Digital Genesis

Computers, Evolution and Artificial Life

The intertwined history of evolutionary thinking and complex machines

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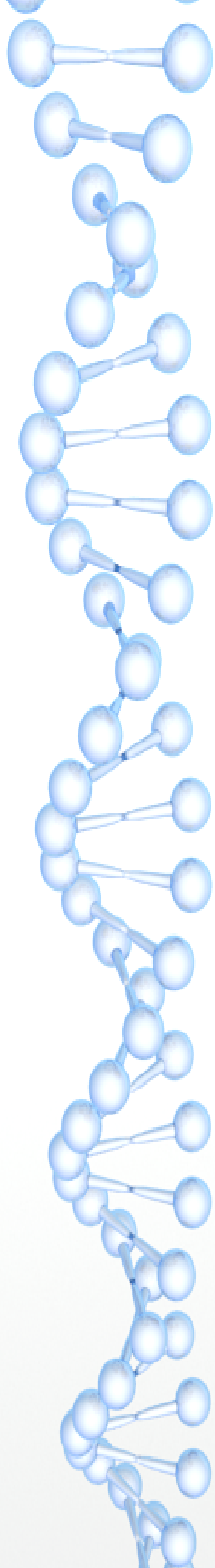


Talk outline

- Some caveats...
- A whirlwind tour...
  - Evolution: a recipe for creation?
    - Applicable to machines and computers?
  - Babbage and Darwin
  - Early thinking on the evolution of machines
    - From the 1860s to 1960s
  - Contemporary work in artificial life
    - Current problems
  - Future directions

Evolution: a recipe for creation?

- Darwinian natural selection requires:
  - Variation
  - Differential reproduction
  - Inheritance
- The logic of Darwin's argument seems to apply to **any** system with these features
  - Including real and virtual machines
- There has been a close relationship between ideas of evolution and complex machines dating all the way back to Darwin and earlier

Babbage and Darwin

- In the 1830s, Babbage used his Difference Engine to demonstrate how discontinuities can arise in a system without external intervention
- Compared this behaviour with discontinuities in Nature such as the appearance of new species
  - God creates the world initially, but it then runs according to natural law
- Darwin saw Babbage's demonstration (c. 1837, soon after *Beagle* voyage)
  - Emboldened Darwin's ideas of nature being governed by natural laws?

Samuel Butler (1863)

- *Darwin Among the Machines*

  [An essay published in *The Press*, Christchurch, New Zealand, 13 June 1863]

  - Compared the development of machines to the evolution of biological life
  - Noticed that machines were already used to make other machines, and predicted the appearance of self-reproducing machines
  - Humans would become subservient as machines quickly evolved to become the supreme creatures

Darwin Among the Machines

[To the Editor of the Press, Christchurch, New Zealand, 13 June, 1863.]

Sir—There are few things of which the present generation is more justly proud than of the wonderful improvements which are daily taking place in all sorts of mechanical appliances. And indeed it is matter for great congratulation on many grounds. It is unnecessary to mention these here, for they are sufficiently obvious; our present business lies with considerations which may somewhat tend to humble our pride and to make us think seriously of the future prospects of the human race. If we revert to the earliest primordial types of mechanical life, to the lever, the wedge, the inclined plane, the screw and the pulley, or (for analogy would lead us one step further) to that one primordial type from which all the mechanical kingdom has been developed, we mean to the lever itself, and if we then examine the machinery of the *Great Eastern*, we find ourselves almost awestruck at the vast development of the mechanical world, at the gigantic strides with which it has advanced in comparison with the slow progress of the animal and vegetable kingdom. We shall find it impossible to refrain from asking ourselves what the end of this mighty movement is to be. In what direction is it tending? What will be its upshot? To give a few imperfect hints towards a solution of these questions is the object of the present letter.

Alfred Marshall (late 1860s)

- *Ye Machine*

  [One of four lectures that Marshall presented to the Grote Club, Cambridge in the late 1860s]

  - Discussed basic designs for a machine that could learn
    - From basic instincts to higher cognitive functions including language, mathematics, science and art
  - As a side note, suggests that the machine could make others like itself:
    - “We thus get hereditary and accumulated instinct... The principle of natural selection, which indeed involves only purely mechanical agencies, would thus be in full operation” (p.119)

John von Neumann (1940s-50s)

- *Theory of Self-Reproducing Automata*
  - The first substantive theoretical work on the logical design of self-reproducing machines capable of evolution

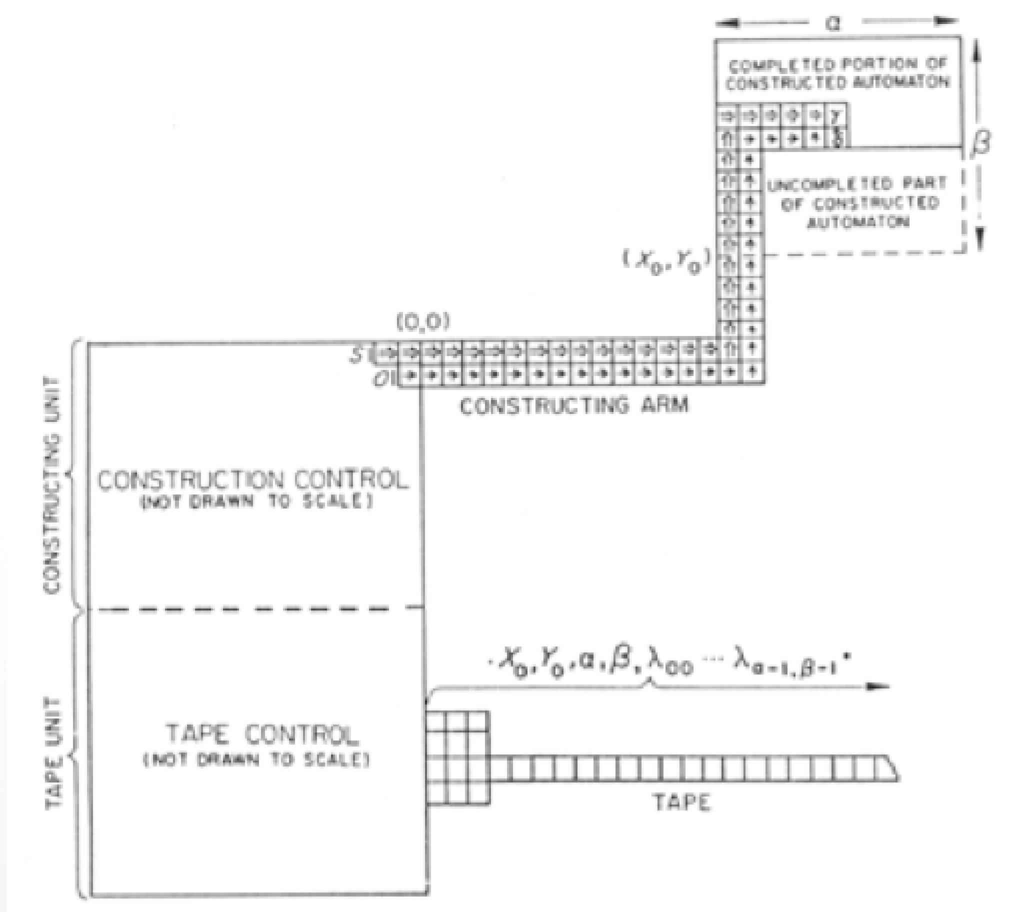


Image from *Essays On Cellular Automata*, A. W. Burks, ed. (1971)

John von Neumann (1940s-50s)

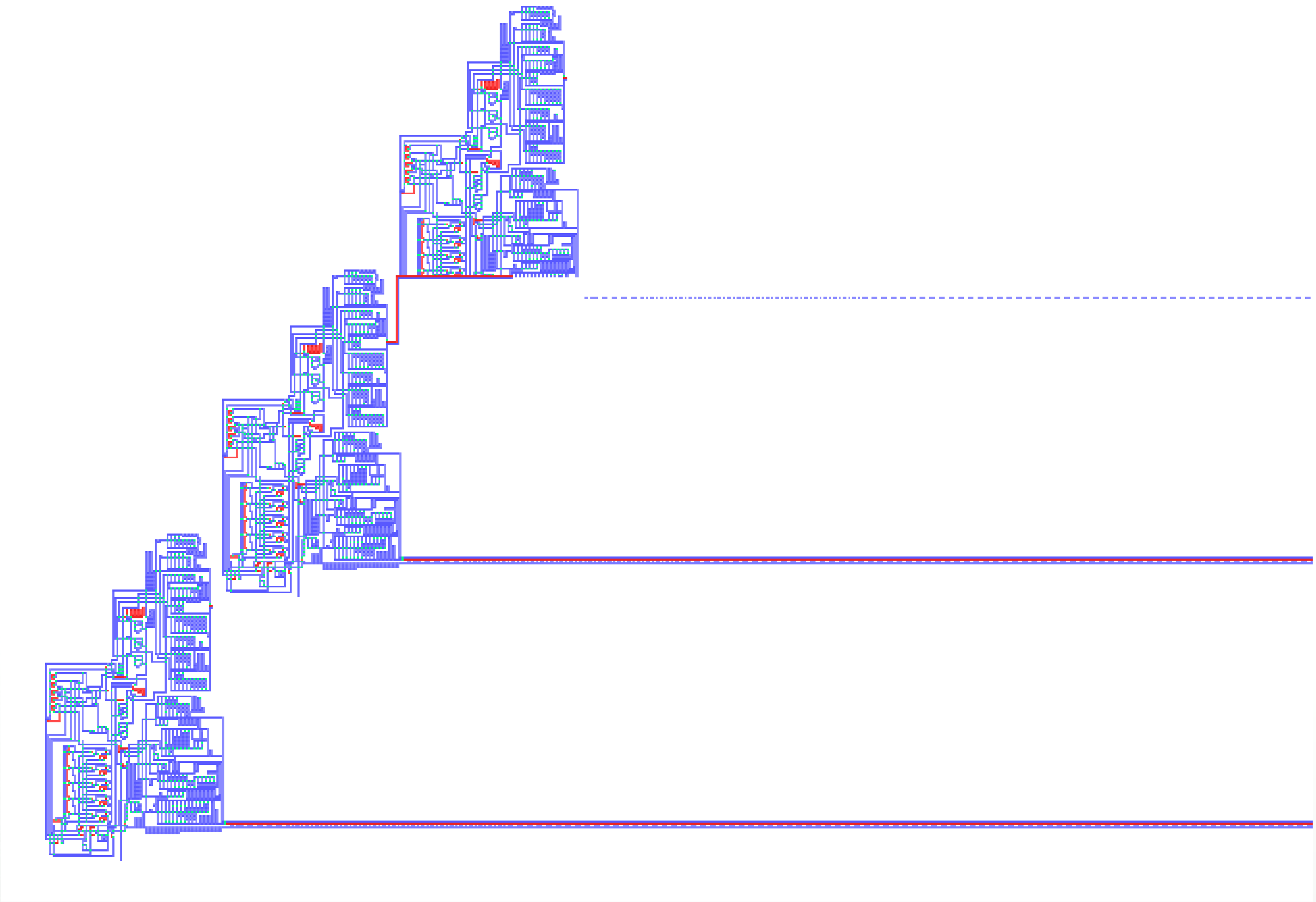
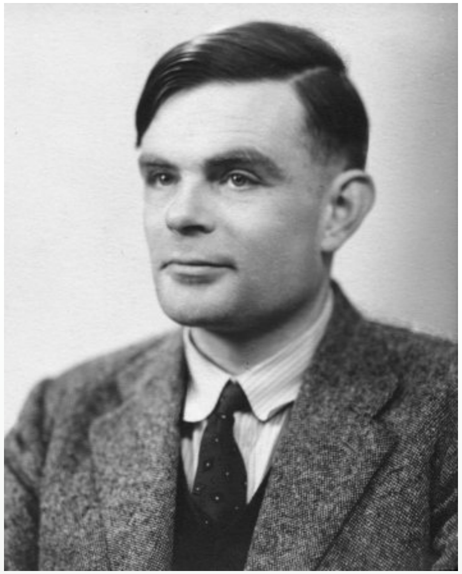


Image from Pesavento (1995)

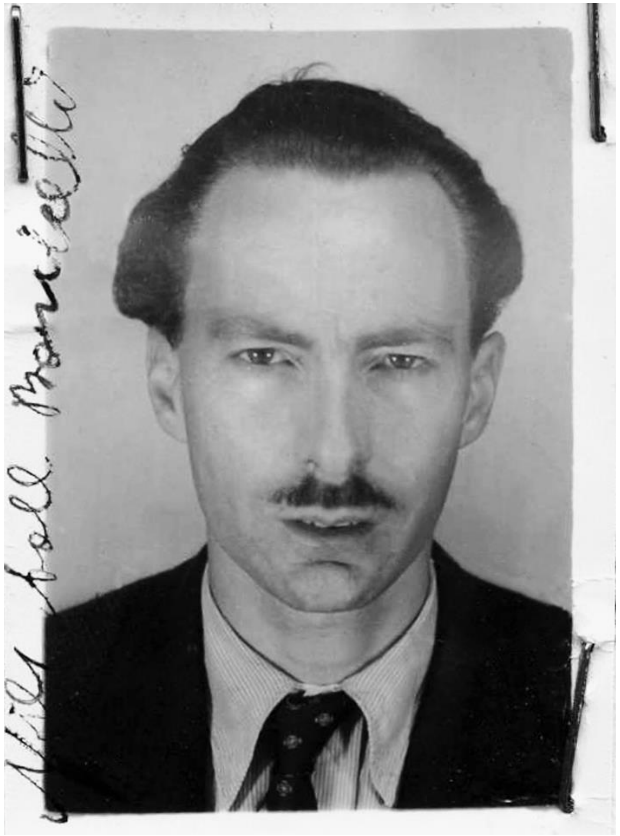
The Ratio Club (1949-1958)

- A regular meeting of British cybernetics pioneers
- A recurring idea was that of intelligence as a *search problem*
- Explicit parallels drawn between lifetime learning and evolution:
  - W. Ross Ashby (late 1940s-early 50s)
    - *Intelligence amplifiers* (evolution plus information theory)
  - Alan Turing (1948-1950)
    - Machine learning using mutation & feedback from a human

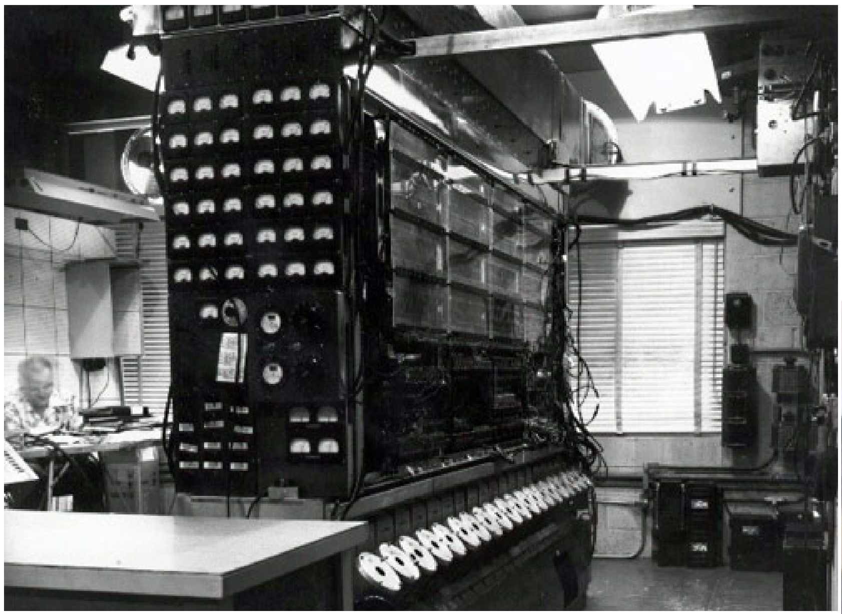


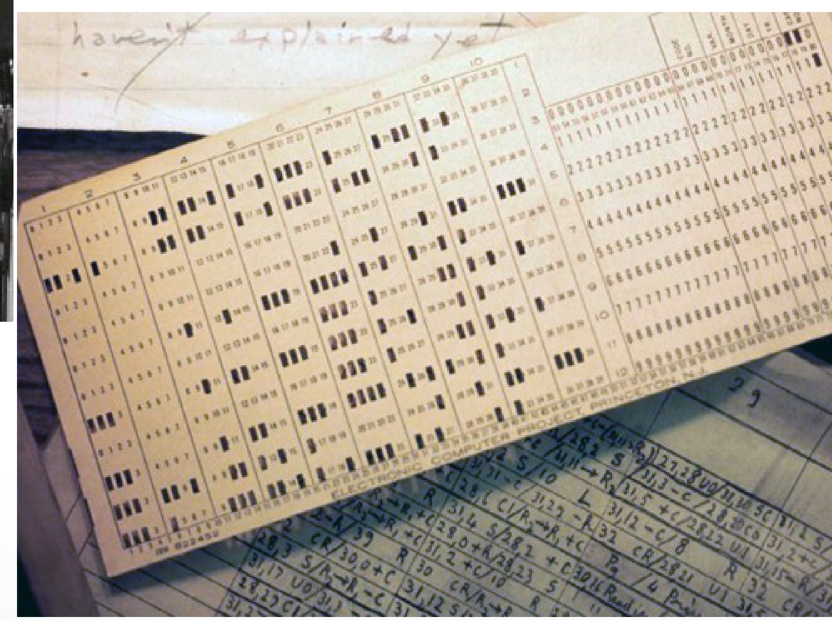
Nils Aall Barricelli (1950s)

- Performed the first substantive experiments with evolution on computers
- Working in von Neumann's group at IAS over 1953-56 (and at other institutions later on, up to the late 1980s)
- Interested in testing Darwin's ideas of natural selection, and in creating an “unlimited evolution” process within a purely numeric system
- Used a 1D cellular automata model



Barricelli at IAS





Barricelli results #1

Self-Reproduction & Mutation

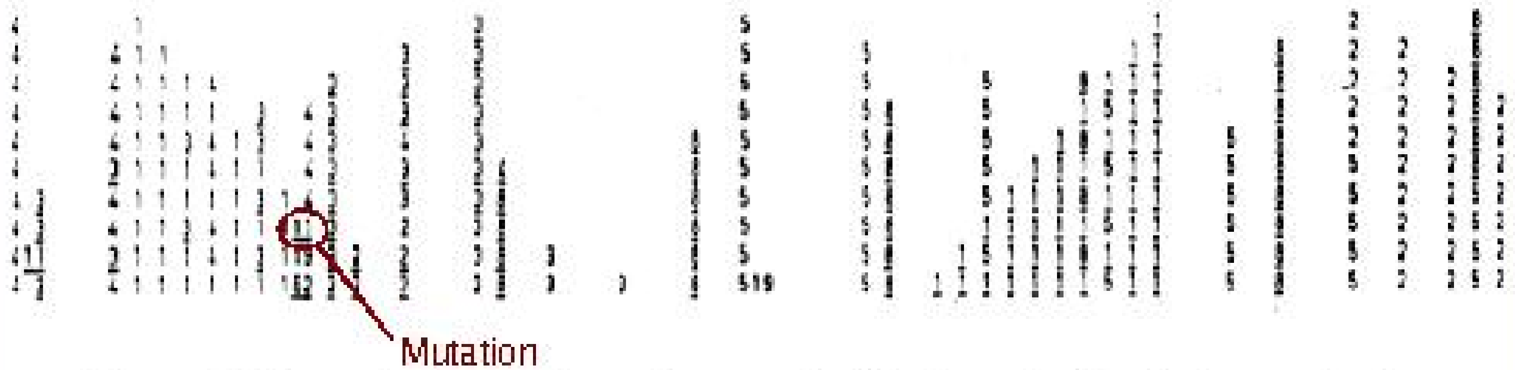


Fig. 1. Selfreproducing numbers (see text). Adaptive selection but no extensive evolution phenomena are possible.

"The numbers which have the greatest survival value in the environment created in Figure 1 by the rules stated above, will survive. The other numbers will be eliminated little by little. A process of adaptation to the environmental conditions, that is, a process of Darwinian evolution, will take place."

Barricelli results #2

- “[the model] clearly shows that something more is needed to understand the formation of organs and properties with a complexity comparable to those of living organisms. No matter how many mutations occur, the numbers ... will never become anything more complex than plain numbers”
- An extra ingredient is needed
- Looked at theory of symbiogenesis, by Kozo-Polyansky (1924) and others, as a possible solution

Barricelli results #3

Reproduction requiring symbiosis

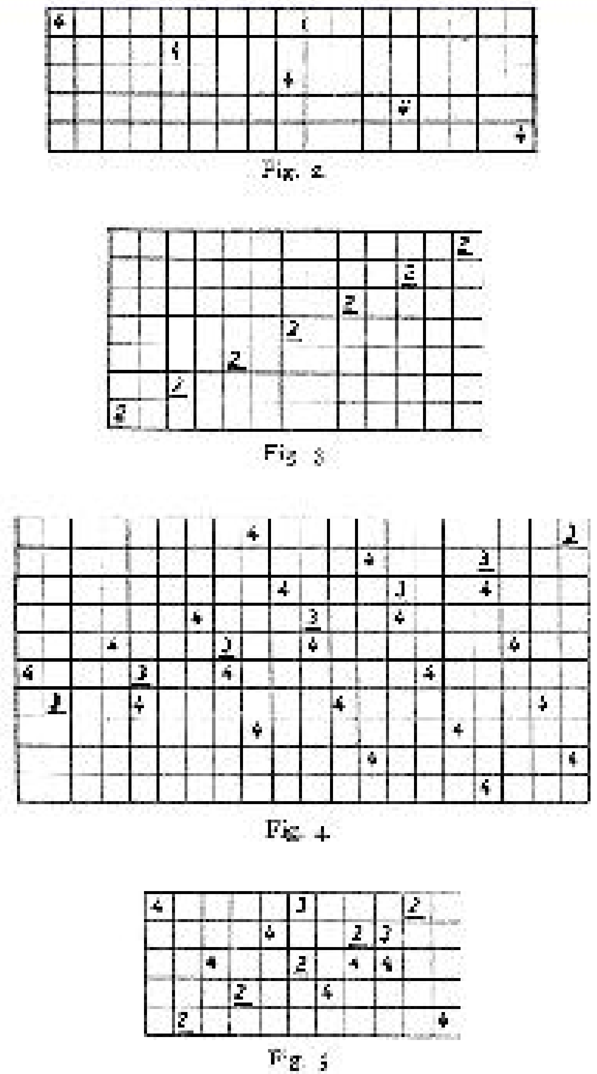
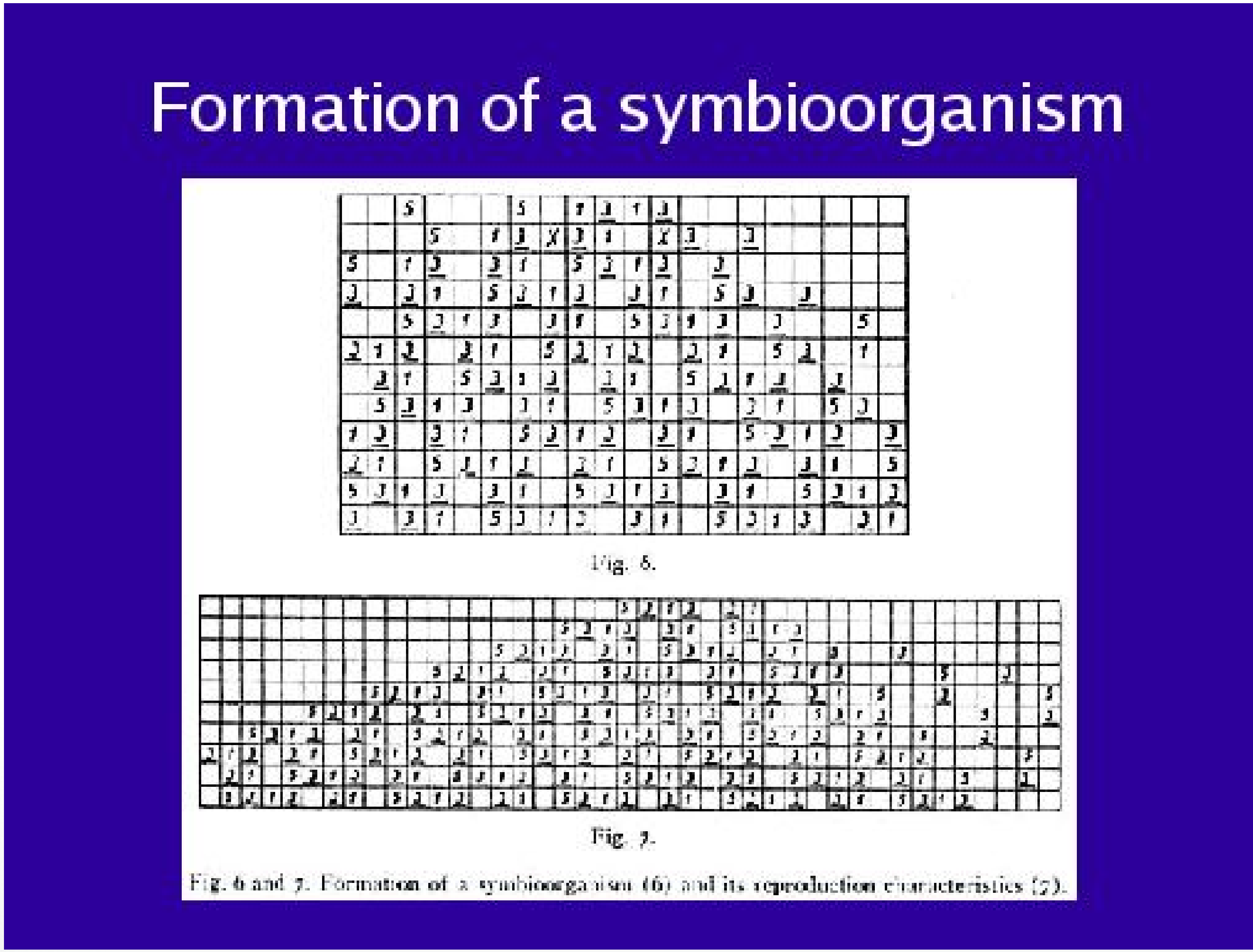
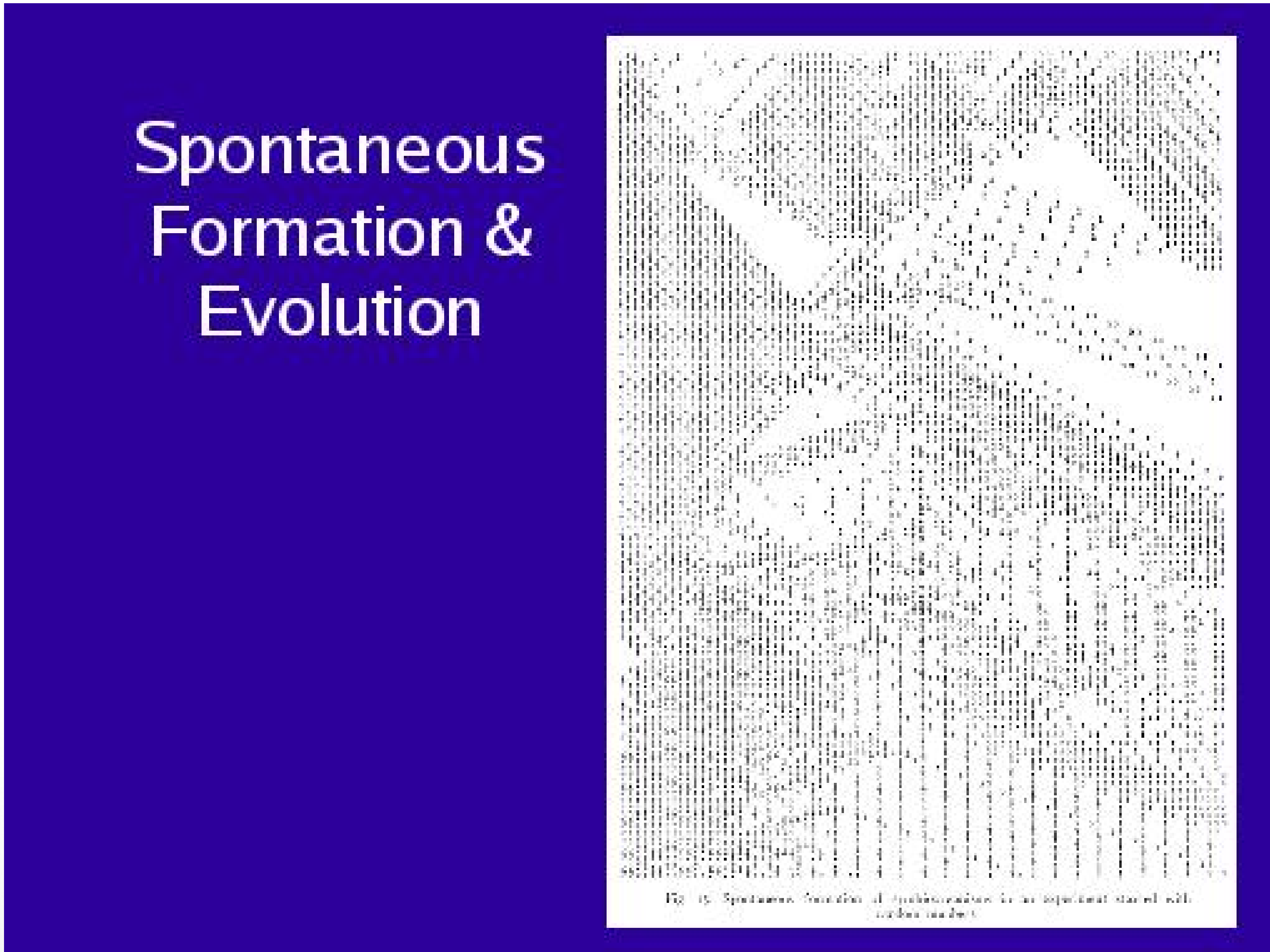


Fig. 2, 3, 4, 5. Reproduction rules requiring symbiosis (see text).

Barricelli results #4



Barricelli results #5



Barricelli results #6

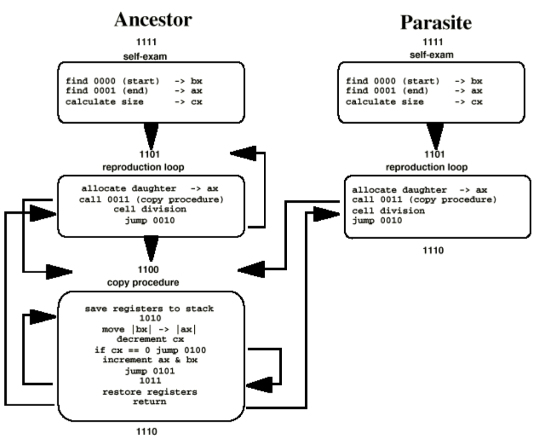
- Observed results included:
  - Self-reproduction
  - Crossing
  - Great variability
  - Mutation
  - Spontaneous formation
  - Parasitism
  - Repairing mechanisms
  - Evolution
- Considered how to provide organisms with more “toy bricks” to play with (more complicated phenotypes)

Skipping forward...

- From the 1960s to the present day
  - Artificial life versus evolution as an optimisation process
  - Both fields have flourished since the early work in the 1950s and 60s
  - The modern field of Artificial Life was stimulated by Chris Langton's workshop in 1987
    - In the same year, Barricelli published his last paper on digital evolution, in an obscure journal in Oslo
  - Well known work by Tom Ray (Tierra), Larry Yaeger (Polyworld), Adami, Ofria at al. (Avida)
    - Also work in evolutionary robotics, evolvable hardware, etc.

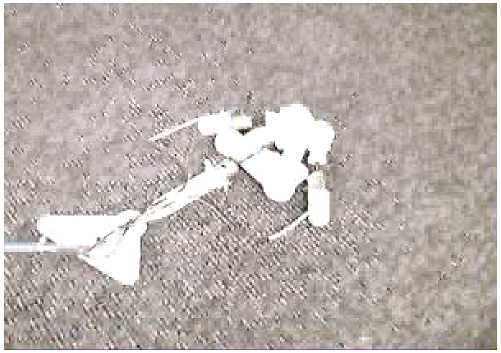
Recent(ish) examples

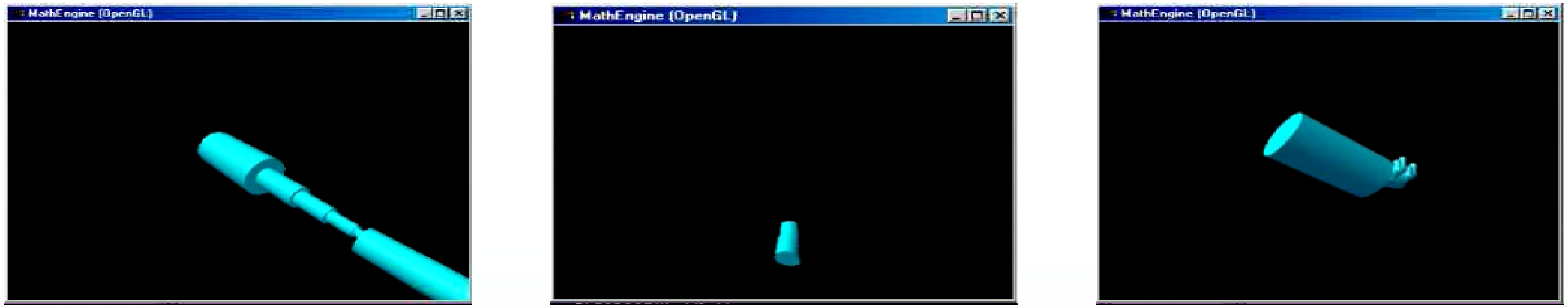
Ray (1992)



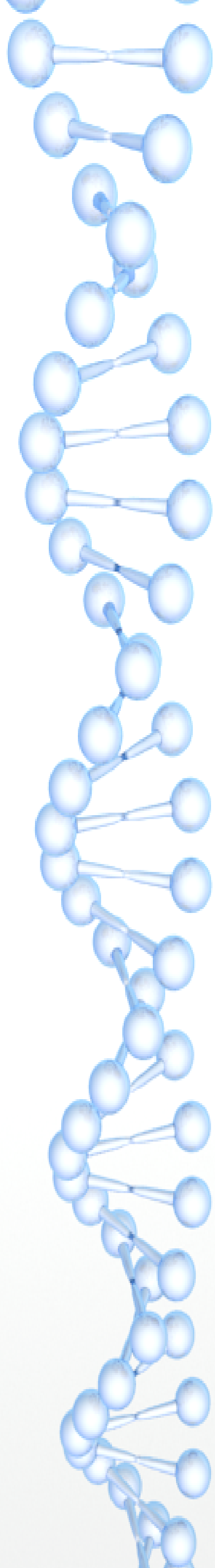
Lohn et al (2004)

Lipson et al (2000)





Taylor & Massey (1999-2001)



State of the art

- The challenge of indefinitely continuing evolution (“open-ended evolution”)
  - Major transitions in organisation and niche space

“More or less independently of the starting point ... the end point is a rather small molecule, some 200 bases long, with a particular sequence and structure that enable it to be replicated particularly rapidly.

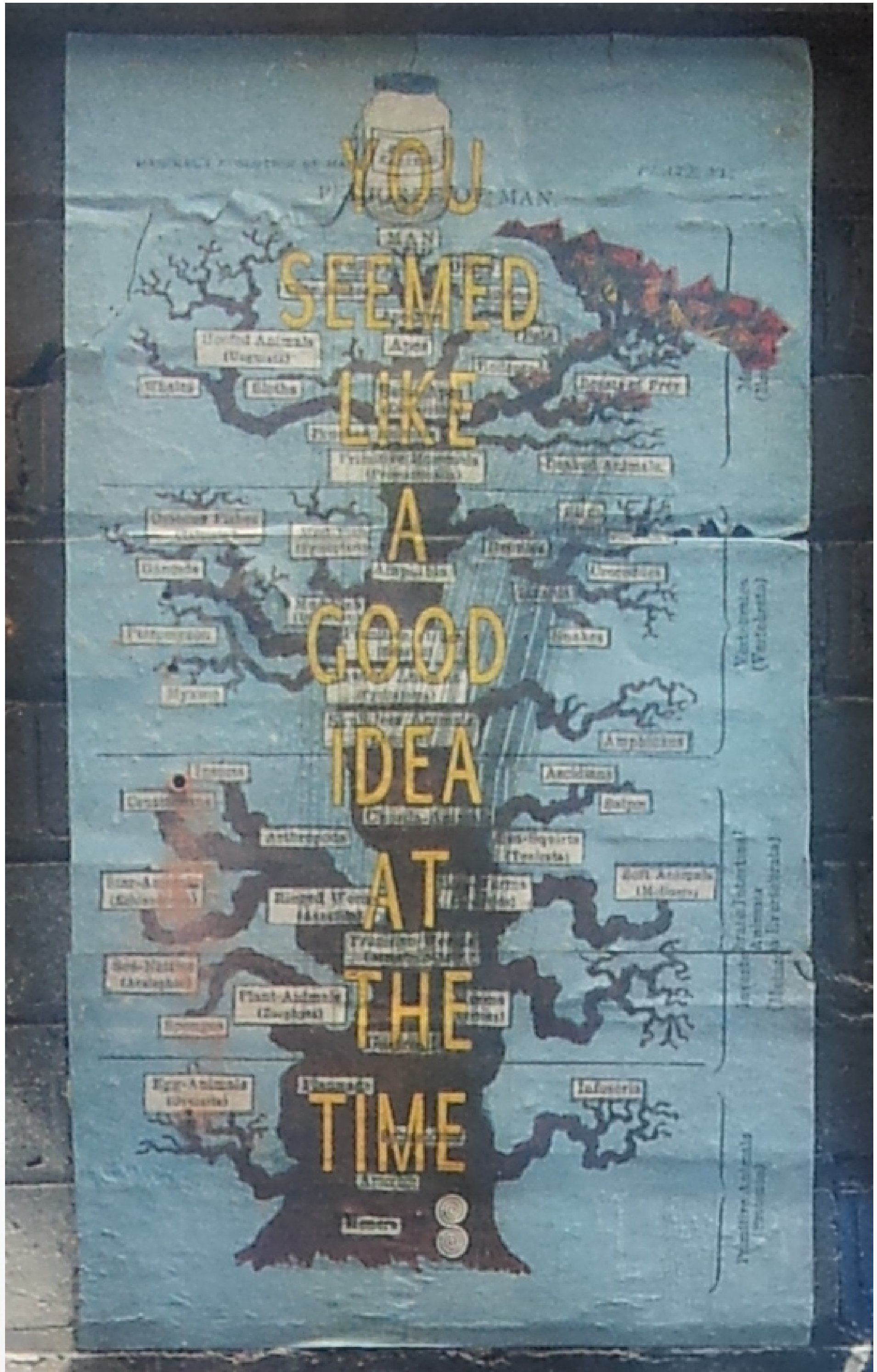
In this simple and well-defined system, natural selection does not lead to continuing change, still less to anything that could be recognized as an increase in complexity: it leads to a stable and rather simple end point.

This raises the following simple, and I think unanswered question: What features must be present in a system if it is to lead to indefinitely continuing evolutionary change?”

Comments on results of in vitro evolution of RNA molecules by Maynard Smith (1988)

Future directions

- Need both **capacity** and **drive** for open-ended evolution
- Emphasis not just on individual organisms but on **their relationship to the environment**:
  - Start with complex environments, and address the question of how organisms evolve to utilise the complexity
  - Connectedness between organisms and environment
    - Multifunctional components for evolution of new sensors and effectors
    - Model ecosystem relationships (exchanges of materials and energy) to provide drive for continual evolution
    - Niche construction



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