The Relevance of Systems Dynamics and Evolutionary Concepts to the Development of New Technology

By David Dahmen

The following is an attempt to expand the conceptual framework for considering technology to be a cultural product best characterized by the same overall pattern exhibited by the evolution of biological systems in general. Brent Silby has written an essay titled *The Evolution of Technology* where he uses the metaphor of evolution to explain why it is problematic to claim that technology springs full-blown from a single creative leap of intelligent design and argues that evolution as we understand it in the biological sense offers a more appropriate paradigm.

His argument is highly reminiscent of the arguments long preferred by those of the hypothetical realism school of evolutionary epistemology, originating in Vienna during the late 1930's. Silby begins well by positing generalized criteria for natural selection that permits transcending a domain strictly limited to organic life and allows cultural products such as technology to come under the cover of his expanded criteria. He then correlates Richard Dawkins's concept of meme with the genes of the genetic code to flesh out the metaphor.

This approach has been roundly criticized by Paul Thagard and many other philosophers because, according to Thagard, human intentionality is central to the creation of knowledge (or technology in our case) and the factor of totally random variation of a single base pair at specific isolated points on the chromosome is incompatible with the emergence of the type of purposive behavior so evident in the development of technology. I believe that this statement of Thagard is correct but that that an alternative argument exists that saves the applicability of the evolutionary metaphor.

Silby's first step in his essay is to generalize the criteria of natural selection. This is very reminiscent what the biologist David Hull did many decades ago with the same general aim of naturalizing epistemology by defining the concept of evolution in terms of a structure including an algorithm governing reproduction, a mechanism of random variation permitted by the algorithm, and a filtering process that favors principally those variations, product of the reproductive process, that manifest a competitive advantage in an ongoing environment that eliminates most of the instances of the reproduced.

This is all well and good but how can human intentionality be factored into the concept? David Hull did not succeed in this respect, in part because some critical developments were still unknown to him. First, he did not know that random mutations of a single point of base pairs on a gene came to be displaced as the mechanism considered to be responsible for the emergence of the *bauplan* basic to all life forms with bilateral symmetry (including humans) at the onset of the Cambrian period. Only large scale genetic variation could explain punctuated evolution that was famously championed by the late Stephen Jay Gould. It indirectly questioned the original simplistic explanation of genetic variation originally elevated to a doctrine of molecular biology. Gould thus incurring the persistent ire of traditional biologists such as Hawkins who had a vested interest in insisting on the supremacy of the concept of gene conceived of in its most elementary presentation.

Eventually Gould was forced by universal professional disdain to recant before his death, but the tide of learned opinion changed posthumously when Antonio Garcia Bellido[1] pioneered the concept of selector genes. It was he who successfully elucidated the function of the HOX series of genes as controlling the expression of entire groups of genes at subsequent points on the chromosome of determined sequences. Bellido never was awarded the Nobel Prize. It went to Lewis who investigated HOX genes for over 20 years without ever coming to understand how they really worked.

The basic idea was that at some point an entire sequence of genes was replicated along the length of the chromosome, and was even replicated several times. Subsequently the more normal cases of mutation occurring at specific points of each replicated sequence gave rise to differences among those tissue types that would be expressed within each repeating sequence under the control of the particular HOX gene at the lead point of each repetition. This basic change in structure occurred only once in the history of evolution on this planet and the fundemental structural concept remains unchanged and prevalent for all higher animals up to the present time.

The concept of genetic replication thus became transformed into one of considerably greater complexity than one based on simple point mutations. It is at this point where the concepts of system dynamics come to bear for its compatibility with a modular concept of evolution which is that which ultimately is implied. Such a modular concept is practically indispensible if the emergence of purposeful behavior is to

[1] The argument about genetics that follows is taken from Javier Sampedro's recent book Reconstuyendo a Darwin.I know of no English translation.

be explained. Systems dynamics would be meaningless if the differing components of a system could not be thought of as semi autonomous sub wholes that at some point in time enter into binding relationships with each other to form an expanded system, usually with very surprising emergent properties. An excellent and accessible exposition of why this scheme is indispensible to biological evolution was presented by Herb Simon and Arthur Koestler at one of the Altenberg Symposiums a few decades ago in Austria.

It also corresponds to the way engineers design technological artifacts. It would be impossible to build complicated designs without starting from semi autonomous components. Look inside any computer to verify this point.

The longer the genetic code, the less is the mathematical probability that a random variation will turn out to be significantly favorable over the entire sequence. On the other hand if two viable autonomous components are merged and become related to each other, what is unlikely to be favorable as a result of several random point variations has indeed some possibility of turning out to be favorable.

A striking example offered by biology is that event in which a gram positive bacteria descended from an archaea, merged with a totally different type of bacteria, gram negative, and out of the symbiotic relationship emerged eukaryote structure. The genes of the gram negative are specialized in the regulation of metabolic processes whereas the gram positive bacteria contributed an advanced set of genes for regulating genetic replication.

This symbiosis thesis led to professional disdain for Lynn Margulis for many years, but is practically irrefutable using the theory of variation of gene signatures to identify the bacteria from which eukaryotes arose via a merger. Radhey Gupta of McMaster University in Ontario has done the crucial investigations that tip the balance of evidence to favor the symbiosis theory of Margulis, although it appears that her identification of the exact types that merged was mistaken since her thesis antedates gene sequencing and was based on morphological considerations.

The two examples cited above illustrate an all too common tendency on the part of the community of theorists of both science and technology. On one hand, for each outstanding conceptual breakthrough there is a predisposition to extend the domain of valid applicability for the theory far beyond what the real defensible range eventually turns out to be. I have been arguing that this has been the case for the initial theory of genetics that first emerged from Watson and Crick's discovery leading to the original concept of DNA replication. No less a figure than Jacques Monod maintained that the theory valid for a bacteria was also valid for an elephant. That obscures the complexity introduced into the process by mitosis which is foreign to bacteria. Monod's exaggeration set the scene for the incautious projection of the theory that led to the persecution of Lynn Margulis and Gould, not to mention the well known case of the even earlier theory of transposition discovered by Barbara McClintock that was also rejected for decades. Had McClintock been taken seriously 25 years earlier it would have led to a more rapid penetration into the nature of HOX genes since it constituted a clear example of large scale genetic variation. I am not saying that point gene mutations are not also important. They are very definitely important. However things are always more complex than how they appear to be initially. Really great breakthroughs occur only extremely rarely and are generally projected to be true in a simplistic way that obscures work leading to the discovery of relevant complexities.

In science a similar case prevailed for the concept of absolute time and space according to Newton. When Einstein received the Nobel Prize it was for his discovery of the photoelectric effect and its theoretical implications and not for the special theory of relativity which was far more difficult for the physical theorists of his time to accept.

The same pattern persists with respect to technology. Tried and true technologies normally attract excessive investment combined with emotive empathy for the familiar. That is until the next crisis arrives and the worst excesses are blown away by new technologies that had been previously invented but rarely perfected. That at any rate is the thesis of the systems dynamics group at MIT that attributes this tendency as being a major casual contributor to long wave economic cycles and the periodic financiaql crises that ensue.

However I stray from the connection between modular evolution, purposeful activity and systems dynamics. Some excellent illustrations of the connection are illustrated by Rupert Riedl's 1981 work, *Biologie der Erkenntnis*. I have read it in Spanish translation as *Biologia Del Conocimiento - Los fundamentos filogeneticos de la razon.* In this work he analyses an ascending spiral of seven levels of types of learning. Roughly they correspond to stages defined as precelluar, structural, instinctive, associative, subconsciously rational, fully cognitively rational and cultural representations produced on a supra individual level. The genetic structure of each level is differentiated not on the basis of molecular biology but on the functional structure needed to support the capabilities of each level from a systems viewpoint. The evidence comes from ethnology, that is animal behavior studies documenting changes corresponding to each level as complexity gradually increases. Nevertheless Riedl insists that each progressive level is built upon the merging and refinement of previously unassociated modular elements that are themselves products of genetic variation (whether or not we understand the exact mechanisms involved). Point mutations are specifically declared to be dominant only on the first two levels, whereas subsequent variation is predominately modular. The fundamental characteristics of each module brought into the system, according to Riedl, are surprisingly stable over time and the greatest increases in cognitive capacity derive from the emergent properties of ever more complex modular combinations. Many times a given module acquires in the process a new function at variance with its original one, but employing only slightly modified mechanisms.

Nature is opportunistic.

For me the most fascinating aspect of this work is that Riedl's thesis can be interpreted as a prescient program for investigation of the basic variations of neural structures that have evolved and come to be progressively investigated once more sophisticated technologies become available.

It is surprising how the research initiatives of neuroscientist Rodolfo Llinas gradually builds up evidence layer by layer, as if the program had been traced out by Rupert Riedl. In his popular book, *The eye of the vortex* Llinas makes it clear that he does this in a premeditated way as a good systems thinker should. Although Darwinian to the core, he also emphasizes that as the capabilities arising from the interrelationship of previously disconnected modules increase, then the functional ends also tend to reach out in unsuspected directions.

The end result is that the role of purposive behavior is shown by Llinas to follow a gradual and progressively articulated ascent from the first modest attainments of unicellular life up to the astounding capabilities of *Homo sapiens*. The novelty that is not popularly appreciated is that even the very modest parenicium has an autonomous regulatory system manifesting some aspects of at least proto intentionality. This arises because the cell membrane manifests varying electric potential over its surface. This allows it to respond to differing stimulus with a variety of responses. A combination of electrical and chemical signaling permits a structure of adaptive behavior on a far finer scale than is permitted by the object oriented concepts usually contemplated by philosophers. According to Llinas, right from the beginning all those forms of life capable of mobility are capable of distinguishing aspects of the state of the outside world exterior to the cell membrane and the relation that this state bears to satisfying the needs of its preferred internal state. Just within the membrane are found proteins that control the passage of ions, and even more sizeable molecules, through the membrane wall in order to maintain homeostasis. All this is done without a single neuron to guide the action. Who is to say that here there is not a glimmer of intentionality?

There are two different aspects to the concept of intentionality. On one hand we humans are strongly predisposed to associate it with a feed forward command system that translates a self conscious desire into appropriate action. But there is a weaker sense associated with the creationist argument of intelligent design. In this second sense the existence of an obviously complex system with a structure that exhibits highly adaptive responses to an equally complex and varying environment implies the existence of something like God as the creator or unmoved mover, as in the philosophy of Aristotle.

Biological science brings into question both versions of the meaning of intentionality. With respect to the initiation of appropriate action in the interests of survival, it is obvious that the even a parenicium has a structure that promotes an appropriate response to present eventualities with implications as to future events. From this level on up in evolution all organic structure is future oriented. However, according to human prejudices, what is missing is the self consciously perceived urge to initiate an appropriate response. How important really is such a self conscious urge?

Consider how the presence of the automatically regulated internal plan of response to externally varying conditions that becomes progressively more sophisticated as organisms evolve toward having the first neural cells and then toward a highly differentiated central nervous system. According to Llinas the capacity of an organism to move implies right from the beginning a competitive advantage if it also attains the capacity to predict and respond to the probable consequences of movement and this capacity becomes incorporated into the functional structure of the organism. It matters little that the predictions are not commanded by a top down conscious command system. At first it was pure bottom up: that which had been proved to be simple, tried and approximately true prevails. As an example consider instinctual responses such as those of pheromone signaling between ants. Thanks to these simple mechanisms ants perform astounding feats of construction. By the time of the evolution of socially organized groups of predators such as wolf hunting pacts, the finely tuned responses to ever more complex and finely discriminated opportunities had advanced to near human levels of proficiency without self conscious commands having evolved.

There are those that claim that even during those very early moments of history when speech and the ability to fashion arms and boats had evolved, the ability to project forward looking scenarios involving human agents regarded as self was extremely undeveloped. Action followed as an immediate response to situations that were innocent of casual thinking beyond the most immediate and simple reactions. When Agamemnon appropriated the favorite mistress of Achilles, the epic reports that he offhandedly justified himself by saying that Zeus had prompted him to do so. Certainly this response is not indicative of a fully developed ability to consult an internal mental space of projection within which the self is examined as an objective causal agent in interaction with possible scenarios.

This example, extracted from Julian Jaynes' theory of the bicameral mind, is simply intended to illustrate how recently the component of self conscious motivation in an ample and modern sense has possibly evolved. The classic experiments by Benjamin Libet, and more recent ones by JD Haynes measuring the delay between unconscious mental processing, motor responses and conscious awareness of the decision to initiate the corresponding motor response suggests that self consciousness grew initially from a deeper and more hidden capacity to consult the rear view mirror and evaluate what the alternatives might have been when a sequence of events involving the self were played back. In that case it could have been tacked on to the fundamental motors of neural activity leading to the consciousness of volition as a more superficial and recent evolutionary development and would not represent all that immense a jump biologically.

I do not want to get into a discussion of free will at this point. Even if the line of command runs directly from autopilot to motor response, once self consciousness gets added, even with a slight delay, there is no doubt that the use of the rear view mirror strongly conditions behavior on the next similar occasion. The door is left open for free will.

The central idea is that a pronounced degree of purposive behavior is possible even without self consciousness. There is little reasonable doubt that biological paradigm of variation and selection was casually operative in order to evolve to such a state, even if the exact genetic mechanisms are not fully understood at the present time. The last step in order to arrive at self consciousness was perhaps not all that biologically extreme even though the consequences were indeed tremendous.

Systems dynamics becomes much more pertinent to the biological metaphor for the development of technology when the implications of the mathematical approach incorporated within is analyzed. Philosophy of science got off on the wrong foot due to its initial preoccupation with Newtonian physics, Dalton's chemistry and similar

areas where the theory can be reasonably resumed by a few formulas or laws involving a small number of independent parameters.
Theorists like Carl Hempel were spoiled by such a start that fitted very well with linear analytical mathematics. Biology is different. The evolution of the cell membrane changed every thing. The multiplicity and casual proximity of what would be distal factors without a membrane greatly augments complexity. Now the agency of about 30,000 different proteins must potentially be taken into account for they can all be simultaneously casually active within a given cell. This considerably reduces the possibility for deriving universal laws expressed in a few mathematical equations. The possibility of finding analytical solutions for the overall state of the cell is nil.

A totally novel mathematical methodology is required. Instead of simple laws there exist overall limitations in biology that favor the creation of models, frequently complex, over finding laws, that is analytic solutions. In part this is because of the necessity of having to be able to model relationships between greatly expanded numbers of parameters. This is to be expected if the nature of the system to be modeled is modular with many components. The second requirement is to be able to model the effects of non linear relationships. There is ample empirical evidence that underline the importance of trigger effects in biological processes. For example if a critical enzyme is missing, metabolic reactions do not follow even if all the other components to sustain a process are present. There are many feedback loops, both positive and negative. The model must permit that the quantitative levels of many parameters enter into the calculation non linearly.

Von Bertalanffy, in his *General Theory of Systems*, devised an analytic method to model with an expanded number of parameters based on the use of a Wilson expansion. This approach, however, was not pragmatically successful since a Wilson expansion uses derivatives of the functions expressing the relationships and thus is only valid if the relationships are continuously differentiable. Since this is not the case the method fails for biology. Nevertheless the direction of this first step was positive since a Wilson expansion is a method of numerical approximation.

The methodology of systems dynamics takes numerical approximation to a new and higher level. It models the relations between parameters subject to the effect that the quantitative level of other parameters might have on a given relation even if such effects are non linear. In effect it slices the process modeled into extremely thin segments of time and proceeds to compute the changes in the parameters for each subsequent time slice using techniques of mathematical approximation.

This would be pragmatically impossible except for the invention of very powerful electronic computers. Take, for example, the successful implementation of Denis Noble's computational model, referred to as the virtual heart. It required about 8 hours of computer time on the fastest supercomputers available at the turn of the century to model a single heartbeat. This model used about 20 independent variables to capture the action of the human heart as a whole.
Even so the model has some severe limitations. It assumes that degenerative effects triggered by replication of normally inactive DNA in the nucleus of the heart's cells do not alter the structure of the heart

over the span of time modeled by the process. In some real life situations this assumption can sometimes hold for only about 15 minutes. To include such effects is the current goal of the model. It is a problem that beside the increase in the complexity of the model, many of the fundamental mechanisms triggering DNA replication are only gradually yielding to investigative efforts. Computational modeling must go hand in hand with investigations generating hard empirical data.

In effect the computational model becomes an investigative tool in itself. One plugs real data into the model and compares the computational output to data measured in an in vivo experiment at a time later than that of the input measurements. Any appreciable discrepancy requires further fiddling with the model until it achieves predictive accuracy.

In some areas programs exist to predict the out put of a system with a given arrangement of components. This particularly is the case for electronic circuits. Similar but ruder programs exist for calculating the effects of combination of genes in bacteria with respect to the bacteria's metabolism.

It turns out that the unaided human mind cannot rationally predict the combined effects of numbers of variables that run into the thousands. Consequently the idea was born to use the computer to directly specify the configurations of electronic components or genes and subject the arrangements to probabilistic modifications with subsequent computational analysis of the effects of having done so. This procedure corresponds to the birth of so called genetic programs that purport to emulate the paradigm of natural selection.

The variations generated run into the millions, and the positive models finally selected are few but very interesting.

Genetic programs represent a specific although limited example of both the appropriateness of the biological evolutionary model for technological development and an argument for Andy Clark's philosophy of taking a deep look of how mankind is situated in his material world (including the disposition of his material artifacts) and how this influences his mental processes and attainments.

Biology illustrates how and why pure rationality fails if it is not backed up not only by the theories of Karl Popper's third world, but also the extensions to our capabilities represented by computers and the many other artifacts afforded by high technology.

It is especially notable the extent to which systems thinking devaluates a philosophical fixation on "being" as opposed to "becoming", that is process.
Computational modeling changes the emphasis to process and ties the act of hypothesis closely to the generation of empirical data relevant to the model.
It is capable of incorporating stochastic effects within the model which appears to be fundamental in order to model the workings of nature itself.

Consider the case of the emergence of eukaryote cell structure or that of the Hox genes. It is perfectly conceivable how the mutual presence of autonomous components for millions of years can eventually become functionally related as a result of being brought into close proximity due to fortuitous circumstances. Alternativly a module within the genetic code can be replicated due to fortuitous circumstances. Similar cases occur very frequently in the history of technology. Most technologies evidence a lapse of at least 20 or more years between the time of their conception and their commercial adaptation. A very frequent cause for this delay is that a successful new technology requires combining a particular mix of components or capabilities. It is frequently a simple case of good fortune when the missing piece of the jigsaw puzzle is finally found or invented. Often pure luck brings something relevant to the attention of the prepared mind as was the case of the discovery of penicillin.

Finally, the emphasis on process in computational modeling implies that as the time span covered by the model expands, the nature of the components change due to feedback effects and the dynamic nature of the model itself. That is one of the reasons why a famous essay of Jay Forrester is titled All Models are Wrong. This is similar to the cautionary advice expressed in Dennis Noble's Ten Commandments of Systems Biology. He advises against taking any component of the model as a fixed entity unto itself. It has significance only in the context of the dynamics of the total model (and that changes with time due to feedback effects). For example there is very respectable opinion that the morphological details of the human central nervous system are far to complex to be rigidly defined by a particular genome. It arises from interplay between general rules defined by the genome and the fortuitous circumstances encountered epigenetically during its development.

To sum up, we should be far more modest epistemologically compared to past aspirations. On the other hand the future will be even more interesting than the past. The end of science is not even remotely in sight.

David Dahmen 2010