# Exploring Complexity

In Science and Technology

Nov. 3, 2010

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# Logistics

- Due
  - Lab4: GA due today online on Blackboard
  - HW6 and Lab5 due Monday Nov. 15
- Ideas for final papers
  - Proposals due next Monday
- Missing Assignments
- Questions?

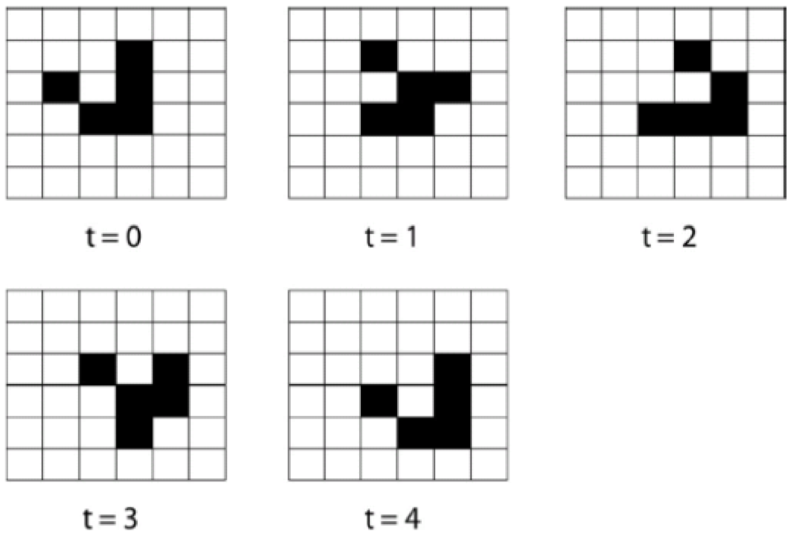
## What is a cellular automaton?

- Models of parallel processes with simple rules
  - Emergence
- light bulbs pictures
- relation to Turing machines
  - "non-von-Neumann-style architecture"
- invented by von Neumann
- CAs and universal computation

## Example: Game of Life (John Conway, 1970s)

- Neighborhood: 2 dimensional 3x3 neighborhood:
- Rules:
  - A dead cell with exactly three live neighbors becomes a live cell (birth).
  - A live cell with two or three live neighbors stays alive (survival).
  - In all other cases, a cell dies or remains dead (overcrowding or loneliness).
- Demo:
  - http://www.bitstorm.org/gameoflife/
  - http://golly.sourceforge.net (Golly.exe)

# A “glider”



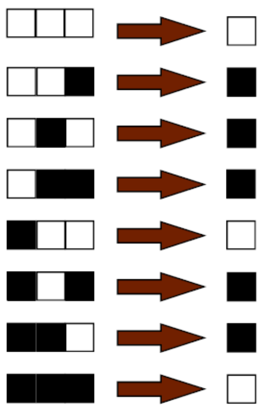

# Predictability?

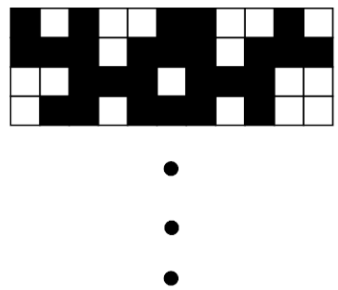
- Is there a general way to predict the behavior of Life from a given initial configuration?
- No. Life is Universal.

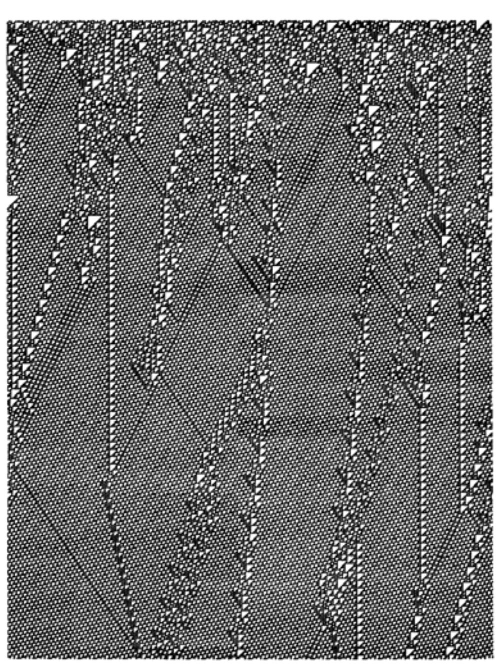
# Elementary cellular automata

- one-dimensional, two states (black and white = on and off)

Rule:







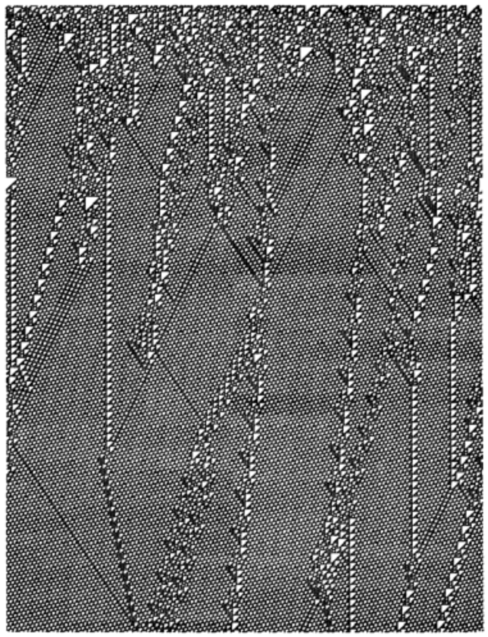
# Stephen Wolfram

Stephen Wolfram. (Photograph courtesy of Wolfram Research, Inc.)

- http://mathworld.wolfram.com/ElementaryCellularAutomaton.html

# Wolfram's Four Classes of CA Behavior

- Class 1: Almost all initial configurations relax after a transient period to the same fixed configuration (e.g., all 1s).
- Class 2: Almost all initial configurations relax after a transient period to some fixed point or some temporally periodic cycle of configurations, but which one depends on the initial configuration
- Class 3: Almost all initial configurations relax after a transient period to chaotic behavior. (The term ``chaotic'' here refers to apparently unpredictable space-time behavior.)
- Class 4: Some initial configurations result in complex localized structures, sometimes long-lived.



From: http://www.stephenwolfram.com/publications/articles/ca/86-caappendix/16/text.html

- Transfer of information
  - moving particles
- Integration of information from different spatial locations
  - particle collisions

# Wolfram's hypothesis

- All class 4 CAs can support universal computation
- Outline of Proof
  - Define "cyclic tag systems" (http://en.wikipedia.org/wiki/Tag_system )
    - Created by Matthew Cook under the employ of Stephen Wolfram
  - Prove they are universal (they can emulate Turing machines).
  - Show ECA 110 can emulate a cyclic tag system.

## Outline of Wolfram's A New Kind of Science

(from MM review, Science, 2002)

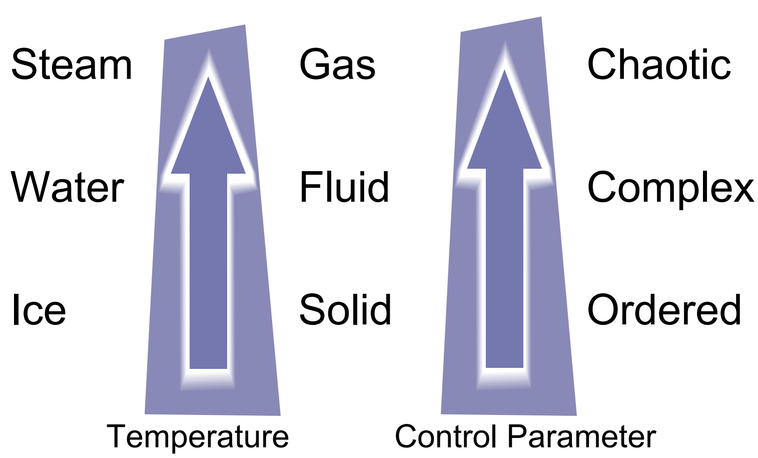
- Simple programs can produce complex, and random-looking behavior
  - Complex and random-looking behavior in nature comes from simple programs.
- Natural systems can be modeled using cellular-automata-like architectures
- Cellular automata are a framework for understanding nature
- Principle of computational equivalence

## Principle of Computational Equivalence

- The ability to support universal computation is very common in nature.
- Universal computation is an upper limit on the sophistication of computations in nature.
- Computing processes in nature are almost always equivalent in sophistication.

- What is the relationship between the dynamics of cellular automata and their ability to compute?

# Phase transitions



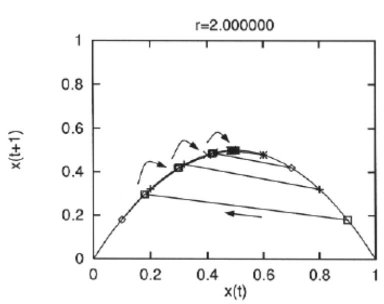
# Hypothesis (Langton, Packard, Kauffman, others)

- Need maximally "fluid" state to maximize potential for:
  - information processing
  - complexity of dynamics
  - ability to adapt

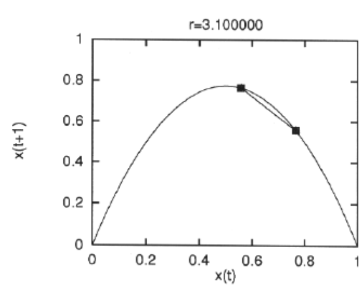
# Recall the "logistic map" model of population dynamics

- $x_{t+1} = r\, x_t (1 - x_t)$
- Order parameter is population growth rate,

Fixed point

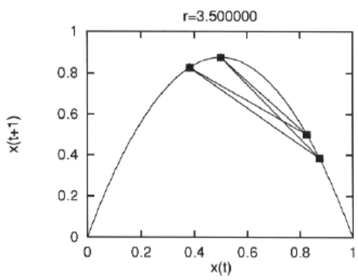



Period 2

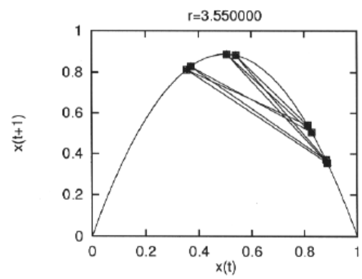


$$x_{t+1} = r\,x_t\,(1 - x_t)$$

Period 4

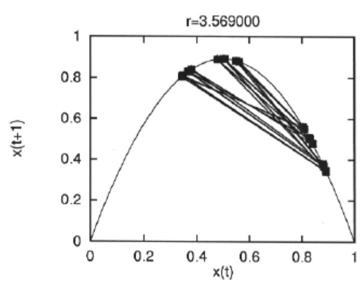



Period 8

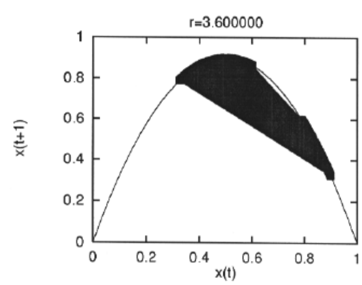



$$x_{t+1} = r\,x_t\,(1 - x_t)$$

Period 16




Chaos




- The onset (or “edge”) of chaos is r = 3.569946

## The ‘edge of chaos’ in cellular automata

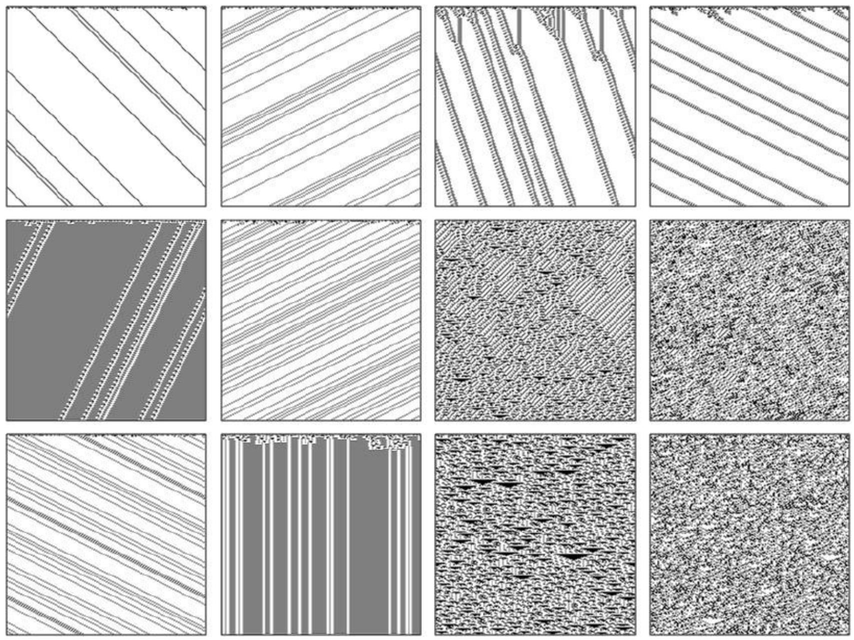
(C. Langton, Physica D, 42:12-37, 1990)

- Langton devised an “order parameter” for
- cellular automata called λ.
- • For binary-state CAs, λ is defined as follows:
- $\lambda = \dfrac{\text{number of 1s in rule table's output bits}}{\text{number of entries in rule table}}$

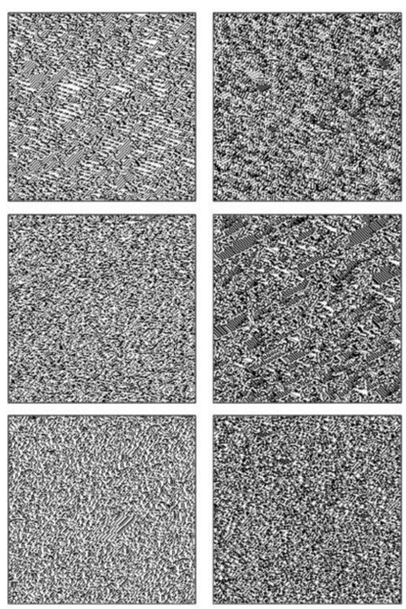
## The ‘edge of chaos’ in cellular automata

(C. Langton, Physica D, 42:12-37, 1990)

- Building on Wolfram’s classes of behavior for CA, Langton found evidence that cellular automata can be “ordered” or “chaotic” roughly according to lambda
- He showed evidence that the “complexity” of patterns formed by cellular automata is maximized at the transition between order and chaos
- He argued that the potential for computation must be maximized at this “phase transition”



λ = 0.1 λ = 0.2 λ = 0.3 λ = 0.4



λ = 0.4 λ = 0.5

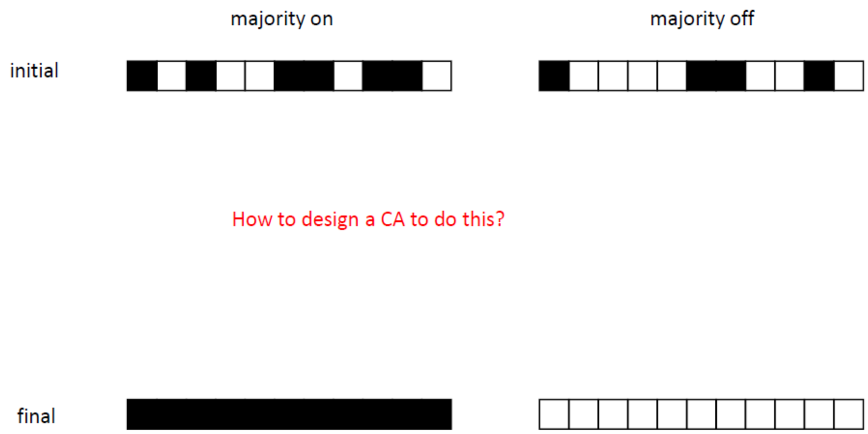
http://math.hws.edu/xJava/CA/EdgeOfChaosCA.html

# How to define “potential for computation”?

- Adaptation to the Edge of Chaos (N. Packard, 1988)
- Main ideas:
  - Define a task for cellular automata requiring non-trivial computation.
- Use a genetic algorithm to evolve a population of cellular automaton rules, with fitness defined as performance on the task.
- Analyze the distribution of lambda values in the final generation.

# A computational task for cellular automata

- Design a cellular automata to decide whether or not the initial pattern has a majority of “on”cells.
  - If a majority of cells are initially on, then after some number of iterations, all cells should turn on
  - Otherwise, after some number of iterations, all cells should turn off.




- Deborah Gordon (ant behavior)
  - Watched
  - http://www.ted.com/talks/deborah_gordon_digs_ants.html
- Bonnie Bassler (bacteria quorum sensing)
  - Next time
  - http://www.ted.com/index.php/talks/bonnie_bassler_on_how_bacteria_communicate.html