

Autopoiesis Facilitates Self-Reproduction

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Abstract

The first *in silico* models of self-reproduction only focused on the logic of the mechanisms that execute and copy the genome or renew the membrane, but neglected associated physical constraints. This may have resulted from modeling through cellular automata, which are unable to represent the cohesion of objects in movement and interaction. In previous work I presented a new, well structured and powerful tool based on a graph rewriting system embedded in a spatial automaton. This tool employs combinations of a unique symbol and can represent an unlimited variety of moving and interacting objects. As transitions are local and occur at random, each trajectory of the system differs. However, dependent events can always be represented in their natural order.

With this tool, I built a representation of an autopoietic individual. More recently, I hypothesized that this model could also be used to demonstrate self-reproduction because most of the mechanisms required for growth are already available in the autopoietic individual and few additional functions are needed. Here, I report the advancement of the model to demonstrate the ability of the autopoietic individual to self-reproduce. During self-reproduction, autopoiesis remains active and the lifespans of the various components are unchanged.

Pathological morphologies can be observed when some metabolic pathways are disturbed. Using appropriate approximations, some thermodynamic parameters can be evaluated. Additionally, a second autopoietic and self-reproductive individual can be represented within the same environment. Further, the model could be used to describe the space phase domain and invariants characteristics of each of these individuals, whose systematic enumeration and classification can be envisioned. Based on this model, I propose that autopoiesis facilitates self-reproduction.

Introduction

An entity capable of self-renewal is said to be autopoietic (Maturana and Varela, 1973). Commonly, biological entities (e.g., cells, tissues, societies) are observed to be able to generate almost all the components with which they maintain their structure and functions. I hypothesize that this can result from the association of two independent properties: persistence and cohesion.

Persistence is the property of the entities that are able to maintain their composition while constantly renewing themselves. Under this property, each part of the entity is produced by at least one transformation and destroyed by another; these transformations regulate one another¹. Such

¹ It identifies each part of itself at least twice: once to synthesise it and once to destroy it. We might assume two relationships exist, such that, 1) the more complex a component, the more efficient it is, and 2) the more complex a component, the more complex the operations required to build or destroy it. Then, because they are constrained to operate constantly on one another, all components of one persistent object will tend to share similar levels of efficiency and complexity.

entities depend on a permanent input and output of energy and materials. The ingoing components are rich in potential energy, while the outgoing components are poor. External components can be classified as resources, neutrals, or toxins. When exposed to a toxin, the whole may be able to compensate for its effects. If it is not and this results in the defect of a major regulatory pathway, it may not remain persistent. It controls its composition, which fluctuates around a mean, but not its shape and size, which depend on the limits provided by its environment. Its lack of cohesion hampers its transfer in another environment. It can split in two persistent entities if each resulting part keeps the initial composition and is provided with input and output pathways, but it cannot control this process and self-reproduce. Conversely two persistent entities of compatible composition in direct contact with each other can merge. Persistence could have been a property of some instances of the “prebiotic soups” imagined by Oparin and Haldane (see Popa, 2004).

A persistent entity is autopoietic if some of its components, other than the entering and outgoing ones, ensure its cohesion. Compared to a simply persistent entity, an autopoietic individual is endowed with several new properties. First, it controls not only its composition but also, at least partly, its limits, inputs, outputs, shape, and size. It can keep its shape longer than the parts composing it can. Second, in so much as its state remains stable, its entropy remains roughly constant while that of its environment increases (Schrödinger, 1944). Third, the more energy is available in its environment the more it controls its use of this energy (Virgo, 2011). Fourth, it can attain a maximal performance in extraction and use of energy from its environment. Conversely, pathological states exist where its global performance is reduced. Fifth, it can be moved and then maintain itself in any non-toxic environment providing only its inputs. Sixth, it can be associated to self-reproduction. Seventh, it loses these properties if split (giving rise to the etymology of the word “individual”). Correlatively, two similar autopoietic individuals in direct contact with each other will not merge (McMullin, 2004). Cohesion can be obtained by including all the components in a compartment. Another possibility would be to link them all together. The existence of such a kind of individual would demonstrate that the presence of an interior milieu is not a necessary condition for autopoiesis.

Prior work has proposed that self-reproduction is a particular case of self-production (Sharov, 1999). In self-reproduction, an individual is able to extract some energy and matter from its environment and use it to produce a new individual that is similar to itself and that remains distinct. Once the reproductive process has been completed the new individual cannot be distinguished from the other by anything but their history. The model I describe here supports the hypothesis that autopoiesis can facilitate self-reproduction and show the details of this process in the case

of self-reproduction by budding. As most of the mechanisms required for growth are already available in an autopoietic individual, few additional functions are needed for this individual to reproduce itself.

Autopoiesis and self-reproduction were first described in bottom-up models (see Discussion). Recently, a first top-down model based on ordinary differential equations was described (Karr et al., 2012). This model is a proof of concept. It shows that some properties of a real living object can be computed. However, not all these properties can be simultaneously represented in detail. This is due to the impossibility of completely isolating an object as well as to a lack of knowledge and of computing power (Zwirn, 2000). Karr's model represents both some biochemical mechanisms (non-biological *stricto sensu*) and some biological properties. These are mainly the reproduction cycle, autopoiesis, and the energetic balance of *Mycoplasma genitalium*. As it uses successive approximations of several sub-models, this model is redundant. The redundancy contrasts with the minimal expression of the same properties in the bottom-up models. However, one can expect that top-down and bottom-up approaches (analytical and synthetic) will converge towards one another (Hucka et al., 2003). Bottom-up models could help to define properties and to extract only the meaningful information relevant for each of them from top-down models.

Anatomical characteristics of life have been beautifully described by Goodsell (see images following References) (2009). His work seeks an integrated view of all the components of a cell. He erases the mechanistic details that would be required for a comprehensive description of all the functions of those components and extracts only those that enable the approximation of the main anatomical and physiological properties of the living. Thus, his drawings inspire this work.

Methods

The previously described platform associates a graph rewriting system to a spatial automaton and provides a new, well structured and powerful language to represent almost any biological phenomena (Sirmai, 2011)². It can be seen as a new artificial chemistry (Dittrich, 2009) that can apply to any phenomenon characterized by a great variety of forms and interactions. This diversity suggests the use of a combinatorial method. To enable such a possibility, I introduced indexes (previously called "links") in the cells of a spatial automaton. An index belongs to a cell and points to a neighboring one. A set of cells pointing to one another by their indexes is an object. The cells of the state containing indexes then become nodes of a graph and the indexes are the edges. These edges are oriented and weighted, as many indexes can point towards the same neighbor.

Each object is an isolated part of the graph. It is completely described by the location and orientation of the indexes that compose it. This formalism does not limit the size, shape or number of objects. In the present model, no index may designate an empty cell and only adjacent cells can be designated. These parameters could be modified.

Each transition associates a set of conditions to a set of operations. All the conditions are the same type: they test

² The open-source program is available at www.interactor.fr.

the number of indexes in a given location and orientation. All operations are of the same type: they move an index from a place to another. This formalism does not limit the variety of movements or transformations that can apply to each object or couple of objects. In the present model, no operation changes the total number of indexes arranged in space or the number of indexes of a cell.

The automaton deals only with indexes in the cells. It uses no conditions on the objects such as a name or a color. Users can recognise the objects drawn using these indexes (Figure 1, left panel) but this recognition is made easier by the use of colors (Figure 1, right panel), as can be seen by comparing the two panels (Fig. 1), which display the same workspace. A second-level language may be superimposed to the first to recognize the objects and enable the user to interact directly with them rather than with the indexes. In the present model, the workspace is a two-dimensional hexagonal matrix without boundaries, wrapped over a torus.

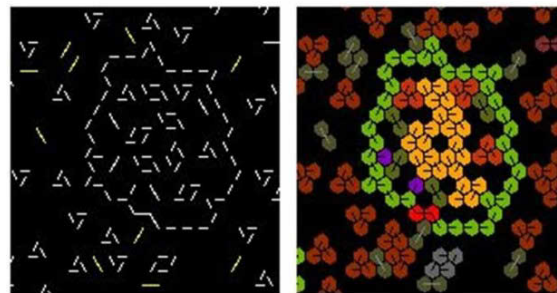


Figure 1: Two views of the same space state.
Left, indexes alone. Right, colored particles.

The space is not explored using its coordinates but according to its content. Each transition converts only a part of the space. This part is centered by a randomly chosen index. It is then assessed through different sets of conditions. If a set of conditions is satisfied, then the set of associated operations is performed.

All information regarding the description of objects is in the space. All information concerning their movements and interactions is in the transitions. No other information is encoded.

Transitions can move, deform, transport, or transform objects. Displacements, deformations, and transports maintain the objects in the same class. Transformations shift them from one class to another. Each class is associated with some characteristic pattern of indexes that can be identified by some adequate conditions' sets.

Here, interactions are not associated with one object, but with at least two and possibly more. They are thus described only once. The downside is that each transition must identify each object involved (pattern recognition). Each transition can apply to the few neighboring cells representing one object to move or to parts of two objects in interaction and not necessarily to the entire space at one time.

The objects to which transitions apply are chosen at random. Transitions occurring in a random order adequately represent independent events. Yet, it happens that an event depends on another one which determines it, and the determining event always occurs always before the dependent one. In the same way, the transition representing

the determined event must always occur before the transition representing the dependent event. This can be achieved by using an intermediate state, which is the result of the first transition and the beginning of the second. There must be no transition going directly from the initial state of the first transition to the final state of the second. If this rule is followed, the second transition will always occur after the first, although the order in which transitions occur is chosen at random.

Hereafter, the environment will be hidden to concentrate on the description of the individuals. Importantly, some space remains always free in the compartment and outside enabling a permanent random movement of all objects.

Results

Two individuals will be described: one called “Tiuccia” and the other “Lagny”³. When the model is running, Tiuccia is easily recognizable as it is circled in green and Lagny looks like a yellow little worm.

Tiuccia is made of seven varieties of aggregates: five are implied in autopoiesis, two in reproduction. Tiuccia comprises a membrane enclosing an internal compartment. The membrane ensures the cohesion of the whole. It is made of one-index particles pointing each to the next one. Because of its asymmetry (all its indexes are oriented clockwise) its inside and outside faces can always be locally recognized. The internal compartment contains freely-moving tetramers, trimers, and dimers (Figure 2). Trimers and dimers are also present in the environment (not shown in this view). An arbitrarily high potential energy is assigned to the trimers (food) and a low one to the dimers (wastes). The membrane is selectively permeable: trimers can only enter (**te**; See Table 1) and dimers can only exit (**de**). In the environment a mechanism converts permanently dimers in trimers to maintain a favorable condition.

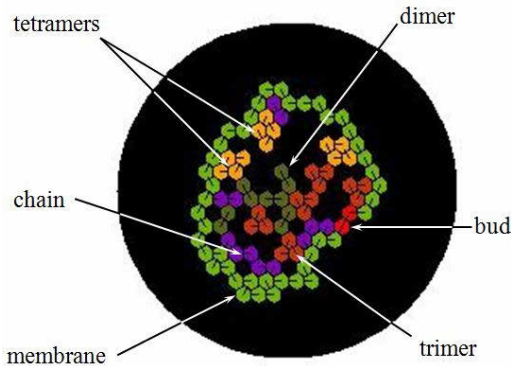


Figure 2: Anatomy. Screen capture of Tiuccia indicates the objects it comprises.

Small chains of one, two, three, or more units long are attached to the internal face of the membrane. When the membrane wrinkles near an attached chain, one of its units can be removed and transformed into a chain unit. This transformation (**mc**) lengthens the chain while the membrane shortens. The membrane’s continuity remains

³ From the names of the cities where they were first observed.

ensured. When a chain is at least four units long, its terminal end can fold in on itself and transform into a tetramer (**ct**). Therefore, the presence of tetramers indicates that some membrane catabolism (destruction) occurred. When the tetramer concentration increases, tetramers catalyse their own catabolism. If three tetramers are adjacent, the central one will be transformed into two dimers (**td**).

When two trimers are close to the membrane, one of them catalyses the transformation (**tc**) of the other into a one-unit chain and a dimer. The one-unit chain is attached to the internal face of the membrane and will lengthen as previously described. The presence of many trimers in the cell is an indicator of a high level of accessible food. This signal initiates membrane catabolism.

When a tetramer and a trimer are close to the membrane, the tetramer catalyses the transformation (**tm**) of the trimer in a unit of membrane and a dimer. The unit is inserted in the membrane. Tetramers are a signal of a previous membrane catabolism and a condition of its anabolism (synthesis).

Because of this coupling of regulation, the size and shape of Tiuccia remain almost constant while all its components are permanently renewed. Inputs and outputs are in competition with the synthesis and destruction of the membrane that regulate its length. Figure 3 and Table 1 depict this metabolism.

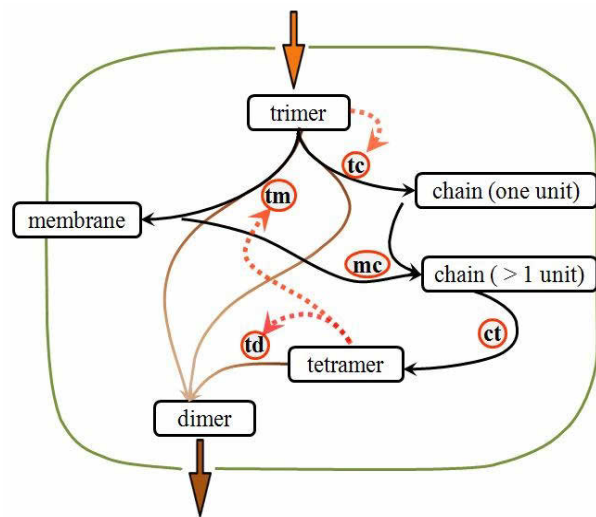


Figure 3: Metabolic pathways and their regulations.

Budding

The “budding” process occurs through ten transformations and transports. Only four of these are specific to reproduction. The other six occur in both autopoiesis and reproduction, and their denominations remain unchanged in the following description.

The first step of budding consists of the capture by the bud of a double-index dimer moving near it in the environment (Figure 4a; budding transformation 1). The bud itself is made of particles containing two indexes. The captured dimer is integrated close to the bud into the membrane and the whole gives rise to a 4-double-index particle sequence: the cord.

Name	Description (effect)	Conditions of realisation and metabolic meaning
te	trimer entry	trimers are present in the environment; free space is available inside the membrane is flexible; no chains are attached locally
tc	one trimer → one dimer + new chain (one unit)	presence of another trimer means that a high food content is available the new chain is anchored to the internal face of the membrane
mc	membrane (one unit) → chain (one unit)	the membrane must wrinkle towards inside the chain must be attached to that part of the membrane
ct	chain (four units) → one tetramer	the chain length is almost four units long it can fold in on itself at random
tm	trimer → one dimer + membrane (one unit)	the new unit is inserted in the membrane; this transformation depends on the presence of a tetramer that acts like a catalyst and is left unchanged
td	one tetramer → two dimers	two other tetramers are adjacent and act like catalysts
de	dimer exit	free space is available outside; the membrane is flexible no chains are attached to the membrane locally

Table 1: Metabolic pathways. The names refer to the names in figure 3 and in the text.

The cord catalyses the second step (Figure 4b): it captures a tetramer and transforms it in a short membrane fragment (budding transformation 2). This fragment is located outside of the main compartment and attached to it by its two extremities. Tetramers can be found in the cell only and they are a sign of its maturity and good nutritional status. The position of the cord between the two compartments that it both links and separates is asymmetric at its insertions. The main compartment will be called the parent and the smallest the offspring.

The asymmetry enables the cord to specifically catalyse the elongation of the new fragment of membrane starting from trimers provided by the parent (budding

transformation 3). A particle of a parent trimer close to the cord insertion is added to the offspring's membrane. The remaining dimer stays in the parent and will be eliminated later (de).

These three transformations are enough to initiate a complete new autopoietic process that enables the growth of the offspring. The next steps are part of the autopoietic process. They occur when the offspring's membrane becomes long enough to absorb trimers (Figure 4c; te) and to release dimers (de). As soon as two trimers have been absorbed, they can give rise to a one-unit chain (tc). As the offspring's membrane keeps growing, due to the parent's assistance, the chain can lengthen (Figure 4d; mc).

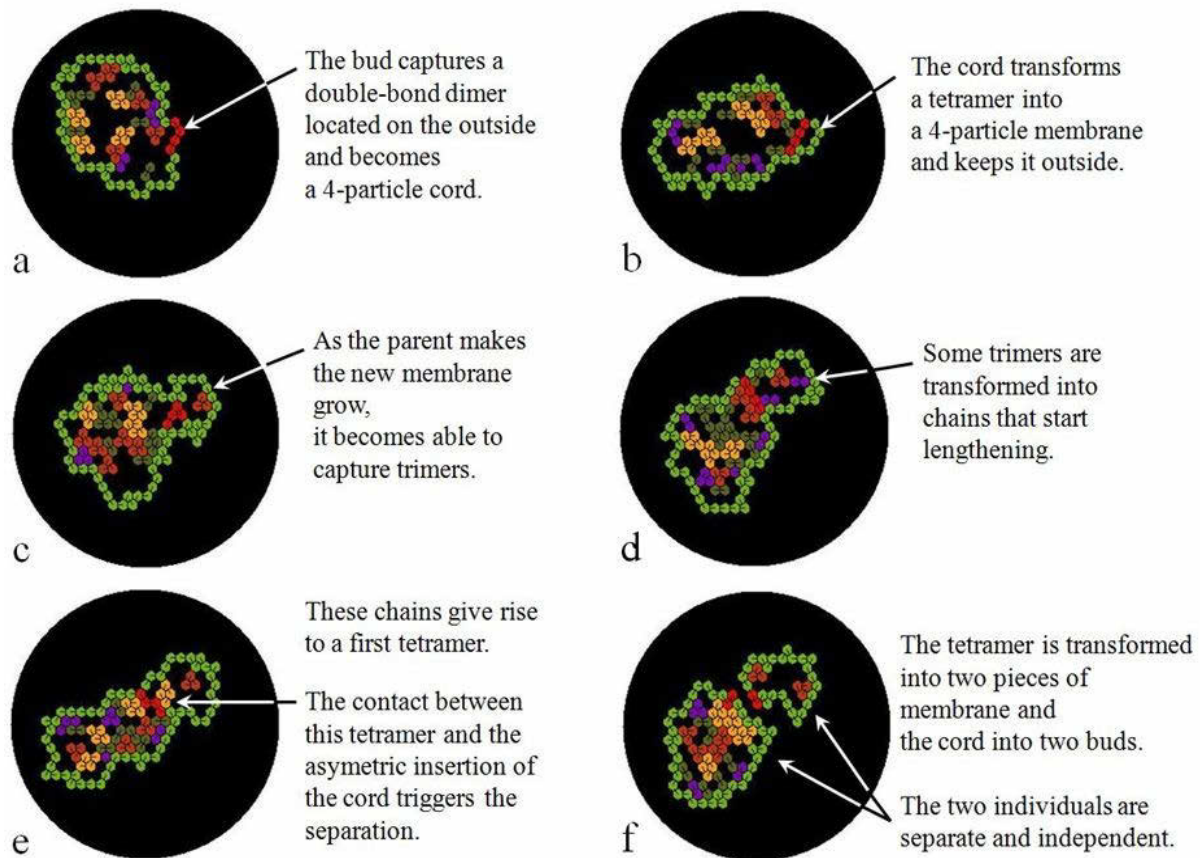


Figure 4: Budding.

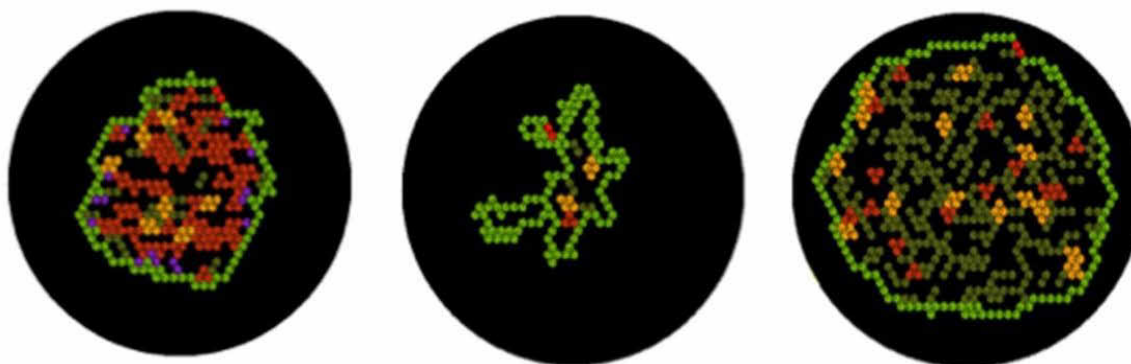


Figure 5: Three abnormal morphologies associated each with a different metabolic defect.

When it attains a four-unit length, its transformation in a tetramer becomes possible (Figure 4e; **ct**). The production of a tetramer by the offspring is a signal of maturity. It guarantees that the membrane has grown enough to ensure first its own degradation and second its own production. This signal is recognized by the cord and initiates the separation (Figure 4e; budding transformation 4). The cord divides in two buds of two particles each, one belonging to the parent and the other to the offspring (Figure 4f). These individuals become completely independent.

As an offspring's tetramer is transformed into membrane during the separation, the offspring may be found to have only one tetramer or none at this stage. This feature is characteristic of a young individual and will not persist. Other tetramers will be produced continuously, and, once there are two tetramers, the number will not decrease anymore because the presence of two tetramers is required to catalyse the destruction of a third one (**td**). The two individuals produced will then remain completely similar and only distinguishable from one another by their history.

As long as the environment remains atoxic and provides the required resources the autopoietic and self-reproduction processes never stop.

Pathology

For some given values of the metabolic fluxes, the individual seems to remain in a basin of attraction. The measured lifespans of each of its components appear always in the same characteristic distribution. The histograms describing the distributions of their quantities are the same, and the correlations between are also unchanged. Of course, these observations are not a demonstration that this will always be the case.

Modifications of the flux of the metabolic pathways result in various morphological changes. Indeed, for each different metabolism a different shape results. Three examples of such morphologies are presented here (Figure 5) to demonstrate the diversity of the patterns that can be obtained. Reciprocally, modifications of the individual's shape can result in modifications of its metabolic fluxes.

The present set of regulations of Tiuccia enables always its total recovery. In some extreme cases, its metabolism can almost be stopped but no lysis or apoptosis phenomena can be observed. These phenomena constitute new properties and require the addition of new metabolic pathways to be attained.

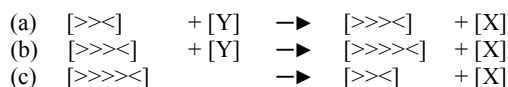
Description of "Lagny"

Lagny is a short chain of one-index particles each pointing towards the next. Only the last one points back towards the previous.

The whole looks like this: $[>>>><]$.

Let's call $[><]$ the "head" and $[>>>]$ the "tail".

The length of Lagny varies cyclically. Only three transitions are possible. During transitions (a) and (b), the head $[><]$ "eats" a trimer $[Y]$. Trimers are rich in potential energy. "Eating" a trimer means releasing a dimer and keeping one unit of the trimer, which becomes a part of the head. Another part of the head is also transformed and lengthens the tail. The dimers $[X]$ are poor in potential energy. Transition (c) releases a dimer from the end of the tail when it is long enough. The whole reaction set could be written as follows:



As each of its parts is continuously renewed by itself and it always keeps its cohesion, Lagny is an autopoietic individual.

Lagny can reproduce itself when it eats a dimer made of two two-link particles, $[2-2]$. This can happen only when its length is maximal. Once ingested, the $[2-2]$ dimer transforms the beginning of the tail into a new head and settles between it, the one-unit tail, and the other head. The two heads continue eating as usual, and $[2-2]$ serves as their link with each other and the tail. But, as the two new bodies keep growing, $[2-2]$ is progressively pushed back towards the tail. Finally, when the two new bodies are long enough, the ancient tail completely disappears and a $[2-2]$ dimer is expelled. This separates the two new similar Lagnys, which then continue independently.

As two identical shapes would have the same potential energy, nutrients, wastes and all their metabolic intermediates must have different shapes. These shapes are pure conventions and can be changed. Other components or transformations can be added. The following rules, however, must always be applied:

- If two components have different potential energy they must have different shapes.
- Each component of the individual must always be destroyed and renewed.
- Cohesion of the individual must always be ensured.

Discussion

This model demonstrates that autopoiesis and self-reproduction are not only compatible, but that in the case of budding, the first can facilitate the second. It also confirms that bottom-up models, that were first used to analyse complex biological objects by representing and defining some of their functions, can now be used to synthesise new objects associating several of these properties. Additionally, in this model, pathological morphologies can be observed when some metabolic pathways are disturbed. Finally, several individuals of different natures can be simultaneously represented interacting within the same environment. The abstract characteristics of this model allow not only biochemical but also robotic, nano-physical, or other interpretations.

Comparison to Other Models of Self-reproduction

In other models of self-reproduction, the individuals produced are not exactly similar and they are not autopoietic (Hutton, 2007). In some, they are not clearly separated (Ono and Ikegami, 2000). Some require the association of two different formalisms to represent movements and transformations (Smith et al., 2002) or small and large objects (Wishart et al., 2005). Others, partly because they use CA⁴, are neither autopoietic nor mobile (von Neumann, 1966; Langton, 1986; Sipper, 1998; Ishida, 2010). They invade space only during reproduction and then stay immobile. Some, like in molecular dynamic studies, are oriented towards the detailed description of a mechanism more than towards the integration of all of them to produce a biological property (Bersini, 2010). Swarm chemistries (Sayama, 2009) or diffusion–reaction models (Virgo et al., 2013) conform to some thermodynamic constraints but the “individuals” or their components do not have defined boundaries and anatomy. By contrast with agent based models, this formalism doesn't associate several functions to one object but several objects or parts of objects to one function. Functions are therefore described only once.

Autopoiesis and Self-reproduction: Which Came First?

This model supports the hypothesis that, in the case of a budding mechanism (as opposed to division), a single structure could be sufficient to perform all of the mechanisms required for adding self-reproduction to autopoiesis. This structure would be synthesised when the individual's state indicates that it is healthy enough to reproduce itself. It would be able to separate and maintain linked a part of the membrane from the initial individual. When the inflow in the parent individual is sufficient, it would favour the use of a part of it to increase the size of this new membrane. As soon as this membrane has grown enough to perform its own entries itself, the autopoietic

⁴ Cellular automata, because their rules modify only one cell's state, are unable to represent the coherence of objects in movement and interaction. Furthermore, starting from a given initial state, they calculate a determined unique trajectory and cannot show other possible evolutions and make probabilistic predictions. They are therefore more suitable for the description of an history than for prediction of possible future events. They can hardly be used to know what range of initial states and what kind of laws would have produced a given final state.

regulations take over. Since the membrane is the energy entry point, the processes (metabolism and its regulation) that depend on the energy source will be activated. All the autopoietic regulations successively add up until the offspring has acquired most characteristics of the parent. The acquisition of the last of these characteristics would signal the separation. The structure that initiated budding disappears. Parent and offspring are identical. New budding processes can begin.

Can this relationship between autopoiesis and self-reproduction help us to understand how they appeared? According to the Oparin-Haldane hypothesis (see Popa, 2004), let's consider the case of a simply persistent individual capable of giving rise to an autopoietic individual. The transition to autopoiesis may, for example, be the creation of an isolate of the same composition as the parent but whose components are organized differently. The parts of this isolate are now linked together while it is still able to renew itself. We do not know if such a transition is a rare or common event since it does not produce a self-reproducing individual and, therefore, does not leave any trace.

Knowing that a single component may be sufficient to initiate and complete the process of self-reproduction, we can imagine that such a component was included in an isolate during a transition towards autopoiesis. If such an event occurred, it immediately created a new individual endowed with three major biological properties: autopoiesis, self-reproduction, and the ability to evolve.

If these properties did not arise simultaneously, one of them was acquired during the evolution of the other. However, only autopoietic individuals can acquire and control their self-reproduction. Persistent entities can only split and merge. Therefore, this model supports the hypothesis that self-reproduction was acquired either simultaneously with or after autopoiesis.

Autopoiesis and Tolerance

The ability of autopoietic individuals to evolve depends on the control they exert on themselves. On one hand, this control enables them to better resist environmental variations than objects that are only persistent. On the other hand, if total, it may be an obstacle to any subsequent change. To acquire the ability to differentiate themselves from their parents, autopoietic individuals must be able to interact with new components. This implies an ability to tolerate some unexpected entries that are not constitutive parts of the individual.

Such a tolerance can seldom be passive, but most, if not all, known biological individuals are endowed with several active tolerance mechanisms, for example, redundancy of metabolic pathways, use of degenerate coding, compartmentalization, and ability to actively eliminate non-self components. This is associated with permanent identification of their self through an unceasing destruction and reconstruction.

The diversification of the entries has several consequences: it enables them to extract food from a greater variety of sources, and it allows new interactions with unknown foreign components which—even if insufficient—is a condition to the acquisition of new metabolic pathways including those required for self-reproduction.

Tolerance should be a target for future models.

Compatibility with Physical Laws

The model presented here allows an association of an entropy to each state space or part of the space. This entropy can be calculated by systematically enumerating all the possible distributions of the objects this space contains (complexions). Because each individual remains in a quasi-stable state in a basin of attraction, it is postulated that its entropy remains constant. Because the content of the environment is modified (for example, two trimers are removed while three dimers are added) it is postulated that the entropy of this environment increases.

To represent the conservation of energy, we must be able to calculate a quantity that remains constant from one transition to another. This quantity is equal to the sum of kinetic and potential energies of all the objects. A potential energy, a speed and a mass can be arbitrarily assigned to each object. From these data it is possible to calculate how the objects' speeds changed during conversions between potential energy and kinetic energy. However, in an asynchronous model, the speeds of all objects cannot be changed simultaneously and approximations are required⁵. It must be noticed that, due to the use of intermediate states (see methods), these approximations do not modify the order in which the dependent reactions occur.

Until a better approximation of kinetic energy is achieved, the only available reliable rule is that two identical shapes have the same potential energy. Therefore, nutrients, wastes, and, more generally, all their metabolic intermediates must have different shapes.

Domain of the Individual in its Configurations Space

Here, the analogy between the biological reality and the model is consistent enough to justify the word "pathology". In both cases, we can distinguish a normal situation from several pathological ones. In "healthy" situations, the individual can attain its maximal performance in extraction and use of energy from its environment. In pathological situations, something is missing or in excess and the global performance is reduced. Each situation associates some anatomic (morphological) and physiological (functioning) characteristics.

In the case of Tiuccia, it has been observed that its mean renewal was faster with particular adjustments in the efficiency of some metabolic pathways. As this study is not extensive, it remains possible that better performance can be achieved with other adjustments.

Each possible morphology is a spot in the configurations space of the individual. This configurations space is an abstract space whose number of dimensions is equal to the number of classes of components of the individual. The individual is always in one place of this space. It can be in some places but not others. The set of places where it can exist constitutes its domain.

This model enables a systematic study of an individual's domain. This domain can be described spot by spot. However, by analogy with what is known of other physical (but not yet biological) systems, there may be approximations that allow more simple descriptions than

⁵ A possible approximation that remains to be evaluated is to rank the objects according to each one's speed. Fast objects will then be treated more frequently, and the frequency of their interactions will be higher.

such an extensive enumeration. Such descriptions could rely on some characteristic parameters of the metabolism or associations of them. Some invariants might also be characteristic of the domain of each individual.

Another representation equivalent to the configurations space could be a transformations space whose number of dimensions would be equal to the number of transformations, each transformations varying in intensity.

Towards a Systematic Enumeration of All the Life-as-It-Could-Be Forms?

It can be hypothesised that the domain description provides the most complete and simple representation of an individual as it comprises all its various metabolic states and the associated morphologies.

Domains descriptions could provide a method to distinguish an individual from one another. Given a set of constituents in a defined state and a set of relations between them, it should also be possible to know if they can constitute an individual or not.

These descriptions could also show how each individual is linked to its "relatives" and, therefore, open the way to a method allowing a systematic enumeration and classification of all the life-as-it-could-be forms (see Langton, 1986).

Finally, these questions are linked with epistemology since it can be hypothesized that, altogether, the description of all those life-as-it-could-be forms could constitute a Logical Tree of Life, independent of the Historical Tree of Life. All the statistical knowledge concerning reproducible biological phenomena should go in the first one; all the deterministic non-reproducible in the second.

Conclusion

This model shows that, at least in the case of budding, autopoiesis facilitates self-reproduction. It analyses autopoiesis as an association of persistence plus cohesion and offers a rational definition of individuality. It supports the hypothesis that autopoiesis is simultaneous or precedes self-reproduction. It may be a guide towards a method allowing a systematic enumeration of all the life-as-it-could-be forms. It investigates the difficulties in representation of physical constraints and proposes some empirical rules.

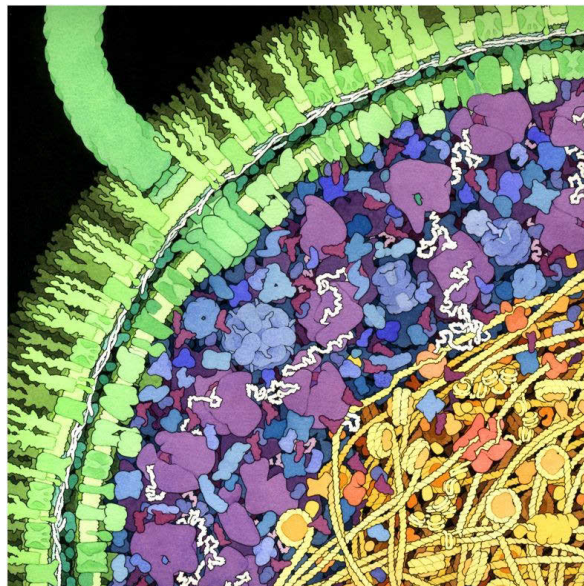
The new platform used for these representations is a graph rewriting system embedded into a spatial automaton. It provides a simple and powerful language using combinations of a unique symbol to represent phenomena characterized by an unlimited variety of forms and interactions.

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