7 Self-Replication

Krachend trifft die glatte Schärfe.
Wahrlich, brav getroffen!
Seht, er ist entzwei!
Und nun kann ich hoffen,
Und ich atme frei.
Wehe! wehe!
Beide Teile
Stehn in Eile
Schon als Knechte
Völlig fertig in die Höhe.
Helft mir, ach, ihr hohen Mächte!

Johann Wolfgang von Goethe (1797)

```
main(a){printf(a="main(a){printf(a=%c%s%c,34,a,34);}",34,a,34);}
```

Dario Dariol

Note 1: The strange line above is called a 'Quine' [from the name of the logician Willard van Orman Quine, via Douglas Hofstadter]. It is a C program that, when executed, will print out an exact copy of its own source code. This is a very small example of a self-replicating program. Can you figure out how it works?

Note 2: Replication is an ontogenetic, developmental, process, involving no genetic operators, resulting in an exact duplicate of the parent organism. Reproduction is a phylogenetic, evolutionary, process involving genetic operators such as crossover and mutation, thereby giving rise to variety and ultimately to evolution (distinction due to Sipper et al,. 1997).

7.1 Introduction

Evolution works by making many copies of some organisms with a few random changes and by selecting the 'best' ones. The process is repeated over and over again leading to a refinement of the species. There has been lots of work on artificial evolution and 'copying' is always taken for granted, being realized by a centralized control program whose task is just to make copies of the genome. In Nature it is not that easy because all organisms are responsible for their own copying.

The prospect of self-replicating machines offers unimaginable potential benefits for mankind. The concept is pretty simple: build a machine capable of just two processes, (a) build a copy of yourself, and (b) do something, e.g. mine for ore or explore other planets. This leads to a powerful conclusion. Once one machine is built and started, there will be soon two, then four, then eight, etc. With half of the machines replicating and half performing a task, pretty soon there will be a huge number of them all working hard. This is the closest there is to 'something out of nothing'.

This chapter consists of three main parts. The first part discusses the conceptual side of self-replication. We will have a look at NASA's proposed Self Replicating Lunar factory and John von Neumann's Kinematic Beast. The second part details some attempts to create an artificial Self Replicating entity in some form of Cellular Automata. CA's are a good medium for self-replicating entities, since they can model complex, non-linear systems and are mathematically tractable. There is also a discussion of Tierra, which is more like a one-dimensional CA. And finally, before the conclusions, we very briefly look at the mechanical side of self-replication.

7.2 Theoretical Aspects

NASA SRS Concept Team

In 1980, a team at NASA (the Self-Replicating System (SRS) Concept Team) looked into viable applications of self-replication for space exploration and colonisation. The concepts they proposed were staggering, much closer to science fiction than to what we might call real science. Ideas of giant lunar factories starting off from one single egg and spreading like a virus across the lunar surface (Fig. 1) or sending reproductive probes out into the galaxy to multiply and explore. It is a fantastic idea, but even as of today it remains far ahead of its time, essentially because the necessary science and technology to make it reality are still to be discovered.

The proposal for a lunar factory was very detailed. A single spherical ‘egg’ would be sent to the moon, from which a number of small robots would emerge. There would be robots to mine, to transport, to process and to use different materials. The first job would be to begin the construction of a solar array, in order to be able to power the whole system. Some robots would search for the best location, while others would begin with the construction of a communication network. The plant would spread from a centre with mining robots levelling the ground and paving robots providing a smooth, stable surface. Then the central computer would be moved to the centre of this area. Soon areas of chemical processing, parts fabrication, assembly and control would be constructed, which would lead to even more solar panels. After about one year, a large factory would be ready to begin producing whatever would be desired, perhaps more ‘seeds’ for other satellites in the solar system or other areas of the moon. Some parts could not be manufactured by the system, due to either lack of materials or too a sophisticated manufacturing process. These parts could be produced on earth and shipped to the moon. The estimation was that 4%-10% of the required parts would have to be sent. This seemed acceptable to the team. Unfortunately, the project was abandoned in 1983 due to lack of government funding. No wonder.

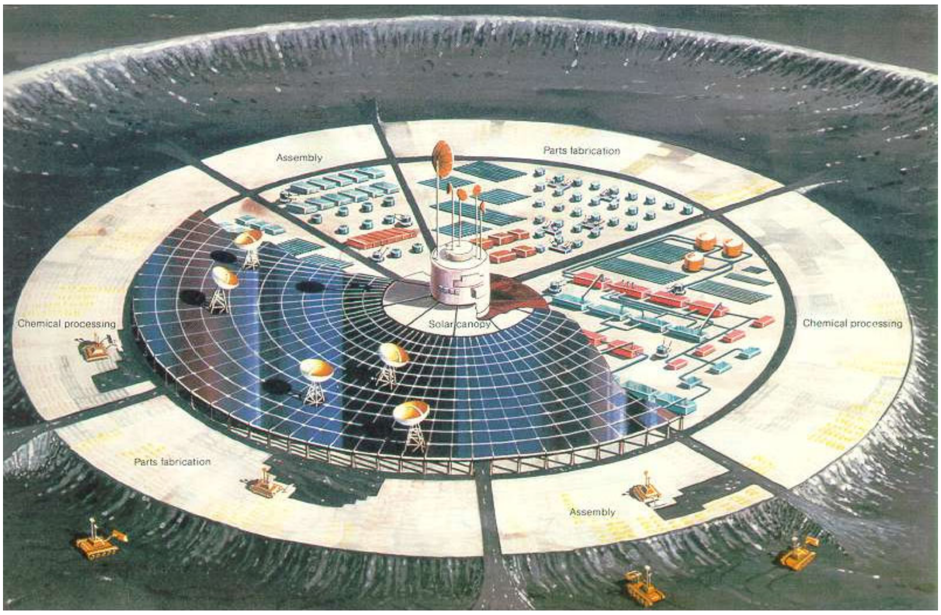


Figure 1: *Artists impression of self-replicating lunar factory.*

Von Neumann Kinematic Beast

One of the first self-replicating machines appeared in the imagination of the eminent mathematician and physicist John von Neumann. Von Neumann wanted to formalise the process of self-replication. He believed that biological organisms could be seen as machines – very sophisticated machines, but machines nonetheless. His conviction was that the important part of an organism was not the matter from which it is made, but rather the information and more importantly still, the complexity of the interactions of the information. The fantastic machine that von Neumann imagined was a hypothetical robot, consisting of a computer with valves and other processing elements (this was in the '40s, many years before integrated silicon chips). In addition to just an electronic brain, the hypothetical robot would be equipped with: a manipulating hand-like element, a fusing element to connect two items, a cutting element to separate two items, a sensing element to recognise different parts and many 'girders' (Deutsch: Stahlträger), rigid structures which would provide not only a chassis for the robot but also a means of information storage. Obviously the 'beast' would need an appropriate environment, for example a large lake containing millions upon millions of elements.

The organism would consist of three sub-units:

1) A general construction machine $\mathbf{A}$. If a machine $\mathbf{X}$ is desired, the general construction machine takes a description $\mathbf{\Phi(X)}$ and makes $\mathbf{X}$:

$$\mathbf{A + \Phi(X) \rightarrow X}$$

where '+' means a machine composed of the left and right components and '→' means construction.

2) A general copying machine $\mathbf{B}$ which make a copy of the instruction tape $\mathbf{\Phi(X)}$ of $\mathbf{X}$:

$$\mathbf{B + \Phi(X) \rightarrow \Phi(X)}$$

3) A control machine **C**. When combined with **A** and **B**, the control machine activates them in the right order to produce **X** and a copy of $\Phi(X)$ and then connects them to each other and separates them from the original machine $(A + B + C + \Phi(X))$:

$$A + B + C + \Phi(X) \rightarrow X + \Phi(X)$$

If we take **X** to be a machine **A + B + C** and give it the name **D** we get:

$$A + B + C + \Phi(A + B + C) \rightarrow A + B + C + \Phi(A + B + C)$$

As you can see, this is a self-reproducing machine. Now let's continue with this logic and see where we end up.

4) Let's make a new machine:

$$E = D + \Phi(D)$$

Therefore, we can also say:

$$E = A + B + C + \Phi(A + B + C)$$

So, **E** can replicate itself: $E \rightarrow E$

5) Now, let's take a new instruction tape:

$$\Phi(D + F) = \Phi(A + B + C + F)$$

where **F** is the instructions for building another arbitrary machine.

6) It possible now to make a machine:

$$E_F = D + \Phi(D + F) = A + B + C + \Phi(A + B + C + F)$$

So we see:

$$E_F \rightarrow A + B + C + F + \Phi(A + B + C + F)$$

7) Which means ultimately:

$$E_F \rightarrow E_F + F$$

So we have finally found a description of a machine that can replicate itself while building an extra machine in the process. What that machine could be would depend on the application. When the technology to build E_F arrives, the possibilities are endless and potentially dangerous.

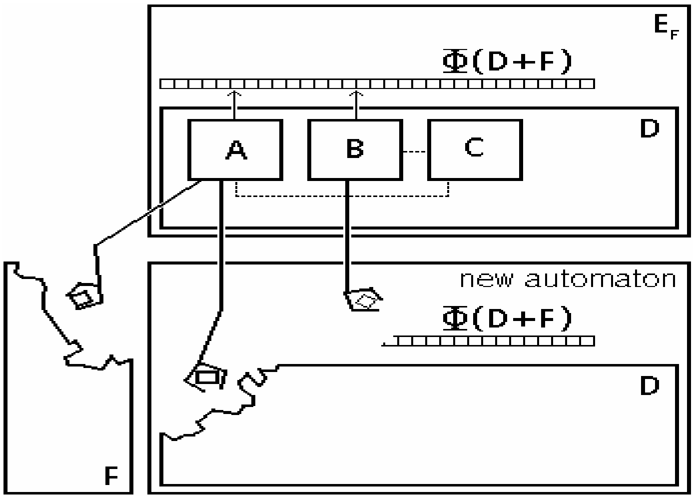


Figure 2: *Schematic view of von Neumann's theoretical self-replicating machine. A: general construction machine; B: general copying machine; C: control machine.*

7.3 Self-Replicating Cellular Automata

Von Neumann Universal Constructor

The problem with the Kinematic Beast was that it was completely hypothetical. It could never be implemented. The logic used by von Neumann was sound, but it did not lead to clues of how to build such a system. The two main flaws with it were that it assumed a huge lake filled with parts and also that the parts were black boxes. Where did they come from? How are they made? What are they made of? The beast was destined to stay hypothetical. Soon after, in the 1950s when von Neumann with the help of Stanislaw Ulam invented Cellular Automata (see Chapter 2), von Neumann began working on an implementation of self-replication. Although CA's have been found to have a huge variety of potential applications in many areas of science because of their ability to describe non-linear dynamics and their tractability, they were originally designed to be the universe in which self-replicating "creatures" could exist. These creatures would be made of information and live in a two-dimensional universe with their state changing over time according to the rules of the system and eventually make a copy of themselves. This is a good example of *emergence*, where local rules produce surprising and coordinated global behaviour.

The way von Neumann's CA works is very complicated. The cellular automaton has an incredible 29 states and each organism is composed of many sub-organisms in the shape of a box spanning 80 cells by 400 (see Fig. 3). This is the creature's main body and control centre but is still only a quarter of the entire organism. The rest of the organism is "stored" in a huge tape of 150'000 cells in a line attached to it. This is the blueprint for constructing a duplicate organism. Each cell updates according to the rules of the system and the states of its local neighbours. Soon the organism starts reading the tape and executing the instructions contained in it. It extends an arm and begins manufacturing a child. After a while the child is complete, the tape is copied and finally the "umbilical cord" is dissolved, and left back is the original organism in its original state and a perfect copy of itself. Now both organisms are ready to self-replicate.

It is important to note that von Neumann's machine has an important feature in common with a living cell. It uses a sequence of instructions to describe the machine. This sequence of instructions is first interpreted by the machine in order to make a replica of itself. Then, the instruction sequence is copied and a copy is given to the replica. DNA is used a similar way in cells. Remember, that all this was done a few years before the discovery of DNA by Watson and Crick in 1953. Unfortunately, the self-reproducing automata of von Neumann were too large and too complex to be implemented. They could not be completed before von Neumann's death in 1957 (the design of von Neumann was completed by Arthur Burks and published in 1966).

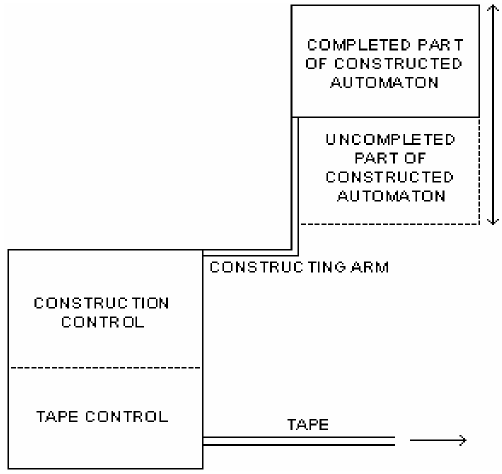
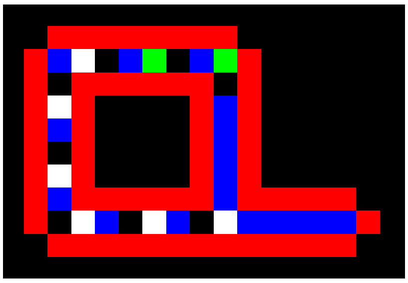


Figure 3: *Schematic diagram of von Neumann's self-reproducing automaton.*

Langton Loops

In 1968, the engineer E. F. Codd reduced the number of states from 29 to 8. This was more manageable but still very complex. Codd introduced the concept of 'sheaths'. The sheaths were two layers of a particular state enclosing a single 'wire' of information flow. This was important in that the information could be contained and protected from the world, analogous to the walls of a cell.

The problem of complexity in the self-reproducing automata of von Neumann and of Codd is a serious problem. In 1979, Christopher Langton set out to create self-replication in a CA. He realised that such a structure need not be capable of universal construction like those of von Neumann and Codd; it just needs to be able to reproduce its own structure. He used the same substrate as Codd, i.e. a CA with 8 states per cell and a von Neumann neighbourhood. He also kept the sheaths. In fact, he began with an element designed by Codd known as a periodic emitter. His "creatures" however were very simple. Consisting of a single loop, replication would occur by extending an arm, which would bend round to create a daughter loop, then dissolve the umbilical and start again. One aspect of the system that Langton emphasized is the use of information in two modes, interpreted and un-interpreted. This is biologically analogous to translation and transcription respectively. The transcription of the information is accomplished by the information being copied at the umbilical junction and the translation is using the data to extend or bend the constructing arm.



```
 22222222
2170140142
2022222202
272    212
212    212
202    212
272    212
21222222122222
207107107111112
 2222222222222
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Figure 4: *Initial configuration of a Langton Loop. Note the red "sheath" (state 2) that protects the flowing information. The data flows round the loop anti-clockwise. It is copied at the junction of the arm and one copy is sent round the loop, to keep the structure "alive", and the other copy is sent down the arm to be interpreted into extending and bending it.*

The way the replication is achieved is as follows. Inside the sheath the data is flowing round in an anti-clockwise direction. An arm 'bud' is formed at one corner of the loop and is automatically extended by the data hitting it. The data is composed of space (black), information carrier medium (blue), "extend arm" data (white) and "bend arm" data (green). The red is the sheath, which protects the data. The two green data bend the arm 90°. It takes 151 time steps for a loop to reproduce. When the arm hits itself, a process of decay of the umbilical occurs that separates the loops and leaves them both "fertile", i.e. both are capable of reproducing again.

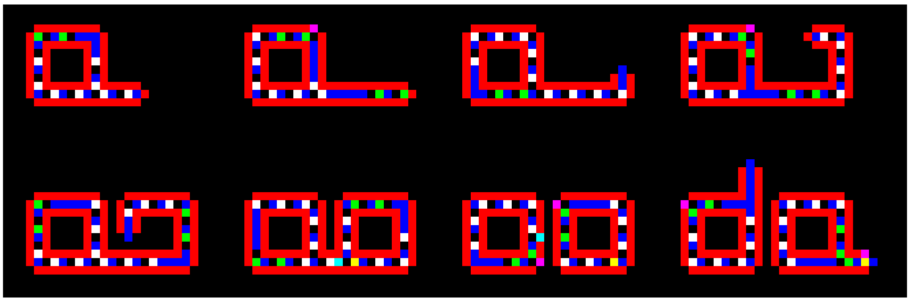

Figure 5: *Self-replication process of a Langton Loop. The parent loop extends an "arm" and bends it round to form a daughter loop. Then the umbilical dissolves to separate the loops. Now both loops are ready to self-replicate again.*

Sayama SDSR Loops and Evo-loops

The main problem with the Langton Loops is their lack of robustness. They assume a single seed loop of an exact configuration on an infinite CA with no obstacles. If there are any other structures in the universe or if the CA is bounded or wrapped then after a while the loops will become corrupt and the information flow will escape the sheath which will result in a big mess and loss of "life." Also, if the structures cannot reproduce in the desired direction, they die and their lifeless structures remain. It is similar to the way coral reefs have living organisms on the outside but the inside is made of the corpses of old, dead coral.

In 1998, Hiroki Sayama from the University of Tokyo extended the rule table for the Langton Loops to increase their robustness (Sayama, 1998). In this system, if an extending arm hits another structure it is either absorbed, or tries to delete the obstacle and continue. Also, the structures can dissolve, which means they decompose gracefully, in order to leave space for other organisms. This robustness allows for a continuous life in a bounded or wrapped CA universe. The Structurally Dissolvable Self Replicating

(SDSR) and the Evo-loops can also be of bigger size, allowing for different species and evolution. Usually the evolutionary pressure leads to smaller loops simply because they can replicate faster.

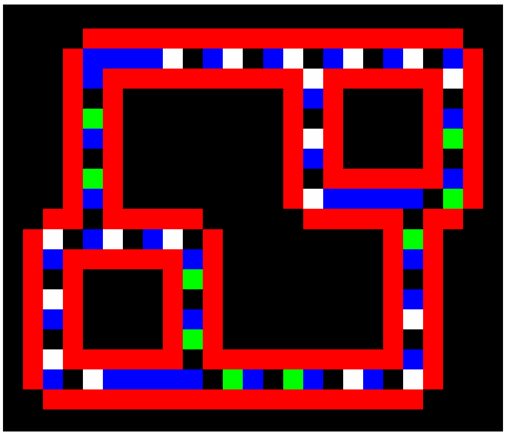

Figure 6: *Stable configuration of two colliding SDSR Loops.*

Tempesti Loops

The self-replicating CA structures described above are very interesting, but they are just half of the story. The whole point of artificial self-replication is to provide a "service for mankind" from a small "seed." They need to be able to reproduce, but they need also to be capable of a second function. Langton abandoned the universal computation and universal construction capabilities of von Neumann and Codd for the sake of simplicity and size. His loops were simply able to replicate. The loops of Giovanni Tempesti can also self-replicate, but after doing so, perform finite computations. The loops replicate *and* write the letters "LSL" (Logic Systems Laboratory) inside themselves.

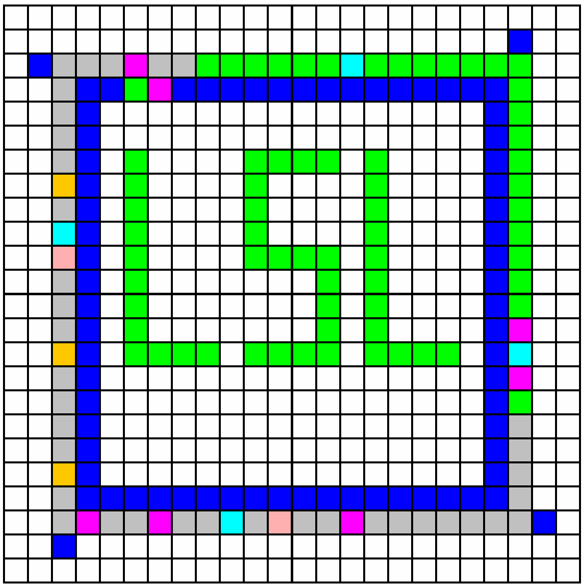

Figure 7: *A Tempesti loop after it has spawned four children and constructed the letters "LSL." Both the information for self-replication and that for building the letters flow around the outside of the loop. Notice the concept of the sheath is still here but only the inner sheath. The rules are robust enough for the data to be subjected to the "void." The inner sheath merely acts as a guide for the data flow, not protection.*

Tierra

Biologist Thomas Ray developed a system of self-replicating computer programs competing and evolving in what is claimed to be the first truly open-ended simulation (Ray, 1990). The creatures are composed of a string of instructions from a limited set of assembly language operands. Each ‘creature’ is a process running on a virtual CPU which means that it is just a computer program living in a very abstract environment. The idea comes from a game of competing computer programs called ‘Core War’, made famous by Dewdney (Dewdney, 1984). The universe for these things is the domain of the computer, competing for space (computer memory) and food (CPU cycles). The universe was seeded with a single organism (hand-coded by Ray), which just had the ability to reproduce. It had a length of 80 instructions and it took over 800 instruction cycles to replicate. The virtual machine that executed the programs was designed to allow a small error rate (which meant mutations while copying, analogous to natural mutation). After a while the parent organisms would have reproduced and the child organisms would begin to reproduce also. Soon the space would be filled with replicating programs, some slightly different from their parents (see Fig. 8a). Once the space was filled by 80%, the organisms started competing for space and CPU cycles. A “reaper” program was included to kill some of the organisms, with an artificial nod and wink to natural catastrophes. Now this is where the analogy to natural selection makes its entrance. The organism that copied faster had obviously more children, which was an advantage. Soon mutations only 79 instructions long proliferated – after a while even shorter organisms. Evolution had begun optimising the code. And actually, this is what evolution is good at. The shorter organisms dominated for a while then something unexpected and seemingly impossible happened. An organism of only 45 instructions was born and started doing very well soon (see Fig. 8b). Ray was confused because he thought that in this system an organism would need a minimum number of instructions to self-replicate, and 45 was certainly not enough. Yet these organisms were doing just as well as the larger ones, with lengths bigger than 70 instructions. The numbers of the longer and shorter organisms seemed to be linked. Then it dawned on him what had happened. Evolution is very good at exploiting its environment and so after a while, some organisms had become parasites. A struggle was ensuing not unlike the celebrated foxes and rabbits idea. These parasites did not have any self-replication code of their own but they somehow had managed to tap into the abilities of the unaware hosts, not unlike real viruses. Of course, when the number of hosts thinned considerably, the parasites began starving, their number dropped and the hosts began to recover. The typical story of negative feedback of population numbers in ecosystems, albeit an artificial one. Then another interesting thing happened. A very long organism that had developed immunity to the parasites emerged. It could “hide” from them (see Figs. 8c and 8d). Soon the parasites evolved into a 51 instructions long parasite, which could find the immune organism, and so the evolutionary arms race continued. Also, hyperparasites evolved which could exploit the parasites. Then these hyperparasites could be seen to “cooperate”, which means that they would exploit each other leading to the evolution of “social cheaters” exploting them both. And so the system continued with its evolution of competing and cooperating self-replicating organisms, leading to surprise after surprise for the creator.

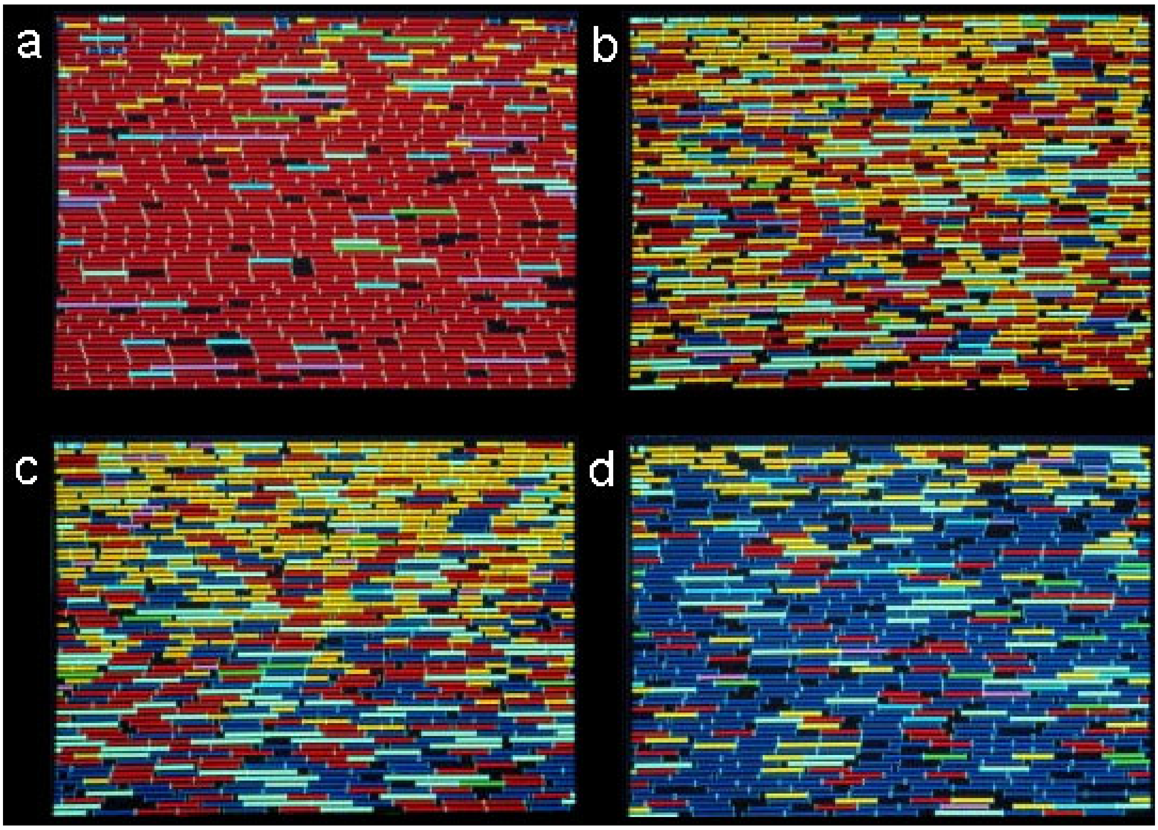

Figure 8: *Tierra universe, growing in ecological complexity. Picture (a) shows the Tierra environment at quite an early stage. The universe is primarily filled with red bars; these are the descendents of the original hand-coded, eighty-instruction organism. Some other colours show mutated organisms, still able to survive and already we see a small but growing population of the yellow parasitic creatures. In (b) we see that the parasites are doing extremely well, exploiting the unaware red hosts. However, we can detect the emergence of the deep blue creatures, immune to the yellow parasites. In (c) we can observe the blue immune creatures, driving out the parasites. The red hosts are still there due to the parasites needing them. The immune creatures are by far the most successful in this run and so we see them proliferating greatly in (d).*

7.4 Mechanical Self-Replication

Penrose Mechanical SR

The Penrose mechanical self-replicator was the first example of mechanical self-replication ever realised. This system consists of a number of identical units with particular shape and mechanical motions. If many units are put into a box and the box is shaken, nothing interesting happens. However, if a "seed" (two connected units) is placed into the box and the box is shaken, pretty quickly the seed uses the other independent units to reproduce. Soon most of the units are connected to another in the same configuration as the seed. The replication proceeds as follows (see Fig 9):

a) The units are composed of four layers of mechanical components with particular shape and motions. The first two layers are responsible for locking together with other units and releasing them during the process of replication. The two components are for the right and left sides. The third layer is a stopper, which only allows units to approach and connect when it is receptive; i.e. during replication. The bottom mechanism allows a maximum of four units (two "organisms") to be in close proximity. This stops the units clumping together in a crystal-like line. The 'seed' is the two connected units in the centre. The other two units are raw material with which the seed will reproduce. Both sides of the seed are in a receptive mode.

b) The left side of the seed has made contact with the raw material. Note that the top layer has released its hold, but the second layer is still secure.

c) The right side has made contact also. Now the second layer releases its grip. Note the bottom layer makes sure that the sides are not receptive until the reproduction is complete.

d) Now there is nothing holding the two halves together so they separate to show two structures, identical to the initial seed and primed, ready to reproduce again.

Very quickly the individual units get assimilated and the box is filled with dual-unit structures, which are direct copies of the ancestral seed. This example shows that non-trivial mechanical self-replication is possible. Although this system is one-dimensional Penrose also designed a two-dimensional example, and it is easy to imagine a three-dimensional possibility, although the details would be of much greater complexity.

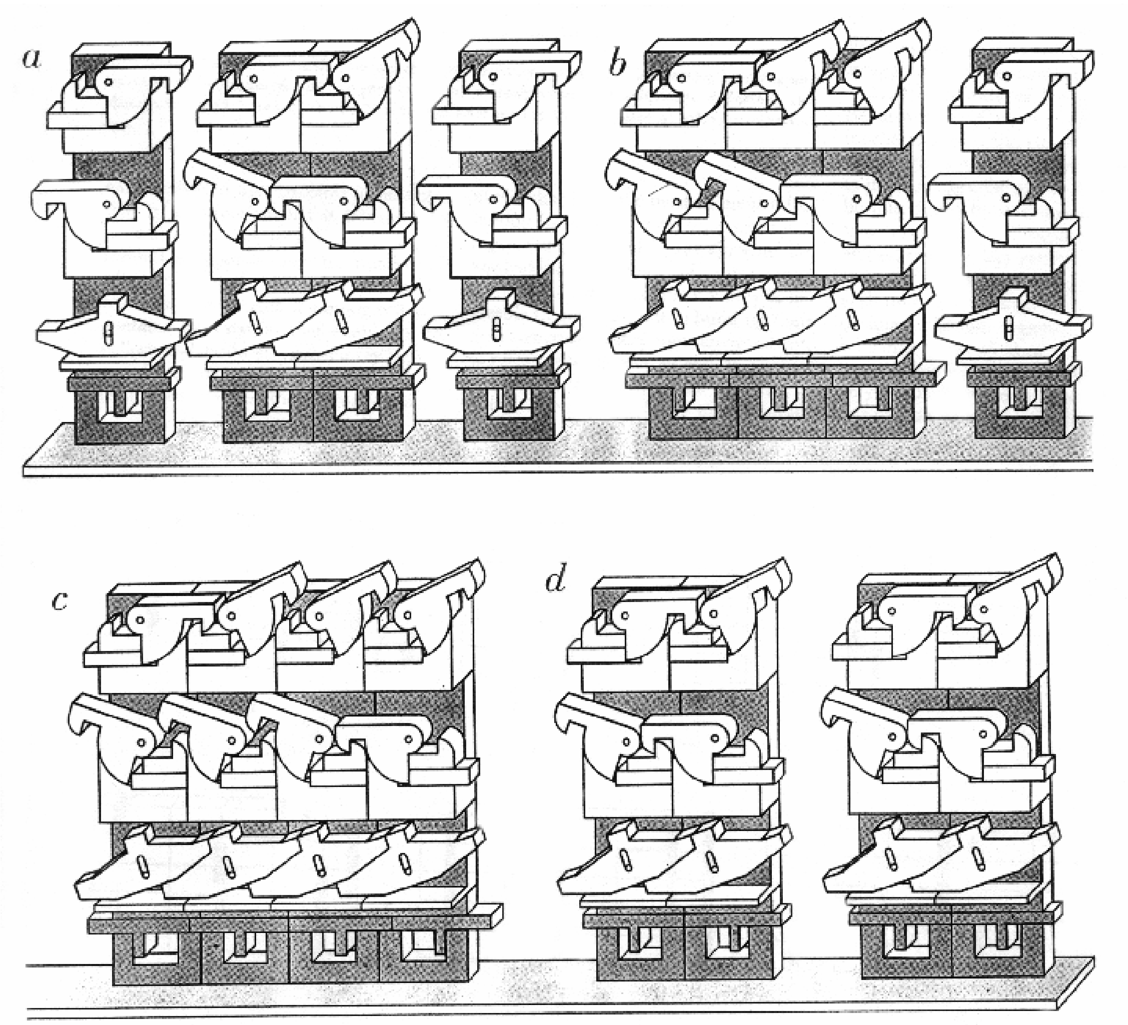

Figure 9: *The Penrose mechanical self-replicator.*

7.4 Conclusions

In this chapter we have seen several examples of self-replicating systems. From the logical aspects to mechanical construction, from evolvability to ecology, the systems presented here are the first few stumbling steps towards the further understanding of such systems, whether real or artificial. As we understand more about such processes, there are two areas of benefit. First, the dream of "something-for-nothing" has already been mentioned. A small "seed" which could replicate exponentially and provide a huge service to mankind: millions of probes exploring planets or the galaxy, or hoards of nano-machines cleaning our insides and building our desires. Second, a greater understanding of biological self-replication could help in many areas of medicine. One can imagine cures for cancer, regeneration of lost limbs or growth promotion of damaged or deformed brains.

The important point to grasp with this type of self-replicating system is that a copy is made without the need for a global copier. The copying is performed by the structure being copied, using only local rules and exploiting self-organisation. This is how nature works. You can imagine how long it would take for an organism to grow, if each cell of the organism would have to be produced by a single "factory" cell. Without even considering transportation problems, the idea of making one cell at a time to make up the 10^{14} cells in the human body is just silly. In computer simulations of self-replication, this is not an advantage due to the serial nature of the processors, but this is a moot point. It is of great importance in terms of parallel processing, self-replicating machines and biology.

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