ARTIFICIAL CHEMISTRIES

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Artificial chemistries are presented. An informal definition is first introduced, followed by a presentation of the various kind of artificial chemistries found in literature. We continue explaining the difference between a qualitative model and a quantitative one. We then explain how a.c. presents a qualitative model, more than a quantitative one. The common measures used to follow the behaviour of an a.c. experiment are then introduced. Artificial chemistries generate particular algebraic structures: organisations. Organisations are then defined, and some of its basic algebraic properties presented. The general behaviour of an experiment is then presented. The article ends with an example of a particular artificial chemistry.

1 What Is an Artificial Chemistry

1.1 Introduction

An artificial chemistry (a.c.) is a tool. It is a type of computer model that can be used to simulate different types of systems. The aim of those simulations is, as we shall see, often quite different from the average type of simulation, aiming more for qualitative results, than for quantitative ones. The type of systems that has been modelled with a.c. range from chemistry, biochemistry (McCaskill 1988), ecology, sociology, to linguistic (Diettrich, Ziegler, and Banzhaf 2001). Also a.c. has been used for practical purposes, for example, to model a robot brain (Ziegler and Banzhaf 2001).

1.2 The definition

Artificial chemistries have often a similar structure, with few important differences from model to model. We will here list the major components, leaving for later the discussion on the possible differences that can be present, and how those differences could affect the outcome of the model. The general elements that are always present in an artificial chemistry are the molecules, the soup and the interaction rule (Dittrich 2001). In simple terms, an artifi-

cial chemistry is generated by a multiset of molecules in a well-stirred reactor (called soup). At every time step some molecules are randomly sorted. Those molecules interact generating some new molecules. Those new molecules are then inserted in the soup, while some others (sometimes the interacting molecules, sometimes others) are eliminated. We will now try to express this process formally.

1.3 The molecules

In each a.c., the possible molecules range within a very definite space: the space of all possible molecules. This space can be finite or infinite (Speroni di Fenizio et al. 2000). In some cases the space is not only finite, but so small that all the possible molecules can be listed (Ono and Ikegami 2000), in some others this is practically or even theoretically impossible.

1.4 The soup

In every moment only a finite multiset of the possible molecules are present in the system (a multiset is a set where the same element can appear more than one time). This multiset will be called soup. In some a.c. the size of the soup (number of molecules inside it, also called population size) will be fixed (Banzhaf 1994), in some others varies as the experiment proceeds (Speroni di Fenizio 1999).

1.5 The interaction rule

Artificial chemistry usually proceeds in discrete steps. It is not possible to give a totally general rule that is valid for all artificial chemistries on what happens at each time step. We will here present a common interaction rule. Let S be the space of all possible molecules, let $*$ be an interaction rule that takes n elements (thus of arity n) and that returns m molecules. That is, σ returns a multiset of molecules, where the size of the multiset depends only upon the particular n molecules taken. For some particular choices of molecules the multiset can also be empty.

$$* : S^n \to S^m \cup \emptyset \tag{1}$$

Often n is equal to two and the returned multiset is restricted to a single molecule. In those cases the interaction rule is restricted to:

$$* : S \times S \to S \cup \emptyset. \tag{2}$$

Normally at every time step n molecules are randomly chosen. The n molecules interact and generate their multiset of molecules. What happens next is different from a.c. to a.c. In some system the generating molecules (the original n elements) are eliminated from the soup and the new multiset is inserted instead (Speroni di Fenizio 1999; Speroni di Fenizio 2000). In other cases (especially if the n elements generate a singular molecule) another random molecule is extracted, eliminated from the soup and the generated molecule is inserted instead. This is in fact the most common interaction rule (Fontana 1992; Bersini 2000; Ono and Ikegami 2000; Dittrich et al. 1998). In this case, the complete interaction rule should then be expressed as:

$$* : S^3 \to S^3; \tag{3}$$

with a, b and x random molecules on S and φ an operation that goes from $S \times S$ to S ($\varphi : S \times S \to S$) this can be expressed as,

$$*(a, b, x) = (a, b, \varphi(a, b)). \tag{4}$$

It is obvious that in this case the population size of the system will remain constant.

2 The Power of Artificial Chemistries

2.1 The problem: the barrier of objects

Often the intrinsic limits of a method are invisible to the people who use the method itself. This is the case with modern scientific mathematical modelling, and the concept of objects. In our time, nearly every serious scientific model of a system is quantitative by its own nature. Once defined what are the objects present in a system, its aim is to study the quantitative relations between those objects: how many a with respect to how many b. To permit such study we need to know which elements are present in the system at any given time, and how they interact with each other. The classical ecological model 'fox and rabbit' requires that we know that two types of elements can be present in the system at any given time. We also need to know that the number of foxes and the number of rabbits follow strictly precise mathematical laws. We can then write a differential equation, solve it analytically, when possible, or through a computer simulation, when not possible, and examine the solution. The a priori supposition that should not be overlooked here is that we need to know what objects will be active in the environment of our system. This has always been true for scientific research, up to now, and scientific research has, consciously or unconsciously, limited itself to systems on which the reacting

elements were known. Yet those are not all the possible scenarios, as we might be interested in studying a system on which we simply lack the knowledge of some of its elements. Even worse, we might be studying a system that can just not be limited inside a finite set of differential equations. An example will clarify this last point. Suppose you wish to study evolution. The elements of your model will then be the different animals existing in the ecological scenario. The aim of your model would be to know which animals would be present. More ambitious than this you might also wish to know how many animals of a given type would be present. You don't know a priori which animals will be present and which absent. You don't also know the particular relations that will then appear between those animals. How do a hare relate to a dinosaur? It is clear that such model would be qualitative more than quantitative. We first want to know which animals are present. And then, in case, their quantitative relations. 3 centuries of dynamic systems don't help us in our aim. We can't write even the first differential equation if we lack the information of which elements are present. The problem was clearly posed by Walter Fontana and Leo Buss (1996) in a paper that placed the theoretical foundations to Artificial Chemistries. In Artificial Chemistries, we first consider the qualitative aspects of a problem, before considering the quantitative relations between its components.

Every set of molecules, present in the reactor, defines a set of differential equations. Those molecules define such a set, and if the set of molecules is algebraically closed we could study its differential equations and understand its quantitative dynamic. Once the closed set of molecules is defined is possible to study its differential equations. Yet, much of the questions that interest a researcher who study artificial chemistries have little to do with quantitative dynamics, and more to do with its qualitative one. The stable structures generated by artificial chemistries, the stable sets of molecules, are called organisations. Understanding which organisation will appear is equivalent to understanding the qualitative solution of an artificial chemistry (i.e., which animals are present). Understanding the relative quantity of the molecules is instead equivalent to understanding the quantitative behaviour of the system. The questions that researchers that study artificial chemistries pose themselves are: "Given an artificial chemistry, how can I know a priori which organisations are possible and which are not possible?" "How can I know which organisations are probable and which are improbable?" "How can I define an a.c. to generate a particular organisation?" "How stable are organisations?" "Can the complexity of an organisation be defined?" "How is possible to generate an artificial chemistry which moves from organisation to organisation in a never ending growth of complexity?" (Bedau et al. 1997) But of course also

the quantitative questions are present as well: "Given an a.c. in a particular organisation, how many stable (attractive) states are present inside it?"

2.2 The possibility to study an AC with ordinary differential equations

Of course, artificial chemistries can be studied also with Ordinary Differential Equations. ODE can be applied when the number of molecule type, diversity, is very small and the population size is high. If the diversity is too high the equations become not solvable due to the high non-linearity intrinsic in the system. When the population decreases the system becomes increasingly dependent upon the discrete nature of its components. Then having one molecule of a particular type inside the system or having none can make a tremendous difference. Is just not meaningful to consider a continuous model where there is half of that molecule (nor is clear which half should we then consider) (Dittrich 2001).

3 The Different Types of AC and Their Relative Properties

Depending on some essential elements, a.c. can develop in different ways. This includes the number of possible molecules, the type of operation used, the possibility of the system to have an influx of new molecules, or an outflow of old ones.

3.1 On a finite or infinite support

The first important element is the size of the support. In other words how vast is the space of the possible molecules. The support can be finite or infinite. Of course, if the support is finite, but so wide that the whole space of all possible molecules is never totally explored, the dynamics will resemble the dynamics of an artificial chemistry with an infinite support. In fact, in every experiment simulated inside a computer, the support will necessarily be finite. For this reason when we speak of an infinite support we are actually speaking of a 'very large finite support', limited only by the memory of the computer.

3.2 The operation

We presented before the interaction rule between n molecules. In such interaction rule we used a particular operation that given n molecules would return us a particular multiset of molecules. Lately we would insert the multiset in the system following a particular procedure. We now will discuss the various possible operations between the molecules. We will treat, for simplicity, only

the case where n is equal to two. The more general case can be trivially derived from that. Give two molecules the reaction between them can be (a) randomly generated, (b) can follow a previously defined algorithm, (c) or can be chosen (through an algorithm or a human being) to reach a particular result. For every pair of molecules is also possible that no reaction is possible. This is normally indicated by writing that the reaction of the two molecules will give rise to $\emptyset$.

Random Operation

Random a.c. are the most simple to do. Every time two elements interact, the result is randomly chosen from a set of possible results. If the support is finite, the result will just be one (or more) molecules from the support. If instead the support is not finite, then, with a certain probability, a new molecule would be generated and added to the soup. This molecule would then increase the complexity of the artificial chemistry (Bagley and Farmer 1992).

Algorithmic Operation

Here the molecules just follow a low-level logic (Banzhaf 1994; Ikegami and Hashimoto 1995; McCaskill 1988; Suzuki and Tanaka 1998). An example of this is shown later, where molecules are combinators. Combinators, similar to lisp programs, have universal computation capability, and applied one to the other generate new combinators, thus filling the infinite reaction table in an interesting non-random way.

Following an Operation Defined by a Human Being or through a Genetic Algorithm

This method is normally used when the number of elements is fixed. Here the whole table of all possible reactions is generated (Suzuki and Tanaka 1998; Ziegler and Bazhaf 2001). This table can be generated in many ways. The table then defines what would be the reaction out of every possible interaction. Of course, if the elements were just inserted in the table randomly, the result would not be different from the previous case. Yet is possible to define some reactions in particular ways and fill the rest of the table in a random way.

4 Organisations

As we study artificial chemistries is important to understand which possible stable states can be reached. The basic element is an organisation (Fontana 1992; Fontana and Buss 1996; Speroni di Fenizio et al. 2000; Dittrich 2001).

4.1 Definitions

From an algebraic point of view an organisation is a pair $< S, * >$, with S a set of molecules and $*$ an operation from $S_1, S_2, \ldots, S_n \rightarrow S$ such that S is a closed and self-maintaining set. A self-maintaining set (respect to an operation) is a set such that for every a in S exists $b_1, b_2, \ldots, b_n$ with $(b_1, b_2, \ldots, b_n)* \rightarrow a$. So every element of S can be regenerated from other elements of S. Note that we don't make any particular requirement on the nature of the $b_1, b_2, \ldots, b_n$. A closed set (respect to an operation, $*$) is a set such that for every $b_1, b_2, \ldots, b_n$ in S $(b_1, b_2, \ldots, b_n)*$ is in S. Therefore, from the closure we have that the elements can generate nothing outside the set, while form the self-maintenance we have that the whole set can be dynamically regenerated. The two properties are independent and many sets are only closed or only self-maintaining. The interested reader is referred to (Speroni di Fenizio et al. 2000) for a deeper study on the basic theory of organisations.

4.2 Finite and Infinite Organisations

Depending on the number of different elements in the organisation, an O. will be finite or infinite.

4.3 Relations: Union, Intersection

Few basic properties of organisations can be proven. Given a set S of elements, it uniquely defines an organisation generated from S. As a corollary of this, it becomes trivial to prove that intersection (union) of organisations uniquely defines an organisation. Therefore, the set of all possible organisations, with the operation of intersection and union generates a lattice (Speroni di Fenizio et al. 2000) In Figure 1 it is possible to see an example of lattice generated by an artificial chemistry.

5 General Behaviour

When an artificial chemistry is permitted to run for a certain number of generations it tend to reach some equilibrium. At the beginning an experiment tend to explore the space of the possible molecules. This time is often referred to as the transition time. After the transition time the system settles around a stable set of molecules (an organisation) . If no new molecules are then added, the behaviour of the system can often (at this point) be predicted through the equivalent ODE. Depending on the support of the artificial chemistry,

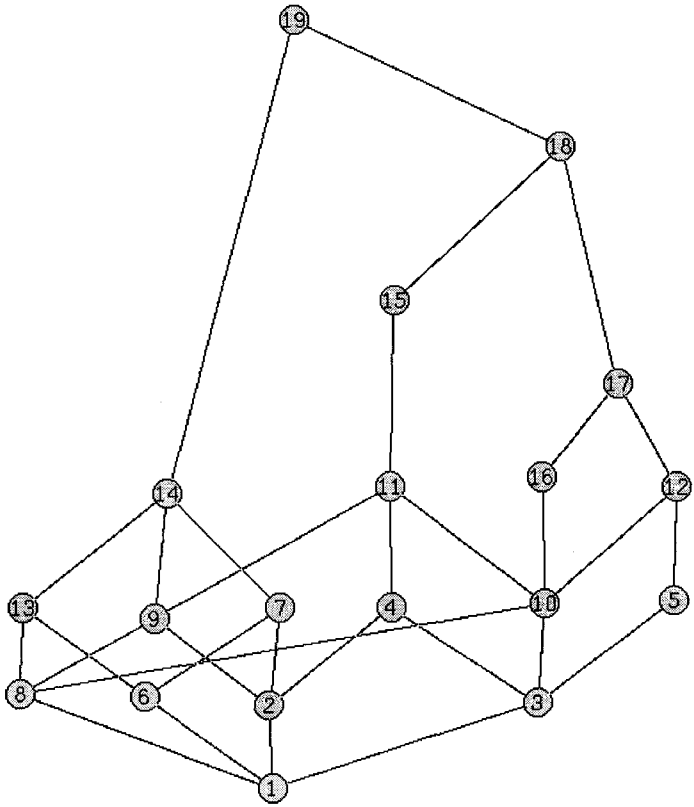

Figure 1. Example of a lattice of organisations. Source: (Speroni di Fenizio et al. 2000)

the transition time can be shorter or longer. If the system can contain many different molecules, this phase can be much longer. If the system contain an infinite number of possible molecules, and new molecules are inserted then is possible that no organisation is stable. The system is always in danger of reacting with the wrong external molecule and slide into a new transition phase with unpredictable results (Speroni di Fenizio and Banzhaf 2001).

5.1 Point attractor

As we said before, an organisation can be finite or infinite. Sometimes finite organisations are very small, with few or only one element. Often only one

element is present and the whole system reaches this tiny organisation and doesn't change anymore.

5.2 Qualitative and Quantitative results from the organisation point of view

We should always remember that an organisation does not represent a state of the system, but rather a set of differential equations. An organisation is a sort of multi-state, where many different dynamic attractor states are possible. In other words, once the system has reached a particular organisation, with molecules $\{a, b, \ldots, z\}$, the relative amount of $a, b, \ldots,$ and z is still to be defined. Two systems can both reach the same organisation, but one with a particular quantitative relation between $a, b, \ldots$ and z, and another with a totally different one. Therefore, while the organisation reached represents the qualitative dynamic of the system (the active equations) the dynamic equilibrium represents the quantitative one. It is interesting to note how, although an organisation has been found, the system is still at risk of falling into a new transition phase. It would be easier to conclude that this can happen only when new molecules are inserted (from outside or through a mutation). This is unfortunately not true, at least theoretically. We have explained before how organisations don't form a partition of the state space. Organisations form a lattice and all the organisations are sub-organisations of a universal organisation U which holds all the possible molecules that can be generated in some ways. Sometimes the organisation present in the system is U itself. This can happen, for example, when U can be generated by a small set of molecules (like in the example presented later). When this happen no information can unfortunately be extracted from the algebraic study of the solution. We are then left with its quantitative study. The author is not aware of any article that faces and tries to solve this situation.

6 Measures of an AC

Many global measures can be taken of an a.c. Some are general (Dittrich 2001), while others can be applied only on particular artificial chemistries (Speroni di Fenizio and Banzhaf 2001). Here is a list of the most common ones.

6.1 Population Size

When the number of molecules is not fixed, the population size is always an important measure. Even when this number is fixed, the behaviour can be quite different between two different experiments depending on the relative population size. In general the bigger experiment will follow more closely the behaviour predicted (when is possible) by the Ordinary Differential Equations. While this might induce to think that a.c. should just be studied through ODE, this is wrong. There are some specific cases where ODE just can't be applied successfully. In general this is true: when the number of possible molecules is too big (or infinite); when an influx of random molecules is added to the system, disturbing its predictable behaviour; in addition, when the size of the system is small or if the system contains some molecules with a strong non-linear behaviour. In all those cases, an Ordinary Differential Equation will just not solve the system. For example, how should we interpret that a molecule type is present with 1/2 molecules? This is a particularly important question in a system where a single molecule can have a devastating effect due to its intrinsic non-linear dynamic.

6.2 Diversity

After the population Size the most common measure taken is the diversity, or the number of different molecule types present in the system. Often a system will limit itself to one or few types of molecules present. Some systems, instead, reache a state where the diversity is not fixed but fluctuates. This can be caused by an external outflow, but also by the inner dynamics of the molecules that are present.

6.3 Time in Generations

All those measures are normally plotted against time, and time is in general measured in generations. If the population size is fixed a generation is considered to be passed when 'population size' interactions has happened.

6.4 Shannon Entropy

Shannon Entropy on the population of the various molecule types is also a common measure. As soon as an organisation falls into an organisation, the Shannon entropy falls. Yet, two different organisations tend to have their entropy vary through different values.

6.5 Novelty

This measure indicates the percentage of interaction, which give rise to new molecules. This is obviously an important measure, since each molecule introduces a higher complexity in the system. In some studies a molecule is considered new if it never appeared in the reactor, so if it is 'absolutely new to the experiment'. In others experiments a molecule is considered new only if no other molecule of that kind is present in the experiment in that particular moment. Both types of novelty should be considered, maybe with different names like absolute novelty and relative novelty. Often the decision upon which measure to use is more dictated by how the system is coded. For example, if the system tends to have a long transition time, it might be just not possible to record all the molecules that have been present. This makes the first novelty measure difficult or, sometimes, impossible to calculate. A third type of novelty, which could be measured, is a novelty related to the organisation present in the reactor. Here a molecule would be considered new if it never appeared while this organisation was present, independently if it appeared before this organisation became dominant. Of course this type of measure has not (to the author knowledge) been used, since it require to automatically calculate what is the present organisation – a daunting task to be calculated at every time step.

6.6 Productivity

As we explained, not every molecule can interact with any other molecule. Some interactions might be either theoretically impossible, or filtered out as being elastic to obtain some special effects (Fontana and Buss 1994). For this reason, it makes sense to measure the productivity of the system. The productivity of the system is calculated as the number of colliding molecules who react divided by the number of colliding molecules. This number tends to vary much during a run, yet inside the same organisation is often bounded. For this reason (along with novelty) gives a good hint on when does the system enter an organisation.

6.7 Other measures

Each a.c. has, of course, also other measures, often unique, that address either the singular characteristics of the particular model or the unique characteristics the problem that the system is trying to solve. For example, in the system presented below the molecules are generated upon a set of basic atoms. The total number of those atoms is fixed, so for each type we measure the free

atoms available to the system. Obviously, such measure just does not make sense in many other systems. Figure 2, taken from (Speroni di Fenizio et al. 2001), shows an example, where the population of some particular molecules are plotted against time, then the diversity and the productivity. The system (which is kept unstable through a random inflow of elements) passes through at least three main organisations, at generations 250, 600 and 900. We can see how the main molecules succeed to each other as the system is pushed from one organisation to the next.

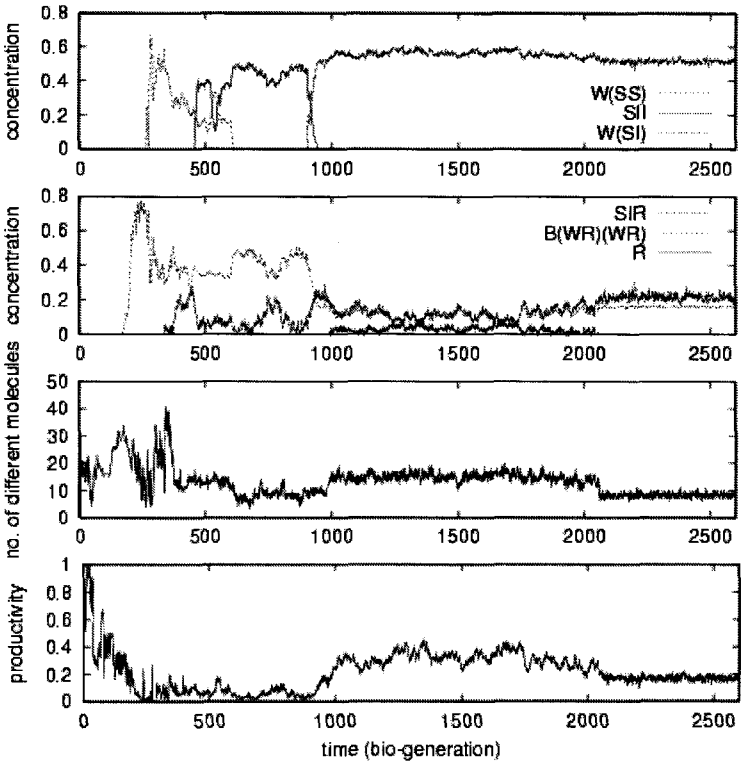

Figure 2. Example of measurements taken from a simulation of an artificial chemistry. Source: (Speroni di Fenizio et al. 2001)

7 Examples of Artificial Chemistries

7.1 The Combinatorial AlChemy system

We will present as a general example a particular a.c. on which the author has worked for some time. In this work we try to build an a.c. that can support living process. We are not here speaking about natural biological life, but of a more abstract concept. We will say that a particular sub-system of a system is alive if some particular relations are presents between its elements. We will say that a sub-system is alive if: (1) is able to self-heal (Varela et al. 1974); (2) it possess a metabolism (Bagley et al. 1992; Speroni di Fenizio and Banzhaf 2001) and (3) it generates a boundary that identify it from the external world (Varela et al., 1974; Ono and Ikegami 2000; Speroni di Fenizio et al. 2001). Discussing this list would take a long time and the interested reader is referred to the mentioned papers for more details.

What Artificial Chemistry

The artificial chemistry we use has some unique characteristics. This a.c. uses an infinite set of molecules. Each molecule tends to act in a different way. This is a general statement, as we shall see some duplication might sometimes be possible. The molecules are made up of seven types of basic atoms. When two molecules a and a collide, they generate a multiset of resulting molecules. The size and content of this multiset directly depends on a and b. When two molecules collide, the two molecules are extracted from the soup, while the resulting new molecules are inserted. From this rule follows that the population size of the soup is not fixed, but varies. While the total number of molecules is not fixed the total number of atoms of each type, present in the soup, can never exceed a certain limit. While the population size (number of molecules) in the soup is not fixed, the limit in the total number of atoms does indeed limit the total number of possible molecules, keeping the system from exploding. Not every molecule in the soup can interact with any other. Some times a collision either does not produce nothing, or the product would require an excessive use of atoms of some type. In this case, the collision is considered elastic and the interaction never to have happened.

Infinite type of molecules

In this artificial chemistry, we use combinators as molecules. Let S be the space of strings with balanced parentheses. Combinators are operators from S to S. Thus a combinator c is an operator $c : S \to S$. Combinators can themselves be expressed as strings with balanced parentheses over a particular alphabet. From this follows that given two combinators a and b is possible

to apply one to the other to obtain a third combinator. This can be done in two different ways: $a * b$ and $b * a$. This will sometimes lead to two different results.

Finite types of atoms

While the number of possible molecules is infinite (theoretically, since is still limited by the memory capacity of the machine we are working on), the number of base elements on which the combinators are built is finite. We have explained how each combinator can be expressed as a string with balanced parentheses on an alphabet. The alphabet is the alphabet of the basic combinators we will use in our experiment. We use only seven basic combinators, and we will call those combinators atoms. Those combinators are: B, C, K, I, S, W and R. For a complete explanation on those combinators and their behaviour please refer to (Hindley and Seldin 1986; Speroni di Fenizio and Banzhaf 2001). The number of atoms inside the reactor is finite and fixed. In every moment, a separate account is kept for the number of free atoms. That is, atoms not used in any molecule and ready to be used in a new reaction. As we said before, atoms are not a universal feature of artificial chemistries. Here their presence introduces a physical conservation law that stops the system from exploding. In fact, the system would explode as soon as the first molecule able to make copies of itself (replicator) would be generated.

Reaction Following an Algorithm

As we explained before, three are the main types of operations that can be present in an artificial chemistry. Casual operations, operations following a (men made) finite table of reaction, and operations following an intrinsic logic. In this artificial chemistry we are obviously in the third case. At every time-step two combinators are randomly selected. If their reaction is not elastic, the two combinators are applied one to the other; the solution is released in the soup while the two original molecules are eliminated. It is interesting to note that given any string s on an alphabet $\{a_1, \ldots, a_n\}$ there exists a combinator c on the alphabet B, C, K, W such that $c*((((a_1)a_2)\ldots)a_n) \rightarrow S$. The same result is also true if we choose c on the alphabet S, K, I. For this reason B, C, K, W and S, K, I are called a bases of the space of combinators (Hindley and Seldin 1986). In our system, we use both bases; this will of course generate some redundancy, as the same operator can be written in (at least) two different ways. On the other hand, since we limit the number of possible atoms of each type, this redundancy permit to reach a particular type of operator even when one of the atoms has been all used up. While the atoms B, C, I, K, S and W are taken from the standard theory of combinators, the operator R has been introduced ad-hoc to give the possibility to combinators

to react giving more than one result. Of course, if at every reaction two molecules interact to generate only one, and if at every reaction we eliminate the two molecules which has been used up, we would soon find ourselves with no molecules left in the soup. A common solution to this has been not to eliminate the reacting molecules at all, consider their action as catalytic on a flux of basic elements on the background. The basic elements would then be so common and universal not to be modelled at all. Instead, a random molecule would be eliminated, representing an outflow of elements or a random death. So the operation could be expressed as:

$$a + b + x \rightarrow a * b + a + b, \tag{5}$$

where x is the random element. In this artificial chemistry we worked to maintain a form of conservation law on the atoms. Now if a and a interact, we eliminate from the reactor a copy of a and a copy of b, while we insert the resulting molecule(s). So:

$$a + b \rightarrow c_1 + c_2 + \ldots + c_{n_{a,b}}. \tag{6}$$

The number of resulting elements $c_{n_{a,b}}$ depends strictly only on a and on b. The average number of elements generated by a random reaction tends to fluctuate during the experiments but soon always stabilises at 2.

Slight influx or outflow

To study the stability of the system we kept a slight influx of random elements. The influx is so small not to prevent the system from finding stable solutions (organisations). Of course, those solutions are stable with respect to the elements present. They are also stable with respect to a subset of the possible elements that can be inserted. Yet, there is always the possibility that a particularly complex molecule can be randomly selected, inserted, and pushing the system into a different organisation. We also added to the system the possibility to have an outflow of elements. This was added in some experiments and not in others. The outflow was inserted mainly to prevent the system from collecting too many molecules too complex to be used. When we added in the system the 'K' molecule, that gave the possibility that a whole other molecule could be destroyed the necessity for an outflow disappeared. Instead, the system started to 'evolve' molecules to destroy those big molecules, thus taking care by itself to 'clean its environment'.

Results

In Figure 3 we can see an example of a run taken from (Speroni di Fenizio 2000). We run the system to study the space of its possible attractors as well as to study their stability. Each attractor was a qualitative solution, a different

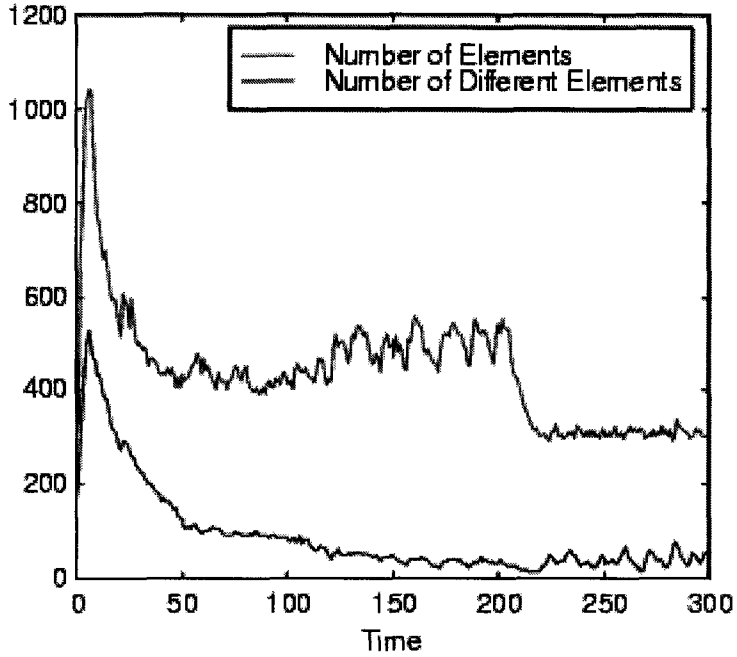

Figure 3. Example of an artificial chemistry passing through different organisations. Source: (Speroni di Fenizio and Banzhaf 2001)

set of molecules, and a different set of equations. The attractors appeared to be of two different kinds: attractors that used the inflow of elements to increase in size, and attractors that did not need the inflow. Since the first needed such a flow of molecules which would then be modified to generate more molecules of the same type of the attractors we called the first type metabolic organisation, for it metabolises inserted molecules (Bagley and Farmer 1992). The second type of organisation always contained different types of molecules, some that would generate more and more molecules (using the R atom), and others that would destroy some of the existing molecules (using the K atom). Such organisation was called balanced organisation since it contained and held in balance at least two different types of molecules: molecules that would expand the system and molecules that would contract it.

8 Conclusions

Artificial chemistries are now beginning to be used in various fields. If every 'molecule' is a replicator (able to generate copies of itself), the system can represent a social system, or an ecological one, with the 'molecules' being human beings or animals. If, instead, the 'molecules' represent 'firms' we are probably trying to model an economy, while if every molecule represents a specific human being, in relation to its language, we are probably dealing with a linguistic model. Artificial chemistries are, in a sense, only a tool. Like ordinary differential equations. This tool was born inside artificial life, but its range of action is much wider. Some of the problems it addresses are universal: the difference between qualitative and quantitative solutions; the nature of qualitative solution and what is an 'attractor' in the space of possible 'types' of solutions. It seems to be a promising tool to be used in different disciplines. As a last note, we wish to point out that this tool has not been used only for theoretical disciplines, but also for practical purposes. A robot controller using an artificial chemistry in his brain has already been developed (Ziegler and Banzhaf 2001), while an algorithm to automatically prove theorems, which uses an a.c. as its main part has been built too (Busch and Banzhaf 2000).

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