Self-Reproduction and Evolvability

Tim Taylor

Institute of Perception, Action and Behaviour
School of Informatics

tim.taylor@ed.ac.uk
http://homepages.inf.ed.ac.uk/timt/

Lecture outline

- Introduction
  - Why study self-reproducing systems?
- John von Neumann's self-reproducing automata (late 1940s)
- Other studies (1950-1990)
- Tom Ray's "Tierra" artificial life platform (1990-2001)
- State of the art
- Problems, challenges, and future directions
- Sources of further information

Self-reproduction and evolvability

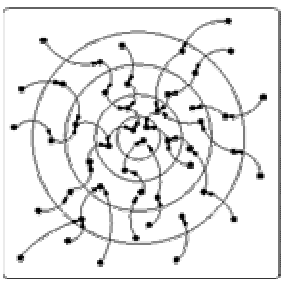
- Darwinian evolution requires that organisms have the following capacities:
  - Multiplication
  - Variation
  - Heredity
- In conditions of competition for limited resources, natural selection leads to survival of well-adapted organisms
- Can we use these processes in artificial systems to evolve complex, well-adapted machines (robots, programs, etc.)?

John von Neumann (late 1940s)

- How can machines manage to construct other machines more "complex" than themselves, in a general and open-ended way?
  - With the potential for unbounded evolutionary growth of complexity

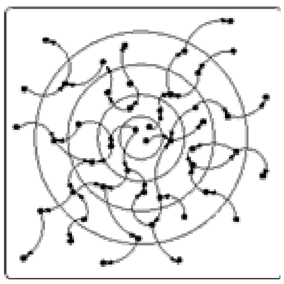
Slide adapted from original presentation by Barry McMullin

Degeneration of Complexity (Engineering)



Slide adapted from original presentation by Barry McMullin

Growth of Complexity (Biology)

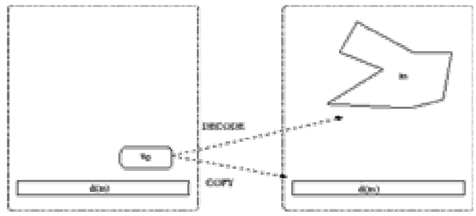


Slide adapted from original presentation by Barry McMullin

The challenge

- Develop a formal description of a system that can support self-reproducing machines which are robust in the sense that they can withstand some types of mutation – and pass these mutations on to their offspring
  - Such machines could therefore participate in a process of <u>evolution</u>
- Design a concrete system that fulfils this description

The General Constructive Automaton

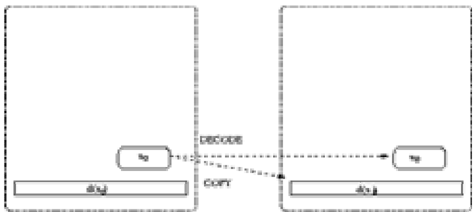


$$(u_0 \oplus d(m)) \rightsquigarrow (m \oplus d(m))$$

(Inspired by the idea of the Universal Turing Machine)

Slide adapted from original presentation by Barry McMullin

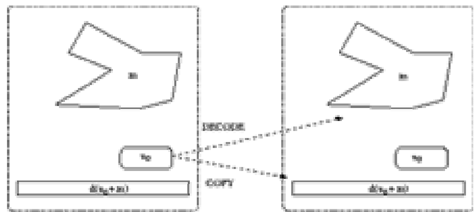
Von Neumann SR: Minimal Case



$$(u_0 \oplus d(u_0)) \rightsquigarrow (u_0 \oplus d(u_0))$$

Slide adapted from original presentation by Barry McMullin

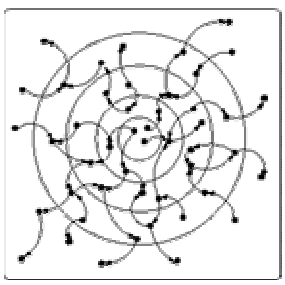
Von Neumann SR: Generic Case



$$((u_0 \oplus m) \oplus d(u_0 \oplus m)) \rightsquigarrow ((u_0 \oplus m) \oplus d(u_0 \oplus m))$$

Slide adapted from original presentation by Barry McMullin

Growth of Complexity (von Neumann)

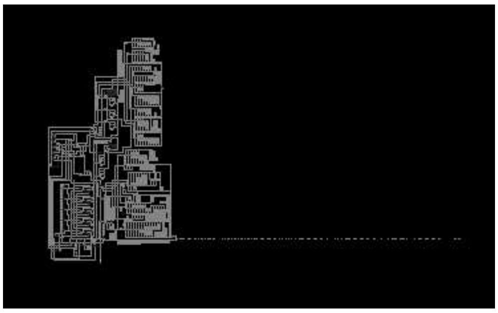


Slide adapted from original presentation by Barry McMullin

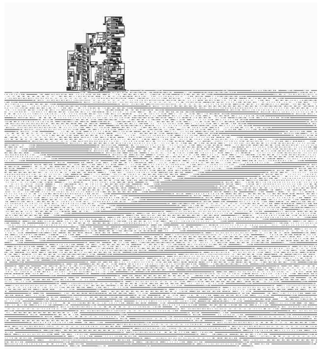
Cellular Automata model

- One of a series of models proposed by von Neumann
  - But the only one fully designed
- 29 states per cell
- Self-reproducing machine comprised thousands of cells
- Von Neumann did not have the resources to implement the model, but it was recently implemented by Pesavento…

Pesavento's implementation



Machine + tape for full self-reproduction



Some other research, 1950-1990

- Elaborations and simplifications of von Neumann's model
  - e.g. Codd (1968), Thatcher (1970)
- Mechanical self-reproduction
  - e.g. Penrose (1959), Jacobson (1958), Morowitz (1959)
- CA self-reproduction without universal construction
  - e.g. Langton (1984)
- Self-reproducing computer programs
  - e.g. "Core Wars" (Dewdney, 1984-1989), "Coreworld" (Rasmussen, 1990)

Tom Ray's Tierra (1990-2001)

- Tierra is a virtual operating system, providing its own machine language and a fixed-size address space (memory)
  - Language is robust to mutations (by avoiding explicit memory addressing) → increased proportion of functional programs
  - Multiple programs in memory are executed in parallel
- Program execution is subject to a small element of stochastic behaviour, and programs are subject to mutations at a low rate
- If there is no memory left, a "reaper" operation kills off some programs to free up space
  - Choice to programs to kill is largely determined by age

Evolution in Tierra

- An evolutionary run is started by introducing an <u>ancestor</u> program into the otherwise empty memory
- The ancestor is a <u>hand-written self-replicator</u> which produces another copy of itself in memory when it is run
- Mutations introduce <u>variations</u> of ancestor, and <u>competition</u> for memory causes an evolutionary process to begin
- In contrast to GAs, no explicit fitness function
  - Natural selection

Self-reproduction in Tierra

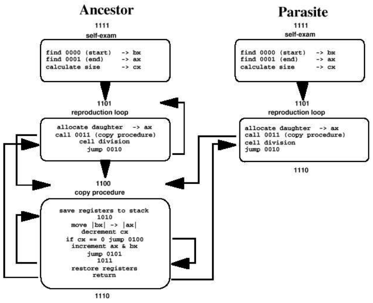
"Self-replication is critical to synthetic life because without it, the mechanisms of selection must also be pre-determined by the simulator. Such artificial selection can never be as creative as natural selection. The organisms are not free to invent their own fitness functions. Freely evolving creatures will discover means of mutual exploitation and associated implicit fitness functions that we would never think of. Simulations constrained to evolve with pre-defined genes, alleles, and fitness functions are dead-ended, not alive."

[Ray 1991]

Tierra: results

Results include:

- Parasites
- Immunity to parasites
- Hyper-parasites
- More efficient replication



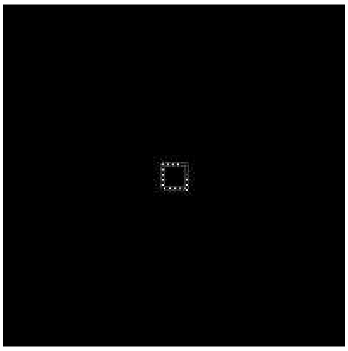
Tierra: limitations

- After initial successes, Tierra failed to evolve any remarkably new innovations in a further decade of research
- Limited, pre-defined set of instructions for interacting with environment (and with other programs)
  - e.g. how to evolve a sensor of the current system time?

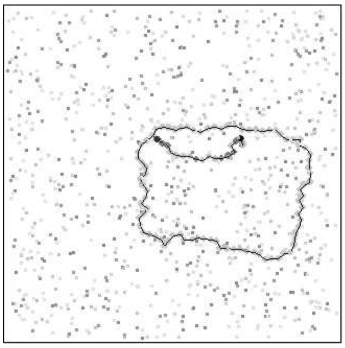
State of the art

- Avida (Adami et al.)
  - A derviative of Tierra, used by (some) biologists (e.g. Lenski)
- Evoloop (Sayama)
  - A derivative of Langton's Loop
- Artificial chemistry models
  - e.g. Hutton, Smith et al.
- EvoCA (Taylor)
- Hardware self-reproduction
  - Macro-scale e.g. NASA (Freitas et al, 1980), Lipson et al. (2004)
  - Meso-scale, e.g. Poulton (2004)

Evoloop (Sayama)

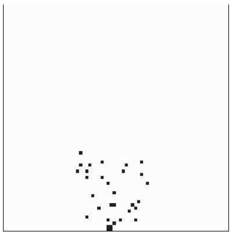


Artificial Chemistry (Hutton)

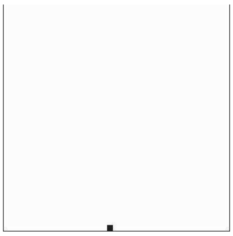


EvoCA

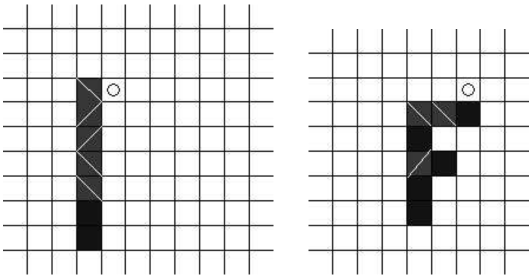
Glider



Spreading Activation



Physical self-replication (Lipson)



Problems, challenges & future directions

- Methodological issues
  - What are these models trying to achieve? Not always clear
- Over-emphasis on self-reproduction
  - To exclusion of other important properties of organisms, e.g.
    - Self-production and self-maintenance
    - Exchange of matter and energy
- Under-emphasis on the environment
  - And on relationship between organism and environment
  - Problem of sensor evolution is a symptom of this

Sources of further information

- The Artificial Self-Replication Page (Moshe Sipper)
  - http://www.cs.bgu.ac.il/~sipper/selfrep/
- Avida
  - http://dllab.caltech.edu/avida/
- Pesavento’s implementation of von Neumann’s Universal Constructor
  - http://people.cornell.edu/pages/up22/jvn.html
- My PhD thesis (esp. Chapters 2, 3 and 7)
  - http://homepages.inf.ed.ac.uk/timt/papers/thesis/