In Search of Systems “DNA”

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***Abstract*—General Systems Theory (GST) has been an attempt to put precision into the term *system* thereby making intelligent communication between its users more attractive, something that provides for migration of ideas and the possible resolution of issues by borrowing solutions from unfamiliar domains. We propose to build on GST and in particular, as von Bertalanffy once did, draw on the biological sciences, now hugely advanced beyond that ever imagined by von Bertalanffy and his peers, and use its findings, architectures and emergent behaviors, to argue for a biology of technology and enterprise systems. We do so by expanding on a system of “togetherness characteristics” and in particular explain how these can be applied to better understand familiar systems, e.g. the automobile, and how such systems form part of diverse wider communities (or containing systems). We seek a science and approach that we believe will provide richer insight into system failure, 'health' maintenance, repair, replication, growth, and mutation, all those features of the evolution of systems which constantly challenge us and which thus far we have only been able to explain via macro-level models and tools. We propose to go deeper into the structure of these systems and to discover the "DNA" (building blocks) of these systems. Thus establishing a foundation to understand their behavior using biological analogies which we believe will turn out to be more than metaphors. We assert that these systems have micro-structures which will explain their individual life cycle and their communal ecology.**

***Index Terms*—systomics, biology of systems, sysDNA, general systems theory, system of systems**

I. INTRODUCTION

The ubiquity of the term system is perfectly illustrated by its frequent use in every conceivable discipline and human endeavor, from politics to pediatrics, from economics to ecology, and from choreography to computer science. How can one word mean so much to so many diverse users and yet mean something to itself, (other than the word *thing*, but with far less precision)? General Systems Theory (GST) has been an attempt to put precision into *system* and thereby make intelligent communication between its users more attractive, something that would provide for migration of ideas and the possible resolution of issues by borrowing solutions from unfamiliar domains. For example, today scientists from a myriad of specialist domains are leveraging the fundamentals systems thinking as evidenced by the wealth of interest in systems biology [1].

However, the world has changed dramatically since the GST vanguard formulated its initial thoughts and partly this change is because of the success systems theoreticians have achieved [2]. Our world is now replete with complex systems produced by an admixture of arts and sciences professionals and this population of systems now appears to have a life-force all of its own. Systems, in their own right, are said to be essential, interdependent, vulnerable, decaying, replaceable, sustainable, removable, regenerative, reproducible, governable, adaptable, agile, and resilient [3, 4]. Advances in nanotechnology, artificial intelligence, and robotics have led futurists to declare that systems will become increasingly more autonomous and possibly even self-aware [5]. Perhaps, at some point, these systems will want to form a more perfect union with equal rights for all and a government of them, for them and by them? Whether in their progress they will avoid tyranny and strife among themselves better than their designers is unknown. Until such time it is clear to us that a revisitation of GST is essential, but now the goal is not so much facilitating a communion of systems professionals. It is rather to deepen our understanding of a system as a system which will enable us to access this notion of a system’s life-force and thereby make appropriate intervention, for any system, to enhance resilience, reduce vulnerability, improve governance, facilitate reproduction, and possibly enable cooperative interdependence among systems.

Therefore, we propose to build on GST and in particular do as Ludwig von Bertalanffy [6] once did, and that is to draw on the biological sciences, now hugely advanced beyond that ever imagined by von Bertalanffy and his peers, and use its findings, architectures and emergent behaviors, to architect a ‘concept exportation’ [7] for a biology of systems. While systemic and cybernetic theory focuses on processes and the bringing together [8], we want to focus on the essence of “togetherness” and a science that can explain and leverage this.

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As GST sought to “more fully understand the intersection between values and assumptions or a particular framework and its theoretical formulation” [9], we seek a science and approach that we believe will provide richer insight into system failure, ‘health’ maintenance, repair, replication, growth, and mutation, all those features of the evolution of systems which constantly challenge us and which thus far we have only been able to explain via macro-level models and tools. We propose to go deeper into the structure of these systems and discover the “DNA” (building blocks) of these systems. We assert that systems have micro-structures which explain their individual life cycle and their communal ecology.

Boardman and Sauser [10] presented a set of five characteristics to capture the essence of togetherness which we understand to lie at the heart of what makes any system a system, and which conceivably can provide a unique signature of that system. They used these “togetherness characteristics” to draw striking differences between a system (of parts) and a System of Systems (SoS). The provenance of these characteristics is provided by an extensive search of the SoS literature and analysis of the most significant findings from that search. In an earlier paper [11] we explored these characteristics to a deeper level, one that defines the genesis of systems or SoS. The objective was to provide a pragmatic basis for better decision making during the conception, realization, and operation of systems while exploring their utility and purpose. In this paper we further articulate our ideas for a systems DNA. We do so by expanding on the “togetherness characteristics” and in particular explain how these can be applied to better understand familiar systems, such as the automobile, and how such systems form part of diverse wider communities (or containing systems). In regard to automobiles, we seek to ensure that these not only be driven in the right direction but, at least as importantly, be designed in the right direction, i.e. towards having an greater intelligence within themselves supporting a smarter involvement at higher order levels such as traffic, social networking, and corporate resilience.

II. THE SEARCH FOR SYSTEMS “DNA”

To define a living cell or a computer we use differing and diverse definitions based on fundamentally different building blocks, but to describe them as systems, we use equivalent distinguishing constructs first presented as GST. When Ludwig von Bertalanffy wrote about systems as GST in the 1940s, he described eight fundamental constructs that provide for a unification of all systems across domains. GST addressed the transdisciplinary study of the abstract organization of phenomena, independent of their substance, type, or spatial or temporal scale of existence, while in a continual attempt to develop integrated phenomena of study in any of a number of different disciplines [12]. It is these 8 fundamental constructs that underlie all systems and provide a basis for unification: (1) system-environment boundary, (2) input, (3) output, (4) process, (5) state, (6) hierarchy, (7) goal-directedness, and (8) information [6]. Despite these constructs, they do not define fundamental building blocks of systems, but rather the functional and physical states of what we may define as a system.

When Ashby further defined these constructs of general systems theory he stated that a system has a self-organizing process where the organization of a system spontaneously increases with a decrease in statistical entropy and an increase in redundancy, information, and constraints [13]. This too does not tell us what the fundamental building blocks of systems are, but expands our understanding of the state relationships that may occur in a systems life cycle. The evolution of GST from von Bertalanffy in the 1940s has seen the fundamental concepts applied to many areas and brought about new disciplines and phenomena: systems engineering, systems design, systems analysis, systems approach, cybernetics, and systems science to name a few [14]. While the theory of systems is still evolving, there are still no defined and developed building blocks of systems.

Most sciences have fundamental building blocks by which they can define and build upon the scientific study of their discipline (e.g. biology, genomics, DNA). The traditional approach in the sciences has been a reductionism and discovery approach to understand what the fundamental building blocks of their discipline are. For systems, it has been this same reductionism and discovery applied to understanding what makes them function, not what are they made of, to define what they are. Biologists have used this approach to take a holistic look at biology which is termed systems biology. But in biology we know the fundamental building blocks of all biological systems, DNA. These building blocks are assembled based on an architecture that is dictated by their behavior. The architecture of DNA comprises a double-stranded helical structure in which the two twisted legs of the ladder are made of phosphates and sugars, and the rungs made of nitrogen bases. The work of many scientists contributed to this definition but it was Watson and Crick [15] who discovered what the rungs were made of and how they joined together and to the legs. From the biological perspective the crucial questions to be resolved were those of growth and reproduction. The architecture settled this with the particular sequence of nitrogen bases in the rungs containing the coding or instructions for growth and the bonding within bases, being limited to specified pairs, conveying the reproductive signature.

What might it mean to speak of “A Systems DNA (sysDNA)?” If such existed and were possible it could mean that we had access to the vitality of a system in terms of its growth and reproduction, in and of itself, and possibly a means or perhaps the means to adapt it at a genetic level with some guarantee of the out turn, which perhaps we do not normally have by traditional systems studies. But why should it exist? There are many reasons why it should not. For instance we know of no body of knowledge for systems that is equivalent to chemistry for physiology or biology. Perhaps it is mathematics but the application of this to systems per se rather than to models of particular systems is notoriously lacking. Another primary reason for the non-existence of a systems DNA is that there is no prima facie reason for it to exist. It is one thing to explore natural systems, since life is what they have in common. But what do designed systems have in common that is a mystery we might believe will yield to an equivalent biology, physiology, chemistry or physics? How can so very many ad hoc man-made designs possibly bear a common imprint that would suggest an underlying DNA. It's unlikely if not inconceivable. And yet we search.

Then for systems, which are mostly technology intensive, can we define the fundamental building blocks by which we can then apply a systems study to? One thing that systems do have in common or at least is said that they do is an architecture. However this is codified and there are multiple instantiations. What this does convey is conceptual design from which the detailed system later takes its form and thence its function. Is system architecture the systems DNA? Unlikely since it is almost certainly specific to each system, although patterns might be observable across the spectra of system architectures, certainly across given types of systems. So somehow or other the system architecture may have something to do with a systems DNA, but revealing the independent existence and nature of the latter is still what we desire. If it exists. Traditionally, the attempts to understand the lifecycle of systems has been through the engineering of systems or systems engineering. Some have stated that systems engineering provides us with a process by which we can design, develop, and manage systems, but it does not tell us what makes up a system. What are the systems building blocks, so we can define and study the biology of all systems?

We want to be able to rely less on reductionism and discovery to understand systems, but move to a more hypothesis-drive and discovery science approach to systems. Most systems are fundamentally complex with multiple parts, and it is almost impossible to fully understand and study something with so many parts. In reductionism we would reduce that down to the lowest level possible, but leaving ourselves with the improbable task of trying to relate this to the original problem. Systems biology has attempted to apply general systems theory to being able to explain the integrated and interactive nature of biology from the molecular level to the macro level. The study of systems has no molecular level, there is no "systems systology." GST has given us the architectural constructs to understand, design, and describe the behavior of systems at a level comparable to the study of proteomics, and GST has allowed us to architect at higher levels of functional, physical, and environmental. We present here that we contend that there is a molecular level below GST that we have not fully discovered or defined, which we define as *systomics*, the study of sysDNA. Therefore, we are asking the fundamental but not trivial questions, "What is the DNA of systems?"

III. FORM AND FUNCTION

Systems, as objects in the real world or as concepts imagined, are said to have two primary aspects to their being: form and function. Form determines or reflects the shape or structure of the system, and function represents the behavior or purpose of the system. Designed systems, such as automobiles, aircraft, computer operating systems and city libraries, are meant to have a form that enables them to perfectly fulfill their function. Natural systems, whether they be 'designed' or evolved, seem also to have this fit of form for function. As functions change, for example with the need to adapt to different living conditions, so form will change to suit these new environmental circumstances, as though the system had some higher-level purpose e.g. to survive or to prosper, and a 'knowledge' that form must always follow function. By the same token, a system's form affects functionality and may itself be a driver to adopt new types of behavior. In other words, form and function interact making the system what it is.

Relative to conceptual systems that are actually a means of design (of other systems), for example systems engineering, considerable emphasis is placed on translating functional requirements into structural elements by a complex process of elicitation, comprehension, decomposition, allocation, validation integration and verification.

The systems engineering system, for the design of many complex products like aircraft and automobiles, places great reliance on a particular style of form, or structural organization, and that is hierarchy. This is no bad thing since it is a premier organizational form for many living systems. But it is not the only one. Networks are a different organizational form and these are the chief signature for food webs, the way the human brain is organized, and social 'circles'. Recognizing the virtue of these systems as being naturally robust, and this being a property of the network organizational form, designers, including systems engineers, have leveraged this signature for their own purposes in for example the design of utility networks, airline transportation systems, and data communication systems. Interestingly where some systems are left to evolve, for example the Internet, subject to a few rules, network signatures emerge similar to those of wealth distribution in unplanned economies and river drainage [16]. Form, whether it be designed or evolutionary, and whether it be hierarchy, network or some other signature, is a clear pointer on the journey to discovering sysDNA.

A. *Hierarchy as form*

We have come to use the hierarchy form very strongly when we think of an automobile, for we see it largely in terms of the assemblies from which it is made: the engine, the transmission, the suspension, the steering and the interior which of course includes seats, controls and instrumentation. Holding these together is the chassis, a primary assembly all of its own, and the body of the car. Now for some this last item is the most important. Appearance is everything, denoting status. Others different perspectives emphasizing ride quality, or safety in the unlikely event of a serious collision, or infotainment quality in terms of satellite navigation, audio and video. Regardless of the priority that drivers give to the qualities or functions of the automobile, it is natural to think of this system in terms of its primary elements, any one of which can undoubtedly be broken down even further into smaller pieces. This organizational form is a powerful force that grants stability to the various components making it easier to organize these even further as we move from basic pieces to the automobile itself. From bottom to top, hierarchy is an unrivalled mechanism for bringing order. Hierarchy works. But it's not the only organizational form.

B. Network as form

Hierarchy can apply to technology systems, such as an automobile, and to people systems, such as a corporate organization. Networks apply to people systems but it applies to technology systems, and in more ways than is self-evident. In fact this non-obvious application is one of the roots of our thinking. The clamor for network-centricity from industry and commerce generally, and for net-centric operations/warfare from the U.S. Department of Defense in particular illustrates the power of the network form but sadly deafens us to the whispers of broader and more imaginative applications.

From their inception, or thereabouts, Sun Microsystems gave us 'The network is the computer'. It sounded great. No-one really knew what they meant. It turns out they didn't know what they meant! But not only did it sound great, it seemed right. The history of computing had focused on the machine, the artifact, the thing that processed data. It had inner workings; it had an input device, so that you could tell it what to do and with what information to work; and it had an output device so you could check the results of a processing operation. We had a strongly node-centric view of the computer. It was a machine. It may have been made up of much complex circuitry, a labyrinth of wires that suggested its interior was a network, but it, the machine, was not a network. It was discrete, monolithic, integrated and mechanistic. If it was anything, it was a hierarchy of elements: a central processing unit (CPU), input/output (I/O) devices, memory elements of various forms, and a clock, to keep its heart beating. Whatever was the network was 'out there', outside of the machine, something that the machine – the computer- would get plugged into. A network of many machines, and a variety of devices, spread far and wide. Now we were being told that this network was the computer. It was like being told that the particle was really a wave.

The computer is no longer that which is in our possession, in our grasp, held by our hands and under our control, but it was really part of an ever rolling ocean that throws up in ways beyond our control a perpetual series of waves. Perhaps the mantra was pointing to new forms of architecture in which computers would operate? The client-server architecture certainly shattered the traditional notion of the mainframes and of its smaller, more agile progeny the minicomputer. Suddenly you were not alone; you were part of a computer society. You still had your autonomy but if you were smart you joined this society. Your belonging benefited you and affected it, stimulating its attractiveness, growth and expanding both its connectivity and diversity with each new client bringing a unique individuality. Unsurprisingly, this architecture became the forerunner to a global technology system we know today as the Internet overlaying which is the World Wide Web, the global village's new wheel. Maybe that is what Sun Microsystems meant?

Interestingly, one of Sun's founders wrote a $100,000 check as seed-corn for two young men, who had recently dropped out of Stanford's computer science PhD program, in order to found their new corporation to exploit a search engine they had developed. That initial investment is today worth in excess of $500 million and Larry Page and Sergey Brin, are multi-billionaires. Their company Google is rapidly approaching the size of Microsoft and its core technology is all about finding the right information, for maybe as many as 100 million people everyday, from the network that is the computer!

C. Function as form

Of course we can build networks using technology; transportation and communication networks have long since been part of the engineer's repertoire with highways, railroads, airways, and telecommunication systems being prime examples. That much is clear. But can we build pieces of technology, components of systems or systems themselves, in accordance with the network form, as opposed to hierarchy? And what might this mean? How would such pieces of technology differ? In both form and function? And what methods (fit) do we use? The same ones for both or different ones?

The answers to these questions lie in the philosophies of design expounded by Goode and Machol [17]. They spoke of two types of interdependent design: interior and exterior. Today, systems engineers concentrate heavily on interior design, in other words finding the form of systems relative to the function that they must perform. Because the functions derive from a consideration of the exterior, systems engineers believe that they are in effect doing both. But in fact this is a false view. The design of the interior and exterior must proceed *simultaneously* so that changes in function could be reflected in form and vice-versa.

The environment for today's systems has never been more turbulent, uncertain, unknowable and hostile. Terms such as asymmetric threat, co-opetition, and globalization capture this dynamic. The appropriate response to these conditions, with the associated demand that the design of systems must respond to dynamic capabilities rather than simple statements of function, is to adopt function as form whereby system structure mirrors behavior and form itself is a dynamic blend of hierarchy and network.

IV. THE CHEMISTRY OF TOGETHERNESS

The cell and a system (in the abstract) have three things in common: structure, function and lifecycle. The cell has the advantage of chemistry to explain structure. The system does not. The cell has its vitality encoded chemically. But this encoding, essentially deals with patterns of organizational form to which we can usefully impute anthropomorphisms. Carbon, for example, is very agreeable, more so than any other element. It happily builds relationships with other elements. Some architectural forms are rugged, difficult to break. Others are fragile. And yet both types may consist of the same elements, just differently arranged. This line of thinking gives us a clue as to how to build a conceptual chemistry and with that the fundamental building blocks of systems such as satellites, battleships and the product development teams that build them. We believe that the essence of a system is 'togetherness', the drawing together of various parts and the relationships they form in order to produce a new whole that will have its own structure, function and lifecycle. That said, we want to embark on a discovery of 'togetherness,' and our conceptual chemist set currently consists of five elements: autonomy, belonging, connectivity, diversity, and emergence [10].

For each of these elements, there are opposing forces or paradoxes that are influenced by fluxes in realizing or recognizing a system [18]. This balance is considered reversible. Reversible is conditions under which the forces are so nearly balanced that an infinitesimal change in one or the other would reverse the realization of the system. In any system we seek ideal conditions that the realization of the system is carried out reversibly. Under these conditions the realization of the system yields the maximum possible performance; although, reversibility does not hold true in practice. The flow of these forces and their relationship work in distinguishing types of systems (i.e. system or SoS) and determines the togetherness of a system which fortifies its realization.

In biology energy plays a fundamental role in the chemical and physical process that help to realize all living systems. For systems, we contend that this energy is to biology as togetherness is to systems. In this section we want to explain their meanings and origins. In the remainder of the paper we will concentrate on their utility and development.

A. Autonomy

This is the ability to make independent choices. The beauty of independence is to be able to pick and choose interdependence. Thus autonomy is less to do with the freedom of something, from all other things, and more to do with the exercising of choice among several decisions that affect and are affected by other things, including those that increase or decrease choice. Autonomy always finds, though it be argued that it never needs, context, and it is fully exercised within a forever changing firmament of contexts.

The reality of legacy systems relative to an envisioned SoS is inescapable just as individual freedom of choice is incontestable. For human beings autonomy is a person's ability to act independently. What of a system? Each legacy system that is envisaged to become a constituent system in the SoS must be accorded autonomy, the right to pursue reasons for being and to fulfill purposes through behaviors. Respect for this autonomy is paramount and it is a respect that the SoS itself must pay. That is not to argue that the legacy systems cannot be migrated or morphed to more aptly serve the SoS, but it is to argue that such transformation must be out of respect for that constituent system's autonomy. To do otherwise is to imperil that constituent system's functionality and essence of being which might then be lost to the SoS, a foolish thing since it is these features that are wanted for inclusion. We argue that the capabilities of the SoS are enhanced by the exercising of constituent systems' autonomy, and that the opposite is true of a system that is not a SoS, whereby its parts must cede whatever autonomy they might have had in a totally subservient act of granting autonomy to the system.

Smuts [19] introduced the term 'holon' which later was explained in more detail by Koestler [20] as being that which is both whole AND part. This term aptly fits constituent systems relative to a SoS. However, it is proposed that a SoS cannot be so called on the basis of structure alone, including hierarchies and holarchies. It must also qualify on the basis of dynamics, for which the remaining distinguishing characteristics provide further explanation.

B. Belonging

Just as legacy systems are a reality so also is the problematique which goes unsolved by these systems, singly and additively. By the same token the envisioned SoS is a reality if only in concept. Someone or some persons see that the SoS, by making use of the constituent systems via a new framework, will in a real sense deal with the problematique. So there are two new realities: the problematique and the envisioned SoS. This makes the second differentiating characteristic, *belonging*, a key one. The SoS cannot translate from conceptual reality into physical reality without the constituent systems belonging. But why should they? What's in it for them? Who can make them belong? What will become of them once they do belong, given that they won't lose autonomy? How will they belong? Will they continue to belong, come what may, or will their belonging be strictly conditionally? Can they exit without hurting the SoS and/or themselves? These are questions that simultaneous interior and exterior design addresses.

The parts of a system (that is not a SoS) have no choice in the matter of belonging since they have no reason for existence and no dynamics to contribute without belonging. Parts in such a system are integral and the system cannot function without them. In a SoS the parts, also wholes and therefore holons, are integrable, i.e. capable of being integrated. It is proposed that for a SoS there must be negotiation between it and each constituent system about the latter's belonging and the former's acceptance. There will be manifestations of the problematique when it is better for a constituent system to unbelong or for it to be believed that they do not belong when they actually do. We must continually bear in mind that the existence of the SoS is to confront a perpetual problematique for which no single point solution, no single system, is adequate. It is not about the system as such but about the SoS capabilities for resolving or addressing the problematique. Hence 'belonging' becomes a core competence or stratagem available to the SoS for dealing with the problematique.

C. Connectivity

Some argue that belonging means being connected. True. Yet, autonomous systems can choose to unbelong and stay connected to the systems with which they once belonged in the system. Connections exist within systems and within the contexts of systems, and they may transgress system boundaries. Belonging is confined within a system boundary, of some description.

For the U.S. military, interoperability translates into net-centricity [21]. They want the same powers of connectivity between their warfighters, commanders and others who 'need to know' that global commerce has acquired via the Internet and the World-Wide-Web, instruments which have transformed business models. No surprises there, except there is an irony considering the U.S. Department of Defense's chief concern is with an enemy that is organized as a network, testimony to the maxim 'fight fire with fire?' (i.e. meaning perhaps both the similarity of retaliation and the willpower/passion behind it). Later we will get into the practical application of the 'connectivity' distinguishing characteristic but for now we want to explain its central importance.

Most designed systems require the relationships between elements to be designed simultaneously with the design of the elements themselves. Thence connectivity between components is considered alongside the design of these components, regardless of the topology of the connections be this integrated, distributed, hub and spoke, or whatever. This design pattern normally leads to hierarchies (or holarchies) and a valued stability in development whereby parts or sub-systems are themselves stable enabling a gradual build up of the designed whole, which of course must also be stable. However many such wholes or systems (that are not of the SoS kind) have designed connectivity to their environment, and this is fixed; it cannot emerge. The problematique that confronts a SoS will ensure that such limited, presciently designed connectivity leads to inevitable system failure.

Therefore we argue that a distinguishing feature of a SoS is that the internal connectivity of the SoS is not presciently designed but emerges as a property of present interactions among holons. Net centricity is a form of prescient design, enabling full connectivity by supporting interactions and connections between all the elements, according to defined protocols. Further it supports extension as more holons are added to the SoS, provided that is these holons conform to the protocols. In our scheme for a SoS this connectivity is itself adapted as holons enter and exit the SoS. And this takes place in a way that enhances the connectivity or interactivity of the SoS with its environment, i.e. dealing with the problematique. In the context of this discussion, connectivity has to do with a lot more than just topologies and protocols and interoperability standards, although it does address these practical matters, and is more concerned with the agility of structures for essential connectivity in the face of a dynamic problematique that defies prescience.

D. Diversity

This is the first characteristic that simply cannot be applied to a single entity, be this part, relationship or whole. Of necessity it must be a comparative notion and it is this kind of thinking that supports the integrative nature of a system, be it cell or satellite. We use this conceptual chemical to argue for the dependence of a system on its diversity, that is its own, that of its parts and that of its relationships. Diversity can affect belonging; for example, some will not join if the system is already too diverse, or not sufficiently diverse. Likewise belonging or not, affects diversity. Diversity can also affect connectivity; great diversity can cause huge technical challenges in supporting connectivity and with that, communication and hence control.

Imagine soldiers who are not soldiers but who wage war that is not war. Citizens who are loyal to no nation state to which they notionally belong but who really belong to the vision of an integrated, faith-based, global-wide superpower governed by a single ruler headquartered in the Middle East. Imagine warriors who are not trained in their country of origin but in foreign lands including that of their enemy and trained by that enemy in skills needed for battle. Fighters who have no armor nor weapons to speak of save the legacy systems of their enemy, namely the Internet, cell phone technology, Boeing aircraft, the air transport infrastructure, up to a point and box cutters. Can you imagine that? If we had could 9/11 have been averted? Our problem in perceiving these threats to an extent lies in our inability to cope with diversity. Ross Ashby [13] posited a law of requisite variety asserting that for a system to be sustained it must have at least the same number of degrees of freedom as the environment in which it operates. To paraphrase, interior diversity must match exterior diversity, or the boundary which separates them is futile. Post 9/11 efforts have largely concentrated on the boundary – understanding it, strengthening it, and in one sense extending it, for example, by military occupation of some nation states. Greater attention is now being given to increasing interior diversity and reducing exterior diversity a role, we argue that falls to SoS thinking and acting, consistent with Goode and Machol.

Engineers have a problem with diversity, summarized in the maxim 'keep it simple, stupid (KISS)'. In an age when complex systems give rise to simple patterns and simple systems produce complex behavior [22], perhaps it is time for diversity to be seen less as a problem and more as an opportunity. There is still ample scope to apply KISS and this will undoubtedly continue in traditional systems engineering. Given that legacy systems ab initio present a given and possibly great diversity, what should the SoS designer do? The purpose of the interoperability framework is to get the legacy systems, holons, to work together, and to do so not additively as in the current underachieving case, but synergistically. Does this mean reducing diversity, and if so how can the SoS match the huge diversity in the problematique it faces? The opportunity for the SoS is to increase connectivity, which probably translates into standard protocols and specific architectures or topologies, an imperative for uniformity, AND increase diversity. This respects the autonomy of the holons, allowing them to maximize their contributions to the SoS but within the context of the SoS.

Increasing diversity is not a license for anarchic design, but it is a spur to realizing resilient capability. Situational awareness is enhanced by multiple perspectives. But in the end a common operating picture that informs command decision is just that: a final conclusion. But no-one wants to make decisions based on a conclusion that is not richly informed, that is lacking a vital piece of data, information, knowledge or wisdom. Diversity, through a variety of viewpoints, processes, technologies and functionalities ensures richness, and the SoS must be able to leverage this, in an unencumbered fashion.

E. Emergence

This is normally attributed to the system level rather than to the system's parts or relationships, but then in one sense scale takes care of these. Our interest is also in knowing how parts emerge by belonging and having connectivity with others, in a diverse whole. The extent to which this occurs can have a dramatic affect on the type of system we have, including Systems of Systems (or SoS). In the cell, the nucleus, part of the cell at some point grows, constricts in the middle and finally divides in two, an elegant piece of choreography that precludes the division of the cell itself. In this case two cells emerge from a single cell but before that occurs the nucleus emerges, merely by belonging to the cell.

The terms emergent and system are inseparable. By definition when parts and their relationships are assembled together what emerges is the system. All systems are emergent. Herbert Simon [23], a Nobel Prize winner, said this another way when he argued that complex systems will evolve from simple systems much more rapidly if there are stable intermediate forms than if there are not; the resulting complex systems in the former case will be hierarchic.

The properties, behaviors and purposes attributed to systems can also be said to be emergent. Some of these, for designed systems including the engineered variety, are intended. For example, it is intended that an automobile serves the purpose of transporting goods and people across reasonable distances and terrains safely, comfortably and in timely fashion. This is an emergent or resulting property of that system. The same emergent property cannot be attributed to any of the parts therein, although every one of these will have its own emergence. Each one is engineered to a specific purpose, to deliver an emergent property: for example the power train to provide propulsion, the wheels to provide traction, and the steering to provide guidance control. With this example in mind one can move up and down the scale of systems enumerating specific emergent properties for each part, sub-system, and system.

Some emergent properties are unintended and of these some are undesirable and others serendipitous. Relative to the auto, perhaps the chief undesirable and unintended behavior is atmospheric pollution most acutely experienced in city traffic. At that level traffic jams are another example of unintended emergence: not a single vehicle is responsible for a traffic jam, it takes a bunch of interacting autos to make one of these. Yet a desirable emergent property at that level is a personal mass transit system, highly convenient if not altogether rapid, one that obviates the need for investment in alternatives such as subways (for cities) and rail networks (for inter-city travel).

The question arises, if all systems are emergent, is there anything different or special about a SoS? A SoS must match the agility of the problematique which calls for greater emphasis on strategic capability than on rigid tactical measures. The exact nature of the SoS is often determined in real-time and indeed at higher clockspeed than that of the environment (or the threat within that environment). The simplest way this can be further explained is to draw a comparison between a system and a SoS.

A system provides a response to a set of predetermined 'requests' i.e. threats or opportunities arising from the environment in which it operates. By contrast, a SoS is an anticipatory responder having an a priori undetermined and unknowable range of responses subordinated to auxiliary mechanisms for anticipation, including disturbing the ability of the environment to pose threats or limit opportunity. In the next section we will use a case example of a proclaimed SoS to show how these characteristics may define and realize a SoS.

V. THE BIOLOGY OF SYSTEMS

We are attempting to provide greater formalism to the notion of system ubiquity, that is to describe a system in the abstract so that system designers and managers of specific systems can take account of this abstract knowledge thereby ensuring that whatever they build is a system not merely because it carries that term in its description but also because it bears the marks of a system as we understand that term. We rely on the notion that a system is a collection of parts and their interrelationships assembled together to fulfill a purpose. Our differentiating elements have something to say about these parts, their interrelationships, the assembling together (process), and the fulfillment of purpose – all in the most abstract sense but in a way that this relates to the specifics of the system under consideration.

We now want to go a stage further from defining the elements and their specious use to making stark contrasts between systems (of parts and SoS). That step is to visit the notion of holon, that which is both whole and part simultaneously. We liken the holon to a spherical object and argue that as such it consists of an inner core and an outer coating, or series of coatings; coatings and core are in continual 'communication' or the holon ceases to exist and becomes either part or whole.

The core of the holon is its competence or competency set and we make the point that this represents the autonomics of the holon, i.e. its dependability to do what it is supposed to do without continual supervision or management attention (see Figure 1). A soldier in an army is not autonomous in the sense that he is under authority. Yet, he is autonomous once he is given an order or command, part and parcel of the authority regimen. In fact, the very order itself signals and emphasizes the soldier's competence to act and to act without further intervention by the authority figure. If this core did not exist no command could be given, otherwise, what would that command be? Similarly, when the driver of an automobile hits his brake pedal he is issuing a command to the braking sub-system having confidence that that sub-system has the competence to perform its duties, execute its autonomics, utilize its competence set, and altogether play its part. So we argue the core of the holon is its competence, its core competence. What then are the coatings?

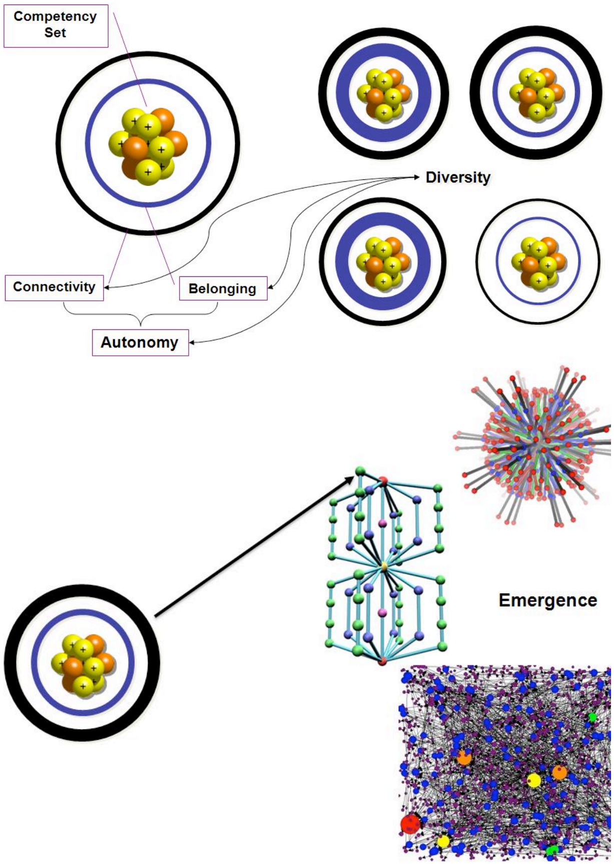

Fig. 1. The Biology of Systems.

We argue that the coatings are principally those of belonging and connectivity but may also include diversity. We think of these coatings as shielding the competence of the holon from whatever higher-order system (or holon) in which it finds itself serving. They act in the best interests of the holon but must also pay proper 'respect' to the higher-order system in which its serves, which will also include other holons. In essence these coatings give the holon its autonomy since they can determine matters of timing, choice to act or not act, and even negotiate the wisdom of actions that call upon the holon to act. The degree of holon autonomy is reflected in the degree of coatings, recognizing that to belong at all means having a will to act in the best interests of the higher-order system at least as far as the holon sees matters. For a soldier this autonomy is limited, but perhaps not non-existent. For a braking sub-system in an automobile, the degree of autonomy is changing as the vehicle becomes more intelligent and in principle able to do a better job than many drivers. However that superior performance relies on decentralized control in which sub-systems (aka holons) have not only superior cores (autonomics) but also superior coatings. Our search then is for how these coatings can be applied, how they can be changed, in light of experience and new knowledge, and how they interact with the core and with the higher-order system.

VI. AUTOMOBILE PARTS AND WHOLES

The need to regard an automobile hierarchically is seemingly inescapable. A car must have an engine, a transmission, a suspension and so on. Each one of these assemblies in order to be what it is must have an internal structure. We could and we do go on down the line, each branch forming part of an inevitable irresistible hierarchical structure. The organizational form of the automobile is clearly laid out for us. Each part does its work and in so doing the car has propulsion, it has traction, it is navigable; the vehicle can be made to move forward, accelerate, brake and stop. It can be made to turn. It can get you where you want to go. In comfort and safety, all the while with you being informed and entertained. The car is built with all these functions so that the joy of driving is maintained. So what's the problem? No problem at all if this satisfies. But in the increasingly sophisticated world in which we live we demand more. We want no traffic jams. We want our car to be our office and a place where we can plan and organize our leisure. We want no collisions, no wrong turns and no surprises. The burden of all this demand falls on our shoulders because what engine can help us book our theatre tickets, what suspension system can avoid traffic jams, what transmission system can eliminate collisions, and what navigation system can serve our office needs? We have chosen this mismatch of functional assemblies and driver requirements deliberately. Our motive is to shatter the notion that specific components deliver only on specific functionalities. We believe that intelligent design is recognizing that it is the collection of them, the network of them, that can do this and much more in the bargain. And our networked automobile can deliver on each and all of them and more as yet unspecified and unmet needs. How?

In order to avoid a serious collision many things come into play: speed, braking, weather conditions, traffic conditions, driver's state of mind, steering, information over-loading, tire pressures and vehicle dynamics. This is just scratching the surface. And all of these variables, snapshots of the pieces of technology of the car and the psychology of the driver, interact continuously and probably in non-linear fashion. Driver skill smoothes out the non-linear wrinkles. Most of the time. And this skill should never be abandoned or eliminated. But neither can it be relied upon entirely. And in the blink of an eye maybe it should not be relied upon at all. In the blink of an eye, the nervous system of the automobile could make informed decisions, if it's allowed to and if the society of technology pieces from which the car is made is appropriately consultative, fully informative and given choices to act in their own best interests and always overridingly for the good of the car's occupants.

Building on the ideas of the previous section, think of the car now in this way. Each part, every single one of them of which there could be a total of over a million, has two basic components: an inner core and an outer core. The job of the inner core is to keep the autonomics of the part – the thing that the part does entirely well and for which no oversight nor management attention is needed by any other part. The core knows what to do and does it slavishly, autonomically, perfectly, promptly and optimally. The outer core tells anybody who is interested who the part is and how available it is. It also wants to know what is going on, what is expected of it and how serious the 'case' is. This is the part's master and at the same time, on behalf of the part, a servant in the technology society in which the part is included. In this way the part has autonomy but it also has every opportunity to be part of the society – autonomously. It has the opportunity to belong not merely as a slave but as a contributing member of society. It has an openness to connections with other parts, more precisely the outer core of the other parts since the only thing that 'commands' a part's inner core is the part's outer core.

By this design, the network form of organization, the major parts and maybe down to much lower levels have an openness with one another that forms a stronger community of technology pieces thereby enabling enhanced cooperation via shared understanding of whatever demand is placed upon them. The drive is no longer the sole responsibility of the driver whose previous slaves were summoned by his crude signals to speed up, slow down, turn and shut down. Now the drive is the collective responsibility. It always was but in the most unintelligent way possible. Now we have the wisdom of crowds to leverage, a collective wisdom built upon autonomic expertise and autonomous networking [24].

The automobile in its crudest sense was a personal means of getting form A to B. In our complex world when myriad of us execute this operation we get traffic congestion. Likewise getting from A to B should not preclude our being available to family and friends, nor should it cause us to be ineffectively engaged on behalf of our corporate employers (or self). Each of us are drivers and motorists, but we do not cease to be citizen, neighbor and co-workers. The simultaneous design of the interior and exterior requires our automobiles (indeed any one of our possessions for that matter) to not only 'get us from A to B' but enhance our being who we are in the wider systems. Additionally, the automobile itself is part of various wider systems, e.g. a statistic in the manufacturer's strategy, an asset in our employer's inventory, and an heirloom in our family's history. All systems are made up of parts and in that sense we can say they have wholeness. But all systems live within greater wholes and this should allow us to say they have partness. We are arguing for a determination of system microstructure, in the abstract, that gives us access to both – wholeness and partness, and therefore to a system's lifecycle and communal ecology.

The luxury car makers are already headed this way. In time the trickle down economics will bring such benefits to the lower end of the automobile spectrum. But when we all come to realize the impact on our society of missed opportunity costs and needless road deaths maybe then the trickle will turn to a flood and our use of hierarchy will be supplemented and complemented by the network paradigm.

VII. CONCLUSION

We have presented our conceptual chemical components from which we believe we can construct 'systems DNA'. Our proposition for this line of experimentation is simple to state but far from trivial to accomplish. It consists of proposing various models of 'systems DNA' comprising various arrangements of our conceptual chemical components, simulating these models using agent-based technology and then validating the results against the various real and hypothesized systems we use to develop the models. The latter model type will be a simplified abstraction of a real system so that in every case the model has traceability to some aspect of reality be this a battleship, a Boeing (aircraft) or the battle itself (episode in a military conflict).

We will endeavor to decompose each chemical concept into finer grain constituents by scrutinizing the meaning of each and exploring their various interdependencies. This decomposition will give us our system of agents. We will be careful to note valid architectures, forms of organization, for inter-relating the decomposed concepts, and these architectures will give us our agent-based model. The behaviors we obtain from simulation results will be compared to what we might have expected or what we know to be true in life-like situations.

The prize for this line of reasoning is to have a far greater understanding of the nature of a system and its distinction from other systems. But we shall also learn how a system that is not a priori a SoS might become one and thereafter, either maintain its identity as such or return to being just a system or indeed a 'non-system of systems'. Mutation of systems, by nature or by design, becomes 'genetically' grounded perhaps leading to at long last not just more systems theory but a theory of systems.

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