Systems Engineering STEM Overview

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Engineering disciplines (ME, EE, CE, ChE) sometimes argue their fields have “real physical phenomena”, “hard science” based laws, and first principles, claiming Systems Engineering lacks equivalent phenomenological foundation. Here we argue the opposite, and how replanting systems engineering in MBSE/PBSE supports emergence of new hard sciences and phenomena-based domain disciplines with deep historical roots. Supporting this perspective is the System Phenomenon, wellspring of engineering opportunities and challenges. Governed by Hamilton’s Principle, it is a traditional path for derivation of equations of motion or physical laws of so-called “fundamental” physical phenomena of mechanics, electromagnetics, chemistry, and thermodynamics.

We argue that laws and phenomena of traditional disciplines are less fundamental than the System Phenomenon from which they spring—an historical fact that was well-known and equally remarkable 200 years earlier to the pioneers of mathematical physics. This is a practical reminder of emerging higher disciplines, with their own phenomena, first principles, and physical laws. Contemporary examples include ground vehicles, aircraft, marine vessels, and biochemical networks; ahead are health care, distribution networks, market systems, ecologies, and the IoT.

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Introduction

As a formal body of knowledge and practice, Systems Engineering is much younger than the more established engineering disciplines, such as Civil, Mechanical, Chemical, and Electrical Engineering. Comparing their underlying scientific foundations to some equivalent in Systems Engineering sometimes arises as a dispute, concerning whose profession is “real” engineering based on (or at least later explained by) hard science, with tangible physical phenomena, and accompanied by physical laws and first principles. This paper summarizes the argument for a different perspective altogether (Figure 1), and the reader exploring this paper is warned to avoid the trap of the seemingly familiar in parsing the message. A more complete discussion is provided in (Schindel 2016) and (Schindel 2019).

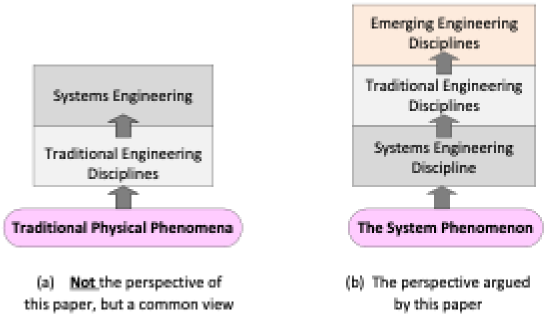

Figure 1: Two Different Views of Systems Engineering. (SEBoK Original)

Beyond that argument, this paper addresses a more pragmatic goal—the means of identifying and representing the tangible physical phenomena that emerge in new system domains, along with their respective physical laws and first principles. This is of more than philosophical or professional significance. Challenged by numerous issues in emerging systems, society has an interest in organizing successful approaches to the scientific understanding of laws and first principles about, and engineering harnessing of, the related phenomena. Individuals entering or navigating the technical professions likewise have personal interests in this evolving roadmap.

While recognizing the formidable works of systems theorists in these still early days of systems engineering (Ashby 1956; Bertalanffy 1969; Braha et al 2006; Cowan et al 1994; Holland 1998; Prigogine 1980; Warfield 2006; Wymore 1967), this paper focuses on even earlier contributions of science and mathematics to the flowering of engineering's impact over the last three centuries. We will extract the "System Phenomenon" at the center of that foundation and consider its impacts and implications for systems engineering practice. This perspective helps us understand the phase change that Systems Engineering is going through, as model-based representations enable the framework that has already had profound impact in the traditional science/engineering paired disciplines.

Phase Change Evidence: Efficacy of Hard Science, Phenomena-Based, STEM Disciplines

Science, Technology, Engineering, and Mathematics [STEM] —300 Years of Impact

Our pragmatic argument is based on assessing the impact of the physical sciences and mathematics on engineering by their joint efficacy in improving the human condition. In a matter of 300 years (from around Newton), the accelerating emergence of Science, Technology, Engineering, and Mathematics (STEM) has lifted the possibility, quality, and length of life for a large portion of humanity, while dramatically increasing human future potential (Mokyr 2009; Morris 2012; Rogers 2003). By the close of the Twentieth Century, the learning and impacts of STEM along with other factors (e.g., market capitalism as a driver of prosperity, as in (Friedman 1980)) were increasingly recognized as critical to individual and collective human prosperity. During that same period, the human-populated world has become vastly more interconnected, complex, and challenging. New opportunities and threats have emerged, in part out of less positive impacts of human applications of STEM. Understanding and harnessing the possibilities have become even more important than before, from the smallest known constituents of matter and life to the largest scale complexities of networks, economies, the natural environment, and living systems

"Phase Changes": Emergence of Science and Engineering as Phenomena-Based Disciplines

Over those three centuries, the “hard sciences”, along with the engineering disciplines and technologies based on those sciences, are credited with much of this amazing societal progress, as well as some related challenges (Mokyr 2009; Morris 2012; Rogers 2003). Our point here is the enormous impact of these “traditional” (at least, over 300 short years) disciplines, as their foundations emerged in understanding of physical phenomena and related predictive and explanatory models.

How can the foundational roots of Systems Engineering be compared to engineering disciplines already seen as based on the “hard sciences”? The traditional engineering disciplines (ME, EE, ChE, CE) have their technical bases and quantitative foundations in what emerged as physical sciences of what came to be understood as physical phenomena.

It wasn’t always this way, as seen from the shift that began to occur just three centuries ago. It is informative to remember the “phase changes” that occurred in what are now considered the traditional disciplines, by recalling the history of physics before Newton, chemistry before Lavoisier and Mendeleev, and electrical science before Faraday, Hertz, and Maxwell, versus what followed for each. (Cardwell 1971; Forbes et al 2014; Pauling 1960; Servos 1996; Westfall 1980) All of these domains had earlier, less effective, bodies of thought, generated by those attempting to answer questions and, in some cases, provide practical benefits. Instead of dismissing alchemy, astrology, pre-Copernican cosmology, and their counterparts, we can instead see them as grappling with phenomena without the benefit of sufficiently powerful physical-mathematical representation and the verification mechanisms of experiment and refutation to test against reality what we would now call models.

Systems Engineering is Still Young

Contemporary specialists in individual engineering disciplines (e.g., ME, EE, CE, ChE) sometimes argue that their fields are based on “real physical phenomena”, founded on physical laws based in the “hard sciences” and first principles. One sometimes hears claims that Systems Engineering lacks the equivalent phenomena-based theoretical foundations. In that telling, Systems Engineering is instead critically portrayed as emphasizing (1) process and procedure, (2) critical and systems thinking and good writing skills, and (3) organizing and accounting for information and risk in particular ways—valuable, but not as based on an underlying “hard science”.

That view is understandable, given the initial trajectory of the first 50 years of Systems Engineering. (Adcock 2015; Checkland 1981; Walden et al 2015) “Science” or “phenomenon” of generalized systems have for the most part been described on an intuitive or qualitative basis, with limited reference to a “physical phenomenon” that might be called the basis of systems science and systems engineering. Some systemic phenomena (e.g., requisite variety, emergence of structure, complexity, chaos theory, etc.) have received attention, but it is challenging to argue that these insights have had as great an impact (yet) on the human condition and engineering practice as the broader STEM illustrations cited above for the most recent three centuries of physical sciences and mathematics. However, INCOSE’s own stated vision (Friedenthal et al 2014) calls upon systems engineering for such a result.

Respectful of the contributions of those early thinkers in systems engineering, we also note that their contributions can in some cases be expressed as manifestations of the modeled System Phenomenon described below, advancing the scientific foundations of systems engineering.

MBSE, PBSE: Enabling a Phase Change in Systems Engineering

In the case of systems engineering, a key part of the story is that the role that quantitative system models have played, or not played, during its initial history. Most recently, the broader INCOSE-encouraged role for model-based methods offers to eventually accelerate the "phase change" that the successful earlier history of science, mathematics, and other engineering disciplines suggest is now in progress.

Models are certainly not new to segments of engineering practice. However, we are representing an increasingly fraction of our overall understanding of systems, from stakeholder trade space, to required functionality and performance, to design, and to risk, using explicit and increasingly integrated system models. As in Newton's day, this also puts pressure on the approaches to model representations, in order that they effectively represent the key ideas concerning the real things they are intended to describe. "Effective" meant these models described observable phenomena, offered explanatory theories of cause, provided verifiable (or falsifiable) predictions, and increased human understanding. In many cases, this understanding was harnessed by practicing engineers to improve human life. The progress of physical sciences did not arise from models that only could describe single unique instances of systems, but instead represented what came to be understood as more general patterns that recur across broad families of systems. Likewise, there is an increasing effort in systems engineering to recognize that these models must often describe patterns of similarity and parameterized variation. The increasing use of explicit model-based patterns in these representations is a part of this phase change (INCOSE Patterns WG 2015; INCOSE MBSE Initiative 2015). Pattern-Based Systems Engineering (PBSE) as an extension of Model-Based Systems Engineering (MBSE) increases emphasis on representation.

This is a more significant change than just the emergence of standards for systems modeling languages and IT toolsets, even though those are valuable steps. We need underlying model structures that are strong enough--remember physics before the calculus of Newton & Leibniz. As a test of “strong enough”, we suggest the ability to have the kinds of impact on humankind summarized in Section 2—beginning with clearer focus on what phenomena are being represented.

Although this sounds challenging, it is not necessary for emerging systems models to “start from scratch” in their search for new system phenomena, and further argue that what is already known from the earlier phase change of Section 2 helps suggest what aspects of our systems models need to be strengthened during the phase change in systems engineering. PBSE further reminds us of a practical lesson from the STEM revolution. Once validated patterns emerge, we (mostly) need to learn and apply those patterns (laws, principles), not how to re-derive them from earlier knowledge. Examples include the Periodic Table and the Gas Laws. While it may be controversial, “learn the model, not modeling” is advice worth considering, in a time when modeling from scratch seems carry more excitement.

The System Phenomenon

The perspective used in this paper defines a system as a collecting of interacting components, where interactions involve the exchange of energy, force, mass, or information, through which one component impacts the state of another component, and in which the state of a component impacts its behaviour in future interactions (Schindel 2011).

In this framework, all behaviour is expressed through physical interactions (Figure 2). This perspective emphasizes physical interactions as the context in which all the laws of the hard sciences are expressed. (Schindel 2013)

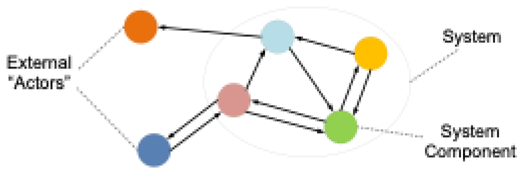

Figure 2: The System Perspective. (SEBoK Original)

The traditional “Phenomena” of the hard sciences are all cases of the following System Phenomenon:

1. Each component has a specific behavior during a

given interaction type, determined by the component's state. (See (4) below for the source of that component's behavioral characteristics.)

2. The combined behaviors of the set of interacting components determine a combined system state space trajectory.
3. That trajectory is a collective property of the system components and interaction, and accordingly is not simply the description of possible behaviors of the individual components. For the systems discussed in this paper, by Hamilton's Principle (Levi 2014; Sussman et al 2001; Hankins 2004), the emergent interaction-based behavior of the larger system is a "stationary" trajectory X = X(t) of the action integral, based on the Lagrangian L of the combined system:

$$S[X] = \int_A^B L(X, \dot{X}, t)dt$$

1. The behavioural characteristics of each interacting component in (1) above are in turn determined by its internal ("subsystem") components, themselves interacting.

Reduced to simplest forms, the resulting equations of motion (or if not known or solvable, empirically observed paths) provide "physical laws" (or recurring observable behaviors) subject to verification.

Instead of Systems Engineering lacking the kind of theoretical foundation that the "hard sciences" bring to other engineering disciplines, we therefore assert that:

- It turns out that all those other engineering disciplines' foundations are themselves dependent upon the System Phenomenon, and emerge from it.
- The related underlying math and science of systems (dating to at least Hamilton) provides the theoretical basis already used by all the hard sciences and their respective engineering disciplines.
- It is not Systems Engineering that lacks its own foundation—instead, it has been providing the foundation for the other disciplines! (Refer to Figure 6.)
- This insight was well-known and remarkable to the sciences 200 years ago, and has continued to be remarked upon by leading scientists for its surprising

coverage ever since: “It [science] has as its highest principle and most coveted aim the solution of the problem to condense all natural phenomena which have been observed and are still to be observed into one simple principle, that allows the computation of past and more especially of future processes from present ones. …Amid the more or less general laws which mark the achievements of physical science during the course of the last centuries, the principle of least action is perhaps that which, as regards form and content, may claim to come nearest to that ideal final aim of theoretical research.” (Kline, 1981)

Historical Domain Example 1: Chemistry

Chemists, and Chemical Engineers, justifiably consider their disciplines to be based on the “hard phenomena” of Chemistry (Pauling 1960; Servos 1996):

- This perspective emerged from the scientific discovery and verification of phenomena and laws of Chemistry.
- Prominent among these was the discovery of the individual Chemical Elements and their Chemical Properties, organized by the discovered patterns of the Periodic Table.
- Emerging understanding of related phenomena and behaviors included Chemical Bonds, Chemical Reactions, Reaction Rates, Chemical Energy, and Conservation of Mass and Energy.
- Upon that structure grew further understanding of Chemical Compounds and their Properties:

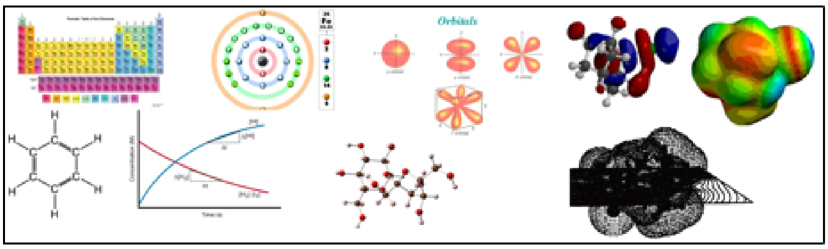

Figure 3: Chemical Interactions, Phenomena, Principles. (SEBoK Original

Even though these chemical phenomena and laws seemed very fundamental:

- All those chemical properties and behaviors are emergent consequences of interactions that occur between atoms’ orbiting electrons (or their quantum equivalents), along with limited properties (e.g.,

atomic weights) of the rest of the atoms they orbit.
- These lower interactions give rise to visible higher-level Chemical behaviour patterns, their own higher-level properties and relationships, expressing “hard science” laws of Chemistry.

This illustrates:

- The “fundamental phenomena” of Chemistry, along with the scientifically-discovered / verified “fundamental laws / first principles” are in fact . . .
- Higher level emergent system patterns and . . .
- Chemistry and Chemical Engineering study and apply those system patterns.

Historical Domain Example 2: The Gas Laws and Fluid Flow

Illustrated by Figure 4, the discovered and verified laws of gases and of compressible and incompressible fluid flow by Boyle, Avogadro, Charles, Gay-Lussac, Bernoulli, and others are rightly viewed as fundamental to science and engineering disciplines. (Cardwell 1971) However, all those fluid and gaseous properties and behaviors are emergent consequences of interactions that occur between atoms or molecules, the containers they occupy, and their external thermal environment. These lower-level interactions give rise to patterns that have their own higher-level properties and relationships, expressed as “hard sciences” laws. So, the “fundamental phenomena” of gases, along with the scientifically-discovered and verified “fundamental laws and first principles” are in fact higher level emergent system patterns. And so, Mechanical Engineers, Thermodynamicists, and Aerospace Engineers can study and apply those system patterns.

[[File: |thumb|center|750px|*Figure 4: Gas, Fluid Interactions, Phenomena, Principles.* (SEBoK Original)]]

Examples from More Recent History

The practical point of this paper is to emphasize the constant emergence of new scientific and engineering disciplines, in domains arising from higher level system interactions. These include domains that have been important to society, even though they arose later than the more fundamental domains from which they spring.

The discovery and exploitation of these higher-level phenomena, principles, and laws is important to future progress and innovation, including enterprises, careers of individuals, and society. These more recent emergent domains, in which formal system patterns are being recognized as describing higher-level phenomena and laws, are illustrated by examples of Figure 8:

1. Ground Vehicles: As in the dynamical laws of vehicle stability that enable vehicular stability controls (Guiggiani 2014)
2. Aircraft: Including the dynamical laws at the aircraft level that enable advanced aircraft design for dynamic performance and top-level flight controls (Pratt 2000)
3. Marine Vessels: Facilitating the design of more efficient hulls and special purpose craft, as well as bulk transports (Perez et al 2007)
4. Biological Regulatory Networks: Advancing our understanding of immune reactions and other regulatory paths in connection with pathologies as well as therapies (Davidson and Levine 2005).

For example, in the case of ground vehicles, dynamical laws of vehicle stability arise from the interactions, modulated through control algorithms, of the distributed mass of the vehicle in motion with the driving surface, transmitted through tractional forces of braking, acceleration, or steering, as further impacted by road surface and tire conditions, along with other factors. It is the overall system interaction of all these domain elements that leads to emergent vehicular laws of motion.

Students of complexity (Cowan et al 1994) will note that nonlinearity, the onset of chaos, and extreme interdependencies are not reasons to avoid representing the interactions manifesting that behavior. Indeed, they provide further reasons to understand those very interactions.

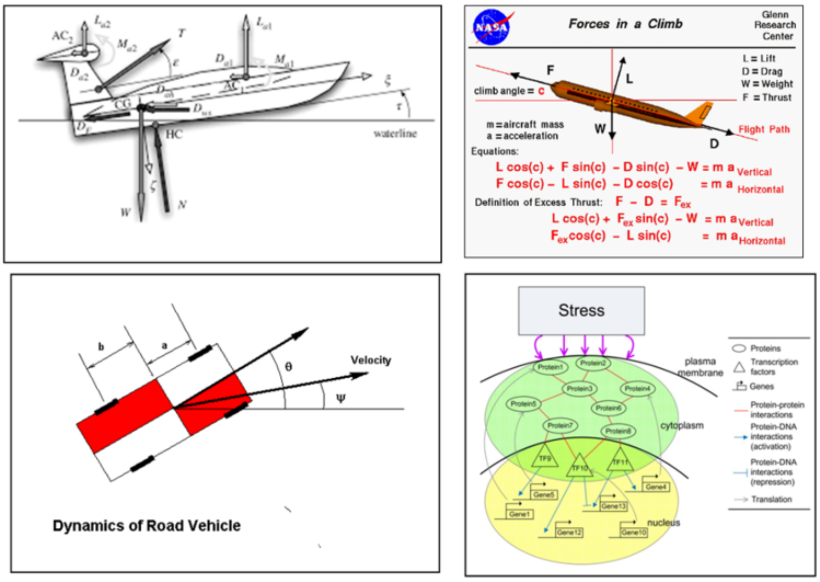

Figure 5: Ground and Marine Vehicles, Aircraft, Regulation in Organisms. (SEBoK Original)

Examples that call out for improved future efficacy in systems engineering include:

1. Utility and other distribution networks: Society depends upon rapidly evolving, often global, networks for distribution of goods and services, in the form of materials, energy, communication, and information services. What are the network-level phenomena, laws, and principles of these networks, bearing on their effectiveness and resiliency? (Perez-Arriaaga et al 2013)
2. Market systems, economies, and human-imposed regulatory frameworks: These systems clearly have direct impact on society and individuals. The "designed" systems of top-down regulation imposed upon them include such prominent examples as regulation of banking, securities markets, development of medical devices and compounds, and delivery of health care. What are the system-level phenomena, laws, and principles of these systems, bearing on their effectiveness and resiliency? (Friedman 1980)
3. Living ecologies: The emergent habitats of living things include rain forests, coral reefs, the human microbiome, and the biosphere as a whole. These demonstrate characteristics that include regulatory stability within limits, along with pathologies. What are the system-level phenomena, laws, and principles of these systems? (MacArthur & Wilson 2001)
4. Health care delivery: These systems, including a

number of important challenges, are much in the public eye. The very definition of effective health care is necessarily dynamic because of the evolving frontiers of medical science. The means of effectively delivering care, financing its costs, and (Hippocratically) protecting patients from harm are all subject of study as to system-level phenomena and principles. (Holdren et al 2014)

5. Product development, general innovation, and related agility: This system domain is the “home court” of INCOSE and our systems engineering profession. While there is a large body of descriptions of the related systems, the study of these systems as modelled technical systems is mostly new or in the future. One such project is the INCOSE Agile Systems Engineering Life Cycle Model Project. (Braha et al 2007; Schindel and Dove 2016; Hoffman 2015)

Strengthening the Foundations of MBSE

Like mechanics pre-Newton, models of MBSE require an underlying framework to effectively describe the System Phenomenon in domains of practice. MBSE requires a strong enough underlying Metamodel to support phenomenon-based systems science. As discussed in (Schindel 2013), Interactions play a central role in such frameworks, inspired by Hamilton and three hundred years of pioneers in the emergence of science and engineering. Interactions are acknowledged by and can be modelled in some current system modelling frameworks, but typical practice and underlying structures need related improvement. Figure 9 illustrates a related, Interaction-centric, extract from the S*Metamodel (Schindel 2011).

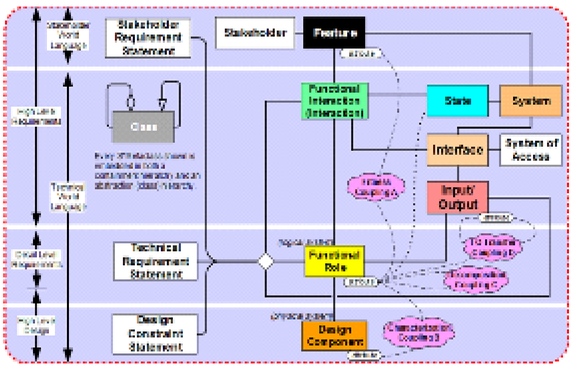

*Figure 6: Summary View of S*Metamodel.*
(SEBoK Original)

This is more than model semantics or ontology alone. It means recognizing that the models we pursue are models of the real physical systems they are about, and not just models of information about business processes concerned with those systems. While that might seem obvious to the physical scientist, a different perspective than that is embedded in forty years of enterprise information system practice. In that history, the traditional (and relatively successful) paradigm is construction of information models that describe information transactions or documents (e.g., purchase of air travel tickets). Symptomatic of that paradigm, today we still encounter MBSE models and human interpretations of them that include notions of databases, "calls", "methods", and other successful software notions that are not the same as modeling physical systems.

Conclusions and Implications for Future Action

1. Like the other engineering disciplines, Systems Engineering can be viewed as founded on "real" physical phenomena—the System Phenomenon—for which experimentally verified, mathematically modeled hard science, laws, and first principles have existed for over 150 years, dating to Hamilton, or earlier, to Newton.
2. Systems Engineering not only has its own phenomenon, but the phenomena upon which the traditional engineering disciplines (ME, CE, ChE, EE) are based can themselves all be seen to be derivable from the System Phenomenon. It is SE that has the more fundamental foundation, while the other disciplines are special cases of both the phenomena and mathematics.
3. The System Phenomenon supports the emergence of hard sciences, laws, and first principles for higher level phenomena of critical importance to humankind.
4. Systems Engineering, along with its related scientific foundations, is a young and still emerging discipline. The re-planting of Systems Engineering in a model-based framework is an important step toward strengthening the discipline, but requires a stronger model framework for that to occur, and the System Phenomenon points the way to a key part of that framework.

5. A practical implication for practicing systems engineers and their educators: All models of behavior should be based on interactions. Nature offers no "naked" behavior outside interactions, but current practice and training often seem to overlook this.
6. Systems research emphasis would benefit from more attention to specific emergent domains, each of which will have their own phenomena, instead of over-emphasizing abstract generic systems. This is a well-described but often overlooked observation, as noted in (Anderson 1972)
7. There are additional phenomena in this space. For a discussion of the Value Selection Phenomenon and Group Learning and Model Trust Phenomenon, see (Schindel 2020).

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