Artificial Life - Lecture 7

Cellular Automata and Random Boolean Networks

In the wide spectrum of approaches to synthesising 'lifelike' behaviour, **CA**s and **RBN**s are amongst the most abstract and mathematical.

A lot of the interest in this comes from people with a Physics background. Cf. Los Alamos, Santa Fe, the 'chaos cabal' .

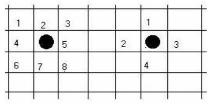
(pop book on the chaos cabal: "The Newtonian Casino" T. Bass 1990 Longmans, (US= "The Eudaemonic Pie" 1985)

The Game of Life

Best known CA is John Horton Conway's "Game of Life". Invented 1970 in Cambridge.

Objective: To make a 'game' as unpredictable as possible with the simplest possible rules.

2-dimensional grid of squares on a (possibly infinite) plane. Each square can be blank (white) or occupied (black).



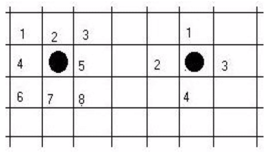
More Game of Life

At any time there are a number of squares with black dots. At the 'regular tick of a clock' all squares are updated simultaneously, according to a few simple rules, depending on the **local situation**.

For the 'Game of Life' **local situation** means, for any one cell, the current values of itself and 8 immediate neighbours ('Moore neighbourhood')

Neighbourhoods

8 immediate neighbours = 'Moore neighbourhood', on L
For different CAs, different neighbourhoods might be chosen; e.g. the 'von Neumann neighbourhood', on R.



Readable pop sci on CAs: William Poundstone "The Recursive Universe" OUP 1985

More formal definition of CA

✓A regular lattice	eg. grid
✓of finite automata	eg. cells
✓each of which can be in one of a finite number of states	eg. black/white tho could be 10 or 100

✓transitions between states are governed by a state-transition table eg. GoL rules

✓input to rule-table = state of cell and specified local neighbourhood (In GoL 2 ^9 = 512 inputs)
✓output of rule-table = next state of that cell

CAs

All automata in the lattice (all cells on the grid) obey the same transition table, and are updated simultaneously.

From any starting setup on the lattice, at each timestep everything changes **deterministically** according to the rule-table.

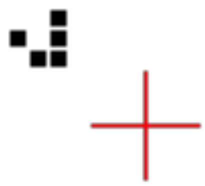
Game of Life: rules

Update rule for each cell:

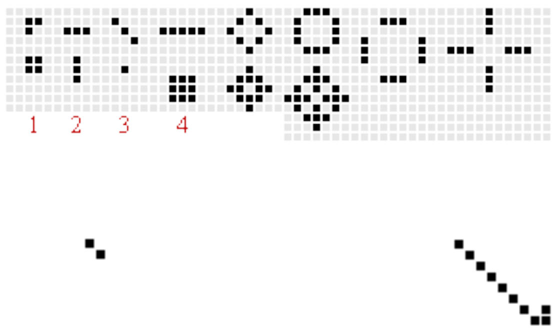
- ✓**If** you have exactly 2 'on' nbrs (ie 2 blacks) stay the same
- ✓**If** you have exactly 3 'on' nbrs you will be 'on' (black) next timestep (ie change to on if you are blank, and remain on if you already are)
- ✓**If** you have less than 2, or more than 3 on nbrs you will be off (blank) next timestep

Thats all !

Glider



Sequences



More

Sequence leading to Blinkers

Clock

Barber's pole

A Glider Gun

Alternative rules

Every cell is updated simultaneously, according to these rules, at each timestep.

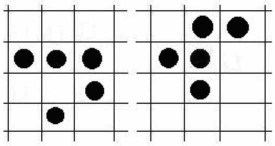
Programming details -- eg maintain 2 arrays for 'this_timestep' and 'next_timestep'.
(Check who would have problems starting to write a program for this)

Alternative (equivalent) formulation of GoL rules:

0,1 nbrs	= starve, die	2 nbrs	= stay alive
3 nbrs	= new birth	4+ nbrs	= stifle, die

Gliders and pentominoes

On the left: a **'Glider'**
On a clear background, this shape will 'move' to the NorthEast one cell diagonally after 4 timesteps.



Each cell does not 'move', but the 'pattern of cells' can be seen by an observer as a glider travelling across the background.

Emergence

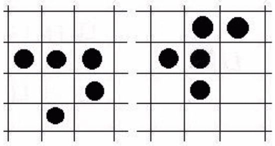
This behaviour can be observed as 'the movement of a glider', even though no glider was mentioned in the rules.

'Emergent' behaviour at a higher level of description, emerging from simple low-level rules.

Emergence = emergence-in-the-eye-of-the-beholder (dangerous word, controversial)

Pentominoes

On the right: a 'pentomino'. Simple starting state on a blank background => immense complexity, over 1000 steps before it settles.



(Pop Sci) William Poundstone "The Recursive Universe" OUP 1985

(Primordial Soup kitchen) http://psoup.math.wisc.edu/kitchen.html
http://www.math.com/students/wonders/life/life.html
http://www.bitstorm.org/gameoflife/

Game of Life - implications

Typical Alife computational paradigm:
✓bottom-up
✓parallel
✓locally-determined

Complex behaviour from (... emergent from ...) simple rules.

Gliders, blocks, traffic lights, blinkers, glider-guns, eaters, puffer-trains ...

Game of Life as a Computer ?

Higher-level units in GoL can in principle be assembled into complex 'machines' -- even into a full computer, or Universal Turing Machine.

(Berlekamp, Conway and Guy, "Winning Ways" vol 2, Academic Press New York 1982)

'Computer memory' held as 'bits' denoted by 'blocks' laid out in a row stretching out as a potentially infinite 'tape'. Bits can be turned on/off by well-aimed gliders.

Self-reproducing CAs

von Neumann saw CAs as a good framework for studying the necessary and sufficient conditions for
self-replication of structures.

von N's approach: self-rep of abstract structures, in the sense that gliders are abstract structures.

His CA had 29 possible states for each cell (compare with Game of Life 2, black and white) and his minimum self-rep structure had some 200,000 cells.

Self-rep and DNA

This was early 1950s, pre-discovery of DNA, but von N's machine had clear analogue of DNA which is **both:**

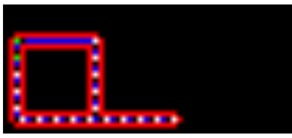
✓used to determine pattern of 'body'
  interpreted
✓and itself copied directly
  copied without interpretation as a symbol string

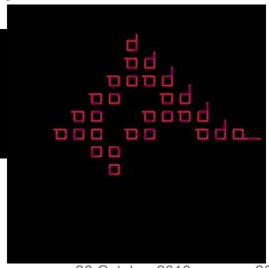
Simplest general logical form of reproduction (?)

How simple can you get?

Langton's Loops

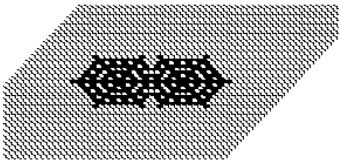
Chris Langton formulated a much simpler form of self-rep structure - Langton's loops - with only a few different states, and only small starting structures.





[Further developments -- eg 'Wireworld'.]

Snowflakes



One dimensional CAs

Game of Life is 2-D. Many simpler 1-D CAs have been studied, indeed whole classes of CAs have been.

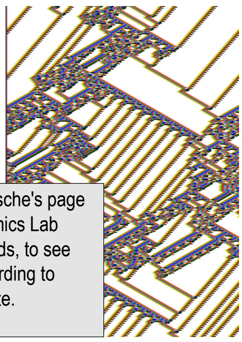
Eg. a 1-D CA with 5 states (a b c d and - = blank) can have current state of lattice such as

- - - a - b c d c a - - -

or pictorially with coloured squares instead of a b c d
Then neighbours of each cell are (typically) one on each side, or 2 on each side, or ... ...

Spacetime picture

For a given rule-set, given starting setup, the deterministic evolution of the CA can be pictured as successive lines of coloured squares, successive lines under each other



This spacetime picture was taken from Andy Wuensche's page www.ddlab.com DDLab = Discrete Dynamics Lab
Wuensche's work allows one to run CAs backwards, to see what previous state(s) of the world could (according to the rules) have preceded the present state.

Wolfram's CA classes 1,2

From observation, initially of 1-D CA spacetime patterns, Wolfram noticed 4 different classes of rule-sets. Any particular rule-set falls into one of these:-:

CLASS 1: From any starting setup, pattern converges to all blank -- **fixed attractor**

CLASS 2: From any start, goes to a limit cycle, repeats same sequence of patterns for ever. **-- cyclic attractors**

CLASS 3 ...

CLASS 4: Turbulent mess, no patterns to be seen.

Wolfram's CA classes 3,4

CLASS 3: From any start, patterns emerge and continue continue without repetition for a very long time (could only be 'forever' in infinite grid)

Classes 1 and 2 are boring, Class 4 is messy, Class 3 is **'At the Edge of Chaos'** - at the transition between order and chaos -- where Game of Life is!

Langton's lambda parameter, and later Wuensche's Z parameter give some measure along this scale between order and chaos.

Dangers of Formalisms

BUT (quote from von Neumann):
"By **axiomatising** automata in this manner, one has thrown half of the problem out of the window, and it may be the **more important half**. One has resigned oneself **not** to explain how these parts are made up of real things ...actual elementary particles..."

Dangers of formalisms. Issue of Embodiment.

Applications of CAs

Modelling physical phenomena, eg diffusion.

Image processing, eg blurring, aliasing, deblurring.

Danny Hillis's Connection Machine based on CAs.

Modelling competition of plants or organisms within some space or environment.

Eg Iterated Prisoner's Dilemma -- see later in course.

Typical Alife Computational Paradigm

To repeat: Typical Alife computational paradigm:
✓bottom-up
✓parallel
✓locally-determined

Complex behaviour from (... emergent from ...) simple rules.

Random Boolean Networks (RBNs)

Messier (and more general) version of CAs:-

throw away the organised neighbourhood relationships and substitute randomly chosen neighbours.

NK RBNs

Think of: **N nodes** [cells], each with **K directed links** (arrows) arriving from other nodes [link = input]

Each node can only be white or black (0 or 1)

This is Kauffman's NK RBNs (careful -- do not confuse with Kauffman's NK fitness landscapes !!)

The links are directed at **RANDOM.** And unlike CAs (where update rules are the same at every cell) the (Boolean) rules are chosen at **RANDOM** for each node.

RBNs as models

Kauffman (eg in "Origins of Order") uses these RBNs as an abstract model of the genetic regulatory network.

Many genes 'switch on or off' other genes, the precise linkage and rules for doing this is unknown.

Kauffman's question: Is there any **GENERIC** property of all RBNs, which we can expect the genetic regulatory network to follow, even tho we don't know details ?

Kauffman's NK RBN conclusions

Take N nodes ('genes') each with K input links ('regulation from other genes'). There are a **mind- boggling number** of different ways to wire-up the links and choose different rule-tables (new state of node as a Boolean function of inputs).

Nevertheless, generic behaviour is very predictable, with a transition **'from chaos to order'** from K<2 to K>2.

When **K=2** the number of **attractors** of RBNs is surprisingly small, about sq. root of N. And typically, from any starting position, the system only takes about $\sqrt{N}$ steps to get there.

Implications for Genetic Regulatory Systems?

For human genetic regulatory system, N = 100,000 (say – tho more recent estimates are lower, say 24 or 25,000).

Wire up 100,000 genetic switches to each other at random and you might expect the 'lights' at the nodes to flash randomly for ever -- but (for K=2, and sq root of 100,000 = about 300) after only 300 or so timesteps the system 'falls into' one of **only 300** or so 'attractors'.

Kauffman notes: there are roughly 300 or so different human cell types -- coincidence or not ???

Can we trust the conclusions?

Kauffman's thesis is part of an important 'ideological' position, against the 'extreme neo-Darwinists' such as Richard Dawkins who seem to suggest that Darwinian evolution can explain just about all biological phenomena.

Kauffman's claim is that here, and elsewhere, there are **GENERIC CONSTRAINTS** on what is possible, and evolution 'merely' selects within these constraints.

Alternative views

But is this particular work sound, or is it (to quote John Maynard Smith)
(a) "Fact-free science"
(b) "Absolute fucking crap. But crap with good PR."
(see Andrew Brown "The Darwin Wars" Simon and Schuster 1999)

SemiSynchronous - Asynchronous

One criticism by Harvey that Kauffman's RBN work misleadingly uses **synchronous** updating -- as a model of biological phenomena should it not be **asynchronous** ??

Asynchronicity makes a big difference.

"Time out of Joint", Harvey & Bossomaier. My web page.