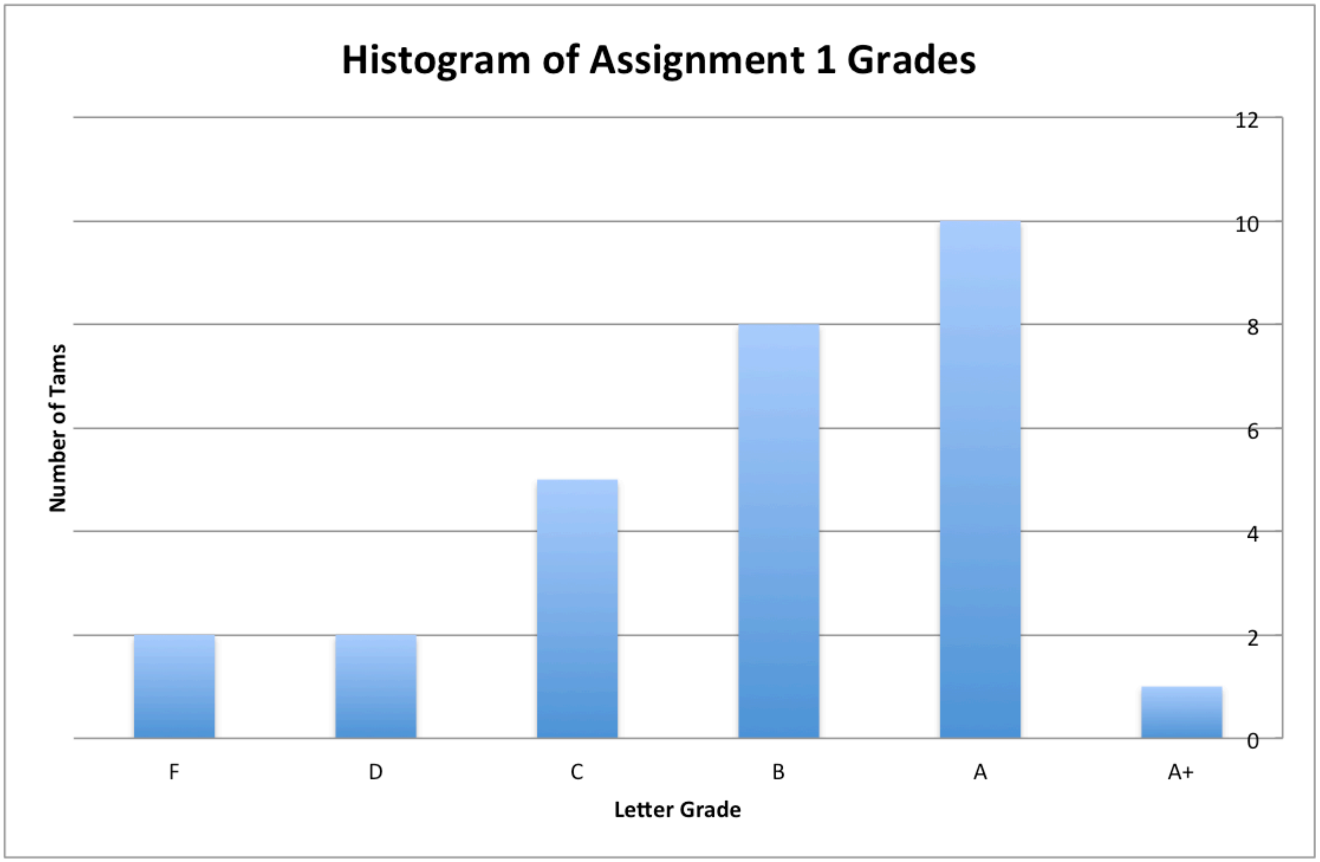
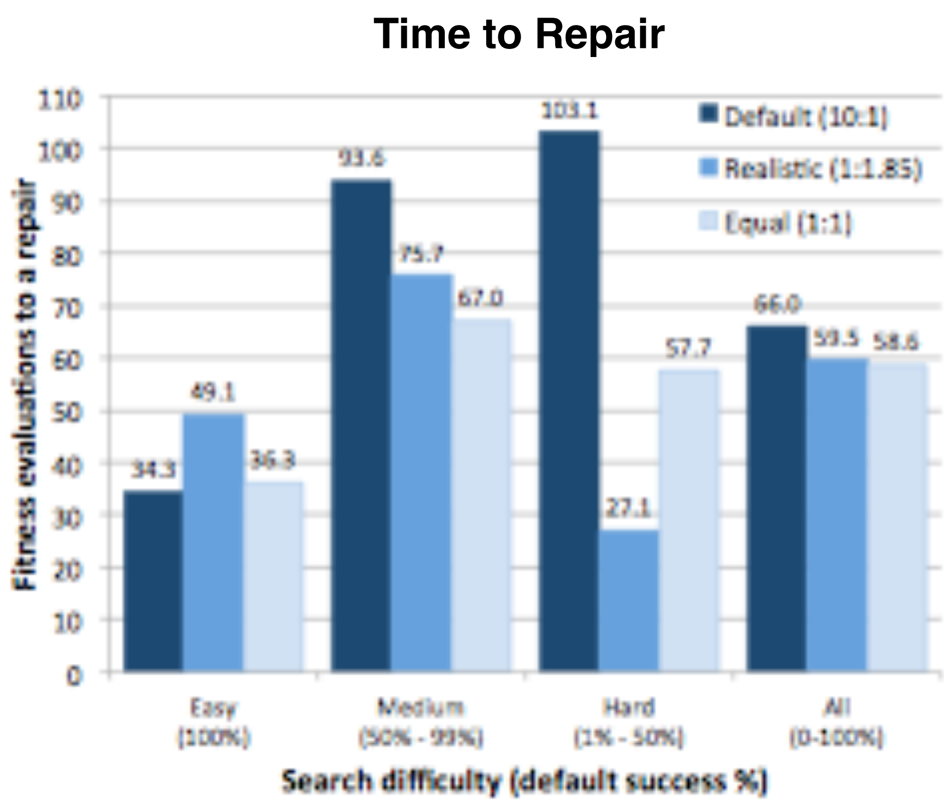


- See Karl after class in CS computer lab if you have a question about your code grade
- See me or Mathew if you have a question about your report grade AFTER filling in rubric & examples.
- If you got <75%, office hrs Th am, Mon pm. Also writing tutors at Office of Grad Studies.
- Meet after class if you need a partner for Project 2
- Send presentation slides to Matthew

GAs

- Claire LeGoues talk
  - Weighted path & constraining the search space
  - GAs challenge assumptions by finding bizarre solutions
  - Crossover
  - Fuzz testing & real-world automated repair for security vulnerabilities
- Natural selection
  - has No Goal
  - operates at multiple levels
  - evolves robustness & evolvability
- Project 2 Part 2
  - evolve cooperation & maybe competition
  - code is in C++

Weighted Path Schemes



Conclude: Both new weighting schemes cause the GP to repair a bug on which the default weighting scheme failed.

Mitchell Chapter 10

- Living systems compute
- Living systems are open systems that exchange energy, materials & <u>information</u>
  - E.g. Erwin Shrodinger (1944) & Lynn Margulis (200) books: *What is Life?* discuss how life creates order from disorder
- Computation is what a complex system does to adapt to its environment
- Life *is* computation?
- Cellular Automata: simplified demonstrations of how life might compute

Rule 110

0	0	0	→	0
0	0	1	→	1
0	1	0	→	1
0	1	1	→	1
1	0	0	→	0
1	0	1	→	1
1	1	0	→	1
1	1	1	→	0

Read the bit string BOTTOM to TOP

111 is leftmost (most significant) bit

000 is the least significant bit

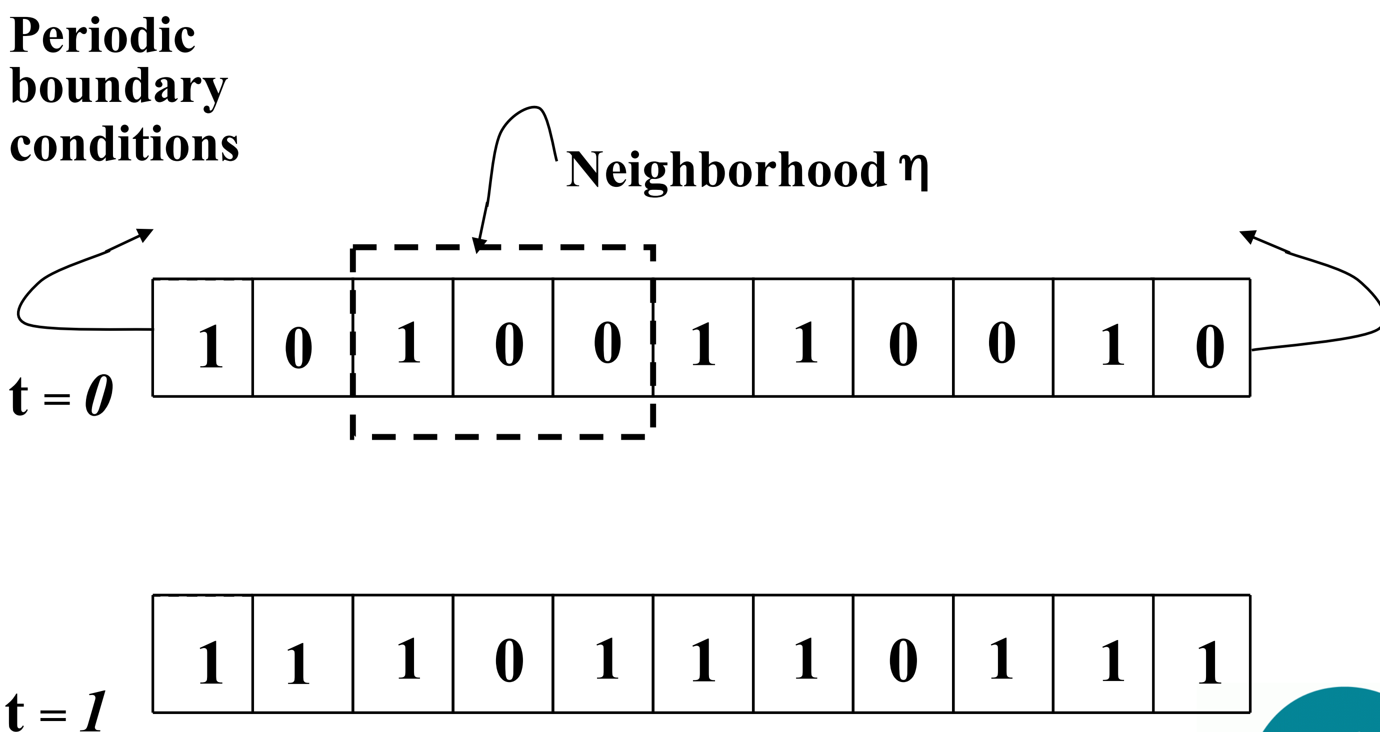
000	001	010	011	100	101	110	111
0	1	1	1	0	1	1	0

0 1 1 0 1 1 1 0 = 0+ 2 + 4 + 8 + 0 + 32 + 64 = Rule 110

Rule Table ϕ :

Neighborhood:	000	001	010	011	100	101	110	111
Output bit:	0	1	1	1	0	1	1	0

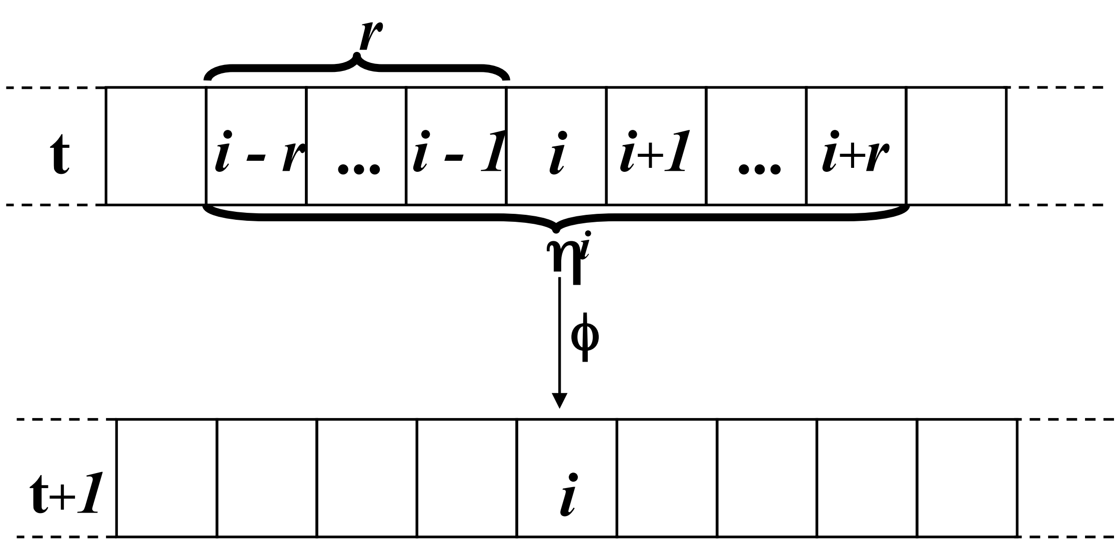
Lattice:



Introduction to Cellular Automata (CA)

- Invented by John von Neumann (circa~1950).
- A cellular automata consists of:
  - A regular arrangement (lattice) of cells.
  - Cells can be in one of a finite number of states at each time step.
  - All cells have the same synchronous update rule.
  - Cells have a local interaction neighborhood.
- Example: The game of life.
- Many cellular automata applications:
  - Hydrodynamics, fluid dynamics
  - Forest fire simulation
  - Models of ecosystems and epidemics
  - Ferro-magnetic modeling (ISING models)

One-Dimensional CA Illustration



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One-Dimensional Cellular Automaton (CA)

- Consists of a linear array of identical *cells* (called a *lattice*), each of which can be in a finite number of *k* states.
- The (local) *state* of cell *i* at time *t* is denoted: $s_t^i \in \Sigma = \{0,1,\ldots,k-1\}$
- The (global) state s_t at time *t* is the *configuration* of the entire array,

$$\mathrm{s}_t = (s_t^0, s_t^1, \ldots, s_t^{N-1}) \in \Sigma^N$$

- where *N* is the (possibly infinite) size of the array.

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One-Dimensional CA cont.

- At each time step, all cells in the array update their state simultaneously, according to a *local update rule* $\phi : \eta \rightarrow s$.
- This update rule takes as input the *local neighborhood configuration* η of a cell.
- A local neighborhood configuration η consists of s_i and its 2*r* nearest neighbors (*r* cells on either side):

$$\eta_i = (s^{i-r}, \ldots, s, \ldots, s^{i+r})$$

- *r* is called the *radius* of the CA.
- The local update rule ϕ
  - is the same for every cell in the array
  - Represented as a lookup table, with all neighborhood configurations
- The state of each cell at time *t*+1 is determined by applying ϕ to each cell at time *t:*

$$s_{t+1}^{i} = \phi(\eta_t^i)$$

Rule 110

0	0	0	→	0
0	0	1	→	1
0	1	0	→	1
0	1	1	→	1
1	0	0	→	0
1	0	1	→	1
1	1	0	→	1
1	1	1	→	0

The number of rules in the rule table
is the number of neighborhood configurations

$$(|\eta| = k^{2r+1})$$

Each rule can map to one of k states, so
The number of possible rules is

$$k^{2r+1}$$

$$k$$

000	001	010	011	100	101	110	111
0	1	1	1	0	1	1	0

0 1 1 0 1 1 1 0 = 0+ 2 + 4 + 8 + 0 + 32 + 64 = Rule 110
Read the bit string BOTTOM to TOP

Example One-Dimensional CA Rule 110

- The number of states, k=2.
- The alphabet $\Sigma = \{0,1\}$ $\quad |\Sigma| = k$
- The size of the array, N=11.
- The configuration space η

  $$\Sigma^N = \{(0,0,0,0,0,0,0,0,0,0,0),(0,0,0,0,0,0,0,0,0,0,1\,1),\ldots\}$$

- The radius r = 1.
- The rule table : $s_{t+1}^i = \phi(\eta_t^i)$

  k^{2r+1} neighborhood configurations in ϕ

000	001	010	011	100	101	110	111
0	1	1	1	0	1	1	0

- In Wolfram notation this is rule 110 (base 10) because the output states are: 01101110 (base 2).

- Rule 110 supports universal computation.

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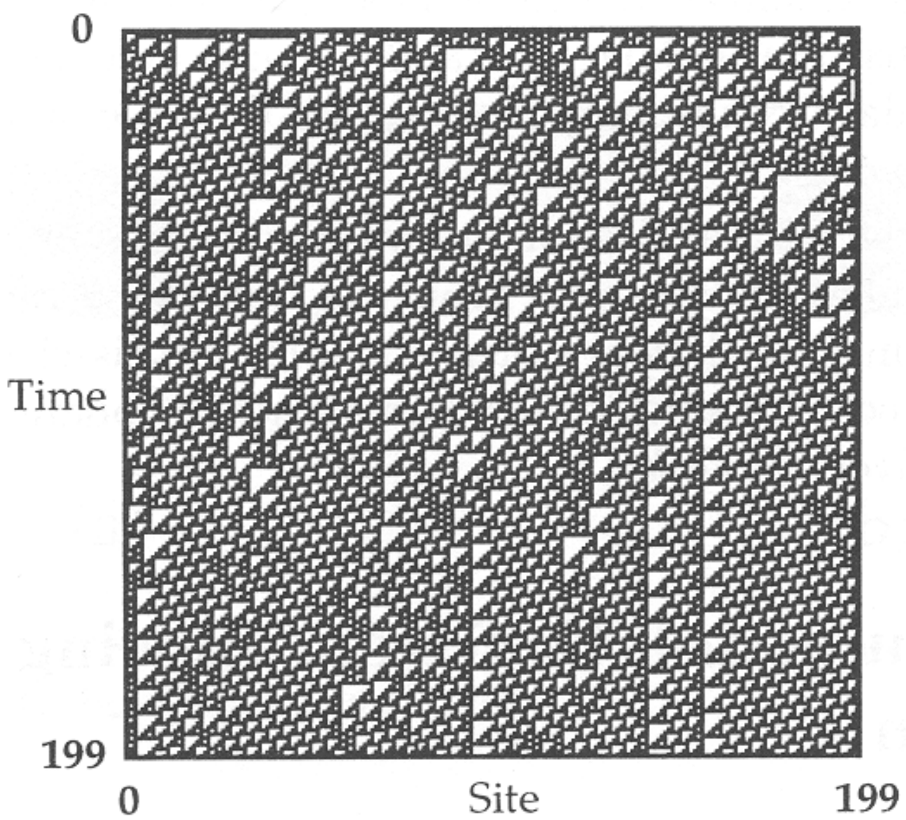
Rule 110 Space-Time Plot



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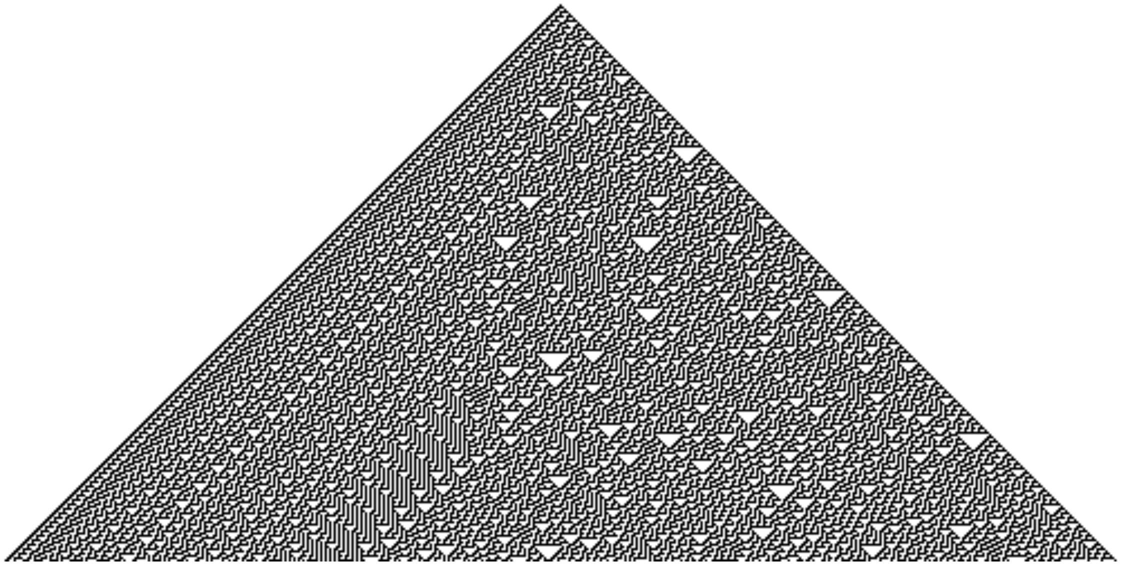
Rule 30



current pattern	111	110	101	100	011	010	001	000
new state for center cell	0	0	0	1	1	1	1	0

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Comments on Rule 30

- Generates apparent randomness, despite being finite
- Wolfram uses the central column as a pseudo-random number generator in Mathematica
- Passes many tests for randomness, but many inputs produce regular patterns:
  - All zeroes
  - 00001000111000 repeated infinitely (try separating by 6 1s)

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Wolfram's CA Classification

- Class I: Eventually every cell in the array settles into one state, never to change again. Analogous to
  - computer programs that halt after a few steps
  - dynamical systems that have fixed-point attractors
- Class II: Eventually the array settles into a periodic cycle of states
  - computer programs that execute infinite loops
  - dynamical systems that fall into limit cycles.
- Class III: The array forms "aperiodic" random-like patterns.
  - computer programs that are pseudo-random number generators (pass most tests for randomness, highly sensitive to seed, or initial condition).
  - Analogous to chaotic dynamical systems. Determinisitic but almost never repeat themselves, sensitive to initial conditions, embedded unstable limit cycles.

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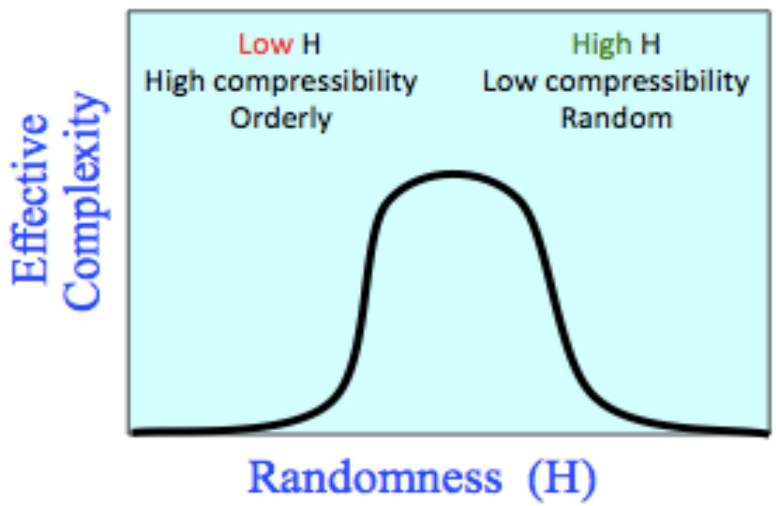
Wolfram's Classification cont.

- Class IV: The array forms *complex* patterns with localized structure that move through space and time:
  - Difficult to describe. Not regular, not periodic, not random.
  - Speculate that it is interesting computation.
- Hypothesis: The most interesting and complex behavior occurs in Class IV CA---"the edge of chaos".
- Example: Rule 110



Wolfram Class I

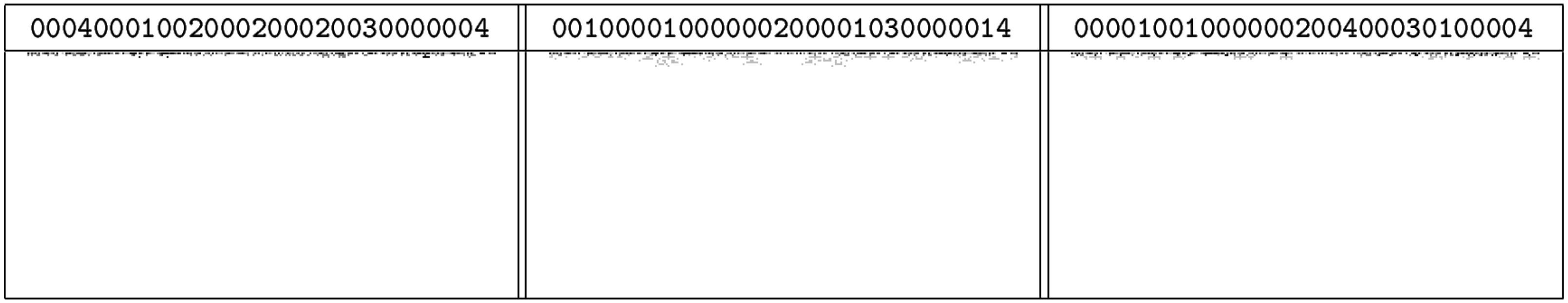


Figure 15.5 Examples of Wolfram's Class I

Wolfram Class II

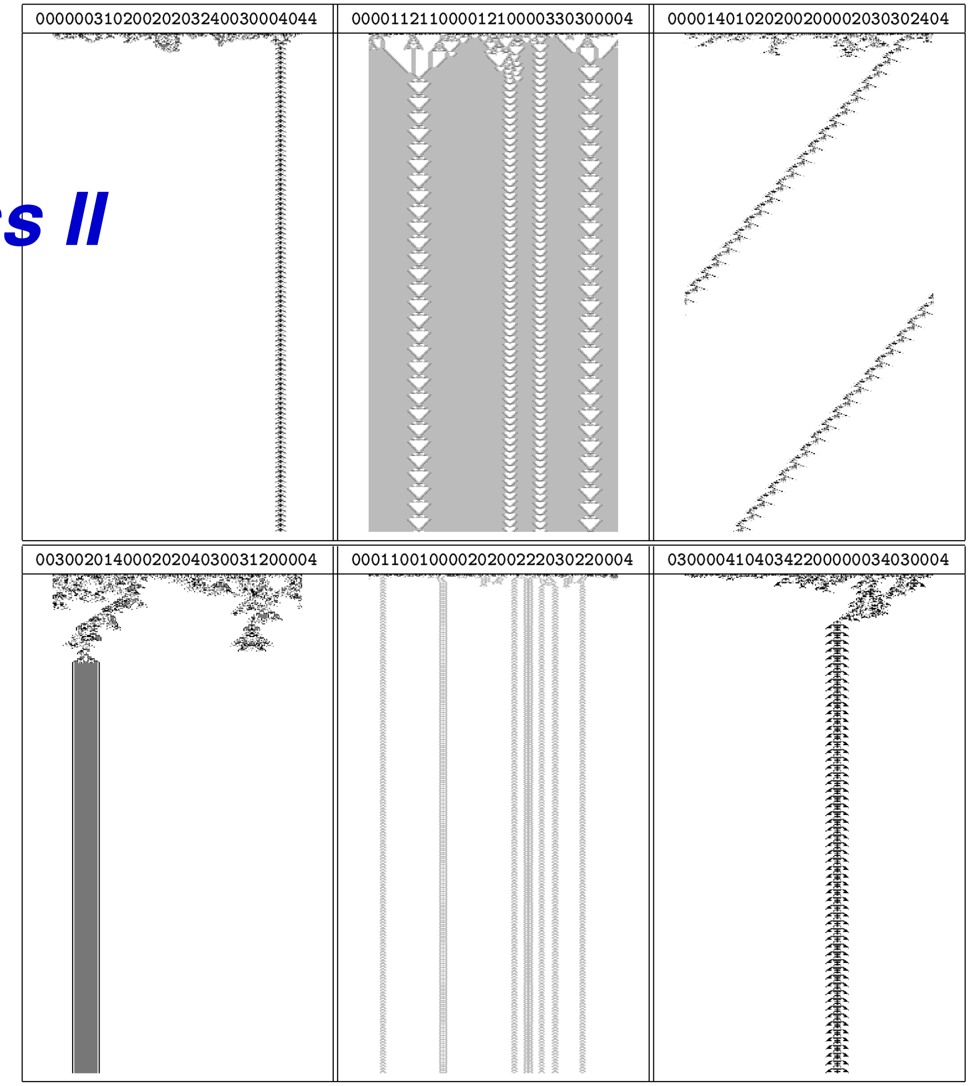


Figure 15.6 Examples of Wolfram's Class II

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Wolfram Class III

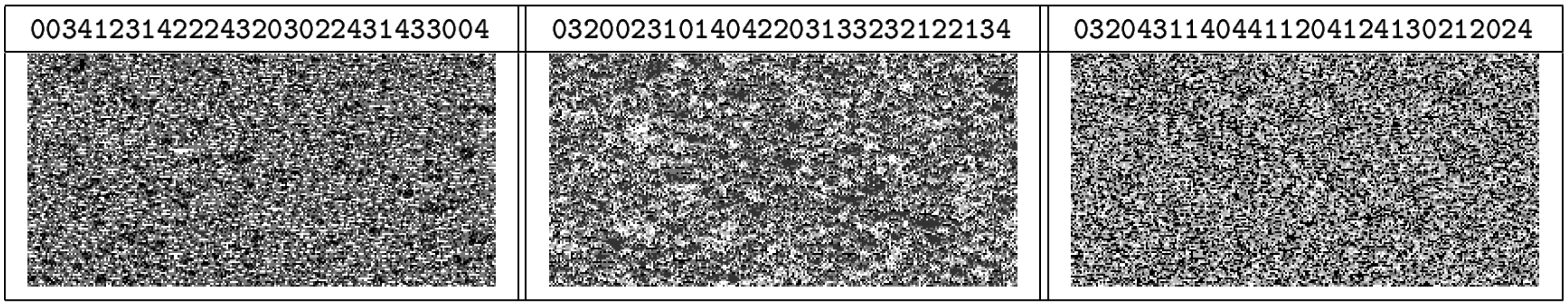

Figure 15.7 Examples of Wolfram's Class III

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Wolfram Class IV

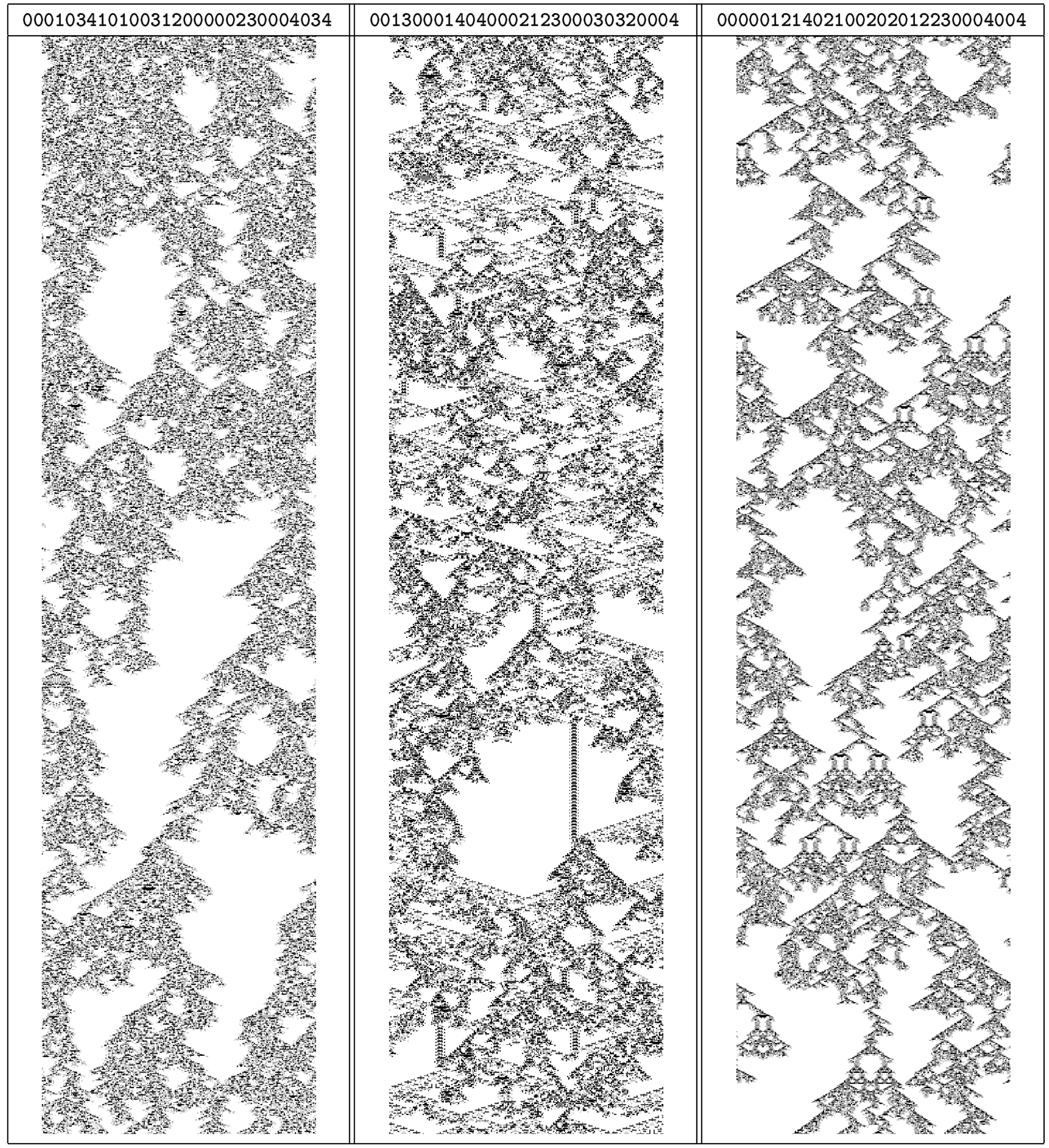

Figure 15.8 Examples of Wolfram's Class IV

Cellular Automata as models of complexity
Wolfram *Nature* 1984

http://twilightstarsong.blogspot.com/2009/03/
shaping-future-stephen-wolfram-ray.html

- 4 classes
  - I: Fixed point
  - II: Limit cycle
  - III: Random or chaotic (unpredictable)
  - IV: Complex
- Beyond $r = 1$ (Figs 3 – 6)
- Entropies & Dimensions
- Information Propagation
- Class IV supports universal computation (?)
  - Long-term behavior undecidable and intractable
  - Simulation is necessary

Entropies & Dimensions

Class I: no randomness in space or time (0 entropy)

Class II: randomness in space, predictable in time after a transient

Class III: unpredictable in time and space

Class IV: undecidable

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Information Propagation

Class I: no information propagation

Class II: propagation in a finite region

Class III: propagation over an increasing region, at fixed speed, over time

Class IV: irregular propagation over (potentially) infinite region

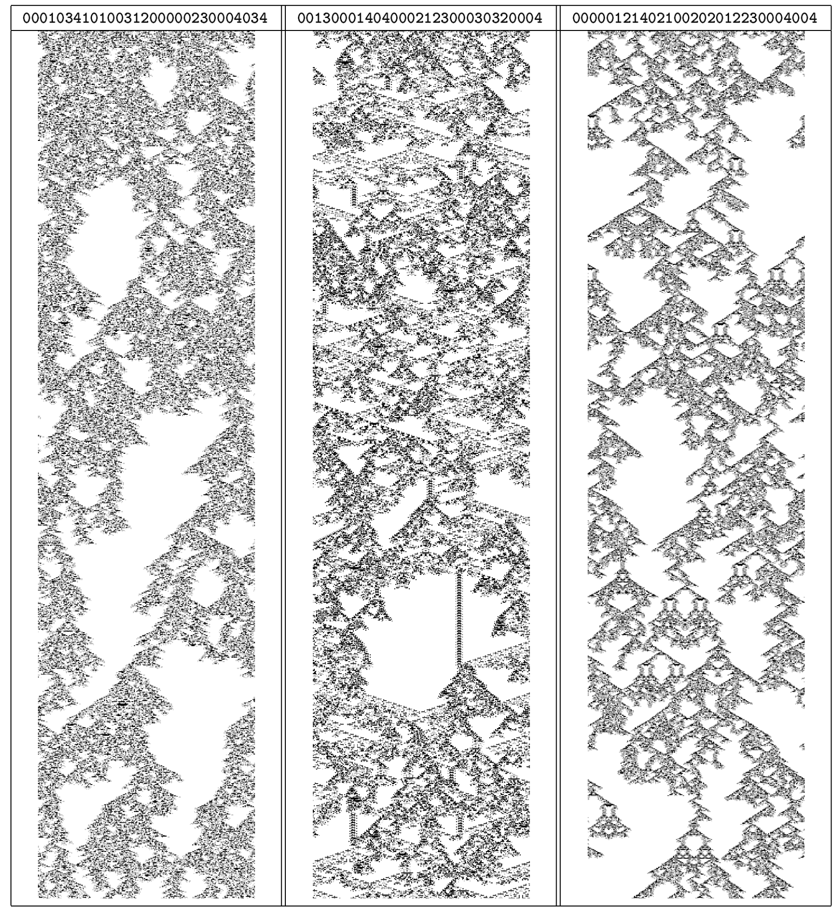

Figure 15.8 Examples of Wolfram's Class IV