

Evolutionary Innovation Viewed as Novel Physical Phenomena and Hierarchical Systems Building

Tim Taylor^{1,2}

¹Independent Researcher

²Department of Data Science and AI, Monash University

tim@tim-taylor.com

Introduction

In previous work I proposed a framework for thinking about open-ended evolution (Taylor, 2019). The framework characterised the basic processes required for Darwinian evolution as: (1) the generation of a phenotype from a genetic description; (2) the evaluation of that phenotype; and (3) the reproduction with variation of successful genotypes/phenotypes. My treatment emphasized the potential influence of the biotic and abiotic environment, and of the laws of physics/chemistry, on each of these processes. I demonstrated the conditions under which these processes can allow for ongoing exploration of a space of possible phenotypes (which I labelled *exploratory open-endedness*). However, these processes by themselves cannot *expand the space of possible phenotypes* and therefore cannot account for the more interesting and unexpected kinds of evolutionary innovation (such as those I labelled *expansive* and *transformational open-endedness*¹).

In the previous work I looked at ways in which *expansive* and *transformational* innovations could arise. I proposed transdomain bridges and non-additive compositional systems as two mechanisms by which these kinds of innovations could arise. In the current paper I wish to generalise and expand upon these two concepts. I do this by adopting the Parameter Space–Organisation Space–Action Space (POA) perspective, as suggested at the end of (Taylor, 2019), and proposing that all evolutionary innovations can be viewed as either capturing some novel physical phenomena that had previously been unused, or as the creation of new persistent systems within the environment.

Parameter Space, Organisation Space and Action Space

In any system (real or virtual) governed by global laws of physics, dynamics come about through the action of these laws upon the matter (objects) within the system. If the behaviour of the system is determined solely by the initial conditions of the system and by the global laws of physics that

act upon it, there appears to be little room for *agency*, i.e. for organisms within the system that appear to follow their own rules of behaviour. However, the behaviour in any given subregion of space at any given time is affected by local constraints.² At the most fundamental level, the way in which living organisms “break away” from these global laws of physics and seemingly follow their own rules of behaviour is by creating local constraints on dynamics from information stored in their genomes (Pattee, 1972).³ This genetic information accumulates over evolutionary time through the action of natural selection upon organisms.

Understanding how novel organismic behaviours might arise in an evolutionary system first requires an appropriate conception of what a behaviour is. In the context just described, we can say that an organism’s behaviour in a (real or virtual) physical system comprises three core aspects: (1) *information* stored in a persistent memory that can generate⁴ (2) specific *configurations of matter* (constraints) that (3) are acted upon by the global *laws of physics* to produce specific actions. Accordingly, behaviour can be viewed as comprising components in three distinct but interacting spaces, which I call *Parameter Space*, *Organisation Space*, and *Action Space*, respectively (see Figure 1). I refer to this as the *POA* perspective.

These concepts can be applied not just to real and virtual

²Montévil and Mossio (2015) define constraints as “contingent causes, exerted by specific structures or dynamics, which reduce the degrees of freedom of the system in which they act.” Some authors in this area tend to use the term *boundary condition* rather than constraint, e.g. (Kauffman, 2020), and others use both terms, e.g. (Pattee, 2015). Here I use the term *constraint* in a general way that also encompasses the concept of boundary conditions.

³At a higher level, some living systems also store information in cognitive memories or in cultural or environmental memories too. In this paper I restrict my attention to information stored in the genome.

⁴At the most basic level, sections of the memory act directly as constraints upon the local dynamics. In more highly evolved systems such as modern biological organisms, there might be a complex hierarchical system acting as an interpreter of the information stored in the memory. These more complex cases are discussed later in this paper.

¹See (Taylor, 2019) for a full description of these three kinds of innovations and the differences between them.

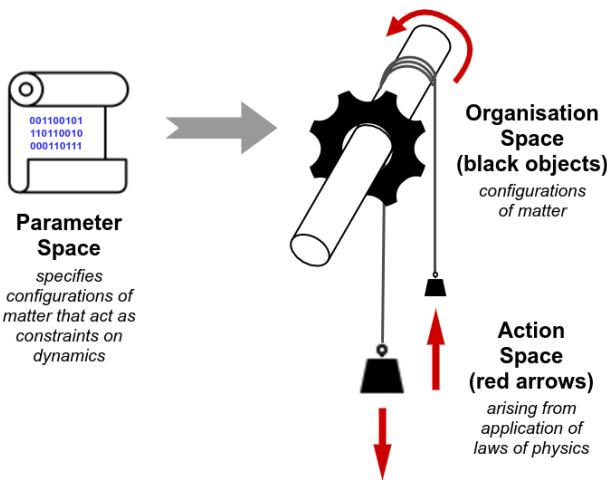


Figure 1: Parameter Space, Organisation Space and Action Space. In this mechanical example, the information in parameter space specifies a material configuration of weights, rope, an axle and a cogwheel. This configuration constrains the system's dynamics arising from the application of the laws of physics to produce the rotation of the cogwheel.

physical systems, but (at least partially) to more abstract artificial worlds too. For example, a program in *Tierra* (Ray, 1991) comprises a linear list of symbols—it is an object in Organisation Space. The program produces a behaviour in Action Space when acted upon by the CPU. In this simple 1-dimensional world, there is a 1-to-1 mapping between Parameter Space and Organisation Space, although modifications of *Tierra* have been developed in which that is not the case, e.g. (Baugh and McMullin, 2013).

If we adopt this perspective, where the information contained in an organism's genome is “merely” constraining and sculpting dynamics caused by the application of global laws of physics, what opportunities exist for the emergence of evolutionary innovations? This question will be addressed in the following sections.

Evolutionary Innovations via Novel Physical Phenomena

In the kind of system described above, an evolutionary innovation can arise if an organism generates constraints that trigger a physical phenomenon that was not previously utilised.

A classic example is a wing (an object in Organisation Space, specified by the organism's genetic information in Parameter Space). When acted upon by the physical laws of aerodynamics, the wing produces uplift and enables flight (in Action Space).

Another classic example is a photosensitive pigment such a rhodopsin (an object in Organisation Space, specified by

the organism's genetic information in Parameter Space) that, following the laws of molecular physics, changes its shape when it absorbs a photon (in Action Space). In so doing, it can act as the basis for photosensitivity and vision.

These kinds of evolutionary innovations, based upon capturing new physical phenomena, are generally absent from computational evolutionary systems.⁵ This is because objects in computational systems usually only have a single domain of interaction (i.e. only one class of laws of physics apply to them). Objects in the real physical world, on the other hand, possess multiple properties across various domains of interaction (mechanical, electrical, chemical, etc.) and can thereby act as *transdomain bridges* (Taylor, 2019)—that is the reason why they can represent exaptations for innovations in different domains.

It is noteworthy that we *do* see these kinds of innovations in artificial evolutionary systems that are embedded in the real world rather than being purely virtual systems. Examples include Pask's evolved “ear” (Cariani, 1993) and Bird and Layzell (2002)'s evolved radio receiver. In these cases the system's components, being physical objects, *do* have properties in multiple domains of interaction and therefore *can* act as transdomain bridges.

Evolutionary Innovations via (Hierarchical) Systems Building

Even without the discovery of new physical phenomena, an evolutionary system can produce innovations by combining existing components in novel ways. The threefold view of innovations adopted in (Taylor, 2019) was based upon Banzhaf et al. (2016)'s proposal. That proposal took a systems view of evolutionary novelties. However, even though the authors defined an innovation as “a change that adds a new type or relationship” (Banzhaf et al., 2016, p.142) (emphasis added), their discussion tended to focus specifically upon the introduction of new *entities* into a system. Here I would like to build upon this systems view of evolutionary novelty, and to emphasize the role of *new relationships* in generating novelties too. The potential benefit of doing this is nicely described by philosopher William Bechtel as follows:

What is possible when components are put together in creative ways is often obscured when one focuses just on the components themselves... One can appreciate this point by turning one's focus from science to engineering. Engineers do not build new devices by creating matter with distinctive properties *ab initio*. Rather,

⁵The closest we could get to finding a novel physical phenomenon in a *Tierra*-like world would be if we provided an instruction in the instruction set that was unused in the ancestor organism (for example, an instruction to read the system time), but which appeared in a descendant by a fortuitous mutation—assuming the mutation operator allowed for this.

they start with things that already exist and put them together in novel ways. What can be accomplished when the parts are put together is typically far from obvious. (Bechtel, 2007, p.277)

Lenton et al. (2021) have recently argued that natural selection can occur in systems above reproducing individuals (e.g. ecosystems) based solely upon differential persistence. Persistence in these higher-level systems is largely driven by “self-perpetuating feedback cycles involving biotic as well as abiotic components” (Lenton et al., 2021, p.333). This view offers the possibility of a consistent understanding of all levels of biological life, from the cellular level to the levels of cultures, ecosystems and biogeochemical cycles, in terms of the evolution of persistent systems, with higher-level complex systems being hierarchically composed of a series of lower-level systems.

In addition to entities (components) and feedback cycles, various proposals exist for a common vocabulary for describing the general structure and operation of biological, technical and cultural systems. For instance, de Rosnay (1975) describes the principal *structural* characteristics of a system in terms of its *limits* (boundaries), *elements*, *reservoirs* and *communication networks* (the latter two applying to energy, material and information within the system). Furthermore, the principal *functional* characteristics are described in terms of *flows* (of energy, material and information), *valves and regulators*, *delays*, and *feedback loops*.

De Rosnay (1975)’s attempt to develop a general vocabulary and visual representation for describing the structure and function of systems is perhaps more all-encompassing than approaches typically found in cybernetics, e.g. (Wiener, 1948), or in general system theory, e.g. (von Bertalanffy, 1968). The kind of approach set out by de Rosnay has more recently been developed into separate notations for diagramming a system’s stocks and flows and its causal loops, e.g. (Sterman, 2000). Attempts to develop a general language for describing system structure and function can also be found in other disciplines, such as engineering, e.g. (Pahl and Beitz, 1988), and artificial life, e.g. (Grand, 2000). While none of these proposals feels like the last word on the subject, they nevertheless hold out the prospect of a universal language for describing systems, comprising a relatively small set of common structural and functional elements.

The lines of development described above suggest that it might be possible to adopt an all-encompassing view of evolutionary innovations as *the creation and modification of information-driven persistent systems in the environment*. Such a view could be applied to innovations at all levels, from within individual organisms to higher-level systems involving multiple biotic and abiotic elements and cycles. Specific innovations could be classified in terms of a universal set of structural and functional elements, and in terms of whether the innovation represents:

1. A change to an existing structural or functional element within a system,
2. An addition of a new element (or deletion of an existing element), or
3. The creation of a new hierarchical level of system built upon existing lower-level systems.

To give a few examples: a Type 1 innovation might be a change in a regulatory connection in a genetic regulatory network resulting in the production of an additional copy of a body part; a Type 2 innovation might be an addition of a new species into an ecosystem; and a Type 3 innovation might be a major transition in individuality from single-celled to multicellular organisms.

While the importance of systems and feedback has long been recognised at various levels of life, from genetic regulatory networks to ecosystems, an all-encompassing systems view of the kind described above could highlight a much broader range of commonalities among innovations in different kinds of systems.

The Generation of Phenotypes

Earlier, when discussing how information stored in a persistent memory specifies configurations of matter that act as constraints upon a system’s dynamics, I remarked that this specification might be a simple 1-to-1 mapping or it may be more complex. As mentioned, a 1-to-1 mapping exists in ALife systems of linear code such as Tierra. One step up in complexity would be to have the laws of physics act upon a linear information string to generate a specific constraint, as happens in the self-organised folding of RNA molecules to form ribozymes. But of course the process of generating phenotypes from genotypes in modern organisms is much more complicated than that, and can be viewed as a complex hierarchical system of constraints and dynamics initiated by the genetic information that ultimately cycles back to control the transcription and translation of that information.

The generation of phenotype from genotype therefore involves both the POA perspective (information specifying constraints upon dynamics) and the Systems perspective (in terms of how the genetic information is ultimately interpreted as complex constraints and dynamics). In modern organisms it is a complex system entailing the processing of information, matter and energy based upon low-level self-assembly processes but using those basic levels to build further hierarchical layers of more complex structures and dynamics. This view of complex phenotypes being generated by hierarchically structured interpretation processes that at the base level utilise dynamics governed by self-organisation and other laws of physics/chemistry but at higher levels utilise non-elementary tasks constructed from the lower level systems, is echoed in recent work on *constructor theory* (Marletto, 2015) and in Sloman (2017)’s concepts of *fundamental* versus *derived* construction kits.

As the generation of phenotype from genotype is handled by increasingly more complex hierarchical systems of interpretation, the genetic information can move from a more-or-less direct representation of physical constraints to a representation in progressively more abstract and sophisticated languages of interpretation: cf. (Pattee, 1972, 2015), (Baricelli, 1987). In the context of procedural content generation for computer games, Michael Cook discusses the distinction between *possibility space* (defined as the set of all possible worlds we can image, represent or describe) and *generative space* (the set of all things a given generative system can produce), where the latter is a subset of the former.⁶ We can usefully borrow these concepts to say that the evolution of higher-level, more complex systems of interpretation of the genetic information into physical constraints and dynamics results in the creation of new generative spaces that increase the likelihood of generating complex, adaptive organisms and higher-level persistent systems.

Looking Forward

In the sections above I have suggested that evolutionary innovations can be understood in terms of capturing novel physical phenomena and of system building. Of course, I do not claim that this is necessarily the *best* way of viewing innovations—that will depend upon one’s goals. Nevertheless, it is an alternative perspective that connects questions of evolutionary innovation to existing literature on systemic approaches to understanding biological and technological phenomena.

Viewing evolution as the process of selecting persistent information-driven systems offers the potential of a consistent description of evolutionary innovations at all levels, from cells to ecosystems and cultures. The successful development of this approach will depend upon the elaboration of the kind of general systems vocabulary proposed by de Rosnay (1975) and others into a more formal and comprehensive general descriptive language of system design and function.

The systems view gives a general description of the types of novelties described in (Taylor, 2019) as *non-additive compositional systems* and suggests three distinct ways in which these kinds of novelties can arise, as listed on the previous page. These kinds of novelty, together with the discovery of novel physical phenomena, allow evolutionary systems to expand their search spaces and thereby have the potential for interesting (i.e. *expansive* and *transformational*) types of open-endedness rather than mere *exploratory* open-endedness in a fixed search space.

If successfully developed, a general systems view on evolutionary innovations would be useful in categorising novelties across many different types of open-ended system and in

⁶<https://www.possibilityspace.org/tutorial-generative-possibility-space/>

suggesting mechanisms for designing new artificial worlds with improved open-ended evolutionary potential.

References

- Banzhaf, W., Baumgaertner, B., Beslon, G., Doursat, R., Foster, J. A., McMullin, B., De Melo, V. V., Miconi, T., Spector, L., Stepney, S., et al. (2016). Defining and simulating open-ended novelty: requirements, guidelines, and challenges. *Theory in Biosciences*, 135(3):131–161.
- Barricelli, N. A. (1987). Suggestions for the starting of numeric evolution processes to evolve symbioorganisms capable of developing a language and technology of their own. *Theoretic Papers*, 6(6):119–146. (A publication of the Blindern Theoretic Research Team, University of Oslo).
- Baugh, D. and McMullin, B. (2013). Evolution of G-P mapping in a von Neumann self-reproducer within Tierra. In *ECAL 2013: The Twelfth European Conference on Artificial Life*, pages 210–217. MIT Press.
- Bechtel, W. (2007). Biological mechanisms: Organized to maintain autonomy. In Boogerd, F. C., Bruggeman, F. J., Hofmeyr, J.-H. S., and Westerhoff, H. V., editors, *Systems Biology*, pages 269–302. Elsevier.
- Bird, J. and Layzell, P. (2002). The evolved radio and its implications for modelling the evolution of novel sensors. In *Proceedings of the 2002 Congress on Evolutionary Computation. CEC'02 (Cat. No. 02TH8600)*, volume 2, pages 1836–1841. IEEE.
- Cariani, P. (1993). To evolve an ear. epistemological implications of Gordon Pask’s electrochemical devices. *Systems Research*, 10(3):19–33.
- de Rosnay, J. (1975). *Le macroscope, vers une vision globale*. Éditions du Seuil, Paris. English version entitled “The macroscope : a new world scientific system” first published in 1975 by Harper & Row, New York.
- Grand, S. (2000). *Creation: Life and how to make it*. Weidenfeld & Nicolson, London.
- Kauffman, S. (2020). Answering Schrödinger’s “What Is Life?”. *Entropy*, 22(8):815.
- Lenton, T. M., Kohler, T. A., Marquet, P. A., Boyle, R. A., Crucifix, M., Wilkinson, D. M., and Scheffer, M. (2021). Survival of the systems. *Trends in Ecology & Evolution*, 36(4):333–344.
- Marletto, C. (2015). Constructor theory of life. *Journal of The Royal Society Interface*, 12(104):20141226.
- Montévil, M. and Mossio, M. (2015). Biological organisation as closure of constraints. *Journal of Theoretical Biology*, 372:179–191.
- Pahl, G. and Beitz, W. (1988). *Engineering design : a systematic approach*. Design Council, London.
- Pattee, H. (2015). Cell phenomenology: The first phenomenon. *Progress in Biophysics and Molecular Biology*, 119(3):461–468.
- Pattee, H. H. (1972). Laws and constraints, symbols and languages. In Waddington, C. H., editor, *Towards a Theoretical Biology*, volume 4, pages 248–258. Edinburgh University Press.

Ray, T. S. (1991). An approach to the synthesis of life. *Artificial life II*, pages 371–408.

Sloman, A. (2017). Construction kits for biological evolution. In Cooper, S. B. and Soskova, M. I., editors, *The Incomputable: Theory and Applications*, pages 237–292. Springer.

Sterman, J. D. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill.

Taylor, T. (2019). Evolutionary innovations and where to find them: Routes to open-ended evolution in natural and artificial systems. *Artificial Life*, 25(2):207–224.

von Bertalanffy, L. (1968). *General system theory: foundations, development, applications*. George Braziller, New York.

Wiener, N. (1948). *Cybernetics: or Control and Communication in the Animal and the Machine*. Wiley, New York.