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Got Phenomena? Science-Based Disciplines for Emerging Systems Challenges

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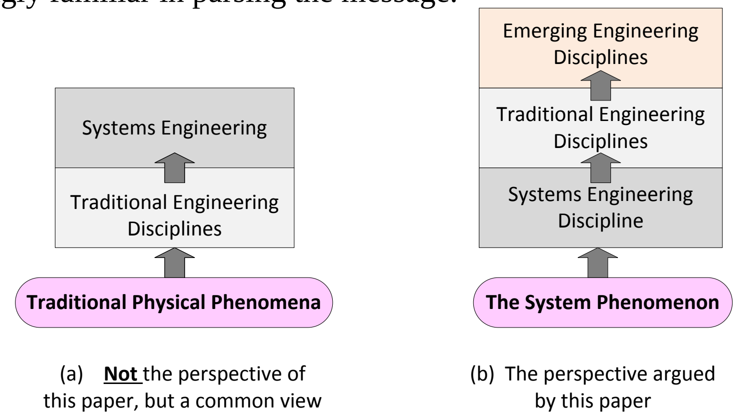
Abstract. Engineering disciplines (ME, EE, CE, ChE) sometimes argue their fields have "real physical phenomena", "hard science" based laws, and first principles, claiming Systems Engineering lacks equivalent phenomenological foundation. We argue the opposite, and how replanting systems engineering in MBSE/PBSE supports emergence of new hard sciences and phenomena-based domain disciplines.

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. This is a practical reminder of emerging higher disciplines, with 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.

1. 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 argues 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) **Not** the perspective of this paper, but a common view

(b) The perspective argued by this paper

Figure 1: ***En garde!*** **Not what you may be expecting**

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 1993), 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.

Section 2 of this paper reminds us of the "phase change" that occurred in STEM approximately 300 years earlier, when means of representation advanced, and argues efficacy from the pragmatic perspective of the dramatic impacts on human life. Section 3 argues that we are now in the early days (when trends can still be confusing) of a similar phase change in the STEM of general systems. Section 4 provides the main argument, introduces the System Phenomenon, and asserts that it is not only the hard physical phenomena basis for systems engineering, but surprisingly also for all the traditional disciplines' phenomena, reversing the "who's got real phenomena?" argument. This section also suggests the means of identifying and representing the tangible physical phenomena emergent at all levels, and their respective physical laws and first principles. Section 5 returns to the subject of current trends in systems engineering, the need to strengthen its foundation, and the opportunity to use model representation of the System Phenomenon to that end. Section 6 concludes with implications for action.

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

Science, Technology, Engineering, and Mathematics —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). Among the measures of this impact are Figures 2, 3, and 4. 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

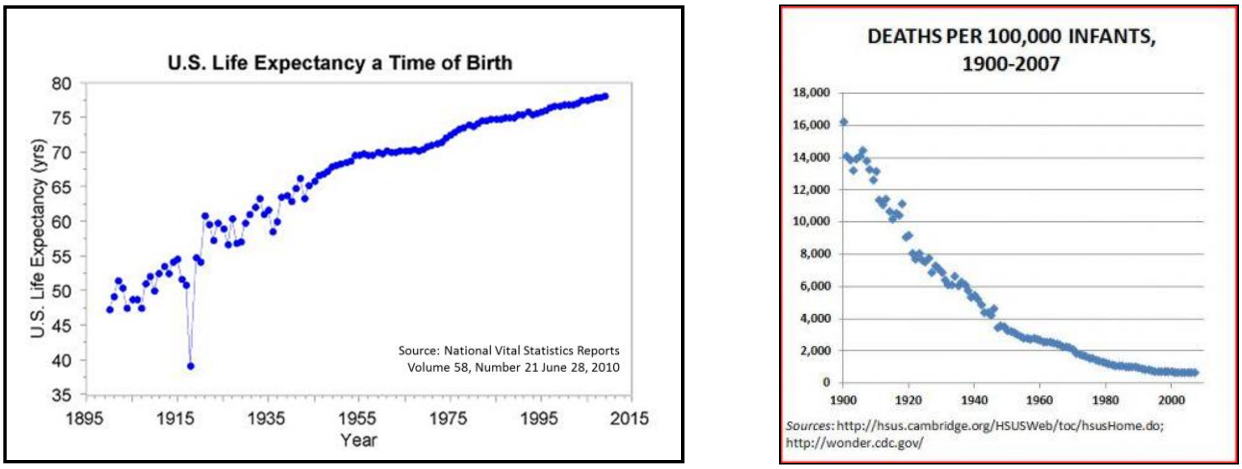


Figure 2: The length of human life has been dramatically extended

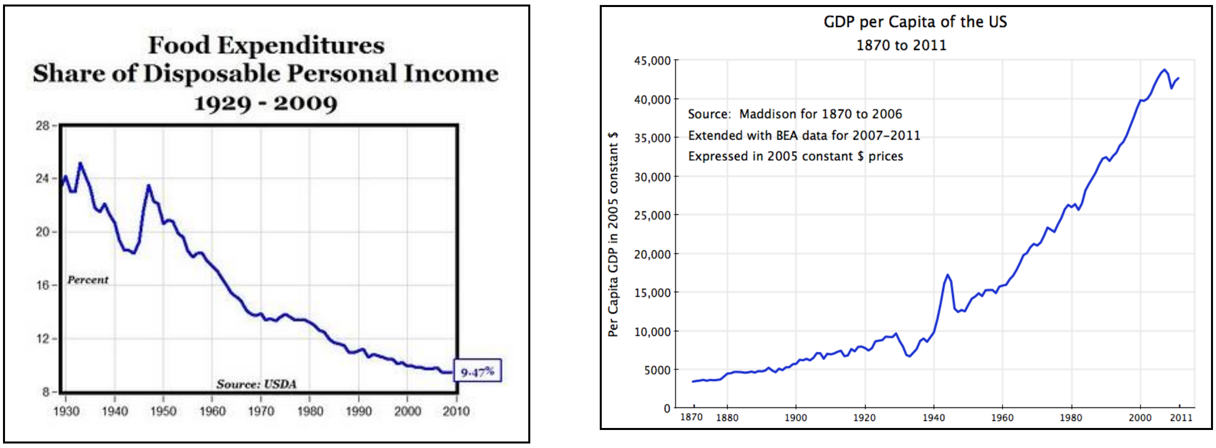
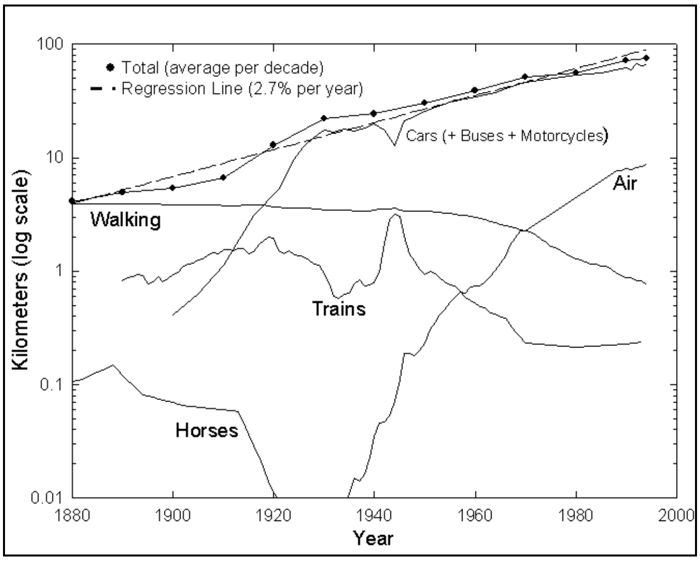


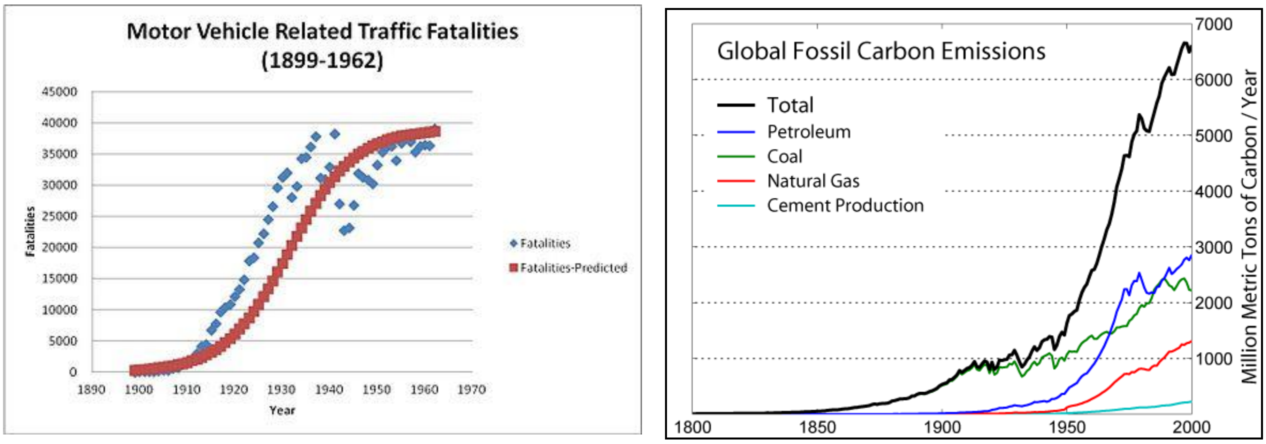
Figure 3: Simply feeding ourselves consumes less labor and time



US passenger travel per capita per day by all modes. Sources of data: Grubler , US Bureau of the Census , US Department of Transportation

Figure 4: The range of individual human travel has vastly extended

constituents of matter and life, to the largest scale complexities of networks, economies, the natural environment, and living systems. Figure 5 illustrates other parameters of these impacts.



NHTSA and FHWA data

In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, United States Department of Energy, Oak Ridge, Tenn., U.S.A

Figure 5: More available energy and mobility have brought unintended consequences

Because we argue here from the efficacy shift as STEM advanced, one might question how much other causes (for example, market capitalism as noted above) accounted for these advances. To remember that these shifts were more than just correlations in time, Table 1 reminds us of some of the more familiar and yet dramatic STEM-based advances associated with the above impacts:

Table 1: STEM Drivers that Contributed to the Above Impacts

Impact	Notable STEM Drivers (sample only)
Increased life expectancy	Life sciences, nutritional science
Reduced infant mortality	
Reduced cost of food production	Agronomy, herbicides, fertilizers, mechanization
Increased GDP per capita	Mechanized production, mechanized distribution
Increased range of travel	Vehicular, civil, and aerospace engineering
Increased traffic fatalities	Vehicular engineering, civil engineering
Increased carbon emissions	Vehicular engineering; mechanized production

"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”? As illustrated in Table 2, the traditional engineering disciplines have their technical bases and quantitative foundations in what emerged as physical sciences about what came to be understood as physical phenomena:

Table 2: Phenomenon-Based Disciplines

Engineering Discipline	Phenomena	Scientific Foundations	Representative Scientific Laws
Mechanical Engineering	Mechanical Phenomena	Physics, Mechanics, Mathematics, . . .	Newton’s Laws, others
Chemical Engineering	Chemical Phenomena	Chemistry, Mathematics, . . .	Periodic Table, others
Electrical Engineering	Electromagnetic Phenomena	Electromagnetic Theory	Maxwell’s Equations, others
Civil Engineering	Structural Phenomena	Materials Science, . . .	Hooke’s Law, others

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 & 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 mathematics and the verification mechanisms of experiment and refutation to test against reality what we would now call models.

3. 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 perhaps understandable, given the initial trajectory of the first 50 years of Systems Engineering. (Adcock 2015; Checkland 1981; Walden et al 2015; Wymore, 1977) “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 (Beihoff 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, conveying enough, and not too much, about the key ideas concerning the real things they are intended to describe.

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 variation. This recognition of recurring patterns is necessary both from the perspectives of science and economics. 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 were being represented.

Although this challenge sounds sobering, we will next argue that 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.

4. 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 6). This perspective emphasizes physical interactions as the context in which all the laws of the hard sciences are expressed. (Schindel 2013a)

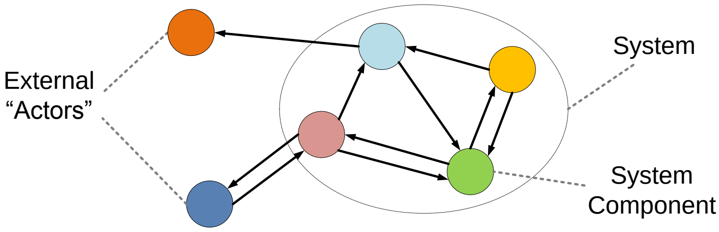


Figure 6: The System Perspective

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

1. Each component has a specific behaviour during a given interaction type, determined by the component's state. (See (4) below for the source of that component's behavioural characteristics.)
2. The combined behaviours 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:

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

4. 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 scientific 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 1.)

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 behaviours included those of 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.

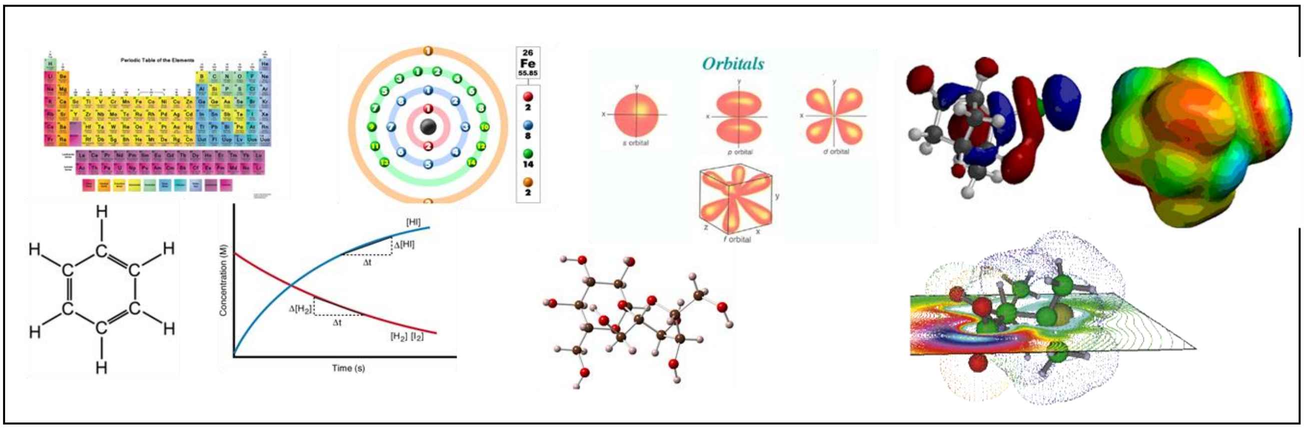


Figure 7: Chemical Interactions, Phenomena, Principles

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 level interactions give rise to the visible higher level Chemical behaviour patterns that have their own higher level properties and relationships, expressed as “hard science” laws of Chemistry.

So, we see that this illustrates:

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

Historical Domain Example 2: The Gas Laws and Fluid Flow

Illustrated by Figure 8, 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)

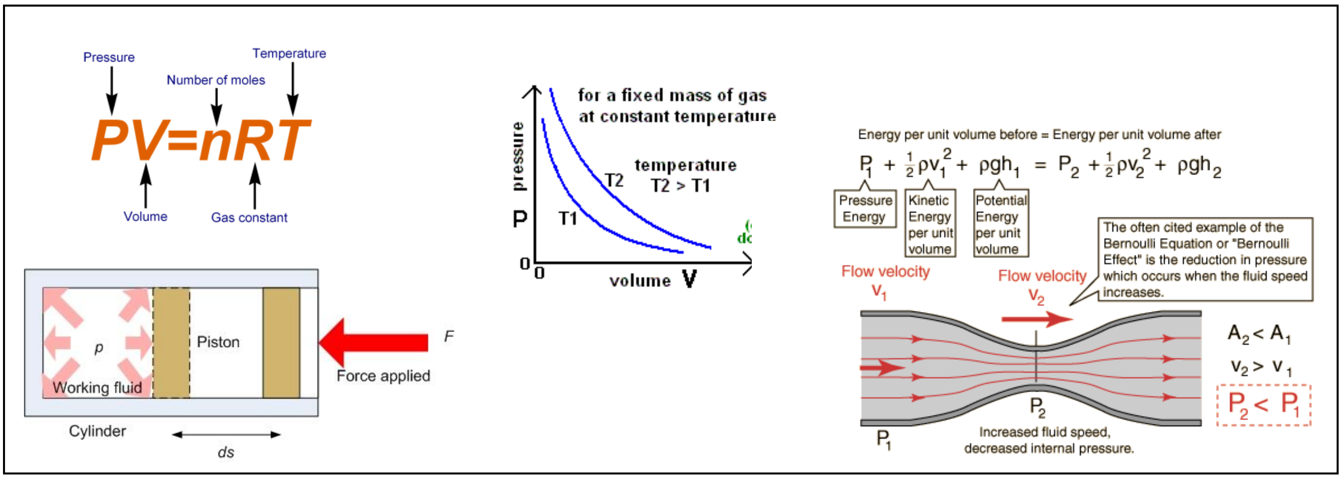


Figure 8: Gas, Fluid Interactions, Phenomena, Principles

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.

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 9:

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 (Gene Regulation Wikipedia)

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 behaviour. Indeed, they provide further reasons to understand those very interactions.

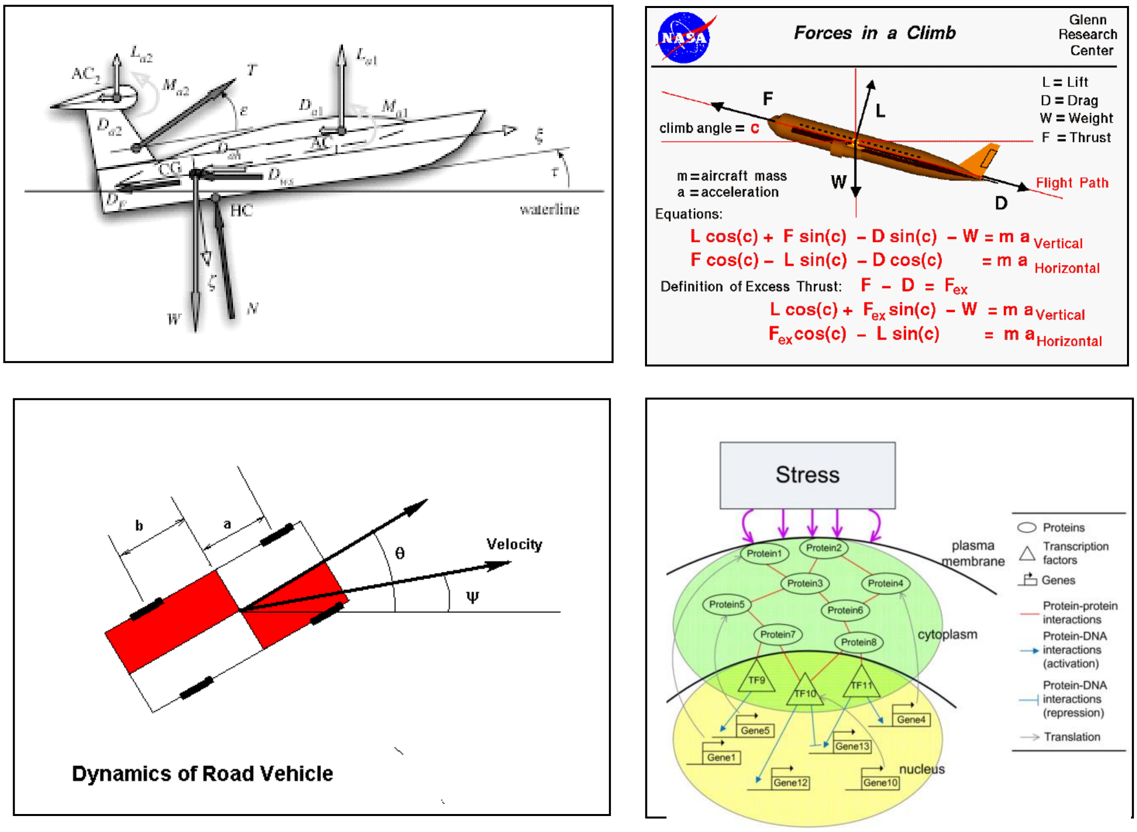


Figure 9: Ground and Marine Vehicles, Aircraft, Regulation in Organisms

Future Applications

Examples (Fig.10) that call out for improved future efficacy in systems engineering include :

1. Utility and other distribution networks: Society has come to depend on 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. <u>Living ecologies</u>: 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. <u>Health care delivery</u>: 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. <u>Product development, general innovation, and related agility</u>: 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 2015; Schindel and Dove 2016; Hoffman 2015)

Figure 10: Domain Systems of Future Interest

5. Strengthening the Foundations of MBSE

Like mechanics before Newton, the models of MBSE require a strengthened underlying framework to effectively describe the System Phenomenon in the domains of practice. MBSE requires a strong enough underlying Metamodel to support a phenomenon-based systems science.

As discussed in (Schindel 2013a), Interactions play a central role in that framework, 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 11 illustrates a related, Interaction-centric, extract from the S*Metamodel (Schindel 2011).

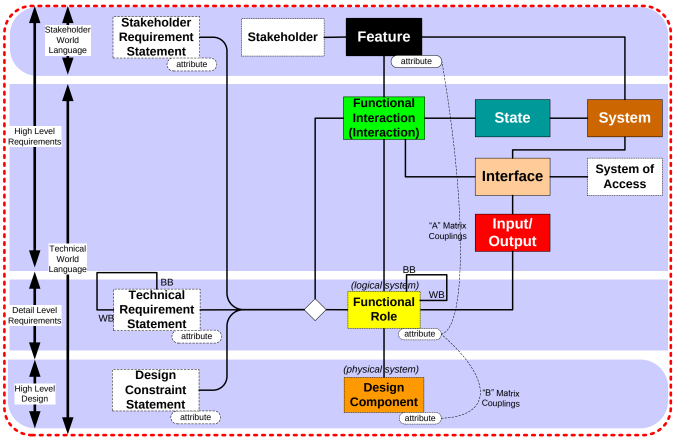


Figure 11: Summary View of S*Metamodel

This is something more than model semantics or ontology alone. It also 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 modelling physical systems. Executable models add to this challenge. In the midst of this phase change, we live in interesting times.

An Illustration of Related Systems Engineering Impact: Design Review

As an example of the beneficial impact of this Interaction-centric view of Systems Engineering, consider Design Review, where the System Phenomenon appears front and center. Figure 12 is an extract from a guide to such a review in an MBSE setting. (Schindel 2007) This diagram summarizes six questions relevant to reviewing whether a proposed system design will satisfy a set of technical requirements. Note Question 2, which compares the behaviour that emerges from interaction of its "white box" subsystems to the desired behaviour expressed by the system's "black box requirements".

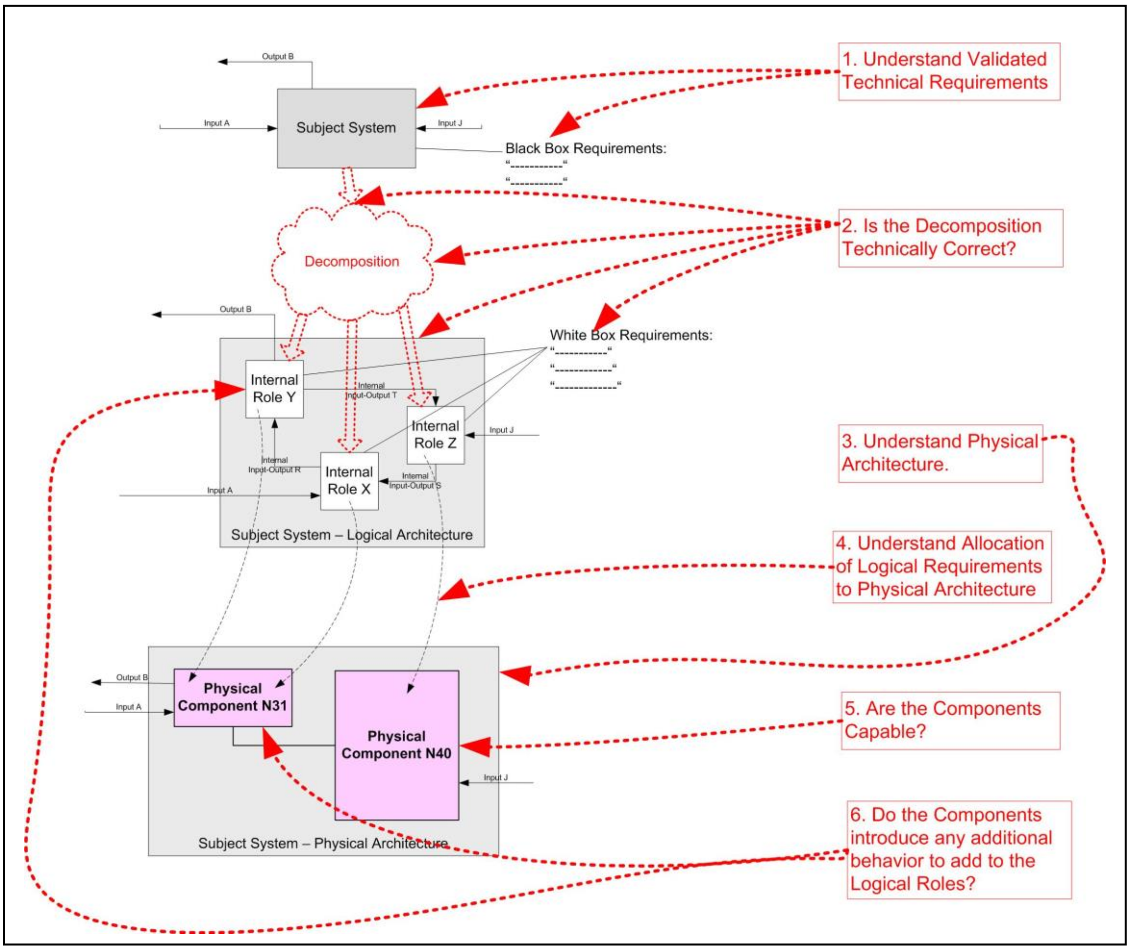


Figure 12: Related Extract from MBSE Design Review Guide

Whether viewed as composition (bottom up, emergence) or decomposition (top down), the ability to effectively answer Question 2 above is central to the design or design review process. Question 2 is about Hamilton's Principle in a specific domain setting. A verified library of knowledge of the related emergence or decomposition patterns that apply in an enterprise's or industry's or society's domains can be valuable. The capture and verification of such a library can be seen to be a form of System Science in the tradition of the domain-specific hard sciences—whether the domain is lower level or high level systems discussed above.

6. 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 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. (Note carefully that nothing about this suggests modeling behavior of an aircraft carrier from models of molecules—it simply notes that the same general interaction-based System Phenomena is the basis of emergence of behavior at each higher system level.)

3. The System Phenomenon supports the emergence of hard sciences, laws, and first principles for higher level systems of critical importance to the well-being of 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.

Implications for future action include:

5. Beyond the scope of this paper, there are also other aspects of that strengthened modeling framework in need of attention. The purpose-oriented nature of Engineering reminds us that a stronger representation of Value, Fitness Space, and selection is a part of that framework. (Schindel 2013b)

6. The INCOSE MBSE Patterns Working Group is practicing the PBSE representation of S*Patterns, which are MBSE models of recurring whole-system characteristics important to Systems Engineering. Participation in this INCOSE Working Group is invited. (INCOSE Patterns WG)

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Biography

William D. (Bill) Schindel is president of ICTT System Sciences. His engineering career began in mil/aero systems with IBM Federal Systems, included faculty service at Rose-Hulman Institute of Technology, and founding of three systems enterprises. Bill co-led a 2013 project on the science of Systems of Innovation in the INCOSE System Science Working Group. He co-leads the Patterns Challenge Team of the OMG/INCOSE MBSE Initiative, and is a member of the lead team of the INCOSE Agile Systems Engineering Life Cycle Discovery Project.