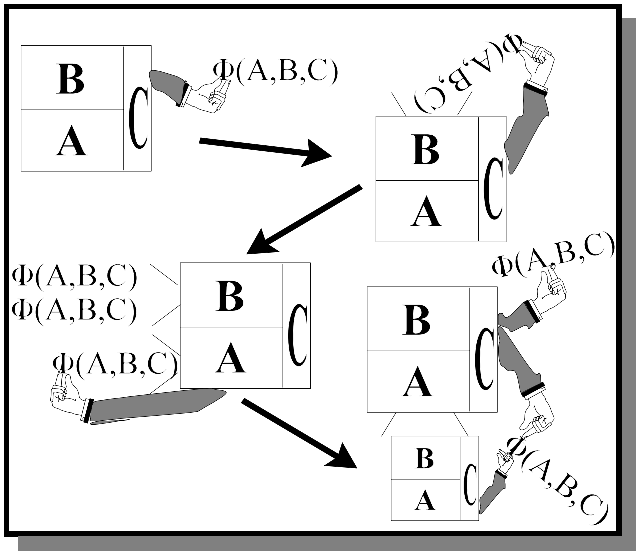
6. Von Neumann and Natural Selection

6.1 Von Neumann's Self-Reproduction Scheme

Von Neumann thought of his logical model of self-reproduction as an answer to the observation that, unlike machines, biological organisms have the ability to self-replicate while seemingly increasing their complexity without limit. Mechanical artefacts are instead produced via more complicated factories (as opposed to self-production) and can only degenerate in their complexity. He was searching for a complexity threshold beyond which systems may self-reproduce (with no outside control) while possibly increasing their complexity.



Von Neumann concluded that this threshold entails a memory-stored description Φ(*X*) that can be interpreted by a universal constructor automaton *A* to produce any automaton *X*; if a description of *A*, Φ(*A*), is fed to *A* itself, then a new copy of *A* is obtained. However, to avoid a logical paradox of self-reference, the description, which cannot describe itself, must be both copied (uninterpreted role) and translated (interpreted role) into the described automaton. This way, in addition to the universal constructor, an automaton *B* capable of copying any description, Φ(*X*), is included in the self-replication scheme. A third automaton *C* is also included to perform all the manipulation of descriptions necessary—a sort of operating system. To sum it up, the self-replicating system contains the set of automata (*A* + *B* + *C*) and a description Φ(*A* + *B* + *C*); the description is fed to B which copies it three times (assuming destruction of the original); one of these copies is then fed to *A* which produces another automaton (*A* + *B* + *C*); the second copy is then handled separately to the new automaton which together with this description is also able to self-reproduce; the third copy is kept so that the self-reproducing capability may be maintained (it is also assumed that *A* destroys utilized descriptions). Notice that the description, or program, is used in two different ways: it is both *translated* and *copied*. In the first role, it controls the construction of an automaton by causing a sequence of activities (*active* role of description). In the second role, it is simply copied (*passive* role of description). In other words, the *interpreted* description controls construction, and the *uninterpreted* description is copied separately, passing along its stored information (memory) to the next generation. This parallels the horizontal and vertical transmission of genetic information in biological organisms, which is all the more remarkable since Von Neumann proposed this scheme before the structure of the DNA molecule was uncovered by Watson and Crick[1953]—though after the Avery-MacLeod-McCarty [1944] experiment which identified DNA has the carrier of genetic information.

The notion of description-based self-reproduction implies a language. A description must be cast on some symbol system while it must also be implemented by some physical or a logical structure. When *A* interprets a description to construct some automaton, a *semantic* code is utilized to map instructions into construction commands to be performed. When *B* copies a description, only its *syntactic* aspects are replicated. Now, the language of this semantic code presupposes a set of primitives (e.g. parts and processes) for which the instructions are said to "stand for". Descriptions are not universal insofar as they refer to these building blocks which cannot be changed without altering the significance of the descriptions. The building blocks ultimately produce the dynamics, behavior, and/or functionality of the overall system, and may be material or computational. In Biology, we can think of the genetic code as instantiating such a language. Genes are descriptions that encode specific parts: amino acids chains. In a computational setting, parts are typically logical operations, but they can also be, for example, the building blocks of neural networks coded by genetic algorithms and L-Systems. Von Neumann [1966] (posthumously aided by Arthur Burks) produced a specification of a universal constructor using a 29-state cellular automaton. Implementations of this automaton appeared only fairly recently [e.g. Pesavento, 1995, see Sipper, 1998]

6.2 Open-ended evolution and natural selection

Perhaps the most important consequence of separate descriptions in Von Neumann's self-reproduction scheme is its opening the possibility for open-ended evolution [Rocha, 1998; McMullin, 2000]. As Von Neumann [1966] discussed, if the description of the self-reproducing automata is changed (mutated), in a way as to not affect the basic functioning of $(A + B + C)$ then, the new automaton $(A + B + C)`$ will be slightly different from its parent. Von Neumann used a new automaton $D$ to be included in the self-replicating organism, whose function does not disturb the basic performance of $(A + B + C)$; if there is a mutation in the $D$ part of the description, say $D`$, then the system $(A + B + C + D) + \Phi(A + B + C + D`)$ will produce $(A + B + C + D`) + \Phi(A + B + C + D`)$. Von Neumann [1966, page 86] further proposed that non-trivial self-reproduction should include this "ability to undergo inheritable mutations as well as the ability to make another organism like the original", to distinguish it from "naive" self-reproduction like growing crystals.

Notice that changes in $(A + B + C + D)$ are not heritable, only changes in the description, $\Phi(A + B + C + D)$, are inherited by the automaton's offspring and are thus relevant for evolution. This ability to transmit mutations (vertically) is precisely at the core of the principle of natural selection of modern Darwinism. Through variation (mutation) populations of different organisms are produced; the statistical bias these mutations impose on reproduction rates of organisms will create survival differentials (fitness) on the population which define natural selection. In principle, if the language of description is rich enough, an endless variety of organisms can be evolved: open-ended evolution.

The evolvability of a self-reproducing system is dependent on the parts used by the semantic code. If the parts are very simple, then the descriptions will have to be very complicated, whereas if the parts possess rich dynamic properties, the descriptions can be simpler since they will take for granted a lot of the dynamics that otherwise would have to be specified. In the genetic system, genes do not have to specify the functional characteristics of the proteins produced, but simply the string of amino acids that will produce that functionality "for free" [Moreno et al, 1994]. Furthermore, there is a trade-off between programmability and evolvability [Conrad, 1983, 1990] which grants some self-reproducing systems no evolutionary potential whatsoever. When descriptions require high programmability they will be very sensitive to damage. Low programmability grants self-reproducing systems the ability to change without destroying their own organization, though it also reduces the space of possible evolvable configurations [Rocha, 2001].

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