Agency in Natural and Artificial Systems

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Abstract We analyze the conditions for agency in natural and artificial systems. In the case of basic (natural) autonomous systems, self-construction and activity in the environment are two aspects of the same organization, the distinction between which is entirely conceptual: their sensorimotor activities are metabolic, realized according to the same principles and through the same material transformations as those typical of internal processes (such as energy transduction). The two aspects begin to be distinguishable in a particular evolutionary trend, related to the size increase of some groups of organisms whose adaptive abilities depend on motility. Here a specialized system develops, which, in the sensorimotor aspect, is decoupled from the metabolic basis, although it remains dependent on it in the self-constructive aspect. This decoupling reveals a complexification of the organization. In the last section of the article this approach to natural agency is used to analyze artificial systems by posing two problems: whether it is possible to artificially build an organization similar to the natural, and whether this notion of agency can be grounded on different organizing principles.

I Introduction

These days most theoretical and experimental work on behavior, perception, and cognition is permeated with ecological notions according to which meaning or meaningful behavior arises from dynamic interactions between agents and their environments. Sensorimotor activity is *embodied*—evolutionarily and developmentally conformed to the structure of the environment (mutualism)—and action and perception are recursively interlocked: action provides occasions for perception and perception guides action. This approach, very influential in Alife-inspired robotics as well as in dynamically oriented theories of cognition, brings together important criticisms of the classical view of cognition as representation of the world (cognitivism). This emphasis on sensorimotor activity has permitted some progress in the elaboration of naturalized models of agency. However, it is not clear whether situated activity via sensorimotor loops is sufficient to define agency and to construct autonomous agents.

Two important forerunners of ecological theories, Gibson's ecological psychology [22] and Varela's theory of enaction [43, 44], base the study of behavior and cognitive phenomena on situated sensorimotor activity. The two approaches stress different aspects, although both try to dissolve (most) mental representations in sensorimotor activities. Gibson proposes a realist version of what a meaningful environment is, which aims to specify the structure of environmental "information" and how it is captured by organic perceptual systems. Varela's approach is more focused on the agent, as it is grounded in the earlier notion of *autopoiesis*, a theory according to

which an autonomous system creates and maintains its identity as a dynamic network of component production that builds a membrane or boundary between the system inside and the dynamics of the environment.

An interesting consequence of an approach of Varela's type is that all interactions with the environment may be ultimately referred to the task of preserving an autonomous being. A consequence of this is that it is the organism who produces a meaningful world, because the "meaning" is relative to a point of view or perspective created by the very task of self-construction while interacting with a given environment. Nevertheless, although the interlocked nature of self-construction and interaction with the environment is an important aspect of Varela's approach to understanding life and cognition, his work was not extended to levels higher than that of the minimal autopoiesis. And, from this focus on minimal systems,[1] life and cognition appear to be properties of the same kind of organization, or even names given to the same kind of process. This is a confusion that can be clarified if the problem is carefully examined at different levels of organization.

In this article we suggest that to define agency we need to consider the task of self-construction while interacting with a given environment (that is to say, the relation with the environment can be considered to serve self-construction). Yet the two aspects of this task, autonomy or self-construction and the relation with the environment, may or may not be entangled. The nucleus of our discussion is precisely the analysis of the different situations for these two aspects: In the natural case, different complexity levels are distinguished, and they are compared with the approaches taken to build artificial systems. We explore the origin and evolution of sensorimotor systems in organisms, especially with regard to motility, and use our findings to analyze the possibility of building robots that may be autonomous in the same sense as we say that organisms are.

The argument goes as follows. In the first organisms, metabolic self-construction and adaptive interaction with the environment cannot be distinguished, because both are based on the same mechanism; thus saying that a given process has to do with the maintenance of the system (life) or with dealing with the environment (adaptation) is mostly a conceptual distinction. Yet, as the size of organisms with motility increases, the situation changes, first in eukaryotic cells and later in multicellular organisms. In fact, with the appearance of the nervous system, a new subsystem able to manage the sensorimotor coordination emerges. Although this subsystem is, of course, embedded in the metabolic network of biological processes, it is also, in a way, decoupled from it, for its dynamics is, to a certain extent, underdetermined by the dynamics of metabolic processes. At this point, the conceptual distinction between living or biological processes (to keep the system alive, and even reproduce and evolve) and adaptive or cognitive ones (act in the environment or plan behavior in some other way) acquires a structural correlate, and usually people tend to distinguish life and cognition according to it.

In the case of robots, the continuity between life and cognition is missing. Their activity in their world is situated, due to their possession of sensorimotor systems carefully designed under ecological principles, but no process corresponding to the metabolic self-maintenance of organisms can be found. Although the exploration of the abilities of (often minimal) sensorimotor systems is rather sophisticated, including considerations of body form, it is not clear that truly autonomous systems can be obtained this way. Thus, the question is if the decoupling of the nervous system makes it possible to emulate forms of cognitive autonomy based on the operational closure at the level of the nervous system, without basic autonomy.

Our concern about whether agents can be defined solely in terms of sensorimotor activity can then be reformulated as this: Is the characteristic dependence found in the living domain a consequence of its evolutionary origins? Can it be generalized to all kinds of agents, including the artificial ones? This article looks at the origin and evolution of agency in living systems (Section 2

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1 When studying sensorimotor behavior, the autonomy of the system (operational closure) and the relation with the environment (structural coupling) are studied at the level of the nervous system, and although this is considered to be "embodied," the relation between the basic or metabolic level of self-construction and the higher or cognitive level permitted by the nervous system is left unspecified. More elaborated work on autonomy can be found in [20].

characterizes *metabolic* agency, and Section 3, *neural* agency) and compares this situation with the mechanisms of agency production in artificial systems (Section 4). Our conclusion is that living organization depends on a special materiality, and it is still not clear whether robots can fully emulate it.

2 Metabolic Agency

It is difficult to offer a good definition for agency. For Kauffman [25], an agent is a system doing something on its own behalf. For Emmeche, "agency is the establishment of a 'sentient' or subjective point of view..." [17, p. 181]. For Smithers, agents are "systems that can initiate, sustain, and maintain an ongoing and continuous interaction with their environment as an essential part of their normal functioning" [41, p. 97], and for Maes, an agent is simply "a system that tries to fulfill a set of goals in a complex, dynamic environment" [27, p. 2]. Similar definitions can be found in the literature; they mostly emphasize these elements: The activity of the system has goals; the system needs the (dynamical) consequences of its actions for its own (dynamical) endurance or maintenance; the system has a particular point of view.

In sum, an agent has the capacity to interact with the environment so as to contribute to its own maintenance. An agent's action is not merely a physical interaction, because its own viability is affected by it. The actions of an agent are functional in the sense that they serve the viability of the system. A big stone in the river keeps water from flowing, and some bacteria in a milk medium ferment it, producing yogurt. Both do something, but we do not call the stone an agent, whereas the bacteria we can; the difference between the two cases is not in the performed change, but in that the performers gain self-maintenance as a consequence of their actions (the most elemental sense in which we can say that something experiences a change). Thus, one could say that these interactions with the environment are, in an extended sense, a constitutive aspect of the very processes of system organization. If they are oriented, that is to say, if they seek a goal or obey a norm, this will be the maintenance of the acting system itself.

Therefore, there is a reciprocal dependence between what defines the subject or the self, and the actions derived from its existence: The being of the system is not separable from its doing. Thus the foundation of agency is the appearance of systems whose organization is maintained because the system actively separates itself from the environment (for example, pumping out ions to conserve a difference in concentration), thus modifying it.

2.1 Formation of Autonomous Systems and Adaptive Capacity

Now, where does the agent's capacity come from? When dealing with a problem of origins we cannot appeal to an external (and certainly, more complex) agent or creator for the system; it is necessary to begin with self-organizing processes in far from equilibrium conditions, namely, with the so-called dissipative structures. Yet, instead of spontaneous dissipative structures, whose maintenance is entirely dependent on a specific set of external boundary conditions, we need to look for the kind of dissipative structure whose organization can be *recruited* for contributing to its own self-maintenance: Their internal organization should be potentially capable of creating local and selective control mechanisms. However, as Bickhard has pointed out [4], in order to become an agent, a system has to be able not only to perform processes that contribute to its own self-maintenance (a candle flame does that), but also to deploy different processes depending on differences in its environment. In other words, we are looking for a system able to achieve *adaptive* self-maintenance. Thus, minimal agents are complex dissipative systems that can, under different external conditions, dynamically self-maintain. Now, only chemical systems can develop into complex self-producing dissipative organizations, due to their capacity to form a great variety of plastic recursive component production networks.

In organizational terms, recursive chemical systems only become viable autonomous agents when they can build a physical structure that separates them from the external environment, thus creating

specific internal conditions. Maturana and Varela [30] have called such recursive, self-enclosing chemical networks *autopoietic systems*. An autopoietic system is a component production network that produces its own physical border, and this latter is in turn a necessary constraint for the recursive realization of the former.

Now, the realization of an autopoietical system has to solve the following three fundamental problems: (i) the danger of an osmotic crisis, (ii) the spatiotemporal coordination of all processes—and their couplings—and (iii) the achievement of an efficient energy transfer through the components and processes of the system. The minimal set of components necessary to overcome these problems are [38]: a selectively permeable *membrane*, through which the system controls concentrations, establishes a clear-cut distinction with the environment, and channels the interaction with it; a group of *energy currencies* (at least one soluble in water, like PP_i or ATP, and one directly related to transport processes, like the electrochemical potential gradient of protons or sodium ions across a membrane); and a set of *catalysts* responsible for modulating the rates at which reactions take place, for setting up regulation (homeostatic) mechanisms, and for carrying out mediated transport processes. The appearance of minimal agents requires the three types of components to be appropriately interacting.

Such a system brings about an organizational asymmetry between the *inside* and the *outside* domains, separated by a membrane able to select the flow of components across it, via active transport (a hint at the importance of this basic mechanism is that 30% of the whole energy consumed by the cell is used for it). Thus, the system must selectively organize the transport of the surrounding matter and energy for its self-maintenance. Hence, the key element for the origin of agency is functional action as an extension of the recursive self-production processes; active transport is the most basic form of agency, but primitive autonomous systems probably developed other mechanisms of functional action as well (for example, release of chemicals into the environment).

The evolutionary path that led from these (hypothetical) autonomous agents to the early living beings about 3.5 billion years ago is unknown. The most transcendental change was probably the introduction of genetic mechanisms to stabilize metabolism [39]—on the one hand, because genetic material allows the production of highly complex proteins (as well as other regulatory factors, as can be seen in [28]), which enhance metabolic plasticity and permit the fine detection of relevant environmental features; and on the other hand, because genetic material makes it possible to store a pool of sequences that can be used to synthesize new proteins in somatic time according to new needs or the detection of new conditions. In present-day bacteria metabolism can make use of genetic information for some (lifetime) adaptive changes, and in certain colonies there is a collective pool of genetic materials, as single individuals horizontally exchange strings via conjugation.

2.2 The Origin of Motility

Despite its simplicity, bacterial agency displays many forms of lifetime adaptation: In the case of motility, bacterial organization provides for a wide versatility and complexity of forms (some of them are sessile). Motility is an agent's capacity to move by its own means, so that it is able to perform fast directional movements to change the environment in looking for preferred conditions. In the world of prokaryotes, both sensors and motility devices are based on very precise proteins, and that is the reason why they have to be understood as adaptive capacities. In bacteria, motility is assisted by membrane devices (flagella), single or multiple, to effectively drive the whole body with rotatory movements (it is interesting that they are the only "wheel-based" motility system in the living domain). Despite their minimal size, bacteria display very efficient forms of motility. Some of them can change their flagella according to the viscosity of the medium: if it is low, they swim across using a polar flagellum, but if it is high, they generate several lateral flagella with which the organism moves with rowing-like movements [3]. Researchers have described a number of bacterial sensors: chemical (chemotaxis), light dependent (phototaxis), magnetic, and so on. The movement of flagellated bacteria (such as *E. coli*) consists in a sequence of smooth-swimming runs punctuated by inter-

mittent tumbles (to randomly change the direction of the runs). They are capable of comparing current and past chemical environments so that the probability of tumbling depends on the chemistry of their immediate surroundings compared with the chemistry they previously encountered. When they run up a gradient of attractants or down a gradient of repellents, they tend to continue their run [47]. Thus, although the bacterium does not *detect* distant features (it only *senses* the medium through certain contact proteins), its action as a whole can be interpreted as directed by a distant goal. Another consideration is that what the system can sense is those components that are needed or harmful for its self-maintenance.

Yet prokaryote motility is not substantially different from other adaptive capacities, in that we do not find essential organizational differences between different taxa of prokaryotes (although there can be different degrees of complexity). For example, when the prokaryote *Caulobacter* lives in a very humid medium, it remains fixed to the soil like a vegetal type, whereas in dry periods it reproduces and the new cells grow a flagellum capable of transporting them to a more humid environment. The example shows that movement does not change this organism's fundamental organization; at this level it is arbitrary to distinguish specifically sensorimotor responses from the metabolic ones, since both are sustained by similar mechanisms. In this sense, the ability to move could be considered as an extension of the set of mechanisms required for self-maintenance. In the smallest living beings, moving to find food (as opposed to capturing primary energy, like sunlight, or fermentation processes) does not require them to develop fundamentally different, or more complex, devices. At this level, all adaptability is based on the maintenance of a chemical organization through the control of energy flows, sometimes aided by very complex proteins, but diffusion is the main way in which components are transmitted inside the cell.

Although some investigations involving detailed models of bacterial sensorimotor activity [47], or even proposing artificial models based on them as control mechanisms for robots [48], seem to suggest that there is some capacity for complex information processing, comparatively speaking we find a big difference between this adaptability and other forms that we will discuss in subsequent sections, and it has to do with the existence of specialized devices.

2.3 The Limits of Metabolic Agency

At bigger sizes the organization of motility faces new problems raised by the need for fast internal sensorimotor coordination. As eukaryotes are larger than prokaryotes (by about 10,000 times), their surface is smaller relative to their volume: they are bigger inside. That is why, in addition to diffusion processes, eukaryotic cells are equipped with mechanisms to provide precise and speedy internal communication and distribution of substances. Fast adaptive responses are organized in a different manner than in small prokaryotes: they possess microtubules, which contribute not only to chemical channeling and plastic reorganization of selected parts of the internal structure of the cell (cytoskeleton), but also to external movement by means of undulipodia. In eukaryotic cells we find also a functional specialization of subcellular parts (organelles), and some symmetries (anterior-posterior, etc.) appear in their bauplan, which in some cases provide some sense of directionality to the movement.

External eukaryotic organs for movement, such as cilia or flagella, have a different, more complex structure than prokaryotic flagella. The construction of motility organs in eukaryotes, based on microtubules, requires larger genes because of the high complexity of the involved proteins (e.g., dynein). Directed motion is a result of the coordinated activity of cilia. In some cases, fast movement is accomplished with the symbiotic collaboration of certain prokaryotes, like spirochaeta, inserted in the membrane of the eukaryotic host.

But this new organization conveys a conflict between simultaneous movement and reproduction [9, 29]. According to Buss, a crucial step in the origin of multicellularity is the appearance of gastrulation, in which a hollow ball of cells is transformed into a multi-layered structure with diverse patterns of cell differentiation. His study seeks the origins of multicellularity in the necessity to combine movement and reproduction in single cells. This derives from the observation that the cells

of a metazoan can be either ciliated or prone to divide, but not both. The reason is that both undulipodia (cilia or flagella) and mitotic spindles require microtubule-organizing centers, and in these cells either one structure or the other is possible, but not both. The gastrula is the solution to this problem, where the cells on the surface remain ciliated and those of the interior lose their cilia so they can divide.

This conflict is already pointing to an organizational problem that becomes more critical as size increases: the difficulty encountered by the basic metabolic organization in efficiently supporting quick and versatile sensorimotor action. The reason is that as the size grows, it becomes harder for metabolic organization—whose function is the material and energetic self-maintenance of organisms—to produce a fast and versatile enough dynamics of internal patterns to coordinate sensor and motor surfaces, allowing quick adaptive movements of the organism. As the size of the organism increases, metabolic organization faces the problem that the energetic and material cost of the production of internal structures for fast sensorimotor coordination becomes incompatible with the accomplishment of the very function of self-maintenance.

The path followed by eukaryotes, to grow in size though remaining unicellular, reaches an evolutionary limit with them, and most of the bigger organisms adopted a multicellular organization. Yet, there is a further question that will be very important for our argument: Why do cells not grow any further? Why is the cell size of most organisms constant? According to Bonner, this has to do with energy considerations: "If one thinks of the rates of different chemical processes occurring within the cell, the distances needed for diffusion, the surface boundaries needed for isolating different chemical components of the motor, and so forth, all of these lead to the conclusion that there is an optimal size with sharp upper and lower limits, which is the size found in nature" [7, p. 61]. For others [45], it has to do with the appropriate size to transmit genetic products via diffusion. In any case, large forms of life on Earth have only been able to maintain an efficient metabolism by retaining a cellular organization.

3   Neural Agency

An important factor contributing to the appearance of individual multicellular organisms was the big potentiality for cell differentiation exhibited by eukaryotic cells, in particular by those lacking a cell wall. The lack of a cell wall, coupled with the possession of an internal cytoskeleton, permitted the ancestors of animal cells to interact directly with each other through apposed plasma membranes, to adhere to each other, to crawl on surfaces, to differentiate into complex shapes, to engulf other cells by phagocytosis, and to engage in junctional communication with other cells [21, 11]. Thus, new living beings appear, constituted by many functionally differentiated but highly integrated cells. These new multicellular organizations are true organisms, with new forms of agency.

At the same time, the significant increase in size of these new multicellular organisms posed further challenges for the organization of motility. Possibly the motion of the first multicellular organisms was simply based on the coordination of local structures: for example, in the case of *Porifera*, a very primitive type of sessile multicellular organism, responses to stimuli are local and independent [23]. Yet it is evident that this could not lead to the development of multicellular motility.

The problem is that, at this size, it is practically impossible to organize fast and versatile motility with the sole aid of metabolic mechanisms. There are two factors here: the enlarged internal distance between points that need to be connected with small delays (so that the organism can move fast), and the need to selectively modulate the organization of connections (to get adequate sensorimotor correlations). Some multicellular organisms do display fast movement based only on metabolic devices (for example, Dinae plants are able to perform very fast and coordinated movement of millions of cells [40]), but the mechanisms involved lack the flexibility and plasticity required to favor further increase in the complexity of the motor response. Therefore, wherever organisms display fast and versatile movement at a multicellular scale, it is the result of the existence of an internal structure in the organism formed by a type of cell, the neuron, specialized in connecting sensorimotor surfaces

in a plastic, fast, and (metabolically speaking) cheap way. Neurons differentiated as cells capable of forming branches, which may be interconnected through ion channels in their membranes (controlled either by the electrical potential over the membrane or by ligands). Hence nearly 600 million years ago, the first network of interconnected neurons appears in the *Cnidaria*, as the most primitive nervous system.

3.1 The Body and the Nervous System

In very primitive neural networks there is neither differentiation between sensor, motor, and associative units, nor directionality of nervous impulses, but they are already capable of producing a dynamics of impulse patterns within the interconnected neurons. Unlike chemical signals circulating within the body, which directly interact with metabolic processes, chemical or physical exchanges among neurons allow for recurrent interactions within the network; thus they generate an independent (*autonomous*) domain of patterns [33]. The dynamics of these patterns is therefore decoupled from the dynamics of metabolic processes, although their material maintenance as well as their functionality still depend upon them. *Decoupling* means that the organism (or creature) is organized in such a way that (1) part of it (the nervous system) constitutes a relatively independent or autonomous level of interactions whose rules are underdetermined by the dynamics of the remaining system, and (2) the two levels remain causally connected and they depend on each other [31]. Therefore, when we say that the nervous system is a dynamically decoupled system, we mean that nervous interactions obey a dynamics (or a set of rules) not governed by the general metabolic organization, although it is structurally maintained by it. Because of this dynamical decoupling from the metabolic operations, the appearance of the nervous system gave rise to an enormous variety of internal patterns of fast connections, capable of unlimited internal recursivity.[2]

However, the non-basic, or *derived*, character of the autonomy of the nervous system has an important implication: The nervous system cannot generate its own functionality by itself. Although the nervous system is a recurrent dynamic network like metabolism, the two differ in that the recursivity of the former is somehow monitored by the basic metabolic level. Neural dynamics only acquire functional meaning if embodied in a self-maintained organization, within a given environment. Configurations become functional when recruited for the tasks of (1) sensorimotor coordination of the animal in its environment, and (2) coordination and fine control of the organism's metabolic processes. Therefore, the operations of the nervous system ultimately depend on metabolism, on the one hand because its components are cells whose behavior is metabolically organized, and on the other because the nervous system as a whole serves a specific function within the whole organism, which contributes to its capacity to stay alive. Since the global maintenance of the animal's metabolism requires an adequate sensorimotor activity, nervous system and metabolism are connected in that they depend upon one another for their maintenance (and therefore, existence).

Interestingly, this decoupled, but complementary, relation between the neural and the metabolic organizations brings about a body reorganization, which increases the adaptive complexity of multicellular organisms. As a result, individual lifetime interactions do not rely mainly on changes in body structure, but on the neural network. Thus, for these organisms—animals—behavior, understood as functional body movement, is the most important adaptive capacity: their metabolic self-maintenance is largely produced through neurally controlled secretions and motor actions.

In addition to quick and efficient motility for organisms with body masses larger than protozoans, the appearance of the nervous system opened up new, qualitatively different modalities of adaptive interaction. Already at early stages of nervous system evolution, rudimentary forms of learning, categorization, and memory appear [1]. We tend to ascribe the main significance of the arrival of

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2 One may wonder why large protozoans did not develop some kind of organization similar to the nervous system. Actually, eukaryotic cells already possess complex and diverse subsystems. For example, given the distributed character of the cytoskeleton, it could be considered to be a subsystem of channeled communication capable of producing supple interconnections between membrane sensor and effector structures [24]. However, it is a molecular system; therefore, it cannot be really decoupled from the metabolic organization or endowed with potential for internal recursivity, precisely because it works at the same scale and under the same mechanisms that metabolism does.

nervous systems to these capacities, because they begin to appear as specifically cognitive (insofar as they show increasing similarities with ours).

However, the potentialities of the nervous system cannot be developed independently of changes in the general organization of the body. In fact, body organizations and nervous systems of animals coevolve—they shape one another—so that, to a high degree, they are complementary. Not only did the muscular system evolve in close connection with the increase in complexity of the nervous system, but also the organization of internal circulation, the system of fixation, and even the body shape. The appearance and evolution of the nervous system brought along with it changes in the skeletal, respiratory, circulatory, and immune systems, which required building more complex and centralized nervous systems. This fact is manifest when we consider, once again, size increase related to motility: An animal of a certain size requires, in order to be able to move fast, a system that ensures muscle fastening, as well as an adequate flow of nutrients and oxygen to the muscles that execute movement. In the case of a big animal, whose way of life is based on fast movements, the work of its muscles requires a circulatory system, not only closed but also finely regulated in pressure and flow, depending on different internal and environmental circumstances. This is achieved by a system of receptors distributed along the blood vessels, which detect blood pressure, oxygen concentration, and acid level. This also requires a more complex immune system, because the required circulatory system permits easy access of pathogens to any body part. Yet, the very existence of a more complex cardiorespiratory system cannot be conceived without direct control by the nervous system, which regulates cardiac rhythms, arterial pressure, and blood concentrations of certain substances. In vertebrates, for example, a nervous subsystem—the so-called autonomic nervous system—exerts autonomic control of viscera. All this makes manifest that there is a close relation between body and nervous system complexification [31]. Thus, the ability of nervous systems to support complex forms of adaptive behavior is accompanied by new ways of organizing body structures (bauplans). The evolution of agency is to a large extent the history of the interaction between the body and the nervous system: a continuous process of mutual constraining, which sometimes imposes bottlenecks and sometimes enables new evolutionary forms.

3.2   A World of Qualities

One of the most dramatic consequences of the development of sensorimotor systems in mobile organisms is that the perceived environment becomes an *umwelt*, that is to say, a world of qualities *affording* very sophisticated experiences and activities. In order to be able to see how organisms can make sense of their worlds, we may consider how perceptual systems evolve from very specific ones, each able only to detect one kind of environmental component (in general related to metabolic needs of the system) to more general ones, which not only bring about richer perceptual worlds, but also allow for more complex behaviors or activities. Enzymes, which bind to very specific substrates, are very specific. Many regulating factors affect them in subtle ways and determine the metabolic paths in which components get involved. Nevertheless, each of them recognizes a specific pattern. The sensors that help bacteria swim along (or against) chemical gradients belong to this very class: Protein receptors on the bacterial surface bind with the attractive (or repellent) substance and stimulate the locomotor system [6].

A different case is indirect detection, where there is a deferred relation between the substrate with which the sensor binds and the domain of reality with which the organism interacts. For example, in many organisms vision does not enable a response to light, but to something else. This case can be made clearer by using a borderline example: the primitive acquisition of an "eye" by a paramecium [36, 46]. Some single-celled organisms can use light as nourishment, via photosynthesis, in which light is absorbed directly as energy. They present forms of phototropism: they can sense light and move towards the light. This detection is not usually considered to be *vision*; it is a case of the mode considered above, of direct detection. Other organisms cannot nourish themselves from light directly, but by eating plants they obtain substances they cannot produce themselves, including vitamins, which enable them to be sensitive to light and to develop eyes. Thus, in evolutionary terms,

the search for light starts as a search for nourishment, not for information. Wächterhäuser reports the case of a paramecium, a single-celled creature, that feeds on green algae and that uses one of them (a chlorella) both as food and literally as eyes [46]. The paramecium sticks the chlorella on itself and maintains a symbiotic relationship with it: as an eye, the chlorella is used to steer the movement of the organism, and as a stomach, it gives back part of its light nourishment to its host. The chlorella couples energetically with the light, but, for the paramecium, the same chlorella is a visual sensor, an eye, used as a means to detect light and thus coordinate its locomotion.

This example points to the difference between coupling only with specific substances or specific patterns, and elaborating further the physical, causal effect that certain processes trigger on an organism. The highly evolved perceptual systems of animals can be confusing with regard to what it is to be a sensor or a perceptual system. As a consequence, often perceptual operation is supposed to be completely separated from the energetic/metabolic structure of the organism. This is not the case for those sensors responsible for direct detection.

In fact, not all the highly complex perceptual systems share common signal-processing strategies, and this difference is related to the specificity of the information acquired by the organism. A comparison of the visual and olfactory systems of insects shows many differences between them—different neural processing strategies and different neural architectures [34]. Visual perception is influenced by the structure and statistical properties of optical signals, which are complex, but highly constrained. Olfactory signals, on the other hand, carry less information; they are less constrained and predictable. Arbitrary patterns of excitation on the olfactory receptors have to be parsed and learned, and then recognized against a complex background of smells. Vision is hard-wired, its neural circuits tailored to specific behaviors, while olfaction lacks the ordered and highly differentiated neural circuits used for vision and may use an associative network at an early stage to recognize patterns. This difference suggests a further difference in the functions the two systems accomplish. Probably the olfactory system has to recognize specific substances, while the main task of visual elaboration is not to recognize objects, but to elaborate different types of behaviors, for example locomotion. Vision has evolved to allow many different behaviors, some related to locomotion, others to the recognition of a variety of features (relevant for the organism but not always specifically directed to recognition of objects) through an organism-specific elaboration of the properties of one single physical phenomenon: light.

Both kinds of perception—direct and indirect—are important for understanding how organisms are involved in meaningful interactions with the environment. Yet one may wonder whether systems with no direct form of perception can autonomously develop indirect ones.

3.3 Towards Minds

So far we have sketched the path from basic agency to the arrival and first developments of nervous systems in multicellular organisms. We tried to show that, at the beginning, there is no significant difference between different forms of adaptive capacity: We cannot say that motility per se makes agents more complex, because it is based upon the same metabolic devices used by other strategies (although in the world of prokaryotes there are huge varieties of adaptive forms, some of them more complex than others, all of which rely on the same metabolic principles, occurring at similar speeds). However, a major bifurcation arrives with nervous systems governing multicellular motility, as it implies a qualitative jump in the complexity and variety of agency. When body size increases, agents that adapt via motility require more complex forms of internal organization and interaction. The evolution of multicellulars with nervous systems (animals) brings along a complexification of body structure and organization, as well as of forms of adaptive interaction (behavior, communication), that do not appear in plants or fungi.

The emergence of this new form of agency involved wider and more complex interactions with the environment, and it opened a process of increasing complexification of the body organization (an entangled relation between the neural and the basic biological organization) leading to a new, qualitatively different evolutionary process. As we have explained earlier, there are enabling and

disabling constraints that explain why only one special bauplan—the chordates—within the animal kingdom made possible the development of an integrated body and neural changes, able to allow a new increase in body size compatible with versatile movement. In this process, leading to a new complexification of agency, a key feature was the development of new ways of decoupling affecting the nervous system itself, together with different relationships with the rest of the body organization.

This new decoupling within the nervous system was crucial for a line of evolution leading to a self-sustained process of encephalization and producing the emergence of new levels of cognitive phenomena, such as emotions and awareness. In the course of the evolution of vertebrates, an increasing part of neural processing is devoted to the internal visceral control tasks and to coordinating all this with sensorimotor activity. At some stage, probably when vertebrates became capable of complex and fast terrestrial movement and their brains attained a certain threshold of complexity, neural activity devoted to the control of behavior through emotions became the basis of what would eventually constitute the *mind*, understood as a kind of slower, second-order neurosomatic activity by means of which the animal is able to attain a basic sense of self. This sense of self would be linked to new and more complex forms of coordination between the limbic system and the somatic nervous system [16] and even involving the viscera [13, 14]. Thus, rather than a fast and reactive form of agency, the mind appears to rely on anticipative (non-reactive) control of sensorimotor behavior, based on neural activity, involving an ongoing feedback between the environment, the somatic nervous system, and the autonomous nervous system, mediated by changes in visceral and metabolic states. Probably the non-reactive agency is a consequence of the fact that some neural configurations of the animal, instead of controlling action, contribute to building internal models of reality (virtual interactions with the environment). These internal models, assisted by emotional phenomena, allow for more complex modes of anticipatory behavior, such as self-directed learning, and probably also for some form of awareness [31].

In short, the evolution of agency is linked to the increase in size of those organisms whose way of life is based on motility. Although the evolution of agency took many different paths and contingent modalities, the general principles here stated are probably not contingent. This means that the evolution of any form of organic life in which a tendency to increase in size comes together with adaptive strategies based on motility is likely to develop more complex forms of agency. Only in multicellular organisms whose main form of agency is motility do we find sufficient and necessary conditions for the appearance of cognitive phenomena.

Nevertheless we may still question whether those principles are valid outside the natural realm. If what we want is to build physical artificial systems endowed with agential capacities similar to the ones that (natural) organisms exhibit, maybe it is not necessary to base them on the same organizing principles. We will come back to this issue at the end of this article.

4 Embodying Agency: Some Clues for Robotics

These days the old dream of reproducing living agency in artificial media appears to many as a feasible one, for, in the last decades, great progress has been made in the manufacture of robots able to perceptually guide their interactions with the environment. However, the extent to which they are autonomous is a matter of perspective. If we compare them with the artificial systems built under the classical AI principles, we have to recognize that they have come a long way from those, and that the field has learned a lot and built many interesting robots. Yet, if we compare them with the organizing principles of living systems explained in previous sections, the situation is very different. Unlike organisms, robots are autonomous in a rather limited sense, more related to situatedness than to self-maintenance. It is evident that their behavior is more *their own* than it used to be in older devices, but it is not yet self-maintaining or truly autonomous in the same sense as for living beings.

Looking at the history of artificial systems emulating living capacities, we observe that some of these capacities seem to be easier to reproduce or emulate than others, and, paradoxically, the more abstract ones (which are intuitively more complex, at least in the sense that it took evolution longer

to arrive at them) are easier than those that appear simpler (or less evolved). This seeming paradox has to do with the natural inclination human minds possess for abstraction: For us it is a lot easier to abstract than to materialize or embody a given phenomenon. In this context we may pose a further question: whether the creation of autonomous robots has to rely on the organizational principles of organisms at all.

We may distinguish two aspects of this question. One is whether it is possible to build an organization similar to that of organisms on a different scale and with different material building blocks. The other is whether it is possible to ground autonomy and cognition on different organizing principles. We will discuss them in the following two subsections.

4.1 Materiality and Organization in Organisms and Robots

As we have seen, the autonomy and agency of organisms is based on a particular kind of organization: autopoiesis (self-production) realized via metabolism, that is to say, by a recurrent network of component production. For an organism whose behavior, or whose agency, is continuous with its autopoiesis, the organization is such that actions are a consequence and a cause of the structure of the system. This structure is dissipative: If living beings stop functioning, they will vanish. That is the reason why there is a deep entanglement between what a structure does and what it is.

Now, how can such an organization be realized? Can it be achieved through macroscopic components, as a physical, rather than chemical, system? In theory, a recursive organization of component production can be conceived as a physical system, whose building blocks might be microscopic or macroscopic. An example of the latter would be a fully automatized factory, which could reproduce itself starting from simple components. Now, "fully automatized" means that it must be possible to generate all the system devices starting from other devices that are parts of the system.

The problem is that, in this case, a great part of the structural complexity of the devices—or even of the building blocks that make up the system—would have to be externally designed, because those building blocks are inert aggregates, which need additional design (i.e., an external level of organization) to become functional constraints harnessing the flows of matter and energy so as to achieve self-construction. For instance, the structure of a microchip does not emerge from its intrinsic composition, but requires external shaping. This system's organization would not be really self-constructive, because it would depend on a set of external material devices whose design required more complex processes than those produced by themselves, and so on, in an infinite regression. It would never achieve (full) constructive closure, because of the constitutive inertness of the building blocks,[3] this organizational logic requires that the external degree of complexity be always greater than the internal one.

How is this regression avoided in the case of natural systems? The organization of these systems is really self-produced, because some (macromolecular) components act as devices that constrain the flows of energy, so that the constrained release of energy can be used in turn for generating new macromolecular components acting as constraints, and so on, so that the system can recursively produce the constraints themselves. In other words, the constructive closure of the system is based on a work-constraint cycle [2, 25, 32]. But the realization of such a cycle requires starting with building blocks endowed with certain interactive capacities, derived from their material structure, that is to say, with intrinsically active elements whose combinations may generate new forms of activity. Thus, the system can achieve constructive closure because it creates high-level constraints that act on the (low-level) individual elements, harnessing their dynamics, which in turn recursively produces those control constraints [35].

So, self-constructive autonomy cannot be realized but from a highly complex chemical organization. These chemical components acting as functional constraints should be big molecules; smaller aggregates cannot achieve either the highly specific catalysis nor the storage and replication

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3 If building blocks were designed at a molecular scale, they would cease to be inert elements, and in fact we would really be speaking of a chemical system.

of information that are needed (they only yield *passively* self-organized and self-maintained systems). These components are big enough to act as highly precise devices, but at the same time, small enough to exploit the self-organizing capacities of recurrent chemical networks. Precisely for this reason, in the course of evolution, new, more complex organizations appeared as sets of molecules and intracellular organelles, and later as multicellular structures, still retaining the cellular organization, as we explained earlier.

The conclusion is that living organization is crucially dependent on the materials with which it is built. Hence, to reproduce this organization we would have to use molecular—and even biomolecular—components.

4.2 Functional Autonomy in Organisms and Robots

We may now turn to the second question: whether other organizing principles, different from the ones we have described for living systems, can produce systems that are similarly autonomous. In the case of animals, their interaction with the environment is made possible by a sensorimotor system partially decoupled from a basic metabolic organization. What organisms do depends on a complex dynamics emerging from different factors (metabolism, organization of the body, nervous system, condition of the environment, etc.) entangled in a closed organization, whose maintenance is the ultimate goal of behavior.

The crucial question is, then, how decoupling can be interpreted in constructive terms, that is to say, whether it suffices to treat the nervous system and its regulation of motility and behavior as a basis for autonomy (defined at an interactive rather than a self-constructive level) or whether we require a dynamic entanglement with a basic infrastructure [41], metabolism (as in organisms). Decoupling implies, at the same time, a dependence of the interactive system on the metabolic one (because it is an integrated system) and the establishment of an independent (or autonomous) dynamics, in the sense that the operation of the higher level system is underdetermined by metabolism. Does this imply that the autonomous behavior of robots can be successfully emulated at this sensorimotor level only, if this independent high-level dynamics is properly grasped? What is the role of metabolism (or other functional systems acting in an integrated organism) in autonomy?

In order to answer this question, we need to take into account some characteristics of adaptive or autonomous robots. Their structure and behavior are designed so that there are ongoing couplings between their bodies (at least in biomechanical terms [12]), their nervous systems, and the environment, so that the robot displays real-time adaptive operation: Their behaviors are embodied, embedded, and situated [10, 11, 42]. Thus, rather than being imposed by the programmer, the behavior of these artificial agents arises from real (or realistically simulated) perception-action cycles: they are (or tend to be) able to measure the relevant parameters of the environment to control certain degrees of freedom of the system from the very situation in which the system finds itself (not from the point of view of an external observer), and to act in it physically. This way the results of sensors causally influence motor devices (and vice versa). Recent models even include some kind of functional bodily self-assemblage in the context of the robot's motor tasks [26], based on the use of some plastic electrochemical building blocks (made of thermoplastic linear activators) that self-assemble according to neural instructions. Hence, these systems explore forms of autonomy at a level that is independent of metabolism, that is to say, of the physical functions responsible for the capacity the creature has to "stay alive."

In self-constructive terms, however, this strategy may produce situatedness, but not autonomy [18]. Although the behavior of the system is controlled by adaptive mechanisms that are inherent in the point of view of the system itself, it is not clear that the system has its own purposes or goals, as it is not the need to maintain its structure that constrains situatedness in its environment. From an approach grounded in the notion of biological organization, situatedness arises as a function of the need to energetically maintain the organism, arising from those processes that endow the agent with identity (i.e., the self-organizing processes that maintain it as a physical system in a physical domain);

thus, behavior is a manifestation of the self-maintaining structure, and meaningful interactions emerge from the whole pattern of system-environment relations.

In order to emulate that, the actions of the robot should be a consequence and a cause of the structure of the system. One problem is that, in a robot, new functional forms of behavior emerging from its interactions with the environment do not affect its material structure (which is inert), but only its behavioral organization. Thus, the reciprocal causality between what it is and what it does and endures, that exists in the animal, appears in a broken version in the robot [15]. As the robot's material structure is essentially inert (a quasi-rigid physical structure, mainly conservative), plasticity is obtained at the level of the software, not of the hardware.

How can an artificial system of this kind have autonomous goals or purposes? Di Paolo [15] has proposed to address the autonomy of robots at a higher level, so that certain behaviors need not be grounded directly on metabolic needs, nor be dependent on adaptation and survival, but on sets of "values," or preferences, of the creature emergent at higher levels. It is evident that this approach may provide interesting results for further investigation of the operation of the decoupled high level (which, as we said, is underdetermined by the metabolic one and, in this sense, may even generate values or goals proper to that level), but it does not eliminate the requirement of a strong grounding for the integrated system.

In sum, we have tried to show that the functional autonomy of living systems emerges from a structure-process relation that is intrinsically dependent on rates, energy flows, and mass, and that the variations in the values of these elements are crucial for the realization of the closure, and therefore for the organization of agency. This is the reason why in the biological domain the fast-movement–body-size dialectic has brought about the appearance and development of new capacities, such as basic forms of cognition, and (with further development of body plans) an expansion of the cognitive phenomenology and the emergence of a sentient identity (the phenomenon of decoupling played an important role in this evolution). However, in robots the relation between the virtual structure and processes is independent of rate, energy, and matter, and these variations do not substantially affect the organization of agency. As a consequence, we should not expect that work in artificial systems will generate forms of agency similar to that in living ones.

5 Conclusion

In this article we have analyzed the conditions for agency in natural and artificial systems. In living beings, agency arose through an evolutionary process initiated by basic forms of autonomy, whereas in the construction of robots and simulated artificial agents the starting point is human cognitive capacities. We have tried to show that this difference in beginnings is concurrent with a difference in principles. In animals the phenomenon of decoupling reveals a complexification of the basic organization, because the sensorimotor system serves a function in the integrated whole organism, whereas its characteristic dynamics is somehow autonomous.

So far, the research program in robotics and artificial intelligence has focused on autonomy at the sensorimotor level, without basic autonomy. Instead of trying to reconstruct the conditions for triggering a process of spontaneous organization starting from chemical components, computers and other complex technical tools are the building blocks. The lesson of artificial life is that we can build "creative" artifacts in which human action appears only in an indirect way, "getting ourselves out of the loop," as Langton says [5, 37]. From this perspective, evolution in the computer may generate functional structures without full design (as is the aim of evolutionary robotics), yet artificial evolution is different form natural evolution, and the two evolutionary trends will have different characteristics [19].

The reason for the (in spite of all progress) still evanescent expectation of reproducing true agency and cognition in robots is not that there is something extra in living matter that we do not know (an idea that brings old vitalisms back to life). It is not that computer power needs to be improved or that the organizing or mathematical principles need to be reformulated, as Brooks

suggests [8], nor that there is a mysterious capacity of living matter (as Penrose and Chalmers suggest). The difficulty is in the deep and radical interrelation between forms of organization and materiality: The material structure of robots is very different from that of living systems, and this imposes qualitative differences on the form of organization.

Acknowledgments

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