Robots, cells and baroque music: Creativity as an emergent phenomenon

Andrea Roli[1,2]

[1] *Department of Computer Science and Engineering, Campus of Cesena, Università di Bologna*
[2] *European Centre for Living Technology, Venezia, Italy*

Abstract
At a first glance, it might seem unlikely to find any common properties in robots' behavior, cell dynamics and baroque music performance. Yet, from a systemic perspective they all share an essential and crucial emergent phenomenon: their dynamics is the result of the interaction between their structure and the environment. In this perspective paper, we discuss this property and build upon it to outline a guiding principle for artificial creativity.

Prelude

"[...] every behavior is emergent. You cannot program a behavior into the system. You need the physical body and the minute you have a physical body you have an interaction with the environment." (Rolf Pfeifer [1])

"The number of possible gene expression patterns is virtually unlimited. What is more, these patterns are determined at higher levels of the organism in the context of its interaction with the environment. [...] So, all essential characteristics of gene function except for the coding are *moulded by the outside world*." (Denis Noble [2])

"Musical notation is always under-determined; imprecise and incomplete in one way or another, concealing many well-understood elements that are in effect the performance practice of the period." (Bruce Haynes [3])

1. Introduction

The fundamental role of embodiment in cognition is currently acknowledged among cognitive scientists and AI scholars [4, 5]. A prominent example is behavior-based robotics [6], which makes the relation between the robot and its environment a pillar for robot programming. The central role of the environment for the resulting dynamics is also shared by biology, e.g. in the context of cell dynamics: the activation patterns of genes are crucially influenced by the environmental conditions in which the cell operates. In

CREAI2022: Workshop on Artificial Intelligence and Creativity
EMAIL: andrea.roli@unibo.it (A. Roli)
ORCID: 0000-0001-9891-5441 (A. Roli)

both the cases, robotics and biology, the same *controller* may produce different results as a function of the environment in which it is executed. With some caution, we can identify an analogous phenomenon in music performance. Baroque music is a representative case of this process: the music that is performed is the result of a score (the music that is notated on the paper) processed by the musicians according to some rules and conventions (defined by the performance practice). Such conventions constitute the specific environment in which the written music is executed.

In all the three cases mentioned above, the observed dynamics is the emergent result of the interactions between the system and its environment. Here we refer to the broad definition of *emergence* as a characteristic of a system whose behavior cannot be solely reduced to its properties: also its interaction with the environment (i.e. what is external to the system and interacts with it) must be taken into account for describing and possibly understanding its behavior [7, 8, 9].

Emergence has been widely advocated as an enabling condition for creativity, artificial or not. As for artificial creativity, a case in point is the use of evolutionary computation techniques for generative art [10] and for music composition [11]. The most frequent idea supporting those works is to evolve a description of the artifacts according to suitable genetic operators and fitness functions (either based on external evaluations by experts or automatic, or both). We believe that the mechanisms that favor emergent dynamics from the interplay between the system and its environment have not yet been fully explored. The aim of this perspective paper is to focus on the main elements of these mechanisms and outline their role in creativity as well as a possible use in artificial creativity. In section 2 we first depict the three cases in more detail. Abstracting from the examples discussed, in section 3 we delineate a principle that may guide the design of artificial creativity systems. Finally, in section 4 we discuss some implications of this view for creativity in general.

2. Three cases, one phenomenon

In this section we discuss the main features of three paradigmatic examples of emergent behavior. We first illustrate the case of embodied robots, followed by cell dynamics and we conclude with baroque music performance. The aim is to conduce the reader to appreciate the common core of these examples so as to identify a unifying abstract model that can be used also as a guiding principle for artificial creativity.

As the description of the following three examples is necessarily succinct and we only address and discuss the features relevant for the perspective we propose, the indulgent reader will forgive us for discarding other important elements of the systems we discuss.

2.1. Robot behavior

In a keynote speech titled "The Emergence of Cognition from the Interaction of Brain, Body, and Environment" [12], Rolf Pfeifer strikingly exemplifies the "spirit of embodiment" by illustrating several different behaviors exhibited by a simple robot just by changing its body and not its control program. The control program naively consists in setting the two motor wheels at a constant speed, while the effectors connected to the motors are changed, e.g. by using rubber feet or skates. In the same spirit, it is possible to achieve different behaviors by changing only the environmental niche of the robot [7]. For example, it is possible to change the gait by changing the characteristics of the terrain. In other words, the same dynamical core can produce different dynamics depending on its coupling with the environment.

We can state that the behavior of a robot emerges from the interaction among robot's control program, robot's body and the environment. In this context, emergence is not an all-or-nothing property, but it can be observed at varying degrees: from simple behaviors arising from the interaction between a simple pure reactive system and its environment [13] to the self-organized behavior of robot swarms.[1] Here we limit the discussion to the single-robot case, possibly characterized by non-trivial dynamical behavior [14]. The first consequence is that knowing the controller is just a portion of the information needed to predict the behavior, and this partial knowledge is in general not sufficient. The implication for neuroscience is huge: knowing a neural circuit does not mean to know the function that the organism performs when this circuit is activated. The second consequence has dramatic impact on AI: the design of robots with a given behavior must focus on the intertwined relations among the controller and the physical properties of the robot and of the environment. The discussion of the implication of embodiment for behavior and intelligence is out of the scope of this contribution. However, we would like to emphasize some elements that we believe are relevant for creativity.

For simplicity we consider only two entities: the controller and its physical embodiment, which includes both the body of the robot and the environment. The controller is an implementation in some formal language or mathematical notation of a structured set of instructions that maneuvers the actuators, which in turn act on the effectors of the robot.[2] The key point here is to observe that the environment, robot's body included, constrains the physical outcome of the instructions of the controller. Therefore, we have a source of indications (provided by the controller) that manifest themselves[3] by being filtered and transformed through (physical) constraints. The role of constraints in creativity will be discussed in section 4. Here we emphasize the fact that the role of physical constraints, rather than being a limiting factor, somehow enables the actions of the robot and drives them towards specific spaces of possibilities. For example, a rubber foot on a wooden surface enables a different space of possibilities than that of a plastic foot, which exerts negligible friction on the terrain. Therefore, a crucial role of the environment on robot's behavior is that of providing enabling constraints [16, 17].

So far we have considered a single direction in the causal chain observed in the system: the control program sends signals to the actuators, which maneuver the effectors that in turn act on the physical world. However, the effects of controller's actions mediated by the body of the robot and the environment have a feedback on the robot itself through

[1] The absence of emergence characterizes those cases in which the robot interacts with an almost completely deterministic environment and robots's behavior is fully and completely preprogrammed in the controller.

[2] Actuators are such things as motors, while effectors are the parts that directly interact with the environment [15].

[3] Greek philosophers would have used the verb $\varphi\alpha\acute{\iota}\nu o\mu\alpha\iota$, which is the root of the word *phenotype*.

the so-called *sensorimotor loop*: an action performed by the robot influences its next sensor readings, which in turn are used as inputs of the control program [18]. As a consequence, the physical effects caused by the actions of the controller through the active participation of the environment also affect the future actions of the controller itself, producing further (possibly temporary) constraints on its dynamics. The system is therefore characterized by intrinsic feedbacks and the causal chains in the system are bidirectional.

2.2. Cell dynamics

In the highly influential book titled "The music of life" [2], Denis Noble advocates a systemic view of cell dynamics, ultimately confuting genetic determinism. Without disregarding the importance of DNA, he convincingly contends that the genome is just one of the elements that produce the actual functioning of cells. The DNA is not the "program running the cell" but rather it is an organized repository where the machinery inside the cells can retrieve the information needed for their behavior in a given situation, and in a given environment [19]. The DNA is not just quite a CD that needs a whole external system to be played, but rather a repository that can be read in many different ways depending on the actual context. We outline here the main points of cell dynamics that are relevant for our perspective.

We first observe that the participation of a portion of DNA to the dynamics of the cell depends on the state of the cell itself and the current external stimuli. For example, we consider a gene as active if the information it provides is currently used for producing a protein. Notably, one gene can code for a set of different proteins, therefore taking part to different functions, and more genes can code for the same protein.

The activation of a gene also depends on the proteins that are present in the cell, which are in turn affected by the signals that the cell is receiving. Indulging to a computational metaphor—which must be used *cum grano salis*—we could say that the instructions contained in the genome are read, combined and executed depending on the current state of the system and the inputs it is receiving.

Rather than being the "program of life", which prescribes the overall dynamics of the system, the genome is a source of descriptions that are interpreted inside a larger context including the environment. In addition, a sequence of instructions can be read and executed in possibly infinite ways depending on the machine we choose to run it. As for recipes describing a procedure to cook a dish, so in cell dynamics there are some implicit rules that the genetic mechanisms exploit. Changing these rules means changing the resulting behavior.

Lastly, a remarkable property of cells is that the chain of causal actions starting from genes up to the whole organism is not simply unidirectional, but filled with feedback loops. Notably, the organism itself can constrain and condition gene expression. This is a wonderful example of *downward causation* [2], which we have already encountered in the case of robot behavior.

2.3. Baroque music performance

While an analogy between robot behavior and cell dynamics is probably not particularly surprising, pushing the analogy to baroque music performance might sound rather bizarre. Yet, this case completes the picture of our perspective and provides a bridge towards artificial creativity.

Baroque music is usually placed in a time frame spanning one century and a half, approximately from 1600 to 1750. As for all artistic epochs, chronological and geographic boundaries are blurred, nevertheless it is possible to identify some features of baroque music that represent hallmarks of this musical style. There are beautiful introductions to baroque music that we suggest for a musicological, aesthetic and cultural illustration of this music style [3, 20, 21, 22]. In this section we rather focus on systemic characteristics of baroque music performance.

As for many music styles, baroque music performance involves the interpretation of a score, which represents the music written in a conventional notation. Moreover, every execution is characterized by some emergent phenomena [23]. In the case of baroque music the relation between the score and the music executed is particularly important [24] and it is in fact the trigger for the main emergent behavior we can observe in this music.

A distinguishing trait of baroque music is *basso continuo*, often simply named *continuo*.[4] The *continuo* part is mainly played by instruments such as organ, harpsichord, harp, lute, and theorbo and has the role of *leading and sustaining* [25] the upper parts.[5] In a nutshell, basso continuo consists in an extemporaneous completion of a melodic bass line with chords, arpeggios, counterpoint improvisations and other ornaments.[6] Here the main element of our analogy comes into play: these improvisations on a *ground bass* are not free, but they have to be performed according to rules, conventions and preferences of the period. These conventions were both explicit, e.g. detailed in printed books or manuscripts, and implicit, e.g. transmitted from teacher to student by imitation. The same also holds for higher voices, such as the violin: the part written in the score is just a skeleton of the music to be played.

Contemporary performers of baroque music call *historically informed performance practice* a philological approach to early music, which includes the interpretation of the score through the conventions that are supposed to be used in that time [3]. For example, in the case of instruments playing the leading higher voices, the indications provided in the score have to be elaborated, enriched and interpreted by means of *ornaments*—such as trills—and *diminutions* [26], which consist in elaborations of a given sequence of notes, often by adding more notes to the ones that are notated (whence the term *diminution*, which denotes the fact that a given note is substituted by some notes with shorter duration). Diminutions and ornaments should adhere to the musical and

[4] Alternative and interchangeable expressions are *figured bass* and *thorough bass*.

[5] As Agazzari clearly states in 1607 [25]: "[...] sono quei che guidano e sostengono tutto il corpo delle voci".

[6] In modern terms it is sometimes simplistically said that basso continuo provides the harmony of the piece of music. Even though this statement is not totally incorrect, it is a rude oversimplification and it might misleadingly induce one to apply categories of modern harmony to baroque music, which is a severe mistake.

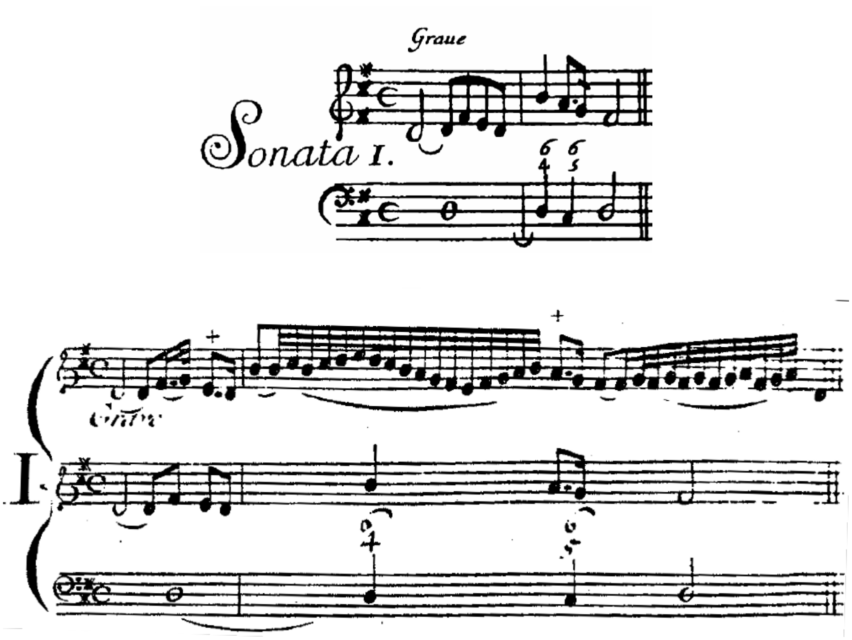

Figure 1: Upper score: Incipit of Sonata no. 1 from Op. 5 by Arcangelo Corelli, as it appears in the first edition (Gasparo Pietra Santa, Rome, 1700). **Lower score:** Same incipit, as it appears in the third edition (Estienne Roger, Amsterdam, ca.1723) with diminutions approved by Corelli himself.

aesthetic conventions of the period, which to some extent constrain and guide performer's execution. A prominent example comes from Arcangelo Corelli's sonatas, which have been published in several editions. In one of them, the original compositions notated by Corelli have been complemented by a part containing diminutions approved by Corelli himself. The comparison of an excerpt from Sonata no. 1 Op. 5 is shown in figure 1.

The discussion of this example is out of the scope of this paper, but it is important to remark that the original part establishes a structure around which diminutions are played (e.g. a long note is substituted by several shorter notes). The notation is descriptive and not prescriptive [3]. The incompleteness originated from the indications provided by the notation together with the musical convention of the period opens the possibility for the arising of a kind of constrained creativity [27].

The analogy with robot behavior and cell dynamics is clear: a sequence of instructions (the score) is "run" by a machine that implements specific rules. If the rules change, also the final outcome of the execution does. It is not possible to predict the overall emerging behavior just by knowing the sequence of instructions. As for robots and cells, the music performed is brought to life by constraints and preferences that constitute its environment. Therefore, these constraints enable the music to exist. Furthermore, as an improvisation attitude is fundamental to baroque music performance, these constraints are also a trigger to create new impromptu executions. Finally, we observe that also in music performance we observe downward causation phenomena: once a choice is made

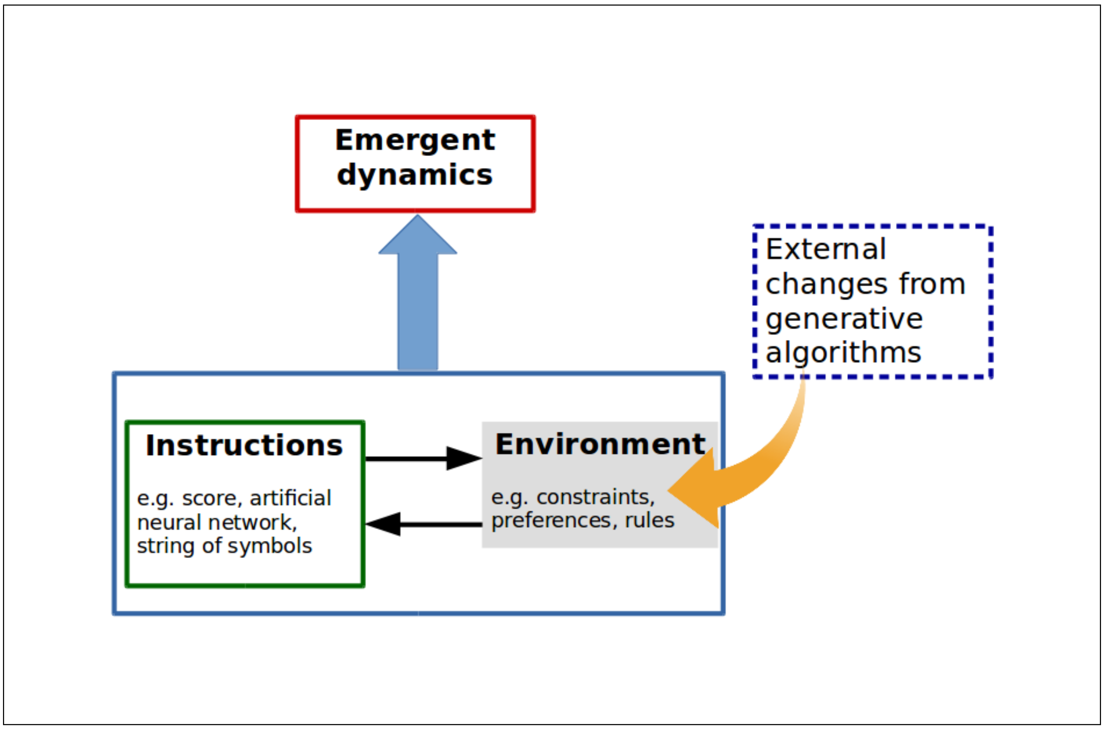

Figure 2: Schema of a generative system inspired by the emergent dynamics between a system of instructions and the environment. The external action on the "environment" component is depicted in figure.

according to the constraints, e.g. a specific chord in basso continuo, the current status influences back further choices.

3. Implications for artificial creativity

A systemic view of the mechanisms we have exemplified in the previous section is illustrated in figure 2. The system has two basic components: a sequence of instructions and the environment. The interplay between the two gives origin to the dynamics of the system. The dynamics is also the result of feedback loops and downward causation links (represented by the two arrows between the two components).

Changes in just one of these components impact the whole emergent dynamics. Artificial creativity approaches usually do not adopt this "dual system" perspective and focus only on the artifacts, keeping the environment implicit in the interpretation of the descriptions of the artifacts, if not completely neglecting its role. We are not claiming that the approach we illustrate is brand new, as there are applications in computational creativity with similarities with the perspective we propose. For example, in artificial music composition, a Markov model of the music is built from a given repertoire and new pieces of music are generated by adding some constraints deriving from the original or a different repertoire [28, 29]. In this way, the descriptive part can be kept constant—i.e. the Markov model—while the creative impulse is given by the constraints. However, to the best of our knowledge, there are no works that explicitly adopt the view we discuss and focus on the automated elaboration of the constraints in the environment.

The essence of the computational mechanism we propose to investigate consists in providing a formal, somewhat incomplete, artifact description that is kept constant; this description is interpreted (in a sense, completed) by and “environment” that provides the rules for the actualization of the formal description. This environment is formalized as well and subject to changes operated by an algorithm, such as a genetic algorithm. The scheme of figure 2 is potentially subject to infinite implementations. Here we outline two possible instantiations that come from our current ongoing work, in two representative fields, namely music and robotics.

One of the most fascinating areas for artificial creativity is the production of an artifact belonging to one artistic field from an artifact belonging to another one. For example, the generation of a picture starting from a text [30]. Similarly, we can produce music from text. In previous unpublished work, we developed a system that takes a text as input, e.g. a poem, and produces a polyphonic music in form of a canon. In this case, the environment is composed of the algorithmic choices that translate the text into music. The environment is a *code*—in semiotic terms—that makes it possible to generate the musical artifact from the text. Instead of being defined by hand by the designer, this code can be parametrized and produced algorithmically by means of an optimization method—or any suitable search technique. Relevant parameters can be the number of voices, the starting measure for each voice, the relation between the symbol in the text (e.g. a letter or a word) and pitch and duration of notes. The algorithm iteratively defines this code and produces the music; the iterative changes in the code can be driven by human evaluation of the music produced or a combination of objective functions (e.g. musical properties such as distribution of intervals and generic functions based on information theory measures). In this way, the description provided by the text is translated into a piece of music according to rules that are subject to changes.

As a second example we mention a recent work in robotics showing that the same controller can be dynamically adapted to accomplish different tasks just by adjusting its connection points with the environment [31]. Here, being creative means being able to adapt and solve a problem. In this work, robots are controlled by Boolean networks [8] and can move and make other actions such as gripping and depositing objects. Each robot is equipped with a Boolean network (BN), which is connected to robot’s sensors and actuators. These connections are not hardwired by can change during the activity of the robot. On the contrary, the BN does not change. The variations on the connections are random, but only the ones that enable the robot to increase its utility are retained. In this way, the internal instructions describing the whole dynamics of the network are kept unchanged, while the environment perceived does change during the adaptation process. The results have shown that different final dynamics (i.e. behaviors) attaining high performance can be produced starting from the same controller. In other words, by changing the environment perceived by the robot it is possible to generate “creative” behaviors that accomplish a given task.

4. Discussion

The analogy we have illustrated in the previous sections is instrumental for outlining the core elements of a general mechanism, whose potential we believe has not yet being fully explored; we hope that this perspective paper can promote explorations in this direction. Besides the implications for artificial creativity, the focus on emerging dynamics from the interplay between a descriptive system and its environment (including constraints and preferences) inevitably evokes some remarks on creativity in general.

The role of constraints in creativity is overwhelming. We have previously emphasized the property of constraints to be "enabler": rather than being a limiting factor, a constraint triggers innovative solutions and, above all, canalizes the creative effort. Uncountable are the examples in the art, from metric in poetry to tools used in painting. This property finds a beautiful example in evolution: when a new species or a variation of an organism appears, it perturbs the environment and introduces new opportunities (more precisely, *affordances*) for the other life forms. Once a new opportunity is exploited, a new constraint is created that is in fact an opportunity for new actions and new evolutionary steps [17]. Evolution is then wonderfully moved by the interplay between constraints and affordances, intertwined in an irreducible unit. This cyclic dynamics between affordances and constraints is the nourishing and sustaining essence of improvisation, e.g. in music and theater. The note played by a musician (or the action performed by an actor) poses a constraint on future choices by the other performers; but this constraint is in fact an affordance and it canalizes the creative intentions of the other performers towards specific spaces of possibilities. These spaces that can be explored constitute the *adjacent possible* [16, 32] of the current state of the artistic performance.

The relation between human and artificial creativity deserves a final remark. The recent impressive results of AI systems in generating artworks, such as paintings [33] and music [34], might induce us to think that natural and machine creativity are substantially the same and explore the same spaces of possibilities. It is true that we are often surprised by artworks produced by algorithms, but this does not mean that the two forms of creativity are equal. They might be indistinguishable in practice by an observer, but there is a crucial distinction that has to be remarked: the space of possibilities in artificial creativity is always bound by some choices made by the designer and, furthermore, it relies on machine capability of identifying affordances, which is believed to be rather limited compared to human one [35, 36].

Coda

"–You adjusted him?– she shrieked. –But it was he who created my light-sculptures. It was the maladjustment, the maladjustment, which you can never restore, that-that..." (Isaac Asimov [37]).

"But what evolves cannot be said ahead of time: what evolves emerges *unprestatably*—I know of no better word—and builds our biosphere of increasing complexity." (Stuart Kauffman [17])

"Insipid is playing [theorbo] without trills and accents [i.e. ornaments, TN], except for the occasions in which the execution speed does not allow it."[7] (Girolamo Kapsberger [38])

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