A Less Abstract Artificial Chemistry

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Abstract

We start with AlChemy system [Fontana, 1992], and with four further modification we move into an Artificial Chemistry system where for each element is present an atomic structure, elements follow the conservation laws on the number of atoms, and the operation permits to two elements to generate more than one element. The resulting system still generates Organisations (self-sustaining, closed sets), but a wider variety of them are easily reachable without imposing any filter rules on the results of the operation [Fontana, and Buss, 1993]. The resulting Organisations are nearly equally divided into two classes (A and B), one (A) which contains Organisations that metabolise external elements to keep themselves 'alive', while the other (B) tends to expand until no place is left in reactor, without any need on external elements.

Introduction

Artificial Chemistries study the interaction of many elements, in a system where their interaction can generate new elements of the same kind. In this respect they are similar to an abstraction of chemistry where chemical elements interact generating other chemical elements.

Artificial Chemistries have been used to show how a self-organising set (organisation) naturally arises in a system of interacting elements. [Fontana, 1992]. Other researchers have developed his work further [Dittrich, and Banzhaf, 1998], [Suzuki, and Tanaka, 1998].

With Organisations, we intend [Fontana, 1992] a set of elements such that each element can be generated by the conjunct action of the others, and such that given any two elements in the system their interaction will always generate only elements of the set.

In many systems studied either the number of possible elements were finite (as in Suzuki), or the number of elements in the system is fixed (as in Fontana). Systems where the number of possible elements is not fixed and the number of elements inside the system is not fixed are rare. We present a system of this kind.

In AlChemy, and in general when the number of elements in the system is fixed, a standard operation is adopted. At each time step three elements are randomly chosen (A, B and X). A function is applied that associates to the first two elements (A and B) another one (C_{AB}), if this new element is acceptable the X element is eliminated and the C_{AB} element is instead inserted in the system.

A different operation is here proposed. Two elements are randomly chosen (A and B) and a multi set (that is a set where the same element can appear more than once) of N elements is generated. That is

$$A+B \rightarrow C_1+C_2+\ldots+C_{n_{AB}} \qquad (n_{AB}>=1)$$

The system using this new operation can model interactions more similar to the chemistry ones. Like reactions of the form $A+B \rightarrow C+D$.

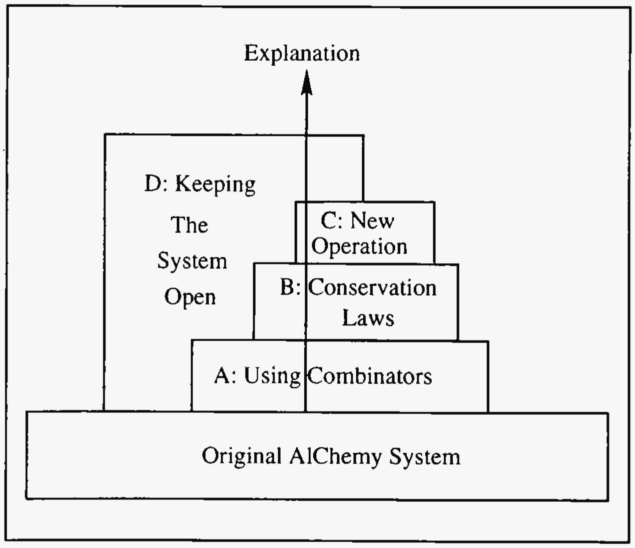

Figure 1. This figure shows the modifications to the alchemy system presented. Each one builds upon the previous. We could have stopped after each modification, but the most interesting results seem to be present only when all the modifications are working together.

Modifications Applied

To build a system where the number of elements is not fixed, the system doesn't explode, and the number of possible elements is not limited either, we need to change the original Fontana AlChemy system in some ways.

a. Combinators are used.
b. Conservation laws are applied.
c. The operation is changed.

d. The system is kept as an open system.

As a first modification the whole system is rewritten using combinators as base elements instead than lambda-terms. We then apply the conservation laws on the number of simple combinators (1-term combinator) used. This is made possible by the atomic structure of combinators. Then the operation is changed, moving to a more chemical-like operation. From now on the number of elements will not be fixed , yet the whole system will be bounded by the conservation laws. Yet the system in those conditions will tend to stop very soon, and to prevent it from stopping we add the last modification. The system is inserted in a small flux of elements that sometimes will produce new elements and sometimes will randomly eliminate one of the existing ones.

A. The Algebra of Combinators

In AlChemy each element is a lambda-term that can be seen equally well as an operator or as data [Fontana, 1992][Hindley and Seldin, 1986]. At each time step two elements are randomly chosen and the first one is applied to the second to generate the new one. In our system each element is a combinator rather than a lambda-term.

A combinator is a string whose elements are either elements from a finite alphabet or combinators themselves [Hindley and Seldin, 1986]. Combinators contained in other combinators are represented with a parenthesis before ('(') and after (')'). The alphabet we normally use contains 6 basic element: I, K, S, B, C, W. Any sequence of those letter is a valid combinator, such as: KI, KIBBBW, BSWWB, but also, K(BBSKI)S is a valid combinator with BBSKI as a sub-combinator. Or even, BBB(SK(KSSI))I is a more complicated combinator with two levels of sub-combinators inside.

As with lambda-terms, each combinator can be seen both as an operator and as data. As an operator it will transform a string (combinator) into another string (combinator).

When a combinator is applied to another the second is added to the first as a sub-combinator, so for example if we apply SSK to KI the result would be SSK(KI). In any combinator the first element is never enclosed by parenthesis, if they are present they can be omitted, so the combinator (SI)KKS is the same as the combinator SIKKS.

Every letter of the alphabet, as an operator, act upon the remaining elements by rearranging them, occasionally making copies of some elements or destroying others. So for example the combinator S, applied to 3 elements x1, x2, x3 (S $x_1x_2x_3$) acts to generate the combinator x1x3(x2x3). This is represented as:

$$S\ x_1x_2x_3 \rightarrow x_1x_3(x_2x_3)$$

The → operation is called 'combinatorial reduction' and each 1-term combinator (element of the alphabet) rearranges the data in different ways (see table 1 for details). Each element just rearranges the first elements leaving the rest unaltered.

A.	Effect	A.	Effect
I	$I\ x_1s_0 \rightarrow x_1s_0$	B	$B\ x_1x_2x_3s_0 \rightarrow x_1(x_2x_3)s_0$
K	$Kx_1x_2\ s_0 \rightarrow x_1\ s_0$	C	$C\ x_1x_2x_3s_0 \rightarrow x_1x_3x_2\ s_0$
S	$S\ x_1x_2x_3s_0 \rightarrow x_1x_3(x_2x_3)s_0$	W	$W\ x_1x_2\ s_0 \rightarrow x_1x_2x_2\ s_0$

Table 1. Basic Atom Types. Note: A. stands for Atom, s_0 is just the remaining sub-string and can be equal to ∅.

Not all combinators can be reduced, a combinator whose first element is not followed by enough terms, and where in each set of parenthesis the first term is always followed by too few other sub terms, cannot be reduced. For example: KK(SKI) can be reduced to K and K(SKKI) can be reduced to K(KI(KI)) which can be further reduced to K(I)=KI. While K(SKI) cannot be further reduced. A combinator which can't be further reduced is said to be in its normal form. Thus when we speak of a combinator we are really speaking of a whole equivalence class of strings, and two combinators will be equivalent if can be reduced to the same combinator. This definition is well posed since [Hindley and Seldin, 1986] if a combinator possesses a normal form this is unique (or in other words by normalising one part of a combinator before another we will never reach two different normal forms). This does not mean that every combinator does have a normal form. There are in fact infinite combinator that either enter into cycles or continue to get longer and longer as they 'reduce'. For example WWW reduces to itself.

The normal form of a combinator is equivalent to the normal form of a lambda-term in Fontana's program AlChemy. In our system our elements will be combinators expressed in their normal form.

B. Adding the Conservation Laws

Having used combinators instead of lambda terms we can now see each element as being constructed from smaller atomic parts. We can thus impose the conservation laws upon the total number of atoms (that in our case will be the 1-term combinator). To permit this a list of all free atoms that are available at each moment is kept. This list will in general be called 'the Pool'. At each time step, as two elements interact, and as the resulting element is reduced and normalised, every atom that has to be added is taken from the Pool, and every atom that is used up is dropped back into the pool. At the end we will consider as acceptable only the operations that don't require the presence of more atoms than the ones present in the Pool.

An example of the use of the Pool could be:

Suppose the Pool contains 20 B, 20 C, 20 I, 20 K, 20 S, 20 W. The two elements SKI and KW are randomly chosen.

The first is applied to the second and the combinator SKI(KW) is generated. 1 S, 2 K, 1 W, and 1 I are taken from the Pool (20 B, 20 C, 19 I, 18 K, 19 S, 19 W). Then the normalisation process begins:

SKI(KW)→K(KW)(IKW); 1 S is added to the Pool and 1 K and 1 W are subtracted from it (20 B, 20 C, 19 I, 17 K, 20 S, 18 W).

K(KW)(IKW)→KW; 2 Ks, 1 I, and 1 W are added to the Pool (20 B, 20 C, 20 I, 19 K, 20 S, 19 W).

KW is a combinator in its normal form. KW is then added to the list of elements and another element is randomly chosen, and deconstructed to its basic atoms that are then added to the Pool. At each time step the number of elements in the Pool is checked and if in any moment there are not enough free atoms the whole reaction is considered elastic (in this environment) and the reaction never to have happened.

C. A Different Operation

Our next modification on the system will be to change the operation that permits the generation of new elements after having chosen the two interacting ones. We want the operation to be such that given two elements we generate a whole family of N elements, with N dependent only on the two interacting elements. We want an operation such that given a pair of elements the generated family is uniquely defined. This will be possible if we just redefine the action of one of the combinators. The key of the new operation will be the combinator K and its action upon other combinators. From table 1 we can see that K keeps the first combinator following it (x_1) and destroys the second one (x_2). We can, instead, consider K as merely detaching the second combinator x_2, leaving it as an independent unit to float away. To make things more similar to the actual chemistry we will eliminate, at each time step, the two elements that interacted, keeping only their product. We are thus using up the elements in the operation, as molecules are effectively used up in real chemical interaction.

The original operation could be written as:

$$A+B+X \rightarrow A+B+A(B),$$

while the new one would be written as:

$$A+B \rightarrow C_1+C_2+\ldots+C_{n_{AB}} \qquad (n_{AB}>=1)$$

Of course every C_i will have to be normalised and the whole operation will happen only if all the element reach a normal form, without exhausting all the free atoms in the Pool.

D. Keeping the System Open

To prevent the system from stopping and to keep a flow of energy through the system we added, as a last rule, that new elements (using the free atoms from the pool) would be inserted, when the number of random elements dropped under a Critical Minimum Value (CMV). For each empty position under the CMV there was a fixed probability (p1) that at each time step the position would be filled by a new random element. Also each element would have a fixed probability (p2) to be destroyed. This didn't modify the behaviour of organisations (where many copies of each element is in general present), but would prevent the system from being stopped by having too many huge unusable elements.

Results

We made 180 runs with parameters: starting number of elements=300, CMV 300, p1=0.1, p2=0.0001, number of atoms=2000 for each type, max length accepted 100 atoms, max depth accepted 20 levels of parenthesis.

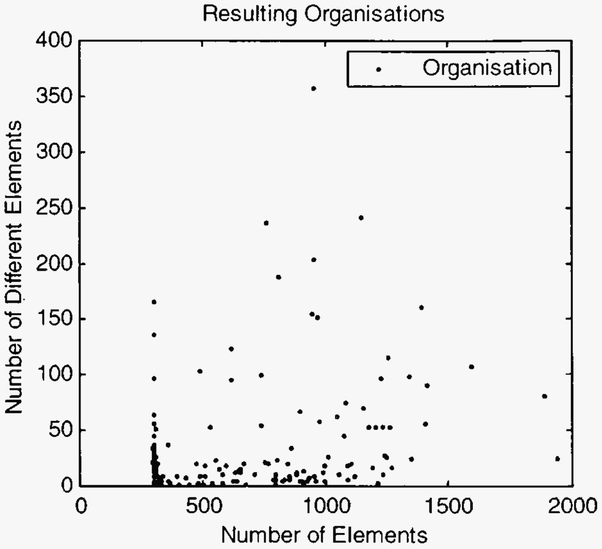

Figure 2. Resulting Organisations. Each resulting Organisation is drawn as a point. Organisations either have around 300 Elements (Class A, Organisations that balance the input of new elements with the destruction of old ones) or are scattered around (Class B, Organisations that expand until all the atoms are used)

Running the system we immediately noticed some results.

1. Even though the number of element is not fixed from the beginning, after a transient phase it tends to stabilise itself around an average value with little or no oscillation around that value.
2. Some rare times the value does indeed generate bigger fluctuation around the chosen value. Those experiments are always very rare.
3. Each time the experiment is run, with a different random seed, we reach a different organisation. We can thus notice that the space of all the possible organisations

is very rich. This makes it possible (as a possible future work) to search for an organisation with certain characteristics.

4. Some of the Organisations hold a finite number of elements, some an infinite number (even if, of course, at any one moment only a finite number can be present in the experiment). Interestingly sometimes an infinite Organisation is generated that holds as sub-Organisations both a finite and an infinite one. The two Organisations are kept in balance by the conservation laws. In fact the Organisations tend to be based on different atoms, and would not compete one with the other, as they do in the original AlChemy program.

5. Two different kinds of organisations tend to be generated

   a. Organisations that get smaller until new random elements are inserted. When this happens they 'use' those new elements to expand and the cycle begins again.

   b. Organisations that gets bigger and bigger until they end the available atoms. Those organisations, under our starting conditions, tend to have between 350 and 1000 elements.

We present an example of organisation for each type.

Organisation of Type A

Our first example is an organisation generated by a single element.

$C(C(K(CKK))(WC))(C(K(CKK))(WC))=\alpha$.

This element applied to any other generates:

$\alpha * a \rightarrow \alpha(a) \rightarrow \alpha, K, a$.

α applied to 'a' releases a copy of K and a copy of 'a'. K element applied to any element 'a' generates K(a).:

$K * a \rightarrow K(a)$

thus $K(\alpha)$, $K(K(\alpha))$, …, $K^n(\alpha)$. are generated, as well as KK, K(KK), …,$K^n(KK)$.

This organisation contains an infinite number of elements. Since $K^n(b)$ applied to any element 'a' generates:

$K^n(b) * a \rightarrow K^n(b)(a) \rightarrow K^{n-1}(b), a$ (for n>1).

$K(b) * a \rightarrow K(b)(a) \rightarrow b, a$.

thus no new elements are generated and $O\equiv\{\alpha, K, KK, K^n(\alpha), K^n(KK)\}$ is an organisation.

O tend to keep its number of elements fixed. Only α can increase, through a reaction, the number of elements present in the reactor. Yet every new element, K, generates a complementary reaction (K *a) that decreases the number of elements present. O tends to remain of a fixed size until some elements are randomly destroyed. When the number of elements decreases too much new elements are inserted and the organisation metabolises them increasing its total number of elements.

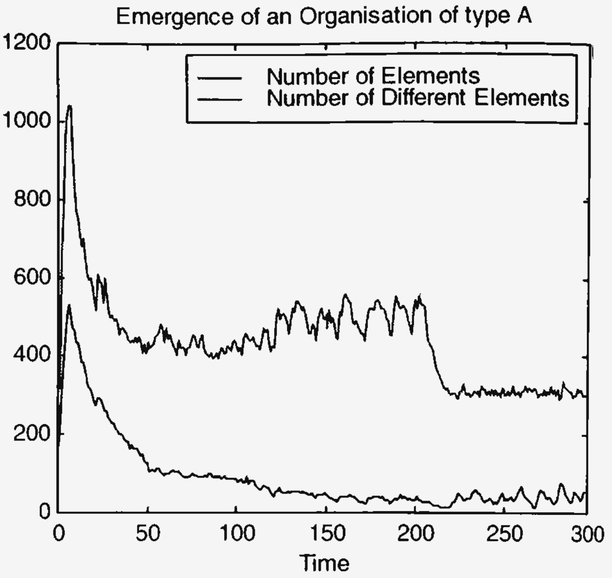

Figure 3. Organisation of type A. After a transition phase of about 210 generations the organisation emerges. The number of elements is always between 296 and 330. The number of different elements present has wider oscillation, since the organisation uses external elements and has itself an infinite number of elements.

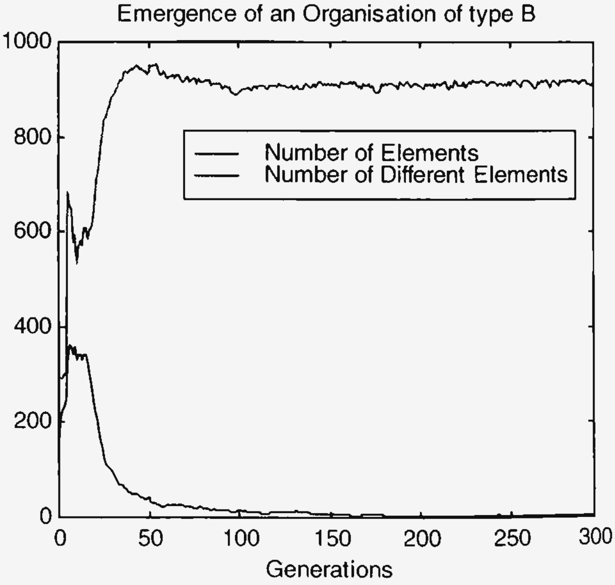

Figure 4. Organisation of Type B. A much shorter transition phase is necessary. The end Organisation has about 900 elements of between 4 and 6 different types.

Organisation of Type B

The second organisation we present is generated by 4 different elements:

$C(K(WC))(K(WC))=\alpha$;

$S(SS(S(W(S(SWB)))))(B(K(S(SS(S(W(S(SWB))))))))=\beta$;

$S(K(SSK))(K(K(SSK)))=\gamma;$
$B(WW)(W(B(WK)W))=\delta$

The relative reactions are:

$\alpha * a= \alpha, a.$

$\gamma * a= \gamma, a, a.$

$\delta * a= aaa(aaa)(aaa), Wa, Wa, Wa.$

$\delta * \alpha = 9\ \alpha, 3\ W(\alpha)$

$\delta * \gamma = 17\ \gamma, 3\ W(\gamma)$

β * a= Out of memory.

The dynamic of the organisation is driven by the γ element that pushes the whole system into having more and more elements. The δ element tend to have no effect since it requires an enormous effort in terms of free atoms. While the α has no effect whatsoever.

Organisations as Abstract Metabolisms

In this section we will show how those organisations differ from the organisations previously built by being a metabolism with respect to the insertion of new elements.

A general definition of metabolism, fit for our work can be found in [Bagley and Farmer, 1992, p. 127]:

> "A metabolism takes in material from its environment and reassembles it in order to propagate the form of the host organism.... Another function of a metabolism is to extract free energy from the environment and make it available for the functions of the organism...".

This definition is totally abstract and can also be applied to non physical systems. There are two different functions that are accomplished from a metabolism: an energetic function and a physical one.

An Organisation can act as a metabolism in two different ways. Directly if are the interactions between its elements and the environment that produce the transformation in the external elements. Indirectly if it generates the conditions under which the external elements cannot survive, without directly interacting with the external elements.

Organisations of the first type (type A) tend to contract until new elements are inserted. As new elements are inserted they interact with those new elements using them to produce more elements of the former organisation.

For example an element of an organisation could be:

a such that a * b = a, b.

Those elements regenerate themselves all the time.

If they are invaded by an element S, chances are that S is applied to 'a' for three consecutive times. When this happen Sa, Saa, and Saaa are subsequently produced. Saaa is then reduced to aa(aa)→ ... → a, a, a, a. So three copies interact with S but four are generated.

Organisations of the second type tend to have a rather different reaction to external elements. They don't need external elements to make copies of themselves. Yet, since they tend to expand until they use up all the atoms of a particular kind, an organisation is then 'interested' in destroying an external atom to free its elements. This cannot be done directly, yet it is possible to prove that the organisation effectively induces an environment where those external elements are easily destroyed. This happens as the system reaches a state where all the free atoms of many different kinds are used up and many reactions are inhibited.

We believe that this work provide a good base to continue the exploration of artificial chemistries and artificial metabolism. We see as a next important step the study of system where sub-elements can both be released and be destroyed. We also see as an important future step the study of a system were such a metabolism is inserted in a metric space to provide the possibility for boundaries to evolve and as a last aim for evolution to start.

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