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Is it alive or is it a cellular automaton?

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"Organic molecules cannot be synthesized my man." (Vitalists)

Introduction

Ever since the fundamental contribution by von Neumann cellular automata have enjoyed a central position in the development of ideas of artificial life ([7]). They are at the crossing point where physical phenomena described by statistical mechanics and information theoretic concepts of computation meet with often surprising results. In this article we will make a brief excursion to this territory.

1. What are they?

Cellular automata (**c.a.**) in their purest form are deterministic rules for describing the evolution of an array of objects. Consider the simplest set-up of a cellular automata defined on the one-dimensional integer lattice. Let each cell (integer site) be in one of two possible states, 0 = dead and 1 = alive. The c.a. rule is the recipe how the cells are updated based on their own and neighbor's states. The same local rule is applied everywhere and the update is synchronous i.e. done simultaneously for all cells in the lattice. Because of this the c.a. are in information theory called sliding block codes; one moves e.g. a rule template like in Figure 1a over the integers (the upper rule computes the value in the grey cell based on two neighboring cells above, the lower according to the cell and its three nearest neighbors on both sides). If the local rule is instead defined on a two-dimensional neighborhood we will get a two-dimensional c.a.

Title mutated from Tom Ray's "ancestor".

The key ingredients in the definition are the locality of interaction of the cells and the fact that the rule, the "physical law" is everywhere the same. Variations exist, e.g. one can add noise to the updating process to get a probabilistic c.a. or do asynchronous updates. These are interesting and important but we'll omit them here.

Figure 1b. shows a 16 step evolution of a simple c.a. The rule is $1{*}0 \mapsto 1, 0{*}1 \mapsto 1$ whereas the other four triples map to 0 ($*$ is the wild card). Zeros are rendered white and ones as black squares and time runs downwards. The rule is simple since it is a linear c.a. i.e. allows superposition of configurations. Yet surprisingly it shows some promise in our quest for alife: by examining the configurations (the horizontal strings of 0's and 1's) one notes that the final configuration (bottom) consists of two exact copies of the initial configuration (top). So the initial configuration has self-reproduced under the c.a. rule! One should note that this is not the property of the chosen string i.e. same would hold for any string of the same length.

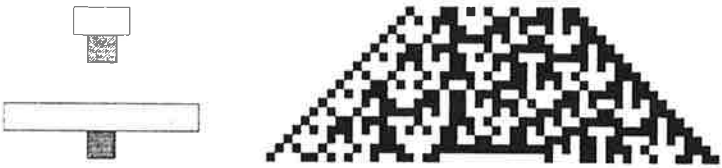

Figure 1a and b

C.a. were conceived by the mathematicians John von Neumann and Stanislaw Ulam in the fifties to find a new formulation to certain problems in computation and also to rigorously define life. It wasn't clear then as it isn't now what being alive really means but capability of self-reproduction seems a necessary criterion. Eventually von Neumann was able to come up with (a highly complicated) c.a. that was capable to that i.e. supporting self-replicating patterns. However the c.a. was extremely "brittle" in the sense that event the slightest error (mutation) in the construction would have destroyed its functionality. So its potential for evolution seemed to be nil.

2. What are they capable of?

In simulations (e.g. [8]) c.a. exhibit a staggering variety of phenomena. Instead of trying describe it all and classify c.a. we will here discuss those types of behavior that seem to have bearing to self-organization and evolutionary phenomena.

Figure 2a. it is not a snapshot of stalactites in an ice cave but it does in a very physical sense model a system freezing towards a ground state. It represents a hundred step evolution of a c.a. with a rule of the type in Figure 1a top. There are six states, which are rendered white, grey and black, each with two shades. The initial state is completely disordered i.e. the "color" and shade of each cell is independent of the other.

The phenomenon at hand is relaxation, evolution towards the ground state of the system where the colors form large contiguous blocks. Another way of describing this process is by considering the boundaries between domains of different colors. These "particles" seem to move in a random fashion and depending on how their types match, upon collision they annihilate or coalesce ([3]). The process is irreversible and indeed this is a prime example of non-equilibrium statistical mechanics. Note that the phenomenon is in a way also self-organization as the system transforms the completely random initial "symbol soup" into something more structured. But the problem is that the complexity of the limit is low i.e. the rule doesn't create patterns with intricate structure so characteristic of life. By complexity we simply (!) mean the length of the minimal description of the object.

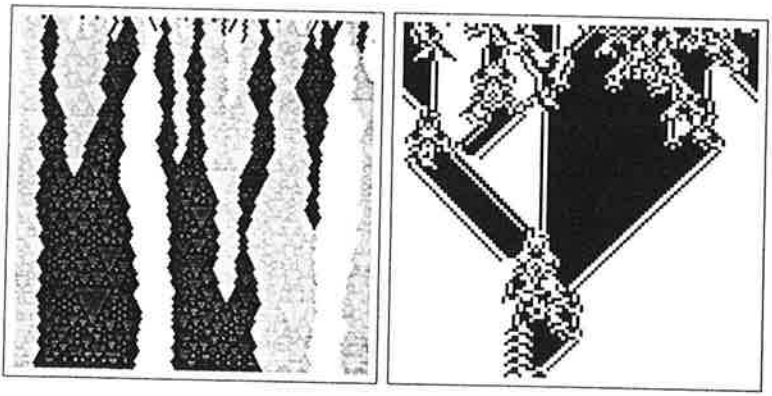

Figure 2a and b

Life is also a non-equilibrium phenomenon, property of certain systems which can persist in states far from the simple ground states. Indeed living processes seem to be able to generate complex structures out of simple ones. Do cellular automata support such evolutions?

The figure on the right represents again an evolution of a c.a. from a maximally random initial state this time on two symbols, 0 and 1. The rule here is to update the center cell to 1 if there is two, four or five 1's in a quintuple of neighboring cells. As in the stalactites the striking feature also here are the particles. But although they are now moving in a much simpler rectilinear fashion their interactions are highly complex.

The key observation here is that the particles act as carriers of information. Through their interplay even sites far away can and will develop correlations. As can be seen the initial randomness is seemingly suppressed with the result that homogenous domains and the particles take over. This is somewhat an illusion – the evolution still depends in a subtle way on most of the initial cells.

The particle dynamics of a c.a. can be used to accomplish computational tasks. It has been shown that in many c.a. including one-dimensional not unlike the ones we have considered here can be programmed! By this we mean that by choosing the correct initial state one can make the desired patterns show up at some later iterates. Indeed they have been shown to be capable of universal computation i.e. to be as potent as any computer. Using the interaction properties of the particles one can build logic gates, from them boolean circuits and higher computational elements ([1], [2]).

But before we go on what does this have to do with alife? The fact that some c.a. support universal computation means that they can generate arbitrarily complex patterns of symbols and process them. Life does not seem much like a computation but operations at the heart of it like copying DNA or RNA and metabolizing according to them the necessary chemical constituents that a living organism needs are computational tasks. So although c.a. look very different their capability is no less than needed for algorithmically the most demanding "live" tasks.

Of course finding or designing such automata might be tricky. An interesting approach to this problem arises by defining the "gene" of a c.a. According to our definition the rule of a c.a. is the lookup table which tells to which symbol each k-tuple is mapped (if the rule template has width k). If e.g. the rule is on 0's and 1's and $k = 5$ as in our last example this table has $2^5 = 32$ entries. Arrange them lexicographically and then call the update string of length 32 the gene of the c.a. It uniquely defines the rule.

Next fix a fitness function which determines what kind of c.a. behavior is rewarded and what is not. Take a random set of c.a. with a fixed gene length and compute their fitness using a set of initial states. Choose the best phenotype c.a. and mate their genes i.e. form crossover (and perhaps also random) mutations between their genes and then repeat the fitness evaluation on this new generation of c.a. and so on. Using this approach interesting results have been obtained in training c.a. for various parallel computation tasks ([6]).

In conclusion it is perhaps appropriate to mention an intriguing observation related to the "location of alife". Consider the set of all c.a. with a given set of symbols and a fixed neighborhood. Through extensive simulation one can assign most of them to a few qualitative classes ([4]). The vast majority of c.a. fall into sets representing periodic or chaotic dynamics. Based on these studies it seems that the c.a. exhibiting complex self-organization (through particle dynamics) are sandwiched between these sets. If one mutates the gene of such rule the c.a. usually falls off the set and into one of the simpler ones. The evolution of complex c.a. as described above represents the reverse process of trying to reach the set of complex rules. So this thin layer is where the live c.a. rules are to be found if anywhere. Related to this it is perhaps worthwhile to recall von Neumann's original vision: "There is thus this completely decisive property of complexity, that there exists a critical size below which the process of synthesis is degenerative, but above which the phenomenon of synthesis, if properly arranged, can become explosive...".

3. Alive or just complicated?

John Horton Conway, the designer of the one of the subtlest c.a. in existence, a two-dimensional one teasingly christened the Game of Life, clearly had high hopes in the capability of this c.a. And indeed in it a universal computer can be implemented via the use of particles ("gliders") and their interaction properties much the same way as in one dimension ([1]). Moreover it is believed but not proved that there are (very) large patches of Life configurations that are self-reproducing. However even if these indeed exist it is fair to say that (in spite of what one sees on the screen) this rule is not alive.

There seems to be a consensus that to be "alive" one would need (at least) two properties: to be able to self-reproduce and to be capable of open-ended evolution. By the latter we mean that the objects can and will be mutated and then selected according to their fitness. However the fitness should not be measured using some preset fitness function but rather in terms of the survivability in an environment of other species. GoL as well as many of the other known computationally capable c.a. essentially cannot tolerate mutations in the configurations.

A recent development in the direction of open-ended evolution in the context of (generalized) c.a. is what is called cellular games. In these one chooses a game, assigns a game strategy at each lattice point and then plays the neighboring players with different strategies against each other. The winning strategy will invade the site of the losing strategy. One particularly simple way of doing this is by considering a well-known co-operation game, the prisoner's dilemma. Simulations of this game show increasingly ingenious survival strategies emerging as the evolution progresses ([5]).

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