Artificial Life and Historical Processes

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Abstract. Artificial Life is partly aimed at understanding the organisation and complexity of living processes. In this paper the concept of a historical process is discussed with the aim of providing a framework with which to approach diverse phenomena in organismic, ecological, and evolutionary contexts. A historical process is such, not because it is subject to contingencies, nor because it may be explained in historical terms, but because it presents a special relation between its dynamics and changes in its own conditions of realisation. Such processes may lead to durable spontaneous patterns and novelty. It is argued that such patterns can provide powerful explanatory tools and that Artificial Life simulation techniques are well fitted for their exploration.

1 Introduction

To different degrees of explicitness, the central theme of much of the work that currently goes under the rubric of Artificial Life (AL) is the understanding of processes that lead to innovations, transitions, and spontaneous organisations which are difficult to explore using more traditional modelling tools, and which are often associated with biological phenomena. The use in this literature of much worn terms such as 'emergence', 'self-organisation', and 'complexity' bears witness to this aim. And, indeed, evidence supporting the case that AL modelling tools are capable of shedding new light on problems involving the synergies between processes situated at different timescales or 'levels', such as the ecological and evolutionary [1], the behavioural and the social [2], the behavioural and the ecological [3], and others, has not been lacking.

What has been less conspicuous, however, is an attempt to describe such phenomena in a systematic form, equally valid for the different problems areas. Not that similar attempts do not exist, (e.g., [4]). It may be questioned whether this is an useful enterprise. What common theme can be fruitfully sought in the spontaneous formation of social hierarchies, autocatalytic organisations, and wasps' nests? Here, instead of a full justification, we will offer a programmatic bet: Systematization is a key element in the scientific toolkit; it leads to shared knowledge between subdisciplines, to the identification of analogous problem areas and search for analogous solutions – these reasons ought to make the attempt worthwhile, although full systematization might be ultimately an utopia.

This article attempts to describe a central theme of AL research which is a mode of explaining the phenomena of interest that appeals to certain properties

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of the dynamics of the processes involved, namely that these are *historical processes*. The precise meaning of this term will be explored and illustrated by the use of some examples. To this aim, the idea of what constitutes a *constraint* to a process will be examined, as well as how it relates to the dynamics of the process both in operational and explanatory terms. This will permit a specialization of the word 'historical' to processes that are able to introduce some temporal heterogeneity due to the interplay of variations at different timescales. As a corollary, it will be found that any process leading to innovations or transitions (which generate much interest within AL) is, by definition, historical.

Some of the concepts presented here are related to the ideas of scientists who have been influenced by A. N. Whitehead's metaphysics, [4,5,6]. However, the purpose of the article is to make a basic presentation of some central concepts in order to facilitate their subsequent use and not to provide a review and comparative exposition of the philosophical and scientific extent of these ideas.

2 From Homogeneous Time to Historical Time

There are different senses in which the word 'historical' may be applied to a process. For instance, a process may be so called if its unfolding involves a set of contingencies that cannot be predicted until the moment they occur. Such factors could take the form of discrete events (e.g., founder effects or catastrophes in biological evolution) or they could operate with constancy, in which case their effects may become manifested over long periods of time (e.g., random fixation of alleles due to genetic drift).

Another related criterion would consider adequate to apply the name 'historical' to a process if an explanation of how its current state has been attained would be best given in historical terms. Such explanations (see [7, pp. 25 – 26] and [8, pp. 283 – 284]) would account for a state or event in a process in terms of previous *key* states or events. A chain of these events would be understandable if it is possible to understand the connection between one link and the next.

The word 'historical', in the current context, is not intended strictly in any of the above senses. Rather, a historical process would lie roughly at the intersection between the cases just mentioned (i.e., contingent or noisy processes and processes explainable in historical terms) and the set of processes which are sometimes characterized as *self-organising*. Such historical processes are indeed contingent and probably many of them afford historical explanations. However, the key feature to be highlighted is their capability to influence their own constraints and thus to introduce an interplay between dynamics at different timescales which may result in open temporal inhomogeneities. In order to understand this capability the concept of constraint needs to be expanded.

2.1 Constraints

All observable events and processes are underdetermined by the fixed universal laws that are presumably at play in them. The trivial reason for this is that such laws can only be universal because they are disembodied and refer to no concrete system in particular. In order to apply them to the understanding of a specific process a description must be provided of how these laws are constrained by the actual structures and conditions that make up that process.

There are two senses for the word 'constraint'. Consider a physical pendulum. A finite mass is hanged from the ceiling by a piece of string. A description of this system could be offered that would permit the application of universal dynamical laws. Thus, a series of idealisations would allow a description in terms of a zero-dimensional particle hanged from a fixed point by an inelastic string under the exclusive influence of gravity, and so forth. In mechanical terms a constraint describes those relations that place direct limitations to the variation of the variables with which the system is described, (see [9]). For the pendulum, such a constraint is found in the position of the particle which must, at all times, conserve its distance to the point in the ceiling from which it hangs.

In a second, more general sense, a constraint indicates not just these relations but also the set of parameters and other relations that make it possible to embody a universal law into a description of an actual system. If the system remains ideally isolated and such contextual factors remain fixed, it seems that calling these factors 'constraints' would be unnecessary. However, the meaning of the word is recovered when one considers that the system may participate in time-dependent coupling with other systems which, through their effect in such contextual factors, may influence the system's behaviour. Thus, the ceiling may vibrate and the length or the elasticity of the string may change with time – changes that would necessitate a redescription of the system.

It is clear though, that any addition of new boundary conditions or any re-description will end up with a new fixedly defined system and a known relation to its environment. Such a tendency for re-describing actual systems is obviously limited since future changes in the contextual (and internal) conditions need not be predictable either because of random factors or because of unexpected effects of the dynamics on the conditions which granted validity to the initial idealisations. In view of this, it makes sense to associate all these contextual factors and a description of the internal structures of the systems involved in a process under the single name of 'constraint'. In this more general sense, a constraint indicates any factor which may exert some influence on the evolution of a process as described by some generalised dynamical principle.

This usage is a generalization of the meaning favoured by S. J. Gould for the case of evolution. According to him, a constraint is "theory-bound term for causes of change and evolutionary direction by principles and forces outside an explanatory orthodoxy", [10, p. 519]. Thus, any source of change apart from the general explanatory framework for the type of process in question would qualify as a constraint. Readers familiar with the work of H. H. Pattee will also have noticed certain similarity between his idea of constraint as an alternative description of a process and the concept as presented here, (see for instance [11]).

The term thus loses the negative connotation of the more formal notion of constraint as limitation and acquires a more encompassing meaning which may include the senses of direction or canalisation, (see also [10], p. 518). The word will be used in this general sense in what follows.

2.2 The Identity of a Process

Although, as seen above, constraints are not necessarily fixed, one could tentatively distinguish their variations from the actual process by one of the following criteria: a) these variations are independent of the operation of the system or b), if they vary dependently, they do so at a much slower timescale so that, at the scale in which the changes of state of the system occur, constraints may effectively be considered fixed. It can easily be seen that these criteria are qualitative rather than strict. In the first case, influence on the constraints to a process may be exerted through coupling with other processes which operate independently. But such coupling may also reflect how those contextual processes were in turn *previously* influenced by the central process in question – a process may so influence its own constraints indirectly. In the second case, when variations in the constraints depend directly on the dynamics of the process, one could question what is exactly meant by a much slower timescale and why are not such changes included as part of the original process itself.

It is necessary to have a more strict criterion. This issue is a manifestation of a bigger problem. If the dynamics of a process may alter the constraints that define the process, is it not possible that things could change so much that the systems involved would effectively become different systems? In such a case, with what right can one speak of a unique and well-defined process? A fixed set of constraints used to do the job of assuring that the systems remained the same from one moment to the next; in consequence it was possible to speak of a process with a single identity. Such rigidity, however, entailed that no process involving some sort of innovation could be so described. But if the constraints can also change there must be something else that one can point to in order to be able to say that one is referring to a same process. There must be an *organisational invariant* of the process which maintains certain relations fixed.

A process can be *defined* as the dynamics of a set of systems whose actual structures, rules or laws of operation as well as their relationships conserve some global organisational feature unchanged. In the example of the pendulum, one could include the applicability of Newton's second law, the relative positions between hanging mass, string, and ceiling, the very existence of these components, and so on. If the string is chemically unstable it will break at a certain point. When this happens, the process, *as defined by the above invariants*, has ceased. There is clearly certain freedom of choice on the part of the observer regarding what is to be called a process. That freedom is in the distinction of the relevant invariants. Thus, if the only invariant in the case of the pendulum is the mass that hangs and the process is the variation in position of this mass, then it does not matter if the string breaks in two, this is just a change of constraints, the process goes on with the free fall dynamics, the bouncing on the floor, etc. *This* particular process would cease only if the mass disintegrates.

These comments apply to processes in general, but they hold a special significance for historical processes, as these are the only processes in which, besides the basic invariants distinguished by the observer, the interplay between process and constraints may lead to the *spontaneous* formation of *new* invariants.

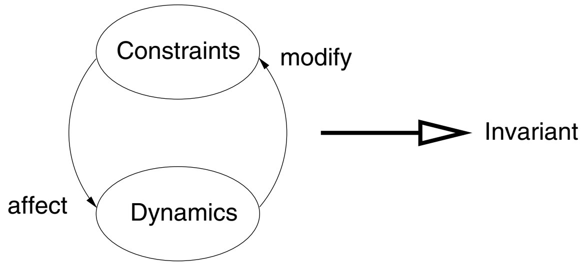

Fig. 1. Circular 'causation' defining a general historical process.

Such spontaneous, durable patterns are constituted by an interplay between the dynamics and the constraints to the process. Due to the amplification of the effects of fluctuations and the breaking of in-built symmetries, complex processes in which many variables interact non-linearly may exhibit transitions to highly ordered dynamics. Such transitions are manifested in a coherent regime which is not pre-specified in the initial definition of the process nor externally imposed. Such processes are often called self-organising[1], [4].

Spontaneous invariants, when they occur and while they last, can be thought of as 'equilibrium' stages in the reciprocal 'causation' showed in Fig. 1. When the accumulated influence of the process on the variation of their own constraints results in little or no extra effect back on its dynamics, constraints will cease to change and the situation will be maintained. This state of order is manifested in the form of durable patterns in the dynamics and its constraints. With a shift of viewpoint these patterns can be seen as affecting the process in ways that tend to their own perpetuation. From this perspective, it is possible to say that a invariant, once established, may be used to 'explain itself'. In addition, these organisational features may also exert an influence over other aspects of the process which need not be directly involved in the conservation of the invariant.

3 Different Manifestations of History

The above considerations give a rough idea of how to differentiate historical processes from processes which are non-historical or merely contingent. A historical process is a process subject to fluctuations whose dynamics affects its constraints either directly or though recurrent coupling with other processes. In order to make the meaning of these concepts clearer it will be helpful to consider some examples of historical processes. Many processes that would qualify as paramount examples, such as stigmergy, cognitive development, cultural change

[1] Historical processes include such instances of self-organisation as a possibility, but describe a wider class. Self-organisation can be a problematic concept (see [12]); especially when dealing with entities that are formed or destroyed in the process. The question of what is the *self* that organises can be better approached from the historical point of view than from the self-organising perspective which would require the identity of a newly formed 'self' to preexist its own formation.

and social norms, structural epigenesis, the economics of increasing returns, etc. will not be discussed due to lack of space.

3.1 Trails on Grass and Pask's Artificial Ear

Consider the trails made naturally by pedestrians on areas that are covered with grass. These trails are made by the action of walking which makes it difficult for grass to grow on zones which are frequently trodden upon. The lack of grass makes walking along the trail easier and people tend to use the trail rather than cutting across the grass, even if this implies a small deviation from the optimal route to their destination. Trail formation has been studied using a very simple and powerful individual-based model, [13]. The process is self-reinforcing and, in the bigger picture, it is also a historical process.

Let the process be the set of individual pedestrian trajectories within a piece of land covered with grass (say a square) with a few preferred entry and exit points. Walkers are driven by two preferences: they want to arrive at their destination cutting across the square and they prefer to walk where the grass is less grown. Initially, no path is marked on the grass and walkers choose a direct route to their destinations. As time passes, and for a certain frequencies of crossings, the effect of the initial trajectories will begin to be manifested in areas where the grass is worn. In the most used trajectories the effect of wear will be so much that the grass will not be able to compensate by growing again before the path is re-used. Thus, trails are formed and maintained in a dynamical equilibrium. The process can be quite complex since the different trails may 'interact' during the process. For instance, it will be common to observe a single exit point halfway between two frequently used and relatively close destinations instead of two exit points corresponding to each one of them, which means that two trails may have converged.

Once a pattern of trails is formed the history of the process has become partially embodied in it and walkers are constrained by its shape to walk along the trails. Thus, the pattern modulates the dynamics of the process but, at the same time, is constantly being constituted by the process as trails can only be maintained if enough people use them.

A similar process was used by cybernetician Gordon Pask for the construction of artificial sensors and effectors out of an initially undifferentiated physical medium, [14]. The system consisted of a network of amplifiers and associated electrodes which were not directly connected but submerged close to one another in a solution of ferrous sulfate. The electrodes acted as sources or sinks of direct electrical current depending of the activity of the system. Crucially, if direct current is passed from a source to a sink, a metallic thread of very low resistance is formed in the ferrous solution which, as the trails on grass, will be much easier to use if current is to pass again between the same electrodes. In contrast, if the thread is not re-used, it will gradually dissolve because of local acidity. After some time, a network of threads may be formed and maintained dynamically.

The system could be 'trained' to respond to different sorts of couplings. The method of training consisted simply in increasing the available energy for forming

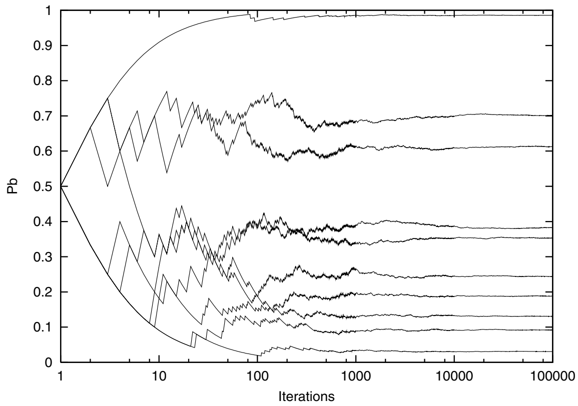

Fig. 2. Illustration of Polya's urn. Probability of drawing a black ball (Pb) vs. number of iterations for 10 different runs.

and reinforcing threads if the system's performance was close to the desired one. Such a scheme translated into a growth and pruning dynamics at the level of the network of threads. Interestingly, being a physical system, there were many ways in which the process of thread formation could be affected: mechanical, thermal, chemical, and electrical. Pask was successful in training the system to respond to acoustic vibrations of a specific frequency. The system responded by growing a network of threads around the vibrating regions of the apparatus.

3.2 Polya's Urn Scheme

Consider the following stochastic process known as Polya's urn scheme [15]. Put two balls in an urn, one red and the other one black. Extract one of the balls, observe its colour and then replace it and put another ball of the same colour into the urn. Repeat indefinitely. What is the expected probability for extracting a black ball after a large number of iterations?

This process was originally proposed as a model of epidemics and it has been applied to models of market dominance [16]. Interestingly, in can be shown that the probability of extracting a black ball will converge to a specific value which can be *any* number between 0 and 1. Figure 2 illustrates this convergence for 10 different instantiations.

The process may be understood as historical if its dynamics are taken to be the extraction, observation and double replacement of balls in a repeated manner. At any moment, the probability of extracting a black ball depends on the number and colour of the balls present in the urn. This is taken as the context or constraint of the dynamics. Such context is itself affected by the same process that it constrains. After many iterations, this interplay between dynamics and constraints reaches an equilibrium. This is because the addition of a new ball, whatever its colour, will not affect significantly the existing distribution within the urn and the accumulated set of added balls will tend to reflect this distribution over a number of iterations. The actual equilibrium, however, is strongly dependent upon the history of the process. In particular, much weight is given to the initial steps; figure 2 shows how the variations can be extreme during the initial 10 iterations, then more moderate in the next 100 iterations and from then on less and less significant. This example shows that historical dynamics may be instantiated in processes which are relatively simple.

3.3 Evolution

Evolutionary processes are historical *par excellence*. Their historical character is rarely denied, although there is a tendency to think of evolution as historical only in the sense of being a process subject to contingencies. These may take the form of 'frozen accidents' or they may indeed be the result of the accumulation of small events, as mentioned earlier.

Until recently, the neo-Darwinian perspective has tended to confine the role of historical factors to that of contextual or initial conditions in a process subject to an 'universal law' of fitness maximization. The process in itself has not often been considered historical in the sense given here to that term. Through a process resembling trial-and-error, random changes in the material inherited by an organism will affect differentially the match between organismic and environmental properties so that some variants will be selected as better adapted to the environment than others. It is the assumption that evolution proceeds mainly in this problem-solving fashion that allows (even requires) the historical nature of evolution to be relegated to that of independent contextual factors. In effect, evolution becomes a process of optimising the adaptation to a pre-existing environment which does not depend significantly of the evolving organisms.

The problem with this view, as pointed out on many occasions [17,18, among others], is that the key environmental features that are significant for the reproductive success of an organism are not independent of the organism itself. According to Lewontin, the "world external to a given organism can be partitioned into *a priori* ecological niches in a non-denumerable infinity of ways. Yet only some niches are occupied by the organisms. How can we know, in the absence of the organisms that already occupy them, which of the partitions of the world are niches?", [17, pp. 159 - 160].

In addition to 'choosing', rather than just adapting to, their own niches, organisms also alter their medium, and that of other organisms, in significant ways, [17,18,19]. Birds and social insects build nests and other structures, rabbits and rats dig tunnels, beavers create ponds and alter local water levels, leaves accumulate under high plants, etc. These alterations may have both short and long term effects.

In spite of the mutual inter-dependence between organism and environment, evolution has been approximated as non-historical by sweeping all contingent factors under the carpet of independent environmental variation. This variation is external, i.e., not part of the process itself; this is characteristic of non-historical processes. It is, therefore, not surprising that the problems related to novelty in biological evolution cannot be so easily accounted for from this perspective, [20, 21], since such innovation can only take place in historical processes.

4 Open Issues and Some Consequences for AL

This fairly broad exposition of historical processes, in no way comprehensive, may be enough to suggest that there is some gain in giving expression to the unifying themes implied by grouping together phenomena as diverse as the construction of wasps' nests, the development of a cognitive skill, the maintenance of a social norm, or the evolutionary conservation of a body plan. The main practical consequence of this perspective is a shift in how these phenomena are studied. History implies a subtle dynamical interplay between change and conservation. It cannot be modelled, like the above phenomena have often been modelled, as changes in the external relations between fixed entities themselves not subject to change.

Historical entities are not fixed in the sense that all changes are subordinated to their fixed identity (a point of view giving rise to extreme structuralist thinking), nor are they fully malleable, yielding without inertia to the optimisation of some objective function (a point of view that leads to some forms of functionalism). The historical perspective steers a careful middle course between these extremes by focusing on understanding why certain patterns are *durable* (as opposed to either fixed or unstable) as a consequence of, and not despite, the constant variations that make up the dynamics of the process.

An important notion in this context is that of spontaneous invariants. Once a durable pattern is constituted, understanding the dynamical relations that allow it to persist can provide a powerful frame of reference for addressing specific questions of what goes on in a complex historical process. It allows the researcher to understand why certain things can change while others remain the same. In other words it can provide a *norm* intrinsic to the process. Contained within a spontaneous invariant lies an explanation of its own perpetuation. Even if the properties of the process in need of explanation are not directly related with its maintenance, the invariant sets conditions to how these properties can change usually by limiting a high dimensional space of possibilities into a few ordered modes.

Saying that novelty and qualitative transitions can only occur in historical processes is not the same as having explained how such phenomena happen. This is indeed one of the major areas for development. What causes the disappearance or transformation of an existing durable structure? Does novelty occur when invariants cannot self-maintain any longer? Or does it occur in historical processes that do not lead to new invariants in the first place? These are important open questions that deserve further development, and in which AL simulation models may play an important role. Such models can indeed show more flexibility than strictly analytical models, although their use as scientific tools also brings a whole new set of problems [22]. For the moment, the historical perspective can offer only a negative take on the issue of novelty. If the process cannot be said to be historical, then it is pointless to look for the conditions that will lead to novelty.

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