A Schematic Representation of Autopoiesis Using a New Kind of Discrete Spatial Automaton

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Abstract

Autopoiesis, or one's ability to renew oneself, is a meaningful concept for the study of life. Modeling of autopoiesis would enhance its study in relation with other biological properties such as feeding, breeding, being ill, healing, dying, etc. Here, we report the design of a "morphautomaton", a new kind of discrete spatial automaton designed to represent within the same space an unlimited number of various complex, mobile, interacting forms. This automaton uses a simple, single effective formalism to identify and localise those forms and describe their movements, transports, and transformations. We make use here of these forms as symbols to schematically represent an autopoietic individual within its environment. This representation can be made consistent with the laws of thermodynamics and conservation. Using this representation, the study of the physiological properties of this individual could be undertaken. Using this platform, the modeling of other biological properties in relation with autopoiesis should also be possible. These models should allow future comparisons, definition, and classification of these biological properties. Representations using our formalism and similar parameters can be combined. Because it focuses on the physiological analysis of whole individuals, this schematic representation method can be used only when structural analysis has been completed.

Introduction

The word "autopoiesis" was created by Francisco Varela and Humberto Maturana in 1971 to designate the ability of something to "create oneself" (Maturana and Varela, 1973). The ability of an individual to renew itself while maintaining its shape and organization is remarkable. Indeed, no inanimate objects have such a property, yet living objects often heal and return naturally to their original forms. How do they accomplish this? Where does the difference arise? Could we acquire control of it?

At one time, the idea that living matter differed from inanimate matter seemed obvious. Today, we have identified most parts that comprise living beings, and there is no doubt that these parts are made of the same material as inanimate objects (Goodsell, 2009). While anatomic knowledge is not sufficient to understand the differences between living and non-living, we can hypothesize that the set of physiological processes performed by these parts give the whole its properties (Schoenheimer, 1942; Schrödinger, 1944; Kleiber, 1947). Thus, here we search within this paradigm for a mechanical explanation of autopoiesis.

We remain far from understanding what roles each piece plays in creating the whole; neither can we perfectly analyze or reconstruct the simplest organisms. We know not what assumptions are necessary to guide such a reconstruction; what we need is not simply a technique but a method or theory providing the guidelines to direct the analysis and representation of our observations. Critical to this theory are the criteria that will enable a strict definition of the properties of the living: feeding, breeding, growing, being ill, healing, dying, evolving, behaving, etc. By removing or modifying some structures and observing changes in the whole, we can distinguish which structures are necessary and sufficient for the existence of these properties. By comparing several living entities, we can acquire an indication of their generality (applying to cell, organism, society) and of their relationships (dependence, anteriority, causality, equivalence, etc.). Indeed, we may go further and study the forms of these entities, to determine whether they can be classified and systematically enumerated, if they derive from each other, and how to most simply represent them.

However, complex systems have unpredictable emergent properties. To gain control over any property of such a system, one must forego, at least initially, studying what might emerge from it, as a system is either controlled or has emergent properties (Liu et al., 2011). Our goal here is to avoid the apparition of any emergent property, while creating an autopoietic representation that may lead to its control. Meanwhile, we wish to retain the ability to later study autopoiesis' associations with division and differentiation to produce systems endowed with the ability to evolve.

To define and control a property, two approaches are possible: synthetic, or "bottom-up" (used here), identifies the property then searches for a mechanism to reproduce it. This kind of approach has been infrequently explored because of several inherent weaknesses, such as its generality, the arbitrary choice of entities to represent the property, or the lack of analysis of physical constraints (Morange, 2005; Atlan, 2011). The majority of modeling works are analytical, "top-down" approaches: beginning with available experimental data, one selects useful parts and tries to reassemble them to reproduce a property of interest. The two approaches, however, are complementary and are needed to validate one another; when these approaches validate the same mechanism, the property becomes correctly established; its full control (i.e., the ability to calculate, reproduce, modulate,

or combine it with others in any particular physical, chemical, or even robotic context) can be envisioned.

To demonstrate autopoiesis, Varela and Maturana worked in a non-experimental, theoretical framework and built a dynamic representation *in silico* by programming a discrete spatial automaton to represent the minimal organization of a biological cell (McMullin and Varela, 1997). They intended to represent a membrane constantly and permanently destroyed and rebuilt through the actions of particles they called substrates, catalysts, and links. The destruction of this membrane was done at random and was offset by new syntheses. This first model was a great launching point for later works (Zeleny, 1977; McMullin and Gross, 2001; Ikegami and Suzuki, 2008; Bersini, 2010). However, Varela's model contains some weaknesses: The definition of autopoiesis (Maturana and Varela, 1980) is not clear and simple and is not fully applied in his later models, as destruction of the membrane, renewal of the catalyst, transmembrane transports, and, therefore, control of the individual's size are not performed by the individual itself. Varela did not used a well-formalized representation platform, but he worked in a time where it was difficult to separate the representation method from the represented object. Most of these works are restricted to chemical materials, and do not consider other potential implementations (e.g., robotic).

To move the study of autopoiesis forward, we propose to reformulate the definition of the property as follows: first, because autopoiesis is dynamic, we may hypothesize that it is a property of a whole that cannot be a unique, static, inanimate block, but that consists necessarily of distinct, interacting parts. To interact, these parts must be mobile. If they are mobile and yet they continue to be part of the whole, then they are joined. What connects them is also an aspect of the whole. The interactions that they continually have renew them. This means each of them can be destroyed by one and re-built by another. Importantly, if all the necessary conditions are met, then the whole can keep its form longer than the parts composing it. Because of continuous movement of its parts and exchanges with its environment, this form and its composition can never be exactly the same; rather, they fluctuate around a mean shape. Indeed, the whole loses this property if it is split or isolated from its surrounding environment, with which it exchanges energy and matter to achieve its renewal. Additionally, if there is a "natural" process of degradation of some of its parts, the whole's renewal speed should remain sufficient to oppose the effect of this process. Importantly, "autopoiesis" should also satisfy McMullin's criterion, which states that two individuals, in direct contact with each other, can reliably maintain their separate identities (McMullin, 2004).

The methods applied to the study of autopoiesis evolved in parallel of the concept itself. Early studies conducted by Tibor Ganti, Robert Rosen, Victor Kunin, Manfred Eigen, and others identified related concepts, but were generally performed using differential equations (Popa, 2004). However, differential equations, developed to describe quantitatively determined and continuous phenomena, assume ideally mixed reactants and are poorly adapted to molecular biology. Instead, discrete spatial automata can associate logical operations to possibly non-linear and probabilistic numerical calculations and can apply them to irregular and discontinuous distributions of matter (Rao et al., 2002; Broderick et al., 2005; Wishart et al., 2005; Morris et al., 2010). Here we designed a particular new class of discrete spatial automata that can represent a set of complex, mobile, interacting forms whose evolution may schematically represent a phenomenon of interest; we use it to represent an autopoietic individual.

Methods: Description of the morphautomaton

Workspace, states, and transition rules

The *workspace* in this automaton consists of a set of regularly arranged, adjacent *tiles*[1]. Each tile has a *state*, which is described as either empty or occupied. A tile is occupied, and thus called a *particle*, when it has at least one *link*. Conversely, an empty tile has no link. By definition, two particles cannot occupy a single tile.

A link represents a directional association between particles. It belongs to one particle and indicates the position of a neighboring one[2]. The state description of the workspace is complete when each tile is known to be either occupied or empty, and, for each occupied tile, the orientation of each link is known. All information required to describe a workspace state can be acquired using only two distinct kinds of *conditions*: one refers to the number of links of a particle (isotropic conditions) and the other the orientation of a particle's links (anisotropic conditions). An isotropic condition contains coordinates for a tile and a number, n. The number of links in the indicated tile is evaluated for equivalence to n. Further, this condition helps determine whether the tile is empty: empty space is defined by a number of links equal to zero. A positive anisotropic condition contains coordinates for a tile and an indicator of orientation, p. This condition assesses whether a link from the selected particle is oriented to p. Because of the possibility of superposition (i.e., a particle may have multiple links in any given orientation), a built-in mechanism considers whether there are superposed links. A negative anisotropic condition contains the tile coordinates and p, as above, and requires that no link is oriented toward p at the specified location.

Each *rule* comprises a set of conditions that, when met, initiates *operations* producing a transition from one state to another (see Figure 1).

[1] We avoid the word "cell" because of potential ambiguity with the biological meaning.

[2] Typically, any tile indicated by a link is considered occupied; however, this restriction can be overcome: individual disconnected particles moving at random and containing an available link may then randomly attach to any aggregate. The connection will result in a change in shape and, potentially, identity of the aggregate. Thus, these disconnected particles could be used for representation of damage occurring to various materials, in some cases acting as a sort of "mutagen."

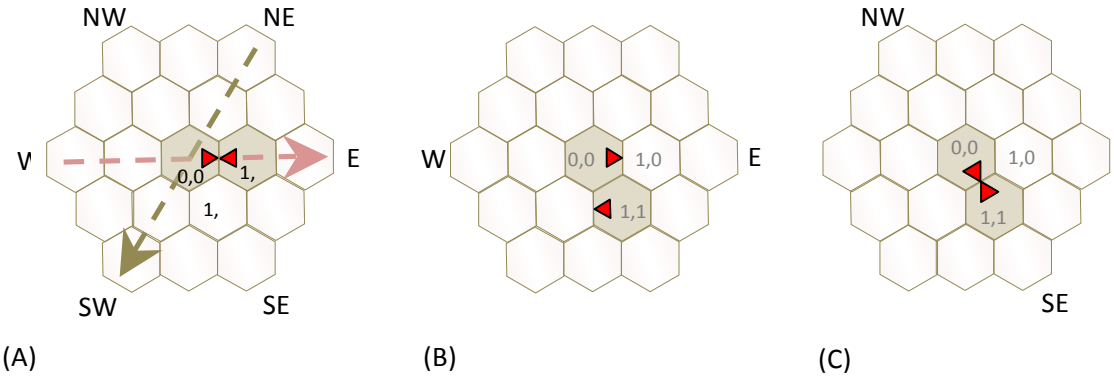

Figure 1. Example of a transition rule that describes simultaneous state change of two particles. A) The workspace above shows the neighborhood of the central cell (0,0). The space contains two dimensions, hexagonal tiling, and two non-orthogonal axes traveling west to east (x) and northeast to southwest (y). The central cell, a particle, contains a link (symbolized by the small triangle) facing east. East of (0,0) is another particle in (1,0), also containing a single link, this time oriented toward the west. The tile below, in (1,1), is empty. The states of other tiles are indifferent; these do not prevent or facilitate the application of a rule whose conditions permit identification of this situation. The following five conditions exist, whose order of evaluation is irrelevant: (a) number of links (0,0) = 1; (b) number of links (1,0) = 1; (c) number of links (1,1) = 0; (d) link (0,0) = East; (e) link (1, 0) = West. In our example, all conditions are met, so the rule identifies the situation and thus can be applied. Several operations are then performed in a specific order: The tiles located in (1,0) and (1,1) are swapped using the operation [move]. The result of this translation is shown in B. Two [turn] operations then change the orientation of links of particles (0,0) and (1,1), which produces the result shown in C.

A rule must contain at least one condition and one operation. Possible operations are either *link rotations* or *particle translations.* Link rotations re-orient one link of a tile from one direction to another. Particle translations exchange the contents of two tiles, adjacent or not. If one of the two tiles is empty and the other is occupied, a simple particle translation occurs. However, if both tiles are occupied, a double translation or permutation occurs. The numbers of links and particles are preserved. The number of links in a particle does not change.

The conditions and operations of a rule do not apply to or affect the entire workspace, but only a particle and its local neighborhood comprising the tiles of interest. Rules must refer to the coordinates of the neighborhood to be evaluated and enacted. A selected particle represents the center of the neighborhood, and one of its randomly chosen links provides a reference orientation for this space. These selections define and orient the neighborhood. The choice of the central particle is made at random, and the automaton guarantees that all particles can be selected and none excluded. Each cycle of the automaton evaluates the same rule set in a different neighborhood. The cycle begins upon selection of a particle and one of its links, delimiting and orienting the neighborhood. Rules are then evaluated individually and sequentially[3]. If any one condition is not satisfied, that rule is rejected and the following one is evaluated. If all conditions attached to a rule are met, then all operations of this rule are performed and the cycle ends. If all rules have been evaluated and none applies, then no state change occurs during this cycle. Once a cycle is completed a new cycle begins. During the evaluation of rules, each tile in the neighborhood can be evaluated for one or more conditions, and, when a rule has been satisfied, can be involved in one or more transitions. Importantly, tiles located outside the neighborhood remain unaffected by this process.

In summary, the workspace contains particles of one-unit size that can be linked and all operations on these particles and their links are performed locally[4].

Aggregates

Aggregates are groups of *particles* associated by *connections* (Figure 2). A particle is a full tile defined as having at least one link. Connections between particles are realized by the links between them. The simplest connection is achieved by one link between two particles; however, the number of links constituting a connection is unlimited. Links can also be superimposed (i.e., there may be multiple links in either direction between two adjacent particles). Additionally, the

[3] An important feature of this automaton is the addition of a random condition to decide between rules with identical local conditions. Sequential evaluation would normally cause the first of these rules to be applied and those following to be always ignored. The addition of a non-local random condition enables all concerned rules to be applied with equal probability. While rarely used, the random condition is essential for reproducing the randomness of some movements.

[4] Multiple threads can work in parallel and asynchronously on the same workspace. This feature requires that each neighborhood is treated separately, thus no interference exists between them. Whether a single thread operates or multiple threads are simultaneously active, the system's history is constructed in random order. Thus, two successive experiments do not follow the same trajectory. Reproducible results therefore testify to the independence of the model in relation to the mechanics of the automaton.

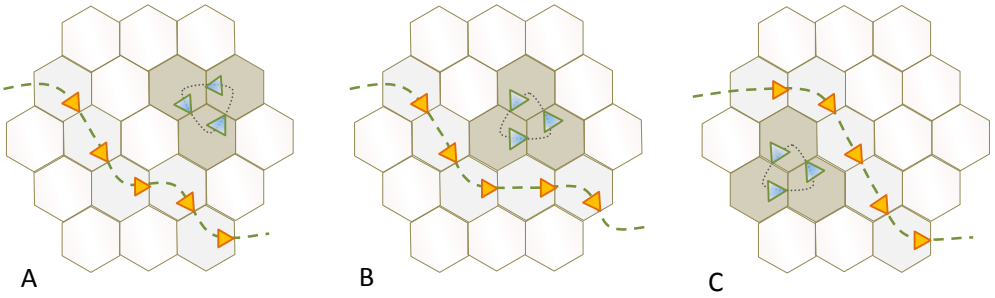

Figure 2. Two aggregates in motion. One aggregate is a grouping of three particles (a "trimer") and the other is a "chain" that is not entirely visible in the neighborhood (dashed line added for visibility); the chain delimits two compartments. As the chain's connections are asymmetrical, their orientation allows local identification of each of these compartments. Different movements apply to these two aggregates. The trimer, fully visible in the neighborhood, can be moved around by the action of a single rule; the long chain can only be distorted by any single rule. However, many successive distortions, performed at different locations, give the chain a full mobility in all directions. The transition from (A) to (B) does not alter the composition of the compartments, but the transition from (B) to (C), a transport, changes this composition because the trimer passes from one compartment into the other.

connection is called "reciprocal" when each particle in a connection has at least one link pointing to its connectedneighbor. It is called "symmetrical" if the two particles run the same number of links to one another. Symmetrical connections are necessarily reciprocal.

The smallest aggregate is a dimer, composed of two particles. Aggregate size is not limited by the tiling used or the automaton mechanism, but may be limited by the dimensionality and the extent of the available space. Further, aggregates can be of any regular or irregular shape: monomer, polymer, chain, ring, bifurcation, helix, knot, cavity, grain, rotor, stator, etc. A good choice of forms and rules can produce representations of many material properties: hardness, flexibility, elasticity, rigidity, fluidity, permeability, etc. These lists are not exhaustive. An aggregate's size or the number and extent of its links are infinite. Further, basic forms can be disjointed or contiguous and combined in various ways. These features mean that this formalism provides open-ended possibilities of creating and combining elementary forms.

The operations performed on aggregates are associations of the basic operations performed by the rules. They can produce *movements* (displacement or distortion), *transformations,* or *transports* (movements from one compartment to another).

Movements can be translations, rotations, or combinations of both, and can be performed on the whole or a specifically identifiable part. They occur easily when the aggregate size is smaller than the neighborhood. When the aggregate size exceeds that of the neighborhood, however, it cannot be moved in its entirety by executing a single rule. However, such aggregates may be distorted. Carried out in multiple locations and repeated, distortions give large aggregates their mobility (Figure 2). The size of the neighborhood can be chosen according to the mechanical properties of the aggregates whose movements are to be represented.

Each aggregate has an identity comprised of morphological local traits resulting from the unique pattern of its connections. The number of identifying properties is unrestricted and each identity can be evaluated by rule conditions. For example, one chain may have a linear structure and asymmetric connections of just one link, while another chain may have symmetric connections, and another, asymmetric connections but with two or three links. As movements translate particles and reorient their links but never break connections, they always preserve the unique identity of each aggregate. By contrast, transformations always break at least one connection and reconnect some particles in another way, modifying aggregate identities. Transports preserve aggregate identities but move them from one compartment to another.

In summary, 1) aggregates are groups of connected particles of various forms whose size is not limited; 2) each one has a specific connections pattern that enables its identification; 3) aggregates are localised (in a compartment or as a limit of a compartment); 4) they can be moved, transported, or transformed; 5) transformations and transports, but not movements, require aggregate identification; 6) movements conserve identity and localisation; 7) transformations break and re-establish links, modifying aggregate identity; and 8) transports respect their identity but modify their localisation.

Summary

The new type of discrete spatial automaton, which we call a "morph-automaton," (from ancient Greek morphè: form) is relevant because it allows the representation by means of a simple, single formalism of many forms moving and interacting in the same space. Indeed, while this formalism does not limit the diversity of these forms or the variety of operations that can be performed on them, the use of a unique rule structure enables automatic handling of the rules (editing, classification, presentation, optimization).

A number of parameters can be adjusted without changing the principles that underlie morphautomata construction and design. These parameters primarily concern the general structure of the workspace: They define its number of dimensions and extent, the type of tiling used, the existence of edges and the representation of general strength fields (e.g., electromagnetic, gravitational). Some parameters concern the shape and size of the neighborhood. Others parameters include the number of links per particle and the scope of these

links—and, thus, the variety of possible connections. Adjustment of these parameters depends on the phenomena that the experimenter wishes to represent. Importantly, models with identical parameters can be combined. Such operations may be formalized.

The variety of aggregates is unlimited, and, even constrained by the necessity of using discrete forms and limited neighborhood size, proper selection of these forms and of the operations that apply to them can produce schematic representations of a variety of complex heterogeneous materials. The experimenter chooses some of these forms and details when editing the initial state. He selects and describes their movements and interactions when writing rules. These choices depend solely on his assumption and the result he wants to achieve: it is his intention that gives logical consistency and value to the writing of the whole. Further, the experimenter is responsible for verifying the logical coherence of elementary conditions and operations composing each rule and their coherency with other rules and the state.

If the rules associated with each aggregate allow movement in all directions, and the automaton uses a random selection of particles, then the motion of each aggregate, isolated or in relation with others, is permanent and random. Transformations, moreover, have some similarities with chemical reactions. Additionally, conservation and thermodynamic laws can be represented. Thus, this platform makes possible a schematic representation of certain physical and chemical properties of macromolecules in solution.

Results: Autopoiesis

Anatomy of the autopoietic individual

Our automaton has been designed with the intent of representing an autopoietic individual moving at random within its environment. It makes use of five varieties of aggregates. First, we describe the initial state of our workspace for the positions of each instance of the five different types of aggregates used to build the autopoietic individual. This detailed and comprehensive description of the initial state is required by the automaton machinery for the representation to evolve, and it must be edited manually. Required characteristics are those that denote each aggregate's identity, shape, and localisation.

The individual is composed of a membrane enclosing an internal compartment (Figure 3). This membrane is a circular chain made of one-link particles each pointing at the next. Because of a unique sense of rotation, its inner and outer faces are locally identifiable, delimiting two compartments: internal

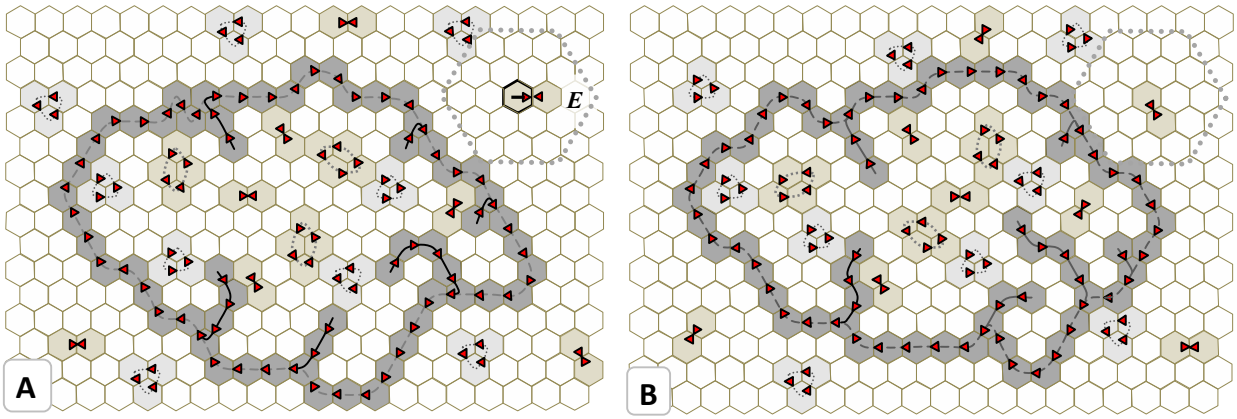

Figure 3. (A) and (B) represent the same autopoietic individual and its environment in two successive snapshots. Each panel represents the same part of the workspace; the two-dimensional space is covered by a hexagonal matrix whose tiles are either empty or occupied. Full tiles, called particles, have a link, symbolized by a small triangle, which refers to another particle; they are thus associated to form aggregates. One of these aggregates is a circular chain, called a membrane, which delimits two compartments: internal and external. In these compartments are several small isolated aggregates consisting of two, three, or four particles. Aggregates of four particles can be found in the interior compartment only. Several small chains ranging in length from one to four particles are attached at the internal face of the membrane.

The large hexagons, delimited by dots and located at the top right of each image, indicate the size of the neighborhood of a particle where evaluation of the rules occurs. (This part of the figure is superimposed with Figure 1A.) The particle at the center of this neighborhood was chosen randomly, and its link assigns the orientation during rules evaluation (black arrow, letter E see fig 1A). This particle is part of an aggregate consisting of two particles, called a dimer. (B) shows the new position of this aggregate after application of the rule.

Comparison of (A) and (B) shows the effect of many random movements of this type. The positions of most small aggregates have changed slightly. The membrane and small chains have been deformed and displaced, but their lengths are identical. The identity of each aggregate has been preserved, as no transformations occurred. The composition of each compartment was also preserved, as no transport occurred. Even if some traits of this abstract representation may evoke a living cell (which was the initial intention), it is definitely not one. This individual may only be an autopoietic representation: it has some very particular features that no real cell will ever have, and is not intended to represent other properties of real cells.

Table 1: Summary of operations performed by the automaton.

		Action	Conditions
Transformation	1	membrane > chain	Membrane can wrinkle, its continuity can be ensured, a chain at least one-unit length is already there
Transformation	2	chain > tetramer	Chain length is almost four units long
Transformation	3	tetramer > dimers	Other tetramers are in proximity
Transport	1	trimers entry	Enough space available, membrane flexible, no chains attached to the membrane locally
Transport	2	dimers exit	Enough space available, membrane flexible, no chains attached to the membrane locally
Transformation	4	trimer > membrane (one unit) + dimer	Only in the presence of a tetramer
Transformation	5	Trimer > new chain (one unit) + dimer	Only in the presence of another trimer
Transformation	6	two chains one unit each > dimer	Other one-unit chains in proximity

and external. Dimers, trimers, and tetramers are small aggregates, disconnected from others and made, respectively, of 2, 3, or 4 particles. As a particular characteristic of this model, tetramers are found only inside the internalcompartment; dimers and trimers are both inside and out. On the inner side of the membrane may be attached small chains comprising 1, 2, 3, 4 or more one-link particles.

In summary, five varieties of aggregates are used in several instances in this representation: membrane, dimer, trimer, tetramer, and chain. Their relative localization and shapes are essential information.

Physiology of the autopoietic individual

We must now focus only on the transport and transformation of aggregates to understand how their concentration variations and interactions drive the dynamic self-maintenance of the autopoietic individual. Our example makes use of six transformations and two transports (Table 1). The small chains, on the inner side of the membrane, walk at random while remaining attached to the membrane. Because the membrane may wrinkle randomly, to the point where it is possible to remove one of its units while restoring its continuity, these chains gradually grow by taking a membrane unit whenever the membrane is folding next to them (transformation 1). Thus, this chain, initially one particle in length, elongates while remaining attached to the membrane. Once a sufficient size, the chain is transformed into a tetramer that is released into the internal environment (transformation 2). The whole chain eventually disappears in this operation. When several tetramers are side by side, one of them is destroyed and transformed into two dimers (transformation 3). The membrane allows trimers to enter and dimers to exit (transports 1 and 2). In the external environment, a built-in mechanism transforms dimers into trimers. Further, when a trimer and a tetramer are simultaneously present near the membrane, the trimer is converted into a dimer and the membrane takes up the remaining particle; the tetramer is unchanged (transformation 4). When two trimers are simultaneously present near the internal side of the membrane, one of them is converted into a dimer, with the remaining particle producing a small chain (one-particle length) attached to the inner face of the membrane. The other trimer remains unchanged (transformation 5). When multiple small chain of one particle length are arranged side by side, two of them are moved aside and transformed into a dimer (transformation 6).

Summary and further analysis

The set of transports, transformations, and movements we have described allows each part of this "cell" (membrane, chains, dimers, trimers, tetramers) to be mobile, linked to others, and constantly destroyed and renewed by others. The whole moves randomly and keeps its size, shape, composition, despite changes in the external environment[5]. The observation that small aggregates move farther than large ones is an indication that this model approximates well Brownian motion. Two individuals simultaneously evolving in the same space maintain their separate identities. Consistent with our definition, this constitutes an autopoietic individual[6].

Why does this individual retain its size, shape, and composition? To answer this question, we must describe the scheme of regulations guiding our representation, which is, in fact, not specific to the representation above. Indeed, another manifestation hardware or virtual setup (e.g., a cubic matrix using other forms) could be regulated in exactly the same way.

We established several controls for our model. First, synthesis of the membrane is regulated by the concentration of tetramers: the growth of the membrane depends on the presence of a tetramer, but tetramers are produced by the destruction of the membrane. Thus, membrane synthesis cannot occur without previous membrane destruction. The yield from the destruction of tetramers plays a key role in the

[5] As the individual state remains constant, we hypothesize that its global entropy (as a state function) remains unchanged, while that of the environment increases. The representation used here enables their precise calculation, but this has not yet been completed.

[6] A demonstration version and additional documents are available at https://sites.google.com/site/morphautomaton/.

regulation of the size of the individual. If the efficiency of this reaction is increased slightly, the number of tetramers decreases. As the membrane synthesis reactions depend on the presence of a tetramer, they become more rare than the reactions of destruction. Accordingly, the size of the membrane decreases. Another effect appears then: as the destruction of the membrane is dependent on the quantity of available membrane, i.e., of its size, this reaction becomes less frequent. A new equilibrium is therefore established when the membrane has reached the size for which these two processes (construction and destruction) become balanced.

Conversely, if we now decrease the efficiency of the reaction of destruction of tetramers, their concentration increases. Therefore, the membrane synthesis reactions that they facilitate become more frequent than the destruction reactions, and the membrane size increases. However, as this size is important, destruction reactions become more frequent. There again, a new equilibrium is established when the membrane has reached the size for which these two processes become balanced.

Additionally, the four processes of synthesis, catabolism, inputs, and outputs are in competition with one another, since the membrane has a finite extent. Several parameters (e.g., the shape of the membrane, the available free space) may favor one process over the others. Finally, many other regulations, unexpected at first sight and unintentionally introduced, directly or indirectly modulate each transformation.

The thermodynamic approach of Virgo and Harvey (2008) proposes a relationship between the amount of energy that can be extracted from the environment and the overall rate at which that energy is used. We searched within our model for such a relationship as a negative correlation between the "activity" of the cell (quantity of metabolic rules executed in a given amount of time) and the potential energy (trimers in the environment) available at the same time, but we did not observe this relationship. However, this first trial must be refined.

This analysis is just beginning. Note, as in physiology, the existence of two kind of regulations whose evolution is either exponential or periodic; the latter probably limits the area where the former can grow.

Discussion

A schematic representation of autopoiesis was created using a new type of discrete spatial automaton, which is based on the principle of encoding functions through an extensive representation of abstract forms used here as symbols. The identities and localizations of these forms give a complete, static description of the system; the operations performed on them give a dynamic description of the system. While our intent was to represent autopoiesis, this platform is versatile and convenient for representing other biological or non-biological phenomena, especially those observed in any complex population ranging from solutions of macromolecules to swarms or societies.

Despite an as-yet incomplete analysis of this model, it conforms to our definition of an autopoietic individual: each of its parts is distinct, mobile, linked to the whole, and continuously renewed by one another. In contrast to previous models, the destruction of the membrane, renewal of the catalyst, transmembrane transports, and, therefore, the individual's size are controlled by the individual itself. Additionally, in our model the continuity of the membrane is ensured; the membrane shape, length, and the internal density are effectors and subject to regulations. Indeed, this individual is "robust" since it can adapt to various environmental conditions. In accordance with McMullin's criterion (2004), each individual remains distinct from another one. Thus, we have defined, demonstrated, and described a virtual autopoietic individual. This model represents an important advance in the field, as none of those properties existed in Varela's initial model, where membrane destruction occurred spontaneously and the other parameters were not considered. Further, the original idea of boundary has been replaced by the less-restrictive idea of link. Finally, the concepts discussed here are not restricted solely to biochemistry but could apply to robotics or any other implementation. Presently, this work provides a reference point for the representation of other individuals, their comparisons, their comprehensive "physiological" analysis, the research of a rigorous definition and formalization of autopoiesis, and the potential to undertake the study of the relationship of autopoeisis to other biological properties. This work was developed with a bottom-up approach. The utility of our platform in representing essential interactions of real systems must now be evaluated via a top-down approach.

The purpose of this work was to generate a system, devoid of any emergent property, which could be fully analyzed and controlled. This aim is significant, as clinicians or engineers cannot use devices that may produce some emergent properties beyond their control. Even with an incomplete analysis, we have, indeed, achieved some control in our model. Approaches that aim to produce, starting from scratch, real biological artificial systems potentially able to generate new emergent properties (Rasmussen et al., 2003) or to observe the apparition of emergent structures in virtual systems [i.e., Conway's Game of Life (Beer, 2011) or Swarm Chemistry (Sayama, 2009)] have a different goal: Their aim is to reproduce properties of interest or to explore or generate new ones, but not, at first, to fully explain or control them. Therefore, an analytic phase is necessary before any application of these works can be envisioned.

To consider more fully how this work may be developed and its usefulness as a tool for theoretical analysis, we must place it in context. At the present time, only partial representations of some biological properties are attainable. A complete representation of any living body—even the smallest—with enough definition that the movements of its molecules reproduces its biological properties is out of reach as molecular dynamic simulations require months of computing time to calculate the movements of a small protein during 1 millisecond (Broderick et al., 2005; Shaw et al., 2010). As a consequence, any representations of known biological structures faces the granularity problem: one must decide what real object each bit or tile will represent, creating a potentially endless hesitation between atoms or macro-

structures. Another problem, once this choice has been made, is the lack of compatibility between the representations of several different properties resulting from different analyses, which makes their re-combination impossible to study later (Hucka et al., 2003). The abstract representation proposed here is a consequence of these constraints: it aims to minimize the representation of the structures using a set of abstract forms—similar to symbols—to capture the essentials of the real network interactions.

Notably, four distinct languages were successively constructed in this work (three used here, one remains to be attained). The first deals with the basic representation of space (tiles containing links and associated operations) and offers only the possibility of combining them to represent more elaborate forms. The second language deals with this potentially limitless set of complex forms (made of combinations of tiles and links) and the operations performed on them (identification, movement, transformation, transport). The third language deals with the schematic representation of the system. The only information the symbols in this language should carry is their identity and localisation. The operations describe their movements and possible transports and transformations. The fourth should describe, in their simplest forms, the laws common to any similar system (here, all autopoietic individuals sharing the same set of regulations). As there exists the possibility to combine several representations developed within the same parameters, our platform could be convenient to individually represent distinct properties of biological systems as well as combinations of them.

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References.

Atlan, H. (2011). *Le vivant post-genomique ou qu'est-ce que l'auto-organisation ?*, Odile Jacob Sciences.

Beer, R. D. (2011). Autopoiesis and cognition in the game of life. *Artif Life* **10**(3): 309-326.

Bersini, H. (2010). Software replica of minimal living processes. *Orig Life Evol Biosph* **40**(2): 121-130.

Broderick, G., M. Ru'aini, et al. (2005). A life-like virtual cell membrane using discrete automata. *In Silico Biol* **5**(2): 163-178.

Goodsell, D. S. (2009). *The machinery of life*. New York, Copernicus Books.

Hucka M., A. Finney, et al. (2003). The systems biology markup language (SBML): a medium for representation and exchange of biochemical networksmodels. *Bioinformatics* 19(4): 524-31.

Ikegami, T. and K. Suzuki (2008). From a homeostatic to a homeodynamic self. *Biosystems* **91**(2): 388-400.

Kleiber, M. (1947). Body size and metabolic rate. *Physiological Reviews* **27**(4): 511-541.

Liu Y. Y., J. J. Slotine, and A. L. Barabasi (2011). Controllability of complex networks. *Nature* 473: 167-73.

Maturana, H. R. and F. Varela (1973). *Autopoiesis: the organization of living systems*. Dordrecht, Holland, D. Reidel Publishing Company.

Maturana, H. and F. Varela (1980). *Autopoiesis and cognition: the realization of the living*. D. Reidel Publishing Co, Dordecht.

McMullin, B. (2004). Thirty years of computational autopoiesis: a review. *Artif Life* **10**(3): 277-295.

McMullin, B. and D. Gross (2001). *Towards the implementation of evolving autopoietic artificial agents*. 6th European Conference on Artificial Life Prague.

McMullin, B. and F. Varela (1997). *Rediscovering computational autopoiesis*. 4th European Conference on Artificial Life, Brighton, UK, MIT press.

Morange, M. (2005). *La vie expliquee? 50 ans apres le double helice*, Odile Jacob Sciences.

Morris, M. K., J. Saez-Rodriguez, et al. (2010). Logic-based models for the analysis of cell signaling networks. *Biochemistry* **49**(15): 3216-3224.

Popa, R. (2004). *Between necessity and probability: searching for the definition of life*. New York, Springer-Verlag.

Rao, C. V., D. M. Wolf, et al. (2002). Control, exploitation and tolerance of intracellular noise. *Nature* **420**(6912): 231-237.

Rasmussen, S., L. Chen, M. Nilsson, and S. Abe (2003). Bridging living and nonliving matter. *Artif Life* 9: 269–316.

Sayama, H. (2009). Swarm chemistry. *Artif Life* **15**:105–114.

Schoenheimer, R. (1942). *The fire of life: the dynamic state of body constituents*. Cambridge, MA, Harvard University Press.

Schrödinger, E. (1944). *What is life? The physical aspect of the living cell*. Cambridge [Eng.], The University press.

Shaw, D. E., P. Maragakis, et al. (2010). Atomic-level characterization of the structural dynamics of proteins. *Science* **330**(6002): 341-346.

Virgo, N. and I. Harvey. (2008). Reaction-diffusion spots as a model for autopoiesis. *Artif Life* 11: 816.

Wishart, D. S., R. Yang, et al. (2005). Dynamic cellular automata: an alternative approach to cellular simulation. *In Silico Biol* **5**(2): 139-161.

Zeleny, M. (1977). Self-organization of living systems: A formal model of autopoiesis. *International Journal of General Systems* **4**: 13-28.