Digital Evolution as a Complex System

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Abstract: Our concepts of biology, evolution and complexity are constrained by having observed only a single instance of life, life on Earth. A truly comparative biology is needed to extend these concepts. Because we can not observe life on other planets, we are left with the alternative of creating artificial life forms on Earth. I will discuss the approach of inoculating evolution by natural selection into the medium of the digital computer. This is not a physical/chemical medium, it is a logical/informational medium. Thus these new instances of evolution are not subject to the same physical laws as organic evolution (e.g., the laws of thermodynamics), and therefore exist in what amounts to another universe, governed by the "physical laws" of the logic of the computer. This exercise gives us a broader perspective on what evolution is and what it does.

Synthetic organisms have been created based on a computer metaphor of organic life in which CPU time is the "energy" resource and memory is the "material" resource [3, 5]. Memory is organized into informational patterns that exploit CPU time for self-replication. Mutation generates new forms, and evolution proceeds by natural selection as different genotypes compete for CPU time and memory space. The creatures are self-replicating computer programs, however, they can not escape because they run exclusively on a virtual computer in its unique machine language. The virtual computer is effectively a containment facility.

A single rudimentary ancestral "creature" has been designed; it is 80 machine instructions long and contains only the code for self-replication. This creature examines itself, determines its size and location in the memory "soup", and then copies itself, one instruction at a time, to another location in the soup. The ancestral creature does not interact directly with other individuals, although there is scrambling competition for access to memory space.

Very quickly there evolve parasites, which are not able to replicate in isolation because they lack a large portion of the genome. However, these parasites search for the missing information, and if they locate it in a nearby creature, they parasitize the information from the neighboring genome, thereby effecting their own replication. This informational parasitism is a commensal relationship, as it is not directly detrimental to the host. However, the parasites do compete with the hosts for space, and may be superior competitors because they can more rapidly replicate their smaller genome. However, their advantage is frequency dependent. As the parasites increase in frequency, the hosts decline, and many parasites fail to locate hosts. In ecological runs, without genetic change, hosts and parasites demonstrate Lotka-Volterra cycles.

In some runs, hosts evolve immunity to attack by parasites. When immune hosts appear, they often increase in frequency, devastating the parasite populations. In some runs where the community comes to be dominated by immune hosts, parasites evolve that are resistant to immunity. The above mentioned immune mechanism can by circumvented by parasites which also re-examine themselves before each replication.

Hosts sometimes evolve a response to parasites that goes beyond immunity to actual hyper-parasitism. Hyper-parasites allow themselves to be parasitized, letting the parasite use their code for a single replication. After the first replication, the hyper-parasite deceives the parasite by replacing the parasite's record of its size and location with the size and location of the hyper-parasite genome. Thereafter, the parasite will devote its energetic resources to replication of the hyper-parasite genome.

Evolving in the absence of parasites, hyper-parasites completely dominate the community, resulting in a relatively uniform community characterize by a high degree of relationship between individuals. Under these circumstances, sociality evolves, in the sense that the creatures evolve into forms which can not replicate in isolation, but which can only replicate in aggregations. These colonial creatures cooperate in the control of the flow of execution of their algorithms.

The cooperative behavior of the social hyper-parasites makes them vulnerable to a new class of parasites. These cheaters, hyper-hyper-parasites, insert themselves between cooperating social individuals, and momentarily seize control of execution of the algorithm, just long enough to deceive the social creatures about their size and location, causing the social creatures to replicate the genomes of the cheaters.

One of the most interesting aspects of digital life is that the bulk of the evolution is based on adaptation to the living environment rather than the physical environment. It is co-evolution that drives the system.

The only kind of genetic change that the simulator imposes on the system is random bit flips in the machine code of the creatures. However, it turns out that parasites are very sloppy replicators. They cause significant recombination and rearrangement of the genomes. This spontaneous sexuality is a powerful force for evolutionary change in the system.

A series of experiments were conducted on the effects of mutation rates on the rates of evolution [4]. The parameter used to compare rates of evolution was the rate at which self-replicating genomes decreased in size, indicating an optimization, in an environment favoring smaller sizes. The optimal mutation rate was found to be a mutation affecting one in four individuals per generation. At higher rates the community sometimes died out, as genomes melted under the mutational heat. At lower rates, optimization was slower. Fully self-replicating (non-parasitic) genomes reduced from 80 instructions to as few as 22 instructions overnight (more than 1500 generations, of populations ranging from 300 to 1000) individuals. The ancestor of size 80 requires 839 CPU cycles to replicate. The creature of size 22 requires 146 CPU cycles to replicate, a 5.75-fold difference in efficiency.

However, not all evolutionary optimizations were achieved through production of the most compact algorithm. Some solutions involved the evolution of more complex algorithms that achieved optimization through efficiency rather than size [6]. These algorithms utilized the technique of "unrolling the loop", which requires more code. Some of these repeated the work two times, and others three times, within the loop. These solutions require more intricate algorithms than the one found in the ancestral algorithm, and illustrate the capacity of evolution to generate increasingly complex structures.

A comparison was made of the patterns of evolution in four different machine instruction sets [6]. These instruction sets vary in the way that information is moved among the registers of the CPU, and the way that the registers are addressed. There were striking differences in the mode and degree of evolution in the four sets. Two sets show gradualism, one punctuated equilibrium, and one punctuated gradualism. Those exhibiting punctuations achieve greater degrees of evolution.

The relationship between evolution and entropy has been studied by measuring entropy as genetic diversity in the soup ($-\sum p \log p$, where p is the proportion of the soup occupied by a genotype class) [6]. This measure of entropy rises rapidly to an equilibrium value, where it remains thereafter, drifting slowly upwards (probably due to an increase in the population due to the decreasing size of individuals). However, there are occasional sharp drops in entropy, corresponding to episodes of extinction. These extinction episodes are not provoked by external perturbations, but are internally generated.

The extinction episodes generally correspond the the origin of some new and very successful mode of existence, which causes the originating genotype to increase rapidly in population, driving other genotypes to extinction. This often occurs when parasites evolve a means of circumventing the immune mechanisms of the hosts. However, the descendents of the new successful genotype rapidly diversify restoring the community to the equilibrium entropy.

Some initial experiments with the evolution of parallel processes have recently been conducted [2]. In these experiments, the standard Tierran self-replicating ancestor was parallelized. The instruction set was enhanced by the inclusion of **split** and **join** instructions, so that new processes could be spawned and terminated by individual organisms. The soup was then seeded with an ancestor which spawned a second process, and divided the work of copying the genome between these two processors, such that one processor copied the first half of the genome while the second processor copied the second half of the genome.

When this organism was allowed to evolve, its descendants learned to spawn two additional processes, and divide the work of copying the genome evenly between the four processors. This higher level of parallelism required some additional computation in preparation for the parallel phase of the algorithm, to coordinate the activity of the additional processors. Therefore the more parallel algorithm was also a more complex algorithm, but one which gained in efficiency through additional parallelism. Organisms have evolved to use up to sixteen processors (the allowed limit), and have distributed the work perfectly among the processors, even when the work does not divide evenly by the number of processors.

These experiments have demonstrated that evolution can work effectively with the mechanisms of parallel computation, yet they are only a first step along a long road. The parallelism evolved in this experiment is still essentially of the SIMD kind, in that each processor is executing the same code, but operating on different data. The next step is to evolve MIMD style programming.

A new initiative is under development in the hopes of challenging evolution with a more complex digital environment and thereby provoking the evolution of MIMD processes. The new project will create a very large, complex and inter-connected region of cyberspace that will be inoculated with digital organisms which will be allowed to evolve freely through natural selection [1, 7]. This space is thought of as a biodiversity reserve for digital organisms. The objective is to set off a digital analog to the Cambrian explosion of diversity, in which multi-cellular digital organisms (parallel MIMD processes) will spontaneously increase in diversity and complexity. If successful, this evolutionary process will allow us to find the natural form of parallel and distributed processes, and will generate extremely complex digital information processes that fully utilize the capacities inherent in our parallel and networked hardware. The project will be funded through the donation of spare CPU cycles from thousands of machines connected to the net, by running the reserve as a low priority background process on participating nodes.

References

[1] Flam, Faye. 1994. Ecologist plans to let cyberlife run wild in internet reserve. Science 264: 1085.

[2] Thearling, Kurt, and Ray, T. S. 1994. Evolving multi-cellular artificial life. Brooks, Rodney A., and Pattie Maes [eds.], Artificial Life IV conference proceedings, Pp. 283–288. The MIT Press, Cambridge.

[3] Ray, T. S. 1991a. An approach to the synthesis of life. *In*: Langton, C., C. Taylor, J. D. Farmer, & S. Rasmussen [eds], Artificial Life II, Santa Fe Institute Studies in the Sciences of Complexity, vol. X, 371–408. Redwood City, CA: Addison-Wesley.

[4] Ray, T. S. 1991b. Evolution and optimization of digital organisms. *In*: Billingsley K. R., E. Derohanes, H. Brown, III [eds.], Scientific Excellence in Supercomputing: The IBM 1990 Contest Prize Papers, Pp. 489–531. Athens, GA, 30602: The Baldwin Press, The University of Georgia.

[5] Ray, T. S. 1994. An evolutionary approach to synthetic biology: Zen and the art of creating life. Artificial Life 1(1/2): 195–226

[6] Ray, T. S. In press. Evolution, complexity, entropy, and artificial reality. Physica D 75: 239–263.

[7] Ray, T. S. Accepted. A proposal to create a network-wide biodiversity reserve for digital organisms. For oral presentation at Artificial Life IV conference. Available by ftp at tierra.slhs.udel.edu as /tierra/doc/reserves.tex