Flying over Mount Improbable

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Abstract. Using Chemical Organisation Theory [1] we present here an analysis of two classical models of artificial chemistries: a system equivalent to AlChemy [2], and the Automata Chemistry [3]. We show that Chemical Organisation Theory is able to explain why AlChemy was unable to evolve, while the Automata Chemistry would produce a stream of novelty that would on the one side explore the space of the possible molecules (and organisations) and on the other build upon the previous findings of the system. We relate to Suzuki's et al. [4] ten necessary conditions for the evolutions of complex forms of life, by adding an 11th one.

1 Introduction

One of the key models that was presented at the beginning of Artificial Life field was AlChemy [2]. AlChemy, which stands for Artificial Chemistry, was used both to suggest a chemical beginning of life [5] (different from the RNA beginning of life, and different from the fat beginning of life), and to explain how our tools to study complex systems were in fact really blunt. It was explained how we were able through an Ordinary Differential Equation (ODE) to study a system which had already all the elements present, but we were not really able to handle a system where new components were being produced [6]. A kind of system were novelty was being generated, in the form of new components, was then called a Constructive Dynamical System.

Twenty years later both threads of research are still alive. Constructive Dynamical System theory gave rise to Chemical Organisation Theory, which expands it, using Algebra, to deal with more general systems. It still studies artificial chemistries, but more generally deals with Reaction Networks, and had been used successfully in bioinformatics, and systems biology to predict and describe the algebraic structure of various chemical systems, from the atmosphere in Mars and Io [7], to the internal metabolism of a unicellular being [8].

Artificial Chemistry, as a research tool, has been used in the study of protolife. The AlChemy system was observed not to spontaneously evolve, and thus

researchers turned their attention to other artificial chemistries. But no one ever answered, or even tried to answer, why was AlChemy unable to evolve, and what additional lessons can we gain from this.

We shall use in this regard Chemical Organisation Theory, so the same theory that was presented using AlChemy, will now, in its more mature form, be applied back to study a system equivalent to AlChemy, finally explaining why was AlChemy unable to produce an evolving system. We will compare this with the study of another Artificial Chemistry, the Automata Chemistry model, and showing how there, instead, we do observe a genuine evolution. So the system keep on being constructive, keeps on producing novelty, and exploring the space of possible organisations. In 2003 a paper was written that listed ten on the necessary conditions for the Evolution of Complex Forms of Life in an Articial Environment. Those conditions were [4]:

1. the symbols or symbol ingredients be conserved (or quasiconserved) in each elementary reaction, or at least, conserved with the aid of a higher-level manager.
2. an unlimited amount of information be coded in a symbol or a sequence of symbols.
3. particular symbols that specify and activate reactions be present.
4. the translation relation from genotypes to phenotypes be specied as a phenotypic function.
5. the information space be able to be partitioned by semipermeable membranes, creating cellular compartments in the space.
6. the number of symbols in a cell can be freely changed by symbol transportation, or at least can be changed by a modication in the breeding operation.
7. cellular compartments mingle with each other by some randomization process.
8. in-cell or between-cell signals be transmitted in some way like symbol transportation.
9. there be a possibility of symbols being changed or rearranged by some randomization process.
10. symbols be selectively transferred to specic target positions by particular activator symbols (strongly selective), or at least selectively transferred by symbol interaction rules (weakly selective).

To those ten conditions we will add an eleventh:

11. The system should not have access to a basis that permits the construction of every possible molecule.

We will then discuss the consequences of this new condition, and it's relations with the previous ten. To do all this we shall first briefly present Chemical Organisation Theory, the Combinator's Alchemy version, and the Automata Chemistry. We will then show the result that we obtained by applying the Chemical Organisation Theory to the Combinators Chemistry, and to the Automata Chemistry. We will then discuss those results, and reach some conclusions.

2 Description of Chemical Organisation Theory

Chemical Organisation Theory has been presented in multiple papers, especially in previous versions of this conference. Although the results that we are presenting here are new, the actual theory has not changed. The theory in its complete format can be found from [1]. We shall now only repeat a brief description. Please note that the Artificial Chemistries we will study here are not the most general artificial chemistries possible, but part of a very specific type of systems called Catalytic Flow Systems. Those systems are often studied in Artificial Life, where as more general system are usually present in biology. We consider an artificial chemistry as a set of molecules M and a function R called reaction. R will be a function of arity 2 from $M \times M$ to M (i.e. $\forall\, x, y \in M$, $R(x, y) \in M$). We define an organisation as a set of molecules which is both closed and self maintaining. That is, let O be such a set, for all $a, b \in O$, $R(a, b) \in O$ (closure). And for all $c \in O$, such that c can be destroyed, there exist $a, b \in O$ such that $R(a, b) = c$ (self maintenance).

Note that this description is similar to the one given by Fontana in 1992 [2]. The only difference, at this stage, is that Fontana's self maintenance was required for every molecule, and not just for each molecule that can be destroyed (either through an out-flux or through a non catalytic reaction). This seemingly small difference is necessary to permit to the theory to study systems where some molecules interact in a catalytic way with every other molecule, and are not subject to an outflux (or destruction process). This is necessary, for example, to model DNA molecules in a biological system. In our simplified systems this difference makes sure that if the system reaches a configuration where no reaction is possible, then the configuration is also (trivially) an organisation.

The organisations generated by an artificial chemistry, form a partially ordered set (ordered by the inclusion), and more precisely form a lattice LO. Also it is possible to define a function GO(S) that given a set returns the organisation generated by that set. So organisations partition the space of all possible sets, and as the system travel in the space of possible molecules, we can follow it on LO. All this becomes important as the system evolves; in fact the evolution of the system will be, mathematically, represented as a movements on the lattice of organisations. All those results were previously presented in [1][9][10]. Briefly we could say that in this paper we are studying and comparing the movement in the lattice of organisations of two different systems.

If a system is left to react to itself, if any change is present, this will always be toward simpler organisations, that is toward organisations laying lower in the lattice of organisations (downward movement). But when the system is seeded with random molecules, those molecule can push the system toward a more complex organisations (upward movement). And if this is unstable fall back in the same organisation, or on a neighbouring organisation (sideward movement). We can now see evolution as an interaction between the random variation which leads the system toward a state of greater complexity, and its simplification by reaching a stable subsystem.

3 Systems: The Combinators AlChemy Version

The first system that we have applied the Chemical Organisation Theory to is the Artificial Chemistry generated by combinators. For a complete description please refer to [11, 12]. For those experiments we will use a simplified version of the system which has no R molecule, only catalytic reactions, and no fixed amount of basic atoms. So a system which is, in all regards, equivalent to Fontana's AlChemy except that it used Combinators, instead of Lambda terms. For a study on how combinators are equivalent to Lambda terms please refer to [13]. Please note, for example, that we could observe the same organisations that Fontana observed. And analyse them from a Chemical Organisation point of view ([10], chapter 6).

We will briefly describe the system. The system is an Artificial Chemistry, whose molecules are combinators in their normal form. Briefly we can say that Combinators are a string with balanced parenthesis over an alphabet of basic operators. Strict rules define how the basic operators in the string are applied, thus a combinator end up being the operator that is produced by the joined reaction of all the operators that compose it. The result is thus an operator, which can be applied to a string with balanced parenthesis, and would then produce a new string (again with balanced parenthesis). So a combinator is an operator which applied to a combinator generates another combinator.

Some combinators are in an unstable configuration, and by applying the operators that compose them, can change their configuration. If this can happen we say that a combinator is not in its normal form. The process that transform a combinator into another is called reduction. A fundamental theorem, in combinator theory, is that if a combinator can be reduced in a normal form, this is unique. In our experiment we shall use only combinators in their normal form, and when the result of a reaction is a new combinator, we shall just permit consider the reaction to be valid if the result can be reduced (i.e. if we could find in t steps a reduction) to a combinator in its normal form.

A family of combinators (called Soup) are present in the experiment, and at each time-step two combinators are randomly chosen, interacted, and if the result is a combinator that can be reduced to a normal form, the result is added to the soup. A random combinator is then eliminated. The basic alphabet that were used were (B, C, K, I, S, W) which include two basis of the space of combinators (B, C, W, K) and (K, S, I). Their behaviour as operators can be found both in [12] and in [13].

4 Systems: The Automata Chemistry

The second artificial chemistry used was an automata chemistry [3]. In this chemistry molecular species are binary strings ($s \in \{0,1\}^{32}$) with a constant length of 32 bits. As in the other chemistry, two strings will catalyze the production of a third string ($s_1 + s_2 \rightarrow s_3$). One of the strings s_1 is mapped to an automaton A_{s_1} according to a well dened instruction table (we used code

table II in [3] allowing self- well defined instruction table (we used code table II from [3] allowing self- replication). The other, s_2, serves as input to A_{s_1}, and the result of the reaction is the output of the automaton $s_3 = A_{s_1}(s_2)$. In each time step, two string are randomly chosen to catalitycaly react. After the reaction the reactants are inserted back into the reactor while one randomly chosen molecule in the reactor is replaced by the product in order to keep the total number of the objects in the reactor constant at value N.

5 Results

We applied the Chemical Organisation Theory analysis to both the Combinator's AlChemy system, and to the Automata Chemistry. The results that we reached were vastly different.

We could not map the whole lattice of organisations in either systems. In the one case (the combinators) this was infinite. In the other case (the matrix chemistry) while not infinite, it was too vast to be calculated. What instead we did was to stop the system in various points, and study the organisation that was being generated by the molecules present in the Soup. Note that we made multiple runs, and each run of the system was unique. Studying such systems presented a challenge, since the differences from one run to the other were mostly qualitative, before being quantitative. This was true both in terms of the differences between run on the same system (example, two runs of the matrix chemistry), and even more between a run on one system and a run on the other. The organisations, that were generated, the historical trajectory through those organisations were often very different one from the other. In both case it would not make sense to make a statistical analysis of a system. Yet there were some general pattern that could be recognised. Some common ways in which the Automata Chemistry system would run, versus how the Combinators' AlChemy System would run. As such, after having observed a number of runs, we are presenting here data from two exemplary runs. They are in all regards typical run, one of the Combinators' AlChemy System, and one of the Automata Chemistry. We then discuss the differences between the two type of systems.

In the Combinators' AlChemy System, not only we could not draw the lattice of all the possible organisations, but we could often also not map the organisations that were being generated. We note that since the system possessed a simple basis (two in fact: S, K; B, C, W, K), it was possible to have a configuration of molecules in the Soup that could potentially generate the whole system. Every possible molecule could be generated (given enough time, and a Soup big enough) by the system in such configuration. As such the organisation generated by the system, in those configuration, was potentially the whole system. And every possible other organisation that existed was a subset of this. We shall call this the organisation Infinity. As the system would keep on reacting, eventually the molecules of the basis would be destroyed, and the system would move downward to a smaller lattice, until eventually it would produce a finite lattice. When the system, was finally simple enough, we could study it with Chemical organisation

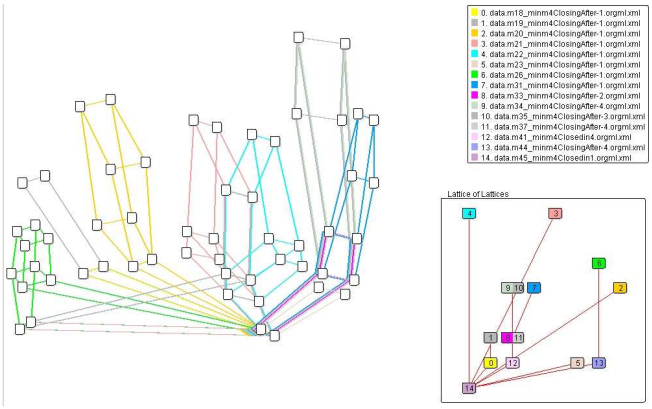

Fig. 1. This is a figure showing the evolution of the molecules in time, above. And the various organisations that suceeded below.

Theory, and we could map its lattice. Although we would limit ourselves to the point in time where the system was simpler, often the system would still be too complex to be nailed down through Chemical Organisation Theory. Usually to study the lattice of the organisations we start by calculating the largest possible organisations. This is done by starting with a set of molecules M, then producing every molecule that can be generated by reacting every pair of molecules together, thus generating M^1. Then repeating the same process taking pairs in M^1 we generate M^2, and so on. Until $M^n = M^n{-}1$. And then the system is contracted to the biggest self maintaining set. (For a complete description of the process please refer to [10], Chapter 2. In all but the most simple cases there was no n such that $M^n = M^{n-1}$. As the $lim_{n->\infty}|M^n| = \infty$. And we often had to limit ourselves to n such that $|M^n| < t$ (with the threashold often = 600).

We know we were very abruptly simplifying the lattice of organisations generated,losing potentially significant data. Still the data that we could collect were interesting, and pointed to some fundamental differences between the two systems.

As the system would keep on reacting, eventually the molecules of the basis would be destroyed, and the system would start to generate a smaller lattice, until eventually it would produce a finite lattice. When the system, was finally simpler enough, we could study it with Chemical organisation Theory, and we could map its lattice. What we would observe is that the system would jump from one organisation to the other. With no sense of historical continuity. Although we recognise that the historical continuity might be present in the data that we could not analyse, much of those data contained the full lattice. And as such the system was essentially going from organisation A to Organisation Infinity, to organisation B, to Organisation Infinity, to organisation C, to organisation Infinity, etc...

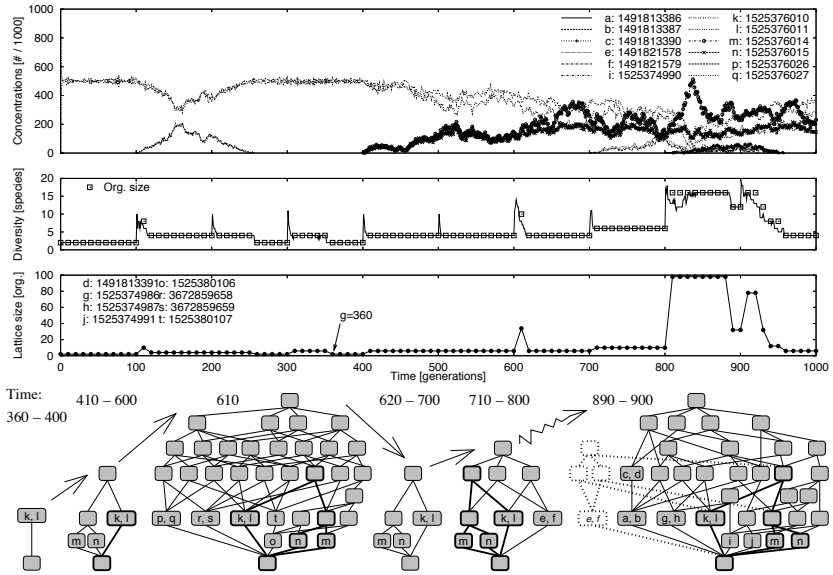

Fig. 2. This is a figure showing the evolution of the molecules in time, above. And the various organisations that suceeded below. (adopted from [9])

When we applied Chemical Organisation Theory to the Automata Chemistry the results were totally different. In this case it was possible to calculate the lattice of all the possible molecules that could be generated by the system.

In this case, not only we could observe the system's organisation in every instant, but we could observe how the random molecule would push the system into a more general organisation, and from there how the system would reach a simpler, but more stable organisation. The net result was a system that would reach an organisation, expand into a more complex, but unstable one. From there either collapse back toward the same organisation, or reach a different organisation. Thus producing a novel behaviour which was generally either an expansion of the previous one, or a partial modification of it.

6 Discussion

What is really striking between those two systems is how different is their evolving process. In a sense both systems are very similar. They both are produced by many molecules (232 in one case, infinite, but actually limited by the memory of the computer in the other), the reaction is equivalent, they both use catalytic reactions, with an out-flux of a molecule every time a new molecule is produced. The size of the experiments were similar (both used Soups of a thousand molecules). Both systems had random molecules being inserted, and in both cases the speed of the insertion was chosen so the system had the time

to settle in an organisation before new random molecules were inserted. And yet the evolutive behaviour was totally different.

In the first case the system would reach a finite organisation, then would wait until a random molecule would push it away. Then it would move into a organisation which was too vast to be studied. Often the soup would contain a basis of the set of all molecules, and thus the generated organisation would be the organisation Infinity. From there the system would move in an unpredictable way, eventually losing the key molecules that could potentially generate the wider organisations. And from there it would move down, to a new organisation. The new organisation would most often have no relation to the previous one. As such the system was similar to a system that was randomly picking organisations from the lattice of all possible organisations. With little or no relation to the previous organisation present in the system. Although this system is effectively moving from one organisation to the other, it was unable to hold build upon previous subsystems discovered.

The second case was very different. First of all we were always able to calculate the organisation generated by the molecules in the soup. Then the set would grow slowly. Often even under the influence of random noise the system would remain unchanged. Then when it would change it would move toward a more complex system (after having incorporated the new molecules), and then drop from there to a simpler system, which sometimes was the original one, and sometimes it was not. There was a very definite continuity from one state of the system to the other. And we could see the system exploring the lattice of organisations, moving through neighbouring organisations.

7 Conclusions

Often in Artificial Life there is a constant search for the most powerful system. The system that can potentially produce a bigger, higher complexity. It is inside this line of thought that AlChemy was developed. AlChemy having universal computation capabilities (U.C.C.) was able to produce every possible lambda term. Thus every possible subsystem would fall in its domain. Yet in this case it is this very power that gets in the way toward a genuine evolutive search of the space of possibilities. For each combinator that is present a counter combinator is possible that can destroy it. And the result is that no organisation is able to be stable enough. The problem is not just with the potential capabilities of the system (the fact that it has U.C.C.), but that a basis was also present. By taking lambda terms Fontana (and then combinators, one of us) was using a system that has been explored by mathematicians for close to a century. In mathematics there is a constant search for the most elegant (i.e. shortest) basis of a system. Thus the basis B, C, W and S, K were developed. By inserting in the system random molecules, composed of those basic atomic structures, the system produced was effectively able to reach too easily the infinite organisation. Per contro, we do not know what is the basis of the Automata Chemistry. Although we know that it exists, we also know that the random molecules that we were inserting in that

system were not often containing elements of the basis (or we would be seeing a much wider organisation appearing). So the system had to explore the space, with no shortcut that could let it easily get rid of molecules that were present. We recall in this regard another historical model, Tierra. Tierra had universal computations capabilities, but the basis was not so elegantly expressed. And Tierra evolutive behaviour was more similar to the Automata Chemistry, with its slow progress, than to AlChemy. We thus conclude that an important element in the construction of a system able to evolve is the absence of a basis of the whole system among the basic building blocks with which the system is fed when random molecules are inserted. Although the basis must necessarily be present, it should not appear too easily.

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