## Feature Article

# Can a "Science" Of Systems Contribute to Systems Engineering?

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I am writing this as if it were an editorial or record of a dinner conversation between you and I rather than a formal journal article. That way, I can include a number of provocative positions, embarrassing or thorny sub-questions, controversies, insights, and caveats that come up whenever I have raised this question in the past.[2] You and I can expect not a single answer, but instead a number of observations and challenges that might sketch a more useful picture of the future than a simple yes or no.

The title question arises from a simple observation. Mechanical, electrical and aeronautical engineers take courses in physical science and mathematics in their preparation, and chemical engineers take courses in chemistry. Why don't systems engineers take courses in systems science?

An honest answer requires us to un-package the title into its many underlying and even more fundamental questions. What do we mean by "science" in this context? What is the relation between science and engineering such that engineers study science at all? Are there one or many Systems Sciences (SS)? In fact, is Systems Engineering (SE) itself one or many? Are all candidate systems theories based on science? If many, which systems science should we use to teach a systems core for SE? Has SE defined what depth and range of systems understanding it needs? What specifically could systems theories, extremely abstract as they are, contribute to practical applications like systems engineering? And very most important, what practical efforts can we do now to improve answers to all of these questions.

**What Is "Science" in this context?** Numerous new fields rush to add the word science to what they do. This is due more to the natural urge to share its status in society, gain its reputation for effectiveness, and secure similar high levels of funding, legitimacy, and recognition. Even in the long recognized sciences there is a pecking order. Physics, mathematics, and chemistry are widely recognized as the "hardest" in terms of "scienceness," ranging through astronomy, geology and biology. All sciences have gone through common histories of stages of achieving the ideal attributes of the scientific method. Astronomy, geology, and biology had long phases of what I would label pre-science, that is, "description," "identification," "naming," and "categorizing" (DINC) before they could progress to key features of the scientific method. These are (1) a theory or model of how things work synthesized from many past, integrated observations or verified mechanisms; (2) the formulation of clear and distinct answerable questions or predictions (from 1) as to how things work best expressed as a set of alternative hypotheses (often expressed as alternative, measurable mechanisms); (3) experiments designed to eliminate hypotheses; (4) associated sets of controls and limits; (5) use of sophisticated tools of measurement that have proven correspondence principles; (6) sophisticated statistical analysis of results; and (7) strong coupling between elimination of some hypothetical alternatives and future cycles of questions to test or integration into the starting model or theory. These several attributes indicate that many things called science today by their proponents are not (design science, social science, management science, etc.). This statement will upset many folks, but we need to set a high bar with which to evaluate the phrase "a true science of systems."

In the context of the title question, many of the authors and contributors that call themselves systems scientists and their lifeworks are still in the initial stages of DINC. For systems science to truly become a "science" of systems, it has to attain the several key attributes of the scientific method. I would suggest that the portions of SS that are termed or derived from "natural systems science" are much closer to a true "science" of systems than many other system approaches. It is very important to note that we are not criticizing these other approaches but rather indicating their limitations in building a true science of systems course for engineering systems that mimics what physics or chemistry studies do for well-accepted engineering fields.

**What is the relation between science and engineering such that engineers study science at all?** In discussing these questions, I have noted that some engineers bristle over the claim that science and engineering are linked. It is true that engineering is a very distinct and differently purposed human pursuit. But it seems reasonable to suggest that one learns from the other; the best of engineering is founded on the best of science. Engineering involves "testing" and "experiment" as much as science. And I can tell you that the favor is returned. Where would modern science and biomedicine be without electron microscopes, MRIs, synchotrons – a very long list of amazing instruments derived from engineering?

If you are an electrical engineer, you take a range of science courses that gave you a grounding in the magnificent synthesis of electromagnetic theory, but only to enable its many practical applications for engineering a vast range of technologies that work reliably. If systems engineering wants to contribute as reliably to a wide range of current crisis human needs as much as fields such as mechanical, aeronautical, space, and chemical engineering have accomplished in the past, it may well want to base its work more on natural systems science (NSS). My analysis of current SE preparation is that it is almost completely ignorant of the riches of natural systems science. Hopefully this and past discussions will show that natural systems science (NSS) [7,8,12] has the several attributes of a true science[15] and would bring the benefits of science to SEs future and much expanded range of praxis.

A relevant and current case study might be that of biomimicry[1] and bioengineering. This area is rapidly expanding with one website listing 1,500 examples of successful engineering solutions arising from study of how natural biological systems solved similar problems. Since the biological solutions arose from nature attempting a vast number of variations over literally millions of years and selecting some of the most “sufficing” solutions, nature has essentially “tested” many alternative solutions and eliminated many.[15] Nature has done a great deal of work for us; mimicking its results might be very efficient. Basing SE more on NSS may lead to a new, explosive growth area that might be called “systems mimicry.” More on this in practical group projects below.

**Is Systems Engineering one or many? Problems arising from the inherent, multi-faceted nature of SE and SS:** Systems Engineering and Systems Science appear to have suffered similar histories and fates. Samantha Brown of BAE Systems, immediate Past President of INCOSE (International Council on Systems Engineering), described no less than 16 specific reasons Systems Engineering was not as widely accepted as SEs think it should be in a keynote talk given at ISSS’11 (International Society for the Systems Science) in Hull, England. My experience as a systems scientist for 45 years indicates that the exact same 16 reasons explain why systems science is not as accepted as SSs think it should be. So how could a field facing the same obstacles (perhaps even more – in[6], I cited 33) help a sister field?

Both SS and SE range across a vast diversity of very distinct applications areas. SE focuses on design, delivery and testing of natural, artificial, informational, physical, human, and hybrid systems of systems as well as management of very large-scale projects and simulations. Indeed, the increased recent sensitivity in SE to a possible need for SS arises from management of large projects faced by the military, aerospace industry, international economy, and law/politics. SS is interdisciplinary like SE, but goes beyond that to the transdisciplinary in that it tries to find what is universal or similar across the multitude of natural and human systems present in the world, in order to define the essence of how systems work. It tries to specify explicitly how “systemness” sustains itself and satisfies necessary functions. SS is also applied in that it tries to develop tools and techniques for humans to use to build, operate, diagnose, develop, and improve both artificial engineered products as well as human and social systems. Since the humans that build, operate, diagnose and develop the systems are organized into institutions, they themselves are “systems” in formation. Therefore management and efficiency of those human systems are subjects of both SE and SS. Clearly, both have similar needs and goals, but these are frustrated by the vast range of types of “systems” which they study and wish to attempt intervention. The major characteristic of both has been increased fragmentation and loss of cohesion as the anthill of humanity has added ever-increasing detail to all parts of the range of coverage.

A unified or integrated natural systems science would show how systems work in much greater detail, yielding many workbooks of proven solutions that real systems across the universe have achieved through 14+ billion years of incomprehensible numbers of events and at scales from $10^{-25}$ to $10^{55}$. [7,8,15] If the goal of SE is to make systems that work, it would seem that at least one year of study of natural systems science combined with coverage of human systems studies might produce systems engineers better equipped to accomplish their goals.

**Are all candidate systems theories based on science?** There is a plethora of unintegrated and fragmented sources of information for a science of systems.[15] One must study and synthesize: systems theories (Bertalanffy's, Odum's, Miller's, Klir's, Troncale's and more); work on specific special features of systems (Lorenz's, Abraham's chaos, Mandelbrot's fractals, Forrester's feedback dynamics, Prigogine's thermodynamics, Haken and Corning's synergies, Wilson's, Pattee's & Salthe's work on hierarchies, Kauffman's emergence, Barabasi's network theory, Ashby's, von Foerster's self-organization, Eigen's hypercycles, Bak's self-criticality, Thom's & Zeeman's catastrophe theory, and more); work on specific types of systems to the exclusion of others (biological, human, physical, Shannon's information-based, manufactured and more)[a 20 min brainstorming exercise at a recent workshop resulted in a listing of 97 different types of systems]; work on natural systems sciences (Mesarovic's, Hood's systems biology, Whiteside's systems chemistry, earth systems science, Troncale's systems pathology)[11]; work on complexity science (Cowan's, Gel Mann's and more); work by physicists at the theory-of-everything level not intended for systems research but containing much on systems (Auyung, Barrow, ); work on systems methodologies (Zadeh's fuzzy math, Langton's artificial life, Holland's agent-based modeling, Meadows, and more); work on systems on various scales of size (astronomical, subatomic, Newtonian, ecological, world economic, world weather, Wilson's, West's allometry & Troncale's systems allometry); work on different domains of systems (Iberall''s, Wymore's, Weinberg's systems engineering, Capra's's or Lazlos' systems philosophy, Beer's, Checkland's, Warfield's, Ackoff's, Churchman's, Senge's systems management); chroniclers summarizing systems research history (Hammond, Francois, Skyttner) -- all have different purposes, emphases, and coverage. There is certainly a considerable and valuable set of products to harvest, integrate, synthesize and unify. And this list of nearly 50 workers is just off the top of my head. Some workers have charted relationships between many more distinct systems approaches or "lifeworks" on systems than these.

Only a small number of these have a firm basis in the natural sciences and can be studied with the scientific method. And even those do not study systems comprehensively as much as partially because they tend to focus on one discipline or cluster of disciplines such as earth systems science, systems biology, or systems chemistry or even a subspecialty such as systems immunology or systems neuroscience or on one scientific phenomenon or process, not how all the processes relevant effect each other using the scientific method. That is what a "science" of systems would be. That is the goal of the "system of systems processes theory" (SoSPT) described briefly below.[3,4,5,13,14,15]

There are three major tasks to achieve to enable the teaching of a "science" of systems. First, there must be a comprehensive integration, or synthesis of these sources, especially the parts that have a basis in natural science, just like the great unification events of the past (a rigorous taxonomy in biology by Linnaeus culminating in Darwin's unified theory of evolution, or the synthesis of electromagneticism via Maxwell's equations, or the periodic table of elements by Mendeleyeev). Second, there must be a very organized, comprehensive campaign to "harvest" the vast natural science literature of proven experimental results to the new science of systems such that the results for particular phenomena, at different scales of inquiry are shown to elaborate the more abstract mechanisms of systemness. These results are proven for particular reductionist disciplines BUT their phenomena are actually also studies of the mechanics of "system ness" on the more abstract level only they have never been applied as such. Third, the integration of factual, reliable mechanisms must be strongly coupled with less scientific, but equally important aspects of SE practice like tools,[10] techniques, and management applications to human teams and institutions.

**What are the strengths and weaknesses of different systems approaches that would help us choose which systems science course to teach?** As SE has such a wide range of applications and application domains, the science of systems that serves it should also represent a wide range of theory and useful guidelines. It does. While natural systems science might give us the result of nature's experiments with systems across the eons,[15] it might not be the best place to find guidelines and techniques to help with small and large scale social systems made up of rather ornery and independent humans. Rather than the current state of antagonism between the soft systems methodology proponents and the scientists, we need a mutual respect for the uniquely different limits and opportunities of both major branches of systems study. They need to complement rather than provoke each other in the new synthesis and the new core courses for SE preparation.

One example. In my several papers on the isomorphic process/structure "hierarchy"[5] I noted that sometimes an isomorphy is actually discovered or manifested (most easily seen) in the human disciplines. While the social and political disciplines are rather far from science, they historically provided the first glimpse of the importance of hierarchy. Indeed, the word itself means "sacred" "ruler." It's characteristics mimic some of the features of natural systems (levels, subsumption, clustering, ranking, empirical regularities across levels, etc.). Studies in the natural sciences also reveal extensive hierarchical structure from the cosmos to your own body to subatomics. But the nature of the hierarchies in those systems yield different take home lessons on the importance of hierarchy to the origins, maintenance, and sustainability of systems. And now the new field of network theory modifies that by showing that some networks and hierarchies are interchangeable (clustered or so-called scale-free networks). Thus, it is the combination of the views of the human disciplines, the science disciplines, and mathematics that gives us the most complete understanding of the systems function of hierarchy. And in turn that more detailed understanding (if it is as specific as how it works and what it does in terms of features, functions, and linkages) makes it more possible to use hierarchy to engineer better systems of all kinds.

The conclusion is that the diverse approaches to understanding systems is an overall strength if the various approaches are integrated and each is utilized for its strengths while complementing its weaknesses with the strengths of other approaches. This attitude would not only enable the hoped for unification but stop the miscommunication and hostility between the approaches.

This note is too short to try to enumerate strengths and weaknesses of different approaches, but its intent is to call for a comparative systems analysis that would do just that. CSA would be another important step toward unification and a science of systems. It would indicate in which types of systems and which disciplines any particular isomorphy was dominant and functional. Such a road map would be very useful to practicing systems engineers.

**Has Systems Engineering defined what depth and range of understanding of systems it needs?** I detect no sustained effort until recently to accomplish this task. Recently INCOSE has initiated two Working Groups that may fulfill this first step: the Systems Science Working Group (James Martin) [our wiki site: https://sites.google.com/site/syssciwg/] and the Complex Systems Working Group (Sarah Sheard, Eric Honour). To date, INCOSE knowledge base and library initiatives present systems science in a comparatively shallow and non-robust manner, typically in mostly the systems management domain leaving natural systems science entirely uncovered. Treatment there is certainly not as comprehensive as advocated here.

We here also advocate a much broader field of applications for systems engineering of the future that will need this more highly specific understanding of systems. Even those paying for systems intervention and engineering will need to study SS to better prepare the performance specifications that control the systems that are innovated. The society that loses its power and facility to innovate, dies. Many very large-scale SE projects are moving decisively to hybrid natural system-human system domains, international economics, international politics, military, pandemics, climate change, systems of systems – all will require a more detailed input of knowledge on how systems work. And before we know it SE will be called upon to perform even at the scale of planet-forming and assist other disciplines in the curation of massive natural systems. SEs of the future will become medical doctors of ailing systems of all kinds at all scales using studies of systems pathology. They will become the "curators" of systems of the future. Now is the time to help accomplish the integration of the fragmented systems approaches to meet this challenge.

**What specifically could systems theories, extremely abstract as they are, contribute to practical applications like systems engineering?** Although the essence of a "science" of systems…. finding the commonalities across a vast range of systems, absolutely requires several levels of abstraction from the particulars in order to "see" the similarities – the mechanisms that are similar are in the pattern of interactions among the particulars, not just the particulars – the expectation is that one could de-abstract from the patterns to apply them to any new set of particulars to achieve the same benefits for sustainable systems. Any of the equations used in aeronautics or mechanical engineering, or is space exploration etc. are themselves abstractions several levels from particulars. It is just that we are used to then reapplying them to exactly the same domain of particulars in much of current practice. A SS basis for SE would enable application to systems of other domains.

This presumes the above cited need for integration and synthesis of the currently fragmented literature into workbooks of proven potential mimicry for engineers. We envision some of the following outputs:

- **Workbook of Proven Systems Processes (50 Isomorphies)** [13]
- **Workbook of System Process Interactions (the key to systemness)** [14]

- **Workbook of Proven Network Motif's**
- **Workbook on Types of Non-Linear Causality and its Uses**
- **Workbook on Systems Pathologies**[11]
- **Workbook of Systems Mimicry**
- **Workbook of Management Guidelines**

In my own work, I have focused on identifying the isomorphic processes proven to be similar across many natural systems from different disciplines, domains, techniques & tools, and scales (which I designate as DDTs, after the poison, because staying focused only on the particulars poisons seeing the similarities). In the System of Systems Processes Theory (SoSPT) [3,9,10,13,14] we have identified more than 105 such isomorphic processes, recently reduced to a list of 50.[13] Each such process has been shown in many different systems as a key contributor to its sustainability and function. Some, like feedbacks, are generally accepted as proven and are found in many systems workers theories. Others are quite unique. Still others are included, but their effects on each other, the key to systems function, are not specified. A major advance of the SoSPT is that such interactions where one systems process affects another, and therefore establishes how the systems work, are captured in explicit Linkage Propositions (LPs). The major advance proffered by the SoSPT is the specific mutual influences captured in the LPs.[14] We have literally 100's of such LPs in the SoSPT. The result is a "theory," on the "abstract" level, but which potentially provides many explicit guidelines, or design ideas for anyone engineering or trying to fix or improve many systems on many levels.

In answer to the original question of this note, we have tried to extend the "science" aspect of the SoSPT by "proving isomorphy," a step assumed and much neglected in the current unintegrated literature, but necessary to raise systems theory more to a level of science. For example, one current presentation and article[16] cites the natural science literature extensively by providing citations from 52 different case studies from….. 6 phenomena in astronomy, 8 phenomena in physics, 10 phenomena in chemistry, 6 phenomena in geology, 10 phenomena in biology, 7 phenomena in computer science, 4 phenomena in mathematics, and 9+ phenomena in human science….. where in each case the presence of the same 12 identifying features for putative isomorphy (systems process) "cycling or cycles or oscillations" are proven using the scientific method and experiments WITHIN the science or scale of each discipline. We suggest that is sufficient to "prove" an isomorphy across real systems and form the foundation for a true science of systems. We now only need to do this for the remaining 50 putative systems processes.

We do not have space in this short essay to elaborate on the SoSPT "spin-offs" from such an explicit integration of past systems work (systems allometry, systems pathology, systems science applied to law & legislation, theory of emergence). But the workbooks mentioned above, filled with direct citations and explanations of how each increases understanding of systemness would be a set of seven products that then could be used as part of the SE toolbox. Explicit understanding of systems-level pathologies,[11] of motifs found in many networks, of the Linkage Propositions between systems processes, of the resulting types of non-linear causalities and how nature has actually used those unpreditabilities to make systems accomplish their function better – ALL might be useful the wider future practice of SE envisioned here.

**What practical projects could we join to enable a "true" Science of Systems useful for Systems Engineering?** So how do we get there from where we are now? Here are a dozen very practical efforts underway organized for your participation. Each has as its charter accomplishing portions of the tasks that must be completed to provide a firm foundation for a science of systems for systems engineering. Even joining to introduce challenges and criticism, or increase diversity of products by including your efforts in the area is important to improving the outcome. Do you want to be a part of this possible advancement for systems engineering? Contact the author (at lrtroncale@csupomona.edu) for more specifics or to add your name and contact information to project teams listed below

- Join INCOSE (International Council on Systems Engineering) Systems Science Working Group (SSWG) and its official project for Unifying Systems Theories. Go to www.incose.org or more specifically the project Wiki site at https://sites.google.com/site/syssciwg/
- Join INCOSE Systems Science Working Group (SSWG) and its official project on initiating the new field of top-down Systems Pathology. Go to www.incose.org. or more specifically the project Wiki site at https://sites.google.com/site/syssciwg/
- Join the International Society for the Systems Sciences (ISSS) and its Special Integration Groups (SIGs) on "Research Toward A General Theory of Systems" or on "Systems Pathology." Go to www.isss.org.
- Join a newly forming professional society, the International Society for Systems Pathology (ISSP). All professionals who join before January 2013 are designated as Founding Members.
- Attend INCOSE International Workshop 2013 in Jacksonville, Florida, January 26-29 which will have multiple session discussions on these topics. Also be aware of paper sessions and panels scheduled for regional INCOSE chapter meetings, especially those in California, and at the INCOSE annual International Symposium (Philadelphia, June 24-27 2013) on these topics.
- Join in the work of ongoing SoSPT professional teams devoted to advancing the above named Workbooks for each of the 50 systems processes, the Linkage Propositions, and SoSPT spin-offs such as Systems Pathology, Systems Allometry, Non-Linear Causalities, SoSPT-derived computer tools, Network Motif's, Theory of Emergence, and Applications to Law and Legislation.
- The author is part of a committee proposing a new M.S. Program in Systems Engineering at California State Polytechnic University (Cal Poly) College of Engineering. We are proposing to the committee that Cal Poly be the first Systems Engineering curriculum to offer a year-long course in Systems Science as part of the core. Become part of the study group measuring effectiveness.
- Suggest an article for an edited volume on "Systems Pathology," probably the first of its kind on the top-down systems-level version of pathologies. We need convincing case studies as chapters.
- Suggest an article for an edited volume on "Systems Mimicry," probably the first of its kind but modeled after several successful volumes on biomimicry. We need convincing case studies as chapters.

- Join and listen to Systems Radio, a new project including several interviews with its founder, SE Kent Palmer, and this author, but soon to be adding a series by three, systems-interested Nobel Laureates and those designated as Founders of Systems Science by the Behavioral Science Foundation. Go to systemsradio.net

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For reasons of space, a full set of references is not included. I have included only a few key references to my own work. Many references to other sources cited may be accessed in the Reference sections of these papers.


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