



System Science WG – MBSE Patterns WG Discussion

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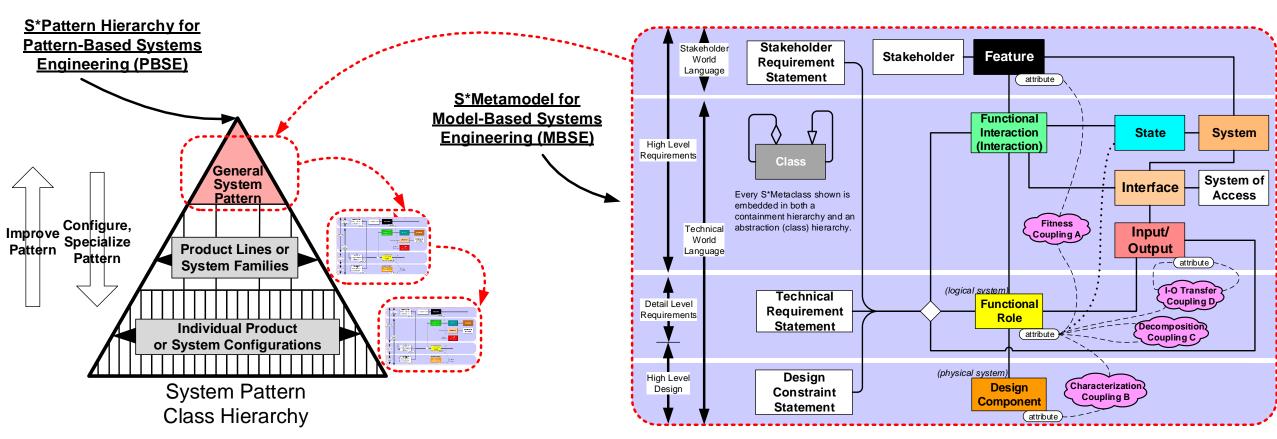
Contents

- (Part I: Limited Content):
 - From the SSWG IW19 Agenda title of this session
 - "System Patterns & Languages"
- (Part II: Main Content):
 - From the verbal request for this session
 - Questions about SSWG-PWG Collaboration
 - Att. 1: From the IW2018 & IS2018 SSWG Meetings



Part I: System Patterns & Languages



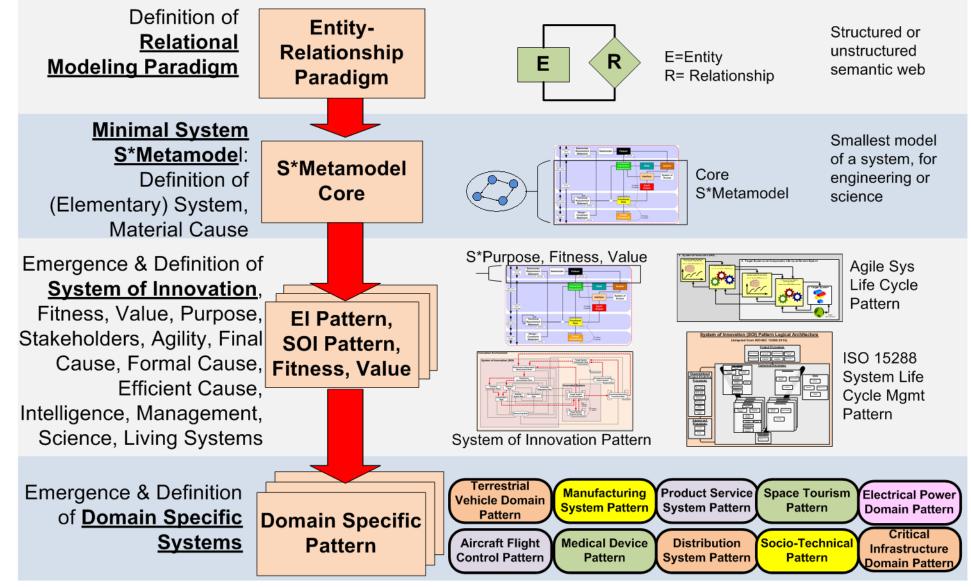


S*Metamodel informal summary pedagogical diagram

(formal S*Metamodel includes additional details.)

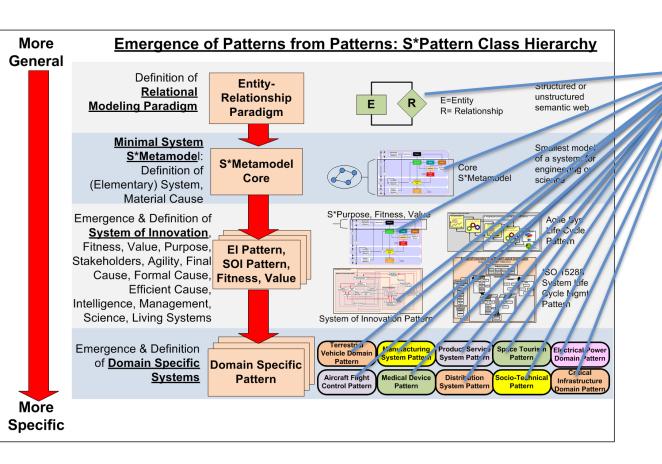
More General

Emergence of Patterns from Patterns: S*Pattern Class Hierarchy





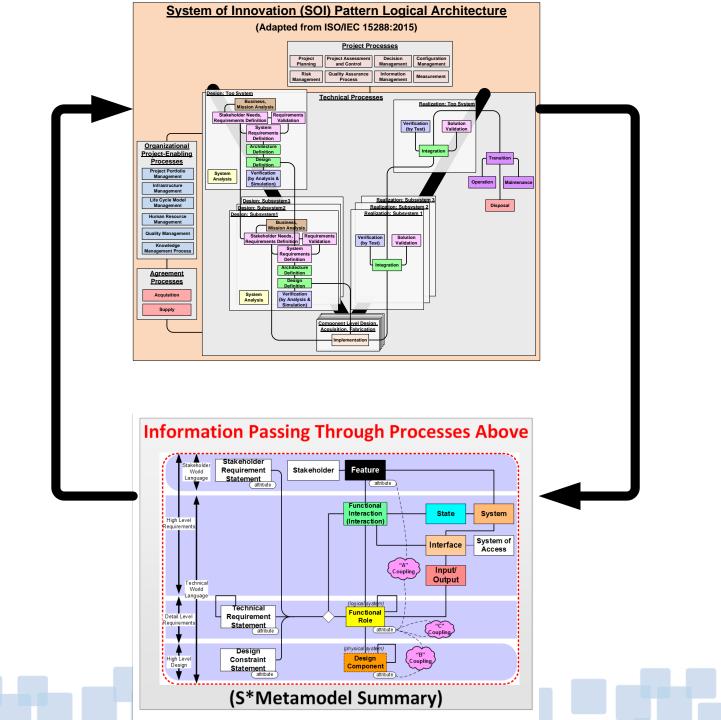




- Each pattern establishes the language of that pattern (domain specific languages)
- In engineering practice, the language of the more specific pattern is more important than the language of the metamodel, which organizes the domain specific language
- Different engineering views: "Learn to model" versus "Learn the model"



Part II: Questions about future SSWG-PWG Collaboration





System of Innovation (SOI) Pattern Logical Architecture (Adapted from ISO/IEC 15288:2015) **Project Processes** Project **Project Assessment** Decision Configuration Planning Management Management and Control Risk **Quality Assurance** Information Measurement Management **Process** Management **Design: Top System Technical Processes** Business. Realization: Top System Mission Analysis Stakeholder Needs, Requirements Validation Requirements Definition Verification Solution System (by Test) Validation Requirements Definition **Organizational** Architecture Integration Definition Project-Enabling Transition Design **Processes** Definition Project Portfolio Verification Management (by Analysis & **Analysis** Maintenance Operation Simulation) Management Real zation: Subsystem 3 Life Cycle Model Design: Subsystem3 Disposal Management Realization: Subsystem 2 Design: Subsystem2 Realization: Subsystem 1 Design: Subsystem1 **Human Resource** Management **Busines** Mission Analysis **Quality Management** Stakeholder Needs Requirements Verification Solution Requirements Definition Validation (by Test) Validation System Management Process Requirements Definition Integration Architecture Definition Agreement Design **Processes** Definition Verification System Acquisition (by Analysis & **Analysis** Simulation) Supply Component Level Design. Acquisition, Fabrication

Implementation

- Engineering & other system life cycle management process areas
 - From ISO 15288 and INCOSE SE Handbook
 - No implied order; concurrent, sequential, otherwise
- Question 1: Does SSWG agree that the engineering community generally recognizes these as the important system life cycle process areas?
- Question 2: Which of these process areas are believed by SSWG to be targets for support by a science of systems?

Questions about future SSWG-PWG Collaboration

- Question 3: Does SSWG agree that the System Phenomenon is real and the abstract parent of all the hard sciences discipline specific phenomena and their related laws?
 - Review of Attachment 1

 Question 4: Does SSWG want to work on engineering-relevant examples with PWG?

Attachment 1: From the IW2018 & IS2018 SSWG







2018
Annual INCOSE
international workshop
Jacksonville, FL, USA
January 20 - 23, 2018



Emmy Noether

System Patterns:

The System Phenomenon, Hamilton's Principle, and Noether's Theorem as a Basis for System Science

IW2018 System Science Working Group Meeting, 01.23.2018 Bill Schindel ICTT System Sciences

ICTT System Sciences

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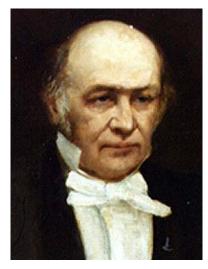
schindel@ictt.com

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2019 Annual INCOSE international workshop Torrance, CA, USA January 26 - 29, 2019

www.incose.org/IW2019







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Abstract

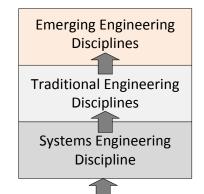


Each of the traditional engineering disciplines (EE, CE, ME, ChE, etc.) are concerned with certain physical phenomena, and founded on related explanatory theories and math-physics models of those phenomena, strengthening ability to perform the engineering practices of the discipline. However, it is sometimes suggested that Systems Engineering so far lacks, and is still seeking, some equivalent underlying theory that is grounded in base phenomena and described by explanatory model content, on an impactful par with those of the other engineering disciplines. Here we argue that (1) that there is such an underlying System Phenomenon, (2) that its explanatory, model-based theory already exists in the form of Hamilton's Principle, (3) that this phenomena and theory are the more general parent cases of the more familiar phenomena and model-based theories of each of the traditional engineering disciplines, and (4) that for the emerging largerscale systems of practical interest to systems engineering and society, new larger-scale phenomena, explanatory model-based theories, and engineering disciplines may be derived from this same general parent.

A traditional view

Systems Engineering Traditional Engineering Disciplines Traditional Physical Phenomena

Contents



The System Phenomenon

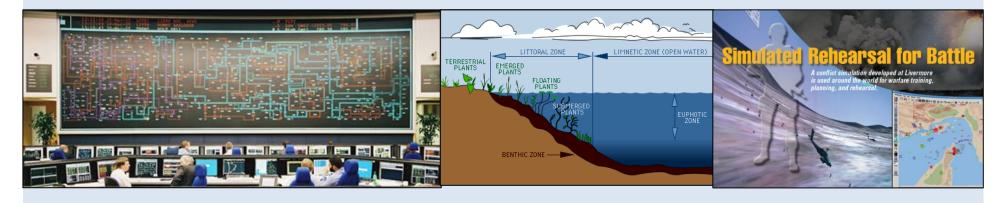
Our view

- Phenomena-based Engineering Disciplines
- The Traditional Perspective
- MBSE, PBSE: A Phase Change in Systems Engineering
- The System Phenomenon
- Hamilton's Principle and Noether's Theorem
- The New Perspective
- More Recent Examples
- Future Applications
- Where Do Systems Come From, and Where Do They Go?
- What You Can Do
- References





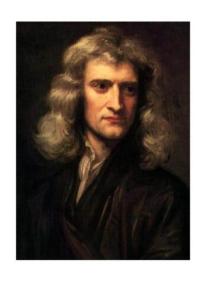
Systems: Big, Complex, and Challenging



- Engineers and scientists are increasingly concerned with understanding or designing large, complex systems.
- Is current Systems Engineering up to this challenge?

Two "Phase Changes" in Technical Disciplines

- 1. Phase change leading to traditional STEM disciplines:
 - Beginning around 300 years ago (Newton's time)
 - Evidence argued from efficacy step impact on human life





- 2. Phase change leading to future systems disciplines:
 - Beginning around our own time
 - Evidence argued from foundations of STEM disciplines

Phase Change 1 Evidence: Efficacy of Phenomena-Based STEM Disciplines





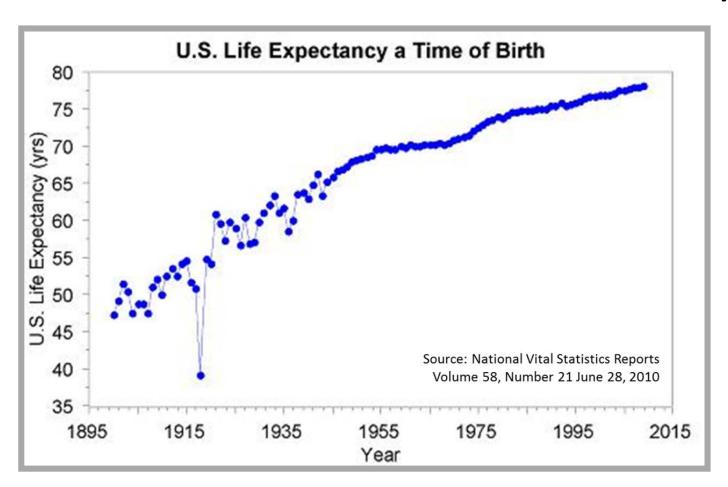


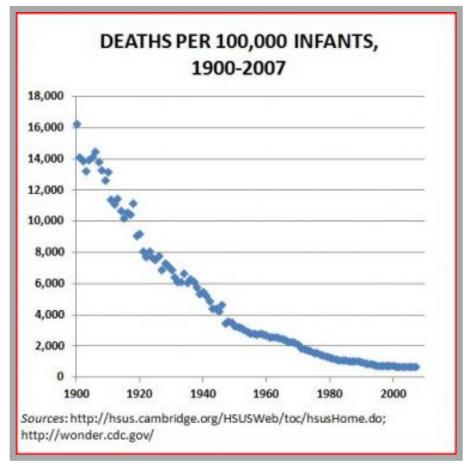


In a matter of a 300 years . . .

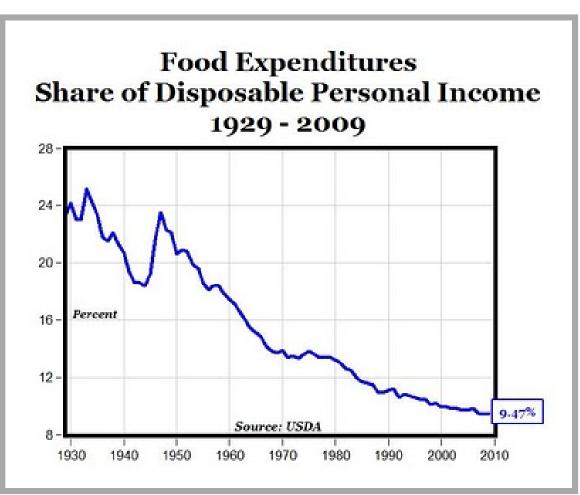
- the accelerating emergence of Science, Technology, Engineering, and Mathematics (STEM) . . .
- has lifted the possibility, quality, and length of life for a large portion of humanity . . .
- while dramatically increasing human future potential.
- By 20th Century close, strong STEM capability was recognized as a critical ingredient to individual and collective prosperity.

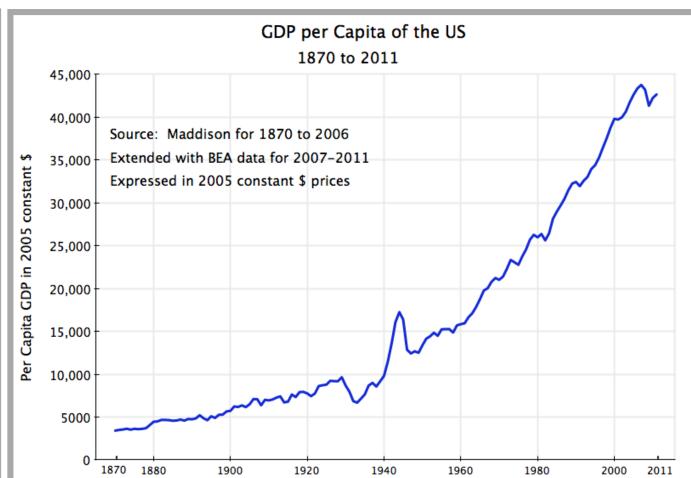
The length of human life has been dramatically extended:



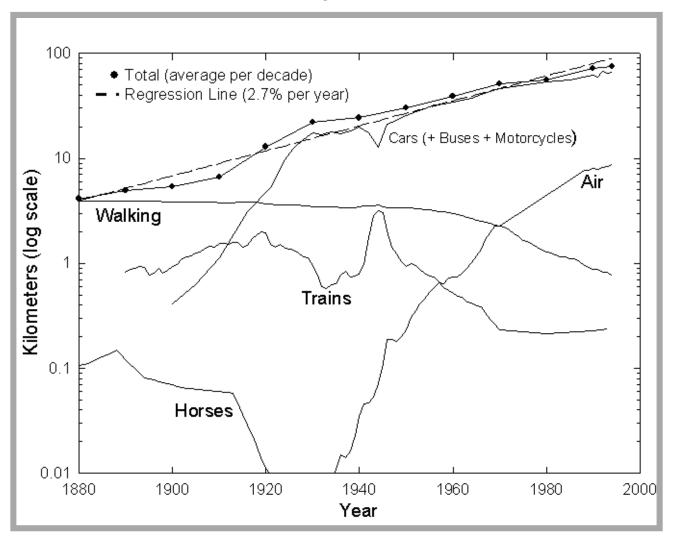


Simply feeding ourselves consumes less labor and time:





The range of individual human travel has vastly extended:

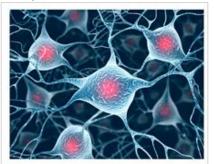


US passenger travel per capita per day by all modes. Sources of data: Grubler , US Bureau of the Census , US Department of Transportation

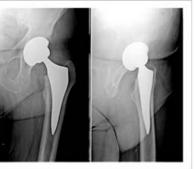
Challenges Have Likewise Emerged



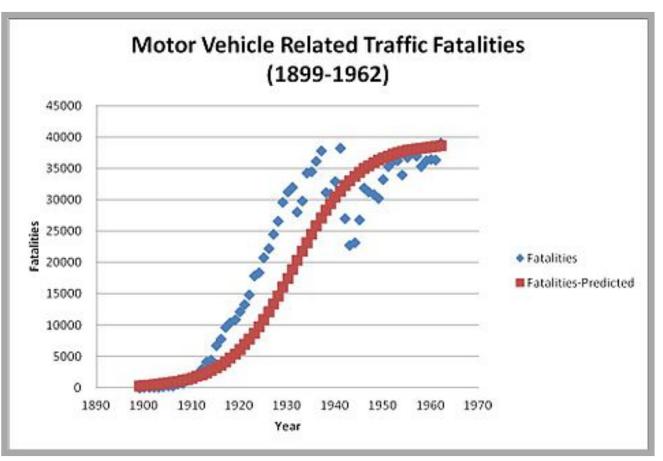
- In recent decades, the human-populated world has become vastly more interconnected, complex, and challenging . . .
- Offering both expanding opportunities and threats.
- From the smallest known constituents of matter and life, to the largest-scale complexities of networks, economies, the natural environment, and living systems . . .
- Understanding and harnessing the possibilities have become even more important than before.

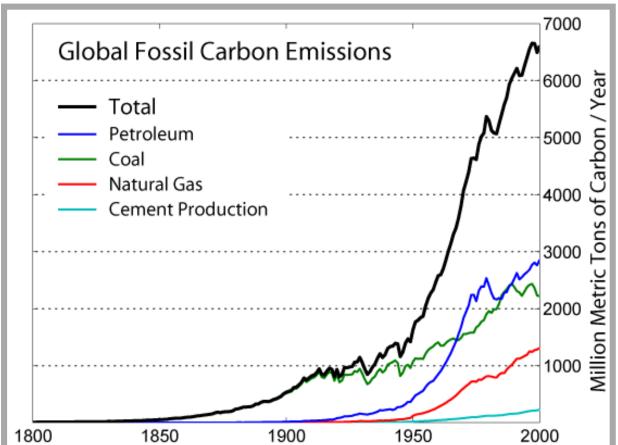






Systems progress has come with challenging side effects:





Not all human progress has been STEM-driven

- For example, the spread of market capitalism can be argued to have also lifted human life.
- Nevertheless STEM has been a major contributor:

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

Emergence of Science and Engineering

• The "hard sciences", along with the "traditional" engineering disciplines and technologies based on those sciences, may be credited with much of this amazing progress, as well as challenges.

 How should Systems Engineering be compared to engineering disciplines based on the "hard sciences"?

Phenomena-Base Engineering Disciplines

• The traditional engineering disciplines have their technical bases and quantitative foundations in the hard sciences:

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











The Traditional Perspective

- Specialists in individual engineering disciplines (ME, EE, CE, ChE, etc.) sometimes argue that their fields are based on:
 - "real physical phenomena",
 - physical laws based in the "hard sciences", and first principles,
- sometimes claiming that Systems Engineering lacks the equivalent phenomena based theoretical foundation.

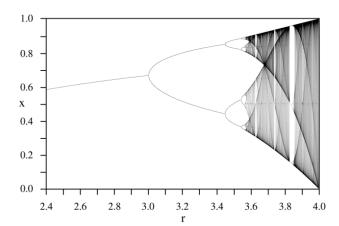
$$\begin{array}{l} \nabla \cdot \mathbf{D} = \rho \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \end{array}) \\ \end{array}$$

- Instead, Systems Engineering is sometimes viewed as:
 - Emphasizing process and procedure
 - Critical thinking and good writing skills
 - Organizing and accounting for information
- But not based on an underlying "hard science"

Traditional Perspective, continued

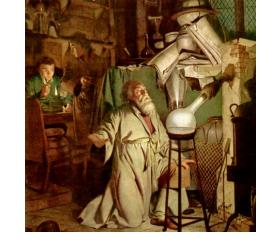
- That view is <u>perhaps</u> understandable, given the first 50 years of Systems Engineering
- "Science" or "phenomenon" of generalized systems have for the most part been described on an intuitive basis, with limited reference to a "physical phenomenon" that might be called the basis of systems science and systems engineering:
 - For example, emergence of patterns out of agent interactions in complex systems
 - Fascinating, but not yet the basis of generations of life-changing human progress such as has marked the last 300 years











However . . .

- The same might be said of physics before Newton, chemistry before Lavoisier & Mendeleev, electrical science before Faraday & Maxwell, etc.
- Moreover, Systems Engineering is also undergoing a "phase change" that might be compared to the emergence of phenomena understanding in the other engineering disciplines . . .

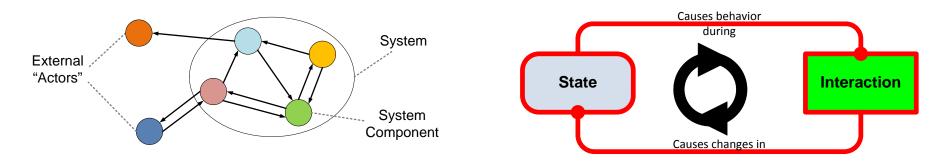
MBSE, PBSE: A Phase Change in Systems Engineering

While models are not new to STEM . . .

- <u>Model- Based Systems Engineering (MBSE):</u> We increasingly represent our understanding of <u>systems</u> aspects using explicit models.
- <u>Pattern-Based Systems Engineering (PBSE):</u> We are beginning to express parameterized family System Models capable of representing <u>recurring</u> patterns.
- This is a much more significant change than just the emergence of modeling languages and IT toolsets, <u>provided the underlying model structures are</u> <u>strong enough</u>:
 - Remember physics before Newtonian calculus
 - We assert here the need to use mathematical patterns known 100 years

The System Phenomenon

• In the perspective described here, by <u>system</u> we mean a collection of interacting components:



- Where <u>interaction</u> involves the exchange of energy, force, mass, or information, . . .
- Through which one component impacts the <u>state</u> of another component, . . .
- And in which the state of a component impacts its behavior in future interactions.

The System Phenomenon

- <u>Phenomena</u> of the hard sciences are in each case instances of the following "System Phenomenon":
 - behavior emergent from the interaction of behaviors (phenomena themselves) a level of decomposition lower.
- In each such case, the emergent interaction-based behavior of the larger system is a <u>stationary path of the</u> action integral:

$$\mathcal{S} = \int_{t_1}^{t_2} L(x,\dot{x},t)\,dt$$
 External "Actors" System Component

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

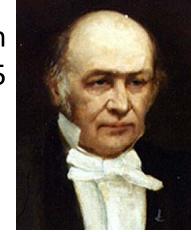
(Hamilton's

Principle)

William Rowan Hamilton Ireland, 1805-1865

Hamilton's Principle: Root of Equations of Motion for All Interactive Phenomena (Dynamics)

- Hamilton's Principle: Stated in language of mathematics (calculus of variations, not just prose heuristics or philosophy):
 - Basis of equations of motion (dynamical configuration change) in system state configuration phase space.
 - The source of derivation of the "specific phenomena" mathematics, such as Maxwell's Equations, Newton's Laws/Mechanics, Quantum Mechanics (i.e., Path Integral formulation), etc.
 - Even when we cannot solve the resulting equations (laws), they are the basis of simulations, in particular HPC computational models (e.g., computational chemistry based on Schrödinger eqn., etc.)

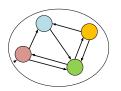


Emmy Noether Germany and USA 1882-1935



Noether's Theorem: Symmetries, Emergent Invariants and Conservation Laws

- Noether's Theorem: Shows us that . . .
 - In the presence of continuous symmetry (e.g., time translation, spatial translation, rotational translation, etc.), . . .
 - Hamilton's Principle will apply and . . .
 - There will be invariant (conserved) emergent quantities (integrals of motion), e.g., energy, momentum (linear and rotational), etc.

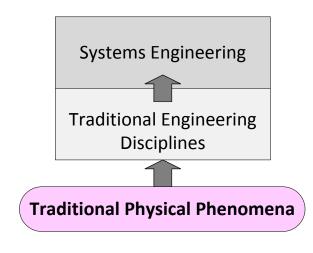


The System Phenomenon

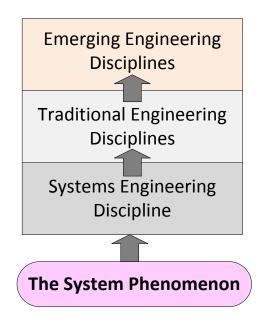
- Instead of Systems Engineering lacking the kind of theoretical foundation that the "hard sciences" bring to other engineering disciplines, . . .
 - It turns out that all those other engineering disciplines' foundations are themselves dependent upon the System Phenomenon.
 - The underlying math and science of systems 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!



A traditional view:



Our view:

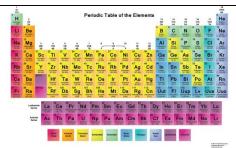


— It is not Systems Engineering that lacks its own foundation—instead, it has been providing the foundation for the other disciplines!

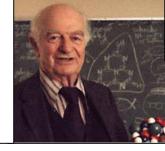
Historical Example 1: Chemistry

Modern Chemist

Priestley: Oxygen



Periodic Table of the Elements

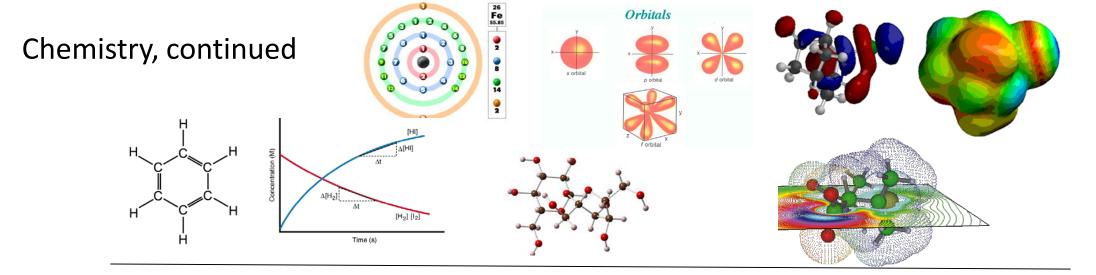


Pauling: Chemical Bond



Mendeleev: Periodic Table

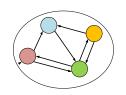
- Chemists, and Chemical Engineers, justifiably consider their disciplines to be based on the "hard phenomena" of Chemistry:
 - A view that emerged from the scientific discovery and verification of laws of Chemistry.
 - Chemical Elements and their Chemical Properties, organized by the discovered patterns of the Periodic Table.
 - Chemical Bonds, Chemical Reactions, Reaction Rates, Chemical Energy, Conservation of Mass and Energy.
 - Chemical Compounds and their Properties.



However...

- All those chemical properties and behaviors are emergent consequences of <u>interactions</u> that occur between atoms' orbiting electrons (or their quantum equivalents), along with the rest of the atoms they orbit.
- These lower level <u>interactions</u> give rise to <u>patterns</u> that have their own higher level properties and relationships, expressed as "hard science" laws.

Chemistry, continued



So . . .



- 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 patterns</u>.

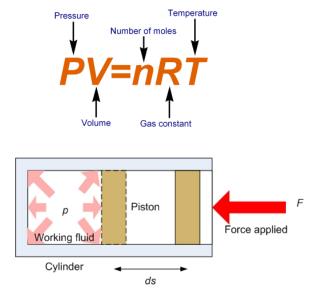


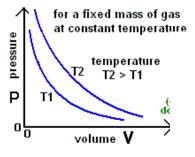
Historical Example 2: The Gas Laws and Fluid Flow

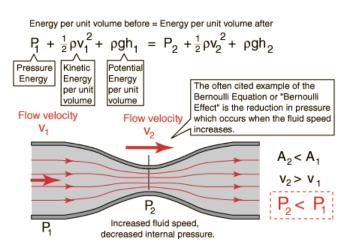


Daniel Bernoulli

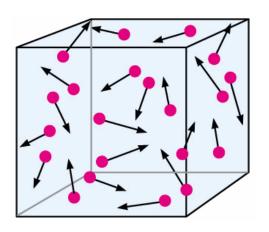
 The discovered and verified laws of gases and of compressible and incompressible fluid flow by Boyle, Avogadro, Charles, Gay-Lussac, Bernoulli, and others are rightly viewed as fundamental to science and engineering disciplines.

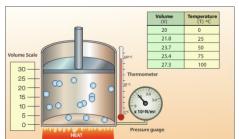


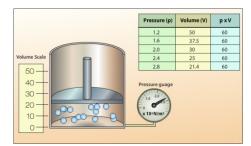


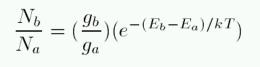


Gas Laws, continued









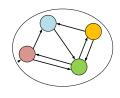


Boltzmann

However...

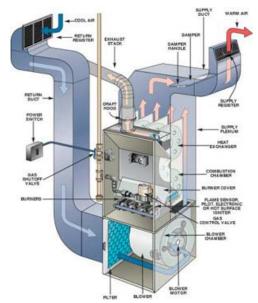
- All those gaseous properties and behaviors are emergent consequences of <u>interactions</u> that occur between atoms or molecules, and the containers they occupy, and the external thermal environment
- These lower level <u>interactions</u> give rise to <u>patterns</u> that have their own higher level properties and relationships, expressed as "hard sciences" laws.

Gas Laws, continued



So . . .

- The "fundamental phenomena" of gases, along with the scientifically-discovered / verified "fundamental laws and first principles" are in fact . . .
- higher level emergent <u>system patterns</u> so that . . .
- Mechanical Engineers, Thermodynamicists, and Aerospace Engineers can study and apply those <u>system patterns</u>.



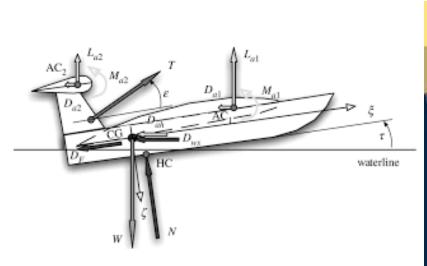




More Recent Historical Examples

- Ground Vehicles
- Aircraft
- Marine Vessels
- Dynamics of Road Vehicle

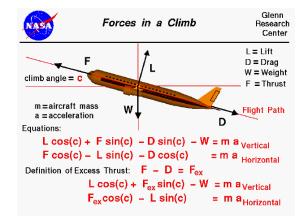
Biological Regulatory Networks

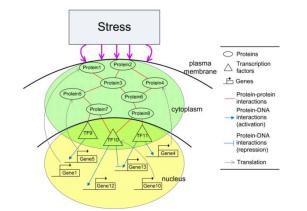




Denoting the angular velocity ω , the equations of motion are:

$$\begin{split} \frac{d\omega}{dt} &= 2k\frac{(a-b)}{I}(\theta-\psi) - 2k\frac{(a^2+b^2)}{VI}\omega\\ \frac{d\theta}{dt} &= \omega\\ \frac{d\psi}{dt} &= \frac{4k}{MV}(\theta-\psi) + 2k\frac{(b-a)}{MV^2}\omega \end{split}$$

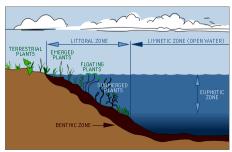


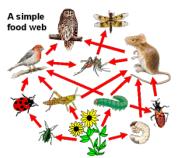


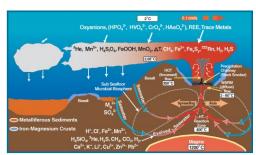
Future Applications

- Utility and other distribution networks
- Biological organisms and ecologies
- Market systems and economies
- Health care delivery, other societal services
- Systems of conflict
- Agile innovation



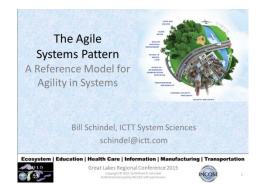










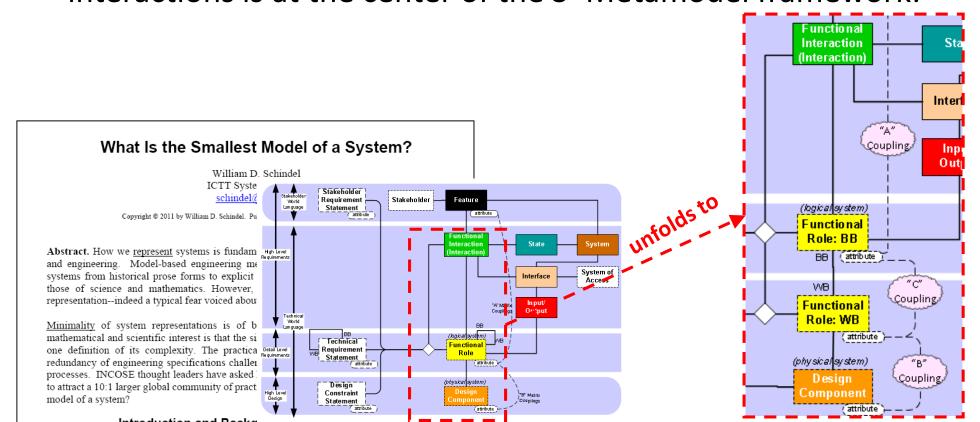






Strengthening the Foundations of MBSE

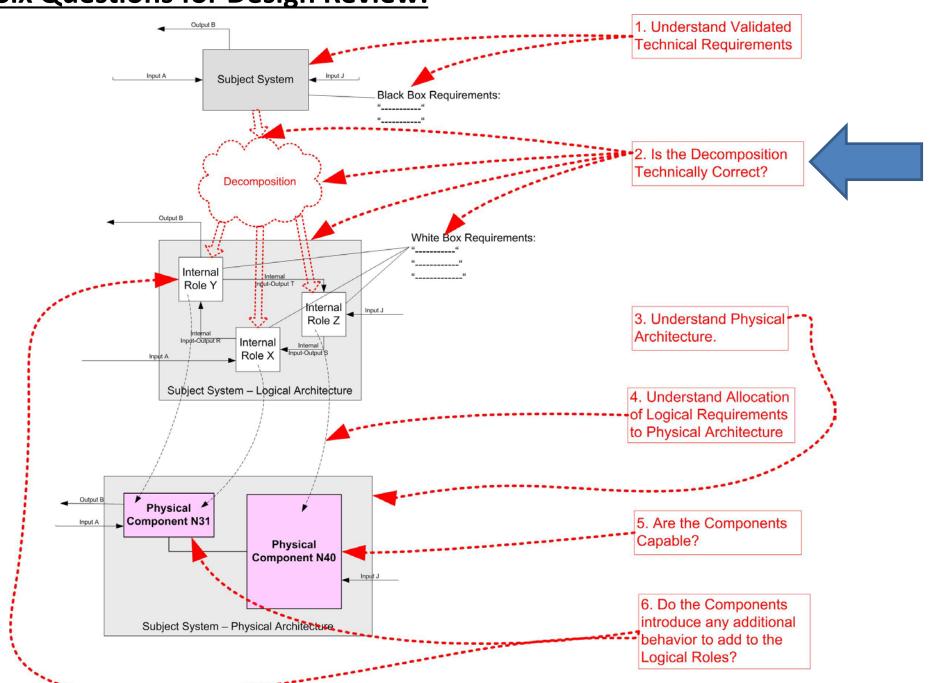
- Model-Based Systems Engineering requires a strong enough underlying Metamodel and Systems Science to equip it for the challenges and opportunities of these higher level systems.
- Example: The model framework of behavior emerging from interactions is at the center of the S*Metamodel framework:



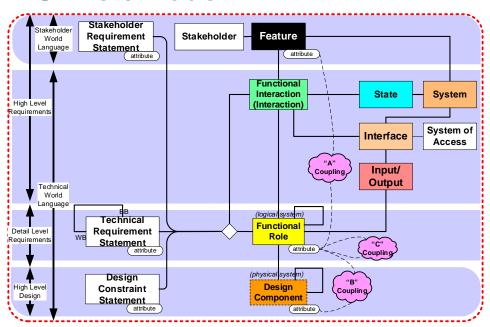
An illustration of Related SE Impact: Design Review

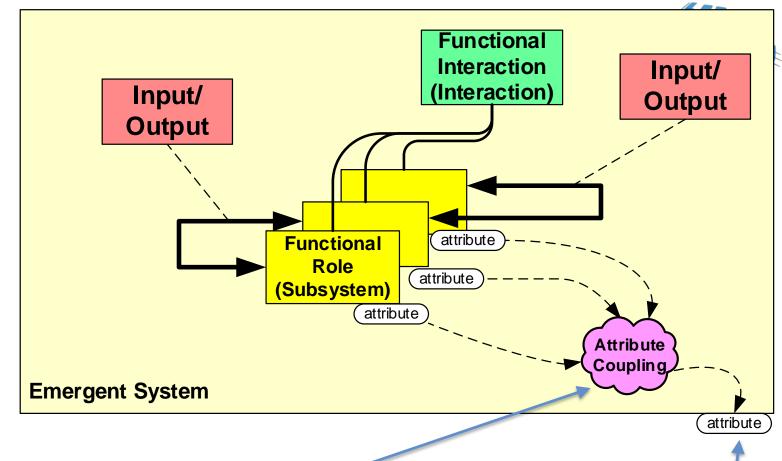
- Model-Based Design Review:
 - An example of beneficial impact of the System Phenomenon viewpoint
- Poses six key questions for any Design Review
 - To determine if a candidate design is likely to satisfy system requirements
- Note Question 2, comparing Black Box behavior that emerges from White Box interactions.
- Whether viewed as composition (bottoms up) or decomposition (top down) . . .

Six Questions for Design Review:



S*Metamodel





Governed by Hamilton's Principle

Emergent, in some cases conserved, properties—Noether's Theorem

Not only the basis for symbolic equations, but also practical simulations, when not solvable by symbolic means:



energytech 2017

A Lagrangian Approach to Modeling, Simulating and Controlling Dynamics of Turboelectric Distributed Propulsion (TeDP)

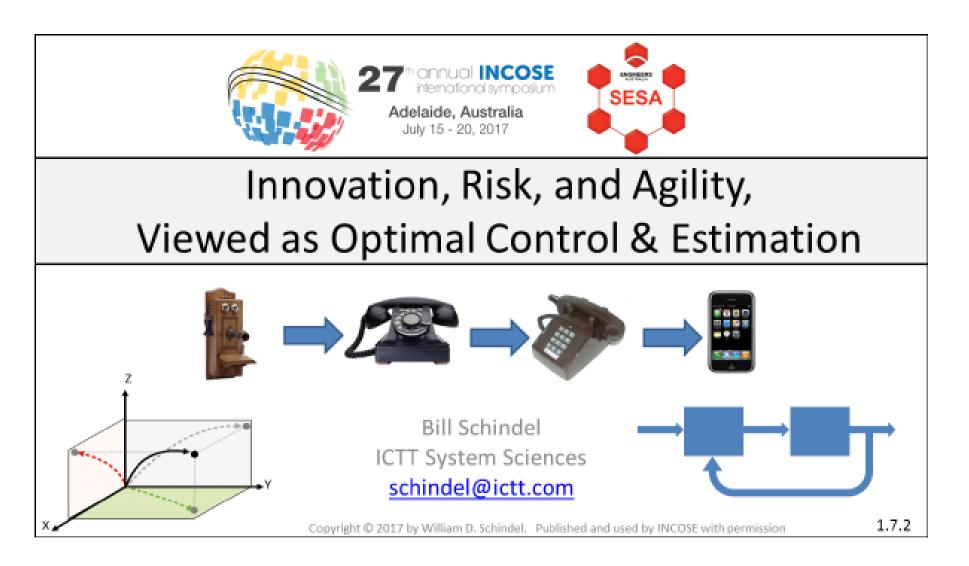
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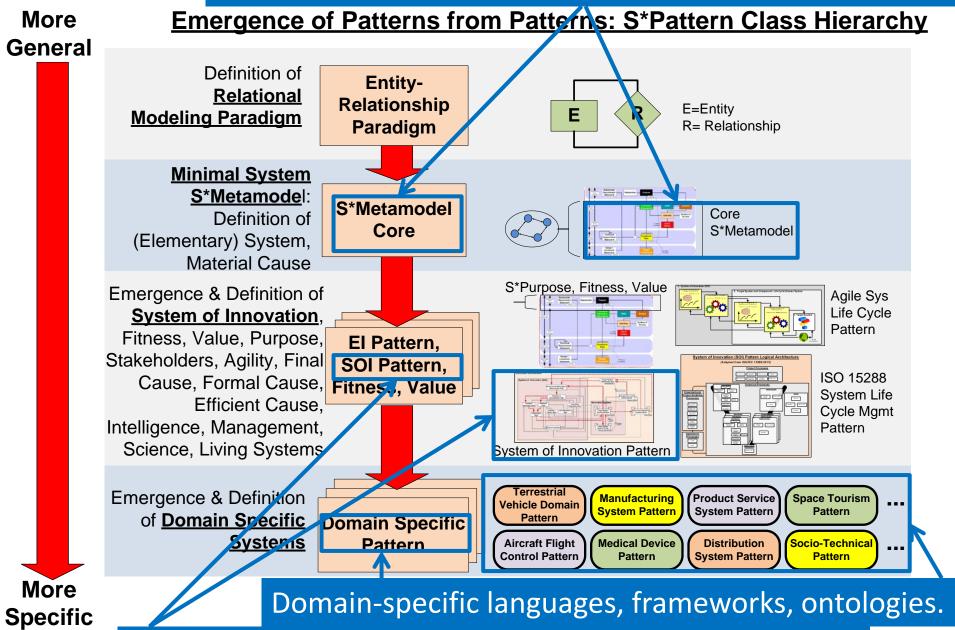




The foregoing was about dynamics of a given system. But, where do systems come from, and where to they go?

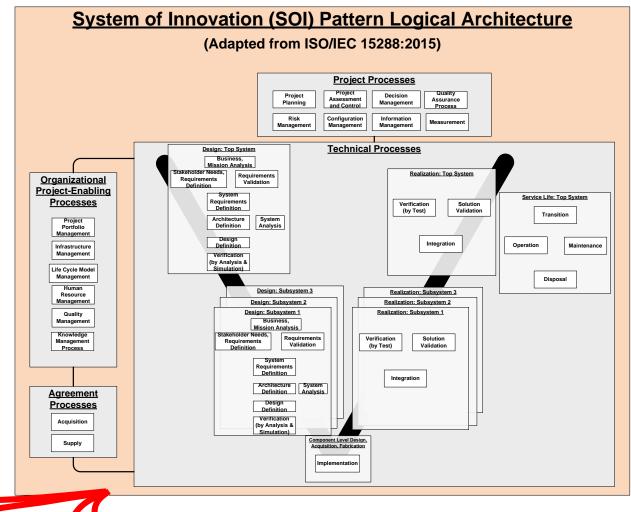


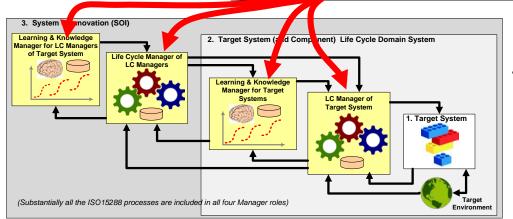
Universal systems nomenclature, domain-independent.



Generator of "new systems"; also maintainer, destroyer

ISO15288 and INCOSE
SE Handbook describe a
framework of ~32 roles
of system Life Cycle (LC)
Management.



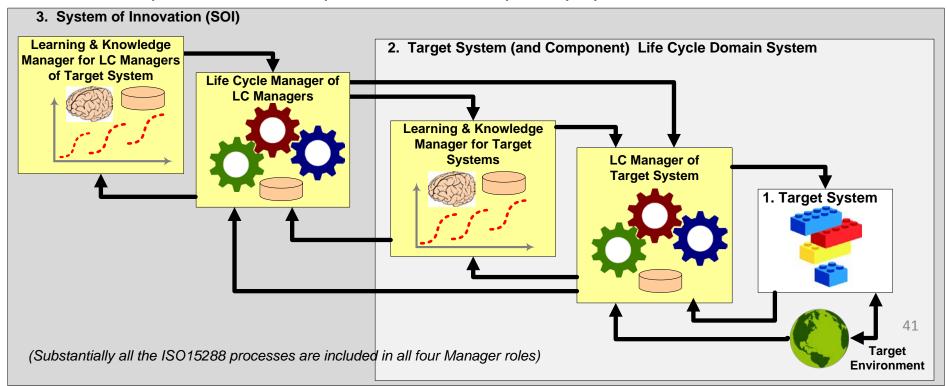


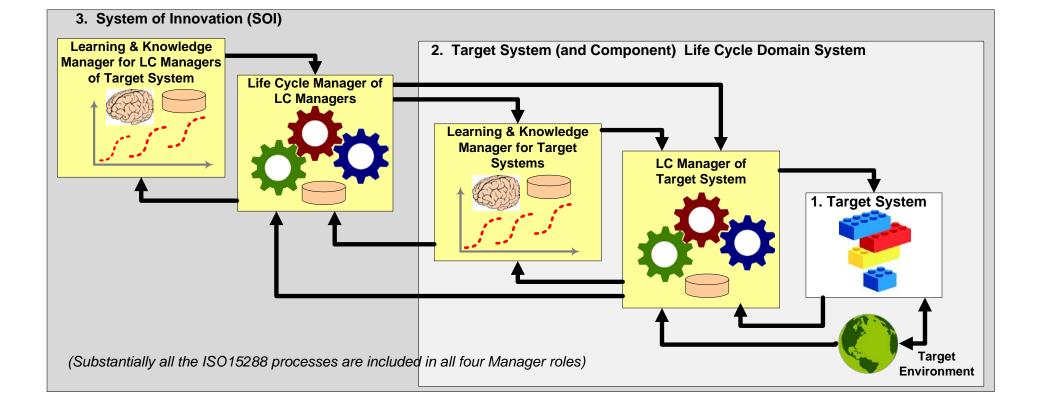
They appear repeatedly, in different ways in the SOI & ASELCM Patterns.

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INCOSE Agile System Life Cycle Pattern: Application of System of Innovation (SOI) Pattern

- A complex adaptive system reference model for system innovation, adaptation, sustainment, retirement.
- Whether 100% human-performed or automation aided.
- Whether performed with agility or not, 15288 compliant or not, informal, scrum...
- Whether performed well or poorly.
- Includes representation of pro-active, anticipatory systems.





System 1: Target system of interest, to be engineered or improved.

System 2: The environment of (interacting with) S1, including all the life cycle management systems of S1, including learning about S1.

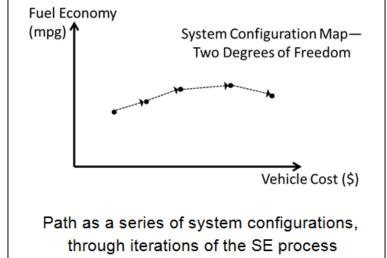
System 3: The life cycle management systems for S2, including learning about S2.

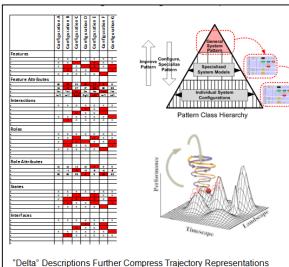
Most of the challenges discussed in INCOSE are System 2 and System 3 problems, not System 1 problems.

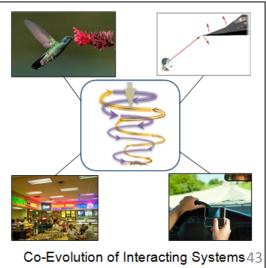
Where Do Systems Come From and Go? System Life Cycle Trajectories in S*Space

- Configurations change over life cycles, during development and subsequently
- Trajectories (configuration paths) in S*Space
- Effective tracking of trajectories
- History of dynamical paths in science and math
- Differential path representation: compression, equations of motion

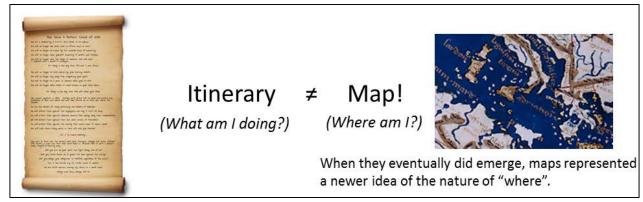




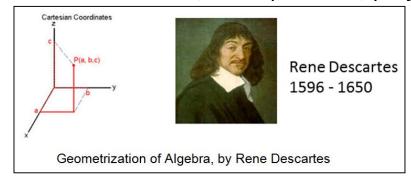


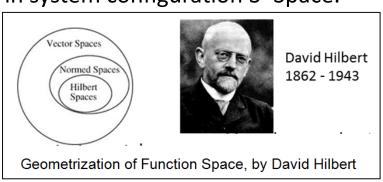


Maps vs. Itineraries -- SE Information vs. SE Process

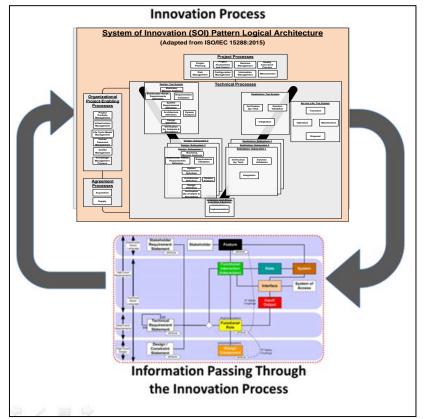


- The SE Process consumes and produces <u>information</u>.
- But, SE historically emphasizes <u>process</u> over <u>information</u>. (Evidence: Ink & effort spent describing standard process versus standard information.)
- Ever happen?-- Junior staff completes all the process steps, all the boxes are checked, but outcome is not okay.
- Recent discoveries about ancient navigators: Maps <u>vs</u>. Itineraries.
- The geometrization of Algebra and Function spaces (Descartes, Hilbert)
- Knowing where you "really" are, not just what "step" you are doing.
- Knowing where you are "really" going, not just what "step" you are doing next.
- Distance metrics, inner products, projections in system configuration S*Space.

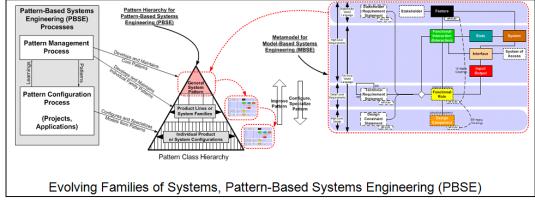




Maps vs. Itineraries -- SE Information vs. SE Process

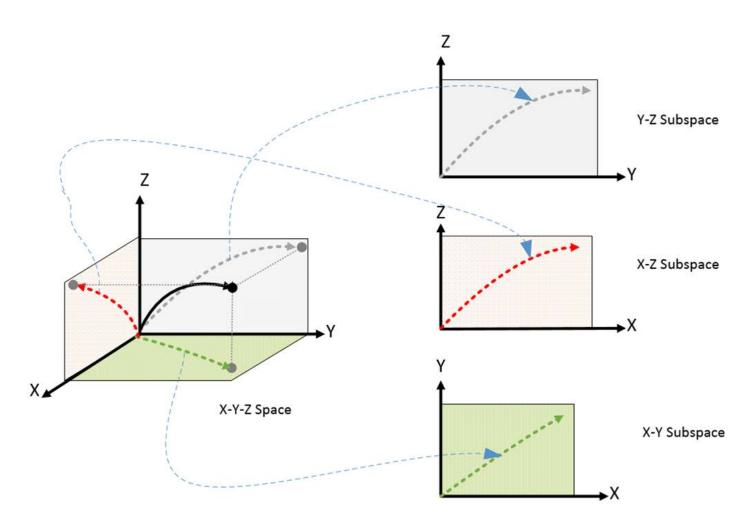




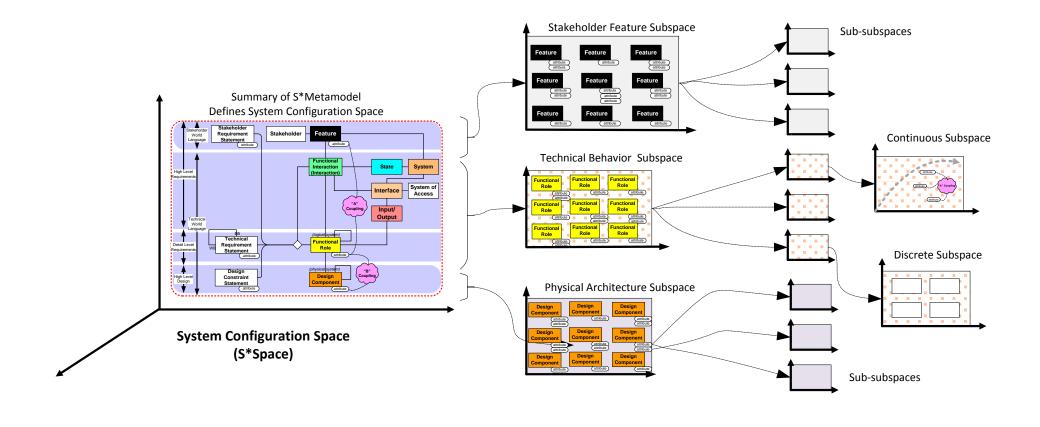


- Model-based Patterns in S*Space.
- Interactions as the basis of all laws of physical sciences.
- Relationships, not procedures, are the fruits of science used by engineers: Newton's laws, Maxwell's Equations.
- Immediate connection to Agility: knowing where you are--starting with better definition of what "where" means. There is a minimal "genome" (S*Metamodel) that provides a practical way to capture, record, and understand—the "smallest model of a system".
- Not giving up process: MBSE/PBSE version of ISO/IEC 15288.

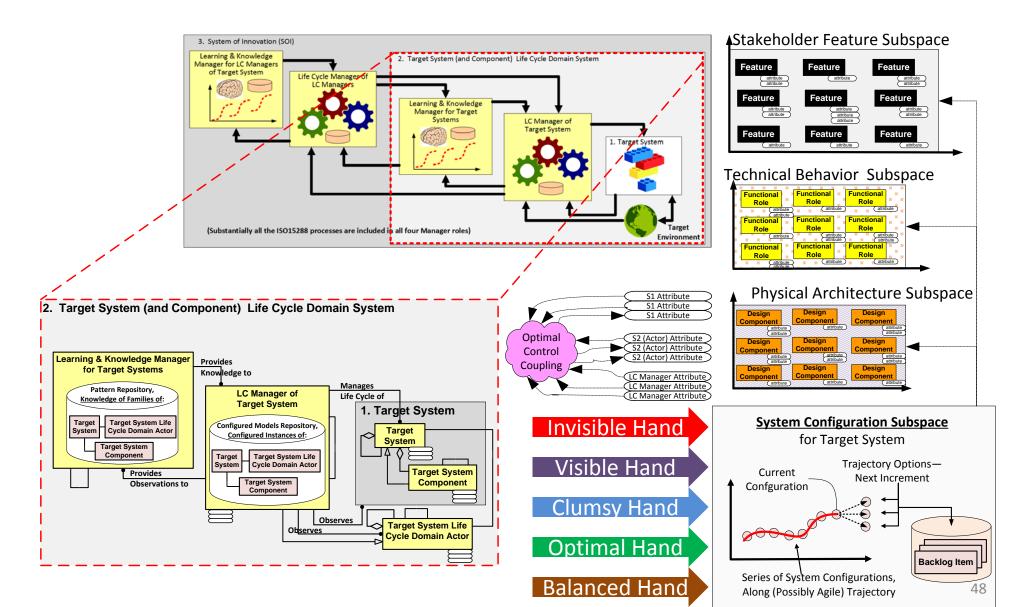
Simple Geometric/Mathematical Idea: Subspace Projections

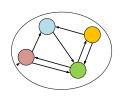


System Life Cycle Trajectories in S*Space, and S*Subspaces



Agility as Optimal Trajectory Control in S*Space: Finding the Best Next Increment "Direction"





What You Can Do

- Practice expressing your systems' requirements and designs using models that explicitly represent their <u>interactions</u>:
 - The S*Metamodel provides a framework; see examples and references
- For the higher level systems challenging your efforts, look for opportunities to discover, express, and verify hard system patterns (repeatable parameterized models) of their higher level "phenomena":
 - See the S*Patterns examples and references
- Help INCOSE make progress: Participate in the INCOSE
 Patterns Working Group on a related project on this subject:

http://www.omgwiki.org/MBSE/doku.php?id=mbse:patterns:patterns

- 1. INCOSE MBSE Initiative Patterns Working Group web site, at http://www.omgwiki.org/MBSE/doku.php?id=mbse:patterns:patterns
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