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Complexity, Information and Autopoiesis: An epistemological and geometric approach

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PhD in Complexity Sciences

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To the Most Holy Trinity - Communio Amoris, Relatio Subsistens, Ipsum Esse Subsistens,
Ratio Sui, Bonitas, Sapientia et Ipsa Pulchritudo;

and to the Immaculate Heart of Mary.

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Resumo

Nesta tese introduzimos o conceito de substância para descrever os objetos do mundo natural que são ontologicamente independentes e mostramos que as substâncias são compósitos hilomórficos, i.e. compósitos de forma e matéria. A forma desempenha um papel crucial na determinação de simetrias e da unidade das substâncias enquanto totalidades complexas. Discutimos também um tipo particular de totalidade complexa caracterizada pelo alto grau de autonomia chamada autopoiése. O nosso objetivo é demonstrar que reinterpretando a organização autopoiética enquanto forma substancial, e com base em recentes avanços na física da informação, bem como recuperando o conceito clássico de informação baseado na forma, podemos conciliar o conceito de informação com a teoria da autopoiése.

O modelo de autopoiése usado foi o autómato de tesselação. O autómato de tesselação modeliza uma estrutura dissipativa subjacente ao processo de reparação da membrana celular. Este modelo foi utilizado para descrever o papel do processamento de informação na auto-produção da organização autopoiética.

Foi apresentada uma quantificação da complexidade desta estrutura dissipativa e da sua viabilidade termodinâmica com base em métodos geométricos e da teoria da informação, tais como a métrica de informação de Fisher.

Concluímos que o conceito de informação não é somente compatível com a teoria da autopoiése, bem como essencial para salvaguardar a primazia ontológica da organização autopoiética sobre as suas componentes, como a teoria original pretende. Concluímos também que tomando a informação enquanto quantidade física, esta adquire um papel crucial na medição do grau de complexidade e autonomia do sistema, mas também na determinação da sua eficiência termodinâmica.

Palavras-chave: Complexidade; hilomorfismo, autopoiesis; informação; estruturas dissipativas; autómato de tesselação; métrica de informação de Fisher

Abstract

We introduce the concept of substance to describe those objects of the natural world which are ontologically independent, and show that substances are hylomorphic composites, i.e. composites of form and matter. Form plays a crucial role in determining the symmetries and unity of substances as complex wholes. Furthermore, we discuss a particular kind of complex whole characterized by a high degree of autonomy called *autopoiesis*.

Our goal is to show that by reinterpreting the autopoietic organization as a substantial form and based on recent advances in the physics of information, as well as recovering the classical conception of information based on form, we can conciliate the concept of information with the theory of autopoiesis.

A model of autopoiesis is the tessellation automaton. The tesselation automaton models the dissipative structure of cellular membrane repair, which we use to illustrate the role of information processing in the self-production of autopoietic organization.

We present a quantification of the complexity of this dissipative structure and its thermodynamic viability using geometric and information theoretic tools such as the Fisher information metric. We conclude that the concept of information is not only compatible with autopoietic theory but also essential to preserve the organization's ontological priority over the components, as the theory originally intends. Moreover, by treating information as a physical quantity, it acquires a crucial role not only in measuring the degree of complexity and autonomy of the system but also in defining its thermodynamic efficiency.

Keywords: Complexity; hylomorphism; autopoiesis; information; dissipative structures; tesselation automaton; Fisher information metric

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CHAPTER 1

Introduction

1.1. General presentation of the research topic

Being is the cornerstone and that which is primary in our experience of the world. The natural world presents to the observer a variety of objects of different nature, properties, composition, among others, whereby each object has its being in the fabric of space-time. Those objects of the natural world which are both *emergent* and *autonomous* beings are called *substances* [1] [2][4].

Substances are those objects that are fundamental to the natural world, that is, they are objects whose being is irreducible to that of its constituent parts, or confused with a greater whole that encompass them [2]. In other words, they are ontologically independent objects that exist in an autonomous fashion, being neither inherent in, nor predicated of, other objects [1] [2] [3].

Moreover, substances produce motion. A motion can be produced by external forces and/or internal fluctuations. By being in motion the substances suffer changes in their structure and in their properties. Motion is defined here in its most general sense as the *reduction of potentiality to actuality*. For something to undergo a process of change there must pre-exist a capacity to acquire a different configuration, or to be in a different state and/or trajectory.

Now, based on the metaphysical composition of actuality and potentiality, we know that substances are also composed of *form* and *matter*, with form being correlated with actuality, and matter being correlated with potentiality [1][2][6]. The composition of form and matter is called hylomorphism [6]. The form denotes that which is invariant in the substance, that is, its nature, while the matter denotes the changeable material-energetic constitution of the substance. While the form, being correlated with actuality, is the ordering principle of the matter and the principle of activity and motion of the substance, the matter, being correlated with potentiality, plays the role of a boundary of the form’s activity. At the same time, the matter also manifests the form in the physical space as a concrete entity with a particular material-energetic constitution.

As uniform beings burgeon into intricate and diverse structures, whose boundaries are often ambiguous, the observer is overwhelmed by the variety that is presented to his mind, but at the same time, it can still make sense of reality by discerning certain regularities, patterns and periodic occurrences. When we examine the natural world, however, we can see that there is more than just loose aggregates of things but, rather, there are actual *integrated* wholes [12][15][19][20][21] that subsist by themselves and distinguish themselves from the rest of the environment they inhabit, through their own powers and operations. It is true that we, as observers, make distinctions regarding what objects we conceive and those distinctions and conceptions are in part filtered by our biological limitations, our cognitive and symbolic domains and practical needs (as in Heidegger's being-in-the-world or *Dasein*). However, certain objects, or unities in the language used by Francisco Varela, have a capacity for asserting their individuality as consequence of the unity's phenomenology. These are not mere agglomerations of parts but coherent and truly integrated wholes which are called *complex systems*.

But what is complexity exactly? There is no exact, much less agreed, definition of what complexity is, but there are some principles and properties that are agreed upon by scholars that are common to complex systems. Properties such as dissipative structures, dynamical instabilities, self-organization, hierarchy and emergence are some of the most discussed [23].

There is, yet, a special kind of complex systems that *self-produce their own components and boundaries*, distinguishing themselves even more radically apart from their environment, called *autopoietic* systems [28][29][30]. Autopoietic systems are composed of *organization* and *structure* [29][30][34]. Organization is that which is *actual, natural* and *invariant* in the system, that is, that which in the theory of hylomorphism is called the form. Structure, in turn, denotes that which is *potential* and *variable* in the system, which in the theory of hylomorphism is called matter. The form-matter and organization-structure compositions form a *composite unity* [34].

The phenomenon of autopoiesis has been discussed as taking place in cellular and neurobiology as well as in sociology, although there is some controversy in the application of the concept [30][32]. Autopoietic systems are highly evolved systems that operate in the midst of order and disorder. In order to maintain themselves in hostile environments, in a self-referent cycle of reproductive operations, these systems develop efficient ways of harnessing thermal resources from the outside and fuel their own internal operations.

One of the difficulties that the theory of autopoiesis poses is whether autopoietic systems are open or closed systems; whether they are teleologically driven and process information like other systems that we are more familiar with from cybernetics and control theory, for example.

The problem, however, is that the notion of information as it is usually understood is not compatible with the phenomenology of autopoiesis at all, or at least is only relevant in the observer's symbolic domain when interacting with the system. Maturana and Varela, who developed the concept of autopoiesis, regarded information as something representational, an external concept that is imposed on the autopoietic system [30]. A psychological interpretation of information, based on the workings of human cognition and sensitive experience, is not suitable to the organization of a system that has its own phenomenology and that manifests itself in the world not through the concepts we use to describe it but, rather, through its very own organization. What we mean by information as a representation of something in the environment has no meaning in an autopoietic system whose organization and operations are of a totally different essence. Not only that, but the very notion of representation is not conceivable in the theory of autopoiesis because the system looks at its environment based on the measure of its own organization and sees only insofar as its organization allows it to see. In some sense, one could say that the organization of the system 'produces' the environment, such is the degree of self-reference that autopoiesis entails.

However, we argue in this work that if we recover the classical conception of information, rooted on the notion of hylomorphism, and make use of recent advances made in the physics of information it is possible to conciliate and make sense of information in autopoiesis. We build our argument based on other solutions that have been developed to conciliate evolutionary and teleological concepts with autopoiesis by Di Paolo [37].

Due to recent advancements in the physics of information [40][41], it has been shown that information itself can be considered a thermodynamic resource that the system can use. From this point of view information is not a mere unit of sensation or something representational but, instead, information is physical and an *organized pattern of matter and energy* [36][39][41][42][44].

Given this reinterpretation of information, complex and autopoietic systems can be modeled as *information engines* [41][42]. Information engines are simple models, usually described as dynamical systems, which aim to portray how systems in nature manipulate, store and process matter, energy and information. The information engine models demonstrate how the system has to account for its thermodynamic constraints and that there are certain thermodynamic tolls associated with processing information.

In certain models of information engines, such as [41], at the end of a thermodynamic cycle that uses information to produce useful work there is an information erasure operation that produces energy dissipation. In effect, the energy dissipation associated with the erasure of information results in a *contraction of the system's phase space volume* through which a *dissipative structure* is formed. The reduction in the volume of the phase space means that the system has stabilized in an *attractor* that lies between order and disorder.

An example of a dissipative structure that describes the process of formation, maintenance and repairing of cellular autopoiesis is the tessellation automaton [43].

The tessellation automaton is characterized by at least two attractors - a thermodynamic equilibrium in which autopoiesis ceases to exist, and a dissipative structure that is capable of supporting life and autopoiesis. Between these two attractors, or bases of attraction, there is a bifurcation point. The smaller the distance between the bifurcation point and dissipative structure the greater will be the thermodynamic viability of the system.

The degree of complexity of these dissipative structures and the thermodynamic viability associated with the transition to a dissipative structure can be assessed through geometric and information-theoretic tools such as the 'information fluctuation complexity' measure, information manifolds and the Fisher information metric.

1.2. Research proposals

To summarize, in this work we propose to i) conciliate the concept of information with the theory of autopoiesis based on a classical interpretation of information which stems from substantial form and on recent advancements in the physics of information. ii) After arguing for this conciliation, we propose that autopoietic systems can be mathematically treated through the perspective of information engines and we present an informational interpretation of cellular autopoiesis based on the tessellation automaton. iii) Finally, we propose the use of information theoretic and geometric tools such as the ‘information fluctuation complexity’, information manifolds and the Fisher information metric to quantify the degree of complexity and thermodynamic viability of autopoiesis. The consequences of this method is that this allows us to study autopoiesis *as organization in itself*, without having to look at the individual components which entails a break of unity and the phenomenological reduction of organization.

CHAPTER 2

State of the art

Our research proposal is based on propositions and developments made in four main theoretical frameworks where philosophy and science intersect, namely, ontology, epistemology, thermodynamics and complexity theory, and the theory of autopoiesis.

The concept of substance originally comes from Aristotelian metaphysics and aims to explain the permanence and unity of beings that exist in a changing world. From Antiquity and throughout the medieval period onwards, the concept of substance was widely discussed and developed and became pervasive in Western philosophy until it fell into disuse with the surge of reductionist paradigms. However, since the advent of quantum mechanics and complex systems science, which exposed the limitations of reductionist paradigms such as atomism, there has been a renewed interest in Aristotelian philosophy and in the concept of substance, which views complexity as something fundamental and insists on the maxim that the whole is more than the sum of its parts. Recently, there has been a Neo-Aristotelian revival not only in philosophy but also in quantum physics, biology, dynamical systems and mathematics.

Although the concept of substance is a concept from metaphysics, it is related to the concept of system adopted in general systems theory, thermodynamics, complexity sciences, and the theory of autopoiesis. In fact, Carnot referred to thermodynamic systems as "working substances". As we will see, having the notions of substance, subsistence and being as touchstones of our theoretical framework will be crucial to criticize Maturana's conception of autopoietic organization, in order to make it compatible with the concept of information and recent developments in the field of information physics.

Therefore, this state of the art will first investigate basic concepts such as substance, subsistence and being, how these relate to questions of composition and the existence of composites that form complex wholes irreducible to the sum of their parts.

We then present some of the main conclusions of general systems theory and complex systems science, paying particular attention to the phenomenon of self-organization and how a series of thermodynamic factors and constraints affect the phenomenon of self-organization in complex systems. The aim is always to understand how nature processes flows of matter, energy and information taking into account a series of thermodynamic limitations and advantages that it encounters in the formation of complex and self-organized patterns.

Another point of great importance to investigate in the literature is the relationship between self-organization and autopoiesis. Although all autopoietic systems are self-organizing systems, not all self-organizing systems are autopoietic systems. Autopoiesis is presented as the minimum and sufficient requirement for the existence of life and is, therefore, more restrictive than self-organization, which applies to living and non-living systems alike. Therefore, some of the properties of self-organization are accidental to autopoiesis and, thus, not essential to its definition as such. That is, the autopoietic system acquires these properties through its history of interactions with the environment. This distinction between what is essential and definitional to autopoiesis and what is acquired or accidental is based on the metaphysics of substance previously presented. It is from here that the original argument of this thesis starts, which rethinks the autopoietic organization and conciliates autopoiesis with information, as has been done elsewhere, for example, for autopoiesis and teleology.

2.1. On the concept of substance

The concept of substance is one of the most important and discussed in the history of Western philosophy, being first systematically expounded by Aristotle and later into the early modern period discussed by Descartes, Spinoza, Leibniz, Locke, Hume and Kant [1]. Substance was also an object of interest and philosophical inquiry in the history of Arabic and Indian philosophies. In contemporary philosophy, substance theory has been applied to a series of problems in metaphysics and science, such as the theory of autopoietic systems [34], systems biology [13], the problem of consciousness [10] and quantum physics [10].

2.1.1. Substance and subsistence

Substance, in Greek *ousia*, means “being”, or a particular thing that exists [2]. Ousia was latter translated, under the concept of *hypokeimena*, to Latin as *substantia* which means “that which stands under or grounds things”, or that which bears properties [1].

In metaphysics, a substance is a particular thing that *subsists* in itself, that is, a particular thing whose existence is irreducible to that of its constituent parts, or confused with a greater whole that encompasses it [2]. In other words, it is an ontologically independent thing, that exists all by itself, in itself, and in an autonomous fashion [1][2][3], being neither inherent in, nor predicated of, other objects [2][3].

There is no consensus among philosophers as to an exhaustive list of objects which constitute examples of a substance [2]. There appears to be an agreement that those objects that belong to the biological realm, that are ‘organic’, are the canonical examples of substances such as molecules, cells, developmental modules, living organisms and human persons.

Moreover, that which is most fundamental to *that which is* is the way in which a substance exists, which establishes and delimits *what* the objects are in their nature, that is, its *subsistence*. Subsistence is defined as the self-contained mode of existence or, in other words, the existence of something for itself and in itself [3]. For example, *this* cell, *this* living organism or *this* person existing in this particular manner, for and in themselves, and not in any other thing or manner. Hence, subsistence is the order to existence that is proper to a substance.

2.1.2. Causal powers, dispositions and the laws of nature

The Eleatic Principle establishes that being, as such, entails the possession of *causal powers* [2], that is, to have being is to cause or have the ability to cause and produce effects. Causality can be of two kinds: transient and immanent [5]. A cause is said to be transient when the effects affect, and have *terminus* in, that which is external to the substance. Whereas in the case of a living organism, for example, transient causality is complemented by immanent causality, whose effects remain, and have *terminus,* within the substance itself. Living substances, due to the presence of immanent causality, are also subject to internal *fluctuations*.

While on the one hand the concept of substance is related to invariance, on the other hand, we can’t grasp a substance without taking into account its operations, activities and manifestations. While we may know substances by their subsistence and relative stability in space and time, such that we can apprehend a certain regularity in the mind, it is also the case that we can only know substances through their acts in the natural world. The importance of the concept of substance comes precisely from the fact that everything changes and that it is impossible for an object to be twice in absolutely the same state.

In reality, all substances undergo processes of change, but not all changes are of the same kind nor of equal depth; some changes affect only external aspects of the substance that are not fundamentally tied to its identity, while others are more radical such as to transform one substance into an altogether different thing. In this way, one may recognize that, evidently, everything that exists in nature is in a process of change and, at the same time, to recognize that there is regularity, or better still, *invariance* despite the constant flux of the world.

Moreover, in the process of change, *properties* are lost and gained. We are talking about all kinds of attributes, predicates and qualities that can be predicated of an object, some of which are quantifiable such as mass, dimension, length, tension, torsion, among others.

Furthermore, let us distinguish between two classes of properties: *categorial* and *dispositional* [2]. The former describes what the substance *actually* is, while the later describes what the substance can *potentially* be, that is, its *capacity.*

According to Koons and Pickavance [2], dispositional properties are the subjects of true counterfactual conditionals, that is, of statements of an "*if..., then...*" form. Dispositional properties, insofar as they describe what a substance can potentially be, tie the presence of causal powers to the truth values of counterfactual conditional statements. It is in this tie between the causal powers of substances and the truth of counterfactual conditionals that the *laws of nature* emerge.

Consider the following example from physics. The inertial mass of a body can be conceived as the disposition to react to the application of a force and manifest, as a result, an acceleration in proportion to the applied force. Now, in this example we have an agent that exerts causality upon the body, that is, it applies a force to the body, the effect of which is the acceleration of the body in proportion to that force. As we can see, there is a proportion between the cause and the effect that is rooted in the inertial mass of the body which plays the role of a dispositional property. Hence, the resulting effect from applying a force to the body and the truth value of the counterfactual conditional describing the situation give rise to a law of nature that governs all the situations where the same causal relation and dispositional properties are present.

So far, we have talked about causal powers, dispositional properties, counterfactual conditionals and laws of nature and the way they relate to one another. However, there is still to answer the question regarding which of them is metaphysically fundamental. Given that in this work we are committed to the Aristotelian perspective, we adopt the metaphysical requirements that this perspective carries, among which is the commitment to a powers ontology where causal powers and dispositional properties are taken to be fundamental and the ground for the validity of the laws of nature and the truth of counterfactual conditionals [10]. Thus, the causal powers, which flow from the essences of substances, are modal properties on which the laws of nature are grounded [2].

In order for the laws of nature to play such a role in the universe as to determine which natural phenomena are possible of being realized, they must be invariant. The invariant and necessary character of the laws of nature cannot be rooted in ephemeral or non-essential properties of the substances but, rather, in things of a higher degree of permanence such as the nature of substances themselves [2].

The notion of the laws of nature is intimately related to that of *symmetry* [16]. Under a symmetry operation the relation between two properties does not fail to hold even if there are changes with respect to other non-fundamental properties, such as changes with respect to the coordinates describing such relation.

Furthermore, we hold that the laws of nature are emergent with respect to the substances, that is, the laws of nature are not something imposed by the outside world, rather, the laws of nature are derived from the properties of the substances themselves, and the unique ways in which their powers and dispositions are distributed [2].

2.1.3. Substances as composed of actuality and potentiality

As we saw in the example of the body that is subject to a force, we are faced with two kinds of causal powers: *active* and *passive*. The active power is exerted by the agent that applied the force to the body, whereas the passive power to be accelerated in proportion to the applied force is attributed to the body as the patient of the active power of the agent.

The exercise of active and passive powers occurs concomitantly. When the patient incurs a certain change by virtue of being affected by an agent's active power and, retroactively, a change is also produced in the agent by virtue of exercising that causal power, then a new relation is established between the two objects.

Hence, substances have simultaneously active and passive powers. They host both kinds of powers and thus, are both agents and patients with respect to the objects they can be in relation with. Based on this distinction we can now talk of the metaphysical composition of substances in terms of *actuality* and *potentiality* [1][2][5].

While actuality is equivalent to being, potentiality however is similar both to being and to non-being. This is so because potentiality limits being, but at the same time it makes no contribution to being itself other than a negative, limiting influence. It is through the potentiality, as principle of relative non-being, that there is difference of instantiation among the objects in the world because each of these objects has different subsistences. In other words, being is the same for all objects abiding in the world. There is no multiplicity in this being as such, the multiplicity comes from the limiting influence played by the potentiality which by contracting the actuality produces that multiplicity we see in the world.

The composition of substances into actuality and potentiality is the basis for the theory of hylomorphism, as we discuss bellow.

2.2. Hylomorphism

With the distinction of actuality and potentiality on the background, Aristotle held that substances are composites of *form* and *matter* [6]. This metaphysical composition is called *hylomorphism* where, in Greek, *hyle* means 'matter' and *morphe* means 'form'.

Aristotle presents two arguments for hylomorphism, where each argument has a different motivation. Aristotle provides the *argument from change* for hylomorphism, where he posits that the composition of form and matter is necessary to explain change in the world, while maintaining that the integrity of substances persists during the process of change. Another argument that Aristotle provides is the *regress argument* for hylomorphism, where he posits that the composition of form and matter is necessary to distinguish between real *composite unities*, or unified wholes, and mere aggregates of matter, or heaps. Aristotelians consider that the components of a composite unity are organized and joined together in a novel way that collectively contributes to the persistence of this unity, whereby the whole really is *more than the sum of its parts* [2][6][12].

In this work we will focus on the motivations of the second argument for hylomorphism.

Before proceeding to explain what exactly form and matter are, it is useful first to say what they are not, in order to better highlight the reason why these two metaphysical concepts are so relevant to contemporary science, in particular to the science of complex systems. In the classic example used to exemplify hylomorphism, the form concerns the shape of a statue and the matter concerns the clay from which the statue is made [6].

Now, even though the example of the statue is a simplification, it is important to note that what we call form is not a shape, it's not even a polyadic relation, but the actuality, or active power, of an object, that is, its operative nature as a particular being that actively exists in space and time. In turn, matter, should not be restricted to something like the clay of a statue but should be understood as potentiality, such as energy fields [13], or symmetries [17]. Therefore, the relevance of hylomorphism is based on the correlation between form-matter and actuality-potentiality in a way that encompasses a wide range of systems and phenomena that do not fit well into the more familiar examples of our ordinary experience.

In this sense, substances are defined with respect to form and to matter, the first being a formal definition and the latter being a material definition. The formal definition concerns those aspects of the substance which are irreducible, emergent and of a higher-order. The material definition, however, concerns the collection of components, or parts, which are connected according to a certain *normative pattern* imposed by the higher-order reality of the formal definition [6][8][9][11][12][14][15].

2.2.1. The role of form

Various contemporary philosophers [6] concur that form plays an important role in defining composite unities, however there are disagreements as to what that role is exactly. Some philosophers [9] interpret the form as a mereological constituent, that is, as being an additional part of a composite. Others such as Koons [9][15], Marmodoro [11][12] and Skrzypek [14], more in line with Aristotle's view interpret the form as a *principle*.

We adopt the latter view where form is interpreted as a metaphysical principle, having the nature of an *operation* or *process* [9], in which the matter participates in and acquires a certain configuration. In this view, the form is not a part, like the organs are part of the body, but the process through which the relations of parthood and integration of the whole are defined.

For the form to be an operation that imposes a certain pattern or configuration on the material parts means that form is an active power, a power that is necessarily actualized and that it cannot fail to be in act if such configuration of material parts is to be maintained. In this sense and according to Skrzypek [14] we must account also for the fact that such a power is always manifested, that is, *in act*. It is not enough to possess the power, the power must be activated for the form to sustain a substance existentially [14].

The form determines also the type of material constitution and parts that the composite unity can foster because potentialities are not randomly distributed or unbounded. If matter was randomly distributed and was not informed by the form, the phenomenon of subsistence and structural plasticity would not be possible, as the unity would be constantly dissolving.

Finally, as a metaphysical principle, form plays a role in grounding i) the similarity between different substances and symmetries and ii) the unity of substances. In order to play this role, the form must fulfill a few metaphysical requisites, namely, it must be *ontologically prior* and *logically simple* [15].

2.2.1.1. Symmetries

Forms must be ontologically prior in the substances they inform, for otherwise it would not be possible to have a common ground between different substances, or to establish objective relations of similarity. In order to obtain an objective relation of similarity it is necessary to exist a common nature between the two substances. Only natural properties can ground similarity as non-natural properties are not necessarily beared, and it is the role of nature, not the observer, to determine which properties make something more similar to another [16].

The natural properties of substances flow from the form. These properties, being natural, must be realized by necessity and, although they are truly immutable and inevitably present, their expression as concrete physical quantities can take on a variety of values. For example, the form of a square entails that a square figure necessarily has four sides of the same length and four right angles. Having four sides of equal length and four right angles are natural properties of the square which are measured in the quantities 'length' and 'angle'. As a result of the invariance of the form, the presence of these physical quantities is imperative to study transformations and similarities between particular squares.

Thus, to distinguish those properties which are natural and fundamental from those which are not, and to grasp their role in relations of similarity we must take symmetries into account.

The concept of symmetry is multifaceted and has undergone developments throughout history in philosophy, geometry and physics [17]. It was first treated in the philosophy and geometry of Ancient Greece. Originally, symmetry was interpreted as a relation of commensurability, and represented harmony, regularity of parts and unity [17]. Later on, this was generalized to mean proportionality, or a relation of proportion, which harmonizes the different components into a unified whole.

Despite the importance of symmetries in philosophy, the greatest success of this concept is in geometry, algebra and physics. For instance, symmetries have been successfully used to study the invariance of the laws of nature, dynamical systems, and particle systems, specifically in determining the ontic status of certain particle.

The algebraic and geometric definition of symmetry according to group theory is perhaps the most used and fruitful conception of symmetry in the field of modern physics. However, this does not mean that symmetries are no longer related to the notions of harmony, regularity and unity of substances, as Brading and Castellani [17] note.

Symmetries are like a mathematical and physical reflection of the metaphysical structure that the form gives to the properties of a substance. Precisely because of this intimate relation with form, symmetries also restrict which set of transformations a certain substance can undergo without compromising its identity and unity.

We can see that by viewing the form as an abstraction of a concrete substance, we find in the form an idealization of the structure that must exist between the properties and parts of the substance as a material composite. What we mean here by an abstraction is the conceptualization we make in our minds based on numerous substances of the same kind that we engage with in the world. Let us consider another geometric example: in the study of geometry one encounters various examples of squares, and despite the different colors and length their sides may have, we can abstract in our minds an ideal square based on the natural property of having four right angles, irrespective of other properties such as color or length which are not essential to the definition of the square. This abstracted or ideal square has the property of having four right angles most perfectly, but when we compare this ideal square to the concrete squares of the material world we see that there is a lacking of perfection, or a lesser-symmetry, as the material world examples of squares do not have four perfect right angles due to the limiting role that matter has.

The structure of properties and parts does not exist in an abstract form but exists only in the physical space, instantiated by concrete material parts and through concrete physical processes that place properties and parts in concrete structural relations. And even though this material and concrete structure is possible due to the action of the form, the instantiation of this structure will always be less perfect than the form considered in the abstract, due to the friction and limitations of matter. In other words, there is an inevitable physical cost associated with bringing about the structure of properties and parts that is encoded in the form.

2.2.1.2 Substantial unity

When it comes to the unity of substances in space and time we must reconcile two facts: that substances exist as particular beings which have a certain unity, and that the structure of those substances, in terms of its properties and parts, have complex structures and a certain multiplicity. So, the problem is one of reconciling unity with multiplicity.

In order to reconcile both of these notions we must posit forms to be logically simple [15]. For only simple things can play the role of a source of unity and *resolve* a complex structure of properties and parts into a unitary principle.

The multiplicity of the complex structures of the natural world is a result of the forms operating on matter which produce *informationally rich mosaic-like* structures. In the science of complex systems we find a similar principle in which a set of very simple rules in a simulation of a cellular automata gives rise to very complex patterns of behavior [24][25][26]. It is in the logical simplicity of form that we can assert that there is an irreducible unity that distinguishes a real composite, or whole, from an aggregate of matter whose structure and multiplicity cannot be traced to a single principle that eminently contains that structure in a simple and unified way, but instead, the source of such multiplicity must be discovered in a variety of sources.

In the theory of hylomorphism, not only do the interrelations between the parts make the whole emerge as an irreducible composite, but at the same time the whole also exerts a normative influence on the parts by *sublating their individuality into the unity of the whole* [12].

Marmodoro wraps up this idea as quoted by Skrzypek [14],

> *"The substantial form that unifies the elements of a substance is a principle. Since what is needed is the shedding of only the distinctness of the elements, the role of this unifying principle must be just that: to strip the elements of their distinctness. I conclude, therefore, that the substantial form according to Aristotle is an operation on the elements of a substance, stripping them of their distinctness..." (Marmodoro, 2013, p.17)*

2.2.2. Composition and complexity

The problem of the existence of complexity and wholes whose powers and properties cannot be reduced to those of their elementary parts is addressed in metaphysics under the Special Composition Question (SCQ) [2]. The SCQ, relates to how, and under what conditions, objects can form a larger and more inclusive whole, such that a composite is formed that includes those objects as its parts. More formally, the SCQ is formulated as follows: for any xs, what are the necessary and jointly sufficient conditions for which there is a y, such that the xs compose y.

A hylomorphic contribution to the SCQ is based on the concept of substance as an *emergent* and *autonomous* whole. Following Koons [2], for a whole to be emergent it must not be a heap – fully grounded in the nature of its parts, and to be autonomous it must not be a fragment – fully grounded on the nature of a larger whole.

Applying the theory of hylomorphism discussed above, we can understand the connection of the composite whole to its parts through a *double dependency* [6], that is, the whole is dependent on the parts to emerge as such, but the parts are also dependent on the whole, in the sense that the whole orders the parts normatively.

The normative ordering of the parts of the composite whole is the effect of the activity of the form of that whole. The form arranges the material constitution of the whole, enabling its material parts to contribute in due measure to the activity and operations of the whole. But for the form to arrange the material parts of the composite whole in a certain normative way, such that they contribute appropriately and harmoniously to the functioning of the whole, the form must exert a causation that unites and integrates the operations and powers of these material parts. This causation has a top-down direction and is called *formal causation*.

On the other hand, the actual relations among the constituent parts are necessary for the maintenance of the whole, and the laws governing the elementary parts still constrain the structures and states the new whole can come to realize.

For instance, a cell, human cognition and social groups are objects of study in their own right, and governed by different laws and general principles, yet there is no cell, brain or society whose workings stand against the requirements of the laws of physics. The causation and partial determination that the material constituent parts exert on the composite whole has a bottom-up direction and is called *material causation*.

There is here a formation of *strata* and a tangled hierarchy of causal loops that generates a truly integrated behavior. In this tangle of causal loops we discover a certain kind of link that glues everything together into a network of components in relation to each other, forming an integrated hierarchical whole, acting in accordance with a purpose and being contained within a certain boundary. To such an integrated whole we call *complex system* [23][24].

In terms of definition, a system is the same as a whole or a composite. But the concepts of system and whole, or composite, do not always mean the same thing and this depends on the position one has regarding the SCQ. Very briefly, a system cannot be identified with a composite if we admit the trivial answer given by universalism to the SCQ [2], since this answer implies that any set of elements forms a composite, or that the composite is identical to its individual parts. From this point of view, the systemic and emerging phenomenon is completely excluded and the concepts obviously do not mean the same thing.

The systemic phenomenon implies the maxim that the whole is greater than the sum of its parts, a level of integration that is found in the middle ground between the amorphous aggregation of elements created by a logical operation, and the totalistic comprehensiveness of the universe. However, neither in Aristotle's metaphysics, nor in ancient and medieval philosophy, nor even in modern philosophy until the 19th century is there any explicit concept of system, much less a precise definition of what a system is. It was only in 1824 that the concept of system appears in the natural sciences, particularly, and not surprisingly, in thermodynamics by Sadi Carnot, which he called *working substance*, in the context of the study of heat engines. For Carnot, the system was a kind of substance that produces work by being in contact with its environment. In his “Reflections on the motive power of heat” Carnot writes [18],

> *“It is necessary to establish principles applicable not only to steam-engines but to all imaginable heat-engines, whatever the working substance and whatever the method by which it is operated” (Carnot, 1897, p.43-44)*

In the next chapter, we will explore what a system is in greater detail, in the light of the Systems Theory.

2.3. Systems Theory

In the previous chapter we have shown how the concepts of substance, composite and system are related. However, we have not said much about systems per se, the further we got was using Carnot’s notion of a ‘working substance’ to define it.

Systems are objects of interest to multiple scientific disciplines. There are general principles and laws characteristic of the systemic phenomenon that cut across a myriad of scientific fields called *isomorphic laws* [20][21]. This is most evident in the life sciences where the same set of differential equations can govern a lot of different phenomena - flows of fluids, heat conduction, catalytic processes, population growth, among others. This may be because there are a limited number of differential equations relevant in the life sciences with analytical solutions. Also, because the methods of physics have been successfully applied in other disciplines, similar models and analogies are adopted in all fields of study, from chemistry and biology to sociology. Or, perhaps, these are nothing more than useful (but often times misleading) analogies rather than general principles and laws that are really present in the objects of the different sciences. If it was so, these wouldn’t be isomorphic laws - a concrete law-like structure emerging from the powers and dispostions of the systemic phenomenon, but coincidences. There is, yet, a real structural isomorphism or *logical homology* between systems, despite the fact that the entities considered are of wholly different natures [20][21].

The systems that are of most interest to the natural and social sciences are open to their environment and exchange with it *matter*, *energy* and *information*. An open system is a system whose boundaries are permeable to the reception of inputs from the environment and processes them, within its boundaries, into outputs that return to the environment in a different form [19][21][22]. Systems are able to be stimulated by the environment and to influence it retroactively according to its dispositions and powers. With respect to the input processing phase, here it implies not only a transformation of the inputs received from the environment but, at the same time, implies a change in the internal structure of the system.

2.3.1. Reversible and irreversible processes

According to Le Moigne [19], every change taking place with respect to matter, energy and information is a *process*. Processes can be of a *reversible* or *irreversible* nature.

Reversible processes are insensitive to time, with the dynamics of the system displaying such a symmetry that, no matter in which direction we are observing the dynamics (either forwards or backwards in time) we observe exactly the same thing; in these processes time isn't relevant in the equations describing the system's evolution. This applies mostly to closed systems.

Open systems, however, deviate from the equilibrium state and undergo irreversible, symmetry-breaking processes where the temporal dimension becomes a factor in the equations governing the dynamics of the system, and now it makes the difference whether we are observing the system's state forward or backward in time. Thus, open systems have the capacity to revert the convergence towards a time-symmetric equilibrium and attain multiple time-asymmetric stable states.

2.3.2. Le Moigne's triadic referential of systems processes

In any given process, two fundamental classes of objects are defined: *processed* and *processor* objects [19]. A processed object is acted upon in three dimensions, in what Le Moigne called a 'triadic referential': in *time*, in *space* and in *structure*. Le Moigne uses the word 'form' instead of 'structure', however, in the context of this work we decided to use the word structure instead to avoid confusion with the concept of form. A process that affects an object in time is a *storage* or *memorization* process; a process that affects an object in space is a *transport* or *communication* process; and a process that affects the object in its structure is a *transformation*.

Therefore, any process is an *act* on a given processed object in at least one of these dimensions, that is, it is an act on the part of a processor that enacts the *potency* in the processed object along one or more of the dimensions of the referential.

A process further defines a *flow* and a *field* [19]. We argue that the flow of the process derives from the principle of potentiality as the flow is realized by a *tension* – a difference between potentials. The field, on the other hand, is the orientation, or direction, ordering the flux. The disrupting action of the field on the flux may trigger *fluctuations* that push the system further away from the equilibrium state and induce symmetry-breaking operations.

Systems and their sub-systems are processing objects par excellence – they are objects that extract inputs of matter, energy and information from their environments to fulfill a given purpose; but depending on the input that is processed and the referential (space, time and structure) along which the processing act unfolds we have different kinds of processors. For example, a processor that processes matter in space has different characteristics from a processor that processes matter in relation to time or in relation to structure. According to the type of object that is processed and according to the referential in which this processing takes place, so will be the characteristics of the processors.

The material separability and distinction between these processors should not, however, lead us to think that they are independent of each other. According to the principles of cybernetics, a processor that processes matter in a given referential must be powered by an energy processor that provides it with the thermodynamic requisites necessary to fulfill the task of processing input matter. Moreover, it will also depend on an information processor to provide it with the commands on how to carry out the task.

To further complicate this picture, processors may have dependency relationships across different levels of the system's hierarchy, i.e., a higher-order subsystem may contain processors in close relationship with processors from a lower-order subsystem and vice-versa Such multi-level relations emerge for the fulfillment of a task that contributes to the functioning and harmony of the greater whole that encompasses the sub-systems. Based on Miller's work, Le Moigne provides a list [19] of important processors, some of which we highlight for our purposes in this work: the *distributor* - processor of matter and energy in space; the *channel* and the *emitter* - processors of information in space; the *memory* - processor of information in time; the *filter* and *catalyst* - processors of matter and energy in relation to the structure; and the *regulator* - processor of information in relation to the structure.

2.3.3. Self-organization

The structure of the network connecting the various processors of the system is not uniform and the network's structure will have 'islands' or 'regions', with important clusters of processors concentrated to carry out certain tasks. Not all processor islands are in charge of participating in all the processes the system undergoes, on the contrary, there will be certain sets of processors that specialize in a single function, while others specialize in other functions. The specialization of the various sets of processors, their density and segmentation develops accordingly to the *functional differentiation* of the system throughout its life cycle [19][20].

Functional differentiation unfolds along the various stages of system development. At the primitive stage we have mostly passive and seemingly purposeless objects, i.e., uniform substances such as crystal lattices. At this stage the system is undifferentiated and in a state of *equipotentiality*.

From its passive state the system undergoes transitions such as to break the state of equipotentiality. In this stage, active substances endowed with a function, purpose and a limited set of processors emerge from the simpler substances such that true systemic behavior is formed. It is only when the system acts in a chronic, or ordered fashion, that we can discern the first vestiges of complex behavior.

Furthermore, the system develops a feedback control infrastructure and the chronicle of the activities and manifestations of the system is well-ordered and the system has some ‘decision-making’ capacity, discerning between possible states. The system learns and contrasts its activity and tests it against a target. The presence of regulation implies the presence of information processors, such as a memory, to correct the behavior of the system with reference to a given target.

The ability to learn and regulate itself implies a certain closure of the feedback loop, that is, a part of the system's outputs are recycled. The system develops a capacity to be more autonomous with respect to the pressures of the environment and to be self-subsistent. As the system differentiates into a complex *mosaic* (akin to Bénard cells), some functions become preeminent with respect to the others. This means that as the system differentiates there is a process of centralization of the system's operations around certain functions [19][22][27]. The emergence of leading functions, is tied to thermodynamic requirements that ascribe priority to certain tasks for the maintenance of certain life processes.

At the next stage of development, the system should be capable of *generating new information* and manipulating information. A complex system is to be understood in the totality of the term when it is both emergent and *self-organized* [19][23][26][27]. Self-organization is defined also with respect to the material-energetic aspect in the sense that it necessitates the system to be open to energy fluxes from the environment in order to renew and give rise to new mosaics. Self-organization marks, thus, the emergence of *thermodynamic intelligence* [19].

Self-organization is produced by fluctuations [27]. Intuitively we could think that fluctuations would have a negative influence on the structure of the system and in its overall organization since fluctuations will have deteriorating effects. But this intuition does not hold for complex systems. Fluctuations in a complex system may not always contribute to its deterioration but, on the contrary, may contribute to the quality of processed information and to the efficient functioning of the system. That is, the system is enriched by the fluctuations because these will destroy certain inertias that have been crystallized by the system over time and in its progression towards greater specialization and segmentation, which make the system less adaptable.

The fluctuations will eliminate these constraints and open up to a series of new ways of reorganizing the structure of the system and the interactions between its parts. The increase in the possibilities of reorganizing the system creates greater ambiguity in the relationship between the parts and makes the system more malleable [20][27]. Naturally, the fluctuations will only have a creative role in the informational enrichment, and in the complexity of the system overall, if for the variety that is inserted by the fluctuations there is the due compensation of redundancy [26][27].

Thus, self-organized systems go through a cycle called *progressive segregation* [20], from equipotential wholes in which the parts are all related in such a way that if one of them suffers a variation all the others will also be influenced, to a differentiated mosaic where the parts act almost independently of each other. When a system grows and becomes more complex and secure in its environment, and begins a process of specialization whereby some set of parts is responsible for certain functions, the relations between the parts can become so segregated to the point that no such relation exists anymore and the parts no longer influence each other. When this happens, we are facing the disintegration of the system resulting from its overspecialization. Complex systems, however, operate between the two extreme cases of uniformity and overspecialization [20].

The predominance of complex mosaics in the natural world has a deep thermodynamic or energetic meaning to it, namely, differentiation from an equipotential substance entails an increase in the degree of complexity of the system. Like any symmetry-breaking operation a transition towards higher complexity entails a reliable source of energy that can be used to harness the necessary resources to push the system away from equilibrium. The emergence of islands or regions in the system’s network of processors is tied to energetic requirements that ascribe priority to the completion of a certain task necessary for the survival of the system.

Moreover, the system may suppress or amplify fluctuations, that is, if the system pretends to stabilize itself it will suppress fluctuations using a negative feedback loop, but, if the system pretends to enact a change it will instead amplify the fluctuations using a positive feedback loop to trigger a cascade-like behavior. It is more likely that a system that is more advanced in its life cycle will employ more negative feedback to curb the uncertainty of the environment, while a system that is unfolding and trying to establish its relation to the environment will most likely use positive feedback mechanisms [19][20][27].

Lastly, the emergence of *self-teleology*. There is a self-fulfillment whereby the system exists in itself and for itself and the teleology becomes something that can't be imposed on the system by the outsider but, rather, it emerges from the elementary, mechanistic interactions within the system, without external determination. Self-organized and self-teleological systems are the natural substances with utmost higher degree of subsistence as they truly differentiate themselves from their environment and are 'closed upon themselves' in the sense that environmental factors cannot determine the inner workings of these systems. However, true autonomy and self-referentiality points towards a more radical kind of subsistence called *autopoiesis*, which we will take on the next chapter.

2.4. Autopoiesis

The theory of autopoiesis, although related to Systems Theory, goes beyond it in that it not only uses a different set of concepts and lexicon, but also because it introduces a radical shift with respect to ontology and epistemology [28][29]. Autopoiesis is to be understood within the paradigm of second-order cybernetics, as it shifts the focus from traditional problems of feedback control to problems of self-organization, self-reference, and autonomy in systems that have the ability to 'self-reflect'. This paradigm is rooted in the primacy of the whole and the unity and, we argue following Dougall [34], that it is in some sense a rediscovery of the Aristotelian theory of form.

The theory of autopoiesis was primarily applied in the field of biology. It proposes a solution to the problem of the origins of life by providing the sufficient and necessary requirements for the organization of living systems, and to provide criteria to distinguish a living system from a non-living system, among other problems. The canonical example of an autopoietic system is the eukaryotic cell [30], however the concept as also been applied to cognition [29][30], Artificial Life [31], and to social systems [30], particularly to the legal system [32], although not without controversy.

Although autopoiesis has been extensively discussed mainly in the field of biology, we should not think that autopoiesis is limited to biology but, rather, it is an abstract concept that can apply to any system as long as a set of conditions are satisfied. In the present work we aren't interested in any particular autopoietic system but in the philosophical and metaphysical underpinnings of the theory of autopoiesis.

Autopoiesis means *self-production* and it describes a complex system that produces its own components and boundaries [28][29][30]. This is contrasted to allopoietic systems which produce something other than themselves, i.e., its product is not a component of the system.

Now, Maturana formally defines autopoiesis, as quoted by Mingers [30], as,

> *"A dynamic system that is defined as a composite unity as a network of productions of components that, a) through their interactions recursively regenerate the network of productions that produced them and b) realize this network as a unity in the space in which they exist by constituting and specifying its boundaries… through their preferential interactions within the network, is an autopoietic system." (Maturana, 1980, p.29)*

Autopoiesis may also be interpreted as a special kind of *self-organization in the physical space* that bridges non-living matter and living matter. In [30][32][35][37] it is argued that autopoiesis is a phenomenon of collective autocatalysis with a *spatial individuation*, and that this spatial individuation is a product of the reaction network itself.

One of the fundamental questions posed by the theory of autopoiesis is the following: How can we distinguish between a non-living system and a living system? There are examples of complex systems such as turbulent fluids that are self-organized, the same can be said of other machine learning and A-life systems, and yet it would be wrong to deem any of these as living systems or autopoietic. And while all autopoietic systems are self-organized, not all self-organized systems are autopoietic. Thus, to give an answer to this question Maturana and Varela proposed the following method: Determine what the system produces and what, in turn, produces the system [30].

According to Maturana and Varela [30] there is a set of criteria that a system must meet in order to be autopoietic, namely i) it must be an identifiable *unity* in the physical space delimited by a *boundary*, ii) it must be analyzable into a set of *interacting components*, iii) the system must operate *mechanistically* and its operation is determined by the properties and relations of the components not as individual systems, but as being subordinated and fulfilling a role in the overall unity, iv) the relations between the components must describe a *network of processes of production*, v) which are contained within the boundary and at the same time also produce the boundary, vi) which is maintained through the *preferential neighborhood interactions* of the components.

The paradigmatic case of autopoiesis is the cell [28][30][43]. The cell has as its material components, for instance, the nucleus, the ribosomes, and the mitochondria which are produced inside the cell, and has as its boundary a plasma membrane made of molecules and proteins that contains and delimits the production processes of the components.

Another perspective through which one can look to understand the concept of autopoiesis and its definition is that of Complexity Theory and Requisite Variety, whereby autopoiesis is defined as a *ratio of the internal complexity of the system with respect to the complexity of the environment*. According to Gershenson [36],

> *"This generalized view of autopoiesis considers systems as self-producing not in terms of their physical components, but in terms of its organization, which can be measured in terms of information and complexity. In other words, we can describe autopoietic systems as those producing more of their own complexity than the one produced by their environment." (Gershenson, 2014, p.4)*

This perspective re-formulates organization in terms of complexity and information, and by employing information theory and the law of requisite variety derives a measure for autopoiesis. The caveat in this perspective, however, is that it does not regard autopoiesis as an all-or-nothing phenomenon, as it has been traditionally understood, but as a smooth and gradual transition from the non-autopoietic to the autopoietic.

Autopoiesis as an all-or-nothing phenomenon was also challenged by Gunter Teubner [32], making use of Eigen and Schuster's theory of *hypercycles* to prove a graduality in the formation and emergence of autopoiesis. For Teubner, autopoiesis, in its embryonic state, consists of a disjunctive set of production processes and circular operations. Only after these processes begin to be integrated to the point where the various corresponding cycles of the individual processes of production are encompassed by the larger hypercycle, integrating all these individual cycles, does autopoiesis emerge in the fullness of its unity. But this unity was already there potentially when the various individual cycles began to interact with each other. Thus, as the production cycles become more integrated until they culminate in a single hypercycle that closes the system in itself operationally and synchronizes what previously were disjoint cycles, a radical distinction between the system and the environment is achieved.

However, despite this high degree of autonomy that autopoietic systems enjoy we should not be led to believe that autopoietic systems are closed to the fluxes of matter and energy of the environment. *Physically*, autopoietic systems are open systems which are governed by the laws of thermodynamics, for otherwise they could not foster any sort of complexity and life. For instance, the cell is open to the flux of energy and chemicals like metal ions which are necessary to renew its complex structure and life functions. *Logically*, or phenomenologicaly, however, autopoietic systems are indeed closed to any external determinations.

From this distinction of the physical and logical aspects of autopoiesis results what is perhaps the most important distinction for the theory of autopoiesis, namely, that between *organization* and *structure*.

2.4.1. Organization-structure distinction

The composite unity of the autopoietic system may be defined, with respect to its *spatio-temporal complexity*, as a product of the different components interacting locally with each other such as to produce a complex whole in the physical space. But the composite unity may also be defined with respect to its *metaphysical complexity*, as a product of its composition of organization and structure. The composition of organization and structure in autopoietic systems is rooted, as we will argue, in the hylomorphic composition of *form and matter* [34].

Maturana, as quoted by Mingers [30], defines the terms of this distinction as follows,

> *"[Organization] refers to the relations between components that define and specify a system as a composite unity of a particular class, and determine its properties as such a unity…by specifying a domain in which it can interact as an unanalyzable unity…"*
>
> *"[Structure] refers to the actual components and the actual relations that these must satisfy in their participation in the constitution of a given composite unity [and] determines the space in which it exists as a composite unity…" (Maturana, 1978, p.32)*

We begin by explaining what the term 'organization' means in the theory of autopoiesis and in Maturana's metaphysics. What immediately strikes the eye based on the definition of organization is that the use of this word in Maturana’s metaphysics is not at all identical to its common use in Systems Theory, and much less to its colloquial use. In the literature, organization usually denotes something which is changeable and reconfigurable, and this is clearly the idea behind self-organization. But in the theory of autopoiesis this is not so.

One of the roles that Maturana assigns to the organization is that of being a source of identity and unity of the system. However, as argued by Dougall [34], to assign this role of a unifying principle to the organization is problematic given the original definition of organization that we are provided with by Maturana.

One problem Dougall [34] identifies is that, by defining the organization as the abstract relations among components organization becomes a subset of the structure. Since the structure contains both the actual components and actual relations, the organization, being defined as the abstract relations, would be a subset of the structure and thus could not play the role of being a source of unity. Moreover, defining organization in relational terms makes it dependent on its *relata* [34], namely the components and, therefore, cannot be the ontological ground for autopoietic unity.

For Maturana the organization is an abstract construct akin to a simple universal that is common to the same class of autopoietic systems [34].

> *"The distinction between structure and organisation is between the reality of an actual example and the abstract generality lying behind all such exemples." (Mingers, 1995, p.14)*

To fulfill the role of the source of unity and persistence of the system, the organization cannot be an abstract construct or a simple universal but an actual causal principle that is operative and orders its parts towards certain processes of production. In other words, the organization must exert formal causation on the components.

We can solve these problems and, at the same time, maintain that the autopoietic organization is indeed a source of unity and persistence by reinterpreting the organization not as a set of abstract relations or a simple universal but as an Aristotelian form, and by reinterpreting the structure as Aristotelian matter.

Now, organization has ontological primacy over the structure, as the form has ontological primacy over the matter. More specifically, since the organization/form is invariant and the source of activity by which the unity exists, its primacy is absolutely necessary, and without it, it would not be possible to predicate properties of the unity because we can only predicate a property of something that exists and is in act.

The structure, on the other hand, describes the composition of the autopoietic unity into the actual material components and boundaries that realize the organization in the physical space.

Moreover, the structure is both static and dynamic. Static because the whole structure implies a certain space-time permanence. Dynamic because the structure concerns the material composition of the unity, which is necessarily in motion and subject to change, but also because the structure encompasses the *accidental* properties of the unity, that is, properties that are not essential and can, thus, be lost and gained.

The astute reader will have noticed by then that any description that can be made regarding an autopoietic system will always concern its structure, even when we wish to describe its organization! This is because the organization is inaccessible to us as observers and we are outside of the system's self-production cycle, since as observers we are not substantially identical to the components that are part of this circular organization, nor to the unity itself.

2.4.2. Organizational closure and structural determination

Organizational closure is one of the necessary conditions for autopoiesis. A system is said to be organizationally closed if the activity that the system can realize will produce further activity in the system in a circular and recursive fashion. The production of the components will generate new components which in turn will be part of further processes of production of newer components of the same kind. The organization is the product of the organization.

The immune system is an example of an organizationally closed system although it cannot be said to be autopoietic because it does not (re)produce its boundaries. In autopoiesis the boundaries of the system emerge at once with its unity, this is why self-organized systems such as auto-catalytic networks, as discussed by Kauffman [27] do not qualify as autopoietic, because they don't determine their own topology. Rosen argues that, from a computational viewpoint, the organizational closure that is exhibited in living systems cannot be reproduced by a Turing Machine [31].

For a system to be organizationally closed simply means that, that which pertains to the nature of the system remains so regardless of what happens in the environment; it means that all the activity of the system proceeds from its own organization and that it is this organization that filters all contact of the system with that which is not-the-system. Thus, everything that is identical to the organization and produced by that same organization is a constituent of the system, and everything that it is not produced by the organization is therefore exogenous to the system, that is, it is non-system.

Autopoiesis is an all-or-nothing type of phenomenon where the organization is the measure of all things. The system uses such a measure as a sort of binary 'code' whereby it identifies what is and what is not part of the operations of self-production [30]. But does this mean, then, that autopoietic systems are closed systems and that they do not exchange anything with their environment or interact with it? The answer to this question depends on which aspect of the composite unity the observer is studying, that is, if we are referring to the organization and the operational domain of the system that concerns the relations of self-production, then we answer affirmatively and say that the system is indeed closed. However, if we are referring to the structure, then the answer is negative, and the system is open.

The language used to describe the interactions and relationships between the system and its environment speaks of input and output, and this language is commonplace in Systems Theory and in Cybernetics. However, the notion of inputs and outputs can be misleading when applied to autopoietic systems, not only because the organization is closed to what is not the organization itself, but also, in contrast to allopoietic systems, the inputs and outputs are not substantially different from the system. For example, inputs from the environment entering an autopoietic system are transformed so that this input is made compatible with the organization of the system and made into a component which in its turn integrates the processes of self-production. There is no such thing as an external determinant that will dictate how the system will manifest itself. Thus, in the language of the theory of autopoiesis, the exchange relations between the system and the environment are properly described in terms of *perturbation* and *compensation* [30].

Autopoietic systems interact with the environment via *structural coupling*. The structure is open to fluctuations and endowed with plasticity that allows it to change without bringing about the ceasing of autopoiesis. The role of the environment in this structural coupling is to perturb the structure and limit the states and manifestations that the system can select.

For every perturbation there is a *structural enaction* that determines whether the system will change its state or remain in homeostatic equilibrium. It is the very structure that selects the environmental fluctuations and whether or not such fluctuations will enact any reaction from the system, thus, autopoiesis is *structurally determined*.

From this state-of-the-art review, we can make some concluding remarks. First and foremost, that autopoiesis remains controversial. Several disputes still exist regarding the concept of autopoiesis itself and its applications, especially outside the context of biology.

Concerning the concept itself, there are two contradictory perspectives – one that sees the autopoietic phenomenon as all or nothing, and another that sees it as a gradual process. There are also two different ways of looking at the autopoietic system: from the standpoint of the interactions between its constituent components, that is, from a mechanistic perspective; and from the standpoint of its organization as a whole, that is, a formal perspective of its unity. After reviewing the state-of-the-art, it became clear that these two perspectives are not contradictory but complementary. The mechanistic perspective was sometimes contrasted with Aristotelian metaphysics without truly understanding the role of form in composite unities. With respect to the autopoietic organization, we can conclude that although there is a shared concern in Maturana's metaphysics and in Aristotelian metaphysics to attribute primacy to organization as defining the nature and subsistence of composite units, there is, however, a difference in the way of defining organization. The definition of organization must be consistent with the role that the theory assigns to it. While in Maturana's metaphysics we saw that organization consists of something abstract and relational, from an Aristotelian perspective, organization is a form, that is, a concrete "hyloenergetic" operation that puts the parts in relation and the production processes in action.

Beyond the theoretical question and the philosophy of autopoiesis, the way we understand organization and structure also has consequences for how the concept is applied in concrete cases. We have found that there is controversy in applying the concept outside the context of biology, particularly when it is applied in the social sciences - describing societies and organizations as systems that self-produce communicative acts. Those who oppose the application of the concept within the social sciences mention, for instance, that social systems do not meet one of the necessary criteria for the existence of autopoiesis, namely, the self-production of a boundary that defines the limits of the system, that is, that topologically limits the system and allows us to distinguish what is organization from what is non-organization.

In fact, in social systems, one does not find such a clear material boundary as in the example of the cell; however, since the membrane is a structural part of the system, it will be seen, from an Aristotelian point of view, as the "matter" that delimits the form. Now, from this point of view, matter is correlated with potentiality, and form with actuality. This means that the cell membrane, which plays the role of containing the self-production processes of the cell's organization, is only a particular case of this more general principle, which is potentiality. By this we mean that however subtle or concrete the material basis that constitutes the boundary of autopoiesis may seem, it will always be a particular case of the more comprehensive notion of potentiality. That is, what the boundary is in its most general form is potentiality which comprehends the powers that the system has that delimit it from other beings. From this point of view, in which what individualizes a composite unit is its potential or its powers, the question of defining the boundary should not constitute an obstacle to the development of a more comprehensive autopoietic theory that includes social systems.

Finally, we have seen how autopoiesis challenges traditional concepts from cybernetics and systems theory in describing the phenomenology of the system. Several of these concepts become obsolete or require requalification if they are to have descriptive, and not merely pedagogical, value in the study of autopoietic systems.

CHAPTER 3

Proposal and validation

Based on the state of the art developed so far, it is possible to find theoretical foundations that allow us to reconceptualize autopoietic organization as an Aristotelian form and avoid a series of difficulties that Maturana's concept of organization suffers from. One of the particularities and advantages of thinking of autopoietic organization as a form is, as we argue below, that it allows us to conciliate autopoietic organization with the classical and physically-grounded concept of information. The argument for the conciliation between the concepts of information and autopoiesis follows some points of the argument already elaborated elsewhere for the conciliation between teleology and autopoiesis. An informational perspective of autopoiesis allows us to study the system without taking into account its constituent parts, but to obtain a more general perspective that views the system as a hypercycle of informational and energetic processes.

To show how information fits with the theory of autopoiesis and what this implies for real information processing dynamics in autopoietic systems that exist in the natural world, we also present a model of cellular tessellation that describes the dynamics of cell membrane repair and reproduction in the autopoiesis of life. Taking as a starting point a model of the cellular tessellation automaton that describes a process of repair and self-production, we use it to demonstrate the role played by information as a physical quantity, like matter and energy, and the role played by information processing and thermodynamic processes in the maintenance of the autopoietic unity.

Finally, with new horizons opened by this informational perspective of autopoiesis, we can also take into account innovative tools originating mainly from information geometry to measure the complexity of autopoietic systems as well as measure the thermodynamic efficiency of the attractors that enable the continuity of autopoiesis in the physical space and the efficiency of the transitions between attractors that guarantee life, as well as understand the conditions that can precipitate the system into its death and disappearance.

3.1. Teleology and information in autopoietic systems

Structural determination makes the system permeable only to environmental fluctuations, and selects states, that are beneficial from the point of view of safeguarding the organization. From this standpoint, autopoietic systems do not have a purpose other than the mechanistic self-production of their own organization and unity.

As we have already had the opportunity to refer in the beginning of this chapter, autopoiesis fits into the paradigm of second-order cybernetics and some of the language of Systems Theory and first-order cybernetics becomes obsolete if applied without qualification to autopoietic systems. In the case of teleology particularly, it is not conceivable to be applied to autopoiesis as it is traditionally applied to control systems, because in these systems teleology reflects the mental schemes of the modeler rather than an emergent property, fruit of the mechanistic interactions of the system's components. Teleology, as it is understood in first-order cybernetics and control theory, is not *immanent* to the system, emerging from its own activity and experience. But as we know, in the autopoietic phenomenon, everything that does not proceed from the organization cannot be considered as a part of the system, since the circular organization is the measure of all things for the autopoietic system, and not the modeler's goals, mental schemes and representations of reality.

Weber and Varela [37] say the following regarding the possibility of teleology in autopoietic systems,

> *"It is actually by experience of our teleology – our wish to exist further on as a subject, not our imputation of purposes on objects – that teleology becomes a real rather than an intellectual principle... Theories about the living can only be conceived from the fragile and concerned perspective of the living itself: "...life can only be known by life" (Weber and Varela, 2002 p. 110).*

The authors implicitly corroborate this distinction between externally imposed teleology and immanent teleology. At the level of immanent teleology, another important distinction is made between *Kantian teleology* and *projective teleology*. This latter distinction is a result of the complicated relation between the thermodynamics of autopoiesis, and its organizational closure and structure-determined behavior.

Kantian teleology is the immanent teleology that emerges as a result of the mechanistic relationships between components that form the whole. It is simply the purpose of all living substances, namely, the maintenance of this living unity.

Projective teleology, in turn, is more problematic because it implies not only maintenance and survival but above all regulation, the assignment of *valence* to states and fluctuations that are more or less distant from the most efficient state.

In contrast to Kantian teleology, in which the maintenance and survival of the autopoietic unity is sufficient, we now have a grading and optimization problem in which the structure is changed not only to maintain unity but to operate with the highest possible thermodynamic efficiency. But how can this be possible if all that the autopoietic system recognizes is its own organization and all the coding it does of the environment is purely binary, that is, organization and non-organization? How is it possible to assign grades, valences and continuity if the system knows only things in an all-of-nothing fashion?

To solve this, it is necessary to recognize that although autopoiesis is a special case of self-organization it does not exhaust the features of self-organization entirely. In other words, there are certain properties of self-organization that autopoiesis in itself, as a minimum requirement of life, does not have essentially but only accidentally and acquired over time, through its history of structural couplings with the environment [34][37].

Usually there is a wide range of states that allow for the maintenance of autopoiesis. Qualitatively, these states are different with respect to their value of viability, even though they all fulfill the most basic purpose of preserving autopoiesis. For instance, two different states within the frontier of viability can be conducive to maintaining autopoiesis, however, one of these states can perform this task with less energetic costs than the other. That is, in the adaptability landscape these states would be located at different points, with the energetically more efficient states being higher on the landscape, and those less efficient being lower.

Following the example given by Di Paolo [37], bacterial autopoiesis needs sugar for its maintenance and the bacteria realize a climbing towards states in the gradient with higher concentrations of sugar. From the binary, all-or-nothing perspective of autopoiesis this climbing up the gradient towards states of higher concentration of sugar makes no sense. In fact, the system would be completely blind to this idea of gradient ascent and optimization, for in itself any of the states of sugar concentration, as long as it has the minimum viability requirements for maintaining autopoiesis, would be qualitatively equal. Therefore, sugar concentration as a factor disappears in the binary understanding of structural coupling.

In order to discern these valences, a sensory and regulatory apparatus capable of making a finer distinction than the aforementioned binary code is needed and must emerge naturally in the system.

The system maps its environment and assigns valences and 'meanings' through the use of symbols to the things that surround it, actively constructing and applying a *schemata* through which it interprets and makes sense of the world. The system is neither passive to the contingencies that perturb it at the structural level, nor a blank slate. On the contrary, the system's history of structural couplings entails that the system has already internalized in its structure a series of correlations, preferential paths of action and a differentiation and specialization of its parts such as to respond to anticipated contingencies.

A distinction is posited between *discovering* a meaning and *constructing* a meaning. A discovered meaning is a meaning that has to do with the attribution of valences to states with a certain viability for the system. For example, in bacterial autopoiesis we saw that the system has a preference for converging towards states with a higher sugar concentration and that these states of higher sugar concentration are more viable from a thermo-metabolic point of view. In this case, the attribution of valence and meaning to these states directly concerns the operations of the system and the physical maintenance of autopoiesis. On the other hand, the system can construct meanings about things that are not directly related to their physical maintenance. We are talking about things that the system can perceive and through which construct a meaning that can become relevant to the physical operation of autopoiesis.

There are certain clues and regularities in the environment that, although not directly related to the maintenance of autopoiesis itself, are perceived by the system as milestones or indicators of trends that may be favorable or unfavorable for the physical maintenance of the system. One such example is the presence of smell, color, among others. The system was thus able to process and construct meaning by filtering and constructing reality according to its operations and organization, which is the measure of all things for the system. In other words, the autopoietic system *projected itself teleologically* in its environment.

Moreover, one of the ways in which the system projects itself teleologically in the environment is through its own *parametric regulation*. The system's environment is interpreted here as being constituted by reservoirs of matter, energy and/or information, and between the system and the reservoirs there are exchanges of the aforementioned quantities. Although the laws of nature determine the nature of the relations of exchange between the system and reservoirs, it is, however, the system itself as an active and causal entity that determines the values of parameters calibrating these relations. Without a regulatory mechanism and the projective teleology the system would not be able to make this detailed parametric determination based on valence and assigned meanings, but would simply remain in a range of parametric values that would make the thermodynamic exchange relations with the environment simply non-lethal for the autopoietic unity, despite being in a sub-optimal state.

The regulation of the parameters and the transition between structurally-determined states is what *information processing* consists following Boyd, Mandal and Crutchfield, [41], Ito [47], and Ashida and Oka [50]. We acknowledge that the usage of such a concept as ‘information’ in the theory of autopoiesis is controversial, as it can be misleading.

In [30], for instance, Mingers notes,

> *“The ideas of a closed structure-determined system and a consensual domain of essentially arbitrary behaviors have major implications for current beliefs and theories about the role that information and representations play in living systems and their thought processes. They challenge a number of current notions. First, for example, it is currently held that DNA and the genes code or contain or transmit information about the structure of their parent organism… Secondly, it is currently held that the messages and communications between organisms are, in themselves, instructive: that is, that the messages contain sufficient information to determine an appropriate reaction on the part of the receiver. Third, a major plank of cognitive science, particularly as embodied in artificial intelligence… is that our minds work by creating and then manipulating objective representations of the environment and the tasks to be performed within it. Cognition is seen as a process of symbol manipulation and information processing.”*

> *“All these ideas are so well established that they seem almost self evidently true, yet autopoiesis suggests that they are all mistaken in the same fundamental way: they confuse the descriptions of an observer with the actual operation of an autopoietic system and ignore its structure-determined nature… Concepts such as “information” and “representation” pertain only to descriptions made by observers who can see both the internal interactions of a composite unity and the behavior of the whole in a particular environment and who can relate the two. So the idea that DNA contains or transmits information, or that the brain processes formal representations or symbols, must be purely metaphorical and does not describe how such systems actually operate in themselves.” (Mingers, 1994, p.46)*

This concern is legitimate and it is born out of the necessity to preserve the organizational closure and structural-determination of autopoiesis. However, as in the case of the use of 'teleology', if the appropriate qualifications are made it will be fruitful to speak of ‘information’ insofar as we understand it, too, as a product of the system's self-organized behavior.

According to Varela [38],

> *“Thus, by discussing autonomy, we are led to a reexamination of the notion of information itself: away from instruction, to the way in which information is constructed; away from representation, to the way in which adequate behavior reflects viability in the system’s functioning rather than a correspondence with a given state of affairs.” (Varela, 1979, p. xx)*

> *“Every bit of information is relative to the maintenance of a system’s identity, and can only be described in reference to it, for there is no designer. In this sense information is never picked up or transferred, nor is there any difference whatsoever between informational and non-informational entities in a system’s ambient.” (Varela, 1979, p. xxii)*

It is worth to make a brief digression in the history of the usage of the term in order to show how it was originally adopted and how it changed over time, into the modern era.

Citing Peters [39],

> *“Information was readily deployed in empiricist psychology (though it played a less important role than other words such as impression or idea) because it seemed to describe the mechanics of sensation: objects in the world inform the senses. But sensation is entirely different from "form" – the one is sensual, the other intellectual; the one is subjective, the other objective. My sensation of things*

> *is fleeting, elusive, and idiosyncratic [sic]. For Hume, especially, sensory experience is a swirl of impressions cut off from any sure link to the real world... In any case, the empiricist problematic was how the mind is informed by sensations of the world. At first informed meant shaped by; later it came to mean received reports from. As its site of action drifted from cosmos to consciousness, the term's sense shifted from unities (Aristotle's forms) to units (of sensation). Information came less and less to refer to internal ordering or formation, since empiricism allowed for no preexisting intellectual forms outside of sensation itself. Instead, information came to refer to the fragmentary, fluctuating, haphazard stuff of sense." (Peters, 1988, p.12-13)*

Information went from a unity of form or inculcation of form to matter, and shifted towards sensations. There has been a shift in focus from the cosmos to consciousness, from a unity of form to units of sensation. That is, information went from its classic meaning based on *unity* and *internal ordering* to mean something related to the senses and exterior to the system. We argue that the classical meaning of information as unity and internal ordering is the most fruitful one to apply in the theory of autopoiesis. This view of information as internal ordering in a physical medium makes it possible to apply the recent advances made in the physics of information as summarized by Bais [40], allowing us to model highly complex systems through simple models that process information called *information engines*, as proposed by Boyd [41][42].

Information engines are usually simple random dynamical systems (for example, a Maxwell demon acting on a particle in a box divided into two parts) which perform tasks that involve manipulating information, energy and matter, and whose environment is composed of reservoirs. These reservoirs can be of different natures. The most common are heat reservoirs, but there can be also particle reservoirs and even *information reservoirs* [41].

In the physics of information, information is a physical quantity as much as heat, energy and matter, which can be used by the engine as a thermodynamic resource to produce work. An information reservoir can be formed by different materials. It can be, for example, an ordered sequence of spins [40], or even be formed by ordered statistical correlations [41]. The point here is that information reservoirs contain within them *order* that can be leveraged by the engine to produce work, and when this order is leveraged by the engine it becomes disorder in the reservoir but is absorbed as order within the engine. Therefore, information can only be fostered as long as we have an *organized pattern of energy and matter*.

Now, when the engine acts on this informational order for its benefit it is destroying the order that exists in the reservoir. But this informational order is not only found in physical arrangements such as spins or in statistics in the form of correlations, but also in the biological world. For example, in the case of bacterial autopoiesis, large concentrations of sugar are an example of this order that the system seeks to leverage for its benefit, or even in the example of cellular autopoiesis when the system needs to repair a damaged section of its membrane it will look for nutrients and ordered molecular material in its environment that it can extract to integrate in its internal auto-catalytic processes and produce a suitable component to repair the membrane [43].

In sum, there are two aspects to information engines: a physical aspect in which the system manipulates, stores and dissipates energy and matter; and an informational aspect which concerns the *temporal and spatial order* of the system. The latter is a product of self-organization and structural openness to fluctuations which creates an adequate structural arrangement to realize the organization-structure composition in the physical space. Szilard [42] speaks of this kind of information as “historical contingency”, the memory of the system’s couplings to its environment.

However, this structural arrangement can only be obtained under certain conditions. It is not possible to obtain a complex and informationally rich structural arrangement if the system is in a state of thermodynamic equilibrium and in perfect symmetry, that is, if it is in the state of maximum entropy where it is not possible to extract any organized structural arrangement from it. When the system *breaks the symmetry* [17] of the thermodynamic equilibrium state and stabilizes in an out of equilibrium state, a complex and informationally rich structural arrangement emerges which is capable of hosting and manifesting the autopoietic organization. But since this structural arrangement is far from thermodynamic equilibrium, it needs a source of energy to maintain itself and the process of maintaining this structure also involves the continuous dissipation of energy, which is why these states are called *dissipative structures*, according to Gabbay [23], Kauffman [27] and Boyd [42].

Taking this into account, the information processing that information engines perform is nothing else than the transition between different dissipative structures. For example, this has been noted by Ashida and Oka [50], where information processing in a model of E. coli adaptation has been interpreted as the *transition between biological states in a noisy environment*.

In the next chapter we introduce a tessellation automaton model of cellular autopoiesis to exemplify how autopoietic systems process information and its role in membrane repair and maintenance.

3.2. Tessellation automaton model

In the theory of autopoiesis, the cell constitutes a network of chemical reactions that produce molecules, such that, through their interactions, they generate and participate in a recursive and circular manner in the network of chemical reactions that produced them and that also produce the membrane, defining the system as a unity in the physical space [30].

The molecules are the components of the network and the chemical reactions are the processes of self-production. Some of the components of the cell are called boundary-components because they form the semi-permeable membrane which plays the role of the boundary. The membrane limits the spatial diffusion of the molecules and avoids the dilution of reactant concentrations which would have the consequence of the chemical reactions ceasing and the network of self-producing processes disintegrating.

The tessellation automaton model describes the process of repairing and maintaining the membrane through the processes of self-production. We will base our discussion on the 3-dimensional tessellation automaton model proposed by Bourgine and Stewart [43]. Let us formally define the model.

The tessellation automaton has a spherical semi-permeable membrane which is composed by a collection of boundary components C. Each C occupies a unit surface area with a rate-constant k_c of disintegrating and leaving that unit surface area unoccupied (hole). When a C component disintegrates it transforms into D which is the energy dissipated to the environment associated with the disintegration of C. Unlike C, D does not belong to cyle of self-production, and it is therefore not part of the system.

Furthermore, there is yet another kind of component, called the B components which are the product of the chemical reactions taking place inside the membrane and relating two substrate molecules $A + A \to B$. These reactions are catalyzed by the C components, which means that the concentration of B components is upper limited by the membrane. Ultimately, it is the intricacy of the network of chemical processes that makes the system self-produced, while the membrane plays the role of a potentiality that constrains the self-organized network. Unlike Varela's automaton where the catalyst was not formed within the system itself, here the membrane plays the role of the catalyst and arises from the system's self-production processes.

The substrate molecules A exist in the cell's environment in high concentrations and the cell harnesses these substrate molecules through the semi-permeable membrane. When the A molecules enter the cell they are 'filtered' through the organization of the system, that is, they acquire a totally different status to that which they had when they existed in the environment. That is, the individual complexity of the A molecules is reduced so that they now play a role in the network of chemical reactions. The A molecules' individual properties are subordinated to the production processes of the system as a whole.

Here we see how structural opening and organizational closure work in practice. On the one hand, the structure of the system as well as its membrane are open to the diffusion of A molecules to fuel the production processes of B components. However, since the A molecules are external to the organization of the system, that is, since the A molecules are produced in the environment and not by the self-production processes, organizational closure will impose that these A molecules, when they enter the system, play a role fixed by the organization.

When the cell membrane is intact, the B components remain inside the membrane. However, when one of the C components disintegrates and dissipates into the environment in the form of D, a hole is created and the membrane is damaged. Given the importance of the membrane in defining the autopoietic unity the tessellation model must account for its reparation. Thus, when the membrane is damaged, the hole will be occupied by a B component which now becomes a C component.

Taking the repair and maintenance process as a whole, from the diffusion of substrate molecules to the dissipation of energy, $A + A \rightarrow B \rightarrow C \rightarrow D$ we see that the tessellation automaton describes a dissipative structure [42].

As noted in the previous section, highly complex systems have been modelled in physics as information engines. Taking this approach we may analyze the repair-maintenance process $A + A \rightarrow B \rightarrow C \rightarrow D$ into a sequence of thermodynamic protocols, namely, *measurement*, *control* and *dissipation* [42].

3.2.1. Measurement, control and dissipation

The measurement protocol takes place when the system looks for A substrate molecules in the environment. At this stage, the system will allow the diffusion of A molecules into its membrane if the quantity of B components is below the upper bound set by the membrane.

The control protocol is concerned with expanding the space of possibility of chemical reactions such as to select those reactions that will more efficiently produce the necessary B components that can be used to repair the membrane. In the control protocol the system undergoes a mixing of the A molecules and the B components. For if there was an absolutely ordered separation of A molecules and B components, then the reparation process would not come about and autopoiesis would cease. Thus, the diffusion that the control protocol introduces in the system helps the system to have a big picture view of the possible chemical reactions and select those more adapted to the current conditions and challenges. In other words, the control protocol by expanding the range of possible reactions the system can select will destroy some of the inertia that the system developed after having crystallized a set of reactions that were better adapted to previous conditions and perturbations the system faced, but which are not necessarily the most adapted for the present conditions. The system will seek a balance between inertia and diffusion.

Finally, in the dissipation protocol, the thermodynamic cycle is terminated by the dissipation of D.

3.2.2. Membrane repair and maintenance dynamics

The dynamics of repairing and maintaining the cell membrane define a random dynamical system [43],

$$\frac{dc_M}{dt} = -k_c c_M + k_B c_B (c_1 - c_M) p c_M \qquad (1)$$

where $c_M(t)$ is the quantity of C components in the membrane at instant t and belongs to the interval $[0, c_1]$ such that c_1 is the maximum amount of C components (when the membrane has no holes). Similarly, $c_B(t)$ is the concentration of B components and belongs to the interval $[0, b_1]$, such that b_1 is the maximum concentration of B components. pc_M is the probability that a B component will occupy a hole left by the disintegrated C component.

The term $-k_c c_M$ describes the dissipation $C \to D$. Whereas the term $k_B c_B (c_1 - c_M)$ describes the repairing $A + A \to B \to C$ that results from executing the protocols of measurement and control.

In the control protocol, in order to maximize long-range correlations and expand the possibilities of chemical reactions that can be selected, there is a diffusion of A and B, such that these follow a random walk which can be approximated for their local concentrations $a_M(x, t)$ and $b_M(x, t)$ as follows [43],

$$\frac{\partial a}{\partial t} = \Delta a - 2k_a a_M^2 c_M (b_1 - b_M) \delta_M \qquad (2)$$

$$\frac{\partial b}{\partial t} = \Delta b + 2k_a a_M^2 c_M (b_1 - b_M) \delta_M \qquad (3)$$

where Δ is the Laplacian operator and δ_M a characteristic function.

The fundamental variable to study the structure of the system dynamics is $c^* = \frac{c_1}{c_M}$, the proportion of the total membrane area that is occupied by the C components. Based on this value the system has at least two fixed-point attractors: $c^* = 0$ where the system converges to equilibrium and autopoiesis ceases, and $c^* > 50\%$ where the system stabilizes in a dissipative structure where autopoiesis is maintained by balacing the rate of $C \rightarrow D$ by $B \rightarrow C$. The equilibrium state is defined by the probability distribution p_{eq}, and the dissipative structure is defined by the probability distribution p_{dis}. These attractors are separated by a point of bifurcation p_{bif} fixed at $c^* = 50\%$.

Therefore, the phase space is divided into a region of death and a region of life. In the transition from one attractor to another, either from equilibrium to a dissipative structure (emergence of autopoiesis) or from a dissipative structure to thermodynamic equilibrium (ceasing of autopoiesis), there is a critical point, or bifurcation point separating the two. For the system to efficiently converge to p_{dis}, the distance between p_{dis} and p_{bif} must be as small as possible.

The problem of optimizing the distance between the two points can be tackled through the use of methods from information geometry such as information manifolds and the Fisher information metric.

3.2.3. Information manifolds and thermodynamic interpretations of the Fisher information metric

The geometrization of thermodynamics was pioneered by Gibbs [46][49]. Gibbs considered a system with states specified by volume V, pressure $-P$, temperature T, internal energy U and Shannon entropy S. The thermodynamic equation,

$$dU = TdS - PdV \qquad (4)$$

defines the Gibbs surface. Temperature and pressure are constants of inclination of a tangent space to the Gibbs surface.

If a system is in a non-equilibrium state, entropy is continuously produced. One can attest this by defining a metric structure on the geometric space. For instance, computing the Hessian of the Shannon entropy, we obtain a metric called Ruppeiner metric in component form [49],

$$g_{ij}^{R} \coloneqq -\frac{\partial S}{\partial \xi^{i} \partial \xi^{j}} = -d\left(\frac{1}{k_B T}\right) \otimes_S dU - \left(\frac{P}{k_B T}\right) \otimes_S dV \tag{5}$$

where $k_B T$ is the Boltzmann constant.

Equation (5) is a Riemannian metric that encodes the total amount of fluctuations the system undergoes to complete a thermodynamic process. Intuitively, we can associate the Riemannian structure induced on the geometric space to the fact that there exists an intrinsic distance notion $ds^2 = g_{ij}^{R} d\xi^{i} d\xi^{j}$ between dissipative states and how far they are from the equilibrium state.

However, the Ruppeiner metric only applies to systems that operate in an adiabatic regime, such as Carnot engines, and to treat biological systems whose dynamics are irreversible it is necessary to go beyond the Carnot engine model and generalize the geometric space where the thermodynamic fluctuations are defined.

As a result, a more general metric will be studied which is appropriate to capture the fluctuations and the complexity of biological systems such as the minimal autopoietic model sketched above.

The dissipative, or out-of-equilibrium, states of the system are intrinsically related to our definition of information as a physical quantity and measure of organization, since the production of informationally rich structures depends on the system being out of equilibrium and in a state characterized by dissipation and fluctuation.

We will then see how information will be crucial to measure the complexity and thermodynamic viability of these states.

Thus, based on the distinction between equilibrium and dissipative states we identify two fundamental geometric spaces in thermodynamics: the Legendre submanifold containing the equilibrium states and the information manifold containing the dissipative states [48]. An information manifold is a differentiable manifold $\mathscr{M}$, which is, intuitively, a set of probability distributions p with a coordinate system ξ. The probability distributions represent the possible attractors or dissipative structures that the system can attain, while the coordinates are the parameters regulating the evolution of the system, such as the concentrations k_a, k_b and k_c.

According to Ruppeiner [46][49], the Riemannian metric structure is natural to the formalism of thermodynamics when fluctuations are included as part of the model. That is, the Riemannian metric structure emerges when the system admits out of equilibrium states and there is dissipation. It is possible to define on information manifolds an arbitrary number of

Riemannian metrics since the inner product structure is not sufficient to uniquely determine a metric. However, there is a unique Riemannian metric that satisfies the conditions of an *information metric* [45]. This metric is called the Fisher information metric.

In this setting, the Fisher information metric emerges as a *complexity measure* [44][45]. That is, the Fisher information metric quantifies the information content of a complex, self-organized structure. To better grasp this idea, we point to the relation between the Fisher information metric and the Shannon entropy.

Following Quevedo and Vázquez [48], the Riemannian structure of $\mathscr{M}$ defines an *invariant volume element* $d\mu(x,\xi) = \sqrt{\left|\frac{g_{ij}(x,\xi)}{2\pi}\right|}\,dx$. Based on the volume element the *probability weight* $\omega(x,\xi) = p(x,\xi)\sqrt{|2\pi g^{ij}(x,\xi)|}$ is defined. Through the probability weight the authors arrived at the definition of the Shannon entropy as a global invariant measure,

$$H(x,\xi) = -\int \omega(x,\xi)\log\omega(x,\xi)d\mu(x,\xi) \qquad (6)$$

The Shannon entropy here denotes the *information potential* of the system, which is the *negative of the information content* given by the Fisher information metric $I = -\log\omega(x,\xi)$.

Bates and Shephard [44] introduced a complexity measure called 'information fluctuation complexity' which is based on the Shannon entropy H and the information content I.

According to Bates and Shephard, this complexity measure is defined as the fluctuation of I around H,

$$\sigma_I = \sqrt{\sum_{i=1}^{N} p_i(I_i - H)^2} \qquad (7)$$

According to the above equation, when the system is in thermodynamic equilibrium autopoiesis ceases to exist, for the fluctuation of I around H is zero and, once autopoiesis ceases, what was once a self-referent composite unity becomes indistinguishable from its noisy environment. In other words, the structural arrangement that realized the organization is lost and the components of the system are no longer interconnected by a network of production processes, but simply follow the random motions caused by the external causes of noise. When this happens the system's degree of complexity is zero.

Moreover, while the information metric is a *measure of complexity* it is also a *measure of thermodynamic efficiency.*

When a system processes information it transitions from one state to the other [47], the efficiency of this transition is measured by a quantity called the *thermodynamic cost* $\mathcal{C}$ [47], whereas a transition is the more efficient when it minimizes the thermodynamic cost $\mathcal{C}$. $\mathcal{C}$ is thus defined as the action integral,

$$\mathcal{C}(\xi_1, \xi_2) = \frac{1}{2}\int_{\xi_1}^{\xi_2} I\,(\xi) d\xi \qquad (8)$$

The thermodynamic cost $\mathcal{C}$ is calculated using the Fisher information metric I. To calculate this cost, the Fisher information metric is interpreted from a geometric point of view as a line element ds, which determines the dimensionless distance between two probability distributions $p(x, \xi_1)$ and $p(x, \xi_2)$ that represent different states of the system. The distance between the two probability distributions depends on the system's parameterization. Although there are many possible parameterizations that change the distance between probability distributions and the energy cost necessary to cover this distance when the system transitions from one state to another, there is only one parameterization that minimizes the distance between the two probability distributions, that is, that minimizes the thermodynamic cost $\mathcal{C}$.

According to Ito [47], the minimal value of the length traced between two probability distributions is equal to the *arc length* of the curve connecting the two probability distributions. This curve is the optimal parametrization which minimizes the action integral $\mathcal{C}$. Therefore, from a thermodynamic point of view, the system is the more efficient in its self-repair and self-production as the curve that connects the bifurcation point to the fixed-point attractor of dissipation is closer to its arc length.

In conclusion, the role of information in general, and of the Fisher information metric in particular, is crucial both in measuring the degree of complexity of the system and its autonomy in relation to the environment but also in understanding the thermodynamic uncertainty relations underlying information processing and the transition between states. Naturally, both the degree of complexity that a living system fosters and the thermodynamic accounting underlying its structural plasticity and change of states are closely related in living systems. For the way the system learns and calibrates its parameters and the organized patterns it fosters are in accordance with certain thermodynamic limits to its persistence and survival as a unity in space and time.

CHAPTER 4

Conclusion

We introduced a hylomorphic theory of substance to account for the diversity and complexity that exists in the natural world. This metaphysical account allows us to consider complex wholes as particular beings that must be studied in their own right, in contrast to other perspectives that deny the existence of complexity or reduce it to a question of latency.

In addition to recognizing that there are in fact composite wholes that emerge through the relationships between their parts, it is also necessary to understand how these complex wholes constitute a composite unity as such. That is, a composite imposes norms on its parts and defines normative patterns and symmetries that its parts follow in their interactions. However, these patterns and symmetries have a principle of unity that defines the identity of a given composite. This principle of unity is given by the concept of form, which must satisfy certain conditions, such as ontological primacy and logical simplicity, in order to play the role of a principle of unity and organization of a composite whole.

A particular kind of composite unity that is characterized by a high degree of autonomy is autopoiesis. Autopoietic systems are composed of organization and structure. We argued for an understanding of the organization-structure composition based on the theory of hylomorphism where the organization is equivalent to form and structure is equivalent to matter. Regarding the organization as a form allows to avoid a series of consistency problems, such as defining the organization as an abstract universal, or defining the organization as a subset of the structure, which results in a relation of inclusion rather than a proper composition.

One of the main consequences of the theory of autopoiesis, is that it makes obsolete a series of ideas and concepts that are commonplace in the paradigm of first-order cybernetics if they are applied without qualifications to autopoietic systems. Two examples of this difficulty are teleology and information. Due to the radical self-reference and organizational closure of the autopoietic unity, these concepts are seen as a projection of the modeler's mind into the system and not as immanent things that emerge as a result of the internal operations of the autopoietic system.

In the case of teleology, this issue has already been addressed in the literature and teleology has been conciliated with the theory of autopoiesis. In the case of information, the conciliation was one of the contributions of our work.

By understanding information in its classical Aristotelian sense, based on the concept of form, and by making reference to recent advances in the physics of information, it is possible to regard information as an immanent physical reality and product of self-organization that is consistent with autopoiesis and that can be used as a measure of the degree of complexity of an energy-dissipating structure supporting the emergence of life and autopoiesis.

Moreover, we presented a tessellation model that describes how a cellular autopoietic system operates as an information engine to repair and maintain its membrane. We concluded that this repair and maintenance process defines at least two attractors: the state of thermodynamic equilibrium where autopoiesis ceases and the living system dies, and an out of equilibrium state which forms a dissipative structure whereby the system's boundary is continuously being disintegrated and repaired by the system's processes of production. In this dissipative structure, autopoiesis and life are maintained. These two attractors are separated by a point of bifurcation.

Finally, we proposed to use information geometric tools such as information manifolds and the Fisher information metric to measure the informational order of the dissipative structure that supports autopoiesis as well as the optimal energy cost associated with switching between dissipative structures. We concluded that by taking information as a physical and immanent property arising from the system's operations we can attribute to it a role in measuring the degree of complexity of the system and its autonomy in relation to the environment but also in understanding the thermodynamic uncertainty relations underlying information processing and the transition between states.

The advantage of this proposal is two-fold. First, by conciliating autopoiesis and information we can study the autopoietic phenomenon as an essentially organizational phenomenon without the need to account for the specific components and their relations. This is important because it preserves the ontological primacy of the organization over its parts. Secondly, it opens a path to mathematical descriptions, in this case by taking the tools and models of the physics of information to describe the thermodynamic underpinnings of the emergence of autopoietic organization and its maintenance

This investigation opens up other possible avenues for future research, mostly due to the ontological and epistemological twist we have introduced regarding the nature of the autopoietic organization and its structure.

A possible avenue of research involves using the correlate act-potency to overcome certain obstacles and objections to the possibility of social autopoiesis. Just as in cellular autopoiesis the organizing principle of the processes of self-production is a specific case of a form - a causal principle relating the parts into processes of self-production; that is, a specific case of actuality. So too is the material cell infrastructure that realizes the processes of self-production in the physical space a specific case of Aristotelian matter, that is, a specific case of potentiality. From this point of view social autopoiesis could be another specific case of this more comprehensive actuality-potentiality correlate.

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Annex A

While developing our thesis topic, we first sought to develop a theory general enough to address various examples of complexity in the world. From the outset, it was our intention to address the physics and geometry of information and information processing in complex systems, but we still lacked a concrete case study or a specific contribution to the vast field of complexity and information theory. To delimit our research topic and develop a geometric theory of information specifically applied to information processes and, consequently, to the thermodynamics of complex systems, we held two workshops within the doctoral program where application proposals were presented and discussed.

In the first worshop presentation, we applied information theory and information geometry to the immune system. The goal was to understand phenomena like energy flows towards fueling defensive tasks of the system, the system's adaptation to a noisy enviroment and the emergence of complex, functional networks as a result of symmetry breaking, etc. Some of the measures discussed were the 'thermodynamic depth', the Kullback-Leibler divergence and the Fisher information metric in order to understand how random immune variables were dependent and denoted a level integration as well as how pattern formation was to took place.

However, in addition to technical implementation issues, this proposal was not an original thesis proposal, but rather a synthesis of past contributions. Another weakness was the philosophical naiveté with which the issue of information and computation at the level of biological systems was approached, incorporating notions from information theory and cybernetics without considering the philosophical consequences and problems this entailed for our theory. For example, the adopted perspective defined the immune system as a product of evolutionary pressures that encoded information and allocated thermodynamic resources to adapt to a noisy environment. This definition is not only overly simplistic but also fails to treat the immune system as a unity in itself, with an operational closure and individualization that cannot be explained by either evolutionary pressures or adaptability issues. From this point of view, our information theory was not so much about how the system self-organizes and maintains its individuality but about the detection of external threats and adaptive decisions to those threats.

In the second workshop presentation, we introduced the concept of an information engine and shifted our view of information more as in terms of transient dynamics and self-organization under novel conditions. One of the examples used to illustrate these ideas was the conformon.

During this phase, greater attention was paid to epistemological questions, particularly those related to the role of the observer. The question of observer participation would be particularly relevant in measurements made in quantum information systems, thus increasingly emphasizing the autonomy of complex systems and a growing concern with 'naturalizing' concepts and measures of information theory and geometry. That is, interpreting these measures beyond our symbolic domain as modelers and considering them as describing real dynamics and processes of nature, not merely tools by which these dynamics and processes are studied. The naturalization of these measures, especially the Fisher information metric, led us not only to deeper epistemological considerations but also to explore the geometric structures of the configuration spaces of complex systems. In other words, in order to naturalize information-geometric and information-theoretic measures we had to take all the relevant observables and geometrize them as part of the geometric structure of the system.

The laws of thermodynamics have geometric roots in the variations of divergence statistics such as the relative entropy. For instance, the contact 1-form structure of the physical space arises from taking the first statistical moment of the characteristic function or, alternatively, the first variation of the relative entropy.

Contact geometry is the geometric ground for Legendre symmetries and transformation – diffeomorphisms of equilibrium sub-manifolds and isometric Hessian metric structures, induced by the Fisher Information matrix.

The Lie group approach to thermodynamics (sometimes also called Geometric Mechanics) was pioneered by Jean Marie Souriau (Souriau, 1975, 1992) in an attempt to unify analytical mechanics, statistical physics and Gibbs covariant thermodynamics under the same theory, in which the symmetries are specified by a dynamic group preserving the covariant structure of the equilibrium states - the Lie group of symplectomophisms. Some elementary properties of symplectic Lie groups suffice to show how a duality is established within a symplectic cocycle between the Lie algebra of the affine space (Planck Temperature) and the Lie algebra on the dual affine space (Geometric Heat).

Souriau set forth the idea that the collection of orbits (motions) forms a symplectic manifold equipped with an anti-symmetric flat tensor, identified with the symplectic 2-form. The consequence of this geometrical model is that it relocates the relevant physical information somewhere else into the depths of the very physical space, that is, it naturalizes these measures. Another important result pointed out was that at Gibbs density it holds the equivalence between the Fisher Information matrix (describing the covariance of the orbit's log-likelihood gradient), a generalization of heat capacity, and the hessian of the characteristic function.

Annex B

Based on these ideas developed in the second workshop we submitted an abstract for the Entropy 2022 conference in Porto which was reviewed and accepted. The abstract is reproduced bellow,

Information processing is bounded by thermodynamic requisites. Efficiency aspects of isothermal small systems which process information in the midst of fluctuations are addressed from a geometric perspective. Molecular motors are isothermal small systems responsible for the maintenance of several spontaneous biomolecular processes in nature. These systems produce entropy continuously when poised in a non-equilibrium steady state and are known to break several limits of classical thermodynamics such as linear irreversibility. Entropy production, as described by an irreversible Fokker-Planck equation, measures the heat dissipated to a medium as information is erased. The amount of heat dissipated is the thermodynamic cost associated to logically irreversible operations and is divided into two contributions - heat cost to maintain the steady state and the excess heat cost of the control parameters variation. The optimal dissipation protocol is computed with respect to the control parameters variation and it's represented as a geodesic in the Poincaré plane of a Riemannian univariate statistical manifold. The Riemannian structure is naturally defined by integrating the fluctuations into the axioms of thermodynamics such that the physical observables are necessarily treated as stochastic quantities. Moreover, protocol efficiency is evaluated by the geometric invariants of the statistical manifold, namely, the Fisher information metric and the Amari-Chentsov tensor. The Fisher information metric in particular captures the total amount of fluctuations and dissipated heat. Finally, we present generalizations of information geometry based on Souriau's symplectic interpretation of thermodynamics and link them to the previous results on heat dissipation. A remarkable result stemming from this perspective is the equivalence between the Souriau-Fisher metric and a generalized heat capacity. This equivalence is interpreted in the context of information processing and complexity.