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V1.7.7

Implications for Future SE Practice as a Discipline:

Initial Elements of a Science of Systems

(awareness version, 1 hour)

INCOSE *SE Vision 2025* : A call for stronger SE foundations

Page 40

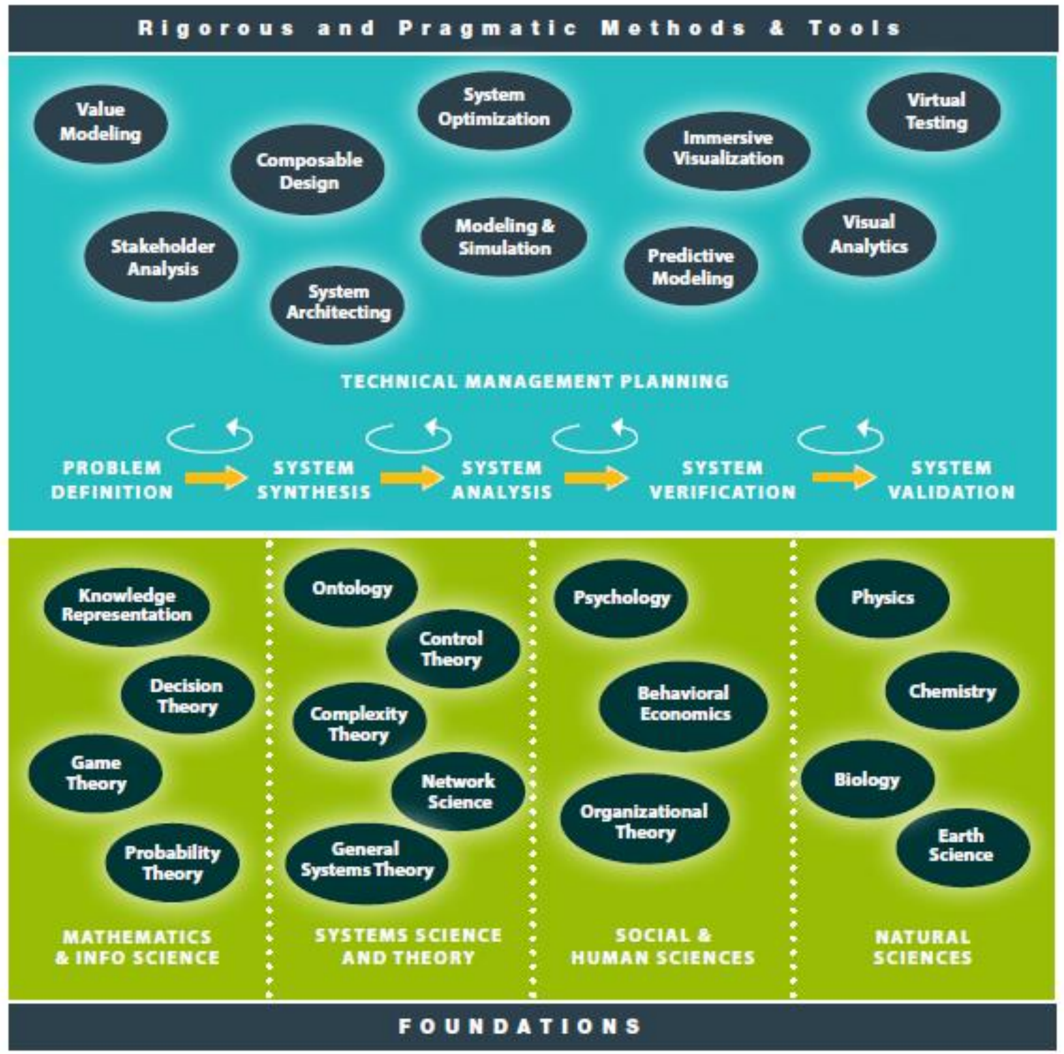
Page 41

"From:

Systems engineering practice is only weakly connected to the underlying theoretical foundation, and educational programs focus on practice with little emphasis on underlying theory."

"To:

The theoretical foundation of systems engineering encompasses not only mathematics, physical sciences, and systems science, but also human and social sciences. This foundational theory is taught as a normal part of systems engineering curricula, and it directly supports systems engineering methods and standards. Understanding the foundation enables the systems engineer to evaluate and select from an expanded and robust toolkit, the right tool for the job."



Systems Theories Across Disciplines

From: Friedenthal, Beihoff, Kemp, Oster, Paredis, Stoewer, Wade, "A World in Motion: INCOSE Vision 2025", INCOSE, 2014.

Max Planck on Hamilton's Principle (aka Principle of Least Action)

"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."

Max Planck, as quoted by Morris Kline, *Mathematics and the Physical World* (1959) Ch. 25: From Calculus to Cosmic Planning, pp. 441-442

Abstract

- The traditional engineering disciplines are supported by companion physical sciences, each with a focal phenomenon. But Systems Engineering had a different kind of origin in the mid twentieth century. Instead of a scientific phenomenon, its focus was process and procedure for improved technical integration of the traditional engineering disciplines with each other and with stakeholder value. More recently, *INCOSE Vision 2025* has called for a strengthened scientific foundation for SE, even as SE also becomes more subject system model-based. A number of paths toward such a system science have been pursued or proposed. How might we judge the value of what has been identified or pursued so far?
- Following millennia of slower progress, in only 300 years the ("other") physical sciences and engineering disciplines that they support have transformed the quality, nature, and possibilities of human life on Earth. That global demonstration of the practical impact of science and engineering provides us with a benchmark against which we may judge the practical value of candidate system sciences. We should demand no less if we claim scientific equivalence.
- This material summarizes key initial elements of proposed scientific foundations for systems, emphasizing their historical basis and success in the other disciplines, and noting their practical impacts on future SE positioning, practice, education, and research as a phenomena-based discipline.

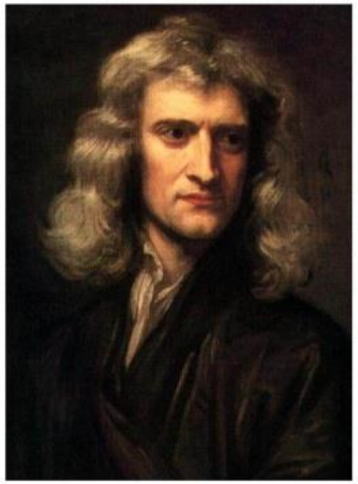
Contents

- Background for a “phase change” in SE
- SE history versus other engineering disciplines
- Two elements of STEM foundation elements for SE:
  - The System Phenomenon
  - The Value Selection Phenomenon
- Implications
- Discussion

- References

Two "Phase Changes" in Technical Disciplines that we'll emphasize

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



2. Model-based 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, nature, 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.

Emergence of Science and Engineering

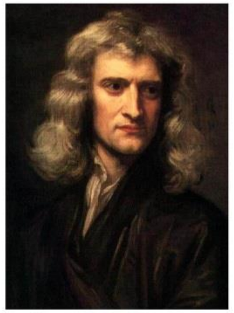
- The “hard sciences”, along with the “traditional” engineering disciplines and technologies based on those sciences, may be credited with much of that amazing progress, as well as challenges.

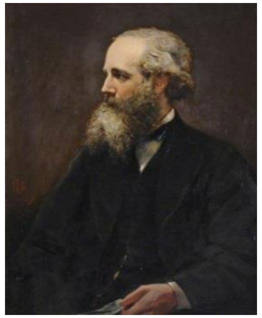
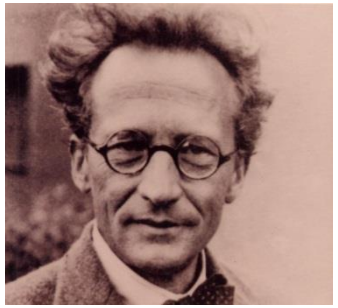
- How should Systems Engineering be compared to engineering disciplines based on the “hard sciences”?

Phenomena-Based 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.



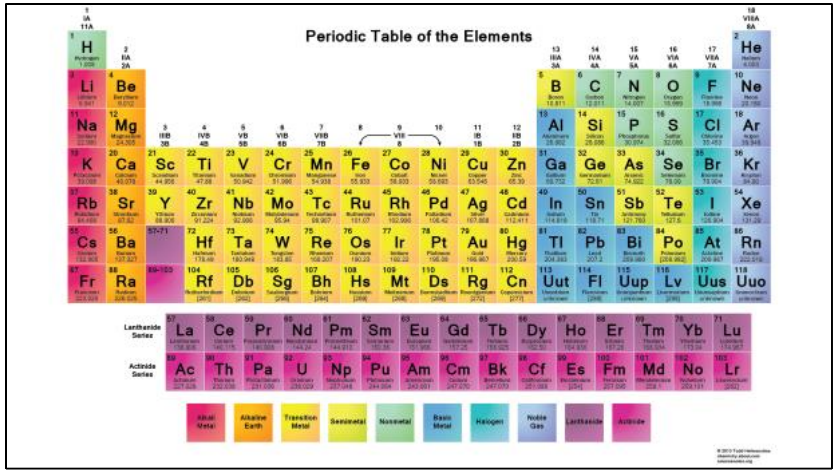
Traditional Perspective on SE—as we know it today

- Specialists in individual engineering disciplines (ME, EE, CE, ChE--we would be nowhere without them today) 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.

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

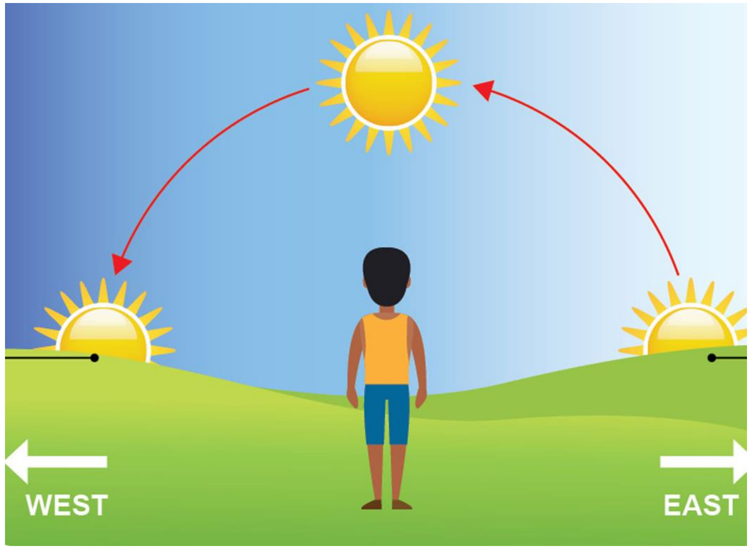
$$\frac{N_b}{N_a} = \left(\frac{g_b}{g_a}\right)\left(e^{-(E_b - E_a)/kT}\right)$$

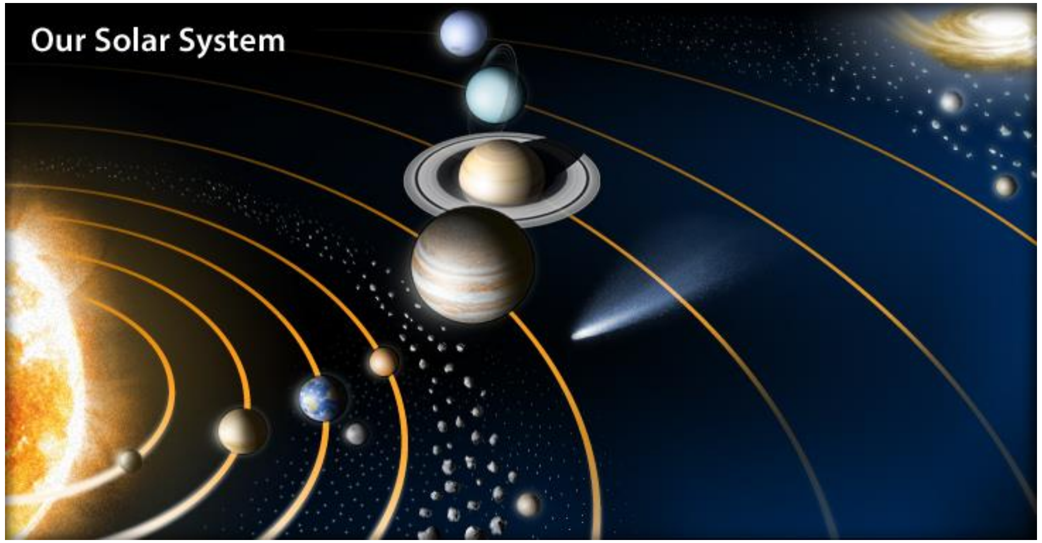
$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

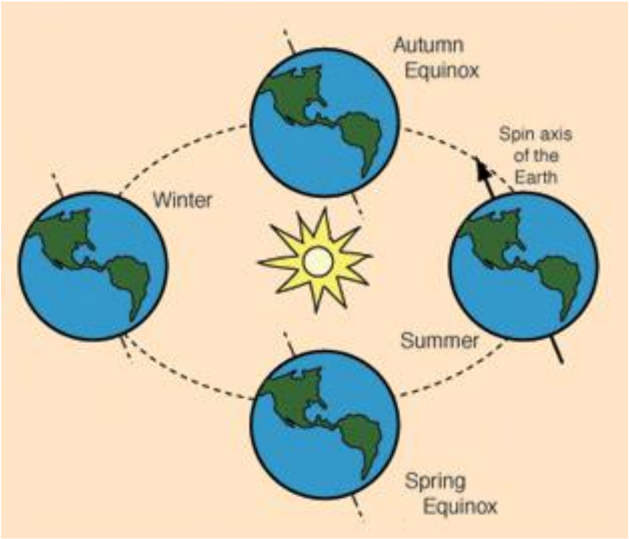


- Instead, Systems Engineering is sometimes viewed as:
  - Emphasizing process and procedure in its literature
  - Critical thinking and good writing skills
  - Organizing and accounting for information
  - Integrating the work of the other engineering disciplines and stakeholder needs
- But not based on an underlying “hard science” like other engineering disciplines

Engineering uses Science/Mathematics to represent, predict, explain

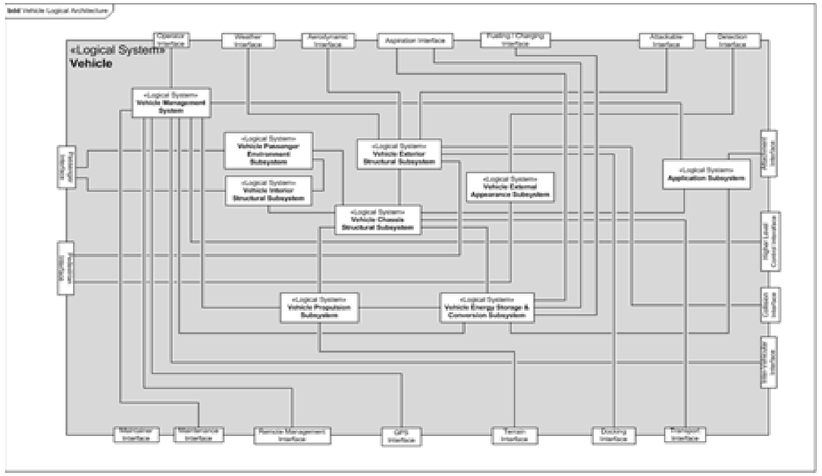






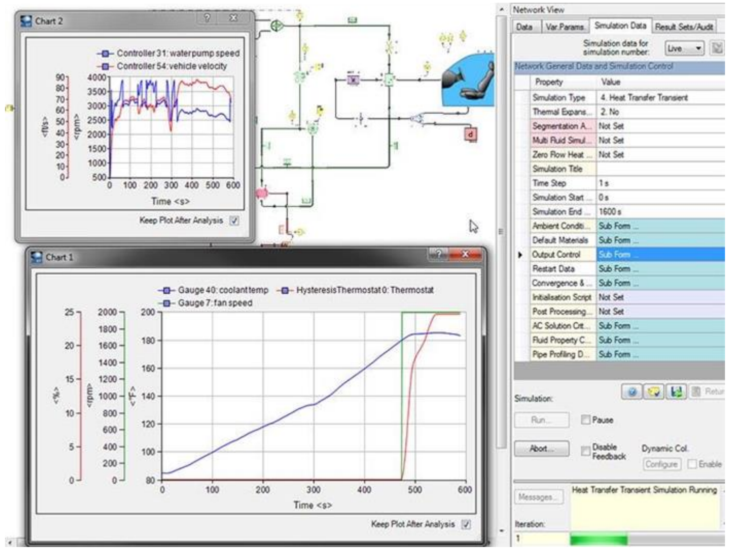
- Predict: For millennia, the evolving passage of sunrise, sunset, Lunar phases, and passage of the seasons has been reliably predicted based on learned, validated patterns, helping feed exploding human population.
- Explain: By the time of Copernicus and Newton, science had provided improved explanations of the cause of these phenomena, to demonstrated levels of reliability.
- Represent: A key to the jump in effectiveness of the “Explain” and “Predict” parts improved methods of representing subject matter, using explicit, predictive, testable mathematical models.
- Systems Engineering should demand the foundational elements of Systems Science to be similarly impactful.

Vehicle Logical Architecture



Phase Change #2: MBSE, PBSE, a phase change in SE

Vehicle Thermal Dynamics

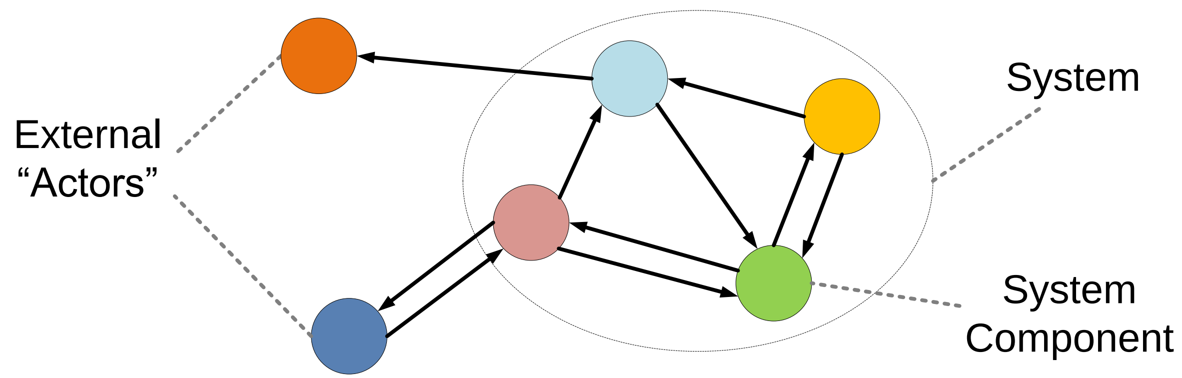


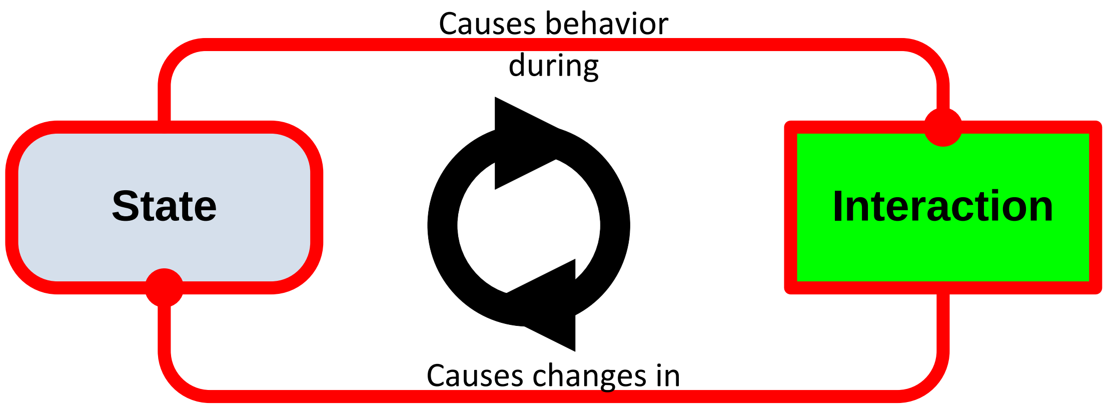
While models are not new to STEM . . .

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

Formalizing System Representations

- *In the perspective described here*, by System we mean a collection of interacting components:





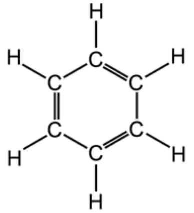
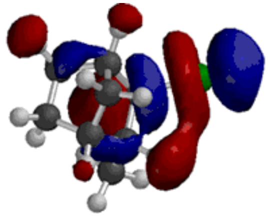
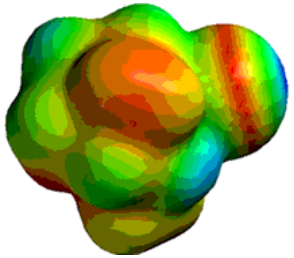
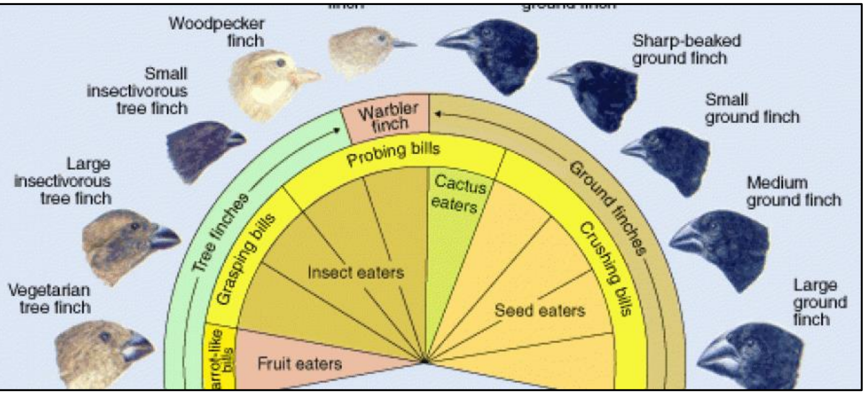
- By "interacting" we mean the exchange of energy, force, material, or *information* (all of these are "input-outputs") between system components, . . .
- . . . through which one component impacts the state of another component.
- By "state" we mean a property of a component that impacts its input-output behavior during interactions.
- So, a component's "behavior model" describes input-output-state relationships during interaction—*there is no "naked behavior" in the absence of interaction*.
- The behavior of a system as a whole involves emergent states of the system as a whole.

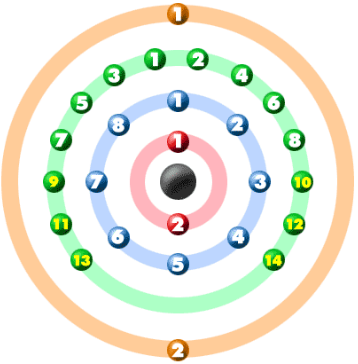


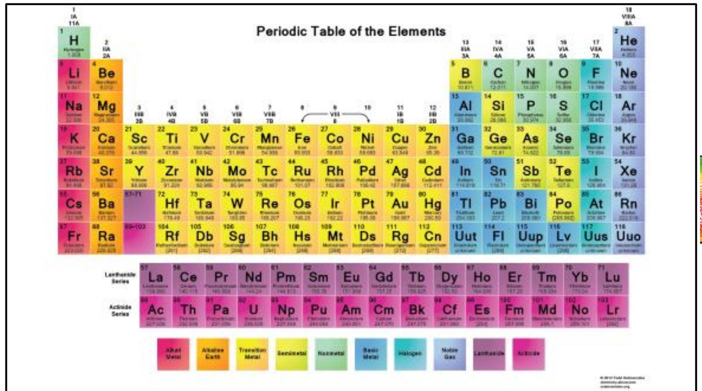


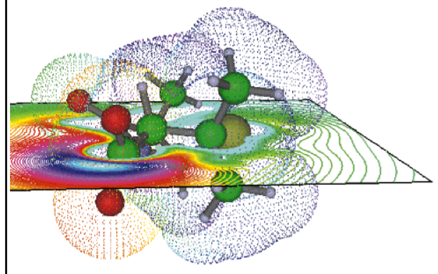

Patterns: At the heart of scientific laws

- All "patterns" are recurrences, having both fixed and variable aspects.
- The heart of physical science's life-changing 300 year success in prediction and explanation lies in recognition, representation, exploitation of recurring patterns.
- Noether's Theorem & Hamilton's Principle: Substantial math basis for all the physical laws: Newton, Maxwell, Mendeleev, Schrödinger, . . .



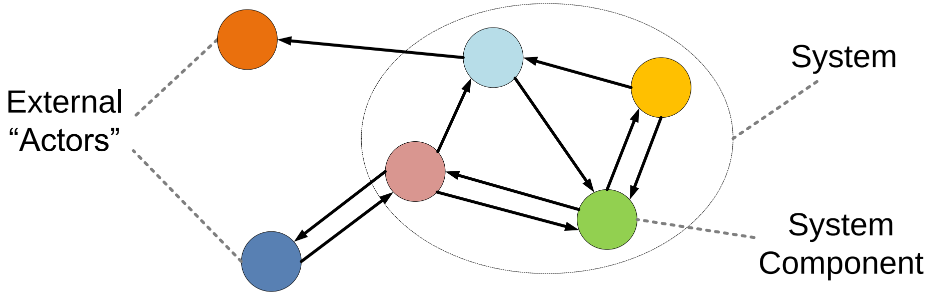





The System Phenomenon

- <u>Phenomena</u> of the hard sciences in all instances occur in the context of special cases of the following "System Phenomenon":
  - *behavior emergent from the interaction of behaviors (phenomena themselves) a level of decomposition lower.*
- For each such emergent phenomenon[1], the emergent interaction-based behavior of the larger system is a stationary path of the action integral:

$$\mathcal{S} = \int_{t_1}^{t_2} L(x, \dot{x}, t)\, dt$$



(Hamilton's Principle[1])

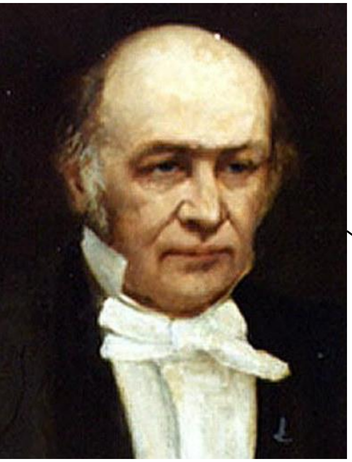
- Reduced to simplest forms, the resulting equations of motion (or if not solvable, simulated/observed paths) provide "physical laws" subject to scientific verification—an amazing foundation across all phenomena.

(1) When stated with rigor, special cases for non-holonomic constraints, irreversible dynamics, discrete systems, data systems, etc., led to alternatives to the variational Hamilton's Principle—but the *<u>interaction-based structure</u>* of the System Phenomenon remained, and the underlying related Action and Symmetry principles became the basis of modern theoretical physics. See later.

Mathematics for the System Phenomenon: Building on Hamilton's Principle

- The System Phenomenon is a more general pattern than the mathematics of the original Hamilton's Principle :
  - Reviewing the conceptual framework of the System Phenomenon should convince you that it is much more general in scope than the setting for the original formulation of Hamilton's Principle (continuous, conservative phenomena).
  - Sure enough, more generalized mathematical treatments were discovered later, and in one important case earlier.
  - It was remarkable (to Max Planck and many others) that the Principle of Least Action was already sufficient to provide the mathematics from which can be derived the fundamental equations of all the major branches of physics…but...
- We are interested in engineering of more general types of systems, and...
- The more general Interaction model framework of the Systems Phenomenon is further supported by all the following later mathematical constructions and their discoverers . . .

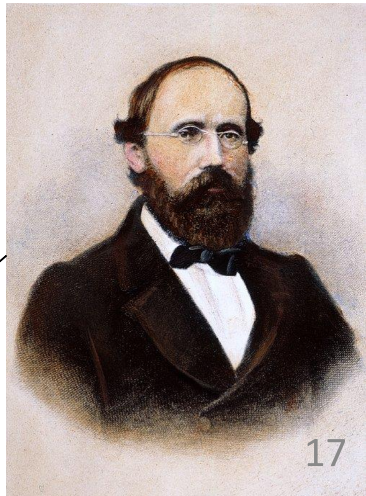
The System Phenomenon,
Building on Hamilton’s Principle



- **Hamilton’s Principle**: Was already strong enough to generate all the fundamental phenomena of physics, from Newton through Feynman

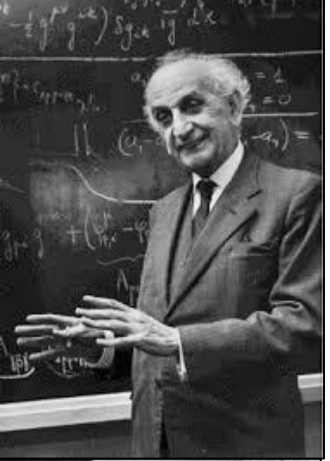
- **Noether’s Theorem**: Deeper insight into the connection of Hamilton’s principle to Symmetry and Conservation Laws

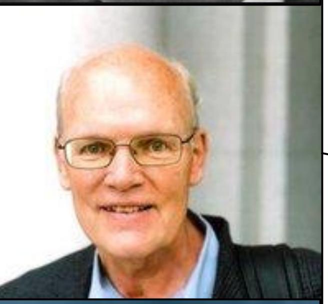
- **D’Lambert’s Principle**: Older than Hamilton, but wider in scope than Hamilton’s Principle, adding non-holonomic constraints, dissipative systems



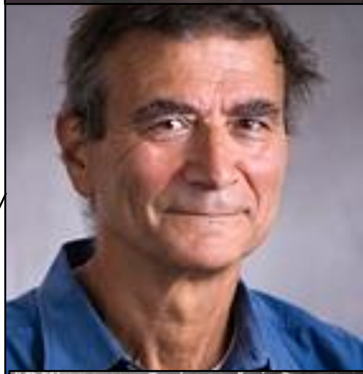
- **Bernhard Riemann**: Embedded Manifold spaces further generalize representation of complex dynamics.

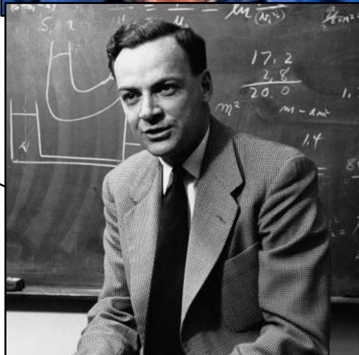
The System Phenomenon, Building on Hamilton's Principle





- **<u>Cornelius Lanczos</u>**: Master elucidator of Analytical Mechanics
- **<u>Prigogine, Sieniutycz, Farkas</u>**: Irreversible and large scale thermodynamic systems
- **<u>JE Marsden</u>**, **<u>A Bloch</u>, <u>Marston Morse</u>**: Non-Holonomic Control Systems, Discrete Mechanics; Symbolic Dynamics, Discrete Hamilton's Principle; Discrete Noether's Theorem
- **<u>Ed Fredkin</u>**, **<u>Charles Bennett</u>**, **<u>Tomas Toffoli</u>**, **<u>Richard Feynman</u>**: Information Systems and Automata





The System Phenomenon: Conclusion

- Each of the so-called "fundamental" phenomena-based laws' mathematical expression (Newton, Maxwell, Schrodinger, et al) is derivable from the above—as shown in many discipline-specific textbooks.
- So, instead of Systems Engineering lacking the kind of theoretical foundation 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 (as stated by Planck and many others who followed).
  - 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!
  - This opens a new perspective on how Systems Engineering and Systems Science can relate to the other, better-known disciplines, as well as future domains . . .

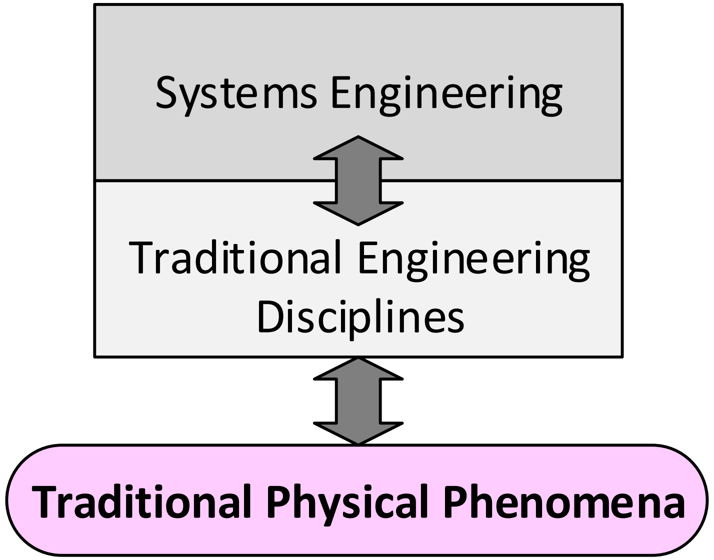
Resulting SE Positioning in the Emerging Frameworks

- As higher-level system patterns are discovered, represented, validated, taught/learned, and practiced, they become "emergent domain disciplinary frameworks".
- This is very evident in the past history of scientific and engineering domains and disciplines, as well as new ones.

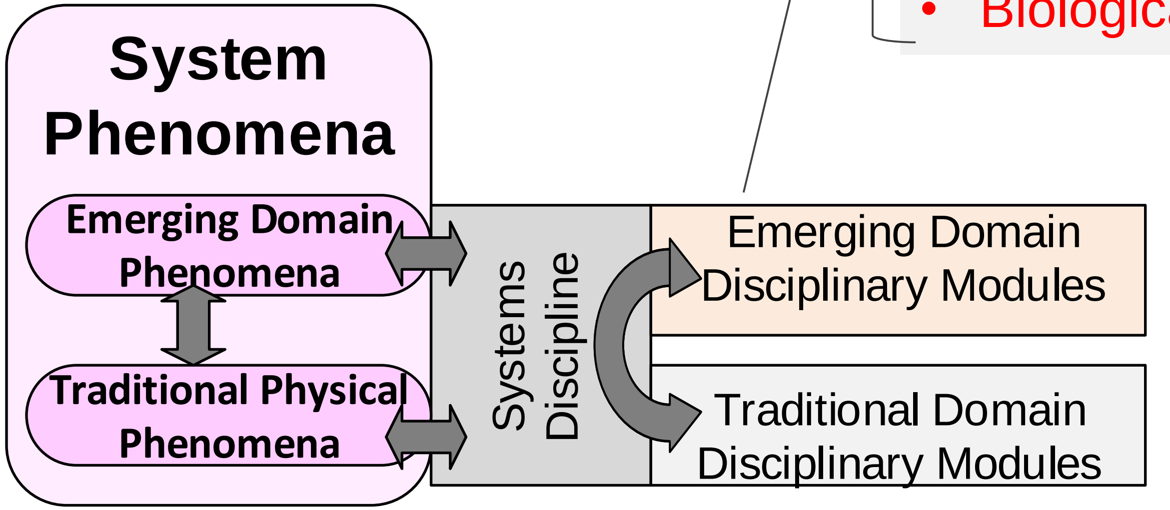
Future
- Distribution networks
- Biological organisms, ecologies
- Market systems and economies
- Health care delivery
- Systems of conflict
- Systems of innovation

Recent
- Ground Vehicles
- Aircraft
- Marine Vessels
- Biological Regulatory Networks

Traditional view:

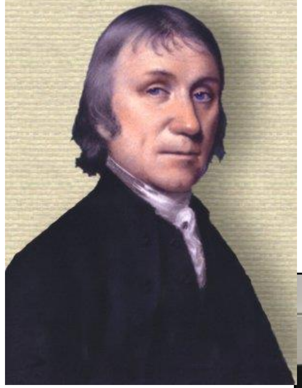


Future view:



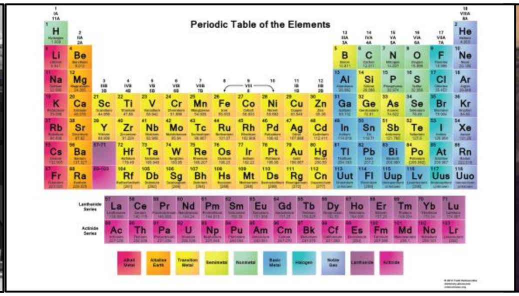
What is the historical evidence?...

Historical Example 1: Chemistry

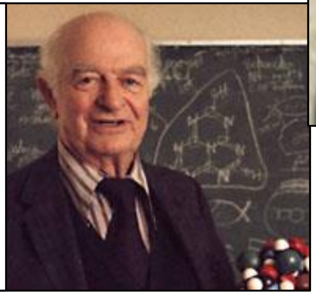

Priestley : Oxygen


Mendeleev: Periodic Table


Modern Chemist

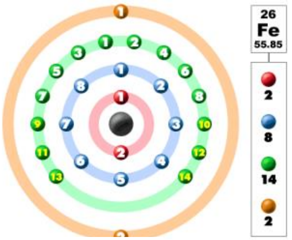


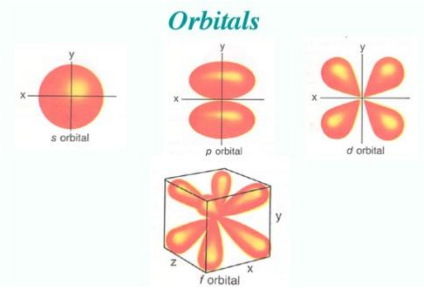
Periodic Table of the Elements

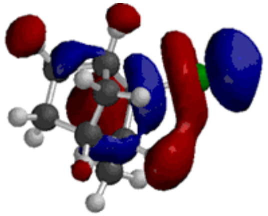

Pauling: Chemical Bond

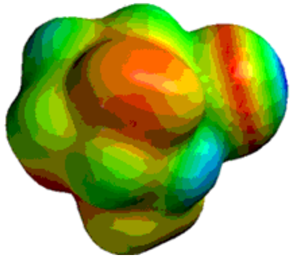
- Chemists, and Chemical Engineers, justifiably consider their disciplines to be based on the “hard phenomena” of Chemistry:
  - A view that emerged from the scientific discovery and verification of laws of Chemistry.
  - Chemical Elements and their Chemical Properties, organized by the discovered patterns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

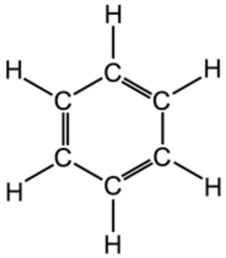
Chemistry, continued

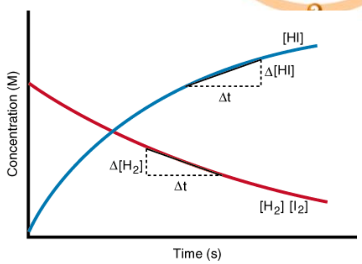


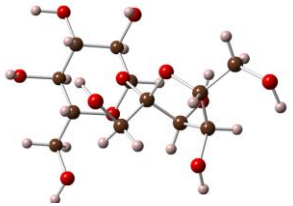


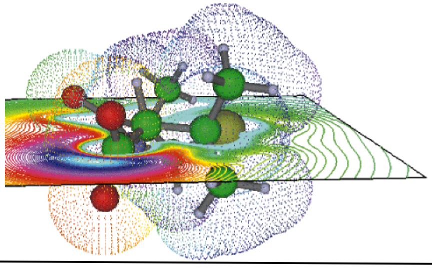








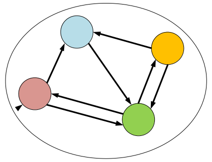




However . . .

- All those chemical properties and behaviors are emergent consequences of interactions that occur between atoms’ orbiting electrons (or their quantum equivalents), along with the rest of the atoms they orbit.
- These lower level interactions give rise to patterns 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 system patterns

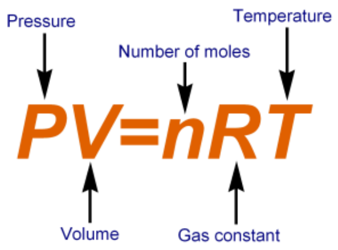
  and . . .
- Chemistry and Chemical Engineering study and apply those system patterns.

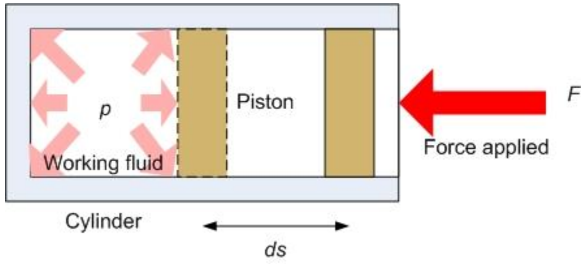
Boyle

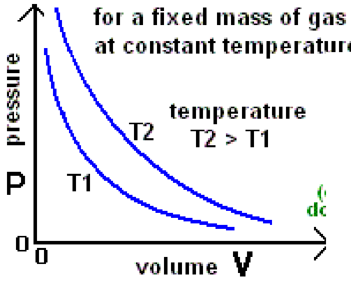
Historical Example 2: The Gas Laws and Fluid Flow

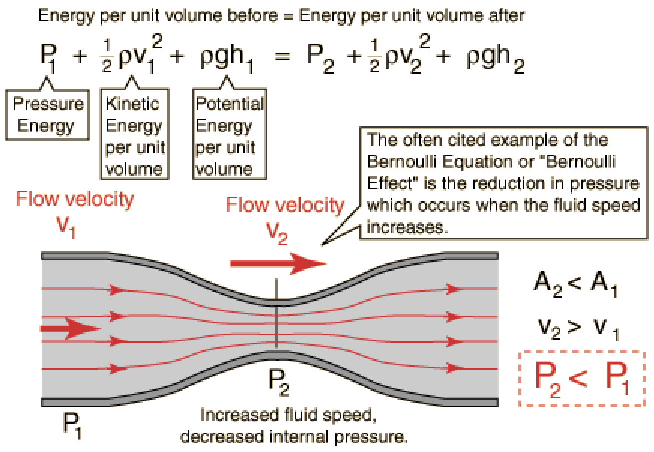
Daniel Bernoulli

- 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.

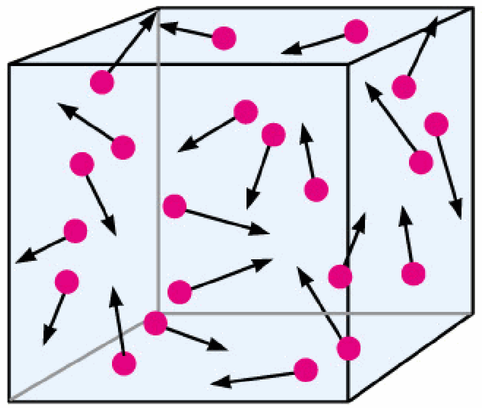


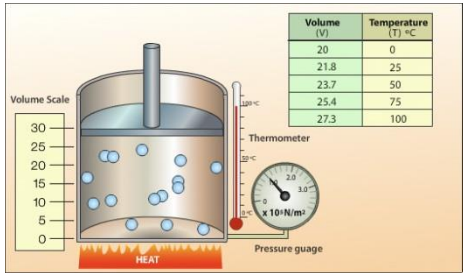


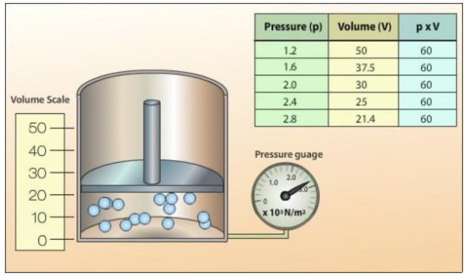




Gas Laws, continued





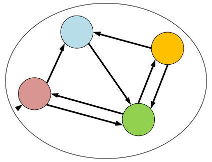


$$\frac{N_b}{N_a} = \left(\frac{g_b}{g_a}\right)\left(e^{-(E_b-E_a)/kT}\right)$$

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.

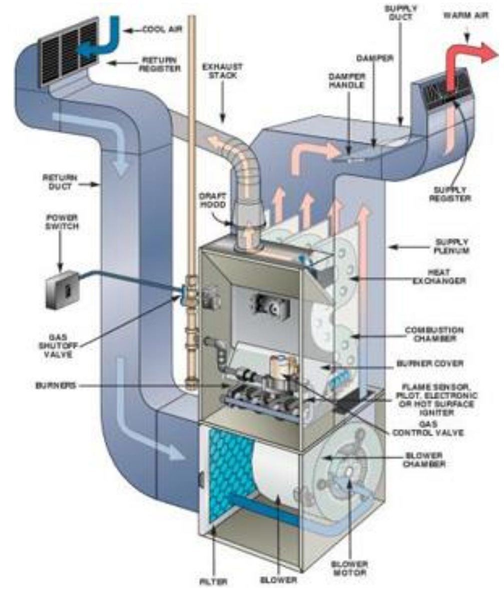


So . . .

- The “fundamental phenomena” of gases, along with the scientifically-discovered / verified “fundamental laws and first principles” are in fact . . .
- higher level emergent system patterns

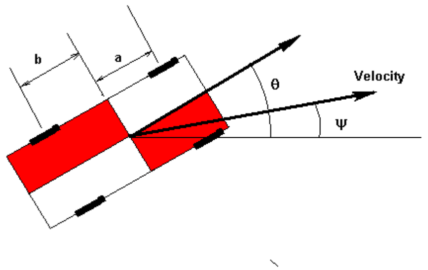
  so that . . .

- Mechanical Engineers, Thermodynamicists, and Aerospace Engineers can study and apply those system patterns.



More Recent Historical Examples

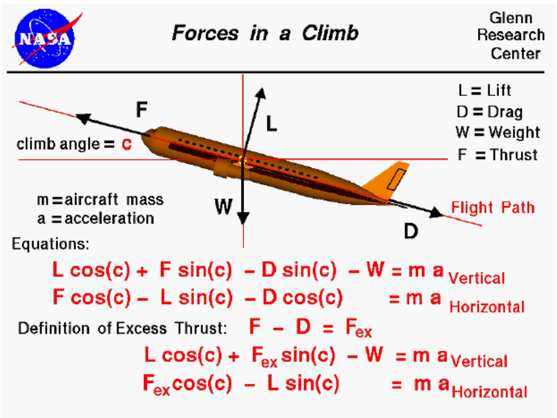
- Ground Vehicles
- Aircraft
- Marine Vessels
- Biological Regulatory Networks

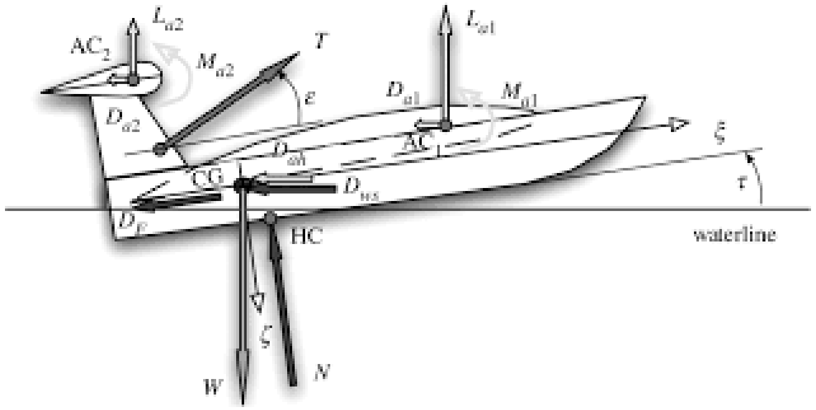


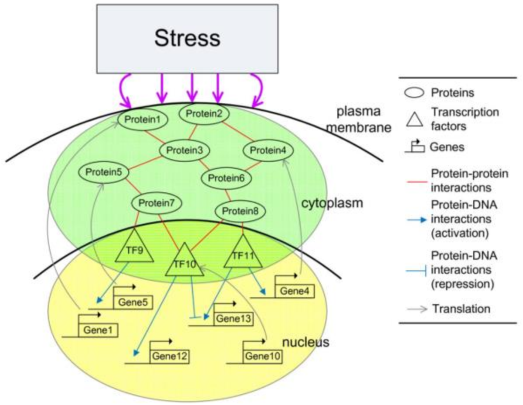
Dynamics of Road Vehicle

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

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

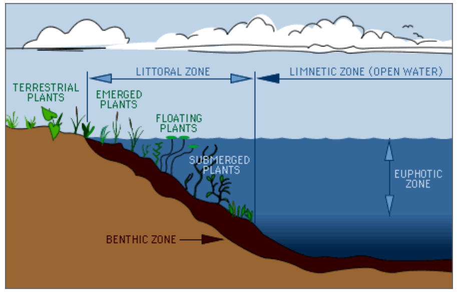


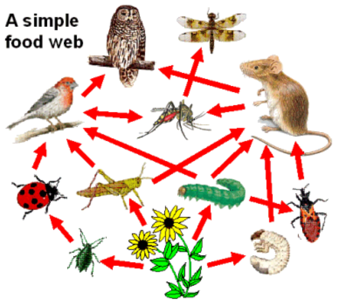


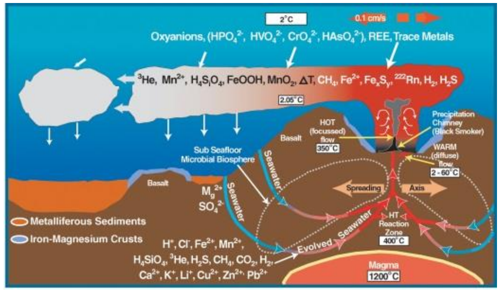


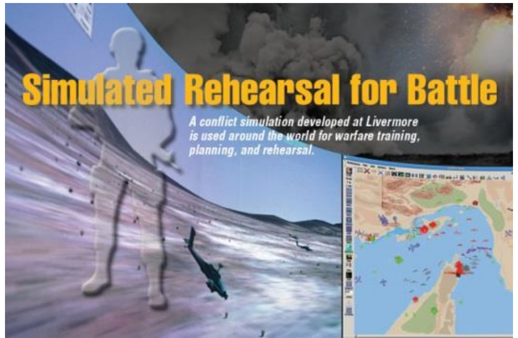
Future Examples

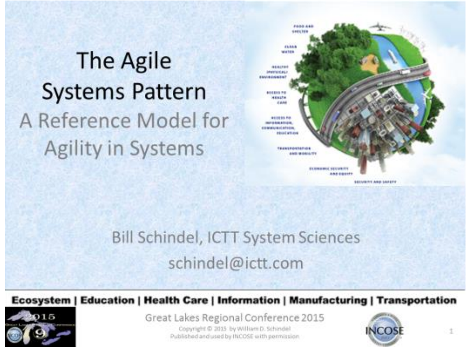
- Utility and other distribution networks
- Biological organisms and ecologies
- Market systems and economies
- Health care delivery, other societal services
- Systems of conflict
- Agile innovation











The Value Selection Phenomenon

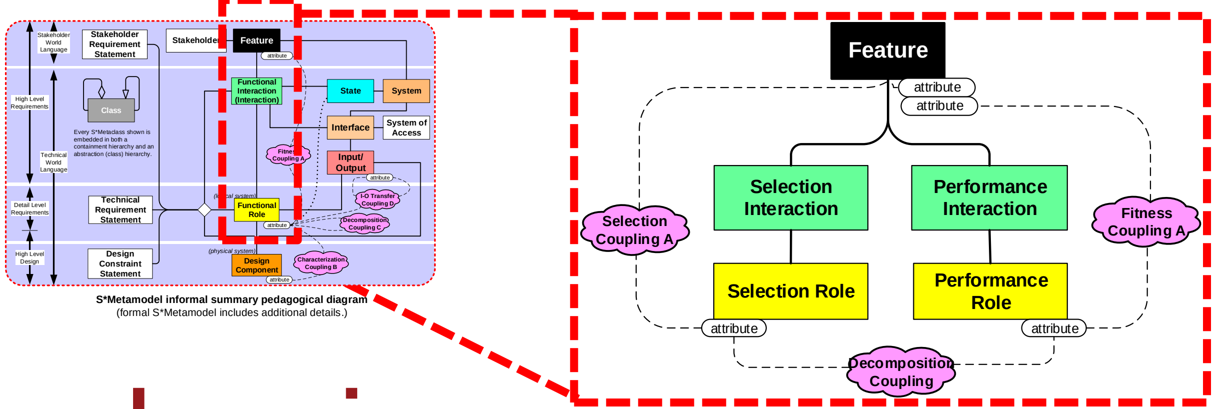
- Engineers know that value is essential to their practice, but its “soft” or subjective nature seems challenging to connect to hard science and engineering phenomena.
- System engineers learn to seek out and represent stakeholder needs, measures of effectiveness, objective functions connected to derived requirements and technical performance, etc.
- But what are the phenomena, what is the bridge effectively connecting subjective value and objective measures, where is the related mathematics and recurring patterns, and what are the impacts on future SE practice?

Even if value (both human-based and otherwise) seems elusive or subjective, . . .

– The <u>expression</u> of value is always via <u>selection</u>, and selection itself is an interaction-based instance of the System Phenomenon:

Settings	Types of Selection	Selection Agents
Consumer Market	Retail purchase selection	Consumer
Military Conflict	Direct conflict outcome; threat assessment	Direct engagement; commander
Product design	Design trades	Designer
Commercial Market	Performance, cost, support	Buyer
Biological Evolution	Natural selection	Environment
Product Planning	Opportunity selection	Product Manager
Market Launch	Optimize choice across alternatives	Review Board
Securities Investing	What to buy, what to sell, acceptable price	Investors
College-Student Matching Market	Selection of individuals, selection of class profile, selection of school	Admissions Committee; Student & Family
Life choices	Ethical, moral, religious, curiosities, interests	Individual
Democratic election	Voting	Voters
Business	Risk Management, Decision Theory	Risk Manager, Decision Maker

The bridge to value: Innovation Steering Mechanism

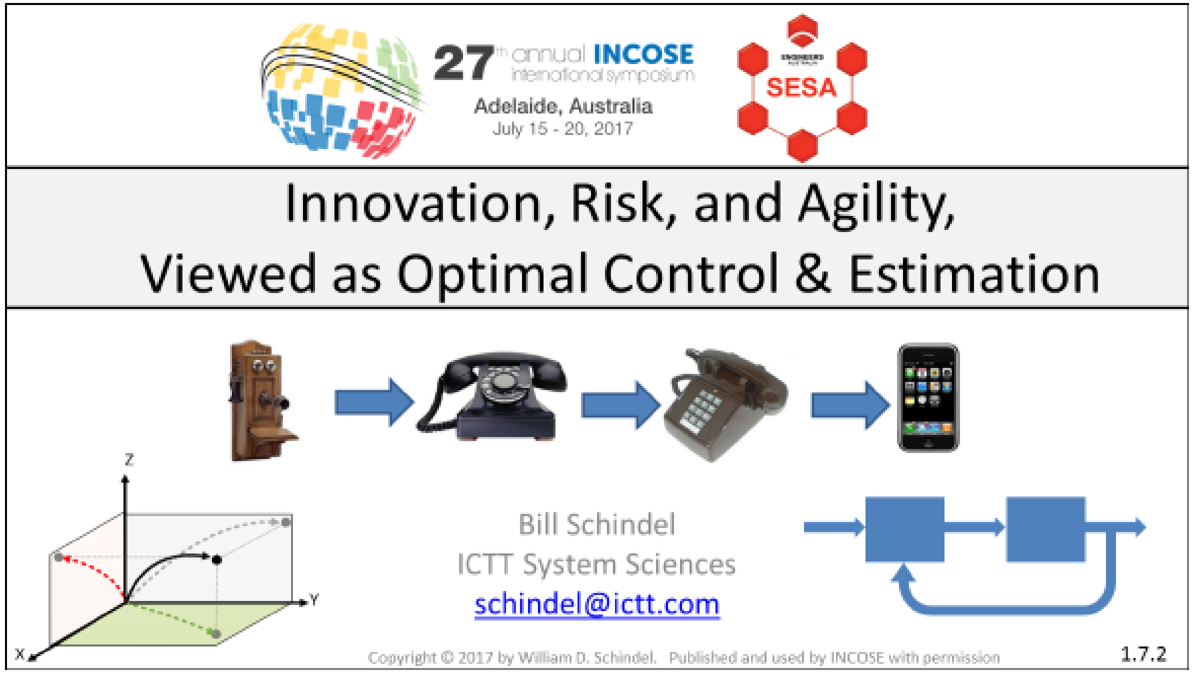


S*Metamodel informal summary pedagogical diagram
(formal S*Metamodel includes additional details.)

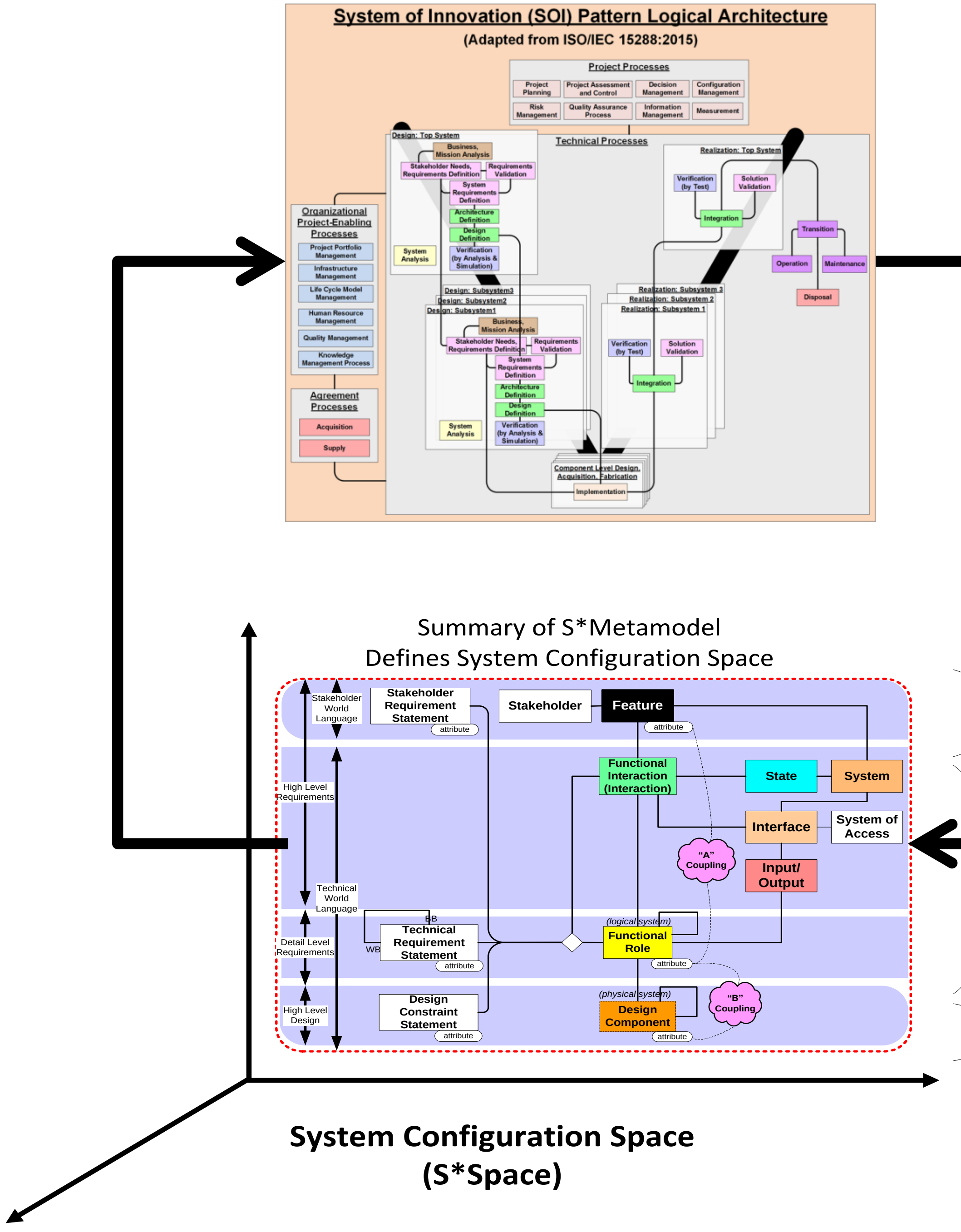
- <u>Interactions</u> connect to Value in two fundamental/different ways:
  - Performance Interactions (real or imagined, present, past, or future) <u>*embody*</u> Value from Performers (this is more familiar to systems engineers);
  - Selection Interactions (human or otherwise) <u>*express*</u> the comparative Values of a Selection Agent / Agency of some form (this is more familiar to consumer marketers, behavioral economics specialists, web-based experimentalists and big data specialists).
- Selection is itself an Interaction:
  - Studying <u>downstream</u> system performance effects of selection is feasible
  - Studying the <u>upstream</u> mechanisms of selection is likewise feasible
  - Bridges upstream technical performance, downstream technical consequence

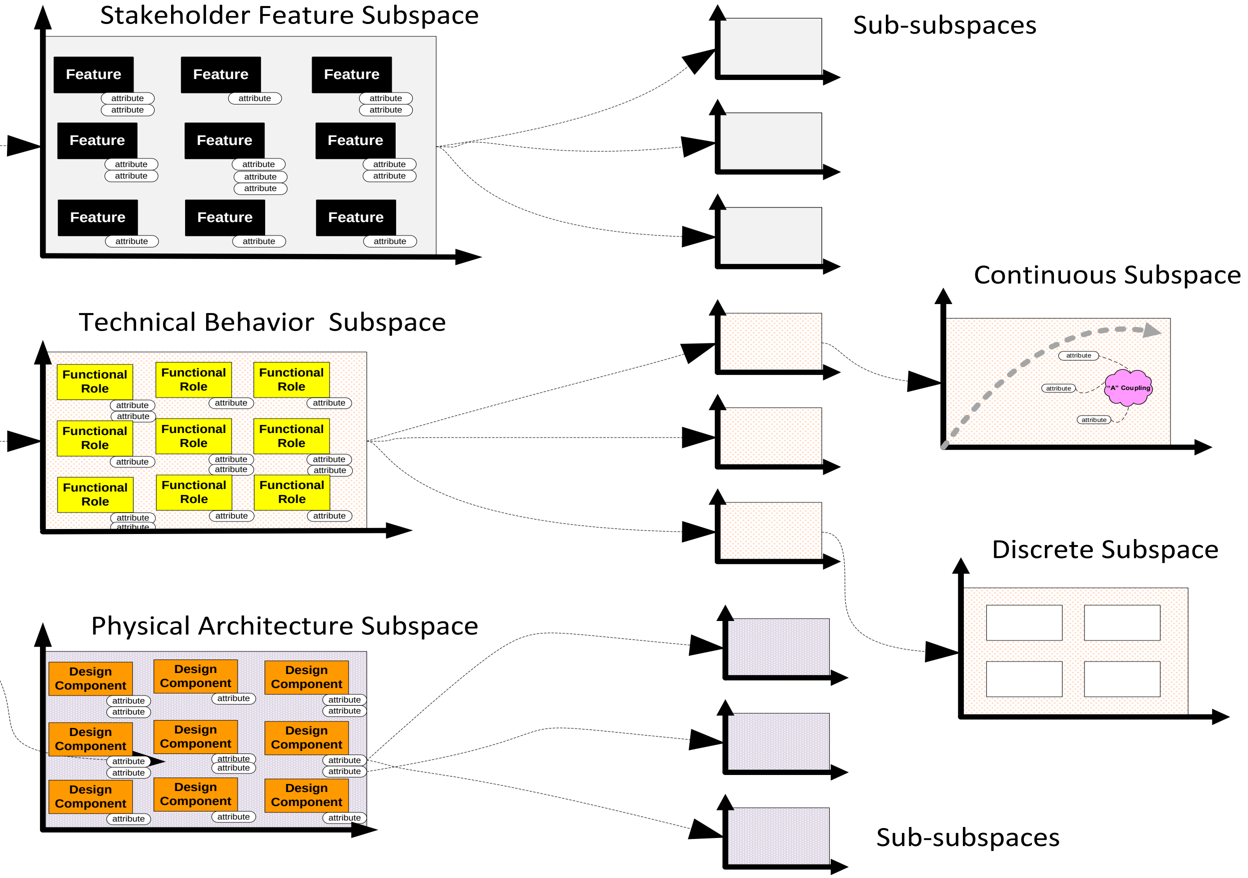
Where Do Systems Come From and Go?
System Life Cycle Trajectories in S*Space

- 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



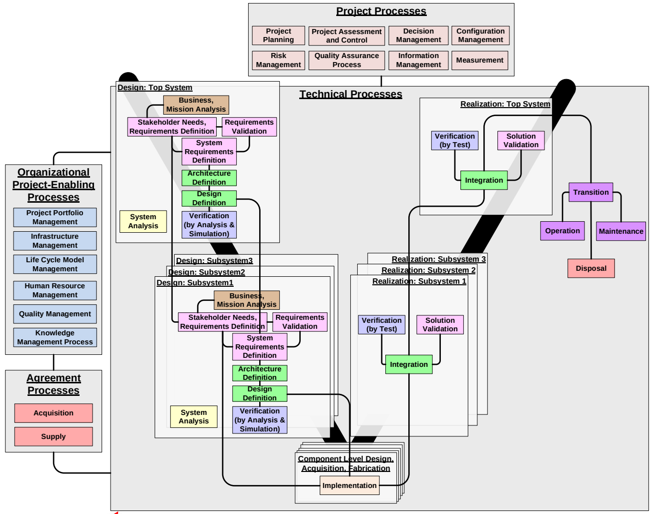
System Life Cycle Trajectories in S*Space, and S*Subspaces





MBSE, PBSE: A Phase Change in SE Emphasis

Process & Procedure



Traditional Systems Engineering Emphasizes ***Process***

Information Consumed

Engineering Process (Iterative)

Information Produced

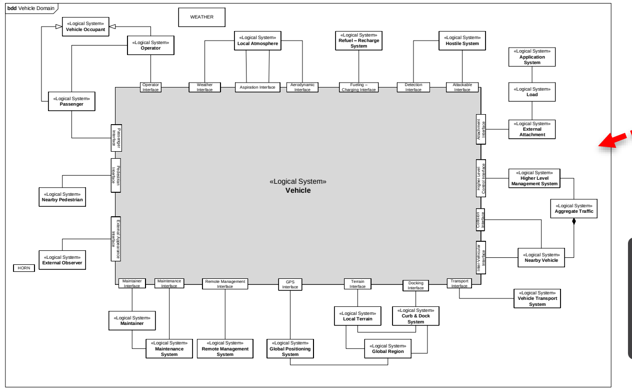
Information Passing Through Engineering Process

MBSE Increases Relative Emphasis on ***Information***

Transformation

Life Cycle Management Process (Iterative)

Information Passing Through Life Cycle Processes



Models

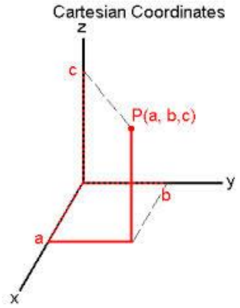
Maps *vs*. Itineraries -- SE Information *vs*. SE Process

Itinerary ≠ Map!

(What am I doing?) *(Where am I?)*

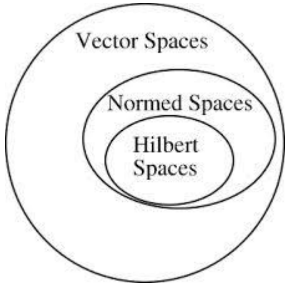
When they eventually did emerge, maps represented a newer idea of the nature of "where".

- The SE Process consumes and produces information.
- But, SE historically emphasizes process over information. (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 *vs*. Itineraries.
- The geometrization of Algebra, Function Space, and Embedded Manifolds (Descartes, Hilbert, Riemann)
- 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.



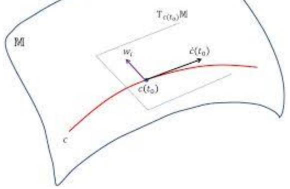
Rene Descartes
1596 - 1650

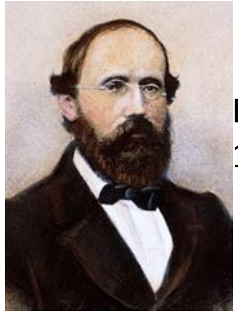
Geometrization of Algebra



David Hilbert
1862 - 1943

Geometrization of Function Space

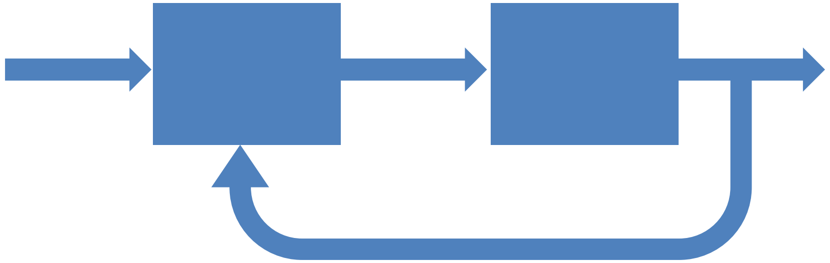


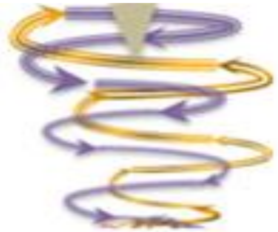


Bernhard Riemann
1826 – 1866

Dynamics on Embedded Manifolds

What Optimal Control and Estimation Theory Tells Us





- 50+ years of successfully applied math, used in other domains:
  - Norbert Wiener (time series, fire control systems, feedback control, cybernetics), Rudolph Kalman (filtering theory, optimal Bayesian estimation), Lev Pontryagin (optimal control, maximum principle), Richard Bellman (dynamic programming), others.
  - Applied with great success to fire control systems, inertial navigation systems, all manner of subsequent domain-specific feedback control systems.
- Model-Based Filtering Theory and Optimal Estimation in Noisy Environment:
  - Estimation, from noisy observations, of current state of a modeled system that is partly driven by random processes, optimized as to uncertainty.
  - Control of a managed system's trajectory, optimized as to time of travel, destination reached, stochastic outcomes.

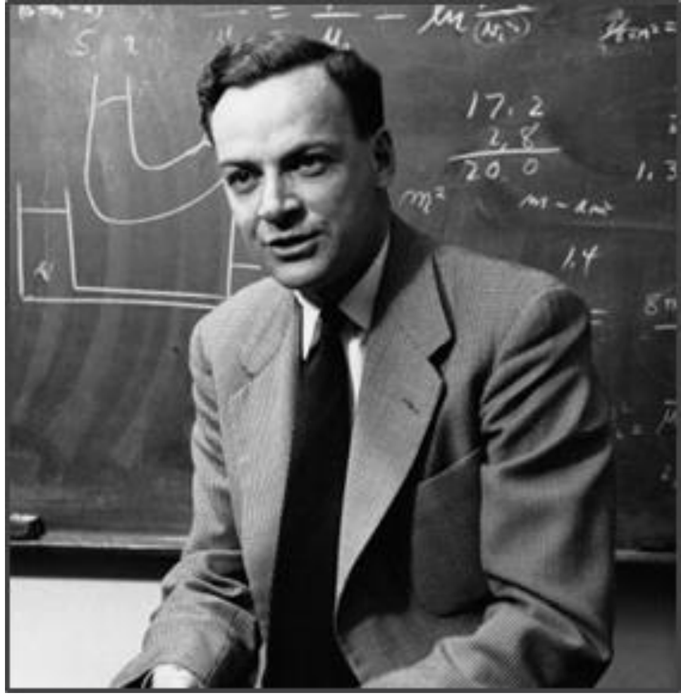
Is it Plausible to Apply Optimal Control to the Innovation Process?

Aspect of Common Theoretical Framework	Application to a Vehicle Guidance System	Application to a System of Innovation
Overall domain system	Propelled airborne vehicle guidance to moving airborne target	Development of new system configuration for a system of interest
The controlled system	Airborne Pursuit Vehicle	The development process
Control system	Flight control system and pilot sometimes	Development management & decision-making process
Other actors	Target, atmosphere	Stakeholders, operating environment of system of interest, suppliers
State space in which controlled performance occurs	Vehicle position in 3-D geometric space	Configuration space of system of interest, including its features, technical requirements, and physical architecture
Driving processes	Target dynamics, pursuit thrust, flight control surface movements	Stakeholder interest, supply chain
Random aspects of driving processes	Buffeting winds	Stakeholder preferences, competition, technologies
Observation process model	Radar tracking of moving target, sensor characterization	Status reporting, market feedback, development status report process
Random disturbances of observation processes	Sensor errors	Inaccuracies or unknowables in development status; sampling errors
Environmental Conditions	Target maneuvers; atmospheric effects	Market or other environmental conditions;
Control input	Flight control surface orientation	Management direction; resources
Objective function to optimize	Time to target	Time to market; Competitive Response Time; Innovated System Performance; Innovation Risk vs. Reward
Dynamical model	Ballistic Flight, Atmospheric Effects, Thrust	Coupled development processes
Outcome risk	Risk of missing airborne target	Risk of innovation outcomes across stakeholders

Implications

1. Understanding innovation learning, IP leverage, trust
2. Representing the System Phenomenon
3. Representing the Value Selection Phenomenon
4. Systems education for all engineers
5. Systems research frontiers, needs, and opportunities

1. Understanding innovation learning, IP leverage, trust



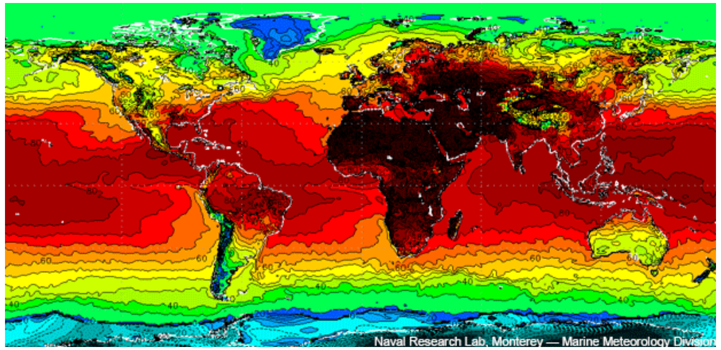
"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong."

– Richard P. Feynman

Given their increasing importance, do MBSE models meet this challenge?

If we expect to use models to support more critical decisions, then we are placing *<u>increased trust in models</u>*:

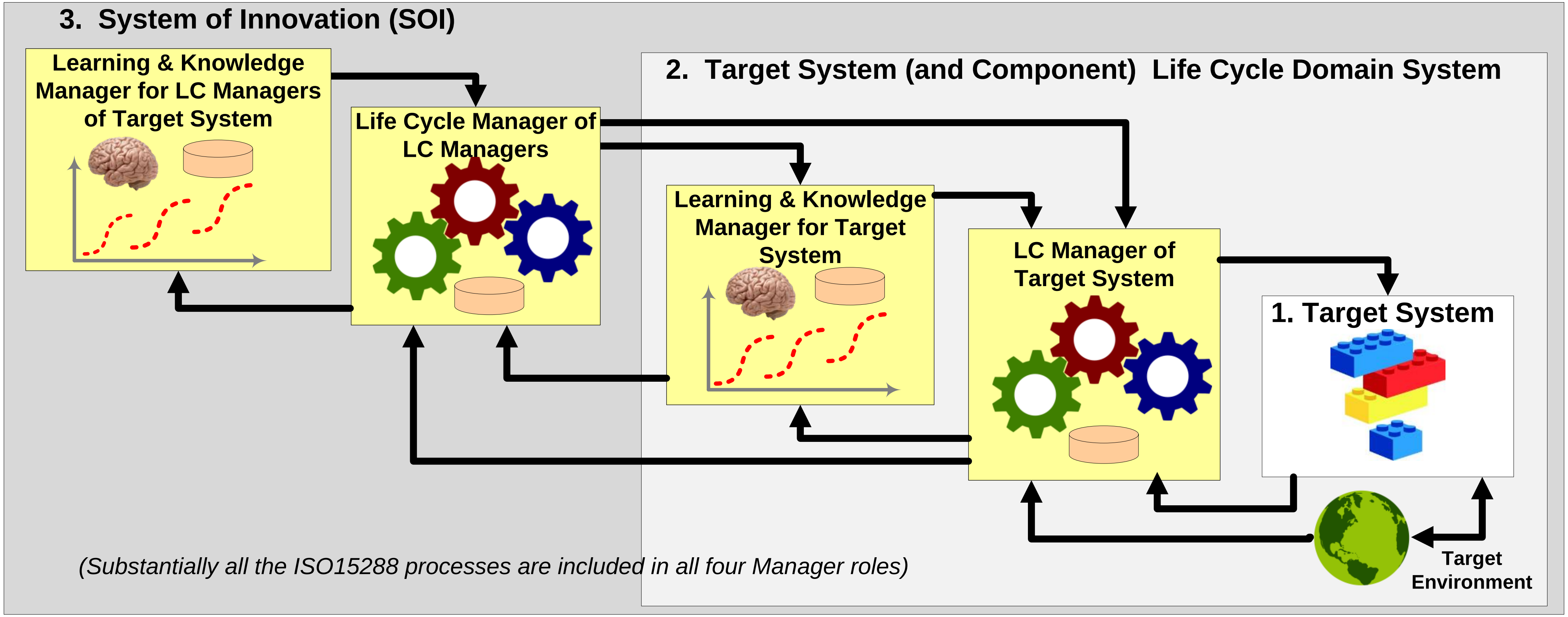
- Critical financial, other business decisions
- Human life safety
- Societal impacts
- Extending human capability



- Related risks require that we <u>characterize the structure of that trust</u> and manage it:
  - The Validation, Verification, and Uncertainty Quantification (VVUQ) *<u>of the models themselves</u>*.
  - Learned models from STEM (~300 years) offer a most dramatic example of positive collaborative impact of effectively shared & validated models

INCOSE ASELCM Pattern (aka System of Innovation Pattern)

Descriptive reference framework, not prescriptive—describes learning in all systems of innovation, whether model-based or not, whether effective or ineffective



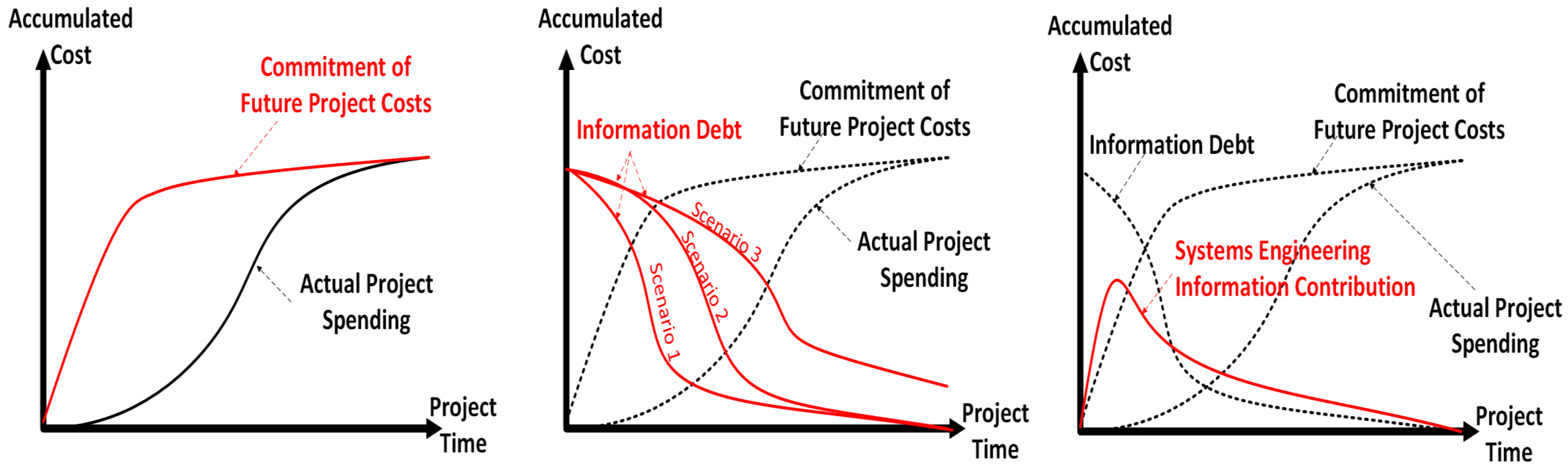
From: Schindel and Dove, "Introduction to the INCOSE ASELCM Pattern", *Proc. of INCOSE 2016 International Symposium*, Edinburgh, UK, 2016.

System 1: The (engineered) target system of interest (e.g., a product system);

System 2: The (ISO 15288) life cycle management systems for System 1, along with the rest of System 1's target operating and life cycle environment;

System 3: The life cycle management systems for System 2

- Pattern data as IP:
  - Information Debt, not just Technical Debt, as a foundation of adaptive, agile innovation.
  - Patterns can be capitalized as financial assets under FASB 86.
- "Patterns as capital" changes the financial logic of project level SE "expense"



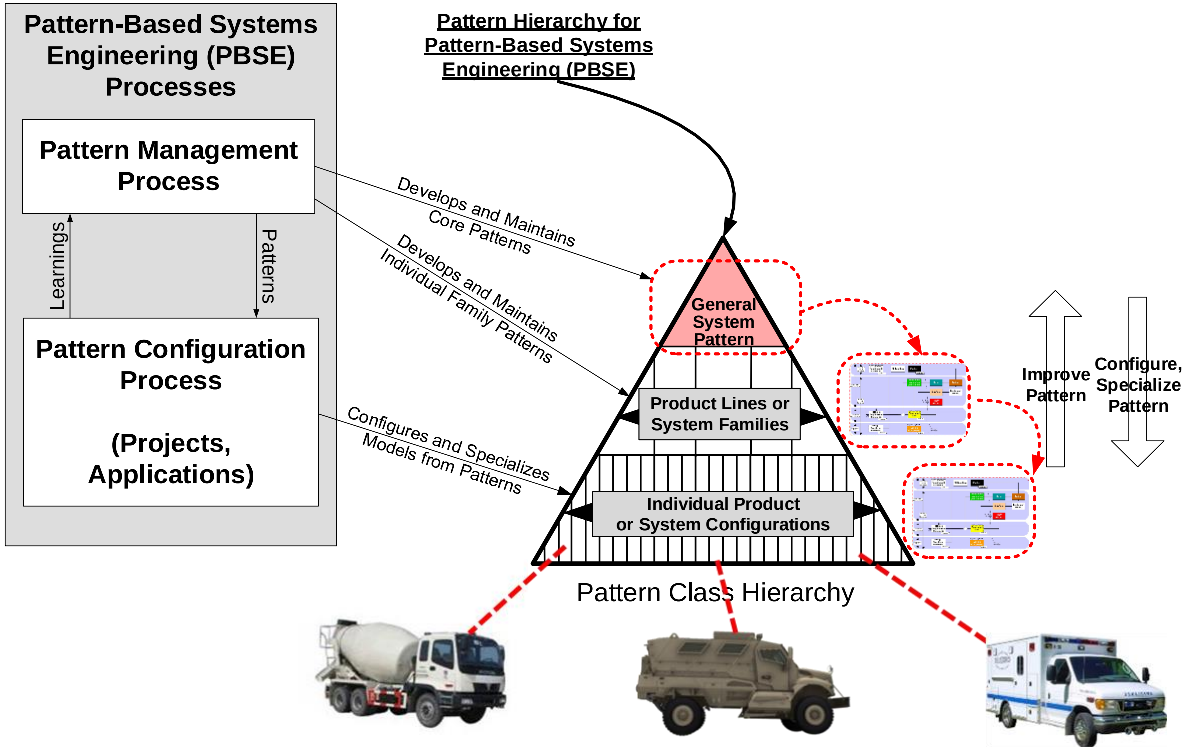
(a) When Project Costs Are Committed versus Incurred

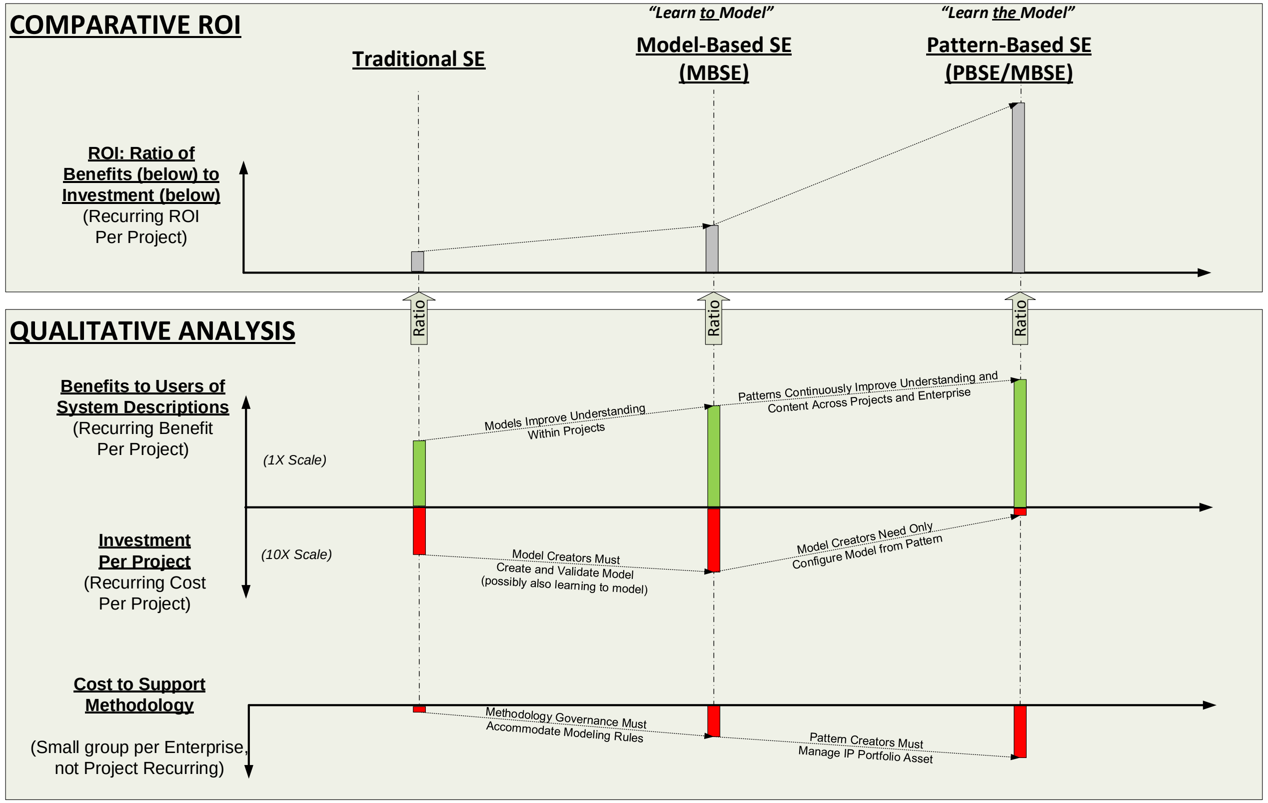
(b) Information Debt is Reduced Over the Course of Project

(c) Systems Engineering Information Is Generated to Reduce Information Debt

From Dove, Garlington, and Schindel, "Case Study: Agile Systems Engineering at Lockheed Martin Aeronautics Integrated Fighter Group", from *Proc. of INCOSE 2018 International Symposium*, 2018, Washington.

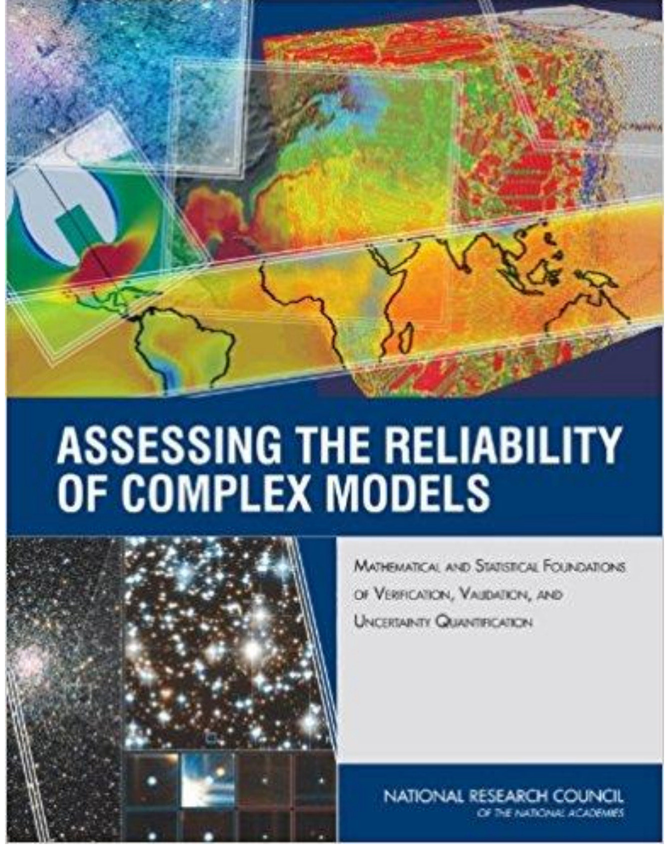
Economics: Rapidly Configuring Trusted Models from Trusted S*Patterns





- Generates high quality first draft models from patterns in <10% of the time and effort to generate "traditional" models of lower quality and completeness.
- Most planned S*Patterns take less than 90 days to generate to point of first use, via "Uncover the Pattern" (UTP).
- Thereafter, S*Pattern becomes the point of accumulation of future group learning--the "muscle memory" that is automatically consulted by configuration in each future project.

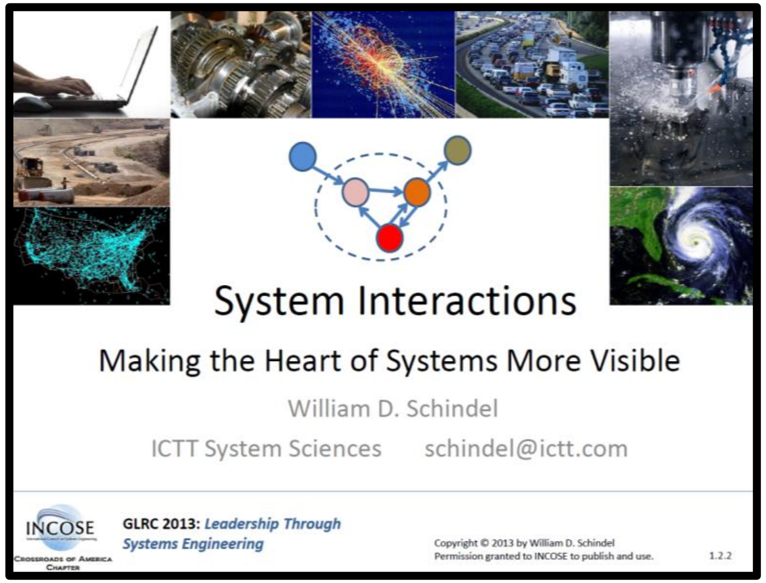
VVUQ: Model Credibility, including Uncertainty Quantification (UQ)



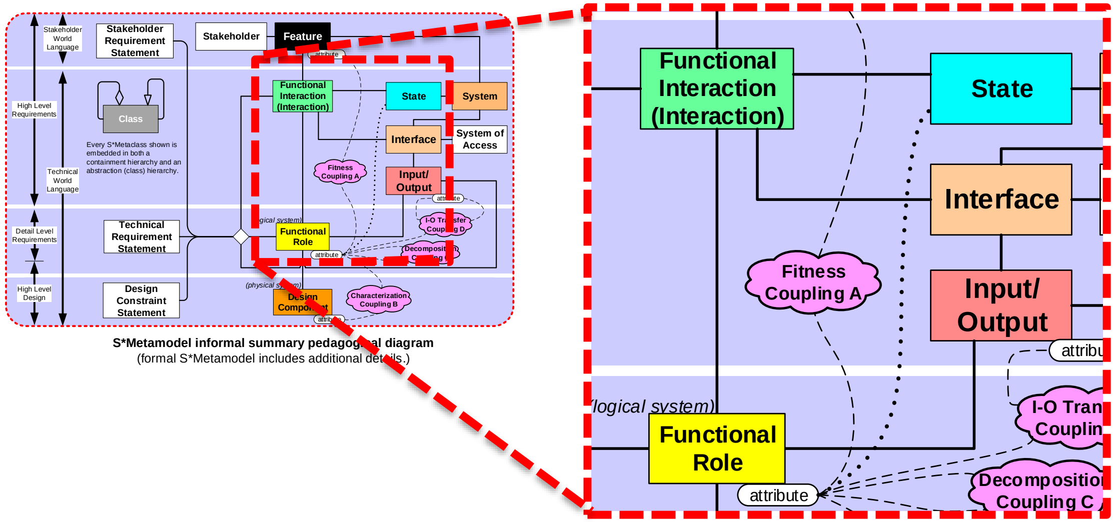
- There is a large body of literature on a mathematical subset of the Model VVUQ problem.
- Additional systems work is in progress, as to the more general VVUQ framework, suitable for general standards or guidelines – see the current ASME / INCOSE VVUQ work.
- <u>System</u> models are part of this--scientifically-based trust is not awarded just by convincing someone your model looks good.
- Increased V&V for critical models will raise the cost of those models.
- This makes the use of <u>trusted patterns</u> more justifiable, and the sharing of patterns more attractive.
- VVUQ of models is connected to model intended uses, risks

2. Representing the System Phenomenon

- Interactions are the phenomenon center of three centuries of highly impactful science and engineering.
- They should appear center stage in every system model
- They more impactful on engineering analysis than unipolar Functions (Functional Roles) alone.
- Because of the System Phenomenon.

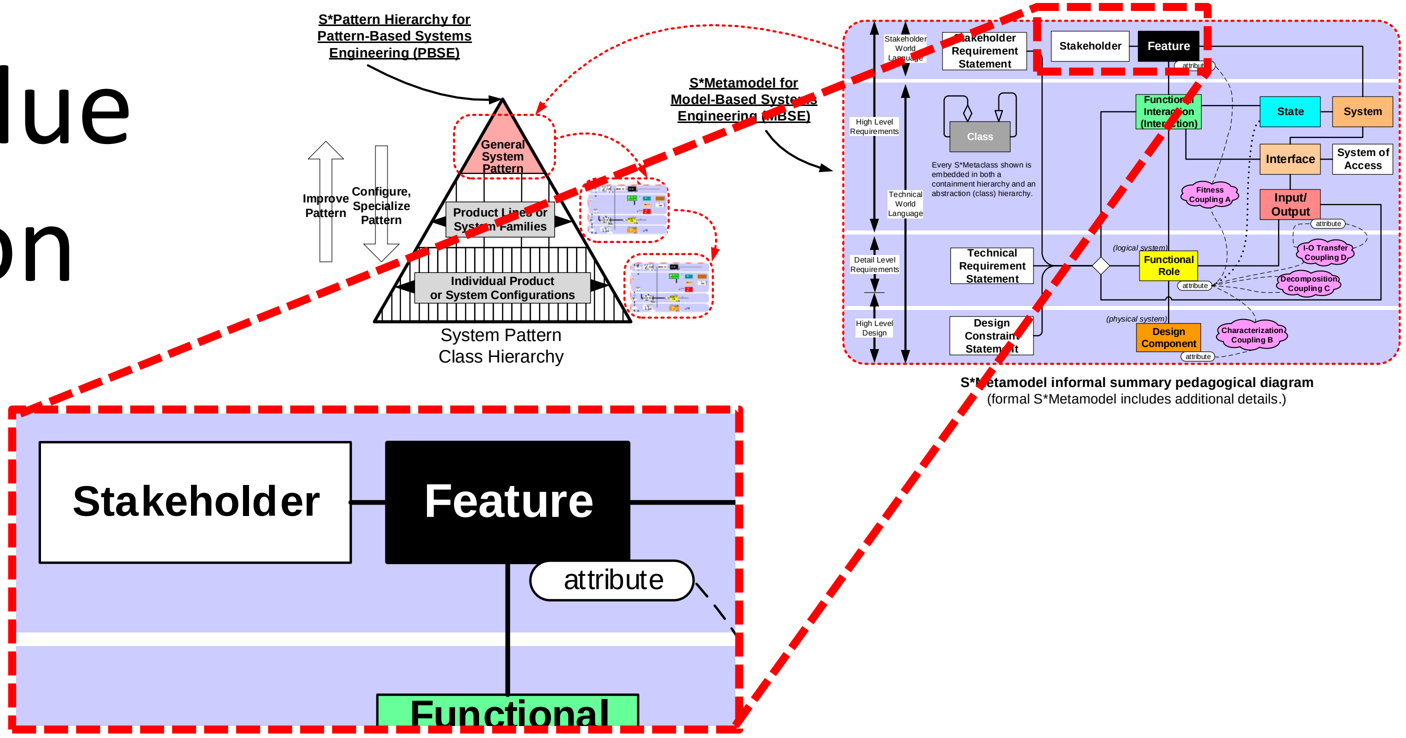


Representing the System Phenomenon



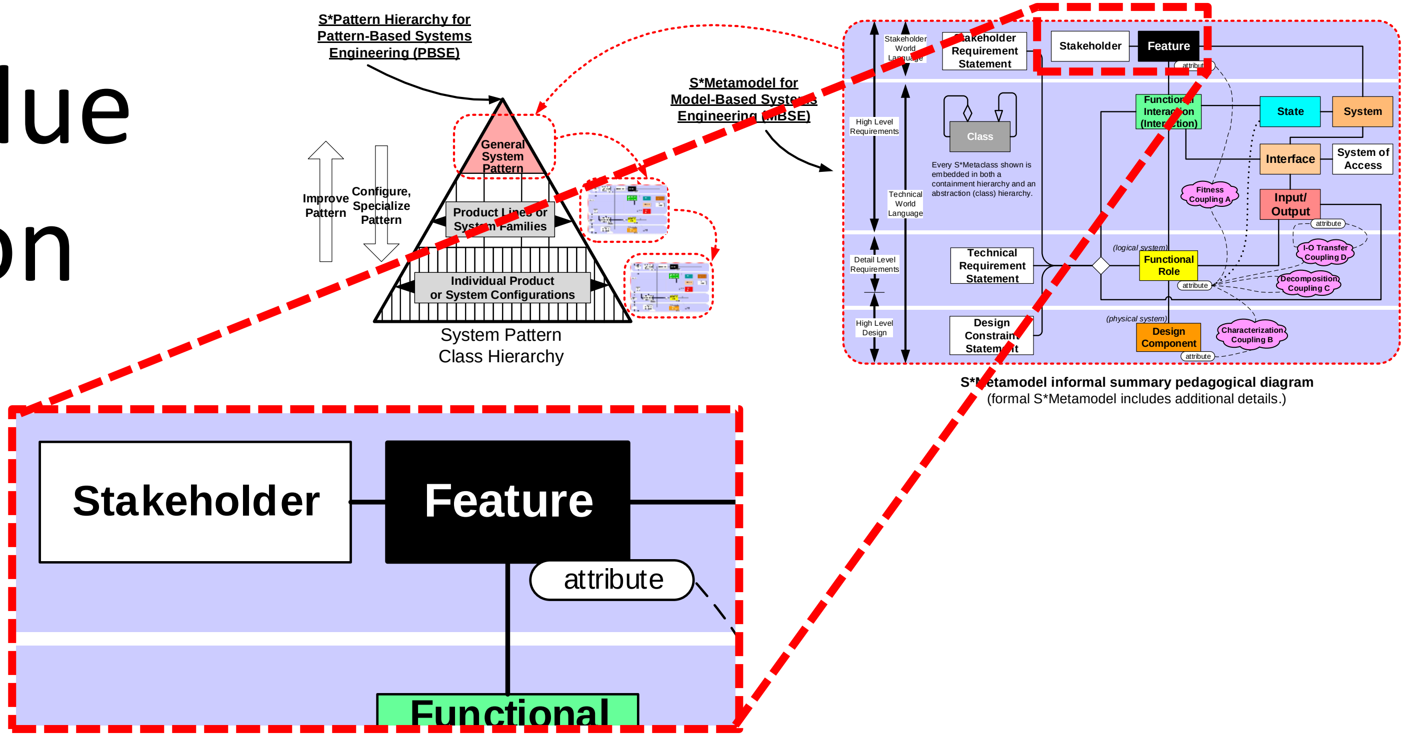
- No matter what your modeling language or tools--Interactions are not optional or peripheral, but central to system models:
  - Are Interactions central to <u>your</u> models and thinking?
  - Are you integrating or dividing?
  - There is no “naked behavior”—it all occurs in interactions.
- The distinction between “system models” and “other discipline models” is largely an accident of history and enterprise organization, not Nature.
- Emergent domain phenomena and languages at each level:
  - From gas laws to plate tectonics to cosmological scales

3. Representing the Value Selection Phenomenon



- Each S*Pattern formalizes a sharable domain-specific language (DSL), including the “value space”, characteristic of that domain.

3. Representing the Value Selection Phenomenon



This simplifies use of the same consistent value space for “different” things:

1. Optimization, frontiers, decision-making, trades, selection;
2. Understanding selection practices of other people, organizations, and Nature.
3. “E” of FMEA—effects of failures, penalties, only things that can be at risk, risk management, project management;
4. Partitioning of platform configuration space for market covering variant minimization;
5. Steering the sequence of adaptive work and investment increments, product trajectories.

4. Systems education for all engineers

- “Tiny” system models (including interactions, value) build system skills for undergraduate engineering students across disciplines—not just for SE majors.
- Particularly effective in cross-disciplinary programs.
- Model-making as a skill first, later building deeper system sense.

26th Annual INCOSE International Symposium (IS 2016)
Edinburg, Scotland, UK, July 18-21, 2016

Helping Undergraduate Students of any Engineering Discipline Develop a Systems Perspective

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ASEE

Paper ID #19345

Development of Enhanced Value, Feature, and Stakeholder Views for a Model-Based Design Approach

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He is currently an associate with IOI Partners, a consulting venture focused on innovation tools and systems. Prior to joining Rose-Hulman, he was a company co-founder and Chief Operating Officer of Montronix, a company in the global machine monitoring industry.

Bill is a Phi Beta Kappa graduate of Illinois College and a Bronze Tablet graduate of University of Illinois at Urbana Champaign where he received a Ph.D. degree in Mechanical Engineering.

Mr. William D. Schindel, ICTT System Sciences

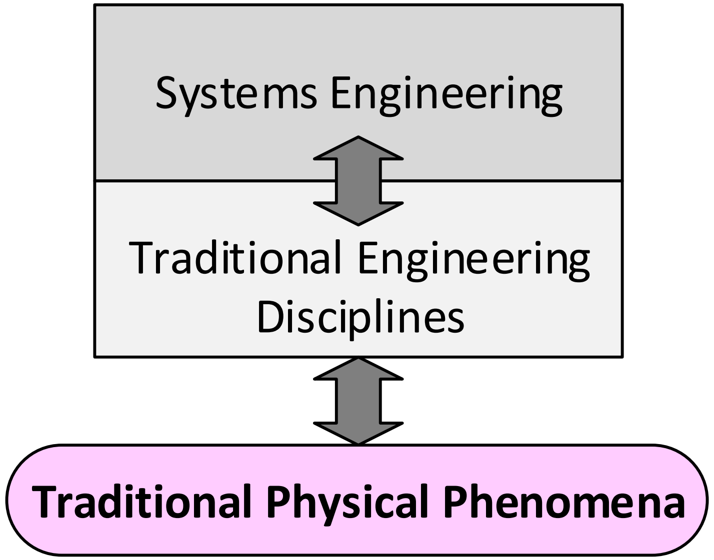
William D. Schindel is president of ICTT System Sciences, a systems engineering company, and devel-

5. Systems research frontiers, needs, and opportunities

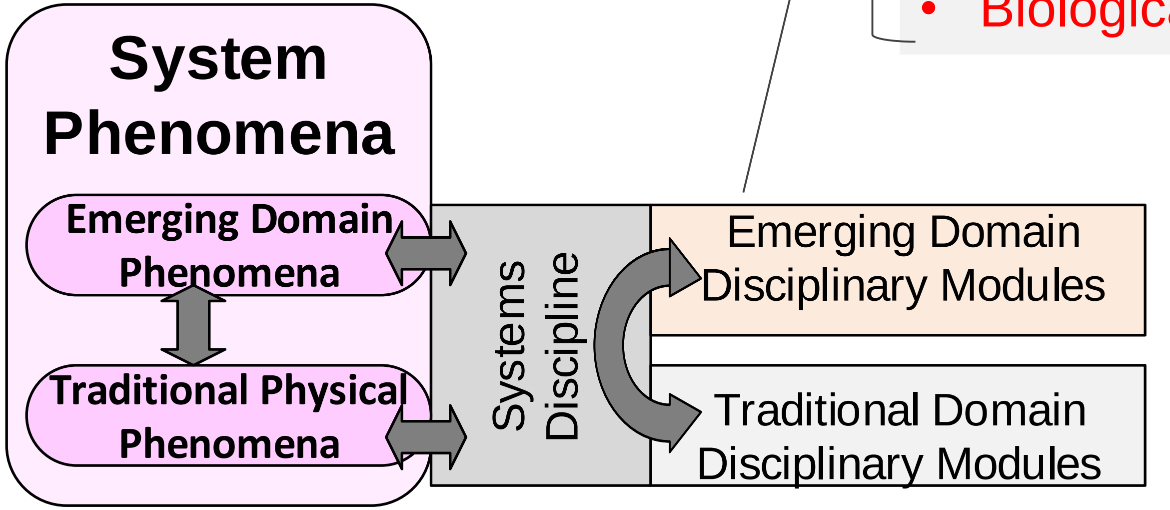
- Future
  - Distribution networks
  - Biological organisms, ecologies
  - Market systems and economies
  - Health care delivery
  - Systems of conflict
  - Systems of innovation
- Recent
  - Ground Vehicles
  - Aircraft
  - Marine Vessels
  - Biological Regulatory Networks

Recall our earlier discussion:

Traditional view:

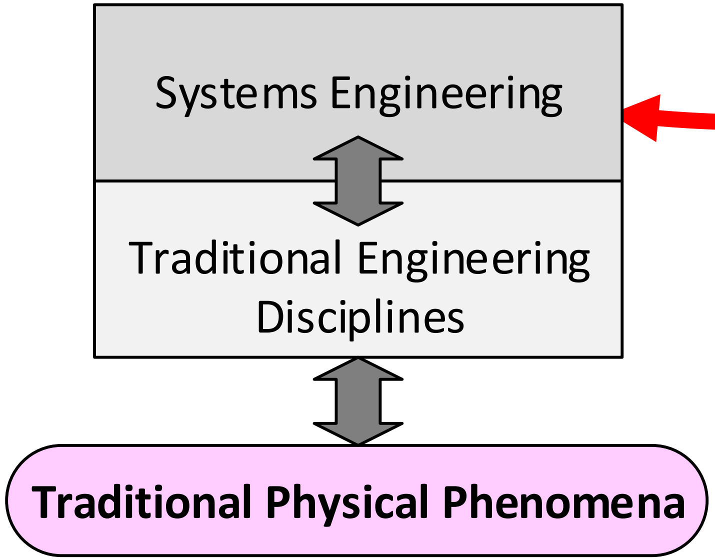


Future view:



Historical Systems Engineering Research Attention

Traditional view:



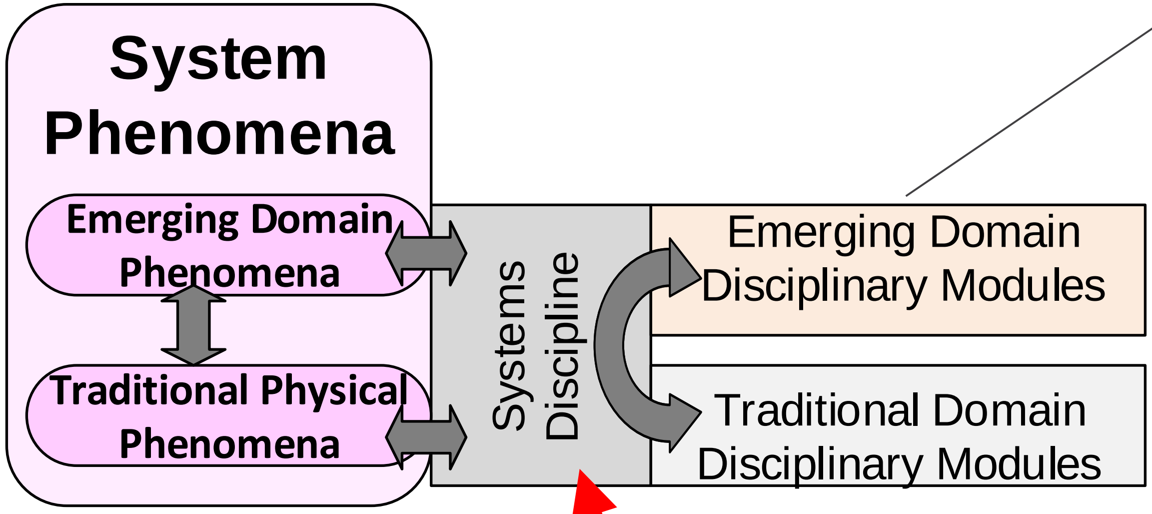
We assert this is focusing on the wrong place.

Instead, target each of the higher emerging levels

Each emerging domain framework has its own patterns of foundational structures. (Same as chemistry, gas laws, electromagnetics, etc.) There are countless research opportunities to discover those domain patterns, their related mathematics, and apply them for the good of each domain. Just like we did in, say, chemistry or gas laws.

- Distribution networks
- Biological organisms, ecologies
- Market systems and economies
- Health care delivery
- Systems of conflict
- Systems of innovation
- Ground Vehicles
- Aircraft
- Marine Vessels
- Biological Regulatory Networks

Future view:



A great deal of math/science already exists here, from 300 years of progress. Better we should be <u>learning it</u> and <u>using it</u> than searching for a replacement. Better to invest in more research in the above domains.

Q&A, Discussion

Reference Starting Points—Including Bibliographies

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The INCOSE Patterns Working Group

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