Autopoietic Systems: A Generalized Explanatory Approach

Part 3: The Scale of Description Problem

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> Context • There is an ongoing debate about the possibility of identifying autopoietic systems in non-biological domains. In other words, whether autopoiesis can be conceived as a domain-free rather than domain-specific concept – regardless of Maturana's and Varela's opinions to the contrary. In previous parts my focus was, among other matters, on the rules defined by Varela, Maturana, and Uribe ("VM&U rules"). These rules were viewed as a validation test to assess if an observed system is autopoietic by referring to Maturana's ontological-epistemological frame. I concluded that identifying possible non-biological autopoietic systems is harder than merely identifying self-organized dynamic systems that are provided with boundaries and some observable autonomous behavioral capabilities in a given observational domain. This is because no assessment could be valid without examining such systems' "intra-boundaries" phenomenology and proving actual compliance with the VM&U component production rules. **> Problem** • Any rigorous approach to investigating possible self-production capabilities within a given dynamic system needs to drill down on the composition and physical conditions of the system's core dynamics. My aim now is to discuss the problem of choosing the adequate spatial and temporal scales to be applied when observing and describing dynamic systems in general. When trying to detect an autopoietic system in a given observational domain, the observer needs conceptual tools to apply rigorously the VM&U rules and decide on the matter. This is particularly useful when dealing with systems with spatially distributed components interacting through cause-effect couplings that are independent of the distance between them, as is the case of social systems. **> Results** • For observing dynamic systems, the choice of appropriate spatial and temporal scales of description is not a trivial operation. The observer needs to distinguish between "instantaneous" phenomena and phenomena possessing extended "durations." I argue that the observer can easily extend the notions discussed by Maturana and Varela to observational domains where the system's components do not constitute an entity showing a topological "form" in physical space. Furthermore, I show that a diachronic perspective must be applied by observers to explain component production/destruction mechanisms as the outcomes of processes involving structure-determined coordination over relatively long time intervals. Finally, these considerations lead to establishing a link with Varela's fundamental concept of autonomy. **> Implications** • The adequate choice of spatial and temporal scales of observation and description are essential (a) to discuss the problem of a possible identification of social autopoietic systems, and (b) to analyze the possibility of designing virtual simulated autopoietic systems in software domains ("computational autopoiesis").

> Key words • Autopoiesis, complex dynamic system, self-organization, self-production, boundary, causation, structure-determined, meta-molecular, interaction network, niche, synchronic/diachronic, processes.

Introduction

Humberto Maturana, the original author of the concept of autopoiesis, and Francisco Varela initially addressed the biological domain. They described the concept using rigorous distinctions, definitions, and epistemological considerations. However, there is an ongoing debate about the possibility of identifying autopoietic systems in non-biological domains, such as social systems, economical organizations, or software and/or hardware entities (artificial life artifacts). The question is whether autopoiesis can be conceived as a domain-free rather than domain-specific concept – regardless of Maturana's and Varela's opinions.

The concept of autopoiesis, as expressed by the rules defined by Varela, Maturana & Uribe (1974, hereafter the VM&U rules), lends itself to an explicit generalization. However, such generalization requires that the focus is set on the most common aspect of all possible types of dynamic interactions between system components, namely on their *causation structure*. This generalization is valid regardless of any explicit description of particular physical interaction mechanisms responsible for the dynamic links established between system components.

One of my aims was to discuss the "intra-boundaries" phenomenology that should be observable with regard to the self-production of components and the topology of the components' interaction structure, as required by the VM&U rules.

In this paper, I address several issues – briefly labeled as the "The scale of description problem" – related to the observation and description of dynamic systems, and encountered when trying to identify possible autopoietic systems existing in meta-molecular domains. In this and the following paragraphs, I am rephrasing with my own concepts what Maturana explained and developed conceptually decades ago. The reader may wonder why the addressed topics are relevant and how their discussion contributes to the broader work begun in Parts 1 and 2 (Urrestarazu 2011a, 2011b), especially when they lead to conclusions and insights that have been widely discussed already by Maturana and Varela.[1] There are fundamentally two reasons for proposing this excursion:

1 | The most important one is that discussing these topics is needed as preparatory clarification work for tackling the topics that will be addressed afterwards in relation to the cases of social and virtual dynamic systems. These discussions are not to be taken as simple digressions departing somewhat from the generality of the main theoretical line exposed in my previous papers, but as a step in the overall progression of my reasoning.

2 | The second reason is that discussing these issues allows me to show that these complex reasoning examples can be conducted consistently and logically with the help of the conceptual tools proposed in this explanatory approach and that these concepts build up a consistent abstract language that appears as a helpful reasoning tool.

All these developments will help us discuss the nature of social systems and will provide insights for addressing some computational autopoiesis issues.

1| Part 1 is essential to understanding the terminology used here. In particular, I defined concepts that refer to a generalized notion of a non-specified realm in which autopoietic systems could be observed and identified as such, which I called the "observational domain." I also proposed a general description of dynamic systems composed of dynamic entities (or objects) capable of performing state transitions and related to each other by observable cause-effect interactions, a view that allowed me to describe those systems as networks of causation flow and represent them with well-defined abstractions. In order to facilitate the reader's understanding, some of the key concepts are presented in summary again at the end of the paper, in the glossary of key concepts introduced so far.

Dual manifestation domains

I claim that while observing and describing a dynamic system from within this explanatory approach, observers can rigorously address all the requirements imposed by the VM&U rules when trying to determine its possible autopoietic nature. But even more interesting than conducting this verification procedure (see Urrestarazu 2011a: 320–323, section "The VM&U validation test"), these proposed conceptual tools allow observers to determine clearly to what extent an observed system departs from the condition of being autopoietic (compliance with all 6 rules) and, by doing so, to what extent it may show other important characteristics that made us wrongly believe that it was autopoietic (compliance with only some of the rules). This paper addresses the problem of circumscribing the system in space and time and of deciding on the kind of physical objects to be considered as components of the *same kind* (see glossary|* entry on "Same kind components") that constitute the unity.

Here I am limiting the discussion to *observational domains*|*, where *dynamic objects*|* arise indeed as material entities coupled by cause-effect interactions and are actually explored by observers in order to determine the set of state-variables ascribable to the observed entities and determine the kind of *dynamic system*|* that they may constitute. The case of "virtual" dynamic objects conceived as such by ways of symbolic software design and "materialized" on computer hardware as electronic (or other kind of physical) processes needs to be addressed separately.

A complex dynamic system may be described in terms of observational criteria that are inevitably observer-dependent, i.e., by way of descriptions made according to a chosen "point of view" with regard to all different possible levels of composition of the said system.

When the observer *describes a composite unity as a whole*, focus is given to the observational domain in which the system arises as a dynamic totality that *operates as a simple unity*; if the observer *describes the composition of the unity*, focus is given to the observational domain of operation of its components.

> "Systems as composite entities have a *dual existence*, namely, they exist as singularities that operate as simple unities in the domain in which they arise as totalities, and at the same time they exist as composite entities in the domain of the operation of their components." (Maturana 2002: 12; my emphasis)

Phenomena occurring in these two dual domains cannot be explained using the same distinctions because the properties of the dynamic objects involved (seen as totalities in their own domain of existence) and the nature of their interaction capabilities are different. Hence, the set of state-variables needed to describe the states of the entities in their respective dual domains may differ also:

D_T *Totality manifestation domain*: in the domain where the composite unity operates as a totality, phenomena are explained in terms of relationships with other *totalities* of the "same kind" without referring to their components, in terms of state transitions undergone by these totalities, and in terms of the history of those *relations between totalities*;

D_C *Components manifestation domain*: in the domain of operation of the composite unity's components (seen as totalities of a lower order), phenomena are explained in terms of relationships between *components* of the "same kind," in terms of their state transitions, and in terms of the history of those *relations between components*.

For each case, there are distinct spatial volumes to be considered, which are defined by the spatial extension of the physical entities and by the spatial extension of their dynamic manifestation. Even if the position of objects in space is not to be considered as a significant variable and member of the set of state-variables (when the considered *cause-effect coupling*|* is independent of the distances between objects), the overall observed behavior is typically taken to occur within a certain spatial volume of a given size and the interacting objects may be also endowed with the property of possessing a delimited spatial extension. As we shall later see, this may not be always easily observable: in some observational domains we may observe dynamic objects describable as totalities without necessarily considering them as spatially *compact entities* (they could exist as spatially distributed objects with a lower, but not specified, composition level).

By "compact entity" I refer here to a compound physical object with components closely packed together in physical space, where distances separating neighbor components in Euclidean space are significantly lower than the size of the said components.

These two spatial volumes (one defined by the entities' maximum spatial extension, and the other by the extension of their overall dynamic manifestation) define two quantifiable scales of observation that allow the observer to distinguish entities properly as interacting objects in physical space. These scales are derived from the observer's choice in focusing on one of the dual manifestation domains, D_T or D_C. For the sake of precision, the relation between both scales of observation could be defined by the ratio between both volumes. This implies that a range for spatial scales of description that is adequate to allow system components to be distinguished as spatially delimited dynamic objects is bottom-limited to the size of components and top-limited at least by the size of the region of space where the considered compound system manifests itself as a dynamic totality, i.e., where its overall behavior is observable and describable.

Similarly, the intrinsic time-related characteristics of the interaction dynamics in domains D_T and D_C can differ in a significant manner. The interaction propagation speeds are not necessarily the same, nor are the reaction delays to triggered transitions. Thus the adequate temporal scale of observation necessary to discriminate significant events in each domain is bottom- and top-limited, too. For example, consider the D_T and D_C manifestation domains for multicellular organisms: in the component's manifestation domain, molecular interactions occur typically within time-frames of the order of picoseconds to microseconds (i.e., protein folding and other molecular events), whereas most externally observable behaviors of the organism as a whole may range from milliseconds to several hours, and even longer (i.e., muscular reactions, circadian cycles, body growth).

Thus the choice between a spatial and temporal scale of description is essential to decide "where, how far, when, and for how long" to observe in order to be able to discriminate a dynamic system in a given observational domain. This is implicitly done as a current and necessary practice in most scientific investigations. But an explicit choice is needed and becomes critical when observing dynamic systems because the component composition/decomposition properties explained in Part 1 of this work (Urrestarazu 2011a) might not be observable at arbitrary scales of observation and description. Furthermore, observation at adequate scales is essential, not only for describing component production, but also for properly circumscribing any observed unity, as required by the first VM&U rule: "Determine, through interactions, if the unity has identifiable boundaries. If the boundaries [cannot be determined], the entity is indescribable and we can say nothing." In the following subsections I shall discuss spatial and temporal scale issues in more depth.

Spatial scales of description

When trying to identify and circumscribe a dynamic system operating in a given observational domain, the observer needs to identify the sort of dynamic objects operating in that domain, the sort of interactions occurring between them (the prevailing interaction mechanism), the set of state-variables that can be associated to the candidate components, and the possible states that those components may attain. When the manifestation of the prevailing interaction mechanism is properly accounted for by ascribing a complete set of specific state-variables to all interacting objects, observing changes in those variables across all dynamic objects over time allow observers to construe a cause-effect coupling relationship that maps into a causation structure graph of state-nodes and *oriented relations* |*, as proposed within this approach (see *causation structure* |* and *equivalent graph* |*). The circumscription problem is then tentatively solved by examining the graph topology in detail (identify *components* |*, *environmental objects* |*, the *medium* |*, the *boundaries* |*, and the *core* |* of the suspected unity under scrutiny).

The choice of a spatial scale

According to this explanatory path, an observer implicitly chooses a component description scale by choosing the associated set of variables assigned to the selected components whose values *at a given time* define the state at which each component is found at that moment. This choice depends on the nature of the causation mechanism *being considered* because the state-variables included in the set must correspond to observable and quantifiable features *that are susceptible to being modified by a specific state transition triggering interaction*. Such features are taken as variables associated to the dynamical object, with assigned values before any interaction occurs. In particular, this requirement means that *the nature and number of the state-variables* to take into account depend on the nature of the interaction mechanism and this defines the type of nodes and their *dimension* |* within the multi-dimensional relational space in which the relational network representing the system may be described. But this also defines the 3-dimensional (3D) physical extent of the region in which the observed dynamic system can be distinguished, according to the observer's experience gathered while observing identified dynamic objects that interact in the considered observational domain via a specific interaction mechanism.

Let us assume that the observer does not know if a circumscribable dynamic system composed by observed dynamic objects does exist in this identified region. The observer needs to adopt an adequate spatial scale of observation in order to describe the interactive dynamics and determine if an emerged dynamic structure is distinguishable as a unity. If the adopted scale is lower than the size of the components manifestation domain (D_C), the observer will probably miss the pertinent causal relations that couple these dynamic objects to each other.

If the scale adopted is larger than the size of the totality manifestation domain (D_T), the observer might confuse the totality manifestation domain with the components manifestation domain and take "small" emerged structures (acting as totalities) as components of a *de facto* higher order unity without being aware of this error.

Discriminating components from other observable totalities

This might appear to be a trivial comment in the case of interaction mechanisms that depend strongly on the distance separating individual dynamic objects and are observed as binding (attractive) forces (in which case locally emerged structures will be observed as 3D spatial *compact* entities: i.e., the case of molecules and aggregates of molecules). But it is not so evident in the case of systems composed of dynamic objects interacting at arbitrary distances and distributed randomly over wider regions of physical space (i.e., the case of some social network systems).

Furthermore, in the case of the quest to identify a suspected *autopoietic* system, the observer needs to pay attention to the existence of possible component transformation mechanisms that could be compliant with the VM&U component production rules that components may undergo (reference to additional details is given in the entry *similarity component production transformations* [*]). While observing *non-compact* 3D emerged dynamic structures (i.e., composed of randomly distributed components interacting at arbitrary distances), the observer might be at pains to choose the adequate spatial scale of observation necessary to distinguish the production (or destruction) of new (or existing) components as a result of the effects of the prevailing interaction mechanism at work in the considered observational domain.

If distinctions made so far are to be consistent in this explanatory path, the nodes of the relational network representing the system in a multi-dimensional relational space should all be of the *same kind*, i.e., they should possess not only the same dimension, but also share state-variables. Other non-spatial state-variables may also participate in the manifestation of additional interaction mechanisms not directly related to component production but otherwise keeping the compound system operating as a long-lasting self-organized totality.

The isomorphism established between the physical system's interaction structure and the theoretical causation graph (network of oriented relations) implies that any system substructure should be represented by a sub-graph involving a defined number of nodes. The question arises as to whether a compound substructure of the system could be inconsistently considered as a single component (i.e., be described as a single node of the equivalent graph). A consistent level of granularity for observing and describing the composition of the system from within this approach should be one in which all components are described as being of the same kind. If the scale of description is not precisely defined from the start, an inconsistent identification of components could indeed occur if the observer does not observe or describe a substructure's internal dynamics but only its interactions with the rest of the system. If an investigating observer chose to identify observed embedded composite unities inconsistently as the operating components of the system under investigation, it would be partly because she was using a spatial scale of observation adequate only at the scale in which these composite embedded unities become noticeable and where lower scale entities of the same kind are not discernible (henceforth called *simple components*). While exploring the topology of the interaction network of these identified embedded unities, the observer would probably discern the embedded system but not the encompassing one. While discovering later – at a lower scale of observation – that there were lower order dynamic objects playing an active role in significant causation flows, by not being aware that they were not of the same kind, she would be tempted to consider them also as components. In that case, the observer would also have to consider the simple components that constitute the embedded composite unities as components of the encompassing system because they would be coupled by cause-effect relations observable at the same scale of description (see Figure 1).

In summary, in this explanatory approach, the components of a higher order embedded dynamic system should all be describable as dynamic objects of the same kind interacting together at their higher level of description without referring to interactions with entities of a lower order and of different kinds. In theory, the observer would then have three circumscription choices: either

Choice I: to consider the embedded system as composed solely of embedded composite unities by describing only their mutual couplings with a suitable state-variables set and to consider all other causal effects provoked by simple components as external to the embedded system, or

Choice II: to consider a more complex embedded system composed simultaneously of embedded composite unities and simple components, or

Choice III: to consider the embedded system as composed solely of simple components by ignoring the fact that some components constitute embedded composite unities.

In the case of Choice I, the observer would not be able to explain the behavior of the embedded systems solely in terms of the causation structure generated by the coupling between the embedded composite unities, but would need to integrate into her explanation the impact of external causal effects provoked by the lower level entities on the embedded composite unities themselves.

In the case of Choice II, and in order to be consistent within this explanatory approach, the observer would be forced to discriminate between different kinds of interactions: those occurring between the embedded composite unities and those involving lower order entities. This would force her to flatten the level of description to that of components of the lowest common order and account for the internal workings of the embedded composite unities in terms of the dynamics of the components of the lowest order. This situation is equivalent to Choice III.

Let us illustrate these considerations by supposing that an observer is tentatively trying to determine the kinds of dynamic objects that could be properly identifiable as system components, and that she is dealing with a substructure composed of more

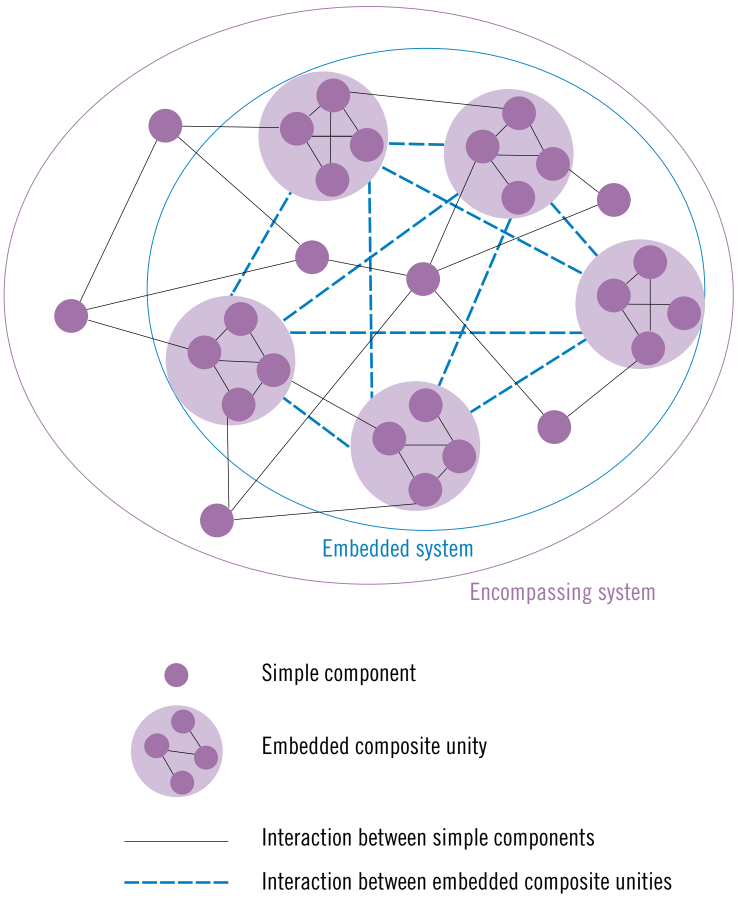

Figure 1: Very schematic representation of embedded composite unities (constituted by lower order dynamic entities) that may constitute an embedded dynamic system within an encompassing wider system composed of lower order dynamic entities (simple components) of the same kind.

elementary dynamic objects (see Figure 1). In fact, if such a substructure is to be considered as a component, all its possible global states – taken as a *totality* – should be describable by means of the *same set of state-variables* chosen to describe the states of the more elementary dynamic objects existing in the considered observational domain and constituting also the said substructure. Otherwise, the type and the relational space dimension of the composite substructure would be incommensurable with the type and relational space dimension of a simple component. This is because there is only one way to "compare" a composite system with a simple component, which is to *define a comparable set of state-variables* valid for describing the observed "external" interaction phenomenology of the composite substructure, seen as a totality, in the same terms as if it were a simple component. This is *possible only if the composite substructure can be described as always interacting– as a whole –* with the rest of the network, *in the same manner as simple components,* and never only partially through its own internal components.

Thus, a substructure emerging as a local autopoietic system within a larger system, for example, could potentially be described as a component of the said dynamic system if:

a | it is capable of performing similarity production transformations by composition/decomposition processes triggered by interactions based on the same causation mechanism affecting simple components; and

b | it is coupled to simple components or other composite substructures of the *same kind* and participates in component production as any simple component does.

This is consistent with what Maturana explained and developed conceptually decades ago. The point in discussing this specific case (autopoietic unities embedded within a larger system) is to show that this is a hypothetical situation that could occur in any sufficiently complex dynamic system. However, this situation does not even occur in the case of biological organisms, because autopoietic cells cannot possibly be described with the same set of state-variables that would suffice to characterize the interactions between the molecules that compose those cells. If compliance with the above mentioned requirements a) and b) was observed in a dynamic system, it would imply that a "scale invariant" dynamic behavior was observable in simple and "composite" components alike. Such a situation would be a very particular case indeed and could not be envisioned as a general property ascribable to all autopoietic systems.

The same considerations apply if the embedded substructures are not autopoietic unities, but more general dynamic systems provided with a boundary that makes them circumscribable, identifiable as wholes, and showing specific observable relational behaviors as the result of their specific mutual cause-effect couplings described at the composition level at which they are identified as totalities.

Interacting embedded unities

It should be noted that the presence of embedded substructures (autopoietic or not) in a dynamic system described as composed of lower level components (that is to say, of the same kind of components that constitute the embedded substructures) does not prevent these embedded unities from interacting with each other and constituting an embedded dynamic system on their own. Nothing prevents this embedded system from being autopoietic either, even if the encompassing system is not. But the description of the operation of these embedded unities would require a completely different set of state-variables to account for the specific interaction mechanism that makes them constitute a circumscribable dynamic system. In fact, the resulting embedded system exists as a system that emerged in *its own observational domain*, distinct from the observational domain in which the encompassing system exists as such.

An example of this situation occurs in the endoplasmic molecular domain within cells where we observe

> "…entities which are known as organelles (vesicles, Golgi bodies, lysozomes) [that] are able to function in concert to maintain a constant and complex molecular flow. Each organelle appears to be discrete by virtue of its own surrounding membrane, but they fold and break off to create a flow across them which is a functional system in its own right." (Fell & Russell 1994)

These dynamic subsystems are embedded in a cell (the encompassing system), but should not be regarded as being of the same kind as its basic constituents if the VM&U rules apply to assess the system's autopoietic nature. Unless these substructures could be considered as giant single macromolecules, they are not to be confused with smaller single molecules of a generic kind that can be described with a same set of state-variables. Fleischaker (1989) conducted laboratory experiences on the applicability of the VM&U criteria to most simple cells, and she

> "…was satisfied as to [their] internal mechanistic operation, because the component properties (which are ionic, electrochemical, steric and hydrophobic) are what determines all component interactions." (Fell & Russell 1994)

But, can organelles be considered as giant single macromolecules of the same kind as the smaller molecules they are composed of? If we describe the cell just as a general dynamic system, we have no clues to distinguish giant macromolecules from smaller ones as they participate in the same type of ionic, electrochemical, steric, and hydrophobic interactions prevailing in their domain of existence. But if we seek to describe the cell as an autopoietic system, we need to consider the similarity production transformation capabilities of all components and then the distinction becomes more apparent. This is because organelles, taken as totalities, do not undergo these types of transformations as a result of "organelle-to-organelle" interactions. Nevertheless, they may probably split, merge, and be seen to "cooperate" in the production of other organelles, but only as a result of interactions distinguished at a lower scale of observation/description. This would be the case of symbiotic mitochondria within cells, for example, "where many other organelles and cell structures are [their] products" (Sapp 2007: 62).

Embedded autopoietic unities

So far, these are general considerations applicable to any dynamic system described within this explanatory approach. Now, if the embedded composite unities happen to be autopoietic and the resulting embedded system is also autopoietic, it will mean that:

- at the level of the *embedded autopoietic unities*, some lower level *simple components* are produced in the core of the said unities as a result of their internal relations of production, and
- at the level of the *higher order embedded autopoietic system*, its own components (*embedded autopoietic unities*) are produced in its core as a result of the internal relations of production prevailing within.

In this case, the higher-order embedded autopoietic system is composed simultaneously of simple components and embedded autopoietic unities that are also composed of the same kind of simple components (see Figure 1). Therefore, the realization of its own autopoiesis would be the result of the relations of production of components prevailing in its core, *including* the production of the embedded autopoietic unities, which is based on the same kind of similarity component transformation properties possessed by the simple components. This means that in order to verify (compliance with VM&U rules) and explain the autopoietic nature of the embedded system, the adequate circumscription choice would have to be Choice III.

At this stage, it is convenient to recall a pertinent consideration of Maturana and Varela:

> "[A] system realized through the coupling of autopoietic unities and defined by relations of production of components that generate these relations and constitute it as a unity in some space, is an autopoietic system in that space *regardless of whether the components produced coincide or not with the unities which generate it through their coupled autopoiesis*." (Maturana & Varela 1980: 109; emphasis is mine)

The above discussion based on the use of the concepts developed for this explanatory approach expresses this same idea.

In order to illustrate these abstract considerations, let us examine the case of multi-cellular organisms. In any biological organism there are significant levels of intermediate structure and organization between "cells" and "molecules" (organelles, molecular complexes etc.), but the mentioned extremes refer to the choice in defining the basic composition elements as interacting components of the same kind. Seen from an oversimplified perspective, a multi-cellular organism can be described as composed simultaneously of cells and molecules interacting together at the level of cells, at the level of molecules, and at a mixed level of both. If it is to be consistently described as an autopoietic system (as a totality), the level of description of components should be the level of a first order autopoietic system existing in the molecular domain and cells be described as composite substructures – composed of molecules – that play just an allopoietic role within the system.

> "An organism as a first order autopoietic system, however, is not composed of cells even though its realization depends on the realization of the autopoiesis of the cells that intersect structurally with it as they constitute it in their ontogenetic drift. The first and second order autopoietic systems that intersect structurally in the realization of an organism exist in different nonintersecting phenomenal domains." (Maturana 1988)

In my view, this is the fundamental reason that led Maturana to emphasize that the only known observational domain where autopoietic systems can be consistently identified, is the molecular domain.

In multi-cellular organisms, *cells* are autopoietic subsystems *composed of molecules* and they can constitute relational networks of cells interacting together (organs or functional cell structures, such as the nervous system), embedded in the core of the organism. Such cellular systems may become describable as autopoietic unities composed of cells. In this case, the lower level molecular interaction processes may be considered as participating in the material manifestation of the interactions' mechanisms that make emerge or allow the survival of a higher level autopoietic entity, (i.e., the molecular phenomenology of endosymbiosis giving rise to symbiotic interactions between a host organism and an embedded symbiote – such as lactobacilli and other bacteria in humans or zooxanthelles in corals). Nonetheless, the whole organism seen as an autopoietic totality is to be considered at the lower level of description as composed of molecules:

> “[A]n organism is an autopoietic system through its molecular composition, not through its meta-molecular existence. Autopoiesis describes the constitution of living systems as discrete molecular systems.” (Maturana 2002: 14)

Considerations concerning spatially compact systems

In my opinion, the central point to be considered in this kind of research is related to the role played by the component production mechanisms with respect to the topology of the interaction network. It happens that in the molecular domain, for example, the composition/decomposition processes produce components showing strong spatial neighborhood interactivity (where relative separation and mutual orientation in space are the most important state-variables).

Compactness

Distance-dependent interactions that involve the manifestation of attractive binding forces tend to maintain interacting objects in relations of lasting spatial vicinity and this situation may foster the manifestation of other cause-effect couplings that would not have been possible if the components were not maintained sufficiently “close” by the effect of the binding forces. Spatial orientation-dependent interactions that involve the manifestation of selective 3D (stereo-specific) couplings tend to arrange components according to spatially-oriented architectural forms (morphogenesis). In the vocabulary of physics, these reactive or geometric forces are called forces of constraint. More or less rigid structures, from natural molecules, crystals, and rocks, to artificial tables, buildings, and bridges are held together by forces of constraint. In the case of biological substances, these forces of constraint are flexible and energetically sustained by permanent material flow.

This is obviously trivial in the case of the molecular domain, but I intend to make the point explicit in order to *highlight the contrast* with the case of spatially distributed dynamic systems where the material manifestations of cause-effect couplings cannot be explained by invoking the compactness conditions that make those manifestations possible in physical terms (localized energy and material flows).

Stated in terms of the conceptual tools proposed in this paper, we could say that in the case of spatially compact dynamic systems *the topology of the relational network tends to coincide with the spatial topology of component structures in physical space* even if there might be other dimensions to take into account for state-variables whose changes are not distance-dependent. These “extra dimensions” may be always present because distant components may interact through cause-effect couplings as the result of mechanisms which are unrelated to the conditions prevailing in the spatial vicinity of components. We could intuitively say in this regard that the *multi-dimensional relational graph's projection into its 3-dimensional spatial coordinates* and the *physical 3D Euclidean space* where observers perceive the physical structure both possess the same topology (see Figure 2). In other words, the relations of spatial vicinity and spatial orientation between components could be interpreted as constitutive relations of the composite system in which *almost all interaction paths are embodied by physical structures of interacting neighbors*.

It should be noted that this consideration is not to be regarded as a claim saying that the elements of the abstract graph (oriented relations) are literally circumscribed by or within the physical elements of the interaction network (the dynamic objects themselves). This would be a confusion of conceptual terms and abstraction levels. I am only saying that the topologies of both structures – (a) the abstract projection of the graph in its spatial coordinates, and (b) the 3D representation of the observed unity's physical structure in Euclidean space – are equivalent (by the way, this equivalence could be an important criterion for judging the appropriate choice of the state-variables set made by the observer.) When I say that almost all interaction paths are “embodied” by physical structures (i.e., forms in physical space), I am pointing to a particular feature shown by some compact dynamic systems, where the occurrence of significant cause-effect couplings is physically contained within the frontiers of physical forms recursively generated by the interaction structure on its own.

Emerged substrates for emerging phenomena

In such systems, the interaction network activity acts as an organizing process that generates a physical substrate where larger scale phenomena can naturally emerge. This emerged substrate may facilitate the manifestation of new phenomena, distinct from those involved in the interactions between components. These may become essential structure-dependent resources for the system's operation, including the maintenance of organizational invariance and the spontaneous “invention” of new mechanisms that maintain autopoiesis in the face of perturbations that would have caused the system's disintegration in the past. In the realm of biological macromolecular systems, we can summon up some examples of such larger-scale physical structures and their associated phenomena: membranes (osmosis, ionic transport, etc. resulting in semi-permeability); vessels (heat transport, capillarity); tissues (elasticity, rigidity); gels (viscosity, refractivity, transparency, opacity); etc. Chemical reactions can be localized by the buildup of physical containers; concentration levels of reactive substances can be “controlled” by physical processes affecting the canalization of fluids; specific molecules can be filtered by semi-permeable membrane structures; molecular or cellular concatenations can be the support for the flow of “signals”; etc. All these phenomena manifest themselves as

"…flexible forces of constraint that hold together the innumerable articulated assemblies of rigid structures … as well as labile assemblies of not-so-rigid structures like the biopolymers … in organisms." (Pattee 2001: 12)

With the exception of molecular systems that do not generate physical contiguous boundaries, such as the distributed immune system, many molecular systems show one of their most important topological features, namely the physical embodiment of their relational boundary as a physical container for the whole mechanical and chemical activity within the "topological unity" constituted by the dynamic system itself.

When some interactions are expressed as attractive forces of constraint, the projection of the relational network topology in a 3D coordinate system will coincide with the spatial topology of a resulting *dynamical form* generated by the composition processes. Dynamical forms are not artifacts "created" by the topology of the abstract relational graph, but physical structures resulting from the interactions between physical components. By definition, the projected 3D topology of the graph should reflect the physical 3D topology if the observer adequately defined the spatial state-variables from the start. Dynamical spatial forms act as physical and chemical supports for the processes themselves and the processes give rise to these forms in a recursive manner, moment after moment, along with the transformations undergone by the interaction structure. At the same time, the interaction dynamics seen as a form building process (morphogenesis) of "labile assemblies of not-so-rigid structures" (Pattee 2001) allows for continuous transformations of the dynamical form that take place along a timeline, so that new macro-structural resources may become continuously available for the emergence of new mechanisms.

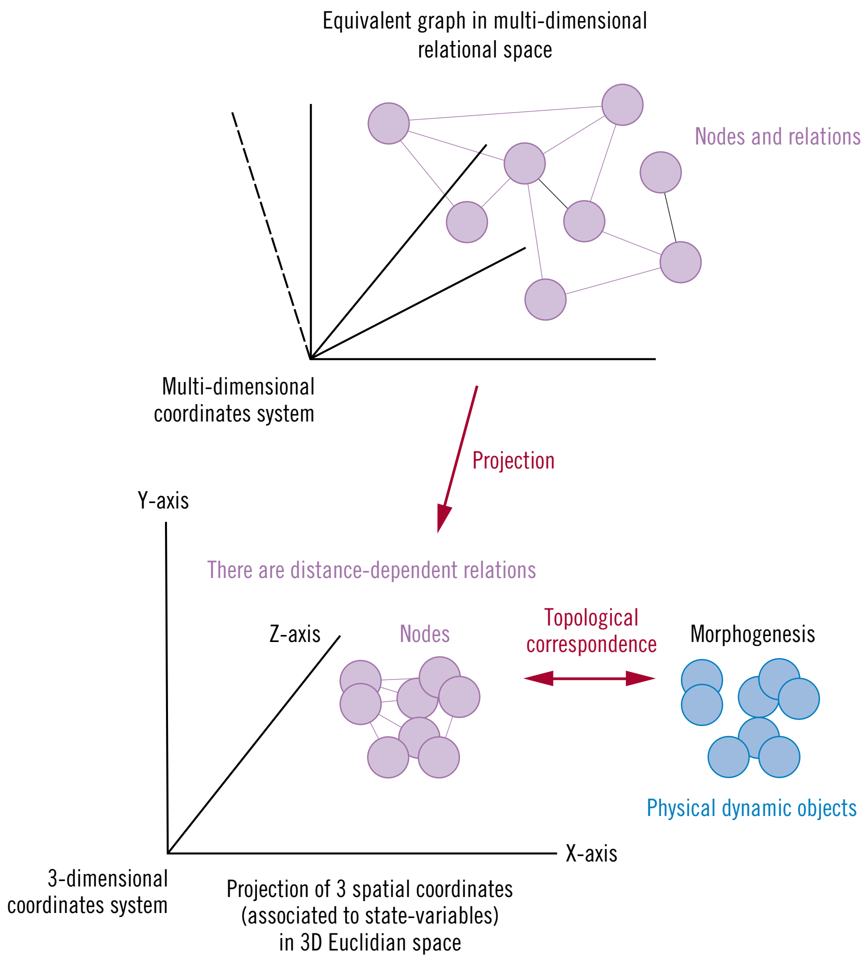

Figure 2: Illustration of the correspondence between the topology of a 3-dimensional projection of the spatial coordinates of nodes in a multi-dimensional graph (defined by those state-variables that express distances separating dynamic objects and their mutual orientations) into Euclidean space and the physical topology (form) of the observed dynamic objects' spatial structure.

A fundamental condition for life?

The relational structure building processes leading to the *manifestation of physical phenomena affecting large physical structures* (macro-structures) facilitates the emergence of higher order mechanisms capable of *playing a role in the emergence of anti-disruptive compensating mechanisms.* Even more significantly, it also facilitates the emergence of complex mechanisms *of substructure building processes* that may become essential for the emergence of embodied capabilities such as system physical replication. Conversely, the emergence of such structures with their accompanying mechanisms recursively facilitates the evolution of the relational structure building processes that originated them. This evolution can be either epigenetic (within the lifespan of the system), or phylogenetic (when reproduction and genetic transmission mechanisms become available in the organism's structure).

The conceptual tools proposed in this explanatory approach allow observers to distinguish the relevance of morphogenetic processes in the face of other processes less concerned with the 3D spatial topology of the overall structure. In my opinion this is extremely relevant, to the point that I think that we have the right to ask whether this spatial topological compactness of molecular interactions was indeed the *fundamental condition* that made life as we know it on earth (and perhaps also autopoiesis) possible.

Considerations concerning spatially distributed systems

In other observational domains, the above-mentioned mapping of the relational network topology with a spatial topology of physical structures may not exist because spatial proximity is not a mandatory category for the state-variables that need to be included in the definition of dynamical objects' states. This is the case, for instance, of those domains where the *spatial distance between components does not play a role* in the establishment of cause-effect couplings. In these cases, the emergence of disruption compensation mechanisms cannot rely solely on the manifestation of the physical properties of large-scale *spatially contiguous macro-structures*.

The following considerations are intended to highlight the conditions that would allow an observer to distinguish the physical effects of purely relational outcomes of the unity's internal dynamics when its components are distributed over distances that preclude the possibility of building up material structures as an *immediate and direct physical effect* of cause-effect coupling. This issue needs to be addressed, not just as a mere theoretical exercise, but mainly as a reasoning path that will prove to be essential to understanding social systems.

Distant agents need to coordinate activities

For systems where components are arbitrarily distributed in space, I would like to point to a situation in which dynamic objects may perform some of their changes of state as physical activities that, once triggered, are no longer related to the component that triggered the said transition. This situation cannot be excluded from our analysis, even if it is not the case for all distributed dynamic systems in all circumstances. Certainly, coupled components may remain in permanent reciprocal interaction conditions, transition after transition (i.e., in the equivalent graph this would be represented by a couple of persistent oriented relations linking a pair of nodes in both directions after each interaction network rearrangement), and in this case, the successive states of coupled components would remain mutually dependent for long periods – locked in a "peer-to-peer" relationship – and the overall systemic dynamics could be explained as a direct effect of those persistent cross determinations.

However, when the evolving relational network topology is less persistent, the following question arises: "how can triggered transitions occurring among "peer-to-peer" momentarily-coupled components produce global effects on the whole interaction network?" At this stage, one may wonder at what point a unity ceases to operate as a distributed dynamic system and becomes instead better described as an exogenous ensemble of interactions. In these discussions, I am assuming that the considered unity has been circumscribed at least as an "identifiable set of dynamic objects interacting together" with a lasting dynamic structure possessing an intrinsic self-sustained lifespan (see Urrestarazu 2011b: 51).

When components are situated in separated physical environments, we need to distinguish the particular region of space where each component is capable of obtaining the necessary resources to accomplish their triggered physical activities (henceforth I will refer to this delimited region by the term *niche*: see Figure 3) Components that do not share a niche, or that exist in spatially non-overlapping niches, need to consume energy and "manipulate" matter taken from their respective niches in a totally interaction-independent manner.

For the sake of clearly exposing this argumentation, let us focus on systems where this type of cause-effect coupling is the only observable one (or where it is extremely predominant). If we are to explain – in purely relational terms – how the interaction structure dynamics generates structure-determined physical results affecting the whole system's structure or any locus within its spatial extension, we need to rely only on explanations concerning the localized activities of the "isolated" components. This is valid for explaining the emergence of all sorts of perturbation or disruption compensating mechanisms and, most importantly, the possible existence of component production transformations involving the participation of several components. This means that the *only available resources* for building up compensating mechanisms leading to the conservation of the system's identity *must be provided by the components themselves* and by exploiting their respective *separate niches*.

In these physical circumstances there is no other reasonable choice but to assume that components should be capable of *somehow coordinating their activities* via the prevailing interaction mechanism that couples them in order to generate collective responses and produce material effects anywhere in the spatial region where the unity exists. By *coordinated activity* I mean a succession of physical actions performed by several components in their localized environment as a result of structure-determined state transitions triggered in them by cause–effect couplings with other components pertaining to the same lasting interaction network.

Individual component's activity may have only a localized scope in physical space, and therefore, in order to *affect the whole system*, these local resources should be used to produce *patterns of coordinated activity among components* whilst the said components could well remain confined to their niches. If components are also capable of *displacing themselves beyond their original niches*, this could result in the occurrence of *physical encounters* between components that would otherwise remain separated. This would obviously enhance the odds that purely relational outcomes of causation flows within the spatially distributed interaction structure could "materialize" as effective physical outcomes, such as new component production.

The emergence of coordinated activity through cause-effect coupling means that components enter into sequences of mutually dependent state transitions or *activity patterns* that constitute triggering events for the manifestation of other activity patterns. If these activity patterns are able to propagate, reach any structural locus within the system's interaction network, and produce specific localized effects resulting in structure-determined material effects that compensate for external disruptive interactions and maintain organizational invariance, the *absence of spatial proximity and the presence of a non persistent "connectivity"* between components involved in triggering and caused transitions *would not hinder the system's ability to behave as a whole*.

In other words, what an observer would expect is that these activity patterns could lead mutually interacting but spatially separated components to reach states in which they can induce specific global network rearrangements capable of continuously maintaining the system's organization and the production of new components in a situation in which components are not necessarily spatial neighbors. This is a capability that we would expect to be observable if we were to identify a social dynamic system as being autopoietic, for instance.

Non-relational self-sufficient activity

The absence of persistent spatial "connectivity" between components of a dynamic system requires a great *self-sufficiency* of individual components, as they need to "react" to triggering activity patterns produced by far-away located components and produce caused activity patterns on their own. These activity patterns, once triggered, cannot be considered as explainable in pure relational terms at the scale of description of the whole system, as they are determined mainly by the local physical conditions prevailing in the component's niche. Nonetheless, they may be "modulated" – although not completely determined – by successive distant interactions by other system's components that impinge on the said component.

In this sense, the distribution of components over space imposes on observers a permanent shift between two spatial scales of observation and description, namely the scale of the overall extension of the unity (where the interaction mechanism manifests itself over distances) and the scale appropriate to observe and describe the components' localized activities in their respective niches. Furthermore, the observer needs to be cautious to *discriminate* the effects that are a *direct outcome* of distant cause-effect coupling from the *derived effects* due to the self-sufficient activity of components.

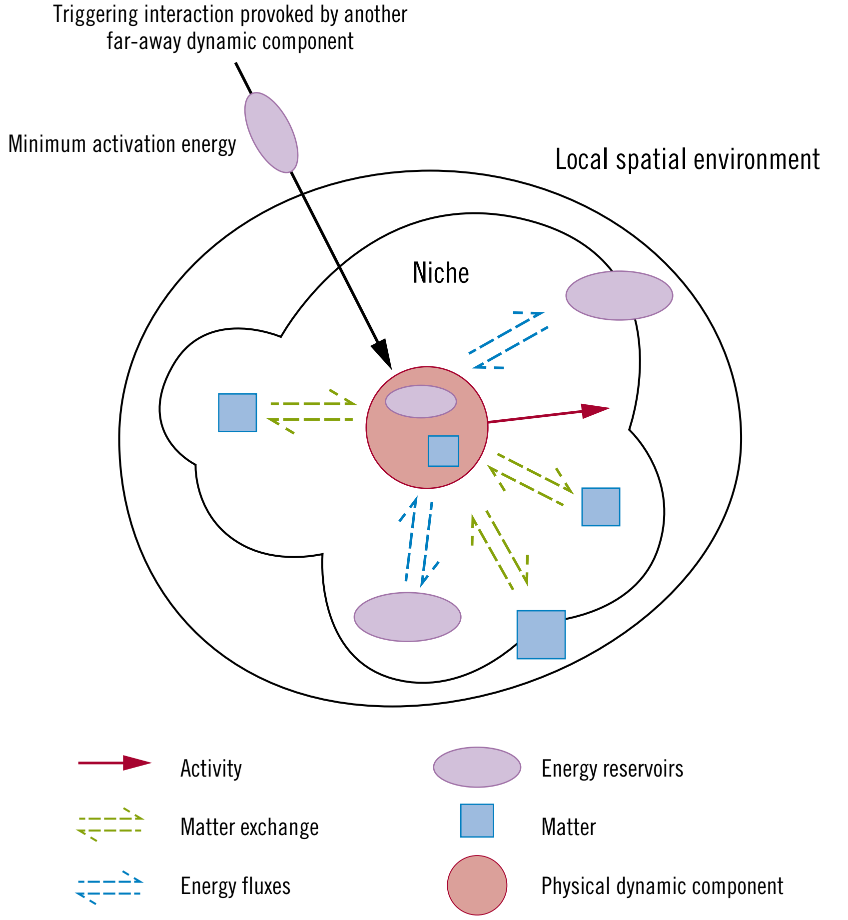

Figure 3: A physical component affected by a far-away source of causation flow reacts with an activity sustained only by local resources of matter and energy available in its niche, which has only a localized scope in physical space.

Temporal scales of description

The following considerations are expansions of an earlier discussion concerning time and causality that I exposed in Part 1 of this work (Urrestarazu 2011a: 311). The notion of time as commonly used in every day life and in most objectivist scientific approaches has been deeply discussed by Maturana:

> "Living takes place in the now, in the moment in which it is taking place. Living is a dynamics that disappears as it takes place… in no time, without past or future. Past, present and future are notions that… WE observers, invent as we explain our occurrence in the now. We invent past as a source of the now or present, and we invent future as a dimension that arises as an EXTRAPOLATION of the features of our living now, in the present. As past, present and future are invented to explain our living now, time is invented as a background in which past, present and future can take place. But life, living, takes place as now, as a flow of changing processes… The awareness that the [explanatory] notion of *time arises as an* ABSTRACTION from the coherences of the experiences of the observer…, is not a problem. What becomes a problem in the long run is the unaware adoption of the notion of *time as an explanatory principle* that is accepted as a matter of course giving to it a transcendental ontological status" (Maturana 1995; all capitalized emphasis are mine, italics are Maturana's).

In the following paragraphs I shall deal with the abstract operation of distinguishing regularities that arise for us (as observers) as the outcome of observations and descriptions performed at different moments in the dynamic history of an observed unity. Up to now, all that has been discussed in previous topics concerning distinctions about spatiality referred to interactions' structures observed and described as they

Research perspectives

These results obtained in this paper could be applied with the aim of exploring reliable possibilities of detecting autopoietic systems in the domain of social organizations and of showing rigorously what are the odds that this quest could be doomed or not doomed to failure. By applying this explanatory approach and its associated conceptual tools, a way is open to discuss more deeply the class-identity status of social systems: it could be worthwhile to assess to what extent social systems can be better described as possessing varying degrees of autonomy (Varela's notion) instead of focusing exclusively on autopoiesis. Results can also be applied to address the case of virtual dynamic systems designed in software environments, and show that in this domain it is essential to distinguish the notion of process – conceived as an abstract dynamic entity existing in an observational domain deployed over time and endowed with observable behaviors determined by phenomena occurring in a material processing substrate (hardware). These insights could then be used to analyze the possibility of exploiting the conceptual tools proposed in this explanatory approach to the design of virtual simulated autopoietic systems in software domains and contribute thereby to problems posed in computational autopoiesis.

appear to us at a "a given moment." But this is intrinsically an idealization because in most cases we cannot observe all that happens in all loci of a spatial extension simultaneously. We observe sequentially in our own successive "nows," and we extrapolate backwards to construe a synthetic picture of an instantaneous structure changing over time and describe it from within this abstracted *synchronic* perspective. When adopting a *diachronic* perspective, we can observe and describe the actual changes undergone by the interaction structure "moment after moment" and here we are also confronted with the choice of an adequate scale of temporal description if we want to identify regularities occurring in a timeline.

Instant and duration

Time-related descriptions of observed phenomena are subject to limitations derived from our perceptive capabilities as human observers and from the technical possibilities of measurement devices (clocks) that we may employ to observe the causal relationships that we wish to establish between dynamic objects undergoing state transitions. The notion of an instantaneous state, for example, is necessarily an idealization relative to the minimum time interval that we are able to discriminate with a clock. Any time interval that is lower than the unit time interval defined by our clock is an "instant." Any time interval that is equal or greater than the unit time interval is "duration." But if we use a higher resolution measurement device, an "instantaneous event" may be described as possessing "duration" in a lower scale of time description.

For example, time intervals separating significant low-level triggering quantum events in molecules can be resolved within durations of the order of picoseconds (10^{-12} seconds), whereas most resulting accomplishments of complex macromolecular events (typically, protein folding, for example) can be discriminated within time intervals ranging from milliseconds to microseconds (10^{-3} to 10^{-6} seconds) at the most. In this case, if the scale of temporal description was chosen such that the unit time interval was of the same order of magnitude as the "duration" of interaction propagation, the "duration" of triggering events could be considered as null (more than six orders of magnitude lower than the unit time interval in this case) and be properly called "instantaneous events."

Pertinent events

The choice of an adequate temporal scale of description, even if it is not bottom-level limited by the observer's clock resolution, is crucial for the observer's ability to distinguish the occurrence of *pertinent events* in a given observational domain. In the most general case, the unit time interval should be chosen to be lower than the smallest time interval separating pertinent triggering events as observed in a given observational domain for an identified interaction mechanism affecting the state evolution of dynamical objects. A description accuracy problem arises when the time separation between triggering events, the "duration" of the triggering events themselves, and the "duration" of interaction propagation are of the same order of magnitude. Stated in observational terms, this difficulty means that the observer would be unable to ascertain that between the initial state of a network node and its observed caused end state, no intermediate states have occurred due to the effects of other temporally indistinguishable triggering transitions that meanwhile occurred in other connected nodes.

A possible way out of this conundrum would be to distinguish *significant end states* from *insignificant intermediate states* by means of a suitable criterion. For example, the criterion could be the selective observation of major local changes of the graph topology in the causal vicinity of a considered node: if the graph topology remains unchanged (or just slightly perturbed) during the occurrence of intermediate states, the corresponding triggering transitions in neighboring nodes could be neglected in the overall description of the dynamics of the considered node's neighboring relational "volume" and be considered as *non-events*. In this sense, significant end states would be provoked by less frequent "significant" causation events and a higher temporal scale of description would be perfectly adequate. In our experience as observers of the molecular domain, for example, this situation is actually an unavoidable matter of fact because the complexity and "temporal density" of molecular structural changes is practically out of the reach of our analytical resolution power as observers.

Distinguishing processes

This consideration leads us to conceive the possibility of distinguishing interactions of a higher order: namely, state sequences of "internal" transition events occurring in a considered node that are correlated with transition events occurring in nodes

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of its relational neighborhood that can be *observed and described as a whole* within a certain time interval. This is nothing less than distinguishing the occurrence of a *process* involving the structure-determined activity of a certain number of nodes. If we express this back in terms of the behavior of dynamic objects existing in the observational domain, we could distinguish groups of components that enter into sequences of cause-effect couplings that constitute a local substructure interacting as a whole with the rest of the structure (and possibly with other similar groups of components). I remind the reader that in the most general case, the term "local" does not refer here to spatial locality, but to a "relational" topological vicinity in a multidimensional relational space (see Urrestarazu 2011a: 320). In this sense, these groups of components can be considered as the "processors" performing the said processes. Nothing prevents us from ascribing to these processors the status of components of a higher order dynamic system if we are able to ascribe them a suitable set of state-variables and consider their abstract representation as nodes of a higher order graph comprising the oriented relations that represent the cause-effect couplings between "processors" groups. This operation of distinction can be captured in language as a higher order abstraction made by the observer by means of the notion of *dynamic process*. This higher order observational entity may be properly understood as a *dynamic object* on its own, described from a diachronic perspective, and possessing a spatial extension related to the volume occupied by the physical objects involved in causation flows during the intervals between the occurrences of significant events.

I mean by this that to a "localized" subset of connected nodes, the observer can assign global collective states and selectively distinguish the "external" causal interactions (external with respect to the subset and coming from the rest of the overall causal graph) that determine the transitions of the subset taken as a partial whole. In this sense, the said processes may be considered to "exist" as dynamic entities in a higher level observational domain (not instantaneously, but within time intervals that are structure-determined by the internal dynamics of the said "processors").

This operation of distinction constitutes an observer-dependent change of perspective in which processes may be seen as interacting with other processes and be considered as components of a more complex system deployed over time. The resulting system, if circumscribable, pertains to a different observational domain, distinct from the observational domain where the lower order dynamic objects exist. Whether this system is autopoietic or not is an issue completely unrelated to the properties of the lower order system and its autopoietic nature needs to be assessed separately.

Interacting processes

Maturana and Varela have referred, since their earliest works (i.e., their definition of the autopoietic machine), to *processes of production of components* in general – and to molecular processes in particular – from the perspective that the coupling between *physical components* (i.e., molecules) gives rise to the relational structure that makes those processes operate, produce new components, and recursively regenerate the same kind of relational structure. Here, Maturana & Varela (1980: 79) distinguish the notion of the "… *network of processes* which constitute an autopoietic machine… in *the space of the components* that it produces" (emphasis is mine), by keeping the notion of *process* distinct from the notion of physical *component seen* from a *synchronic* spatial perspective (from which, processes are distinguished only as a background dynamics that produces *synchronic results* such as component activity and the components themselves). But later, Varela (1989: 46) emphasized further the idea that the *organization* of some dynamic systems is determined by the *relations*, *not between the components* of the mechanistic unity, *but between the processes* involved in component production within, that is to say that they could be considered as "components" within a *more abstract* and complex description of the system's structure.

These process-like components are necessarily distinguished from an abstract *diachronic* temporal perspective according to the ontological consideration concerning the notion of *time* by which "… time is a dimension in the domain of descriptions, not a feature of the ambience" (Maturana & Varela 1980: 133). This cannot be taken to mean that processes "represent" entities as if they were physical material objects, but as observable dynamic objects – as defined in this explanatory approach – *brought forth by the observer* from a diachronic perspective. I endorse here Siegfried Schmidt's views concerning the passage from distinguishing objects to distinguishing processes:

"Processes do not represent 'reality'; instead they produce real-for-us results. Without these results nothing could be represented or referred to… The coupling of processes results and their attribution as 'real-for…' must be socially accepted and thus intersubjectively confirmed." (Schmidt 2011: 4)

My point in discussing these distinctions is to show that the conceptual tools proposed in this explanatory approach may consistently be applied to address both the synchronic and the diachronic perspectives. Moreover, processes may be described as also interacting by means of spatially and chronologically distributed *causation patterns* (Urrestarazu 2011a: 319), which can also be perceived as successions of triggering events that are identifiable by observing the chronological/spatial regularities of their occurrence.

Conclusion

The choice of appropriate spatial and temporal scales of observation/description is not a trivial operation of the observer when it comes to observing dynamic systems demanding a careful distinction between phenomena occurring in the local spatial vicinity of components and in time-frames that we may consider as "instantaneous" and phenomena that manifest themselves over much wider distances and within time-frames that we may consider as possessing extended "durations."

One of the main obstacles appearing in the analysis of potentially autopoietic dynamic systems existing in meta-molecular domains concerns the explanation of possible component production transformations that could be consistently verified by applying the VM&U "validation test," and my proposed formal generalization of similarity component production transformations. From the perspective of this explanatory approach and by using its corresponding conceptual tools, the observer would be able to extend easily the notions discussed by Maturana and Varela for the case of spatially compact systems – namely, most of the aspects related to the topology of the relational structure of molecular systems – to observational domains where the system's components do not constitute an entity showing a topological "form" in physical space.

The spatial distribution of components involving no direct "material" interactions (only cause-effect couplings resulting from "signaling" interactions, for instance) poses a serious problem when observing and describing component production within the core of the system. In this case, component production/destruction transformations due to *purely relational* outcomes of cause-effect couplings cannot be accomplished other than as outcomes of components' coordinated activities performed in their spatially separated niches. In order to circumvent this difficulty, a diachronic perspective must be applied by observers in order to explain component production/destruction mechanisms as the outcome of processes involving structure-determined coordination over relatively long time intervals.

These considerations lead us to establishing a link with Varela's fundamental concept of *autonomy* by showing how the notion of process and the "the recursive interdependence of processes" (Varela 1981: 17) plays an important role in the definition of *organizational closure*, a concept that is intimately tied to describing *autonomous systems* ("Closure Thesis" in Varela 1981): a general class of dynamic systems from which the class of autopoietic systems is a particular case.

Acknowledgments

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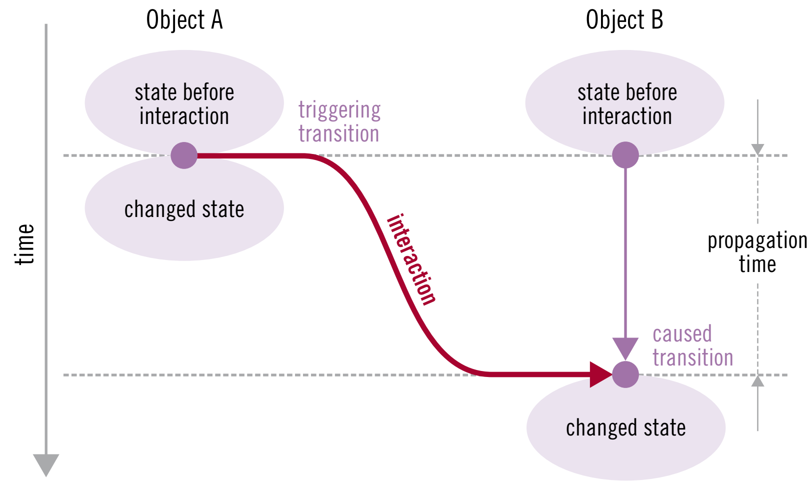

Figure 4: Observer's schematic description of a cause-effect interaction (from Urrestarazu 2011a).

Glossary of key concepts introduced so far

In Parts 1 and 2 (Urrestarazu 2011a, 2011b), I defined some key concepts that are invoked in many explanations and discussions proposed in this part. In order to facilitate the reader's understanding without requiring consultation of the previous papers, I provide here some summarized definitions without further discussion. For more detailed explanations, the reader should consult the references provided for each concept (with "c" referring to column and "p" to paragraph).

Dynamic objects

2011a: 314.c2.p1

Dynamic objects are defined as entities, agents, components (or whatever we want to name as physical entities existing in an observational domain) that are capable of performing changes of state. The *state of a dynamic object* is defined as a set of values ascribed to a number of variables or features that *the observer can associate* with the object at a given time. The chosen variables, called *state-variables*, should express quantifiable features that are subject to changes in the object's dynamics. The *values* of the state-variables should be describable and observable by the community of observers at any chosen time. A *state transition* (or change of state) of a dynamic object occurs when at least one state-variable value changes over time.

Boundary

2011b: 54.c1.p4

The boundary of a dynamic system is a subset of components that have reached states in which they are subject to external interactions. Boundary components may interact or not interact with other boundary components.

Causation structure

2011a: 317.c2.p1–3

The network of oriented relations represented by the graph associated to the interaction configuration constitutes the *instantaneous dynamic structure of the system*. It is a causation structure, i.e., the *path of propagation* for all the possible causal effects triggered by a transition occurring in any dynamical object whose equivalent node is "connected" to the graph.

Cause-effect coupling

2011a: 314.c3.p4–6

We distinguish a cause-effect coupling (interaction) between two dynamic objects *A* and *B* (see Figure 4) if a state transition in object *A* (triggering or causing transition in *A*) is the condition sine qua non of a state transition in object *B* (a triggered transition in *B*). The latter means that:

a | in the absence of any other cause-effect coupling between *B* and any other object different from *A*, the caused transition in *B* never occurs before the occurrence of the triggering transition in *A*; and

b | whenever objects *A* and *B* are in a specified state and a specified triggering transition in *A* occurs, the same caused transition always occurs in *B*, within a finite time interval.

The mechanism responsible for cause-effect coupling between dynamic objects is not specified, but it is assumed to exist.

Component

2011a: 317.c2.p4

A dynamic object *X* belongs to a dynamic structure if there are one or more dynamic objects coupled directly to *X* by an interaction represented by an oriented relation "pointing" to *X* and all of them are coupled in the same way to each other at a given time. Such an object is called a component of the structure.

Core

2011b: 54.c1.p5

The core of a dynamic system is a subset of components having reached states in which they are not subject to external interactions. Core components may interact or not interact with boundary components.

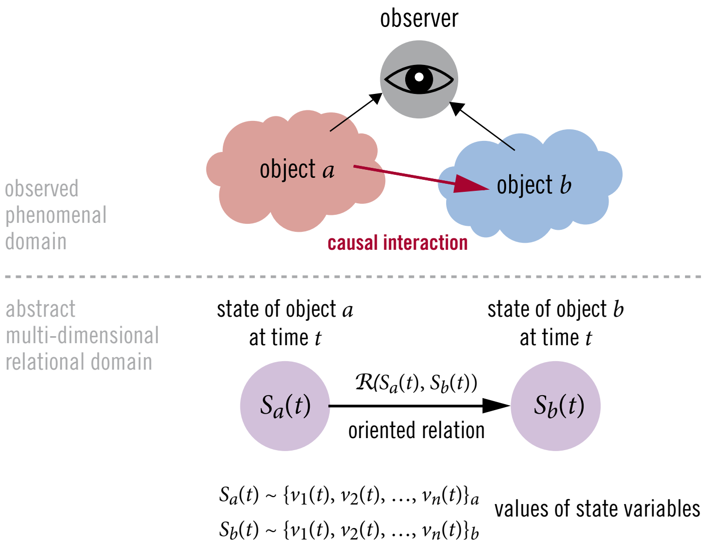

Figure 5: Abstract representation of an observed interaction as an oriented relation in a multi-dimensional relational space (from Urrestarazu 2011a).

Dimension

2011a: 315 Figure 2; 318 Table 1

The dimension of a *node* (pertaining to a causation structure's graph) is defined by the cardinal number of the set of state-variables ascribed to the dynamic physical object that the node represents in abstract terms. The node is defined as a "point" in a multi-dimensional space (i.e., as an *n*-tuple $\{V_1, V_2, ..., V_n\}$, where the V_is are the state-variables and *n* is the number of state-variables considered.

Dynamic system

2011a: 315.c1.p8

A general dynamic system is defined as a set of dynamic objects linked together via cause-effect coupling (i.e., causal interaction) and seen as an interaction network that can be represented by an *equivalent graph* in which each node corresponds to a multi-dimensional point and the edges correspond to the oriented relations linking them.

Equivalent graph

2011a: 316.c3; 317.c1; Figure 3

This is a graph made of nodes and edges representing a network of interactions between multiple dynamic objects existing in a given observational domain, where the nodes represent the interacting objects at a given time and the edges represent the interactions as oriented relations established between them through observation.

Environmental object

2011a: 317.c3.p5

A dynamic object *Y* does not belong to an identified (observed) dynamic structure at a given time if there is no direct cause-effect coupling linking *Y* to any member of the identified structure such that the corresponding oriented relation "points" to *Y*, even if there could be oriented relations originated in *Y* and "pointing" to one or more components of the dynamic structure. Such an object is said to belong (at a given time) to the environment in which the structure emerges.

Medium

2011b: 53.c3.p1

The medium of a dynamic system is the set of all dynamic objects existing in the observational domain that do not belong to its structure (i.e., that cannot be represented as connected nodes of the equivalent graph, but can be described by means of the same set of state-variables). The medium is a part of the environment, namely the collection of those dynamic objects that are potentially capable of becoming components of the dynamic system. A system component interacts with the medium if it interacts directly with at least one dynamic object of the medium (i.e., it is "sensitive" to a state transition occurring in the latter). An interaction of a system component with a medium object is called an *external interaction*. All other interactions affecting a dynamic system component are called *internal interactions*.

Observational domain

2011a: 307.c3.p2–308.c1.p2

The meaning ascribed in this paper to the term "observational," as derived from terms such as "observing" and "observer," is meant to correspond to the notions explained by Maturana (1988). The term "observational domain" refers to any domain of perceived phenomena in which we, as human observers, can perform sensorial and operational experiences through interactions with the observable entities under consideration. It is assumed that any observational domain is a physical domain and that ordinary physical laws are applicable in it. These interactions should occur as phenomena pertaining to our own biological domain (i.e., phenomena of our own direct sensorimotor perception capabilities) or as indirect biological effects resulting from the use of suitable transducers (measurement apparatus). Hence, the attention is focused on the occurrence of humanly observable and describable events occurring in what appears to us as the ordinary physical space. This definition can be extended to software entities evolving in a virtual space since all simulated virtual "objects," "events," "causation flows," etc., correspond to strictly isomorphic and traceable physical events occurring in a material substrate (hardware) that – by virtue of being humanly designed – is entirely accessible to human observation.

Oriented relation

2011a: 315.c1.p.7

A cause-effect coupling can be represented formally as an oriented relation (see Figure 5) in an abstract multi-dimensional relational space (linking multi-dimensional points with as many dimensions as the number of variables considered in the associated state-variables set). A dynamic object can be represented by a point in a multi-dimensional space and an interaction as an oriented relation (ordered pair of points). The order of the pair is defined by placing the object undergoing a triggering transition first, followed by the object undergoing the transition caused.

Same kind components

2011b: 61.c2.p1

Two dynamic objects are considered to be of the *same kind* if their dynamic states at a given moment can be described by the observed state-variable values of a unique set of variables common to both objects, i.e., they share the same multi-dimensional relational space.

Similarity component production transformations

2011b: 62–63, Section "A generalized description of component production mechanisms"

The following is a summary of the relational aspects involved in the production of similar components through three basic mechanisms:

a | *similarly separable* node: due to cause-effect coupling a node can *split* and result in two or more nodes representing components of the "same kind";

b | *similarly compoundable* node: due to cause-effect coupling, two or more nodes can *merge* into one node representing a component of the "same kind";

c | *similarity co-producer* nodes: due to cause-effect coupling, two or more connected nodes can *participate in the creation* of one or more nodes, representing the buildup process of new components of the "same kind."

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