Towards a Unified Framework for Technological and Biological Evolution

Roger Tucker[1,2]

[1]Independent Researcher, Chepstow, UK
[2]Glean, 4 The Boulevard, Leeds, UK
roger.tucker@gmail.com

Abstract

It has long been observed that human cultural evolution is in some ways analogous to biological evolution, having reproduction with variation and a form of selection, but the fact that both technology and biology are physical brings them much closer than culture in general. Many have observed that they share universal traits that pervade their long-term trends, yet they seem so different. What is at the root of this? This paper considers a number of properties that would seem essential to any evolutionary system which produces real artefacts – construction, search, selection and various aspects of structure and organisation – and explains briefly how each operate in technological and biological evolution. This provides an initial attempt at a basic unified framework which can then be extended. Such a framework would help progress bio-inspired design, and suggest features to study on the way to meet the grand challenge of Open Ended Evolution.

Introduction

Technology has been drawing inspiration from biology for many decades, as evidenced by a number of design movements including bionics, biomechanics, biomimicry, biomimetics and bio-inspired engineering, as well as the field of evolutionary computing. More recently, bio-engineering is incorporating biology rather than just being inspired by it, including the examples of artificial organisms produced from biological cells and fuel cells from microbes mentioned in this conference's call for papers. However, less well investigated in this coming together of technology and biology is a clear understanding of the correspondence between their evolutionary systems.

It has long been observed that human cultural evolution is in some ways analogous to biological evolution, having reproduction with variation and a form of selection. Within the study of cultural evolution, technology is seen as an externalisation of knowledge (Mesoudi *et al.*, 2015), with knowledge, construction techniques and technological artefacts evolving in separate but interrelated ways (Brey, 2008).

But the fact that both technological and biological evolution describe physical artefacts or organisms brings them much closer than culture in general. They both have to overcome problems of transport, energy, processing of materials, creation of machinery etc. Many have observed that they share universal traits that pervade their long-term trends, no matter how different they appear at a lower scale (Vogel, 1999; Zinman, 2000; Solé *et al.*, 2013) and ask what is at the root of these potential universals?

Technological evolution is not just the aggregation of all the clever inventions of humankind over a long period of time. In his book "The Nature of Technology", Brian Arthur explains "the collective of technology builds itself from itself with the agency of human inventors and developers much as a coral reef builds itself from itself from the activities of small organisms." (Arthur, 2009, p. 169). He is not overstating the analogy. Technology is part of an interconnected socio-economic system which progresses ever faster, effecting more and more change in our lives, whether we like it or not. What started out as humankind making a few basic tools has become an emergent system which, like all emergent systems, has a top-down impact on its constituent parts.

There are many intriguing analogies in the two evolutionary systems. Vogel names cultural dissemination, natural selection, the role of isolation, conservative bias, the time course of change (though here you have to speed up the timescale for technology), incremental progress, new uses for old devices, parallel developments and extinction (Vogel, 1999). Zinman adds "diversification, speciation, convergence, stasis, evolutionary drift, satisficing fitness, developmental lock, vestiges, niche competition, punctuated equilibrium, emergence, extinctions, co-evolutionary stable strategies, arms races, ecological interdependence, increasing complexity, self-organisation, unpredictability, path dependence, irreversibility and 'progress'" (Zinman, 2000, p. 5). Clearly the two systems exhibit many similar dynamics. To get to the bottom of these, there have been a number of attempts to map concepts from biological to technological evolution to create a similar evolutionary model for technology, reaching different conclusions on the extent that the genotype-phenotype concepts apply, and to *what* they apply (Brey, 2008).

Conversely, there are also many contrasts between technology and biology. There are the obvious ones - technology has a bias towards flat surfaces, right angles, abrupt corners and the ubiquitous wheel and axle – all rarely found in biology. But many contrasts are much more subtle – dry vs wet; the way round levers are used; preference for stiffness vs strength, to name but a few.

A helpful way of understanding the correspondence between the two is to consider *what* needs to be achieved, and then contrast *how* it is achieved. For instance, technology's moving mechanisms – engines – are based on rotation or expansion; most of biology's are based on sliding or contracting. Loading

Downloaded from http://direct.mit.edu/isal/proceedings-pdf/isal/34/63/2035413/isal_a_00549.pdf by guest on 01 October 2022

of materials is usually in compression in technology but in tension in biology (Vogel, 1999). Could there be a set of needs common to the evolutionary systems themselves which together can form the elusive universal framework into which technological and biological evolution can both be fitted?

The most significant contrast, which lies at the root of all the others, is that biology is self-building and self-developing whereas *humans* develop and build technology. Any attempt to properly understand the correspondence of the two evolutionary systems has to embrace and accommodate this difference.

A good starting point is to note that individual technologies are not as much a result of human intention as we might think. There has been a long-running debate over how much technological evolution is driven by the “pull” of the market, and how much it is the “push” of human creativity and imagination (Basalla, 1988). From a number of surprising examples, Basalla successfully shows how even the most outstanding inventions are in fact derived from existing technology. Arthur’s later analysis expands on and confirms this. Much technology development is hidden internal improvement, driven by inefficiencies or ineffectiveness in component parts. These improvement opportunities emerge from the evolutionary system itself. Even the development of a new item of technology, be it physical or software, is very much driven by the opening up of a new market opportunity. Humans have lots of good and creative ideas, but technology succeeds only when it matches a market niche, and so it is the formation of these niches, at a time when the technology needed to service them can become available, which drives much new technology development (Arthur, 2009).

From this socio-economic system-level view of technology we can characterise the role of human creativity as one of a search for opportunities and better solutions. We can then characterise biological evolution's reproduction-with-variation also as a search, and compare and contrast the way the two operate (Perkins, 2000). In a similar way, we can characterise developmental biology as construction, the genome as a form of learning from experience and so on. Using concepts important to technology alongside those associated with biology provides a richer way of understanding how the two systems correspond to one another.

These high-level concepts provide the top level of a unified framework into which evolutionary system properties that describe *both* systems can be fitted. It is not straightforward to identify these properties - most of the time a property is better known in one than the other, and it may work in a common way, an equivalent (analogous) way or in a contrasting way.

Table 1 gives an overview of the initial framework explained in this paper, summarising the properties considered and their relationship in the two systems, with colours to highlight whether at that level it is best described as commonality, equivalence or contrasting. It begins with two fundamental properties of any evolutionary system producing physical artefacts – construction and search - which are performed in largely contrasting ways in the two systems. The role of selection is then considered, followed by several organisational properties which are essential to technological evolution and which have a common or equivalent role in biological evolution.

This property list is not at all exhaustive and the explanations given in the sections that follow are necessarily very brief, but should be sufficient to establish the feasibility and utility of building a unified framework in this way.

Property	Relationship: Commonality / Equivalence ⇔ / *Contrasting*	Inspired by:
Construction		
Use of Material	*Uniform vs molecular construction*	Biology
Assembly	*Precise vs adaptive; components-first vs progressive*	Biology
Instability	*Avoidance vs management*	Biology
Interoperability	*Biology interoperable at a much smaller level*	Biology
Search		
Type	*Goal-Directed vs Exploratory Search*	Biology
Model	*Direct vs generative*	Biology
Solution Forms	*Predictability vs adaptability; Single vs multi-level*	Biology
Accumulation of Experience	Theory, methods, components and tools ⇔ Genome	Technology
Selection		
Feature Selection	Designer’s judgement + selection ⇔ gene recombination + selection	Technology
Role of Environment	Other technology ⇔ biotic / socio-economics ⇔ abiotic	Biology
Organisation		
Modularity	Self-contained units, weakly coupled to everything else, allow independent development and optimisation	Technology
Hierarchy	Reduction in complexity of design ⇔ simplification of control	Technology
Emergence	Something new emerges at a higher level	Biology
Combination	Filling in gaps in possibility space; novel combination. *Recombining existing genes within an organism vs combining anything*	Technology
Re-use	Modular re-use / copy & modify re-use	Technology

Table 1: Overview of a Basic Unified Framework for Biological and Technological Evolution

Downloaded from http://direct.mit.edu/isal/proceedings-pdf/isal/34/63/2035413/isal_a_00549.pdf by guest on 01 October 2022

Construction

Use of Material

Technologists make their component parts by liquefying a material so it can fill a mould, softening it so it can be shaped, removing unwanted parts or by putting down thin layers (as in 3D printing). The designer then fits these components together to achieve the desired structure. This process may be very sophisticated as in semiconductor fabrication, but the principle remains that technology is made from uniform materials.

Whereas biology self-builds using the fundamental properties of matter to create its structures one molecule at a time. At the lowest level these properties are those of the quantum world, familiar to us through the rules of chemistry; at a molecular level it is a combination of those properties and the physical structure caused by the way a protein folds; at a cellular level it is those properties combined with the properties of soft matter (Newman and Bhat, 2008).

From this one difference stem many others. Although many of biology's fundamental design challenges are shared with technology, their readily available solutions are different to those of technology (Vincent *et al.*, 2006).

Use of resources. This difference in types of solution is clearly demonstrated in the use of resources. Technology is consumptive of resources, some of which are starting to run out. Biology ultimately utilises just sunlight and geothermal energy and makes everything by chemical transformation, with one organism's waste becoming another's resource.

Assembly

Precise vs adaptive. Technology depends on every component being made and assembled with reasonable precision. Biology makes extensive use of exploratory processes, which first generate a very large amount of functional variation, often at random, and then select or stabilize the most useful ones, with the rest disappearing or dying back. Microtubule structures within cells, the vascular system, the nervous system, neurons in the brain – all develop in this way (Gerhart and Kirschner, 2007). Exploratory processes are fundamentally adaptive and allow genes to make changes through simple regulatory control.

Components-first vs progressive. In technology, all the components of a design are made first and then assembled according to the design, which is a direct representation of the item being built. If the design is altered then several, or many, parts need to be changed simultaneously. This adjustment to the design requires a higher level of abstraction of the design space that enables a single change to affect all the necessary parts - an abstraction which usually requires a human intelligence.

Whereas in developmental biology multicellular organisms are built progressively, by starting with a single cell, and differentiating the cells as they divide and reproduce, allowing large changes to be made in the final result by smaller, perhaps single, changes earlier on in the development cycle.

Managing Instability

Engineers choose materials and make designs that give total stability and reliability, with maintenance as infrequent as possible whilst still ensuring adequate performance (notwithstanding the modern trend for built-in obsolescence). In contrast, there is a real sense in which biology lives on the edge of instability. Chemical reactions normally move towards a state of thermodynamic equilibrium, but in a cell everything is kept away from this equilibrium, and it is complex feedback systems which maintain a stable but dynamic equilibrium. When these are perturbed, perhaps through a mutation, it is easily possible to go closer to instability, which is normally destructive but might just occasionally prove beneficial and so generate innovation. The instability of the proteins that make up cells, especially in warm bodied animals, requires them to be continually re-synthesized and replaced, with an average half-life for an adult human of about 80 days (Vogel, 1999).

Nature manages instability at many different levels. At one end of the scale, in the avian compass an entangled pair of electrons somehow survive in the face of decoherence for at least a microsecond (Al-Khalili and McFadden, 2014). At the other end of the scale, the instability of the earth's environment (e.g. earthquakes, forest fires) can force the whole local ecosystem to adapt, or very rarely (e.g. a large meteorite strike), the global ecosystem adapts, removing dominant species and allowing others to develop.

Interoperability

Technology's uniform-material approach bypasses a problem that biology's molecule-by-molecule approach has had to solve, that of the interoperability of its basic building blocks. In fact, the low-level building blocks of life - nucleic acids, proteins and regulatory circuits - are very interoperable. Even though each amino acid in a protein has a different shape, the chemical linkage between them is identical. Nucleic acid strands also use a standardised chemical bond to link their component nucleotides. Regulation circuits use a standardised way to regulate genes based on the principle that regulator proteins interact with specific nucleotide sequences on DNA (Wagner, 2014). Since cell structures are self-built from monomeric components such as amino acids, structures can easily be altered by adjusting just one or more of those molecules.

Mature technology does eventually become standardised, but even then it does not mean that it is easy to fit things together. Parts that fit together have to be designed specifically to do that.

Search

As mentioned in the Introduction, the concept of search is a way to accommodate the fundamental difference that humans develop and build technology, but biology is self-building and self-developing. Perkins introduces three general search strategies that can be observed both in biological evolution and in the development of technology - adaptation by revision, selection and coding (Perkins, 2000). He stresses that whilst these may involve human consciousness, intentionality and imagination, these are not required, and both technology (and human creativity in general) and biological evolution make use of all three strategies. However, the focus here is not on these commonalities, but on what is fundamentally *different* between technology and biology – the role of human intention.

Downloaded from http://direct.mit.edu/isal/proceedings-pdf/isal/34/63/2035413/isal_a_00549.pdf by guest on 01 October 2022

Exploratory vs Goal-Directed Search

What makes nature's and technology's searches distinctive can be best explained in terms of intention. Technology mostly progresses by what can be described as "goal-directed" search – technologists look for a way of achieving a specific outcome within various practical constraints, maybe in small easy steps (as in the modern Agile methodology) or maybe with an ambitious goal which is not easy to realize.

By contrast, nature's reproduction-with-variation and selection, from a population perspective, amounts to a high-level exploratory search yielding improvements that offer better reproductive success. This is usually in small steps, either through improving the effectiveness of an existing capability, or occasionally introducing a completely new one. It is a stochastic search where many different search trajectories are explored in parallel lineages to establish useful traits.

Whereas technology's goal-directed search involves individual designers and only a little time, this high-level exploratory search involves whole populations and a very long time. However, nature is not time constrained, and there are considerable developmental constraints which limit the range of phenotypic variability.

A short-coming of goal-directed development is that its goal is not the *actual* goal of the designer's organisation, which may be profit, security, military supremacy, social good etc. and most of all, survival. This indirectness is the cause of many a tech company's failure, as a brilliantly-engineered product does not equate to market success. Even if the goal were actual market success, as the technological landscape changes ever faster what may have been successful when first conceived can be a poor market fit by the time it is ready for product launch. This is yet another reason for the predominance of agile development, particularly for software products.

Compared to nature's exploratory search, often somewhat disparagingly described as "tinkering" (Jacob, 1977), goal-directed solutions are vastly accelerated by human conceptualisation & capability. But they are also limited by human imagination. The engineer Genrikh Altshuller understood these limitations very well and developed the TRIZ methodology to try to overcome the limitation of normal human thinking (Altshuller, 1999). All the bio-inspiration movements are essentially also a way of doing this.

Of course, technology can also have an exploratory element to its search. Sometimes technologists have a goal but no idea how best to fulfil it. A famous example is Thomas A. Edison who, trying to improve the lifetime of a light bulb filament, tested a vast range of different carbonised materials, extending his search worldwide to test as many grasses and canes as possible – in all testing no fewer than six thousand different species of vegetable growths (Dyer and Martin, 1929, p. 262). Edison's search only varied the filament material within certain limits, but a pure exploratory search would have no preconception of what to vary, or what might bring about a useful improvement. Although much trial and error experimentation does take place in research labs around the world, it is never as open as nature's exploratory search.

Direct vs Generative model

In its most general sense, a "model" is any abstraction of a reality that represents its most important aspects. The purpose of the model in goal-directed search is for the designer to predict the outcome of various designs without actually making them. It can be tangible, like a drawing or calculation, or simply in the mind of the designer. As noted earlier, it is a *direct* representation of the intended result. So any exploratory search in technology can only vary a few parameters of the design, and usually ones that can be varied without affecting too much else.

Whereas the model in a pure exploratory search needs to suitably parameterise the *whole* design. This is achieved in biology by specifying the design as a "recipe", a genomic specification of the components which together assemble the organism. It is a model of how the final result is *generated* rather than what it actually is.

This also extends to the approach animals use to build their "technology" – bird's nests, spider webs, termite mounds etc., where the construction process seems to mostly result from an algorithm that links simple behaviour into a sequence that generates the finished result (Boyd *et al.*, 2013).

Solution Forms

The two search types lead to different forms of solution. Two examples are:

Predictable vs adaptable. Engineers dislike feedback if it can't be carefully controlled, as it can easily lead to instability, but nature thrives on feedback systems. This in turn affects the key quality of adaptability, which in biology is at both organism level and species level, but in technology is modest at best.

Single vs multi-level. Technology focuses at one level (an extension of a single human's capability) but nature can develop solutions that work at all organisational levels simultaneously (Vincent *et al.*, 2006). In effect technology focuses on solving problems for individuals but nature solves problems at the level of the whole population, because that is the level at which it searches.

Accumulation and Application of Experience

Search requires the accumulation of experience to help direct it in potentially fruitful ways. Technology has theory (science and maths), methods, components and tools. All these encapsulate experience in a way that makes it possible to construct new technology with relatively little personal experience.

Biology accumulates experience primarily in the genome. It represents all that has been learned throughout the history of that lineage, expressed in terms of how to build it from a single cell of that organism. The most hydrodynamic body shapes in fish, muscle structures, brain structures, how to create a camera eye – all this has been derived from experience and encapsulated in the DNA of the genome, which is biology's alternative to components, tools and methods.

Selection

Feature Selection

Selection in nature is powerful because it can work at many levels. Yes, it can detect if a specific change is an improvement or not, but this is the least interesting aspect of it. In a constantly changing environment it can select for processes and regulatory

Downloaded from http://direct.mit.edu/isal/proceedings-pdf/isal/34/63/2035413/isal_a_00549.pdf by guest on 01 October 2022

architectures that best allow adaptation and maybe even evolvability itself (Payne and Wagner, 2019).

In technology the inefficiency of pure selection is bypassed by the judgement of designers, who use a combination of imagination and trial and error to decide what will work best before turning anything into a product. But ultimately it is the market that decides what succeeds and what doesn't, and this is remarkably hard for humans to predict. Over time it is usage that determines which architectures, components, methods take hold and it is this selection process that ultimately drives technological evolution.

For all this to happen, selection must work at a feature/gene level and not just at a whole system (product/organism or technology/population) level. Selection acts on individuals, so those individuals must exhibit different combinations of features so over time and in populations useful features can succeed and detrimental ones disappear. One important way biology achieves this is through gene recombination in sexual reproduction, which allows selection to operate at the level of individual alleles. In asexual organisms Horizontal Gene Transfer within or between species can sometimes achieve this. It may not be in the organism's interest to share its genes with competing species, but it is in the gene's interest. HGT has been known for a while to be particularly important in prokaryotes, effectively allowing them to share their discoveries with one another, for instance antibiotic resistance, making the phylogenetic tree more like a network. Whether or not it plays a major role in eukaryotes remains controversial.

The Role of the Environment

In this context, the environment can be seen as everything which determines the solution space of potential improvements (to fitness or market success) for selection to act upon.

For biology, this solution space is determined both by the inanimate environment and the impact of other life, often referred to as the "abiotic" and "biotic" environments. These are in effect nature's specification for the genome-based exploratory search for improvements. The feedback within both environments ensures they are always changing, in addition to the natural instability of the earth and its weather systems. Varying environments accelerate complex adaptation (Pál and Papp, 2017) allow newly acquired genes to exploit new niches (Gogarten *et al.*, 2002), can become highly selective and thereby accelerate microevolution (Newman, 2006), help develop a modular design (Parter *et al.*, 2008) and generally allow a continual exploration of phenotype space (Taylor, 2018).

In technology, the environment is other technology, possibly competing, embedded in a complex mix of social, cultural and economic factors. In addition to these there are the less market-driven and more artificial factors of military requirements and governmental regulations (Basalla, 1988). Innovations and new technologies can directly impact all these factors, creating potentially rapid change. They also feed back into existing technology and replace older technology, which further increases the speed of that change.

Technology Research

The 20th Century has seen the rise of technology research worldwide, undertaken by both industry and universities, with ambitious goals such as machine vision, automatic speech recognition (ASR) and artificial intelligence, paving the way for even more ambitious goals such as self-driving cars and humanoid robots. Many decades of research passed by with few products in the market, and a different form of selection has been needed to drive pre-market development. As an example, we will look at how this developed in the case of ASR.

In the 1980s deployed systems were few and far between and only worked in niche applications with barely adequate performance. Progress towards the goal of unconstrained speech recognition was much slower than anyone had anticipated. The problem was that although researchers met up at conferences and published their results, these results were not easily comparable because each system was tested on proprietary data. The only way to find out whose techniques worked the best was to implement and test each one.

In 1988 the first of a sequence of speech databases, TIMIT, was created and made available to the whole community. The Linguistic Data Consortium (LDC) was formed to administer and create a revenue stream to fund the databases. Having databases that everyone used meant that results could be compared directly, revealing the most useful techniques. However, there was also a tendency for systems to become tuned to the exact data, so over time this informal comparison developed into annual competitions where previously unseen data was provided strictly only for the final evaluation. Each participant reported their methods and results in a special session at the annual speech technology conference (see (Reddy *et al.*, 2021) for a recent one).

The community effectively created an artificial selection system so that genuine advancements would stand out against less effective ones. However, this had an unintentional side-effect. In his keynote speech at Eurospeech in 1995, Hervé Bourlard spoke on "Towards *increasing* speech recognition error rates" (Bourlard, 1995). He was referring to the problem that completely new approaches inevitably lead to an increase in error rate, whereas the focus of the ASR community was now on those approaches that reduce word error rate. Boulard was one of the few researchers at that time using Artificial Neural Networks (ANNs), when almost everyone else exclusively used Hidden Markov Models. Now, many years later, the ANNs of deep learning not only pervade ASR, but the whole field of AI. Selection must not be so strong that it stifles important novelty.

Structural and Organisational Development

For technology, structure and organisation is the same in the model (design) and the product itself, since they have a 1-1 correspondence. However, the organisation evident in biology's product (phenotype) is not usually very evident in its model (genotype), with a few notable exceptions like the ancient Hox genes. This lack of 1-1 correspondence has made it very hard to discover exactly how biological organisation has occurred. However, enough is known for us to see how the properties discussed in this section, which are foundational for technology, are not only also evident in biology, but perform similar roles.

Downloaded from http://direct.mit.edu/isal/proceedings-pdf/isal/34/63/2035413/isal_a_00549.pdf by guest on 01 October 2022

Modularity

Modules are reasonably self-contained units, weakly coupled to everything else, which allows them to develop and be optimised independently. In technology this means that the designer does not need to understand the internal workings of the module, in biology it means that regulatory control is simplified. More will be said on this in the Re-use section below.

Modularisation has a lot of organisational advantage. In biology, it may be the result of direct selection for stability, robustness or evolvability (Kashtan *et al.*, 2009) or it may be a dynamic side-effect of evolution, a result of the duplication of genes or subsystems. However it has come about, modularity appears as essential to biology as it is to technology (Gilbert, 2000).

Hierarchy

Hierarchy is a natural consequence of components being grouped together to form larger units. The ability to use or control a component without knowledge of its internal workings reduces the complexity of both goal-directed design and exploratory search. Designers only need to think (and need skill) at the level they are working, and can treat all the modules and components they work with as "black boxes". For example, an architect works at a different level to a builder, who works at a different level to the manufacturer of the building materials.

Nature also exhibits hierarchy. Organisms are constructed of units that are self-contained and yet part of a larger unit. This ranges from organelles to cells, tissues, organs and organ systems. The hierarchy also extends beyond the organism through populations, communities and ecosystems to the whole biosphere.

Emergence

Emergence is a special case of hierarchy which forms from individual artefacts/organisms joining together to form a larger unit which has properties the parts did not have on their own. In technology, emergence happens when someone spots the joining-together potential to build something that already exists better, or maybe a known concept which has had no way of being built until then. Emergence has taken place when this new functionality, as it is incrementally extended, has enough impact for attention to switch away from the joined parts to the functionality they enable. A good example is how transistors were used to formed logic gates, which formed adders, CPU and memory, which formed microprocessors, which formed computers, which formed networks, and are now embedded in so many different devices that we have the “internet of things”.

Emergence in nature is a remarkable phenomenon that has been recognised as a three-stage process along the lines of formation, maintenance, and transformation (Szathmáry, 2015). Other aspects of the three stages are fitness (Okasha, 2005) and causality (Deacon, 2003), both of which are important because the emergent entity must exert a top-down causality and also have a fitness independent of the fitness of its parts. Szathmáry lists no less than 7 emergences, including eukaryotes, multicellularity and animal societies.

Combination

The central thesis of Brian Arthur's book “The Nature of Technology” is that novel technologies arise by combination of existing technologies (Arthur, 2009).

It's useful to distinguish between standard combination that produces something similar to before, filling in gaps in the possibility space, and novel combination that produces innovation. Standard combination allows straightforward adaptation to changing environments/requirements. In technology it is the designer using the tools and methods of his trade to meet a particular need, in biology, it is male and female gene recombination driven by sexual selection. Sexual reproduction constitutes a surprisingly efficient trade-off between exploiting alleles that were fit on average in the past and sampling alleles in new combinations. (Watson and Szathmáry, 2016).

But there is also novel combination which results in innovation. The combinatorial engine of biology is at the genome level, creating new reactions, proteins and complex regulation networks, all facilitated by the interoperability of these low-level building blocks of life described earlier. Gene regulation networks play a particularly important part in this - most of the many and varied anatomical and physiological traits that have evolved in the last 500 million years are mainly the result of changes in regulation networks, according to the theory of Facilitated Variation (Gerhart and Kirschner, 2007).

In technology almost anything can be combined, and it is this which leads Arthur to his thesis that technology is a result of “combinatorial evolution”. In biology, combination is restricted to the components that are already represented in the genome, with useful mutations only occasionally creating new ones. The difference in biology is that all these components are very adaptable, so as the regulatory networks change the way they are combined, new possibilities open up quite easily.

Re-use

In technology, re-use ideally involves modularising and componentisation. As stated above, it is advantageous for easy usage that functionality is encapsulated, so internal workings do not need to be understood, and a component can be used in different applications. In software engineering, where re-use can just involve copy and paste with modification, it is still considered good practice to create a module with a more generalised and encapsulated functionality than to keep on copying and slightly modifying code, though both approaches are common.

In biology, both modular and copy & modify kinds of re-use are important. In the genotype, copy and modification is seen in the duplication of genes, and even whole genomes have been duplicated (Crow and Wagner, 2006). A most remarkable modularity example is the phenomenon of weak regulatory linkage in the animal phenotype, where core conserved processes are controlled with a very simple input signal. These processes are so well encapsulated that although the signal seems superficially to control the response, it invariably turns out that the responding core process can produce its output by itself but inhibits itself from doing so (Gerhart and Kirschner, 2007). This allows the regulatory network to easily try new combinations of core components in new amounts and states, at new times and places in the animal.

Downloaded from http://direct.mit.edu/isal/proceedings-pdf/isal/34/63/2035413/isal_a_00549.pdf by guest on 01 October 2022

A completely different form of module re-use in unicellular organisms like bacteria is when HGT involves the introduction of complex, multigene pathways (Gogarten *et al.*, 2002). For instance, a study on the phylogeny of the flagellum in bacteria suggests that there was a transfer of the entire flagellar gene complexes between proteobacterial lineages after their separation from other major bacteria groups (Liu and Ochman, 2007).

The prevalence of hierarchy means that there are multiple levels of re-use in both tech and biology. The functional unit of one level may make a good component of the level above; Watson observed that in evolutionary systems, selection at one level of organisation can operate like unsupervised learning at a higher level of organisation (Watson and Szathmáry, 2016). This is because anything with a useful function which operates robustly and reliably (both of which will be selected for) is a good candidate for a component of a bigger system, no matter what it actually does. Each one of the component levels in computing mentioned above – transistors, logic gates, arithmetic units and memory, instructions, routines, programs - started out as a specific solution to a particular problem, but in time were adapted to become a more general component of a larger system.

Re-use for multicellularity. A very significant example of this is found in the transition to multicellularity. Newman and Bhat have identified 8 or 10 "Dynamical Patterning Modules" which together lay the foundation of the complex morphology observed in multicellular organisms: adhesion, alternative cell states, phase separation, tissue multi-layering, topological change, interior cavities, tissue elongation, tissue solidification and elasticity, pattern formation, segmentation and periodic patterning. (Newman and Bhat, 2008, 2009). The molecules of the DPMs "mostly evolved in single-celled organisms prior to the evolution of the metazoa, and only took on their DPM-associated roles with the change of spatial scale that was a consequence of multicellularity". That is, they evolved because of the capabilities they gave a unicellular organism, but those capabilities then allowed the transition to multicellularity.

More on the transition to multicellularity has come to light in a more recent study of the genome of 21 species of single-celled choanoflagellates, the closest living relative to animals (Richter *et al.*, 2018). They share some very important genes with animals, including genes essential for early development and genes that help the immune system detect pathogens. The study found that around 372 gene families previously thought to be animal-specific, including Notch, Delta, and homologs of the animal Toll-like receptor genes, instead evolved prior to the animal-choanoflagellate divergence. They conclude "it appears that the single-celled ancestor of animals was already well-equipped for multicellular life".

It seems as if over many millions of years single celled organisms were steadily accumulating base capabilities needed for multicellular life, even though at that stage they may have been used for something different. Then, when enough components were in place to make multicellular life viable, the transition could take place. This long wait also enabled the accumulation of a rich set of other genes which have helped give multicellular life the diversity we observe today.

Discussion

The approach to a unified framework in this paper has been to identify a number of essential properties in both evolutionary systems and to consider how they are accomplished in each. Very often nature and technology contrast with one another, but it is significant that there is always nuance in that contrast, either biology has notable exceptions that work technology's way, or technology on occasion looks a little more like biology. These exceptions are important for a unified framework - expanding on these exceptions would open up the possibility of making technology more biology-like, or even biology more technology-like, through bio-engineering.

The framework, even at this very basic initial stage, could also be useful for Open Ended Evolution simulations (Packard *et al.*, 2019), which was described in 2017 as "the last grand challenge you've never heard of" (Stanley *et al.*, 2017). Are the organisational features described here essential for open-endedness?, If so, it could be helpful to study them individually as stepping stones on the way to a system which can produce them all. A simulation is usually a mixture of extrinsic and intrinsic processes (Taylor, 2018), so it should be possible to have some of these features extrinsic, effectively creating a hybrid between nature's and technology's approach in the simulation. As Channon observes "it is clearly necessary to skip over or engineer in at least some complex features that arose through major transitions in our universe" (Channon, 2019).

To build a full unified framework from this beginning will require the incorporation of many more of the key concepts from both biological and technological evolution. To take some biological examples suggested by a reviewer; *mutational robustness* could be incorporated as a necessary quality of Exploratory Search, *heritability* would help expand out Accumulation and Application of Experience with interesting equivalents in technology, but *plasticity* requires an addition to the framework. The principle is always to consider what is being achieved and then how that is achieved in the other system. What is more explicit in one may help reveal what is much less obvious in the other. As in the above examples, some concepts will be able to fit into one of the main properties introduced here, others will require completely new ones. Some, like Accumulation and Application of Experience, will need expanding with sub-properties – it is a very significant topic particularly for technological evolution. Indeed, Universal Darwinism holds that an inferential system is key to facilitating complex order in many other domains besides biology and culture (Campbell and Price, 2019).

A possible criticism of the framework would be that the emphasis is on the physical, whereas modern technology is dominated by software and algorithms (in a rather analogous way to how nature is dominated by brainpower). The intention has been for most of what has been discussed to apply equally well to both, except of course the subsection on Use of Material, but it maybe that at some point in the future this will need to be addressed explicitly.

What of all those analogies listed in the Introduction? Most of these have still not been addressed, and so are we any further forward answering the key question of what is at the root of these universals? This paper proposes that at the root of them are a number of evolutionary system properties which are

Downloaded from http://direct.mit.edu/isal/proceedings-pdf/isal/34/63/2035413/isal_a_00549.pdf by guest on 01 October 2022

common to both systems, but which may operate in different ways. Each analogy needs to be carefully considered as to whether it either reveals a new property which should be fitted into the framework, or is simply a by-product of properties already in the framework. Thus this basic framework can be extended to consider and hopefully encompass these and the many other observed analogous aspects of technological and biological evolution.

Acknowledgements

Thanks to Wolfgang Banzhaf and Andrew Halestrap for their critique and helpful comments on the initial version of this paper. Thanks also to all the reviewers for taking the time to give thoughtful critical feedback and useful suggestions.

References

Al-Khalili, J. and McFadden, J. (2014) *Life on the Edge - the coming of Age of Quantum Biology*. Random House.

Altshuller, G.S. (1999) 'The innovation algorithm: TRIZ, systematic innovation and technical creativity', *Technical Innovation Center, Inc* [Preprint].

Arthur, W.B. (2009) *The Nature ofTechnology: What It Is and How It Evolves*. Penguin.

Basalla, G. (1988) *The evolution of technology*, *The Evolution of Technology*. Cambridge University Press.

Bourlard, H. (1995) 'Towards Increasing Speech Recognition Error Rates', in *4th European Conference on Speech Communication and Technology EUROSPEECH '95*, pp. 883–894.

Boyd, R., Richerson, P. and Henrich, J. (2013) 'The cultural evolution of technology: facts and theories', *Cultural Evolution: Society, Technology, Language, and Religion*, pp. 119–142.

Brey, P. (2008) 'Technological Design as an Evolutionary Process', in *Philosophy and Design: From Engineering to Architecture. Springer.*

Campbell, J.O. and Price, M.E. (2019) 'Universal darwinism and the origins of order', *Springer Proceedings in Complexity*, pp. 261–290.

Channon, A. (2019) 'Maximum Individual Complexity is Indefinitely Scalable in Geb', *Artificial Life*, 25(2), pp. 134–144.

Crow, K.D. and Wagner, G.P. (2006) 'What is the role of genome duplication in the evolution of complexity and diversity?', *Molecular Biology and Evolution*, 23(5), pp. 887–892.

Deacon, T.W. (2003) 'The Hierarchic Logic of Emergence: Untangling the Interdependence of Evolution and Self-Organization', in Weber, B. and Depew, D. (eds) *Evolution and learning: The Baldwin effect reconsidered*. MIT Press.

Dyer, F.L. and Martin, T.C. (1929) *Edison: His Life and Inventions*. Harper and Brothers Publishing.

Gerhart, J. and Kirschner, M. (2007) 'The theory of facilitated variation.', *Proceedings of the National Academy of Sciences of the United States of America*, 104 Suppl, pp. 8582–8589.

Gilbert, S.F. (2000) 'Modularity: The Prerequisite for Evolution through Development', in *Developmental Biology*. 6th edn. Sinauer Associates.

Gogarten, J.P., Doolittle, W.F. and Lawrence, J.G. (2002) 'Prokaryotic evolution in light of gene transfer', *Molecular Biology and Evolution*, 19(12), pp. 2226–2238.

Jacob, F. (1977) 'Evolution and Tinkering', *Science*, 196, pp. 1161–1166.

Kashtan, N., Parter, M., Dekel, E., Mayo, A.E. and Alon, U. (2009) 'Extinctions in heterogeneous environments and the evolution of modularity', *Evolution*, 63(8), pp. 1964–1975.

Liu, R. and Ochman, H. (2007) 'Stepwise formation of the bacterial flagellar system', *PNAS*, 104(17), pp. 7116–7121.

Mesoudi, A. *et al.* (2015) 'The Cultural Evolution of Technology and Science', *Cultural Evolution*, (November), pp. 193–216.

Newman, S.A. (2006) 'The Developmental Genetic Toolkit and the Molecular Homology—Analogy Paradox', *Biological Theory*, 1(1), pp. 12–16.

Newman, S.A. and Bhat, R. (2008) 'Dynamical patterning modules: Physico-genetic determinants of morphological development and evolution', *Physical Biology*, 5(1).

Newman, S.A. and Bhat, R. (2009) 'Dynamical patterning modules: A "pattern language" for development and evolution of multicellular form', *International Journal of Developmental Biology*, 53(5–6), pp. 693–705.

Okasha, S. (2005) 'Multilevel selection and the major transitions in evolution', *Philosophy of Science*, 72(5), pp. 1013–1025.

Packard, N. *et al.* (2019) 'An Overview of Open-Ended Evolution: Editorial Introduction to the Open-Ended Evolution II Special Issue', *Artificial Life*, 25(2), pp. 93–103.

Pál, C. and Papp, B. (2017) 'Evolution of complex adaptations in molecular systems', *Nat Ecol Evol.*, 1, pp. 1084–1092.

Parter, M., Kashtan, N. and Alon, U. (2008) 'Facilitated variation: How evolution learns from past environments to generalize to new environments', *PLoS Computational Biology*, 4(11).

Payne, J.L. and Wagner, A. (2019) 'The causes of evolvability and their evolution', *Nature Reviews Genetics*, 20(1), pp. 24–38.

Perkins, D. (2000) 'The evolution of adaptive form', in Zinman, J. (ed.) *Technological Innovation as an Evolutionary Process*. Cambridge University Press, pp. 159–173.

Reddy, C.K.A. *et al.* (2021) 'INTERSPEECH 2021 Deep Noise Suppression Challenge', in *Interspeech 2021*, pp. 2796–2800.

Richter, D.J., Fozouni, P., Eisen, M.B. and King, N. (2018) 'Gene family innovation, conservation and loss on the animal stem lineage', *eLife*, 7, pp. 1–43.

Solé, R. V *et al.* (2013) 'The Evolutionary Ecology of Technological Innovations', *SFI WORKING PAPER: 2012-12-022*, 000(00), pp. 1–13.

Stanley, K.O., Lehman, J. and Soros, L. (2017) *Open-endedness: The last grand challenge you've never heard of*. Available at: https://www.oreilly.com/ideas/open-endedness-the-last-grand-challenge-youve-never-heard-of (Accessed: 4 March 2021).

Szathmáry, E. (2015) 'Toward major evolutionary transitions theory 2.0', *Proceedings of the National Academy of Sciences of the United States of America*, 112(33), pp. 10104–10111.

Taylor, T. (2018) 'Routes to Open-Endedness in Evolutionary Systems', in *Third Workshop on Open-Ended Evolution (OEE3), Tokyo, Japan*.

Vincent, J.F.V., Bogatyreva, O.A., Bogatyrev, N.R., Bowyer, A. and Pahl, A.-K. (2006) 'Biomimetics: its practice and theory', *Journal of The Royal Society Interface*, 3(9), pp. 471–482.

Vogel, S. (1999) *Cats' Paws and Catapults*. Penguin Books.

Wagner, A. (2014) *Arrival of the Fittest*. Oneworld.

Watson, R.A. and Szathmáry, E. (2016) 'How Can Evolution Learn?', *Trends in Ecology and Evolution*, 31(2), pp. 147–157.

Zinman, J. (2000) *Technological Innovation as an Evolutionary Process*. Cambridge University Press.

Downloaded from http://direct.mit.edu/isal/proceedings-pdf/isal/34/63/2035413/isal_a_00549.pdf by guest on 01 October 2022