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ORIGINAL PAPER

Recursive Ontology: A Systemic Theory of Reality

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Abstract The article introduces *recursive ontology*, a general ontology which aims to describe how *being* is organized and what are the processes that drive it. In order to answer those questions, I use a multidisciplinary approach that combines the theory of levels, philosophy and systems theory. The main claim of recursive ontology is that being is the product of a single recursive process of generation that builds up all of reality in a hierarchical fashion from fundamental physical particles to human societies. To support this assumption, I provide the general laws and the basic principles of recursive ontology as well as a semi-formalised model of the theory based on a recursive generative grammar. Recursive ontology not only actively promotes a multidisciplinary investigation of reality, but also can be used as a general framework to develop future domain-specific theories.

Keywords Complex systems · General ontology · Generative grammars · Recursion · Theory of levels

1 Introduction

Human beings have always asked: how is the *universe* organized? Is it possible to find some fundamentals that account for *reality*? What is reality? Some answers to these questions come both from science and philosophy. There are some relevant differences between the approaches adopted by these two disciplines. While science is focused on empirical evidence and observation, philosophy is usually more speculative and based upon argument and reasoning from principles. In this paper, I adopt a mixed approach. I rely on philosophy to speculate about the nature of the

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universe, and at the same time, I rely on science to guide my philosophical speculations based on empirical evidences.

Among the many branches of philosophy, general ontology is the discipline that deals with *being* and in turn with fundamental philosophical questions. This discipline should discover the categories of the world and the rules that govern them (Grossmann 1983). Many definitions of being have been proposed over time. For the purpose of this article, I consider being from three complementary perspectives: *structure*, *process* and *organization* as defined by the physicist Capra (1996). Structure is the physical instantiation of an abstract pattern of organization, and is subject to dynamic processes of transformation. In other words, structure accounts for the physical aspect of a construct, organization for the abstract properties and process for the forces which transform both structure and organization. Starting from this point, I define being as the superset containing all physical, biological, psychological and socio-cultural structures, patterns of organization and processes already manifested or yet to manifest. This definition is similar to the concept of universe from a systemic point of view, and is interchangeable with the notion of reality. The systemic approach considers the universe as a system with a structure, organization and a process, which comprehends every component as a subsystem.

The following are the research questions that drive this article:

- Are the different domains of reality related to one another? If so, how are they related?
- How is being organized?
- What are the ontological categories of being?
- What are the driving processes of being?
- What are the fundamentals of being?

To answer those questions I propose a *recursive ontology* (RO), a general ontology which provides a semi-formal description of reality. RO suggests a list of ontological categories, general laws and basic principles that account for the behaviour of being. Furthermore, RO proposes a hierarchical structure of reality, based on a recursive process of aggregation between the elements of being. The theory can be regarded as a general framework of reality, that can be adopted as a basis to develop domain-specific theories.

Previous research has attempted to define a general ontology based on hierarchical levels. Hartmann proposed a *theory of integrative levels*, suggesting that reality can be divided into four *strata* (Hartmann 2012). Feibleman developed some general rules that could explain the behaviour of levels (Feibleman 1954). Pattee proposed a more detailed theoretical framework of reality, which combined the classical theory of levels with systems theory (Pattee 1973). Poli refined these theories and developed a powerful ontology that divides reality into three multi-layered *strata* (Poli 1998, 2001). Finally, Brown proposed a sophisticated mathematical model of the theory of levels intended for emergent biosystems (Brown et al. 2007).

However, all these studies show some limitations. The majority lack a mathematical formalization, which would clarify and empower the theoretical

frameworks. Additionally, some of them (Poli 2001; Hartmann 2012) divide reality into distinct parallel strata (e.g., physical, psychological, social), rather than providing a single unified structure of being. Finally, even though this research acknowledges the hierarchical structure of reality, none of them proposes a specific process of generation, which could explain the organization of being. Indeed, those studies are descriptive rather than explanatory. On the other hand, RO not only suggests a unified structure of being, but also a single recursive process of generation that explains the organizational patterns of reality.

This article has three main aims. First, it introduces the fundamentals of RO. Second, it demonstrates that reality can be regarded as a hierarchical structure engendered by a recursive process of generation. Finally, it provides a semi-formalised recursive grammar, which is capable of producing being as the result of a continuous generative process.

To investigate these topics, I adopt a multidisciplinary approach which combines philosophy, complexity and systems theories as well as complex networks and linguistics. Indeed, given the extraordinary complexity of the issue, I think that only a multidisciplinary approach can provide useful results. Also, I use a theoretical approach which focuses on abstract concepts rather than on empirical case studies, in order to present a general overview of RO. Furthermore, I claim that it is possible to analyse the structure of being by using some constructs specifically developed for natural language, since language and being, as we will see, are inherently isomorphic.

The remainder of this article is organized in three parts. First, it provides a review of the literature which explores the concept of recursion (Sect. 2.1) and introduces the theory of levels (Sect. 2.2). Next, the paper introduces RO presenting the general laws (Sect. 3.1), a semi-formalised model (Sect. 3.2) and the basic principles of the theory (Sect. 3.3). Finally, a discussion summarizes the principal findings (Sect. 4.1), clarifies the implications of the theory (Sect. 4.2) and highlights both the limitations of RO and future necessary research (Sect. 4.3).

2 Background

This section introduces the fundamental theoretical constructs necessary to understand RO. Initially, it provides a definition of recursion and introduces some relevant applications of recursive processes in nature, language and cognition (Sect. 2.1). Then, it outlines the main features of the theory of levels (Sect. 2.2).

2.1 Defining Recursion

Recursion is a universal process that appears within all the domains of reality such as the physical, the biological and the cultural. Even though the recursive process is inherently simple, it is stunningly elusive and difficult to grasp (Koschmann 2010). Moreover, there is no unique definition of recursion. Sometimes, different definitions even oppose one another. Recursion can be understood either as a *process* or as a *structure* (Corballis 2011). It is possible to have a recursive process

that does not necessary entail a recursive structure, as well as a recursive structure that is not necessary entailed by a recursive process (Martins and Fitch 2014).

The term recursion usually indicates the process of embedding some constructs within other constructs of the same kind (Pinker and Jackendoff 2005). This definition focuses only on the structural aspect of recursion. A more useful definition for the present research considers recursion as the set of rules that can apply to their output infinite times (Everett 2009). This definition focuses on process rather than on structure, considering recursion as a steady process that applies either to systems or functions. From a computational point of view, it is possible to define recursion as a procedure that calls itself, or that calls an equivalent kind of procedure (Corballis 2007).

Recursion is a blurred concept that can be confused with other similar processes, such as *iteration* or *hierarchical embedding* (Martins and Fitch 2014). Iteration is the process of repeating a process a certain number of times (Fitch 2010). Iteration neither necessarily involves a hierarchical structure nor entails a structure based on self-similarity. On the other hand, hierarchical structures always involve the embedding of elements within other elements (Martins and Fitch 2014). Hierarchical structures are not necessarily recursive structures. However, the opposite is true. In particular, the ability to generate higher hierarchical levels beyond the one which is already given is a relevant feature of recursion (Martins and Fitch 2014).

One important class of recursive structures is fractals (Mandelbrot 1983). These are structures that have the property of self-similarity. Fractals exhibit the same pattern when observed at different levels of resolution (Fig. 1). Although fractals

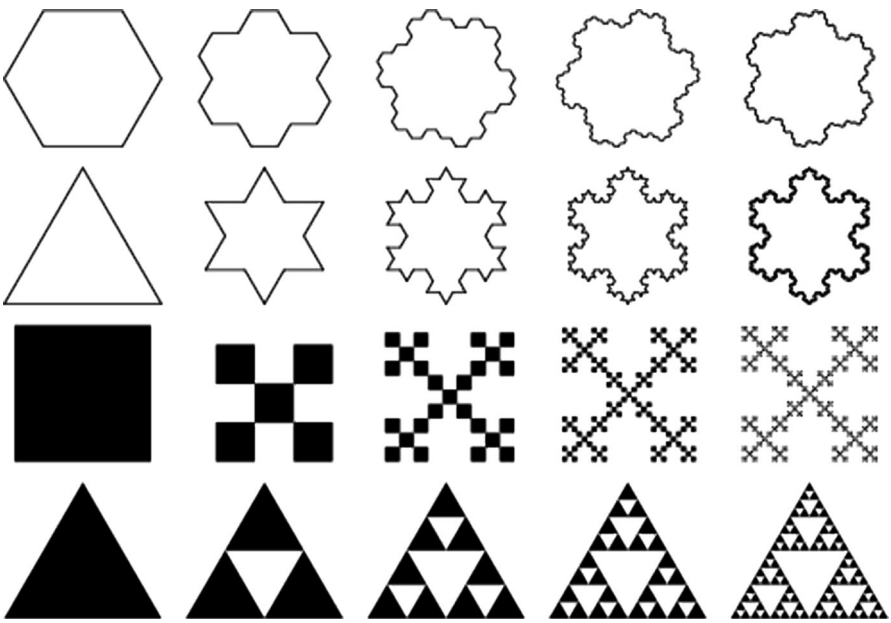

Fig. 1 Examples of fractal structures exhibiting self-similarity

appear as highly complex hierarchical structures, they can be generated by a small set of rules. This property is another relevant aspect of recursion.

Recursion not only occurs at the physical and biological levels, but also within the psychological and socio-cultural domains. Indeed, the only feature that distinguishes human language from the languages of other animals such as birds and dolphins appears to be recursion (Hauser et al. 2002). Humans can generate recursive sentences that embed other sentences. This feature exponentially amplifies the power of human language. The recursive process not only happens at the syntactical level of the language, but also involves the conceptual levels of semantics and pragmatics (Evans and Stephen 2009). It has even been proposed that recursion is what distinguishes us as humans (Corballis 2011). In particular, the capacity of embedding thoughts within other thoughts is the key feature that could explain the astonishing capacities of the human mind and human creativity (Hofstadter 1980).

2.2 Theories of Levels

Many theoretical frameworks that describe reality from an ontological point of view fall under the umbrella of the theory of levels, although they usually have different names. Some examples are the *hierarchy theory* (Pattee 1973; Allen and Starr 1982; Simon 1991), the *theory of integrative levels* (Novikoff 1945; Feibleman 1954; Hartmann 2012), *transdisciplinarity* (Nicolescu 2002) and the *theory of levels of reality* (Poli 1998). All these theories describe reality in terms of hierarchical organization. In particular, they all assume that reality can be regarded as a hierarchical structure, divided into different levels. These theories claim that the universe can be analysed at different levels of resolution along a scale based on complexity. At the base of the scale there are atomic and molecular physical structures, whereas at the top there are complex social systems. Every level considers a particular discrete portion of this hierarchical scale. Moreover, a specific level of reality is implied by the interactions between components of the lower levels, and in turn contributes to the formation of the higher levels (Feibleman 1954).

Although the concept of level is quite intuitive, its definition usually changes depending on the researcher. However, all definitions consider some relevant issues, such as coordination between levels, dependency/autonomy among levels and categorical closure of levels (Poli 2001). Levels can be regarded as collections of units that interact with one another, creating a coherent unitary structure at a particular point within the hierarchical scale of reality (Pattee 1973). This definition stresses the concept of dependency among levels, even though it does not specify the nature of the units. Combining the ideas of the theories of levels and systems, units that make up levels can be considered as systems (Nicolescu 2002). Recursive ontology borrows this idea and develops its implications.

Another relevant distinction between theories of levels is the fact that they either consider levels as discrete or as continuous constructs. However, a majority of researchers support the idea of discrete levels (Hartmann 2012; Pattee 1973; Poli 2009). This theoretical perspective is backed up by the intuitive notion of the

discrete unfolding of the structure of nature, where different constructs—such as atoms, animals and human social systems—show clear quantifiable differences. It is worth noting that, even if most of the literature focuses on discrete levels, these can also be considered as analogue constructs (Nicolescu 2002). This implies an infinite number of hierarchical levels with slightly different amounts of complexity.

Regarding the type of levels, some theories suggest that all levels are of the same type (Nicolescu 2002), while others claim that there are different types of levels (Poli 2001; Hartmann 2012). This difference is crucial. The former typology of theories considers reality as a single structure, where all levels from the physical to the socio-cultural are considered qualitatively identical. On the other hand, the latter typology divides reality into more than one type of stratum. For example, Hartman divides reality into four different strata (i.e., inorganic, organic, emotional, cultural), which are considered qualitatively different (Hartmann 2012). The different strata can interact with each other and concur to compose all of reality, even though they are intrinsically diverse (Minati et al. 2006).

A large number of rules governing the behaviour of levels has been proposed (Feibleman 1954; Austin 1969). However, just a few of them have been recognized as valid by the majority of the scientific community. One rule generally acknowledged by all researchers is the law of *emergence*. The law of emergence states that the properties of the higher hierarchical levels emerge as the result of the interaction between the components of the lower levels (Korn 2007). This concept, based on the principle of self-organization of complex systems (Nicolis and Prigogine 1977), is of primary importance for the development of RO.

3 Fundamentals of Recursive Ontology

This section is the main contribution of the article, since it introduces the basic concepts of recursive ontology. Initially, it provides some general laws that applies to the entire domain of being (Sect. 3.1). Then, it proposes a semi-formalised model of RO, delving into some details of the theory (Sect. 3.2). Finally, it introduces the basic principles of *being* (Sect. 3.3).

3.1 General Laws

This section introduces the most relevant laws associated with being. These laws are intended as general rules that apply to every construct of being, and to being as a whole. General laws of RO affect all of the levels of being, and therefore span several disciplines such as physics, biology and sociology. For this reason, they can be regarded as meta-laws which transcend the specific domain of study. Even though general laws work on a very abstract level, they are susceptible to empirical enquiry. General laws cannot be verified, but can be falsified by finding valid domain-specific counterexamples.

The *law of building blocks* explains what are the elements that compose reality (Sect. 3.1.1). The *law of recursive organization* describes how those elements are connected together, in order to form being (Sect. 3.1.2). The *law of emergence*

clarifies how the properties of reality can emerge in a non-predetermined fashion by interaction between elements of reality (Sect. 3.1.3). The *law of isomorphism between levels* analyses being from an operational point of view (Sect. 3.1.4).

3.1.1 Law of Building Blocks

- The building blocks of being are *systems* with different degrees of complexity.

This law describes the atomic components of being and claims that being is made up of systems. A system is a set of interacting or interdependent components forming an integrated whole (Backlund 2000). Every system is characterized by inputs and outputs, which allow it to establish a relationship with its environment, and to evolve according to new information acquired.

Systems are *content-independent*. Indeed, they transcend their particular domains. Systems are based on the relationships between different components that exchange information, rather than on the content of the information itself. A process can be described from a systemic point of view, even if the specific content of the process is unknown. As a consequence, systems can be used as high-level representations of specific processes.

One evident implication of the law of building blocks, is that systems transcend a particular domain and embrace the whole of reality (von Bertalanffy 1968). For instance, it is possible to describe a molecule, a cell, a rock or even a society as a system. Generalizing, every item that contributes to build up being—such as the aforementioned molecules, rocks and cells—can each be described as a system. Therefore, all items that make up reality are qualitatively equal, in the sense that they can all be regarded as systems, which exchange information with their environment. Being as a whole can be regarded as a system containing systems, which exchange information with one another and which evolve over time.

Of course, different systems in different domains manifest different degrees of complexity. For example, a cell is more complex than a rock, a human is more complex than a cell, and an entire society is a system far more complex than a single human being. Complexity arises when moving from the physical domain towards the biological and the cultural levels (Feibleman 1954).

However, I still have precisely to define the concept of complexity. There are many, sometimes opposing, definitions of complexity which come from different disciplines such as information theory, computer science and mathematics. RO adopts the definition of complexity proposed by the theory of complex adaptive systems, which measures the complexity of a system based on the following attributes:

- Number of components.
- Non-linear relationships between components.
- Capacity to memorize information.
- Presence of feedback loops.
- Non-linear relations between the system and its environment.

- Sensitivity to initial condition (i.e., the *butterfly effect*).
- Capacity to adapt to the environment.
- Capacity to influence the environment.

3.1.2 Law of Recursive Organization

- Systems connect with other systems at the same hierarchical level of being, and build up more complex systems at higher hierarchical levels in a recursive fashion.

This law answers the question of how being is organized. Although I have hypothesized that systems are the building blocks of being, we now need to uncover the process that allows being to be formed. This process is recursive and is based on connections between systems at the same level. Being is an extremely complex system itself. By definition, it is the most complex system of all, since it embraces reality as a whole. Being is organized into hierarchical levels that manifest different degrees of complexity. Every level is made up of systems that have approximately the same amount of complexity. These systems are connected together in very complex networks.

Starting from the lowest level, it is possible to describe the formation of being by following an apparently simple recursive process. Systems which have the least amount of complexity belong to the lowest level. These connect together and tend to form a new super-system at the next higher level. The new super-system is more complex than its components and of course cannot be reduced to its sub-systems (Progogine and Stengers 1984). Indeed, the establishment of new connections between the components of the super-system, which are the systems of the lowest level, adds extra complexity. Recursively, more super-systems tend to connect with each other in order to form a super–super-system (Fig. 2). The process keeps going until it reaches the maximum level of complexity, which corresponds to being itself.

Generalizing, this recursive process unfolds at every hierarchical level of being both on a *horizontal* and *vertical* basis. To explain, one might use the example of atoms and molecules. Molecules, which populate the molecular level of being, emerge as the associations between many atoms, which make up the atomic level. Atoms are spread throughout a horizontal plane, which represents the atomic level of being. A subset of these atoms connect with each other in order to create a single molecule, but at the same time, many other subsets of atoms in other portions of the plane make up other molecules. This process unfolds horizontally throughout the atomic level and recursively organizes many super-systems (i.e., molecules), which belong to the higher molecular level, represented by a horizontal plane positioned above the atomic level. This phenomenon is a *many–many–many* creation process. That is, it involves many sets of many systems at a specific horizontal level, which are projected vertically at the next hierarchical level of being to create many super-systems. As a consequence, it is possible to claim that the total number of super-systems which populate a higher hierarchical level of being is less than the total

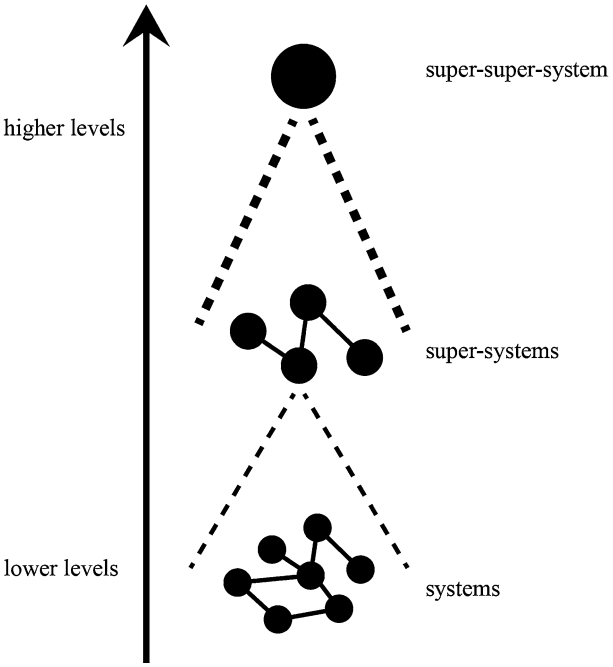

Fig. 2 Systems connect with each other recursively in order to generate higher level systems

number of components at the lower level. This generative process is more than simple hierarchical embedding as proposed by previous research (Pattee 1973; Salthe 1985; Ahl and Allen 1996). Rather, it can be regarded as a recursive process, since it involves the embedding of constructs within other construct of the same type. Specifically, the process involves the embedding of systems within other systems, thanks to a generative process that continuously feeds the output of its previous iterations (i.e., systems) into new instances of the same generative mechanism.

This recursive process partially opposes the claims of some theories of integrative levels (e.g., Poli 2001; Hartmann 2012), which divide being into qualitatively different levels of reality, such as the material, mental and social strata. These levels may sometimes overlap each other, but are generally separated. On the other hand, RO claims that reality is a unitary process that unfolds along a single scale from the lower towards the higher levels. As a consequence, the different strata described by the theories of levels proposed by Hartmann and Poli belong in RO to the same recursive process and are manifestation of being at different vertical levels. In particular, the physical level lies at the bottom of the scale. Next, come the biological level, the psychological level and so on. For RO, all these levels are not qualitatively different, just quantitatively different. Specifically, the difference is based on the degree of complexity of the systems which constitute the levels.

At the end of this section, a couple of questions still remain unanswered: why is recursion the process followed by being to build up reality? Is it possible to justify

this process? Indeed, there might be several other processes to build up being. For instance, new systems might be the result of transformations of other existing systems, or it is possible to postulate that radically different systems such as physical and biological systems might be regarded as qualitatively diverse systems (Poli 2001; Hartmann 2012). However, all these strategies are far more expensive than recursion in terms of resources used to shape reality. Indeed, the epistemological justification of the law of recursive organization lies in the *principle of economy of resources*, which will be thoroughly discussed later in the article (Sect. 3.3.1). This principle claims that systems at every level of being employ the least amount of resources possible. In that regard, recursion is the most resource-efficient process to form being, since it guarantees that brand new systems are born from the simple association of already existing lower level systems.

3.1.3 Law of Emergence

- The properties of being emerge moving from the lower towards the higher hierarchical levels.

The law of emergence accounts for the properties of being. It is possible to define a *property* as a behaviour of a system both *expected* or *unexpected*. An expected behaviour is one we can predict based on the knowledge we already have of the structure, organization and processes of the system. On the contrary, an unexpected behaviour is one we cannot predict based on the information we have.

The law of emergence states that the properties of being emerge while we are moving towards the higher levels. However, a precise definition of the term is needed, in order to avoid ambiguity. 'Emerge' in this context means that a property unexpectedly arises from the interactions of the systems at a certain level. In other words, most of the properties of being are not determined a priori. The emergence of properties is the result of the extra complexity added by the non-linear relationships established by systems at specific hierarchical levels. As a consequence, the super-system at the higher level manifests some unexpected properties that are not predictable from its components.

For example, this is the case with the properties of *consciousness*, *mind* or *society*. All of these can be regarded as emergent properties of being that derive from the interactions of the components at lower levels. Mind can be described as an emergent property resulting either from the complex relationships between neurons (Minsky 1988) or from the non-linear relationships between functional modules (Fodor 1983). Society is an emergent property that arises from the interaction of single psychological systems (i.e., individuals) connected together (Luhmann 1995).

Properties are the result of the complex structure of reality. These are a by-product of the recursive process of organization of systems. Properties are strictly related to the concept of complexity. The more complex the level of being considered, the more unexpected the properties that might emerge from the interactions of its components. Hence, a low level of complexity allows fewer unexpected properties to emerge.

Emergence, complexity and *chaos* are all tied together. Complex systems are systems which evolve on the *edge of chaos*, and therefore can be called *quasi-chaotic* systems. There is a strong relationship between quasi-chaotic systems and emergence, since emergent properties are a peculiar aspect of complex systems. Being is characterised by emergent properties, therefore it can be regarded as a hyper-complex system that evolves on the edge of chaos. It neither follows a completely chaotic dynamic, nor does it follow a completely deterministic path. Rather, being is a quasi-chaotic system characterized by the emergence of its properties based on the interactions between its components. The process of emergence of properties entails an inner creativity of being as a whole, which continuously renews its structures, patterns of organization and processes. Indeed, reality can evolve and manifest unexpected forms of organization and behaviours that otherwise, imagining a deterministic/linear being, would be impossible.

3.1.4 Law of Isomorphism Between Levels

- All hierarchical levels of being can be described by the same qualitative/quantitative models.

This law analyses being from an operational point of view. Specifically, it indirectly states that all the hierarchical levels of being operate in a similar manner. This is not an unexpected assumption, since we are using systems to describe reality. Indeed, systems are content-independent constructs, which can be used to describe numerous abstract processes, even if they are characterized by different contents.

The levels referred to in the law of isomorphism between levels are the different vertical levels that build up being in a hierarchical fashion. Levels show various differences between each other. Levels are characterized by varying degrees of complexity; they are constituted by different kinds of systems; and they are different in the domains they span, since they represent diverse portions of reality. Some levels belong to the physical domain, others to the biological, psychological, or social domains.

However, all levels share a fundamental common feature. They are all based on the same recursive process of connection of systems. Therefore, it is possible to use the same model to describe all the different levels. This is the core idea of systems theory (von Bertalanffy 1968). Indeed, the systemic approach can be regarded as a meta-description of reality based on the interactions between the components of a general system.

Recursive ontology appears as a meta-theory of reality, which provides a general framework for being. The framework is modular and can be filled by many domain-specific theories that describe and analyse specific portions of reality. Therefore, RO traces a general path that can be progressively explored in more detail by domain-specific systemic theories.

Thus, the main idea behind RO is that reality can be regarded as a manifestation of a single recursive process, that gradually builds being in its entirety, moving from

one level of complexity to another. This process is what unifies the different domains of reality such as the physical, the biological, the cultural and the social.

3.2 A Semi-formalised Model of Recursive Ontology

This section introduces a first attempt at formalising the ideas and general laws of RO. Initially, I define a recursive grammar that can thoroughly represent the core concepts of RO (Sect. 3.2.1). Then, I describe in more detail how the systems that make up being are organized in networks, and how they exchange information (Sect. 3.2.2). Additionally, I present an ontological journey from the bottom levels towards the top levels of being, in order to describe the main ontological categories within the framework of RO (Sect. 3.2.3). Finally, I point out the difference between domain-specific and domain-general laws (Sect. 3.2.4).

3.2.1 Defining a Recursive Grammar

There are some striking similarities between language and being. They both are extremely complex systems which can be described in terms of structure, organization and process. Particularly, they both show a syntax and a semantics. The syntax of being tells us how to generate more complex systems starting from less complex systems. Indeed, the syntax associated with being is a simple process that can produce all of reality. On the other hand, the semantics of being informs us about the specific contents and processes of the systems analysed. Therefore, syntax is concerned with how reality unfolds, whether semantics considers what reality consists of.

This isomorphism between being and language can be extended even more. It is possible to trace a semi-formal representation of being based on a generative grammar (Chomsky 1956). This generative grammar of being, can generate all of reality, based on a recursive process. However, in order to recognize the validity of this grammar, it is necessary to find a valid mapping between the strings generated by the grammar and the real constructs of being. In this sense, the strings produced by the grammar are a model of being.

The grammar of being G is a quadruple $G = (N, \Sigma, P, S)$.

- N is a finite set of non-terminal symbols. These symbols represent compound constructs that can be substituted by other symbols. They are mapped onto higher level systems of being, which are made of subsystems. N corresponds to the set of all systems which make up being. Particularly, we have that N is a set of sets $N = \{s_2^1, s_2^2 \ldots s_2^i\}, \{s_2^1, s_2^2 \ldots s_2^j\}, \ldots, \{s_m\}$, where the subscript indicates the hierarchical level of the systems, and the superscript indicates different instances of systems which are at the same hierarchical level of being, since they have a similar degree of complexity. For example, even though oxygen and hydrogen are two different physical constructs, they can be regarded as two instances of the same atomic level. It is interesting to notice that the number of instances of systems at different levels is usually diverse. Moreover, the highest

hierarchical level m has just one possible system s_m, that corresponds to being considered as a whole.

- Σ is a finite set of terminal symbols. These symbols are the elementary constructs of a language. They are mapped onto the lowest level systems of being (i.e., the fundamental particles). Particularly, we have $\Sigma = s_0^1, s_0^2, \ldots, s_0^n$, where the subscript indicates the lowest level system of the hierarchy, and the superscript indicates different instances of systems at the same lowest level.
- P is the set of production rules necessary to build the sentences of the language. These rules are mapped onto the rules of organization of being. P is always in the following form:

$$N \Rightarrow (N \cup \Sigma)^*$$

where * is the Kleene Star operator and $\cup$ the set union operator. The production rule states that the head should always have one non-terminal symbol, whereas the body can have one or more terminal and/or non-terminal symbols.

- S is the start symbol that belongs to the set N. S is mapped onto the first level systems of being. Formally, we have $S = s_1$.

Considering the elements of the grammar presented above, it is possible to formalise the recursive hierarchical organization of being through some simple production rules. To represent these rules, I use the Augmented Backus–Naur form, which is a meta-language that allows an intuitive representation of formal systems. It is possible to devise a simpler form of the production rules by removing the different instances of possible systems at the same level (i.e., removing the superscripts):

$$\begin{aligned} s_1 &\Rightarrow 2s_0 \\ s_2 &\Rightarrow 2s_1 \\ &\vdots \\ s_m &\Rightarrow 2s_{m-1} \end{aligned}$$

These production rules build all of being recursively and appear as a formalization of the law of recursive organization. The higher level systems are the product of the connections of at least two lower level systems. In this manner, it is possible to produce all the complexity of being by connecting together systems and recursively repeating the process on many levels.

Of course, the actual production rules of being are far more complex than these, if one considers different types of systems at the same hierarchical level. Nevertheless, the basic process of production is uniform, and therefore the production rules provided here are still valid. The only substantive difference is the larger number of systems that can be generated at a particular level by the generalized grammar. This process is similar to the horizontal exploration of a single level, that reveals many different systems which share more or less the same degree of complexity. However, the formalization of this generalized process will not be provided here.

The different sentences generated by the recursive grammar can be represented as a tree. Indeed, this is another strategy to visualize being. Every node of the tree corresponds to a specific sentence generated, and every connection describes the relationships between two nodes. This representation ignores the horizontal connections between nodes at the same level of the tree, since it considers only the vertical parent–child relationships. Even though this visual representation is incomplete, it is quite informative about the structural hierarchies of being.

Time plays a central role in the generation of being, since the building up of sentences happens in time. Given the finite amount of constituents in the universe, an issue might arise if the process of generation was the only one to take place. In this case, the number of higher level systems would constantly increase. As time passes by, the generation of higher level systems would increase exponentially, and in the end only systems with maximum complexity which inhabit the top level of being would be present. Obviously, this is not what happens in the real world where it is possible to find instances of systems at every level of being. Furthermore, the generative process does not guarantee the recombination of systems which played the role of constituents for higher level systems. For this to happen, it is necessary to introduce a process of breaking up of sentences, which converts high-level systems into its components. To clarify the breaking up process, it is possible to think of molecules that split into their atomic components, or to the process of body decomposition which breaks down organic substances into simpler form of matter. The generative process and the breaking up process happen in time in a balanced fashion, and work together so that new systems are born at any time while others are decomposed into their components. This cyclic process of generation and destruction is necessary to model being. First, it allows being to continuously renovate its content by relying always on the same raw materials. Secondly, it avoids the analyticity of the generation of sentences, which would lead to an exponential growth of systems inhabiting the higher levels of being.

3.2.2 Systems, Networks and Exchange of Information

Even though the recursive grammar explains how the different levels of being are formed from an abstract point of view, it remains unclear how the different systems physically interact with each other. Every system is an input/output processor that can be connected to other systems. Many systems at the same level can connect with each other. The result is a non-linear complex network, where the nodes correspond to the systems and the links represent the connections between systems. Systems exchange information with one another and coevolve. RO adopts the concept of information as defined by thermodynamics: information is every kind of event that can affect the state of a system.

If we consider an entire network as a system itself, we can shift our point of view to a higher level. This new higher-level system, which is in turn a network, can interact with other networks, in order to generate a super-system, which results in a network of networks. This process iterates until it reaches the top level, which corresponds to being considered as a whole.

These networks are extremely complex systems that follow a quasi-chaotic dynamic. Their behaviour is unpredictable. However, complexity does not depend on the specific content of the network; rather, it depends on the overall non-linear structure as well as on the local connections. This principle directly derives from systems theory and applies to being as a whole. Structure and organization are the most important features of reality, since they determine both the nature and the behaviour of being.

The exchange of information between systems allows being to evolve from one state to another. Exchange of information directly affects systems at every level. First, the exchange of information facilitates change of the internal states of the systems. Secondly, it helps systems to break old connections and to form new ones. These processes reverberate within the entire recursive structure of being. The final result is the emergence of unpredictable behaviours, constructs and properties, which are a simple by-product of the exchange of information.

3.2.3 Levels, Ontological Categories and Domains

Reality is organized in a complex hierarchical structure. Being can be easily visualized in a network of networks arranged in a vertical fashion. Complexity always increases moving from the lower towards the higher levels. Although the concept of level is quite intuitive, we need formally to define it in order to avoid ambiguity. I define a specific level of being as the set of all the systems that manifest a similar degree of complexity and similar emergent properties. The levels correspond to iso-complex surfaces of being. In other words, if we could plot all systems of being in a graph in which the vertical axis represents complexity, a level would be represented by a horizontal slice of the graph, where all systems with the same level of complexity lie. Of course, different systems characterised by different structures serving different functions can be iso-complex, since complexity is totally content-independent. The levels are discrete, since the passage from one level to the next higher or lower level involves a discrete change in the degree of complexity, as well as a manifestation of some emergent properties. Higher hierarchical levels inherit the properties of lower levels.

It is possible to explore being following a vertical and a horizontal path. The former analyses being from the lower levels straight to the upper levels considering every level at each step. On the contrary, the horizontal approach explores a single level and reveals all those systems at a specific level with a certain amount of complexity. The vertical approach is a synthetic exploration, while the horizontal approach is an analytic exploration.

Being is vertically divided into macro-categories which I term *ontological categories*. The definition of ontological categories that I use here is different from the traditional philosophical definitions. For RO, ontological categories are groups of contiguous levels which present an overall similar set of structures, patterns of organization and processes. Ontological categories span many levels of being, since they are extremely complex elements of reality. Different ontological categories manifest radical different emergent properties.

Indeed, the passage from one ontological category to another is a discrete quantum leap that involves an overall reorganization of the systems which inhabit the new category. This passage is a discontinuity of reality, made possible by new emergent properties that completely revolutionize the behaviour of being. Although all levels within an ontological category have different degrees of complexity, they show similar structures, behaviours and properties overall. In other words, the differences between levels within the same ontological category are far smaller than the differences between levels of different categories. Even though there are significant differences between different ontological categories, the overall recursive structure and the properties entailed by the general laws are still the same for every category. This guarantees the self-similarity of being at every level.

The ontological categories considered by RO are the physical, the biological, the psychological and the socio-cultural (Fig. 3). The physical category embraces all physical systems. This ontological category is structured in hierarchical levels that show different amounts of complexity. Starting from scratch, elementary particles build up protons, electrons and neutrons. These new particles connected together

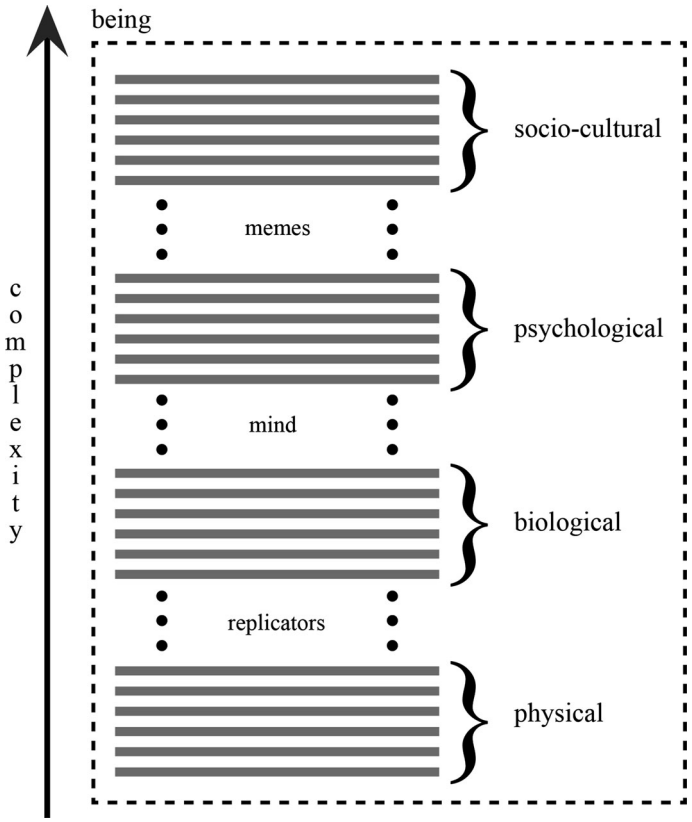

Fig. 3 The four ontological categories that make up being, and the threshold properties which divide them (i.e., replicators, mind, memes)

generate atoms, which in turn create molecules. This process keeps going until it reaches a threshold which allows chemistry to turn into biology. Indeed, the physical category acts as the basis for the biological category.

The biological category arises when *biological replicators* emerge. Replicators are anything in the universe of which copies are made (Dawkins 1999). DNA is the main replicator within the biological category. Replicators allow the evolutionary process to unfold because they mutate over time and are selected depending on their fitness. The biological category considers hierarchical constructs such as cells, organ and animals.

The psychological category arises when *mind* emerges. Mind is an emergent property that arises by the non-linear local interactions of a large number of neurons (Minsky 1988). The psychological level considers constructs such as perception, memory, and different functional modules of mind (Fodor 1983) that allow an individual to interact with its environment.

The socio-cultural category arises when *cultural replicators* emerge. These are called *memes* (Dawkins 2006) and are pattern of information that can spread within a society. Memes are also characterised by an evolutionary process. The socio-cultural domain considers constructs such as society and philosophy. It is worth remembering that the four ontological categories altogether represent the entirety of being.

Summarizing, the ontological categories are vertically distributed along a complexity scale (Fig. 3). Threshold properties allow being to pass from one category to another. In particular, the passage from the physical category to the biological category is made possible by the emergence of biological replicators. The passage from the biological category to the psychological is possible thanks to the emergence of mind. Finally, the last threshold, that allows the passage from the psychological to the socio-cultural category, is the emergence of cultural replicators.

Another useful concept of RO is the idea of *domain.* Domains are sets of functionally coherent systems that can transcend the boundaries of ontological categories. They are portions of being extended in both the vertical and horizontal directions. Domains can embrace many levels and even more than one ontological category. An example of a domain is music. Music is a coherent functional model of reality that embraces all four ontological levels: the physical, the biological, the psychological and the socio-cultural. Music is made possible thanks to physical pressure waves, is encoded in our brains at the neuronal level, is processed by some functional modules of mind, and happens to be a socio-cultural construct.

In conclusion, being is organized into levels, ontological categories and domains (Table 1). In theory, each of these constructs contains the entire structure of being. This is possible thanks to the self-similarity of being. Indeed, reality shows a fractal structure entailed by the recursive process of formation. As a consequence, every component is structurally similar to the whole.

3.2.4 Domain-Specific and Domain-General Laws

Being is characterized by two kinds of laws: *domain-general* and *domain-specific* laws. The former typology of laws transcends the specific domain of interest and

Table 1 Definitions and examples of the main constructs of being

Constructs of being	Definition	Examples
Level	Set of all the systems which have a similar degree of complexity and similar emergent properties	Molecules, animals, ecosystems
Ontological category	Group of contiguous levels which have similar structures, patterns of organization and processes	Physical, biological, psychological, socio-cultural
Domain	Set of functionally coherent systems that can transcend the boundaries of ontological categories	Music, language

applies to reality as a whole. On the contrary, the second typology of laws only applies to specific domains.

The domain-general laws correspond to the four general rules previously stated (Sect. 3.1). These laws are extremely important, since they guarantee both the recursive structure and the behaviour of being. Indeed, by acting on a global scale, domain-general laws allow a complete isomorphism between different domains. Moreover, domain-general laws are the operational manifestation of the recursive structure of being, and apply at each vertical level of reality. The structure as well as the pattern of organization of being is inherently shaped by these laws. Domain-general laws guarantee the fractal structure of being as well. Every level is at the same time a parent of some lower level and a child of some higher level, and expresses the same inner structure at different levels of resolution.

Domain-specific laws only apply on a local basis and cannot be generalized. These laws focus on small regions of being and trace the particular behaviours of one specific domain. Indeed, every domain is characterized by domain-specific laws that are exclusive to that domain and contribute to the uniqueness of the domain itself. Domain-specific laws are qualitatively different from domain-general laws. The difference lies in the diverse scope of the two kinds of law. However, sometimes domain-specific laws apply to more than a single domain. Thus, the distinction between the two typologies becomes blurred. Rather, it appears that laws can have greater or lesser specificity depending on the number of domains to which they apply. Domain-specific and domain-general laws can be regarded as two extremes of a continuous scale that measures the number of domains spanned by a single law. Therefore, laws are distributed on that scale depending on the number of domains they govern.

Both domain-general and domain-specific laws contribute to shape reality. However, their roles are quite different. Domain-general laws guarantee an overall symmetry of being, and a consistent structure of reality. On the other hand, domain-specific laws tend to amplify the differences between different domains of being. The two processes oppose each other. A metaphor taken from physics clarifies the differences. Domain-general laws involve a centripetal process, which tends to flatten the differences between the domains of reality. Domain-specific laws involve

a centrifugal process, which sharpens the differences between domains. However, only a perfect equilibrium between the two opposing processes guarantees both the overall fractal similarity of reality and the specific diversity between domains.

3.3 Principles of Recursive Ontology

This section introduces some basic principles of RO that can be inferred by direct observation of being. Of course, it is not possible entirely to demonstrate these principles, nor it is possible entirely to reject them. However, they can be treated as a plausible set of features that explain some of the constructs involved in being such as structure, organization and semantics.

It is worth remembering that there is a significant difference between principles and laws. Principles are generalizations which arise from induction. Laws are derived using principles and appear in the form of statements about being. Thus, principle are first sources of knowledge from which it is possible to derive other operational statements (i.e., laws).

The section introduces three fundamental principles of being. The *principle of economy of resources* describes the relationships between systems of being and the resources allocated (Sect. 3.3.1). The *principle of digital infinity* delves into the formation process of systems (Sect. 3.3.1). Finally, the *principle of compositionality* analyses the semantic of systems in relation to their components.

There is an evident isomorphism between RO and the domain of language, as stated above (Sect. 3.2.1). Two of these principles (i.e., digital infinity and compositionality) are directly inspired by linguistics (Chomsky 1991). This analogy is possible thanks to the *law of isomorphism between levels*.

3.3.1 Principle of Economy of Resources

- Systems at every level of being tend to use the least amount of resources possible.

This is a principle that reverberates at every level of being. The principle is highly represented in all the physical, biological, psychological and socio-cultural ontological categories. The principle of economy of resources is well known in physics. Physical systems always tend to reach states of minimum energy (i.e., equilibrium). Every physical system uses the least amount of information possible. The principle is also true within the biological category. Evolution usually rewards the individuals that are most energy efficient, because they need a smaller quantity of food in order to survive. The same is true at the genetic level as well. The entire genetic code is based on just four bases: adenine, cytosine, guanine and thymine. Here, the application of the principle of economy of resources is straightforward. Highly complex systems such as plants, animals and humans are the result of the combinations of just four elements.

Language is another example of a domain that exploits the principle of economy of resources. Even though human alphabets contain only a small number of

symbols, we, as humans, are able to express a potentially infinite number of ideas and concepts. Likewise, society follows the principle of economy of resources. Humans are organized in highly efficient clusters which guarantees the economy of resources. Furthermore, the history of society presents a continuous improvement of the way we use resources in order to optimize the results of our processes. In this sense, it is possible to define being as a Humboldt system which makes infinite use of finite means.

These are just a few examples of the ubiquitous principle of economy of resources within different domains of reality. Even though I have isolated the principle, it is still unclear why the entire spectrum of reality is dominated by this process of optimization. One possible answer is that the principle of economy of resources is the only process that allow the formation of complex systems. Since all systems at every level are finite constructs, they cannot process and/or store too much information, otherwise they would just desegregate and/or never gain a high level of complexity. As a consequence, it is possible that this principle provides the only possible basis in order to guarantee the emergence of complex systems. Of course, this is just a hypothesis that requires further research.

3.3.2 Principle of Digital Infinity

- Irreducible atomic elements of being are combined to produce an infinite range of systems at different levels.

This principle is an operational instantiation of the principle of economy of resources. The principle claims that an infinite number of constructs can be formed based on a set of finite (atomic) particles. This idea guarantees a highly efficient generation of systems. The process is directly related to the linguistic domain, since it supports the idea of a generative grammar of being based on fundamental particles.

The atomic particles of being at the lowest level coincide with the elementary particles of the physical ontological category. Therefore, starting from these constructs it is possible to build up the whole of being. The strategy to generate all of reality from the lowest level has been already covered in this article (Sect. 3.2.1), and corresponds to the recursive grammar of the RO.

It is worth remembering that digital infinity is a phenomenon that happens at every level of being. This implies that it is possible to define different 'virtual' atomic particles depending on the domain of interest. For example, in music single tones can be regarded as the atomic particles that, combined together, generate complete musical statements. The same is true also for DNA. If the four genetic bases were regarded as fundamental particles, it would be possible to apply generative rules, which allow the production of the entire genome of a single individual.

Generalizing, it is possible to claim that every domain has its own domain-specific atomic particles. Of course, these are not univocally determined, since every specific level of the domain can be considered as the basic level of generation.

Therefore, the process directly transfers the act of determining the atomic particles of a certain vertical construct to the beholder. For example, if we analyse music at the socio-cultural level it is possible to consider entire musical pieces, rather than single tones, as fundamental particles. This subjective approach is obviously entailed by the self-similarity of being. As a consequence, there are as many possible definitions of elementary particles of a domain as there are levels of analysis. However, this is not a problem at all, since it is an organic element of being itself.

Likewise, it is not strange that the principle of digital infinity is derived from the domain of language. In linguistics, this principle guarantees the generation of infinite meanings from a finite set of symbols. The similarity between being and language is straightforward, and yet again can be implied by the part-whole self-similarity of being. Even though language is a part of reality, its structure is isomorphic with the structure of being as a whole. Hence, it is possible to extend the general principle of digital infinity to the largest possible domain, being. Of course, this principle is a domain-general feature of language that can be applied to being, and differs from many other domain-specific rules of language, which cannot be directly transferred to being as a whole.

3.3.3 Principle of Compositionality

- The properties of systems at higher levels depend directly on the systems which constitute them.

This principle is based on the idea that compound structures rely on the structure and properties of their components. The process is quite intuitive and is true both for simple and complex systems. Higher level systems cannot be reduced to the sum of their components. Nonetheless, their properties are obviously dependent both on their components and on the interactions established by their components.

The principle of compositionality is true at every level of being, and guarantees that the complexity and the number of emerging properties of a high-level system grows exponentially. High-level systems acquire such a large amount of complexity that their behaviour is not predictable any more, though it can yet be deterministic, since systems always follow deterministic laws. Thus, there is a threshold based on the amount of complexity that differentiates systems which show a linear behaviour from systems which show a quasi-chaotic behaviour.

There are endless examples that support the validity of the principle of compositionality within all domains of reality. All physical systems depend on their components. For example, molecules derive their properties from the atoms of which they are composed. Biological systems depend on their components as well. For instance, the cell directly relies on the interactions of its components such as the membrane, organelles, proteins and nucleic acids. The same is true also for humans considered as single systems. From a biological point of view, every human is the product of the interactions between different apparatuses such as the respiratory apparatus, the nervous system and the circulatory system.

At the psychological level, the mind is an example of a complex system which is based on its components. Indeed, the mind depends on the activity of individual neurons and on their interconnections. Society is yet another example, since it relies on individuals and on their exchanges of information. At the cultural level, I propose the examples of music and language. Music is an extremely intricate system, which is the result of the interactions between its components. These components are musical memes that interact with each other in order to create complete musical statements (Jan 2007). Likewise, a sentence of natural language derives its overall meaning from the words that contributes to build the sentence up.

The principle of compositionality reinforces the overall idea of self-similarity of being based on the ubiquitous presence of isomorphism between domains and levels. Indeed, all domains and levels exhibit the feature of dependency on their components.

4 Discussion

This section provides an assessment of recursive ontology. First, it outlines the principal findings that emerge from the RO (Sect. 4.1). Secondly, it analyses the possible implications and applications of the RO (Sect. 4.2). Finally, it discusses the theoretical/methodological limitations of the article and traces avenue for future research (Sect. 4.3).

4.1 Summary of Findings

The article proposed a new logical framework to describe reality, by providing a general ontology based on the concepts of recursion, complex systems and levels of reality. Recursive ontology claims that the all of reality can be regarded as the manifestation of a single process of construction.

RO states that all of being is governed by four general laws that apply at all levels of reality:

- The *law of building blocks* claims that being is composed of systems, characterized by different levels of complexity. This law is derived from systems theory (von Bertalanffy 1968), which analyses the universe in terms of connected systems.
- The *law of recursive organization* states that being is made up of hierarchical levels, which consist of networks of systems recursively connected at different levels. Although RO rejects the idea of multiple parallel strata of reality, the law of recursive organization is directly related to the theory of levels (Poli 2001; Hartmann 2012).
- The *law of emergence* guarantees that the properties of being spontaneously arise while moving from the lower towards the higher levels. This law is strictly related to chaos-theory and to the inner nature of complex systems (Progogine and Stengers 1984).

- The *law of isomorphism between levels* states that a single theoretical model can be used to describe different levels of reality. This law derives from principles of systems theory.

This article has provided a semi-formalised recursive grammar inspired by linguistics (Chomsky 2002). This grammar can be used in order recursively to generate all of being. As a consequence, a direct parallelism between being and language has been postulated.

I have suggested a new definition of *levels*, *ontological categories* and *domains*, one that is completely different from traditional philosophical definitions as well as from the definition provided by researchers of the theory of levels. Indeed, a level is the set of all the systems that share a similar amount of complexity and similar emergent properties. An ontological category is a set of contiguous vertical levels which manifests similar structures, patterns of organization and processes. There are four ontological categories which, from the least to the most complex, are the physical, the biological, the psychological and the socio-cultural. Some threshold properties allow the passage from one ontological category to another. Those properties are: biological replicators, mind and cultural replicators. A domain is a coherent set of systems arranged together in order to form a functional module of being. The systems encompassed by a domain can span several levels and categories.

Additionally, I have defined *domain-specific* and *domain-general* laws. The first typology applies locally to a single domain of reality, whereas the second has a universal impact, since it affects all of being.

Finally, three basic principles have been identified. These three principles are the foundations of RO and all laws can be derived from them:

- The *principle of economy of resources* claims that systems at all levels tend to use the least amount of resources possible.
- The *principle of digital infinity* claims that an infinite number of systems at every level of reality are generated by few irreducible elementary particles. This principle is derived from linguistics (Chomsky 1991).
- The *principle of compositionality* states that the properties of systems directly depend on their components. This principle is yet again derived from linguistics and systems theory.

4.2 Implications and Applications

RO has relevant implications and applications in many domains. RO changes the view we have of reality: it promotes a trans-disciplinary study of being and can be regarded as the basis for future domain-specific theories.

RO radically changes the current view of reality as a heterogeneous group of different constructs not related one another. Indeed, RO reduces all the apparent differences between domains to a common general structure. RO considers the various different levels, domains and ontological categories as different

manifestations of a single process of organization. Hence, reality appears as a self-similar structure which manifests the same structure at different levels of resolution.

RO actively encourages a trans-disciplinary exploration of reality. All the different ontological categories of being—the physical, the biological, the psychological and the socio-cultural—are regarded as different manifestations of a single recursive process. This implies that the trans-disciplinary approach is inherently embedded within RO.

RO can be used as a general framework to develop domain-specific theories. Indeed, RO can act as a meta-theory that provides tools to develop domain-specific theories which can describe society, mind, language and music. RO provides general principles and domain-general laws that can be considered as a foundation for studies of specific domains. In practice, the principles and the laws of RO can help domain-specific theories to avoid a number of epistemological errors. First, by considering the notions proposed by RO, a domain-specific theory would be prevented from being too reductionist. Although reductionism has worked for centuries in several fields, it is now time to use the systemic approach to model reality, due to the complexity of most systems studied nowadays. Second, a domain-specific theory which follows the notions of RO would never be detached from other theories, therefore never losing track of the bigger picture. Too often domain-specific theories are so specific and so much focused on an extremely small set of phenomena to result completely disconnected from other theories. On the other hand, RO promotes integration between theories which describe systems which are horizontally and vertically adjacent in the structure of being. The long term objective of RO is to formalise a series of domain-specific theories each of which covers a section of being and it is connected with all other neighbour theories. A metaphor for this would be a puzzle in which each piece covers a part of the hidden picture and it is connected with all other adjacent pieces both vertically and horizontally. All these theories although radically different in terms of low-level details, would all follow the general principles and laws of RO.

4.3 Limitations and Directions for Future Research

This article manifests both theoretical and methodological limitations. First, it is difficult to prove the empirical validity of RO. Second, this overview lacks specific case studies that could help to support the hypothesis stated within the theoretical framework.

It is difficult to demonstrate the hypotheses stated by RO. The framework is so broad that is almost unthinkable to devise some experiments that could ultimately support the overall theory. However, it is possible to address the complexity of being by dividing it into different domains. Then, one can set up specific experiments that cover just a part of being. Finally, one can analyse the results of the experiments within the different domains and come up with a possible answer regarding the validity of RO.

The present article lacks an extensive analysis of case studies that could support RO. Indeed, the paper sporadically presented pragmatic examples, which examined the possible implications of RO from an empirical perspective. However, I preferred

to propose the theory from a more abstract point of view in order to provide an initial overview of the framework.

Of course, future research is necessary. In this sense, I will improve and formalise the core ideas of RO. Next, I will develop domain-specific theories of music, mind and society based on RO.

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