Evolutionary Inventive Problem-Solving in Biology and Architecture: ArchiTRIZ and Material-Ontology

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Abstract

Phenotypic similarity between unrelated organisms, known as *convergence*, is a result of shared problems of adaptation to similar environments and limited ecological range. Their separate genetic histories imply a developmental route to biological innovation. *Convergence* as a model of evolutionary change has been applied to biological evolutionary reasoning and functional studies. We propose its application to biologically-driven *convergence* for innovations in design. This route necessitates at least the comparability of architecture with biology on three levels: (1) evolutionary design reasoning (2) *convergence* of design solutions, and (3) ecological niche concept. These combine in ArchiTRIZ, which is introduced as a derivative of TRIZ (a Russian system of inventive problem-solving) in architecture. We are building an ontology of *convergence* based on wood and ceramics on ArchiTRIZ model framework called Material-Ontology [MatOnt]. As a computational design tool, MatOnt can activate systematic transfer of knowledge from biology to architecture and integrate data to develop material-based structural systems with multi-functional and adaptive properties that can be adapted for locally specific architectural applications. *Convergence* gives direction by highlighting natural models with potential for innovative design, some of which are discussed briefly.

Keywords: convergence; evolution; systems; epigenetics; TRIZ; ArchiTRIZ; ontology; Material-Ontology; biomimetics; ecological niche.

1: Introduction

Culture changes in response to its inherited history (internal influences), current environment (external influences) and predicted outcomes. It has been compared to biological evolution, whose history is embedded and transferred in inherited DNA, reflecting the successes of survival, for which environmental influences provide the forces of natural selection. Throughout cultural domains, the inclination to concentrate on this particular explanation has more recently been challenged by an increasing awareness to the need for biological parallels based on diverse evolutionary grounds. On this subject and with attention to behavioral and social sciences particularly ethnology and archaeology, O'Brien and Shennan wrote: "Beginning in the 1980s there occurred an emerging interest in applying evolutionary principles to the study of culture, and one area in which considerable advance was made was the study of cultural inheritance. As interesting and valuable as these studies are, there remains areas that need in-depth research, especially with respect to the production of cultural innovation…" (O'Brien and Shennan 2010, x). Another, collective call was raised in the book entitled 'Technological Innovation as an Evolutionary Process' edited by John Ziman: ['Darwinian', 'neo-Darwinian' or 'Lamarckian' schemes] "are only a few of the many mechanisms by which populations of evolving entities – biological as well as cultural – actually maintain and reconstitute themselves, generation by generation…The task is to discover the relevant mechanism in each case, not to squeeze it into one or another of these preconceived categories" (2000, 313). As Steadman argued "This experience and debate…" that occupied other fields of culture for quiet some time "…can perhaps help show the way to a newly developing architectural research, while keeping it from falling into old and demonstrated errors", particularly from superficial metaphors and deterministic approaches (Steadman 2008, 6). The difference between culture and biology is that whereas we inhabit, or we *are*, culture, we are essentially outside most of biology and can therefore study it using objective experimental methods unavailable to social studies. It makes sense, therefore, to see what processes we can find, describe and analyse in biological evolution and to see how far these processes can help us understand, and perhaps even predict, cultural changes. Architecture is an expression of culture: we propose a method to transfer information between architecture and biology using analogy derived from an ontology that describes, in logical terms, the detailed processes and interrelationships which may lead to change and adaptation, since any comparison will highlight differences. Experience shows that this approach yields interesting and practical innovation; perhaps it can also provide clues to progression in architecture.

The establishment of our current understanding of biological evolution was itself a cultural process, and those whose argument led most directly to its establishment were those with the most complete grasp and the most coherent exposition. Although unified in their desire to describe and explain processes underlying biological complexity, the forebears of this field represent two views of the mechanisms of evolution, which may, or may not, be in opposition and therefore may, or may not, be mutually exclusive. In fact as we increase our knowledge of cellular and developmental mechanisms we begin to see that biology is more complex than we thought, and exclusivity blends into complementarity.

Darwin laid his trust in phylogeny and the inheritance of variation moulded by the processes of natural selection, - *homology*. But as Friday (1987) commented: "Such is our familiarity with the idea of evolutionary divergence that we have ceased to recognize it for what it is: an *a priori* model of evolutionary change" (Moore and Willmer 1997). Lamarck assigned primary importance to individual invention and epigenetics, depending on behaviour and usage - *convergence* or the inheritance of acquired characteristics. This is an *a posteriori* model of evolution requiring a contribution from environmental influences to react directly with the organism, thus involving more than variation through genetic inheritance and natural selection based only on that inheritance. So whereas Darwin's Tree of Life is always divergent, the reality imposed by epigenetic adaptation to specific environments will tend to be convergent. Additionally, although the branches of Darwin's Tree are separate, some 30% of "species" can hybridise and are fertile, plants more so than animals (Mallet 2008; Abbott et al. 2013) so traits of convergence may spread more rapidly. Spencer straddled the two views and recognized both adaptive development, through structural change, and natural selection (Spencer 1896). More important, he proposed evolution as a general mechanism of change and adaptation applicable to culture, society, art and science. Yet it was Darwin's Big Idea that had the widest influence on evolutionary thinking. The insufficiency of Darwinian evolution to account for biological innovation was discussed by Lyell, Mivart, Cope and Geoffroy (Reid 2007) and more recently by Webster and Goodwin (1996), Müller and Newman (2003) among others. A recent article covered the two contemporary approaches to evolutionary theory, showing the continued divide in the field (Laland et al. and Wray et al. 2014). All that one can be sure of, therefore, is that ideas of evolution are based on similarity and change.

But there is a time aspect to this, for which organisms have a range of responses. 'Evolutionary' change in Darwin's sense is change in long term, based in classical genetics and of most importance for species and populations of organisms living in a relatively unchanging environment. But an individual, with its relatively short life-span, needs to respond to more transient challenges to existence, which it does by means of physiological and behavioural adaptation. Insofar as people have studied safety factors in biology, they are remarkably similar to those developed in technology. There is a similar margin for error and change. Between these extremes come epigenetic mechanisms, responding to immediate problems of existence but also passing the adaptive solutions on to the next generation. Thus all time scales are covered.

The ideas inherent in the systematic study of artefacts and architecture go back, to Vitruvius, Alberti, Leonardo da Vinci and Durand among others (Kubler 1962; Lethaby 1957). These ideas progressed alongside contemporaneous theories of biological evolution although, of course, they were incapable of proof in the same manner. Inspired by Cuvier's concept of 'type organisms', Semper's comparative method and theory of invention, amplified by Viollet-le-Duc's study of the structural evolution of Gothic architecture, exemplifies the systemic approach to design during the first half of the nineteenth century (Eck 1994; Hvattum 2004; Steadman 2008). The basic method by which a solution is approached is copying (much akin to the classical Darwinism). Yet the root of the evolutionary analogy in contemporary architecture is found not in historical approaches and perspectives but in developments in the field of *Systems*. Although 'Systems' as a concept has a long history in philosophical and scientific thought, from Aristotle through to nineteenth century German philosophers Kant and Hegel and beyond, it was established as a scientific field of problem-solving only at the beginning of the twentieth century by Bogdanov (1921) in *Tektology: The Universal Organization Science*. It is derived from Spencer's concept of evolution (Biggart, Dudley and King 1998) and preceded Bertalanffy's *General System Theory* of the 1930's. Its origins are rooted in the nineteenth century developments in organismal biology, which settled the long-standing differences between vitalistic and mechanistic concepts, and evolutionary theory. Its recognition and spread as an applied science came during the second half of the twentieth century as a tool in engineering and computer science.

Architecture has adopted this Systems approach to design, limiting its application to real objects and cybernetics, systems engineering and operations research, the introduction of which started the computational design movement (see for example

Performance Design issue of P/A Progressive Architecture Vol. 8, 1967). Based on feedback, homeostasis, purposefulness and theories of variation and predictability, this approach assigned priority to the adaptive behaviour of systems as error-correcting changes, and to information as the unit of selection (Rosenblueth, Wiener and Bigelow 1943). This focused problem-solving on trial and error as a cyclic search method, itself the engine of classical evolution. This was not a historical method with interest in the development of design and technology, nor empirical, but a numerical method the success of which required computers. Some of the central exponents of the application of Systems to architectural design, which in different ways relates form and environment *indirectly* through selection, are Simon (1973; 1996), Alexander (1977; 1964) and Frazer (1993; 1995). Alexander argued that design is an inventive problem to which variation and selection are not applicable. Apparently not recognising the inherent contradiction, he proposed a variational strategy for 'form-making'. His views anticipated another, comparatively minor, direction now known as *Soft Systems Science*. More recent digital design has used evolutionary and genetic algorithms.

In most cases, the preferred Systems approach is built exclusively on *homology*, which provides no theoretical base for inventive design. This suggests the development of Systems that includes evolutionary *convergence*, or biological innovation. The unification of these two ideas, *homology* and *convergence*, is central on two levels: for understanding both biological and cultural change, and for the success of Systems as a general evolutionary framework for architectural design. A unified formulation linking Systems to design is not yet available but can lead us to a much less explored area: evolutionary inventive problem-solving in biology and architecture. The technique we propose to use for this exercise is based on the Russian system for solving problems inventively, whose Russian acronym is TRIZ. Its power is in its functional approach that allows it to work within almost any logical environment. It is only the means by which functions are delivered that defines the area within which it is applied. Thus in food science (removing the seeds and core from red peppers), gemology (fracturing a gem stone along pre-existing fault lines) and in biochemistry (breaking open large numbers of cells in suspension) a single function - increasing environmental gas pressure slowly, then releasing it quickly - delivers each of those outcomes. A well-defined, though not necessarily finite, number of functions can thus deliver a wide range of effects; a function identified in one discipline can be used effectively in another discipline; functions identified in biology can be used in engineering and architecture. We thus need to examine the analogies between TRIZ (which is couched in the language of technology) with systemic approaches developed in architecture and design.

TRIZ is closely related to Tektology and General System Theory as a general framework for inventive problem-solving. With this analysis of evolutionary functional *convergence* we challenge the limited interpretation of Systems as a statistical, numerical and optimizing method of trial and error, modelled on *homology*. We use our experience to bring architecture into close comparison with biology on three levels: (1) evolutionary reasoning (2) *convergence* of inventive design solutions (3) ecological niche space as an operative analogy for architectural space. A modern ontological approach (such as that being developed with TRIZ by Cavallucci) can relate many topics within a logical network; for the purposes for architecture we can objectively combine design, materials, environment and ecology, making a logically transparent system driven by (1) hierarchical integration (2) complex causal evolutionary relations and (3) dialectic resolution of design conflicts beyond compromise. We contrast this with (1) hierarchical decomposition (Simon 1962; Alexander 1964) (2) selection and determinism (Steadman 2008) and (3) goal-seeking towards "satisficing" design solutions through trade-offs (Simon 1962). We present some examples and case studies based on wood and ceramics.

Steven Vogel (1998) points out succinctly that, although the store of genetic information in every cell is vast, it is by a huge margin insufficient to determine all the detail of an organism. Genetics describes and quantifies DNA and so quantifies its potential for producing proteins. All other influences are classed as epigenetic processes and include the response of a biological material to its mechanical environment. This response is a most important property of a structural material. Epigenesis is thus a fundamental part of adaptation and, by extension, of evolution. Chance appears to be significant in this process. If, by chance, part of an animal grows to be bigger, epigenesis provides the mechanism by which other parts can grow 'in sympathy'. The various parts could not all grow by chance simultaneously and therefore, without epigenesis, the organism as a whole could not increase in size. Epigenesis enables structural adjustments, which can compensate for variability of materials. If a structure lacks strength, a message 'Make me thicker', is received by the cells. If it were not for epigenesis, biological materials would have to be made to a more precise specification and would not be adaptive.

2: Models of Evolutionary Change

Convergence is the name given to phenotypic similarity between distantly related species, measured and analysed by comparing the character distribution and transformation series between two or more organisms at any or all levels of structural and biochemical hierarchy (Hennig 1950). It is an important tool for evolutionary reasoning (Brooks 1996), not only as a pattern of biological innovation indicating functional adaptation of many types of organism to similar environments and limited ecological niches offered by our world and its chemistry but also because it points to the biological processes which allow the introduction of new traits not present in the ancestor, hence not inherited, as well as their genetic fixation in subsequent generations (Jablonka 2000). As the scales across which inventive processes operate are usually different from the scale at which the unit of innovation is observed, hierarchical integration is required to explain *convergence* and to approach the evolution of biological complexity (Wake 1996, xvii).

Darwinian evolutionary theory restricts evolution to *homology*. The gene is the unit of variation, transfer and storage of information (Jablonka 2000, 36), and the environment (biological and physical) is assigned the *indirect* role of "dynamic stabilization" (Goodwin 1994) driving functional adaptation. This model has been applied to cultural change (e.g., Dawkin's memes) and problem-solving. With the interest in the historical continuity of cultural traits (i.e., material entities, ideas, techniques, behaviour) and locating their origination and spread, the study of homologies has thus been appropriate for modelling cultural history. On the other hand, the Systems approach to problem-solving based on *homology*, or computational method based on "Blind Variations Selectively Retained" (the Darwinian process formalised by Campbell), which Ziman used to discuss the "selectionist" approach to complexity (Ziman 2000, 41–49), corresponds to a deeper tradition in design. For this to work, the design problem needs to be "ill-structured" (Simon) parametrically, hierarchically, combined or otherwise, to determine the set of possible variations by the number of variables and degree of interrelations and interactions within and between the identified and decomposed sub-structural modules. Ideally, the "nearly-decomposed" (Simon) structure, usually expressed as a tree, indicates a one-to-one mapping between structure and function. In this way, a solution will be that which best approximates the measure of quality and is adapted to its environment in a "satisficing" (Simon) way. Trade-offs are inevitable. The congruence of structural and functional modules in technical artefacts is "seen to originate from design methodology" (Krochs 2009, 271). Two classic examples are Simon's two watchmakers and heat-exchange between rooms (Simon 1962, 470-474) and Alexander's system of one hundred lights (1964, 39) with references to D'Arcy Thompson's notion of form as a diagram of forces based on his "theory of transformations, or the comparison of related forms" (Thompson 1942, 16) and Ashby's homeostat (1954, 149). The consequence of this method of design is the tendency towards reductivism, rationalism, certainty, control, predictability and determinacy, and less rigorous approaches using random variation and selection. Systems approach to design based on *homology* affects the way design and context are understood in terms of how a problem is defined, regulated and solved and in the way they are related. The exclusion of the role of development and *direct* effects of context in this model typically results in the wrong conceptualization of growth, development and evolution: they become interchangeable. There are many examples, which demonstrate the successful application of this method to routine problems in engineering and architecture and its use as a source of interesting and useful concepts and techniques. But it fails as a general "design method" for architecture. This is due to the mistake of confusing architectural design with lower-level routine problems and using a Systems framework which is unsuitable for approaching design complexity and inventive problem-solving. In addition, all models of evolution include failure as part of the process of adaptation and improvement; architecture cannot combine failure and success. Success is the only option.

In biology, the limitations of the *homology* model are challenged in the contexts of neo-Lamarckian framework and evolutionary synthesis, following Uexkull's reasoning for epigenetic evolution of biological complexity in relation to changing environment (Reid 2004, 8). This context expands on the Lamarckian theory of inheritance of *acquired* characters and "*indirect* effects of environment" with emphasis on *direct* effects of environment and epigenetics (examined both in terms of "response and inheritance") (Jablonka 2000). More recently, Jablonka suggested this to be a "more helpful source of analogies for some features of cultural and particularly technological evolution" (Jablonka 2000, 31). In this context, the dialectic synthesis of Matsuda (unifying neo-Lamarckism and neo-Darwinism) and Reid (unifying emergence theory and selection theory) are important sources. Through the concepts of pan-environmentalism and genetic assimilation, expanding on Waddington's formulation (1953), Matsuda conceived the evolutionary role of environment both as an "agent of development" and an "agent of selection" (West-Eberhard 2004, 115). In Matsuda's view, as Reid described, "animals changed behaviour, chose different environments, and responded to them physiologically in a way that affected their development. Then they literally assimilated the changes into their genetic and epigenetic makeup, so that it became heritable and independent of (short-term) environmental effects" (Reid 2004, 17). Reid's proposal complemented this by acknowledging "the component of progressive evolution, which involves discontinues, complexification on a *biological* time scale, and the component of dynamic stability (i.e., the selection syndrome), which has dominated the history of life on a *geological* time scale" (Reid 2007, 405) as interwoven. By emphasizing the *direct* influence of environment, both physical and biotic, the evolutionary unit was expanded within "development and epigenetics, functional biology (physiology, behaviour) and association (symbiosis, societies)", thereby advancing the understanding of complex evolutionary causality beyond the gene and population and the *indirect* influence of environment by natural selection (Reid 2007, 5). In this way, the historical, statistical and numerical evolutionary theory could gain causal explanatory power for *convergence*, or why and how biology invents. The contribution of inventive evolutionary reasoning to knowledge about the patterns and processes of *convergence* is two-fold: (1) Understanding specific, unique events from the perspective of "situational logic" (Popper) or "historical narrative" (Mayr 1997, 64) to infer the functional and adaptive significance of inventive change. In this way, the aspect of causally unrelated "accidental" or "unique" occurrences are distinguished from, and made complementary with, causal explanations (Popper 1957, 136). Also important is the statistical power behind the analysis of evolutionary trends. (2) Elucidation of general natural laws, principles and phenomena, (such as allometric scaling, minimum action, exponential law or twistiness-to-bendiness ratios (Vogel 2003, 510) underlying its widespread occurrence through theoretical explanations of complex evolutionary causality. It is interesting to approach causality through Popper's concept of 'propensities' or 'objective interpretation of the theory of probability'. Propensities, Popper argued, "are not mere possibilities but physical realities" which are not inherent in an object but in the context of the object (Popper 1990, 12), as exemplified with the loaded die and Newtonian apples. Popper explained a propensity as the weighted possibility of a certain event to occur in a particular context. Unlike the classical / mechanistic view of causality, 'physical propensities' are indeterministic and can be objectively interpreted using "*a calculus of relative or conditional probabilities* as opposed to *a calculus of absolute probabilities*" (Popper 1990, 16). Ulanowicz illustrated this using the 'events table', contrasting the classical / mechanistic with complex causality (Ulanowicz 2009, 53).

An organism can be considered as a complex of characteristics interrelated within a structural hierarchy. Hierarchy requires modularity, although this is not sufficient to account for *convergence*, which invokes "different processes within and between different levels of biological organisation" (Brooks 1996, 3). This is facilitated by highlighting developmental interrelations and interactions, that is, "spontaneous (epigenetic) self-organisation that depends on the physical and chemical properties of the internal and external environments, as well as on evolved gene-dependent mechanisms" (Jablonka and Lamb 2002, 88) against modular (patterned) structure. Innovative biological processes indicate the developmental route to origination of new traits and inheritance on the one hand, *direct* environmental effects on change with functional and adaptive significance on the other. Unlike *homology* where the adaptive value of change is inferred by way of hierarchical decomposition of structure in terms of function, *convergence* requires integration and adaptation across the hierarchy. Bertalanffy urged that biological change "assert(s) the necessity of investigating not only parts but also relations of organisation resulting from a dynamic interaction and manifesting themselves by the difference in behaviour of parts in isolation and in the whole organism (Bertalanffy 1950, 134). While innovation is recognized by modular "pattern" structure, its contribution to adaptation can be inferred only in the context of a network "process" structure. Commenting on Popper, Ulanowicz reiterated that "any configuration of processes can be considered as a network, and the overall topology of networks leads one to some striking conclusions about some inherent limitations ..." (Ulanowicz 2007, 107). Developmental canalization (Waddington's epigenetic landscape) and plasticity correspond to the developmental route towards regulating change (Jablonka and Lamb 2002, 85). While the former decouples phenotypic and genetic change in explaining dynamic stabilization, the latter is invoked in the explanations of biological innovation, that is, the *convergence* of different developmental pathways on similar solutions (Hodin 2000). There is a counter view of convergent change as the outcome of phylogenetic constraints that drive different biological solutions towards similar ends, given the shared problem of adaptation to a limited set of environments and ecological niches (Moore and Willmer 1997, 12). "Constraints on biological materials and adaptation to particular habits and habitats" concluded Moore and Willmer "will produce widespread *convergence*" (Moore and Willmer 1997, 1). The material basis of change and physical effects, as Müller and Newman discussed, is "among the most fundamental but least understood class of epigenetic factors" behind the evolution of biological innovation (Müller and Newman 2003, 6).

2.1: Convergence as a Tool for Inventive Problem-Solving by Analogy

We see *convergence* in both biological and cultural change. Genrich Altshuller was one of the first to recognize the power of this technological pattern for the inventive solution of problems. Gorelik introduced Bogdanov's *Tektology* as "a dynamic science of complex wholes...concerned with universal structural regularities, general type of systems, the most general laws of their transformation and the basic laws of organization of any elements in nature, practice and cognition" (Gorelik 1980). The power of *Tektology* as an applied general Systems science is best understood in the context of TRIZ - the acronym for the Russian "Theory of Solving Problems Inventively", which was originated by Altshuller in 1947. TRIZ is based on the insight that inventive solutions result from broad knowledge of otherwise distant contexts (Altshuller 1999, 74). This Systems approach to solving a problem of one kind based on solutions from an unrelated context but resolving a similar conflict of requirements is a powerful method for activating design, which it does by way of analogy and knowledge transfer. We consider that Systems approach based on evolutionary *convergence* is a route to its conceptual and methodological success. This biological analogy relates evolutionary inventive problem-solving and design as inverse processes, that is, while the former proceeds from the analysis of solutions (pattern) to infer what the problem was and how biology solved it (process), the latter proceeds from the analysis of design problems (pattern) to infer what the solution may be and how it can be applied (process). From this perspective, the evolutionary pattern and process of *convergence* is a key tool for inventive problem-solving, which is understood along the dialectic lines of: inventive *change* (solution), driven by *resolution* (process) of *conflicts* (pattern). The analysis by TRIZ experts of over three million inventive solutions from different engineering contexts and patents confirmed both the *convergence* of technological change and the tendency of technical development to increased complexity (in line with Lamarckian and Spencerian progressive evolution) and *ideality*. The conception that evolution drives cultural change towards increased *ideality* has a material basis (Salamatov 1999, 141). Salamatov depicted inventive technical change along two-axis: (x) time - following transformation series (developmental pattern) and historical continuity (phylogenetic pattern) by the distribution of invention and variation, and (y) complexity - corresponding to scales of system hierarchy; spanning super-system–system–sub-system levels (Altshuller 1988, 118). In this way, functional integration across scales of hierarchy is highlighted as the problem of invention against functional decomposition. Integration of multiple functions in a design solution creates what Altshuller called *technical* or *physical* conflicts, caused by the improvement of one property having a negative effect on another or assimilation of initially incompatible properties. Development of design as a property (trait) complex corresponds to successive resolution of property conflicts beyond compromise, hence successive change in the property graph towards increased *ideality*. Salamatov pointed out that, “the *ideal final result* is formulated according to the pattern where “the system or environment eliminates a detrimental (superfluous, redundant) effect preserving the capacity to produce a useful effect ***all by itself***' (Salamatov 1999, 155). "... The ideal system is when there is no system but its functions are preserved and carried out" (Altshuller 1988, 288). It is emphasized that *ideality* draws attention to the material basis of change and *direct* effects of environment.

TRIZ uses a number of techniques. The simplest of these is based on the similarity between superficially disjunct technical solutions in the history of cultural evolution. A *Contradiction Matrix* combines observed requirements and disadvantages, apparently mutually incompatible, pointing at *Inventive Principles* at their intersection within the body of the matrix, eliminating design conflicts without compromise or 'optimization' (the technique is based on the Hegelian dialectic triad of thesis - antithesis - synthesis). The *Inventive Principles* are general but transformative: their mode of implementation depends on the context of the initial problem. The *Contradiction Matrix* is a static compendium of directed methods independent of the dynamics of the interaction between thesis and antithesis - it assumes only two basic modes (summarised as A OR B and A OR NOT A). This is by no means a complete description of the ways in which interactions can occur within a problem, but is still very useful. A more dynamic method for inventive change, converting or removing a harmful effect through production of a useful effect without any additional agency other than material influences and *direct* effects of environment, underlies the *Substance-Field* (S-Field) transformations. This involves linking Substance (or material; a provisional definition depending on the scale of interest), Field (a broad definition related to environment, also provisional depending on the context of use), which in TRIZ mainly corresponds to a technical field (i.e., mechanical, thermal, acoustic) through "mutual interaction (effect, action, connection)" (Altshuller 1988, 52). The S-Field Method (SFM) can be used to represent a range of causal effects or events (single or chain) from simple to most complex ones with large number of connections and interactions (Salamatov 1999, 50). It is a much more dynamic approach than the *Contradiction Matrix*. In preparation for these methods, the context of the problem can be explored by techniques such as the *System Operator* which impose categories of cost, time and space on the vision. A third technique is known as *"Trends"* in which a series of developmental trends of structures and mechanisms generate rules of development and evolution. The problems inherent in development of the *Trends* can be solved by the *Contradiction Matrix* or the *SFM*; hence we have a three-part working system which can cover biology and technology.

TRIZ utilizes the evolutionary model of *convergence* for inventive design, but can it bridge the gap between technology and biology? Do engineering and biology converge on similar inventive solutions when faced with similar conflicts? TRIZ has long been touted as a generalised system for the solution of problems, but only when TRIZ was expanded as a general Systems framework for biomimetics (Vincent et al. 2006) was a biological route to sustainable technological development made apparent. Altshuller's view had been that TRIZ was applicable only to palaeontology; perhaps because he found biology too complex. However, although the 40 *Inventive Principles* are framed in such a way that they can be applied generally, the *convergence* of biological and technological inventive solutions is only 12-25% (Vincent *et al.* 2006; Vincent unpublished). Partly because biology is more complex and less well known than technology, and partly because Vincent's team was a fraction the size of Altshuller's when TRIZ was being developed, TRIZ for biology (BioTRIZ) had to be reduced to a more convenient size. The father of Olga Bogatyreva (one of Vincent's team) established the 6-fold division of Substance, Structure, Energy, Information, Time and Space (Vincent et al. 2006, 476). With each of the 40 *Inventive Principles* assigned to one of these six categories, this generated a new 6 x 6 formulation of the TRIZ *Contradiction Matrix*, specifically targeted to solving problems ‘the biological way’. This six-fold classification of existence also allowed comparison between biology and technology. Several hundred examples of problems and their solution, taken from the internet and from research papers, allowed comparison of which of these six parameters was the most important in the solution of problems in technology and biology. In technology the main parameters are energy and materials. By contrast “biology uses information (change interactions or regulation of a system or its elements) and structure (material organization with structural hierarchy or “add, remove, regroup structural parts”), two factors largely ignored by technology” (Vincent et al. 2006, 471). The biological route suggests focus on maximizing use of information and hierarchical structure. It’s important to remember that Information in biology covers more than its technical equivalent, since the ultimate repository of information in biology is the DNA which directs the cell. Thus interactions and regulation are intrinsic at the level of the synthesis of materials and structures as well as extrinsic, where those materials and structures are tested in use.

TRIZ’s history in the field of architecture is short and implementation remained limited since its first introduction to this context by Mann and Catháin (2005), who proposed it as a systematic method for architectural innovation and have been applying, testing and developing it within educational and professional contexts (i.e., Matrix+). They re-configured TRIZ *Contradiction Matrix* according to architectural data for disciplinary knowledge transfer and illustrated 40 *Inventive Principles* with specific examples from architecture and case studies at the building and components scales. A biomimetic path towards advancement of architectural design using TRIZ was emphasized and proposed by Vincent (Vincent 2009; Vincent 2012, 161). One of the first examples derived from it was a ‘heat-selective’ insulated roof designed by Craig (2008). Although Craig’s design has nothing overtly biological in its design, it conformed to the emphasis on information and structure, such that knowledge of temperatures and associated wavelengths of radiation informed the choice of materials, and the structure of the insulation was made directional so that heat could be radiated directly to the night sky, but it was still difficult for heat to pass the insulation during the heat of the day. Technology with its emphasis on energy and materials merely hangs an air conditioner out of one of the windows. In comparison with other fields (i.e., science, art, business, management (Zlotin et al. 2000) TRIZ is yet to have an impact in architecture.

3: ArchiTRIZ and Material-Ontology: Design by Systematic Transfer and Integration

We use the term “Systematic Transfer” to indicate that *convergence* is the result of a defined process. This does not limit the range from which design concepts can be gleaned; rather, it speeds up the process of selection of suitable models. In addition, the emphasis on the evolutionary model of *homology* (biological variation) and thereby lack of a unified formulation linking Systems to design has led our attention to a much less explored area of evolutionary inventive problem-solving in biology and architecture. Consequently the following path has emerged: the development of an evolutionary Systems model for architecture based on *convergence*, complementary to, and not a substitute for, *homology*-based models for architecture. This shifts the emphasis to patterns and processes of inventive change. As opposed to the evolutionary historical / numerical selection model, this comparative-transfer – integrative model highlights the use of *convergence* as a tool for design which builds on a missing link identified in Systems approaches to architecture.

We recognize that TRIZ's power comes from its utilization of *convergence* as a comparative-transfer tool. Its power becomes most apparent in interdisciplinary transfer. Schon presented a powerful conception of function in his "Displacement of Concepts", which is also an approach found in TRIZ for making functional relations between different contexts. Schon exemplified this by expressing polishing as the process of making many tiny "scratches"; and "drum", which can be associated both with a musical instrument or a room. He explained: "these concepts have been displaced to situations outside of their ordinary *patterns of use* and they have been transformed in the *process*. Through their displacement they have been extended. They have been made to include a new kind of instance" (Schon 2011, 30) (we highlight the shift in conception with italics). This generalisation makes functional comparison between unrelated contexts possible. *Convergence* is an analytical tool for functional studies in biology (Vogel 2003, 509) and for evolutionary biological reasoning. It can also be considered as a tool for design and biomimetics (Vincent 2012, 178). TRIZ's extension in biology revealed the gap between biology and technology as the design weakness in utilizing information and structure, on which biology depends as its key sources for invention. Architecture similarly diverges from the biological route to inventive change. With attention to this gap, we offer a particular transfer and extension of TRIZ in architecture for developing a general evolutionary Systems model for design based on *convergence*, that we call ArchiTRIZ. Inevitably every shift in context will bring changes according to the new environment.

Evolution should be viewed as a system "in which organism and environment coevolve, each as a function of the other" (Lewontin 1983, 282). This eco-constructivist view, later named niche construction (Odling-Smee, Laland and Feldman 2003), applies to both biology and culture. The implications for architecture are interesting. First, this displacement brings the ecological concept of niche into the context of architecture, subsequently making niche space, niche construction and ecological inheritance a potential analogy and operative concept for architecture. Second, this implies a shift from the standard architectural evolutionary model as building adaptation to environment (simple replacement of 'organism' with 'building') to modelling architectural change as an inseparable part of the adaptive and integrative link between organism and environment. We create environmental change with our architecture, which in turn changes the architecture we need. This feed-back loop affects more than climate change, availability of resources and loss of biodiversity. It means that architecture is an agency for adaptive (changing) integration of us with our environment. Thus we consciously adapt design to environment while unconsciously adapting environment to design. The latter is invariably destructive, leading to resource-intensive design and the isolation of architecture from our natural environment and ecology. This is unfortunately a common architectural trend of today, especially apparent in restricted views of sustainability, such as low-energy solutions focusing on strategies such as the passive house. This leads to increased insulation of buildings and dependence on mechanical and electrical control of the indoor climate. Architecture has much to learn from biological and vernacular structures regarding integration with the immediate surroundings, adapting to services, which are already available rather than imposing alien assumptions.

From this revised understanding of architectural change, the evolutionary Systems model for design based on *convergence* indicates *convergence, homology* and *development* as nested evolutionary processes of design and forms the basis for correlating biology and architecture by means of inventive problem-solving (Figure 1). This model makes architecture comparable with biology on three levels: (1)

evolutionary reasoning (2) *convergence* of design solutions, and (3) ecological niche space as an analogy for architectural space. Based on the proposed *convergence* model, Material-Ontology is presented as a tool for modelling and mapping pattern – process information and structural hierarchy to activate design by transfer and integration of knowledge to better access the first design path highlighted above.

3.1: Evolutionary Design Reasoning Using Computational Ontologies

Modern ontologies present knowledge in a formal and detailed manner, modelling the world as a network of things (house, tree) and concepts (structure, plant) linked by relationships (is-a, has-part, is-part-of, has-function), all of which can have data properties (size, weight) producing a logical compendium of form, process and context. An ontology uses open world reasoning and so can function with incomplete and partial information (the World will never be fully described) whereas a database requires information to be well defined and structured, as well as complete, and so assumes that it is describing a closed, total, world. A database is thus essentially a static historical document, whereas an ontology is dynamic, can be expanded and changed at will, and has gained importance in a wide range of applications for structuring, analysing, sharing, annotating and integrating data. As an example, one of the most significant developments has been in ontologies of biology. The larger an ontology becomes, the more powerful and accurately it can deduce and interpolate information, which is ideal for a topic as complex and large as medical biology (Robinson and Bauer 2011). The Gene Ontology is contributed to by researchers around the world and provides functional and semantic similarity analysis of genes and their products, together with data-mining, and is capable of delivering clinical diagnostics. Currently we are building an ontology of *convergence* for evolutionary design reasoning. *Homology* is incorporated, since inventive change is made explicit only in the context of ‘phylogenetic’ history or evolutionary design (in the case of architectural change, classified by material). The ontology can be interrogated to extract information relating to specific design problems and locate change indicators.

We choose the name Material-Ontology, MatOnt for short (Figure 2). We use Protégé, an ontology editor publicly available from the Stanford University that supports OWL2, the Web Ontology Language. We are developing MatOnt to provide a general framework and common data standard for comparison and integration of biological and architectural data, spanning various levels of complexity, for systemic analysis, integration and systematic transfer of knowledge. This information can be harnessed to develop material-based structural systems with multifunctional and adaptive properties, always striving for *ideality* (loosely defined as maximum output for minimum input), which can be adapted for locally specific architectural applications. The *Convergence-Homology* part of the ontology models similarities based on patterns of inventive change. This makes it possible to transfer knowledge from biology to architecture, translating the components of the TRIZ *Contradiction Matrix* into architectural terms. Since TRIZ is applicable to the solution of most problems, we have access to most of the problems posed in architecture ranging from physical and geometric to ephemeral. The Development part of the ontology models structural hierarchy, developmental pattern and complex causality (including epigenetic processes of inventive change), integrating heterogeneous data, specific to different levels of complexity, from multiple sources spanning disparate fields. It is possible to introduce Bayesian statistics, allowing parts of the ontology to become decision trees using fuzzy logic. Andersen and Vasilakis explored the possibility of incorporating STEP (an international “standard for the Exchange of Product Model Data”), for linking ontologies with shape modelling as part of AIM@SHAPE research efforts. STEP uses

EXPRESS as its data modelling language based on object-oriented programming, which is widely in use in industry and CAD/CAM contexts. This language is powerful as "it provides system-independent formats for describing product model data, and addresses the key engineering problems of portability, interoperability, longevity and extensibility" (Andersen and Vasilakis 2007, 26). Ontology-based simulation methodologies developed in agricultural systems modelling pave the way for developments related to the latter subject (Beck et al. 2010). The ontology then becomes a legitimate design tool.

MatOnt is not limited to any single class of material. For the present purpose we focus on wood and ceramics. Considering the use and evolution of these materials in architecture we need to consider material, history and environment. An important source of information is Ashby's *Property Charts* (presenting "breadth rather than precision" (Ashby 2005) that map materials into structure-property space. Material properties, which include price, ease of recycling, etc., are presented graphically, two or three at a time, sometimes compounded (e.g. stiffness and density can be compounded as stiffness per unit weight, or specific stiffness). The charts show current usage and properties with design criteria superposed. The empty spaces on the charts present challenges for development of new materials and structures. With its ability to include biologically-derived *convergence* for innovations in design, MatOnt can help fill these empty spaces.

3.1.1 Material-Ontology of Wood

Worldwide, wood is more used than all other materials combined. Culture has evolved in favour of "dense solids: steel, concrete, glass" whereas nature continues to invent using "cellular materials: wood, bone, coral" (Ashby 1983). Could the basis of this divergence be that design in culture has not evolved to match nature's subtleties?

Indeed, the specific properties (importantly, specific strength, stiffness and toughness) of biological materials, occupy the same material property space as artificial, man-made, materials. Thus it is worth developing biomimetic materials since, as Philip Ball said “while we can improve on iron by turning it into steel we haven’t made much significant improvement to wood or leather, for there is no need . . . We still do not have a material that rivals wood in its subtlety of structure and property” (Ball 1997). Wood is the most efficient material in terms of weight supported per unit weight of support, and leather is still the most durable of flexible materials.

In vernacular use wood is durable and tough, and there is plentiful information on its diverse properties, even though emphasis on *Pinus radiate* (a very fast –growing wood of low density) has obscured many of them. Remember that Harrison made the first accurate clock (winning the Longitude Prize) from wood, confirming the predictable and consistent properties of this material, properly used. Many of the properties and uses of wood have been explored in MatOnt, covering a wide range of hierarchy, emphasising that the durability of the tallest tree is ultimately dependent on the predictability and durability of its composite structure of cellulose fibres in a matrix of lignin. Hence we take an alternative path: adapting to the structures of wood, and Material-Ontology describing wood.

In a hierarchical material such as wood there can be no fixed boundary between material and structure. The hierarchical structure covers at least 8 orders of magnitude: (1) a tree has (2) trunk and branches made of (3) xylem (and other) tissue (4) a cellular structure whose (5) cell walls are made of (6) macrofibrils composed of (7) microfibrils, each composed of (8) cellulose molecules. Within the cell wall the macrofibrils are bonded within a network of less well-ordered cellulosics, protein and phenolics. Variation in morphology, chemistry and volume fractions is available at all levels of this hierarchy, giving rise to an exceedingly wide range of properties that can change over very small distances. This can deliver advantage, such as remarkable toughness, but it can also give rise to unpredictable and inconvenient changes in mechanical properties. For instance, as a general rule the best performance is obtained by following the fibrous orientations within the wood and splitting it rather than cutting: the best long bows are made of split yew wood. The resulting continuity of fibres within the structure yields outstanding mechanical properties, but splitting also yields shapes that do not conform to modern automated manufacturing. These factors are all explored in MatOnt.

What if we could control the orientation of the fibres? Charles Neville (Neville 1993, 147) distinguished two processes in the generation of natural fibrous composites (which includes insect skeletons, dogfish egg-case, and a multitude of other biological structures as well as wood): primary (the fibres are laid down in their final orientation by self-assembly mechanisms, which are probably all directed by liquid crystal structures) and secondary (fibres are oriented after deposition due to imposed strain fields or to changed chemical or physical conditions leading to reconstitution of liquid crystal structures). Given that the orientations of fibres and the architecture to which they give rise can be studied in materials such as wood, and that the load-bearing structures of many plants and animals converge on a small range of microfibrillar organizations, we have a morphological *convergence* which points to a biological innovation barely yet explored for technical transfer. Yet we understand large parts of the chemistry and have a multitude of industries, old and new, which rely on the manipulation and orientation of fibres.

3.1.2 Material-ontology of ceramics

Wood and biological ceramics (e.g. bone, sea-urchin test) are natural structural cellular materials. Wood is light-weight and has relatively low stiffness, a trade-off for its remarkable toughness. The crystallinity of biological ceramics gives rise to some of the hardest and strongest of materials, which are more dense but tend to be brittle. Under nature's guidance, materials such as mollusc shell, nacre, bone and hexactinellid sponge spicules are rendered tough and durable, increasing their work to fracture by more than a thousand-fold over the ceramic which forms 60-99% of their structure. In biological structures they replace the metals used in our technologies. As with wood, we need to know what use we might make of such material properties, and understand whether it is worth trying to generate such properties in our convergence on nature.

Biological ceramics are made from clay particles, silica or calcium salts. These might be mixed but usually occur separately, reflecting the limited number of physiological processes leading to their formation. In every case so far examined the mineral is laid down over or within a matrix of protein or protein-polysaccharide. Sometimes this organic scaffold directs the deposition, as in bone where collagen fibres provide an organised haven for microplatelets of hydroxyapatite. In eggshell and sponge spicules the ceramic and scaffold are more intimately associated in a molecular composite. The trick, still not understood, is to produce crystalline structures of a given size, or to deposit the ceramic in an apparently disordered structure that still gives molecular indications of strict organisation. These manipulations produce high quality materials at ambient temperatures that we can imitate only by using high temperatures. Once again the answer is to be found in the control of deposition structures, but the apparent simplicity renders the process inscrutable.

3.1.3 Size matters

However part of the skill of using *convergence* is to understand *scaling*. Will the morphology or function that I wish to adapt work in the same way at a different size? Some aspects do not scale, and an example is fracture mechanics. The size of fault that will give rise to a fracture under a given load is a function of the material and not the structure, although the load and the way it is fed into the material is a function of the structure. Since ceramics are extremely strong in compression but, usually, brittle and susceptible to such small faults in tension, there are ways in which the structure can ensure that the material either remains in compression all the time, or dissipates the energy (and therefore the force) that can feed into the fault. Nature uses curvature in very subtle ways and so suppresses tensile loads. This appears in the evolutionary development of arches. Most effective is the catenary (inverse) arch that is strong under uniform vertical loads. But loads cannot always be predicted either in magnitude or direction and the brutish resolution of the problem is to add more material, which of course increases the load on the arch. In biology the mantra is “Material is expensive, design is cheap”. So with more thought, Nested catenaries (Sunguroğlu Hensel and Baraut Bover 2013) and Complex brick assemblies (Sunguroğlu 2006; 2008), provide very elegant solutions (Figure 3). However, the ideal is to insert safety at all levels of the hierarchy, thus preparing for a wider set of eventualities. In this instance the answer that *convergence* might give is a modification of Catalan vaulting whose use of layered tiles rather than bricks or stone is very reminiscent of the platelet structures of mother-of-pearl (=nacre), an unusual ceramic material made of 95% aragonite (a form of chalk) platelets in a relatively soft protein matrix. Nacre can withstand tension by the platelets moving slightly against each other and, because of their irregular shape, jamming up against each other. The movement dissipates energy; the jamming of the platelets ensures (1) that overall stiffness is regained and (2) that the rogue strain energy is transferred to some other part of the shell where the platelets are still free to move. At the expense of a tiny amount of movement the work of fracture of nacre is increased by a factor of 3 000. A directly analogous example is the primary energy absorption mechanism of wood, which is due to the helical winding of the fibres around the hollow centre of the wood cell. The advantages of such a fibrous architecture are available at any size. Under tension, the helices tend to straighten and collapse into the cell lumen and develop high shear strains relative to their neighbours. The shear strain leads to fracture, but it is the matrix between the fibres, not the fibres themselves, that breaks. Thus the main load-bearing fibres remain intact and continue to function, while strain energy is absorbed. There are, or must be, many other such mechanisms waiting to be discovered and transferred into our technology - unfortunately the transfer is not yet happening.

Rather than bonding strength, we are led to two strategies: topological interlocking (Dyskin, Pasternak and Estrin 2012) and toughening (Ashby 2005, 3255). “Self- shaped brick” with double-curvature which allows (a) close packing, and depending on constraints (b) relative movement of discrete units, is one step forward in this direction. Guastavino vault (a plywood-like tile composite) whose strength relies on cohesion, lacks the material qualities of a cellular solid whose porous structure exhibits properties that are different from a monolithic, homogeneous, material. This limitation had given way to the invention of a masonry tile that incorporates small air spaces, as well as a plaster, called “Akoustolith” (patented in 1916). Guastavino Jr. and Wallace C. Sabine from Harvard, who came up with this idea, showed that when covered with this material the interior wall and vault surfaces act as sound absorbents, eliminating the undesired acoustic effects by 60% (Collins 2002, 36). In this way, the strength and acoustic properties were combined. But porous materials have many advantages covering a wide range of functions. Biology is full of those examples, which demonstrate the remarkable multifunctional properties of structural porosity, one of which is the echinoderm skeletons. Given the relatively low hardness of calcite, the incredible strength of sea urchin spines, which is composed of a single mineral of calcium carbonate, comes initially as a surprise. While being strong, this fenestrate structural material is also light-weight, producing a strength-to-weight ratio that exceeds “man-made construction materials such as brick and concrete, and that of all but one of the mollusc shells tested” (Weber et al. 1969). A simple device: hierarchical fracture control achieves this by distributing stress over a larger surface area, hence maintaining a constant stress state, and localizing crack propagation as a consequence of the redundancy of connections between structural elements. The *convergence* of form in calcite skeletons and calcareous rocks (among others) on cellular solids brings attention to a process other than mineralization, that is, “cavernous weathering system” of tafoni. This complex yet seemingly more immediately accessible phenomenon for transfer of effects to architecture that may offer an alternative pathway to the design and production of porous ceramics. Part of the trick is the concentration of humidity and cyclic desiccation (Turkington and Phillips 2004).

Another scale dependent mechanism is self-bending, which in wood (with the involvement of reaction wood) develops a curvature that determines the inner contour line of a tree fork or branching stem. It is interesting but nevertheless not unexpected that this type of curve found in trees is analogous to the geometry of nested catenaries, in this case forming an arch that follows the path of uniform axial tension under gravitational forces. Using computer-aided optimization method based on finite element modelling, developed at the Karlsruhe Nuclear Research Centre for the analysis of biological growth and for engineering design, it was found out that this shape was critical for uniform stress distribution in the areas where otherwise high notch stress concentrations would develop due to bending loads (Mattheck 1998; Mattheck and Vorberg 1991). In its search for light, a free-standing tree behaves quiet unlike a spatially constrained tree in a dense woodland by bending the branched stems away from each other rather than towards one another. Accordingly, two types of curvature and two types of tree fork are revealed: tension-fork and compression-fork. How closely these curves approximate a catenary both as a continuous (tension-fork) and pointed arch (compression-fork) still needs to be examined. However, it is the level of predictability and consistency to which this heterogeneous material adheres - despite the variations within and between individuals as well as species - that is the more astonishing. The relations between the material architecture of organized fibres across length scales and shape with a load-bearing function can give us clues about the formative processes behind the tension arch in trees.

4. Summary and Conclusions

We have discussed a general unified Systems approach to design, considering evolutionary models based on *homology* and *convergence*. The potential of *convergence* for architecture, has been little explored. We focus on *convergence* as a tool for design by evolutionary reasoning making architecture comparable with biology in the shared problem of functional integration and adaptation. This shifts the attention from change by variation to inventive change. ArchiTRIZ, a derivative of TRIZ in the context of architecture, is proposed as a Systems model, reconfiguring *convergence - homology - development* as nested patterns and processes of design. Based on this model, a unified approach to linking Systems, as an "unrestricted" science (Pantin 1968) of organisation and complexity, to design is presented.

We take the first steps in this direction using a formal ontology and ArchiTRIZ as a model framework. These combine in a Material-Ontology ['MatOnt'], which we introduce as a computational tool for mapping information about wood and ceramics and relating this to structure. MatOnt can then be used for exploring structural systems with multifunctional and adaptive properties that can be adapted for locally specific architectural applications. MatOnt has the potential to generate and modify program code for geometric and topological representation of models as well as to describe model dynamics mathematically for simulation and be connected with external data sources. These two areas of further research will greatly improve modelling and simulation of architectural systems.

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