Enabling conditions for 'open-ended evolution'

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Abstract In this paper we review and argue for the relevance of the concept of open-ended evolution in biological theory. Defining it as a process in which a set of chemical systems bring about an unlimited variety of equivalent systems that are not subject to any pre-determined upper bound of organizational complexity, we explain why only a special type of self-constructing, autonomous systems can actually implement it. We further argue that this capacity derives from the 'dynamic decoupling' (in its minimal or most basic sense: the phenotype–genotype decoupling) by means of which a radically new way of material organization (minimal living organization) is achieved, allowing for the long-term sustenance of systems whose individual-metabolic and collective-historical pathways become thereafter deeply intertwined.

Keywords Open-ended evolution · Preservation/growth of complexity · (Basic) autonomous systems · (Minimal) biological organization · Dynamic decoupling

Introduction

In a broad sense, evolution just means 'a process of change'. So all physical systems, including the whole universe, can be regarded as *evolving* systems. However, the term 'evolution' has a more specific and profound meaning (at least on the Earth): it is normally used in relation to certain systems, biological systems, that show a very peculiar way of changing through time. And we are not referring here to those changes that take place during the 'lifetimes' (the ontogeny) of individual systems, but to those that take place through subsequent reproductive cycles (generations) and have long-term, phylogenetic

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consequences. Evolution, in this standard biological sense, involves a historical and collective dimension, comprising a whole set of systems that interrelate in different ways (at different space and time scales) and display different levels of complexity as a result of this process.[1]

As it is now widely accepted (Prigogine and Stengers 1979; Brooks and Wiley 1988; Weber et al. 1988), the general thermodynamic drift towards equilibrium and homogeneity does not preclude the formation of local fluctuations and imbalances that, given the right conditions, can lead to the appearance of complex dynamic behaviour in open systems. Actually, a scenario that includes local non-equilibrium flows of matter and energy constitutes the right platform to conceive and investigate real systems that may evolve further in that direction: i.e., towards higher levels of diversity, heterogeneity and complexity (like living systems have actually done). Nevertheless, the sustainability of self-organization phenomena (in the most basic, physico-chemical cases: 'dissipative structures', as Prigogine called them (Nicolis and Prigogine 1977)) is not to be taken for granted, because their strong dependence on external boundary conditions makes them rather fragile. And, therefore, the possibilities of these systems to grow in complexity are also quite scarce.

In contrast with that apparent fragility of complex dynamic phenomena in physics and chemistry, nature developed a very intricate, indirect and—at the same time—robust mechanism of evolution (for which Darwin coined the term 'natural selection'), establishing a process of change over time that could give rise to systems with increasing levels of complexity. As a matter of fact, complex patterns of behaviour can be found nowadays across all levels of biological organization, from ecosystem dynamics to reaction-diffusion processes in unicellular organisms. But, to what extent is this type of mechanism (natural selection) really necessary for the long-term sustainability of complex systems? Which are the requirements that physico-chemical systems have to meet in order to achieve similar evolutionary capacities? Are these capacities only characteristic of full-fledged living beings or some infra-biological systems could also have them?[2] And which would be the key concepts to understand and describe those systems? Such are the main questions that will be addressed in this paper. Even if evolutionary parameters/dynamics cannot be adequately defined and studied but in the context of a population, it is still relevant to investigate what kind of systems, with what kind of structure/organization, are necessary to start a Darwinian evolution process.

Up to date the general approach to explore the origins of Darwinian evolution has been strongly biased by molecular biology's great advances in the second part of the XXth

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[1] In the case of development, understood as «a process whereby a relatively unspecified system comprised of loosely connected lower level parts becomes organized into a coherent, higher-level agency» (Coffman 2006), one could interpret that there is also some sort of 'evolutionary pathway', with an overall increase in the complexity of the system, but this would be restricted to an individual organism and its lifetime. The problem is really much more complicated, because development is, in fact, tightly linked to evolution, in that wider and more common, biological sense of the term. Nevertheless, here we will not deal with it: we will focus on the actual conditions for the origin of evolution as a long-term process of change (that takes place in a population of historically related systems), before proper developmental systems appeared.

[2] The terms 'full-fledged living being' and 'infrabiological system' are here used to make the distinction between living systems as we know them and certain (hypothetical) ones with a significantly lower degree of complexity (see also (Szathmary et al. 2005)). Some of us have discussed more extensively the criteria to define life elsewhere (Ruiz-Mirazo et al. 2004), which would mainly cover metabolic ('autonomous') and Darwinian ('open-ended') evolution capacities. These are very demanding conditions, so in the process of origins of life (or any artificial reconstruction of it) there must necessarily be systems below the threshold. In our account open-ended evolution will be the last condition for prebiotic systems to become proper living ones, so the beginning of open-ended evolution would be equivalent to the end of the process of origins of life.

century. Accordingly, most attempts in this direction have focused on the search for molecules (biopolymers or their precursors) that could implement that type of evolutionary dynamics, so often characterised by the triad: 'multiplication, variability and heredity' (Maynard Smith 1986) (previously, and perhaps following more strictly Darwin's original spirit: 'phenotypic variation, differential and heritable fitness' (Lewontin 1970)). As a result, there is a very widespread conception (for a recent example, see (de Duve 2005)) that the onset of an evolution process by natural selection is based on molecular replication mechanisms, which are assumed to appear sometime in the process of the origins of life (typically at an 'RNA world' stage), before full-fledged *living organisms* came about.

This is further supported by the conceptual distinction between 'units of selection or units of evolution' and 'units of life' (Maynard Smith 1986; Szathmáry et al. 2005; Szathmáry 2006). Indeed, the properties of multiplication (reproduction), variability and heredity do not have to coincide with the criterion to define life, so they could, in principle, be achieved by infra- or supra- biological systems (like populations of molecules, colonies, species, ecosystems, societies,…). Thus, the way things stand at present, it is not easy to avoid or discard the idea of a prebiotic scenario where 'Darwinian evolution' takes place without proper organisms, even if Darwin (or Lewontin (1970)) most probably would not subscribe that view.

However, at the beginning of this century the concepts of organism and organization are starting to be a force again in biology, once the limitations of molecular biology's research program are becoming more evident. On those lines, there is a growing number of researchers who are re-opening postponed problems in biology and the origins of life, together with an emergent current of thought claiming that the study of biological phenomena requires a more systemic approach (Keller 2000; Westerhoff and Palsson 2004; Bechtel 2005; Boogerd et al. 2007; see also the special issue of *Science* (2002) on this question). Locating ourselves within that current, in this paper we look into the implications of conceiving precisely the problem of the origins of Darwinian evolution in systemic terms.

To avoid confusion or fruitless discussion, we will here refer to open-ended evolution (rather than Darwinian evolution) as a process in which there is the possibility for an indefinite increase in complexity. And our aim is to specify the material mechanisms[3] that allow that kind of evolution. In order to do so, we will first demarcate as specifically as possible the idea, providing a workable definition of it, and then construct, step by step, a genealogical explanation of how proto-biological systems could get organized to insert themselves in that kind of process. As we will see, this alternative approach will eventually lead to systems capable of reproduction, variability and heredity, but it is more demanding than that. First, it does not allow us to conceive of the implementation of an open-ended evolutionary process just in terms of a population of replicating molecules: these—together with other types of molecular components—will have to meet stronger organizational requirements. And, second, by linking the problem to the maintenance and growth of complexity it will become evident why the mechanisms that make possible the open-ended evolution of a group of systems are actually the same as those that ensure their long-term sustainability (as a highly complex collective phenomenon).

The starting point of the article is, precisely, a review of the idea of open-ended evolution, tracing it back to von Neumann's seminal work. Although our approach to the problem will be very different, exploring the actual, material (not just formal) conditions

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[3] Our use of the term 'mechanism' (following (Bechtel 2005)) is not reductionist: i.e., it is not restricted to local and deterministic molecular devices, but includes more global and emergent organizational principles.

for open-endedness, we cannot forget the strongly influential way in which it was origi-
nally posed. Then, we will try to determine the set of conditions that leads to a scenario
where this kind of evolution becomes a real possibility, analysing critically other—less
demanding—proposals. The last section is devoted to explain the type of material orga-
nization that self-constructing systems have to adopt in order to cross that crucial transition
point, introducing the fundamental idea of 'dynamic decoupling'. Finally, in the con-
cluding remarks, we link this idea to our project of developing a naturalized and biolog-
ically significant concept of information, for which a full additional paper is required, due
to size constraints.

The idea of open-ended evolution

Review of previous conceptions

The concept of open-ended evolution is not easy to define. On the one hand, it tends to be
used as an intuitive idea, rather than as a clear-cut, precise concept; on the other hand, it
evokes a handful of difficult and very controversial issues, like those related with the
notions of evolutionary progress, growth of complexity, directionality in evolution,
unconstrained universe of possibilities…, just to mention a few.

A historical analysis of the concept and its relationship with those issues would lead us
to review the—largely forgotten—theories of *emergent evolution* in the late XIXth and
early XXth centuries (mainly of the type of Lloyd Morgan's, but also of Spencer's), which
made explicit and highlighted the major evolutionary boost coming from Darwin's theory.
According to these emergentists, the continuous appearance of novelty through evolution
(regardless of the specific mechanism advocated) was the main lesson to be extracted from
an evolutionary worldview. Without overlooking the historical roots of the idea, our aim
here is rather to grasp the current way of understanding open-ended evolution and show its
significance for contemporary theories in biology and the sciences of complexity.

This involves searching for the—natural or artificial—mechanisms that could produce
an indefinite increase of complexity. More concretely, the thinking tradition that we have
to trace back in order to find the basis of this conception is linked to researchers who were
mainly concerned with the construction of sophisticated devices, which could not only
cope with or simulate very complex behaviours, but even trigger them off *by themselves*.
This goes back to von Neumann's work with self-reproducing automata and connects
directly with the origins and development of Artificial Life as a discipline. Von Neumann
must be credited for having explored the minimal conditions for complexity to be able to
grow (and not spontaneously degenerate) and for having been able to determine, at least
formally, in what consists this minimal threshold of complexity.

If one reviews carefully von Neumann's writings (1948 [1951], 1949 [1966]) the
expression 'open-ended evolution', as such, will not be found. Yet his description of the
critical threshold of complexity predicting an *explosive* phenomenon of automata pro-
duction above that point is quite significant:

«There is thus this completely decisive property of complexity, that there exists a
critical size below which the process of synthesis is degenerative, but above which
the phenomenon of synthesis, if properly arranged, can become explosive, in other
words, where synthesis of automata can proceed in such a manner that each

automaton will produce other automata which are more complex and of higher potentialities than itself.» (von Neumann 1949 [1966], p. 80)

It is interesting to recall that, at this point, von Neumann himself acknowledges the vagueness of those statements «…until one has defined the concept of complication [complexity] correctly» (von Neumann 1949 [1966], p. 80). And, unfortunately, we cannot but recognize that we are still in a very similar situation: there is a good deal of—more or less overlapping—definition candidates (and an even greater number of different ways of measuring it), but we lack a good universal definition of complexity beyond vagueness. In other words, very precise both measurements and related definitions of complexity are available, but they are quite restricted to specific areas of research and none has yet attained general acceptance.

Nevertheless, to our subject here, we should take note of two important things that McMullin remarks in a paper dealing, precisely, with von Neumann's work (McMullin 2000). On the one hand, he reminds us that von Neumann's fundamental problem was actually the issue of open-ended evolution or, as McMullin expresses it, the issue of 'evolutionary growth of complexity'. The second important point is that von Neumann's statement of the problem and his (theoretical) solution does not rely on any complete and accurate definition of complexity but just on ''the crudest of qualitative rankings'':

> «… Rather, my claim is that this self-reproducing, far from being the object of the design, is actually an incidental (…) corollary of von Neumann's having solved at least some aspects of a far deeper problem. This deeper problem is what I call the *evolutionary growth of complexity*: more specifically, the problem of how, in a general open-ended way, machines can manage to construct other machines more complex than themselves. (…) Note that this claim does not rely on any sophisticated, much less formal, definition of complexity; it requires merely the crudest of qualitative rankings. Nor does it imply any *necessary*, or consistent, growth in complexity through evolution, but merely an acceptance that complexity has grown dramatically in *some* lineages.» (McMullin 2000, p. 350)

In order to support this we may add that, even among those who are trying to provide formal and strict definitions of complexity, the underlying concept remains the same, as for instance in Nehaniv (2000), who says that «…it makes sense to define evolution as open-ended if it supports unbounded increase in complexity». It is also worth mentioning here, within the work more directly related to Artificial Life, the definition of open-ended evolution proposed by Tim Taylor:

> «This term refers to a system in which components continue to evolve new forms continuously, rather than grinding to a halt when some sort of 'optimal' or stable position is reached. (…) Note that open-ended evolution does not necessarily imply any sort of evolutionary progress. (…) Also, by using the term 'open-ended' I wish to imply that an indefinite variety of phenotypes are attainable through the evolutionary process, rather than continuous change being achieved by, for example, cycling through a finite set of possible forms.» (Taylor 1999, Sect. 2.5)

On similar lines, following von Neumann's basic intuition, we consider that there could well be a critical threshold below which complex dynamic behaviour in nature eventually decays, and above which it becomes engaged in a process of non-stop production of ever new forms of that complexity (and, potentially, of higher level complexities). Von Neumann went even further to argue what this threshold would really imply: that a purely

dynamical system, without a separate self-description, would not be capable of successful propagation, through reproduction, of any potential improvement in its organization and, therefore, would not be capable of (open-ended) evolution. This claim is far from being trivial since, as we shall see, several hypothetical forms of proto-metabolic organization could show reproductive and evolutionary capacities, which we may call 'pre-Darwinian', and face important bottleneck transitions at different levels of complexity that would be below that threshold.

So, from our point of view, von Neumann's claims need to be reassessed in the light of a different way to approach the problem. In contrast with his initial (and, unfortunately, also final) way to deal with it, as well as to the general practice in the ALife community, we defend the idea that this question cannot be tackled adequately just in a purely formal way, but requires taking into account also certain material (physico-chemical) aspects of great relevance. Nevertheless, and to be fair, we should acknowledge that von Neumann was also fully aware of this shortcoming, as shown in a frank remark on the limitations of his own (abstract, formal, strictly computational) treatment of the problem:

> «By axiomatizing automata in this manner, one has thrown half of the problem out of the window, and it may be the more important half. One has resigned oneself not to explain how these parts are made up of real things, specifically, how these parts are made up of actual elementary particles, or even of higher chemical molecules.» (von Neumann 1949 (1966), p. 77).

So, what about that 'more important half'?

From the content of the previous quote, one should feel compelled to investigate, particularly if willing to address the question of the first *origins* of open-ended evolution, what could be the material implementation of a system—or group of systems—with potential to grow indefinitely in complexity. Human-made machines or organizations (which depend on an intelligent design *ab initio*) are, thus, discarded from our search, to be focused on simple enough systems (so that their appearance can be explained in a natural context) but, at the same time, with a molecular and organizational structure that allows for a rich enough space of dynamic states/configurations (which is necessary to bring about an evolutionary growth of their complexity). So, what kind of physico-chemical processes could lead to these systems?

One would initially think about spontaneous processes of generation of order, like self-assembly or self-organization phenomena. The former are typically a source of structural order, driven by the natural tendency towards thermodynamic equilibrium; whereas the latter are well-known to create dynamical order at the expense of a matter/energy flow. But neither of these two kinds of phenomena, taken separately, can initiate a process that leads to open-ended evolution. Let us illustrate this by referring to a couple of classical examples, one of each case: (i) first, that of a growing crystal, where the characteristic molecular structure of the system is being continuously replicated, and defects/impurities could be taken as an endless source of variation (even transmittable—i.e., somehow 'hereditable'—variation). All the same, this system cannot get very far in terms of *raising* its level of complexity. Defects or impurities have a very limited potential to trigger real innovations in the system and the global thermodynamic drive towards equilibrium (state of minimal energy) hardly provides opportunities to produce further novelty. (ii) The second example is that of a macroscopic pattern (e.g.: a convection cell or a chemical wave) which spreads/

multiplies through a certain space-temporal domain. Here the problem lies in the small window for variation in global states that these dissipative structures admit. If more than one, there would be just a few macroscopic conformations compatible with similar boundary conditions. Thus, the possible growth of complexity is again (though for different reasons) strongly restricted from the start: the actual generation of diversity.

However, the *combination* of both self-assembly and self-organization processes within the same dynamic phenomenon can give rise to systems with increasing levels of molecular as well as organizational complexity. Quite interestingly, this is not reachable for purely physical systems nor for standard chemical ones. We have to focus on a particular kind of chemical systems, in which the non-linear dynamic properties of the global organization ensure the cyclic production—and reproduction—of certain local interactions; and, in turn, a particular combination of processes of molecular construction bring about a wide range of collective *functional*[4] behaviours (e.g.: global autocatalysis, self-regulation/ self-modification, self-repair, hierarchical self-maintenance, etc.). Several authors have tried to grasp the core of this important idea, developing different—though, somehow, related—theoretical models of chemistries with alleged biological significance: from the 'M-R systems' of Rosen (1973, 1991) to the 'autocatalytic sets' of Kauffman (1986, 1993), the autopoietic systems of Maturana and Varela (1973, 1980), Gánti's chemoton (1975; 2003), the abstract 'component-production-systems' of Kampis (1991), the 'grammar or algorithmic chemistries' of Fontana (1992), or the more specific and recent 'composomes' in the 'lipid world' of Segré et al. (2000).

These approaches draw attention to a crucial point of the issue: that any system candidate for open-ended evolution has to be a recursive or *cyclic component production network*. Otherwise, it would not be possible to have an indefinite source of molecular diversity, an endless process of generation of chemical novelty, in a functionally rich enough dynamic-behavioural space. Accordingly, a self-producing chemical network that manages to keep running and, from time to time, introduces some novelty—e.g., uptakes a new substrate from the environment or makes a change in some of its components—could be regarded, in broad terms, as an open-ended evolutionary system. However, this potentially open-ended production of complexity might be irrelevant in terms of its actual evolutionary growth, unless the innovations in the system provoke some *differential contribution* to the preservation of the new molecular structures and the new global network to which they belong.

The relevance of the problem of preserving complexity has led other authors to link the question of the increase in complexity to the mechanism of replication/reproduction.[5] This is the case of Maynard Smith and Szathmáry (1995; Szathmáry and Maynard Smith 1997; Szathmáry 2000) who developed an insightful—and somewhat more specific—conception, which restricted the notion of 'open-endedness' to replicating/reproducing systems whose «number of possible types by far exceeds the number of individuals (copies, sequences, etc.) in a plausible (realistic) population». In other words, the space of possibilities

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[4] The term 'functional' will be used in this paper in a very broad sense, to describe an action of a part of a system/organization (or a relation between different parts of that system/organization) that contributes to its global self-maintenance (Moreno et al. 1994).

[5] We will distinguish the terms 'replication' and 'reproduction' following Dyson (1985), Fleischaker (1994) and Luisi (1994): i.e., restricting the use of replication for the 'copying' of a specific molecular structure in which sequence is conserved, and taking 'reproduction' as a more general term (close to the idea of multiplication) that can be applied to global organizations. This distinction is not widely spread yet, although more and more researchers are becoming aware of its importance (see, e.g.: (Szathmáry and Maynard Smith 1997; Griesemer 2000; Szathmáry 2006)).

reachable, in principle, to the population must be enormous in comparison to the space that can be actually explored in real time and under real constraints. Therefore, according to their account, not all chemical systems would be apt to evolve in an 'open-ended' way (or with 'unlimited hereditary potential', in their own terms): only those which are made of long enough modular replicators, so that the copying process is fairly reliable and microevolution is feasible with high enough combinatorial numbers involved.

This perspective is, indeed, well articulated and indispensable to cover an important aspect of the problem, but does not capture the real heart of it, since it is excessively focused on the molecular or micro-level requirements for open-endedness. Taking a more integrated or *systemic* approach, one soon realizes (i) that the problems of preserving and producing complexity are, in fact, deeply intertwined, (ii) that all possible solutions to it involve molecules embedded in a global, self-constructing, organization (see next section), and (iii) that the most characteristic feature of an open-ended evolution process is that it should allow for (beware: we are not saying 'push' or 'provoke') the growth of complexity in the system, taking this as a whole.

Therefore, from a genealogical and materially grounded perspective, we propose that the idea of open-ended evolution should be conceived as *a process in which a set of chemical systems re-produce their basic functional/operational dynamics, bringing about an unlimited variety of equivalent systems, of ways of expressing that dynamics, which are not subject to any pre-determined upper bound of organizational complexity (even if they are, indeed, to the energetic-material restrictions imposed by a finite environment and by the universal physico-chemical laws).*

In agreement with previous work (Ruiz-Mirazo et al. 2004) we claim that not until this process is started can we speak about the end of the origins of life stage and the beginning of proper *biological* evolution. And we will here focus on determining the minimal and primary set of conditions that bring it about. Of course, someone could argue that other major biological transitions (e.g., the appearance of eukaryotes, sex, multicellularity, nervous system, language,…) require the fulfilment of further conditions and, therefore, that true open-endedness is not completely guaranteed by the set we will introduce below. However, we will insist that the conditions to bring about the basic core of a biological organization (i.e., the organization of a population of prokaryotes) are not only necessary but also sufficient for open-ended evolution (in the most fundamental sense of the term). This is supported by the fact that more complex forms of biological organization (e.g., eukaryotes, multicellular organisms...) have not erased—but, still, critically depend on—that minimal core (bacteria), whereas the different infra-biological types of organization, which surely appeared in the process of origins of life, were soon ''cleared away'' by full-fledged living beings.[6]

A new approach to the search for systems with open-ended evolutionary potential

Setting up the general scenario

Our aim is then to investigate the set of conditions and material mechanisms required for open-ended evolution: i.e., required to solve simultaneously and efficiently both the

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[6] In other words, we hold the view that, even if sex or conscious intelligence had never arisen (given different circumstances from the ones life has endured on Earth), the type of evolutionary pathway followed by living organisms (also assuming that these remained unicellular) would still be fully open-ended.

problem of *producing* and *preserving* complexity. As we commented in the introduction, up to now most researchers interested in this problem have looked for an answer in the experimental or theoretical exploration of the so-called 'replicator' (Dawkins 1976; Hull 1980) dynamics, i.e., in the chemistry of complex molecular species that show some copying or 'template' activity. The working hypothesis assumed by this approach is that the structural and replication properties of prominent biopolymers (like RNA or DNA), which guide to a big extent the evolutionary pathways of present living organisms, not only can be extended to non-cellular in vitro conditions, but also ought to play a primary role in the first steps towards life (Eigen 1992). Hence the motivation to find a plausible link with other, simpler molecular structures that could show similar autocatalytic behaviour (i.e., autocatalysis with conservation of molecular sequence). In this way, 'replication-first' scenarios have been predominant in the field during the last decades (Eigen and Schuster 1979; Eigen 1992; Joyce 1989; von Kiedrowski 1986; Orgel 1992; Ferris 1994; Anet 2004; Pross 2004).

However, any system/model of artificial evolution based merely on a population of replicating molecules in solution faces very important difficulties to maintain or increase its complexity. It is not just that surfaces or compartments are—sooner than later—required to avoid the problem of parasites; or that there is a critical length of nucleotide chains above which it is no longer possible to carry out a reliable replication process (see the reviews on these issues in (Eigen 1992; Szathmáry and Maynard Smith 1997; Scheuring et al. 2003)). More significantly, the actual appearance, maintenance and evolutionary development of populations of self-replicating molecules is really hard to conceive in the absence of a functional *organization* (i.e., a rudimentary metabolic organization) that somehow channels the matter-energy resources needed for those tasks. Furthermore, an evolutionary process leading to higher forms of complexity would require self-replicating entities that should, in principle, produce an open space for functional variations, so that changes in their molecular sequences have a wide enough range of dynamic-operational effects in the system. However, as Wicken (1987) rightly pointed out, bare self-replication processes cannot account for this widening of 'phenotypic space'. That is to say, if molecules do not belong to an organization (i.e., if they are not the components of a more encompassing self-maintaining/self-producing collective entity), the only way they have to rise their fitness is by improving their individual replication rate or their resistance to hydrolysis. And this, by itself (like in 'Spiegelman's monster' experiments (1967)), does not seem to allow for an increase in complexity (quite the contrary, it may well provoke a reduction of it—e.g.: the shortening of the replicating molecular chains).

All this leads us to investigate an alternative scheme for the origins of open-ended evolution, taking into account both the molecular (-structural) and systemic (-organizational) constraints that shape the process. Therefore, our approach is more in tune with the so-called 'metabolism-first' scenarios (Oparin 1961; Dyson 1985; Harold 1986, 2001; Morowitz 1992; Deamer 1997; Wächtershäuser 1990; Shapiro 2000) in the sense that we are looking for a theoretical framework in which organizational principles should also be relevant for the appearance of selective-evolutionary dynamics/'driving forces' in nature. In other words, it seems evident to us that the establishment of such an intricate mechanism as *natural selection* must have been preceded by simpler forms of evolution, in which the concept of 'survival'/'fitness' ought to be replaced by 'persistence' (Keller 2007), 'capacity for self-maintenance' or bare 'stability/

robustness', and in which systems with a relatively complex organization were already on the scene.[7]

What would be the main features of these infra-biological complex organizations? And what do they further require to start evolving in an open-ended way, i.e., what do they need to become full-fledged biological organisms? In the next paragraphs we specifically address these points, providing an explanation of the type of the molecular mechanisms required and the organizational transitions they would provoke.

On the way towards open-ended evolution

The generation (and preservation) of chemical complexity, as Morowitz (1968, 1992) has rightly stressed over the years, is not for free; rather, it requires a continuous energetic and material inflow, for it is—thermodynamically speaking—an 'up-hill' process. In fact, many changes that involve an increase of complexity (e.g.: polymerization in aqueous solution, creation and maintenance of concentration gradients, heterogeneities,…) are typically endergonic, i.e., do not occur in a spontaneous way. And if they happen to occur, often the new components/processes in the system turn out to be ephemeral, or remarkably fragile (meta-stable states strongly dependent on specific boundary conditions). This—as it was already suggested above—implies that our candidate systems must be a very particular type of chemical, far-from-equilibrium, open systems, in which the exergonic drive of some processes is effectively coupled to endergonic ones, making possible the constitution of a material-energetically well founded (i.e., a *realistic*) component production machinery.

At the roots of this coupling between endergonic and exergonic processes there must be the capacity of a chemical system to build and rebuild (maintain) *by itself* a diverse set of boundary conditions, or 'constraints'. We do not refer here to the standard (typically structural and external) constraints that help to solve a dynamical problem in physics, by reducing the degrees of freedom of a system; but to *self-generated* constraints (new 'high-level rules' that affect 'low-level molecular interactions') coming both from self-assembly and self-organization phenomena. When a varied set of this kind of constraints gets together, they may have the striking effect of creating new degrees of freedom, or opening up the space of possible dynamic behaviour in the system, rather than reducing it.[8]

We have elsewhere defended (Ruiz-Mirazo and Moreno 1998, 2004) the claim that it is precisely the capacity of a system to generate by itself a minimal set of these 'enabling'

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[7] So our approach does not exclude the possibility that, previous to the appearance of a process of open-ended evolution, there were other types of 'selective dynamics' among the members of a population of reproducing and interacting systems. On the contrary, it demands that there actually were. However, we do not agree with authors that tend to consider all of these dynamics as ground for *natural selection* processes ((Maynard Smith 1986; Szathmáry 2000)). If the mechanism of diversification is just the arbitrary variation of any component/set of components of the system, if multiplication simply takes place by autocatalytic growth and statistical division, if heredity can only be understood as a kind of 'compositional invariance' through generations (Segré et al. 2000), or if the fitness function (selection criterion) is defined as a mere physical parameter of each system (e.g., energetic efficiency), without including somehow the relationship/interactions with other systems in the population and with the environment, we consider that such 'selective dynamics' is quite far from Darwin's original idea of evolution by natural selection.

[8] In the context of this article we have in mind complex chemical systems, like self-bounded reaction networks, but a more illustrative example to grasp this idea (that more constraints do not always involve a more reduced dynamic space) consists in the following: a comparison between the complexity of the pieces (components) and rules (dynamic constraints) of chess and draughts, with regard to the richness of the game they can respectively generate on the same board (general physico-chemical scenario).

constraints what provides the key towards *self-constructing* organizations (or, what we have there called, 'basic autonomy'). The main idea, also entertained by Kauffman in some of his recent contributions (Kauffman 2000, 2003), is that the production of constraints is necessary to guide the flow of matter and energy through the system so as to sustain the processes that lead to its own construction. On these lines, a cyclic relationship between 'work' (understood as any form of energy—chemical, mechanical, osmotic,...—which is useful for the actual system, not for an externally established goal) and 'constraints' ('self-harnessing'—local and global—material structures/mechanisms/rules) would underlie the dynamics of production of molecular diversity in a robust, autonomous and indefinite way.

Accordingly, the starting scenario to focus our search would be covered by chemical networks that constitute a kind of 'oligomer/multimer world' (de Duve 1991; Shapiro 2002) embedded in a supramolecular cellular organization (Morowitz et al. 1988), where endergonic–exergonic couplings include the association of transport and reaction processes (Ruiz-Mirazo and Moreno 2004). In this context (protocell chemistry) it is easier to appreciate why—and start identifying which—self-assembly and self-organizational processes must come naturally together to generate the variety of 'constraining-enabling' mechanisms required for minimal self-construction. However, that relatively robust machinery of component production and autonomous generation of chemical diversity would not be sufficient yet to guarantee an open-ended evolutionary growth of complexity.

First, because the production of complexity is still limited. At the molecular level, there is not a well-established process to synthesize polymers (long monomer chains) with aperiodic (non-redundant) sequences, which would lead to the development of stereo-specificity, inter-molecular recognition mechanisms and catalytic efficiency (based on folding and the more elaborate chemistry of multiple weak bonds). At the system level, the lack of efficient regulation mechanisms does not allow anything but a very rudimentary and distributed form of self-construction (proto-metabolism). Besides, this kind of minimal proto-metabolic dynamics faces a strong bottleneck: the higher molecular complexity in the system, the more and more difficult it becomes to keep a robust self-maintenance. Apart from inescapable thermodynamic reasons, human experience in the design of artificial/in vitro systems confirms the latter: as the amount of different components or the number of steps to build each component goes up, so does typically the brittleness of the system.

Second, and perhaps more important at this stage, open-ended evolution is not viable because there are no specific mechanisms to preserve (for long periods or many subsequent generations) the complexity that may be generated in the system. At the molecular level, there is no direct way to conserve new oligomer/polymer species (with their particular monomer sequences); the reinforcement of their production would be caused by indirect and widely distributed mechanisms (like 'collective autocatalysis' (Kauffman 1993)) that involve the global reaction network. At the system level, self-constructing organizations have a certain degree of homeostasis and potential for growth and multiplication, spreading (and, therefore, somehow 'perpetuating') their functional/operational dynamics. But this is carried out following just a statistical type of reproduction process (cell division still strongly dependent on fluctuations/instabilities), which does not ensure that possible increases in complexity are transmitted reliably to the new generations. In sum, there is no guarantee that the components of the system (together with its way of organization) remain unaltered for much longer than their typical lifetimes (or that of the global organization).

So there is a higher threshold of complexity that has to be crossed to reach open-endedness, as we will try to explain below.

Specifying the type of organization required for open-ended evolution

The 'one-polymer world' stage

Minimal self-constructing cellular systems cannot go beyond a certain level of complexity unless they solve two interrelated problems: one is the production of a diverse set of highly efficient catalysts (and associated regulation mechanisms), which would enhance metabolic performance and versatility; and the other is to preserve those functional components reliably in the organization, providing system robustness and also hereditary potential. Solving the first problem requires the capacity to generate more complex molecular aggregates, like polymers constituted by a specific sequence of elementary building blocks (Srere 1984). The specificity in the order of the building blocks (monomers) is important because that is what determines the general shape, active site and possible regulation mechanisms of the polymer, which in turn is what determines its catalytic and control properties. Since this type of task in the system will depend on a specific (and very unlikely) order of certain building blocks, the system has to search for sequential patterns that are functional, and, once found, *fix* them in the organization. Otherwise the potential advantages of this kind of chemical innovations would get lost very soon, in very few generation steps. Now, the only way to retain the new functional patterns in the organization of the system is to establish some 'template' or 'blueprint' copying mechanism: i.e., some local and robust material mechanism, which ensures the renewal of such complex components (keeping their particular sequences in an exact—or almost exact—way).

The preservation of increasingly complex molecular structures (and correspondingly more sophisticated catalytic functions) through a template mechanism requires a very special type of component. This must consist of interchangeable discrete units, which build up a specific one-dimensional (1-D) sequence, and whose global three-dimensional (3-D) shape is such that it allows the recurrent copying—by a chemical complementarity mechanism, like base pairing—of complete, equivalent sequences. Thus, we are not talking here about simple structural templates, like the ones present in the growth of a crystal, for instance. Rather, about more dynamic *modular* templates (Maynard Smith and Szathmary 1995; Szathmáry 2000). That is to say, polymers whose 3-D structure is not altered significantly as a result of particular changes in their sequence of subunits (since that will seriously threaten their capacity to replicate by chain complementarity). This implies that the states associated to the different sequences of subunits must be, energetically speaking, almost equivalent or *quasi-degenerate*, making possible a new type of chemical combinatorics (free—or almost free—compositionality). In this way, the sequential order of particularly relevant components in the system (given their more efficient, fine-tuned catalytic and regulatory properties) can be reliably transmitted during the reproductive process from one generation to the next and becomes a kind of *record* (Pattee 1965, 1968) of the key new features that may appear in these proto-metabolic cellular organizations.

In a first stage the solution to the problem was possibly provided by the synthesis of a single type of complex polymer (e.g., an 'RNA world' type of scenario), which could carry out both template and catalytic tasks within the cell, but both in a compromised, not very efficient way. The reason is that the material basis of a truly efficient modular template must be different from that of the catalytic units controlling/regulating precisely the processes of production of components (the actual *metabolic* network). This incompatibility has to do with the structural limitations of any system based on a single type of polymer (see, e.g.: Benner (1999)). Indeed, the capacity to store and replicate sequential complexity

increases as the capacity to express sequential variety in 3-D variety—diversity of shapes—decreases (Moreno and Fernández 1990). The latter is the key to the functional-metabolic organization of the system, since the fine-tuning of chemical rates depends crucially on the stereo- and substrate-specific features of the molecules involved. Thus, it becomes necessary to convert the sequential complexity present in the chain of subunits making up the template-components into another kind of subunits or building blocks, apt to integrate chains whose 3-D structure expresses functionally their sequential differences.

But even if such hypothetical 'one-polymer metabolic systems' would develop more diverse and efficient strategies to improve their robustness, both at the individual-system and at the collective-population levels (implementing new catalytic, regulatory and transmission-hereditary mechanisms), they would anyway reach a bottleneck of complexity, given the inherent limitations of a single type of polymer to carry out effectively template and catalytic tasks. Presumably, they would generate a kind of pre-darwinian process of evolution in which (as Woese (2002) has pointed out) horizontal ''gene'' (RNA-string) transfer would be predominant, leading to a kind of communal evolution, where selective pressure acts on the whole population of cells. Yet at this stage the 'chemical memory' of the system is not segregated from the metabolic dynamics, so it is very difficult to achieve high reliability in the replication of its complex components or its reproduction as a global organization (Rocha 2001).

The 'two-polymer world' stage

All this amounts to saying that, in order to reach truly open-ended evolutionary capacities, a new type of metabolic, self-constructing organization is necessary: an organization based on two different—though complementary—types of macromolecular components (polymers) and two different—though complementary—modes of operation in the system. Now, acknowledging the forced structural incompatibility between the two kinds of polymer required, one has to assume that their interrelation cannot be established through direct molecular recognition mechanisms, founded on the physico-chemical affinities between their respective subunits (for instance, through a direct base-pairing mechanism). So how can this be achieved?

The solution is to set up a new form of metabolic organization based on an indirect, mediated relationship by which 1-D (nucleotide) sequences are linked—or 'translated'—to 1-D (aminoacid) chains that make up catalytically active polymers. Interestingly, this new type of causal link is strongly circular, since the template polymers (DNA strings) *specify* the synthesis of the functional-catalytic polymers (proteins); and these, in turn, control and regulate all the processes in which the former are involved (not only translation, but also replication, repair, etc.), even if they do not take part directly in the creation and alteration of the sequential order of those components. The link gets fixed (otherwise it would not be a reliable mechanism of molecular synthesis)[9], but in a non-linear loop that involves several different intermediaries (and, ultimately, the whole self-constructing organization). Hence its apparent contingency, physico-chemically speaking. Following Pattee (1977, 1982), we can say that there exist two radically different levels of operation in this new form of metabolic organization: one involved in its fundamental productive-metabolic processes (i.e., ''dynamic'', ''rate-dependent'' processes); and the other, partly decoupled

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[9] 'Fixed' does not mean unchangeable but temporarily stable, dependable as a recurrent mechanism. In fact, we find the co-evolutionary account of the origins of the present genetic code (Wong 1975; Di Giulio 1989) quite a reasonable and interesting hypothesis.

from all that muddle of chemical reactions, putting together a group of special processes and components (''rate-independent'' processes), whose changes take place at a different (dynamic-temporally incoherent) scale (see also: (Umerez 1998, 2001)).

This partial *dynamic decoupling* turns out to be fundamental from the organizational point of view, since it allows the constitution of metabolic systems that are causally connected with the historical-collective process that unfolds through their genetic (self-) reproduction and competition for limited resources. In this way, individual systems may profit from the results (end-products: selected patterns) of a slower, much more encompassing and indirect process of variation and evolution, taking place outside those systems and beyond their ontogenic histories. The—comparatively slow—changes that occur at the level of the sequences of modular templates/records are, thus, largely independent of the underlying dynamic-metabolic processes. In fact, the particular order of the linear sequence of the templates will be determined by an evolutionary process in which the whole population and its environment are involved, not by the metabolic dynamics of each of the autonomous systems within it. This allows a new way to produce or 'search for' novelty, detached from immediate chemical-metabolic requirements: a really free or 'blind' type of compositionality. At the same time, the new templates/records are integrated as operational units in the system, precisely because they start playing a causal 'top-down' role in the synthesis of new, specific and increasingly complex functional-catalytic components. In any case, this is a highly indirect action, which goes beyond their ordinary template activity, since in the process of the specification of those components, the templates remain as almost inert, non-reactive units.

It is important to highlight at this point that the distinctive nature of genetic mechanisms and components does not derive from 'magic' molecular properties associated to polynucleotide chains. For instance, DNA is not a stable molecule per se. Nevertheless, it has a set of chemical properties that make it particularly suited, *within the context of a complex metabolic organization*, to play the role of a highly conserved, reliably replicating structure. As often the case, it is a combination of molecular and organizational features, as well as environmental allowing conditions, what makes possible a major transition (both in pre- and post-biotic scenarios). Thus, it becomes very difficult to ascribe a certain aspect of an emergent phenomenon to a single cause or material property. In our present discussion this is especially noticeable, since genetic stability and fidelity through generations (as it is being more and more widely accepted now (Keller 2000)) crucially depend on an enzymatic-repair machinery, supported by the whole metabolic organization of a living being; even DNA mutation rates, traditionally assumed to be outside the scope of control of the organism, also seem to be subject to some sort of cell regulation (depending on the degree of 'selective stress' that the system undergoes).

Therefore, it is through the emergence of a whole new type of metabolic organization that autonomous cellular systems can successfully and consistently combine the individual dimension of their activity (related to the self-construction/self-maintenance of each agent) with a progressively more important collective dimension (related to their long-term maintenance and evolution as a whole population) (Ruiz-Mirazo et al. 2004). And, thus, open-ended evolution becomes finally possible.

Concluding remarks

The capacity to increase indefinitely in complexity has been argued to be intrinsically linked to the appearance of systems that ensure their long-term stability as a collective

phenomenon. This involves important requirements from the organizational point of view of each of the systems. Indeed, a dynamically decoupled organization constitutes the most basic mechanism able to rearrange a complex integrated system in a way that makes possible its open-ended evolution, because it allows a powerful way to explore new functions, at the same time as it provides the level of catalytic efficiency required for robust self-maintenance, which is reliably transmittable through generations. Without this fundamental mechanism, there would be no solution to the problem of the increasing fragility associated to the growth of complexity, and nature would not be able to overcome a primary (pre-biological) bottleneck.

So we can say that von Neumann's insights are, to a large extent, confirmed by our own treatment of the problem, in the sense that the threshold for complex systems to start a process of indefinite growth (or, alternatively, for life to evolve in an open-ended way) requires two separate, though complementary, domains of interactions, combinations and causal relations in the system. Nevertheless, our approach provides a wider framework to understand and derive further implications of this basic scheme, reaching beyond formal, individual-scale requirements.

The intricacies and intertwined multilevel processes found in this kind of complex self-constructing organizations should not hinder—but contribute to—our effort of identifying as clearly as possible what are the characteristic properties of systems with open-ended evolutionary capacities. In that sense, a strong conception of the phenotype–genotype decoupling (as described above: i.e., as a new organizational principle in the system) seems most appropriate. Otherwise it would be extremely difficult to understand how some complex material components turn out to play so accurately and effectively the role of storing the sequential order necessary for the construction of other highly specific catalytic components. Moreover, as already mentioned, if the changes in the sequential (genotypic) domain were not decoupled from the metabolic dynamics, the system would not be able to develop free compositionality and explore indefinitely (by random variation) a huge space of possibilities, finding (through a selective process of retention, taking place at large space-temporal scales: natural selection) new functional patterns of organization. Having said that, it is also important to recall that the decoupling must be only partial, because (i) the synthesis and maintenance of the genotypic domain and (ii) its actual functional expression requires an underlying and complementary metabolic substrate/activity (phenotypic domain). So we can say that the two organizational levels/domains are *dynamically decoupled* but at the same time interdependent, *hierarchically coupled*. The causal circularity involved in this complementary relationship does not lead to a vicious circle: rather, it is the only way to integrate an organization with both 'ontogenetic' and 'phylogenetic' dimensions avoiding an infinite causal regress.

Actually, this form of organization both requires and supports two interrelated but different phenomenological domains. One is the world of physiological processes taking place in the cell (or, even, in more complex multicellular organisms); the other one is a meta-network of processes that interconnects populations of organisms both in synchronic and diachronic ways. These two domains depend on each other, since genetically organized metabolisms cannot be maintained, in the long-run, without the more encompassing, ecological network of Darwinian evolution processes; and the latter, as we argued quite extensively above, cannot take place without the former.

Thus, the key of this new kind of *global* self-preservation is the following: on the one hand, individual systems can adopt very diverse forms of functional organization (metabolic and developmental diversity), provided that they do not lose their capacity to be reliably transmittable through generations. On the other hand, all of them—however

different they may be—share a common organizational core structure (as has been previously described, based on a strong form of dynamic decoupling: the code-mediated genotype–phenotype decoupling), whose long-term preservation depends precisely on that capacity of continuous, unlimited variation and production of diversity. In other words, when we look at the self-construction process of individual organisms, the dynamical decoupling (namely, the off-line regulatory control of metabolic processes by genes) appears as the internal mechanism allowing (unlimited levels of) complexity in the metabolic organization. And when we look at the population level, this dynamically decoupled form of organization appears as the link between the organismic and evolutionary levels, because it allows transferring the slow processes of change taking place at the evolutionary scale to the sequential (genetic) domain of individual metabolisms.

Finally, we claim that the type of organization described along this paper, as required for open-ended evolution to happen, incorporates and integrates, though within a wider and different framework, what in standard biology is described as genetic information, genetic code, and so on. Nevertheless, we are aware of, first, the limitations and problems of the current understanding of these concepts in standard biological accounts; and, second, of their controversial nature, as the deep and intense discussion in philosophy of biology shows. Therefore, we think that our own approach both demands and supports a very specific conception of genetic information, naturalized and organizational, which we will expound in an additional complementary paper (forthcoming).

Glossary (of specific chemical terms)

Work (thermodynamic definition): any form of energy that, unlike heat, can be kept and used by a system without dispersion.

Exergonic process: A process defined by a decrease in the system's Gibbs free energy ($\Delta G < 0$, at constant pressure and temperature), so it is thermodynamically spontaneous. This involves the release of energy, originally in the form of work, to the surroundings.

Endergonic process: A process defined by an increase in the system's Gibbs free energy ($\Delta G > 0$, at constant pressure and temperature), so it is thermodynamically non-spontaneous. This involves the absorption of energy, in the form of work, from the surroundings.

Endergonic–exergonic coupling: the coming together (in time and space) of two processes, one endergonic and one exergonic, so that the former (non-spontaneous in normal circumstances) takes place at the expense of the latter. The release of energy associated to the exergonic process is, thus, constrained, so that it is absorbed by the endergonic one, leading to an overall production of work.

Supramolecular chemistry: term that refers to the area of chemistry which focuses on the non-covalent bonding interactions of molecules (hydrogen bonds, metal coordination, hydrophobic forces, van der Waals forces, pi–pi interactions, electrostatic effects to assemble molecules into multimolecular complexes,…).

Multimers/Oligomers: molecular chains that consist of a finite number of monomer units (a few—up to 10/more than a few—up to 100)

Polymers: molecular chains that consist of a large (unbounded) number of monomer units (more than 100)

Stereochemistry: a sub-discipline of chemistry that involves the study of the relative spatial arrangement of atoms within molecules, including the case of chiral molecules (particularly relevant in biochemistry).

Active site: small pocket on the surface of an enzyme where catalysis actually occurs. The structure and chemical properties of the active site allow the recognition and binding of the substrate(s).

Chemical affinity: tendency of an atom or compound to combine by chemical reaction with atoms or compounds of unlike composition.

Energetic degeneracy: situation in which the different arrangements of the parts within a system are equi-probable, due to the fact that their corresponding energy levels are the same.

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