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V1.8.9

Implications for Future SE Practice, Education, Research:

SE Foundation Elements

(awareness version, 1 hour)

Abstract

- The traditional engineering disciplines are supported by companion physical sciences, each with a focal physical 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 already established historical basis and success in other disciplines, and noting their practical impacts on future SE practice, education, and research, toward phenomena-based scientific and mathematical foundations for the discipline.

Agenda

- Background and Motivation
- The System Phenomenon
- The Value Selection Phenomenon
- The Model Trust Phenomenon
- Implications for Practitioners, Educators, Researchers

- References
- Attachment I: More about the above phenomena

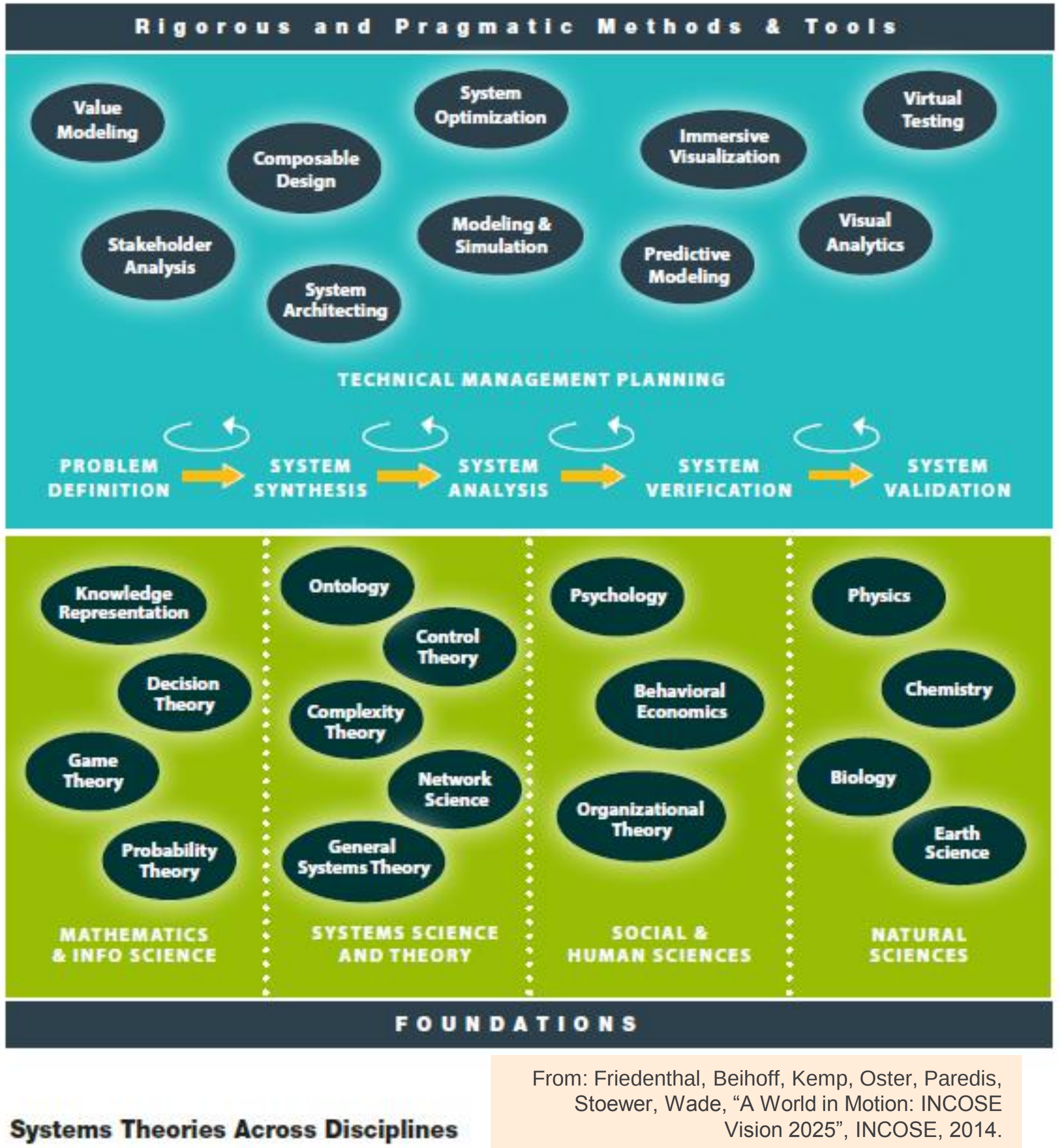
INCOSE *SE Vision 2025* : Called for stronger SE foundations

"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."



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

Background and Motivation

For good reason, math and science foundations for Systems Engineering were called for in *INCOSE Vision 2025:*

- The success of the phenomena-specific engineering disciplines is founded on their related physical sciences and mathematics.
- SE practices and methods across diverse application domains should likewise be understood and selected based on such a foundation.
- Engineering education of both systems engineers and the other engineering disciplines should be based on a shared understanding of their common underlying technical foundation.
- Research and advancement in the practice of SE should take advantage of its underlying and expanding technical foundation.

Background and Motivation

- In the following, we will assert that those foundations are closer than they may seem, not requiring discovery “from scratch”:
  - Already identified in well-established foundations of STEM, discovered and highly successful during three centuries of the transformation of human life
  - Awaiting wider awareness and exploitation by the systems community, providing a powerful starting point for what will follow.
- We will summarize three phenomenon-based elements of that foundation, providing starting points already known.
- Finally, we will point out implications for SE Practitioners, Educators, and Researchers.

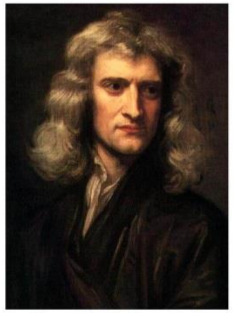
Three Real Phenomena That Are Key to SE Foundations

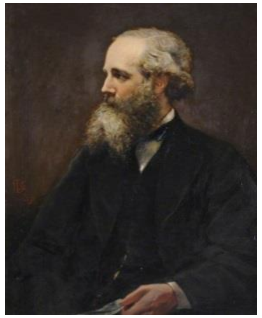
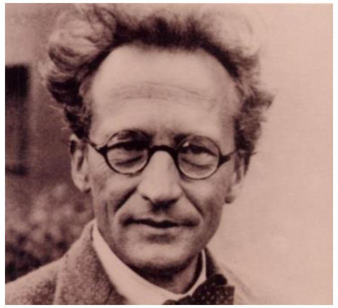
1. **The System Phenomenon**: Each of the traditional physical sciences is based on a specific physical phenomenon (mechanical, electrical, chemical, etc.) and related mathematical formulation of physical laws and first principles. What is the equivalent "hard science" phenomenon for systems, where is its mathematics, and what are the impacts on future SE practice?
2. **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. What is the bridge effectively connecting these, where is the related mathematics, and what are the impacts on future SE practice?
3. **The Model Trust Phenomenon**: The physical sciences accelerated progress in the last three centuries, as they demonstrated means for not just the discovery and representation of Nature's patterns, but also the managed awarding of graduated shared trust in them. What is the scientific basis of such group learning, how is it related to machine learning, and how does it impact the future practice of SE?

1. The System Phenomenon

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.



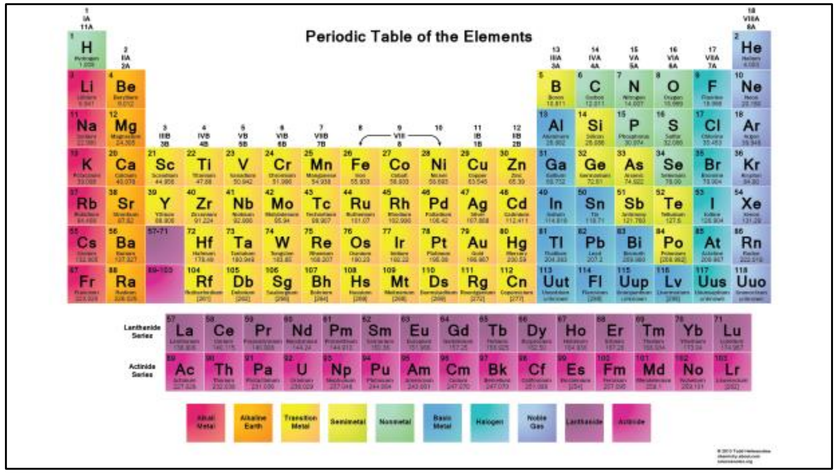
Traditional Perspective on SE—as we know it today

- 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.

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

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

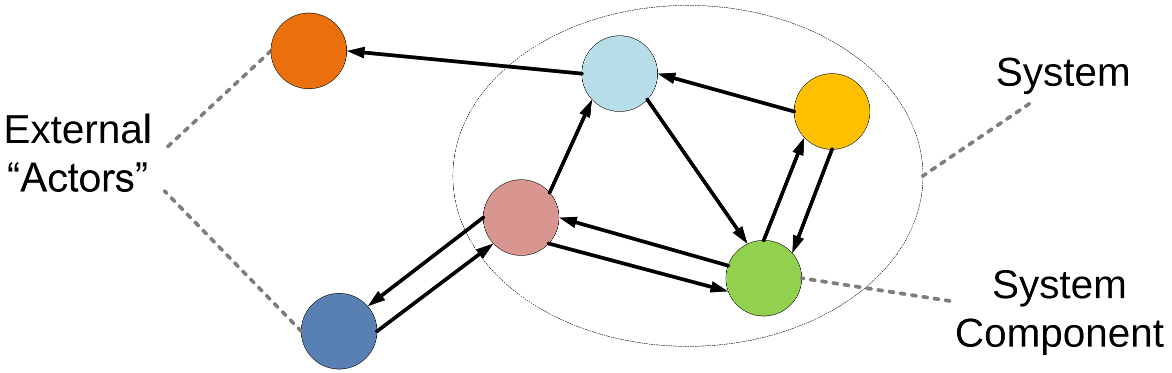
$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

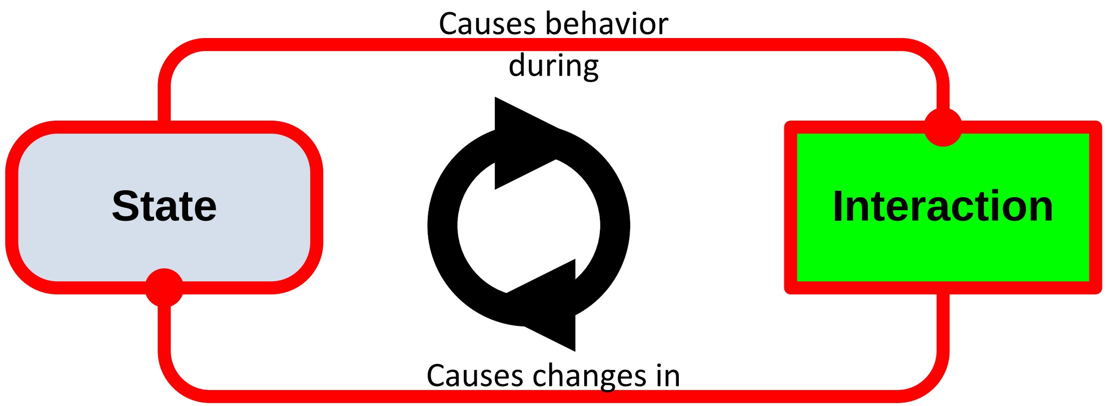


- Instead, Systems Engineering is sometimes viewed as:
  - Emphasizing process and procedure in its literature
  - Critical thinking and good writing skills
  - Organizing and accounting for information
  - Integrating the work of the other engineering disciplines and stakeholder needs
- But not based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

Formalizing System Representations

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

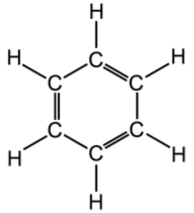


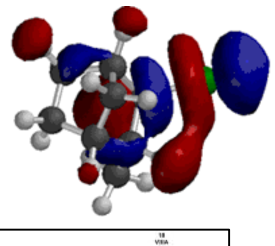


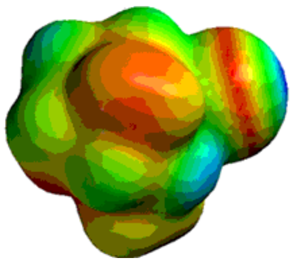
- By “interacting” we mean the exchange of energy, force, material, or *information* (all of these are “input-outputs”) between system components, . . .
- . . . through which one component impacts the state of another component.
- By “state” we mean a property of a component that impacts its input-output 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.

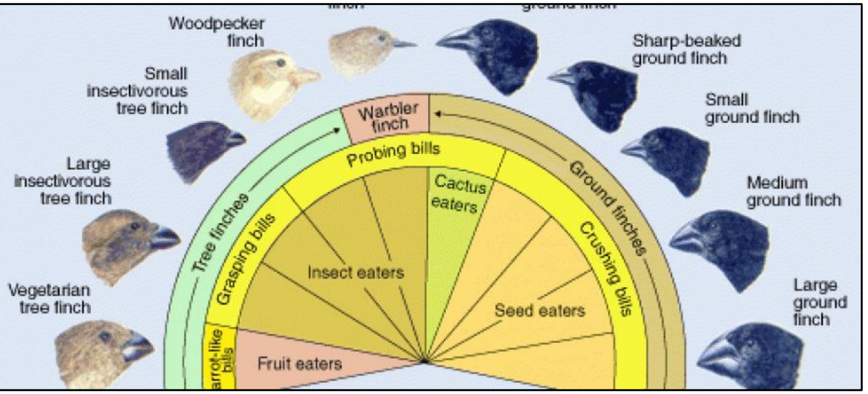
Patterns: At the heart of scientific laws

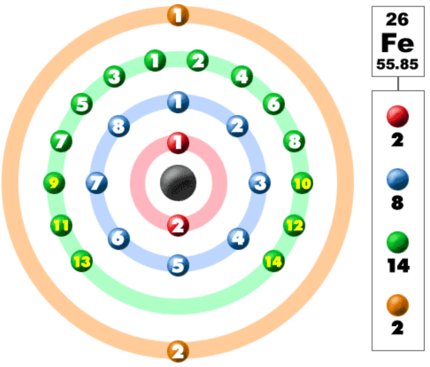
- All “patterns” are recurrences, having both fixed and variable aspects.
- The heart of physical science’s life-changing 300 year success in prediction and explanation lies in recognition, representation, exploitation of recurring patterns.
- Hamilton’s Principle & Noether’s Theorem: Substantial math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

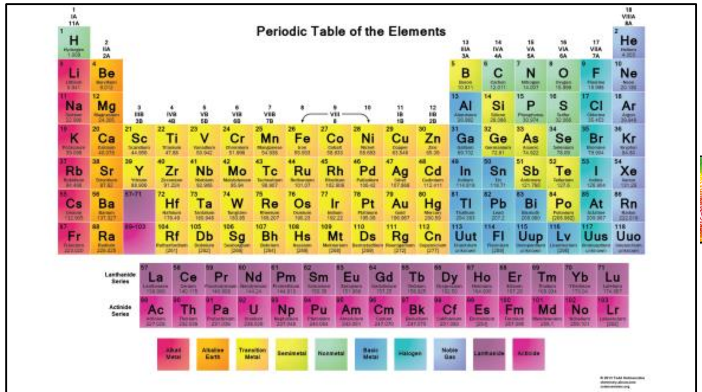


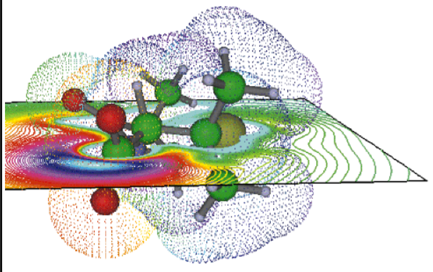








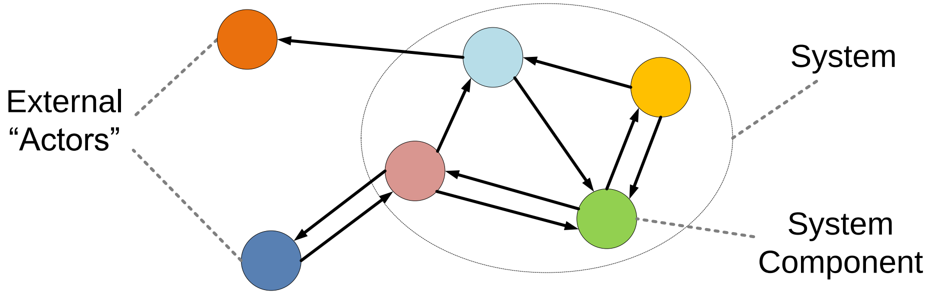




The System Phenomenon

- Phenomena 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 *interaction-based structure* of the System Phenomenon remained, and the underlying related Action and Symmetry principles became the basis of modern theoretical physics. See later.

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

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 . . .

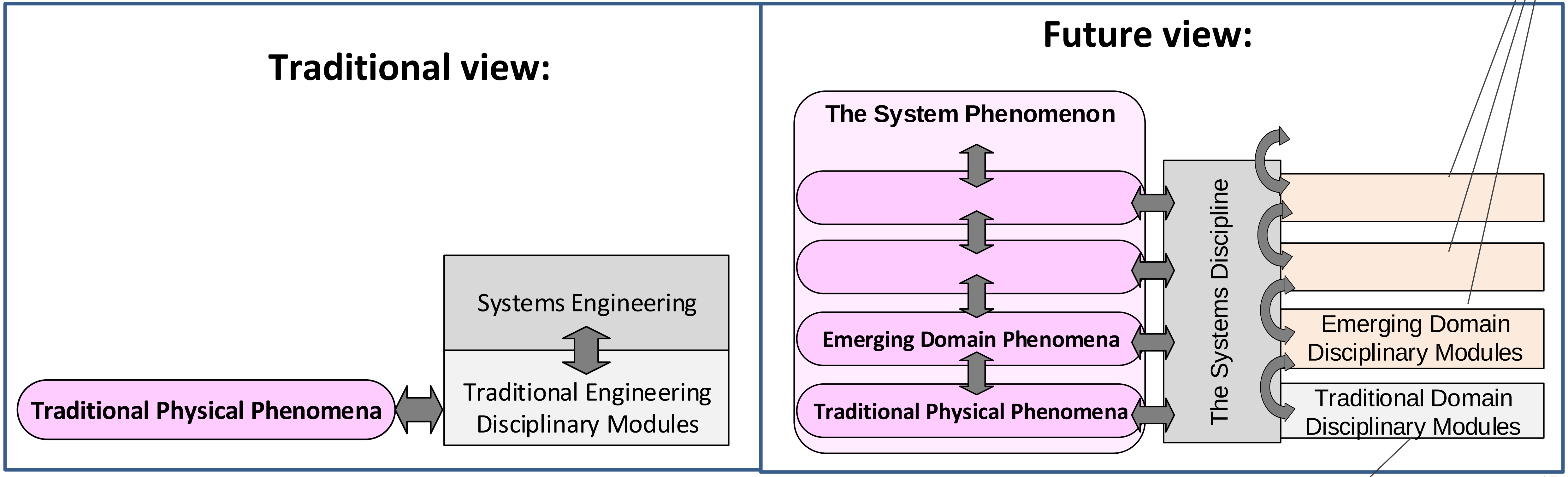
- The System Phenomenon and its supporting mathematics (Hamilton et al) provide the inductive ladder, explaining theory of each new level in terms of the previous level.
- As higher-level system patterns are discovered, represented, validated, taught, and practiced, they become “emergent domain disciplinary frameworks”.
- This is evident in the history of scientific and engineering domains and disciplines, and newer emerging 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



ME, CE, EE, ChE, …

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2. 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 currently 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 associated with value, what is the bridge between subjective value and objective science, where are the related mathematics and recurring patterns, and what are the impacts on future SE practice?

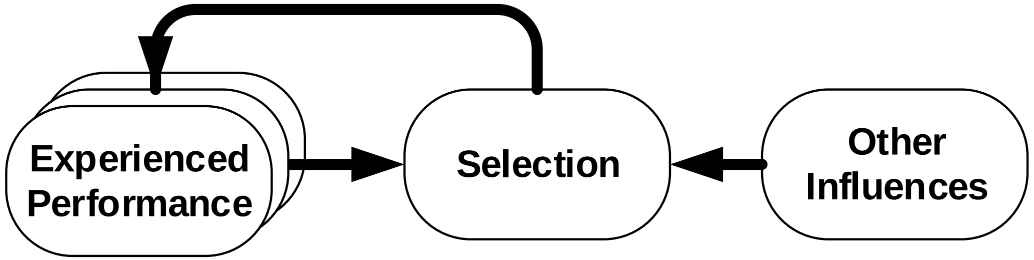
Even if value (both human-based and otherwise) seems elusive or subjective, . . .

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

Settings	Types of Selection	Selection Agents	
Consumer Market	Retail purchase selection	Individual Consumer; Overall Market	
Military Conflict	Direct conflict outcome; threat assessment	Military Engagement	X
Product design	Design trades	Designer	
Commercial Market	Performance, cost, support	Buyer	
Biological Evolution	Natural selection	Environmental Competition	X
Product Planning	Opportunity selection	Product Manager	
Market Launch	Optimize choice across alternatives	Review Board	
Securities Investing	What to buy, what to sell, acceptable price	Individual Investor; Overall Market	
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	

Not all selection is by human choice

Performance Interactions vs. Selection Interactions



Value refers to Interactions of two very different types:

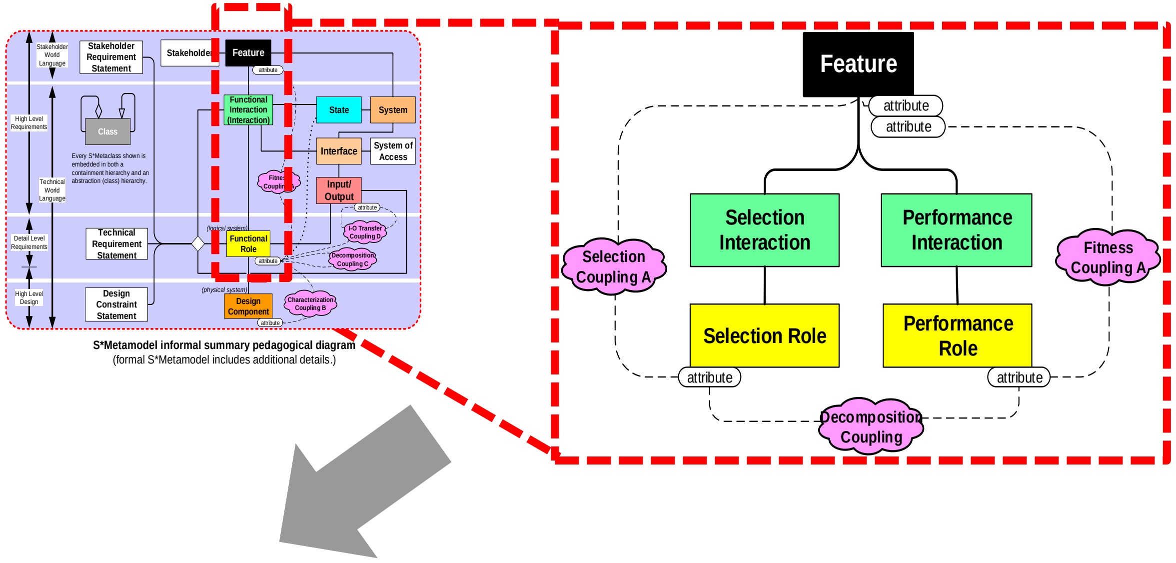
1. **Performance Interactions** (real or planned, present, past, future) *embody and deliver* Value from Performers (this is currently more familiar to systems engineers):
    - Example: The "ride" a passenger experiences, over a bumpy road in a vehicle.
    - An actually experienced, simulated, imagined, or promised performance interaction.

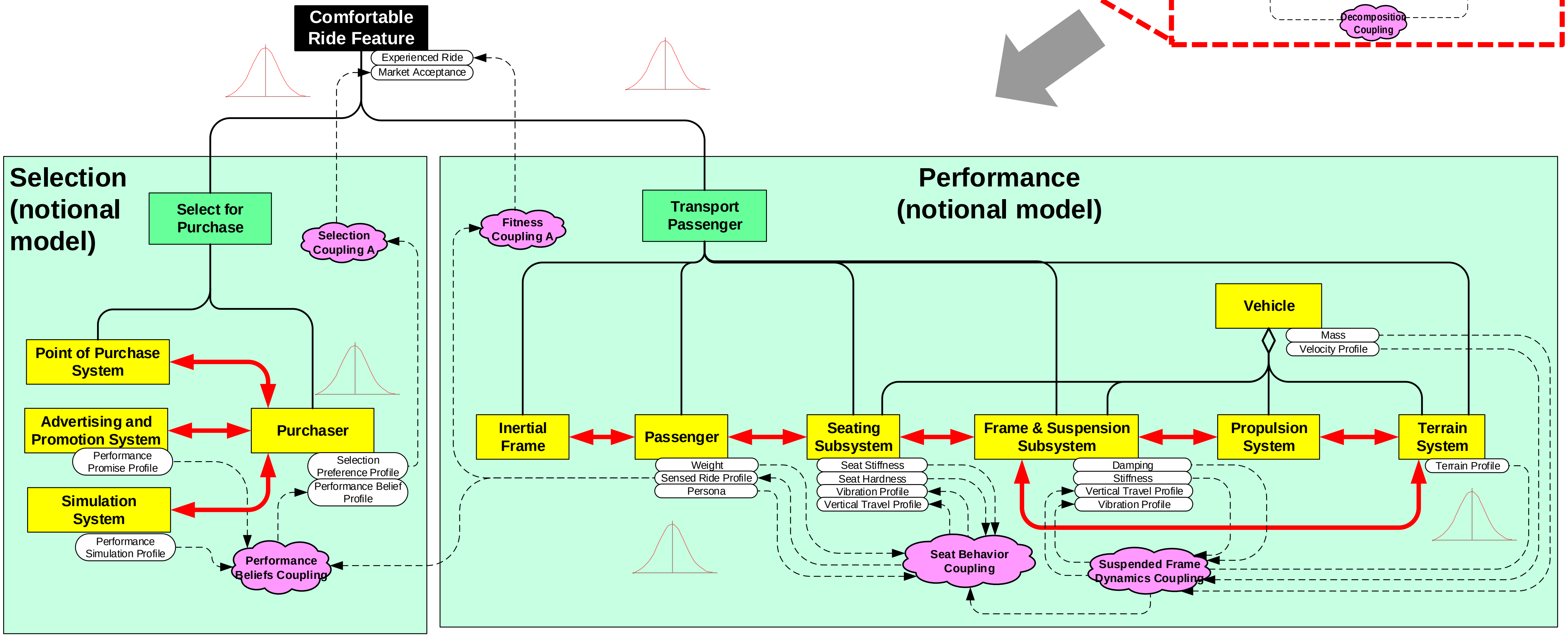
2. **Selection Interactions** (human or otherwise) *express* the comparative Values of a Selection Agent, human or otherwise (familiar to consumer marketers, behavioral economics specialists, web-based experimentalists, big data specialists):
    - Example: The selection of a new vehicle from among competing alternatives.

Emphasizing selection outcome as the ultimate expression of what is valued:

- Performance Interactions remain essential to representing the possible choices.
- Selection Interactions frequently choose across multiple dimensions all at once.

Example: Selecting Vehicle "Ride"

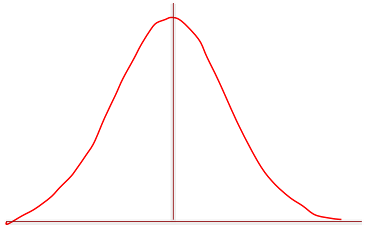




Value is not solely inherent to subject system's performance

- A performing system, moved from one country-culture-application-market segment to another, with no technical changes:
  - Could offer the very same technical performance (assuming the application/operating environment remained the same otherwise).
  - But is valued differently by the new and different stakeholders.
  - As their Selection behavior will ultimately express.
- The Selection Phenomenon is what we want to understand to quantify relative value, always expressed as selection:
  - As influenced <u>in part</u> by the Performance Interaction, . . .
  - But also by the nature and behavior of the Selection Agent, . . .
  - Which is impacted by past experience, learning and habituation, advertising and promotion, trends and fashion, peer groups, etc.
  - Much innovation has been occurring in those other spaces—such as choice and distribution through on-line and other non-traditional systems.

Human Subjectivity



In this framework, human subjectivity appears in two different places:

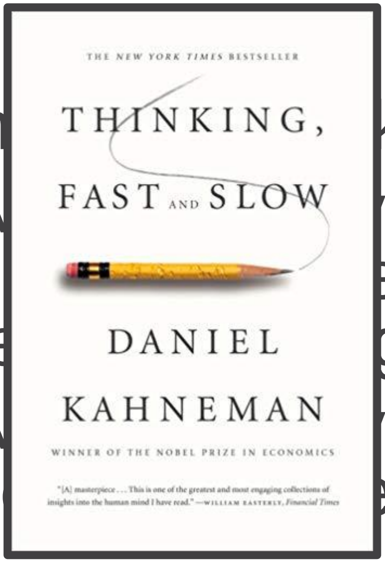
1. A human may be a part of the Performance Interaction, and form sensory and mental perceptions about what performance is occurring—not its value. (e.g., Passenger in above example)
2. A human may be the Selection Agent in the Selection Interaction, acting on acquired beliefs about relative value. (e.g., Purchaser in above example)

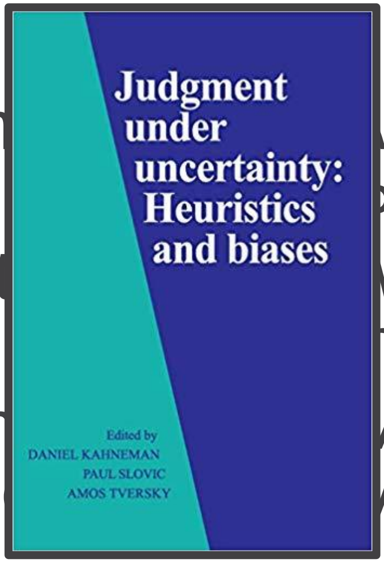
The key insight: *Note that neither of these two parties is the **Modeler**:*

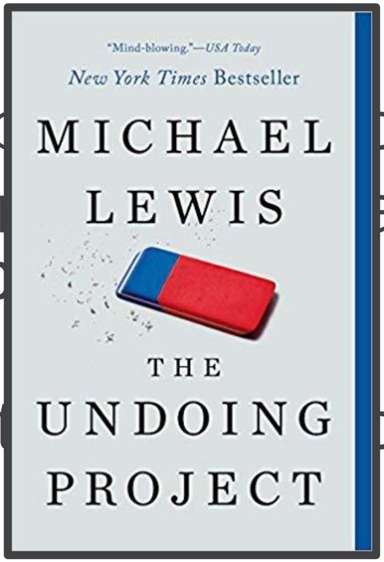
- The role of the Modeler is to discover, express, and validate models of both the Performance and Selection aspects of the systems at hand:
  - Whether those humans are flying aircraft or choosing products.
- This clearly involves modeling of human behaviors:
  - That should hardly be a surprise, after decades of impactful modeling, Nobel prize recognition, and now on-line machine learning and millions of confirming experiments, about the behavior of humans.

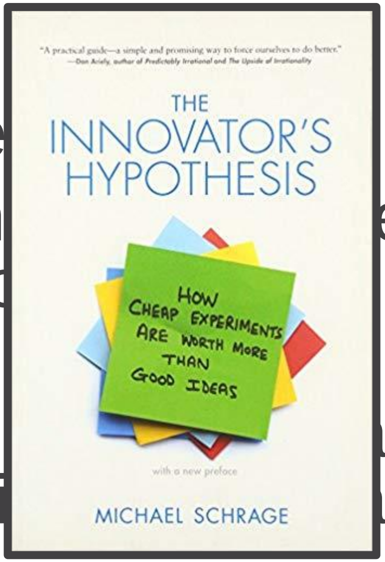
Human Subjectivity

In th k, hun vity ap o diffe
1. A y be a Perfor action ensory a ercept what p is occ its value. (e ger in mple)
2. A y be th Agent ction I acting on a efs ab value. aser i mple)







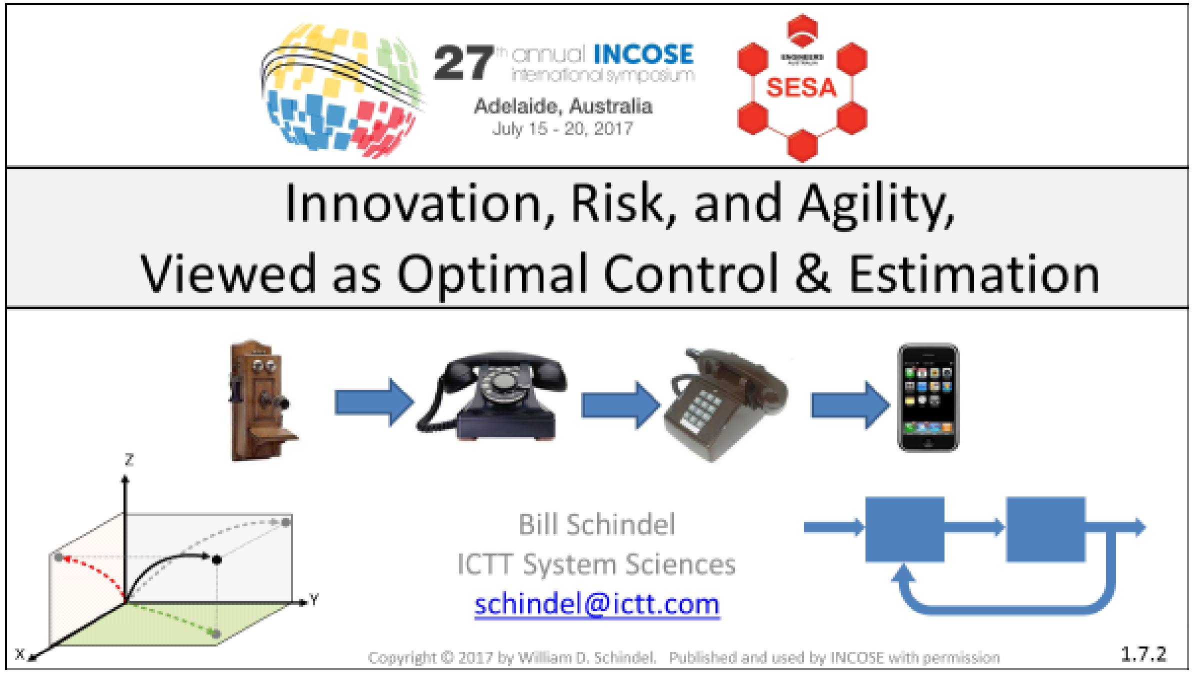


The key insight: *Note that neither of these two parties is the **Modeler***:

- The role of the Modeler is to discover, express, and validate models of both the Performance and Selection aspects of systems (including human):
  - Whether humans are flying aircraft, choosing products, or not humans.
- This clearly involves modeling of human behaviors:
  - That should hardly be a surprise, after decades of related impactful modeling, discoveries and Nobel prize recognition, and now on-line machine learning in millions of confirming experiments, about the value-based behaviors of human subjects.

Lessons from Biology and Agile Engineering: 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

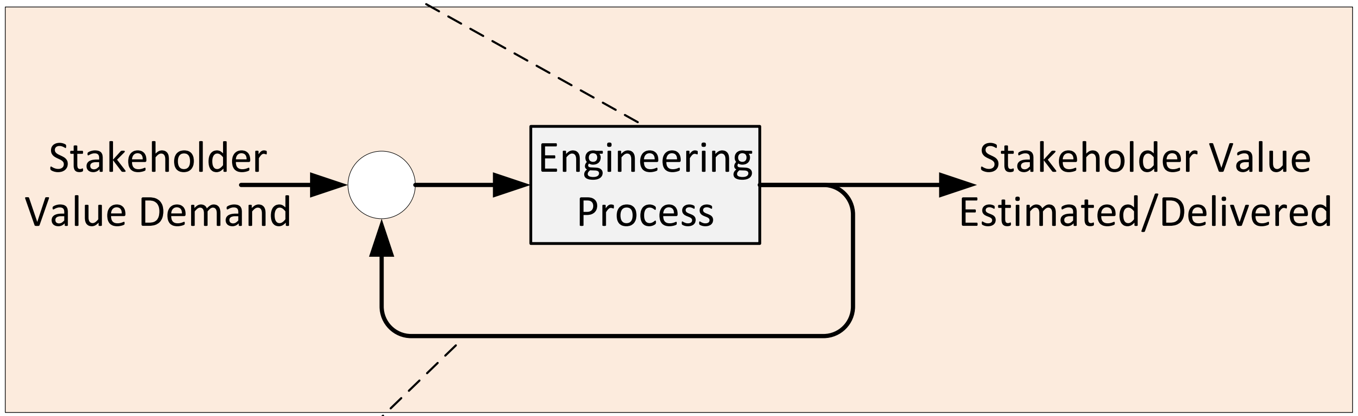


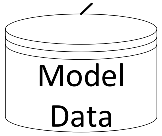
Innovation Trajectory Optimization, in Value Space

- Apply Optimal Estimation and Control Theory
- To Define Direction of Increments in Model Space (not Process Space)
- that Optimizes the Value Space Trajectory Traveled During Processes
- Includes considerations of Travel Time Schedule, Cost, Risk, System Performance

IN PROCESS SPACE:

- Organizes Process Concurrency / Agility,
- By optimizing the incremental model data trajectory in model configuration space





IN SYSTEM MODEL DATA SPACE:

- Mission & other Stakeholder Analysis/MOEs, including Risks, in Value Model Space
- System Requirements Analysis/TPMs, in Technical Performance Model Space
- Architecture Design, in Physical Design Space
- Trade-off Analyses
- System Verification/Validation Confidence

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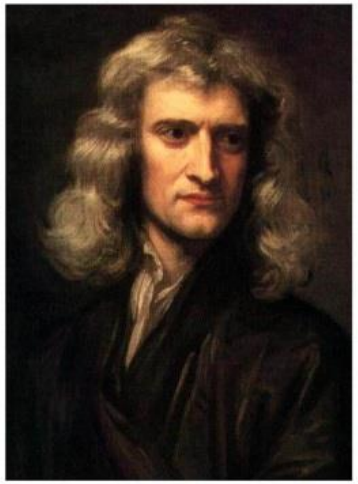
Two Historical "Phase Changes" in Disciplines

1. Model-based phase change leading to traditional STEM disciplines:
   - Beginning around 300 years ago (Newton's time)
   - Efficacy evidence argued from "step function" impacts 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

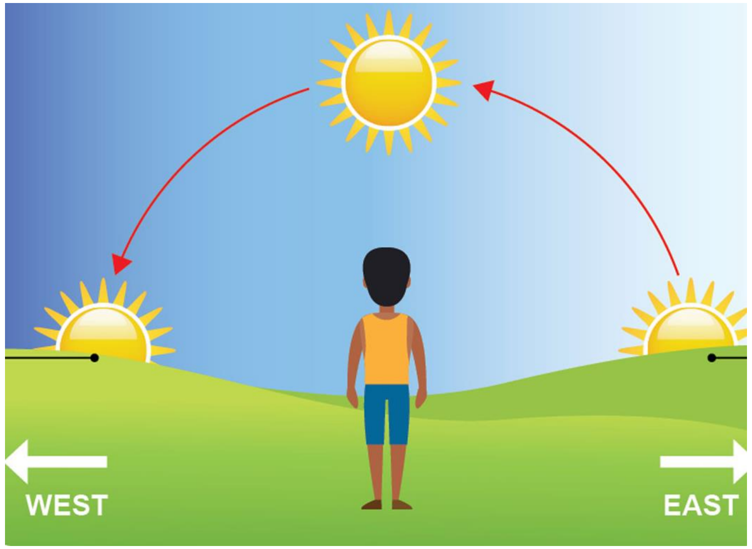
In a matter of a 300 years . . .

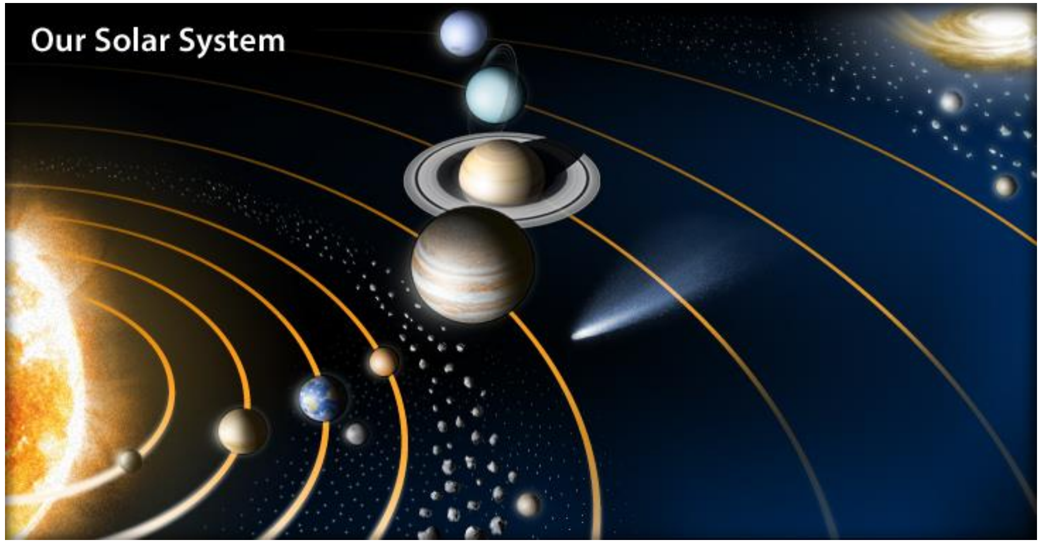
- the accelerating emergence of Science, Technology, Engineering, and Mathematics (STEM) . . .
- has lifted the possibility, nature, quality, and length of life for a large portion of humanity . . .
- while dramatically increasing human future potential.
- By 20th Century close, strong STEM capability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

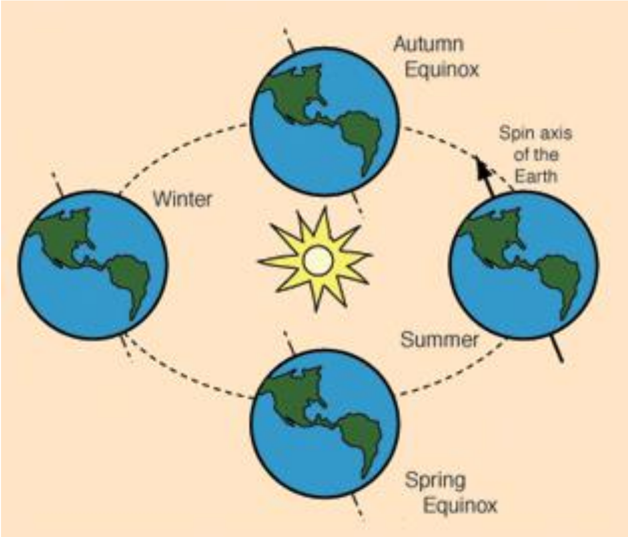
A Standard of Performance for MBSE

- The “hard sciences”, along with the “traditional” engineering disciplines and technologies based on those sciences, may be credited with much of that amazing progress.
- When it comes to use of models, how should Systems Engineering be compared to engineering disciplines based on the “hard sciences”?

Engineering uses Science/Mathematics to represent, predict, explain

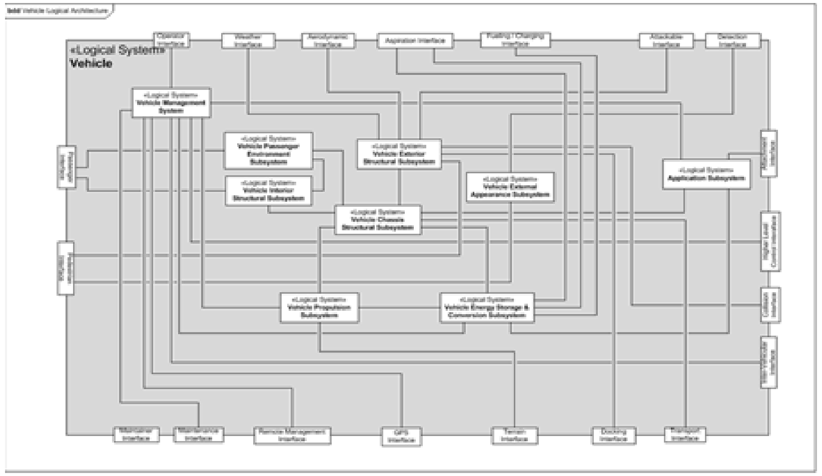






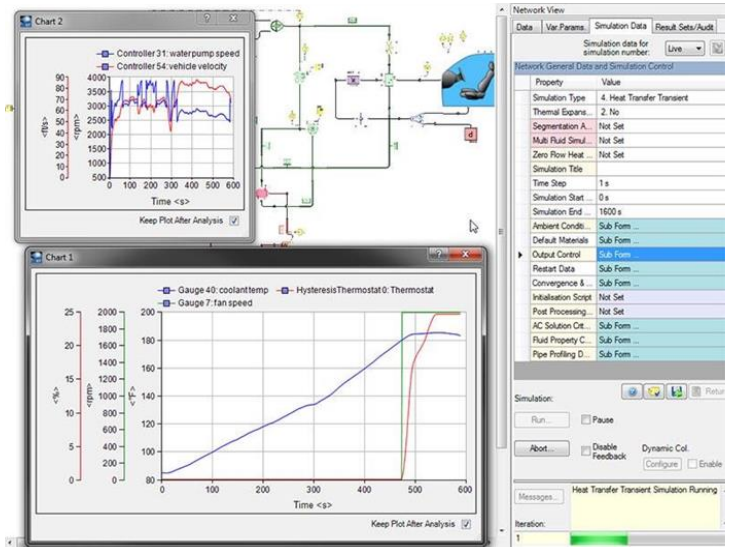
- Predict: For millennia, the evolving passage of sunrise, sunset, Lunar phases, and passage of the seasons has been reliably predicted based on learned, validated patterns, helping feed exploding human population.
- Explain: By the time of Copernicus and Newton, science had provided improved explanations 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



<u>Phase Change #2</u>: MBSE, PBSE, a phase change in SE

Vehicle Thermal Dynamics



While models are not new to STEM . . .

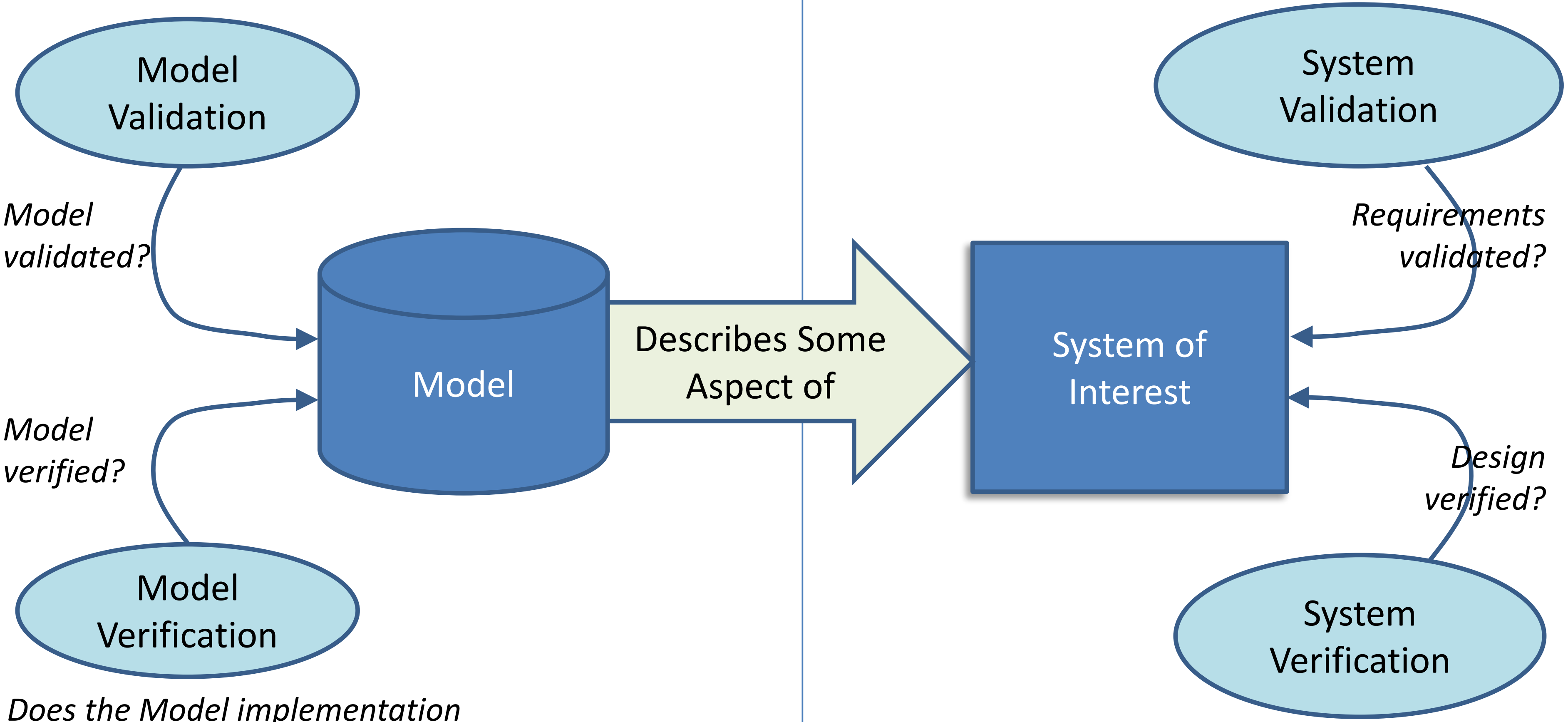
- <u>Model- Based Systems Engineering (MBSE)</u>: In recent decades, we increasingly represent our understanding of <u>systems</u> aspects using explicit models.
- <u>Pattern-Based Systems Engineering (PBSE):</u> We are beginning to express parameterized family System Models capable of representing <u>recurring patterns</u> -- 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, <u>provided the underlying model structures are strong enough</u>: Remember physics before Newtonian calculus.
- We asserted earlier above the need to use mathematical patterns known 100+ years.

V&V of *Models*, Per Emerging ASME Model V&V Standards

Does the Model adequately describe what it is intended to describe?

V&V of *Systems*, Per ISO 15288 & INCOSE Handbook

Do the System Requirements describe what stakeholders need?



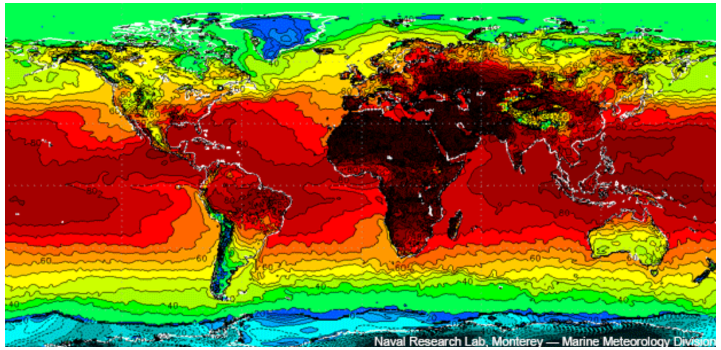
Does the Model implementation adequately represent what the Model says?

Does the System Design define a solution meeting the System Requirements?

Don't forget: A model (on the left) <u>may</u> be used for system verification or validation (on the right!)

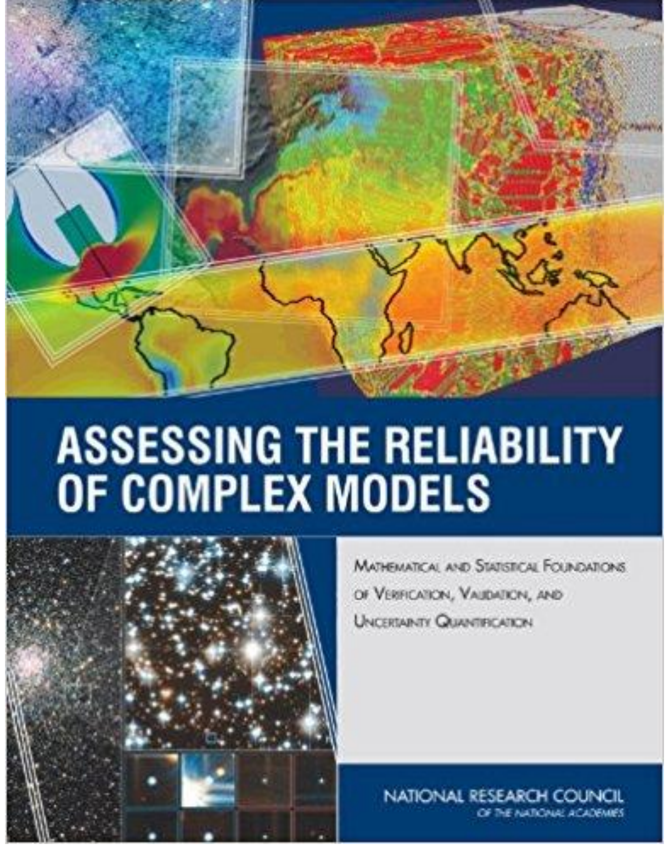
If we expect to use models to support more critical decisions, then we are placing *increased trust in models*:

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



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

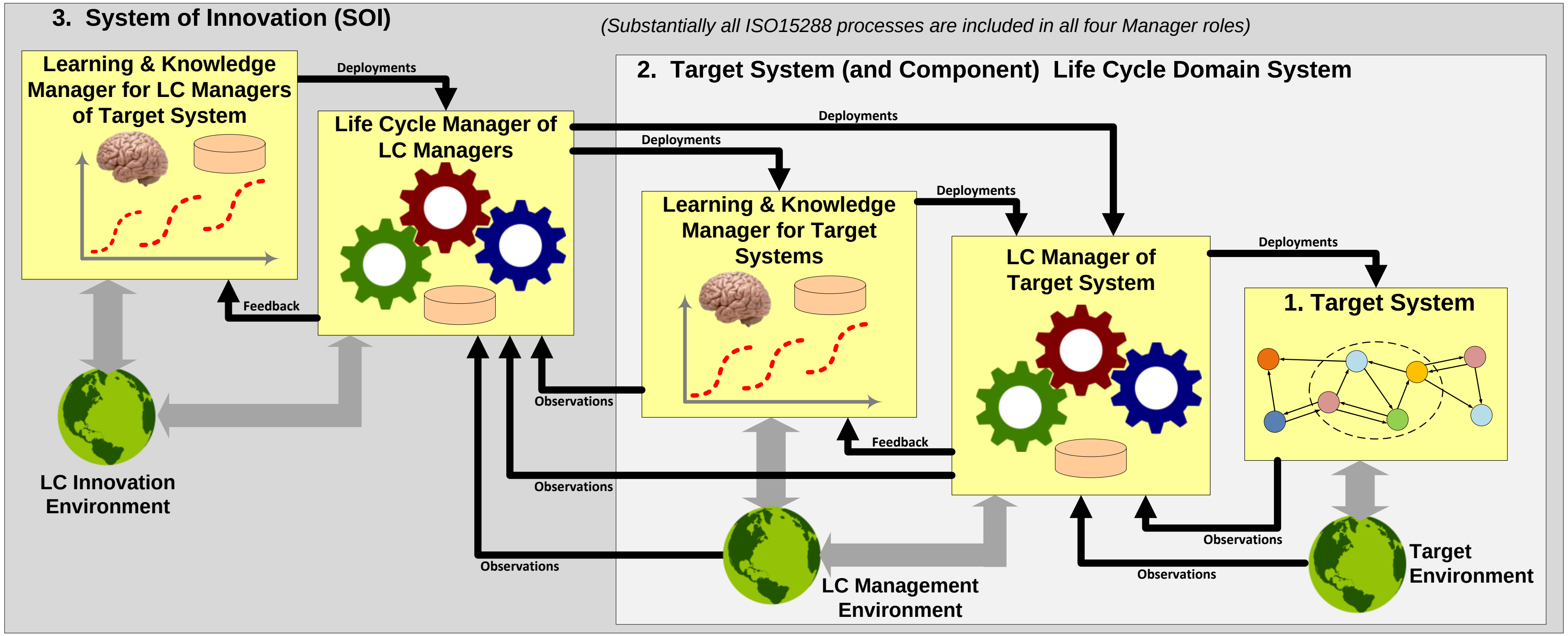
VVUQ: Model Credibility, including Uncertainty Quantification (UQ)



- 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.
- System models are part of this--scientifically-based trust is not awarded just by convincing someone your model looks good.
- Better quantification of model uncertainty, credibility, and maturity are all advancing.
- Increased V&V for critical models will raise the cost of those models.
- Makes use of trusted patterns more justifiable, the sharing of patterns more attractive.
- VVUQ of models is connected to model intended uses, risks

Model Trust Phenomenon: The bigger picture

- Learning, validation, and use of trusted models over time, whether informal tribal knowledge or formalisms of engineering and science, is central to the programs of engineering and science.
- INCOSE has developed and applied a reference pattern describing that overall frame, applicable from the most informal pre-model to the most formal modeling engineering environments.
- It is the ASELCM Reference Pattern, and it contains ISO 15288 while also generalizing it.
- Concerned with how accumulated knowledge is combined with new learning, in the case of formalized MBSE it makes possible the unification of the Bayesian view of mathematical foundations of science with the practical frameworks of Systems Engineering.



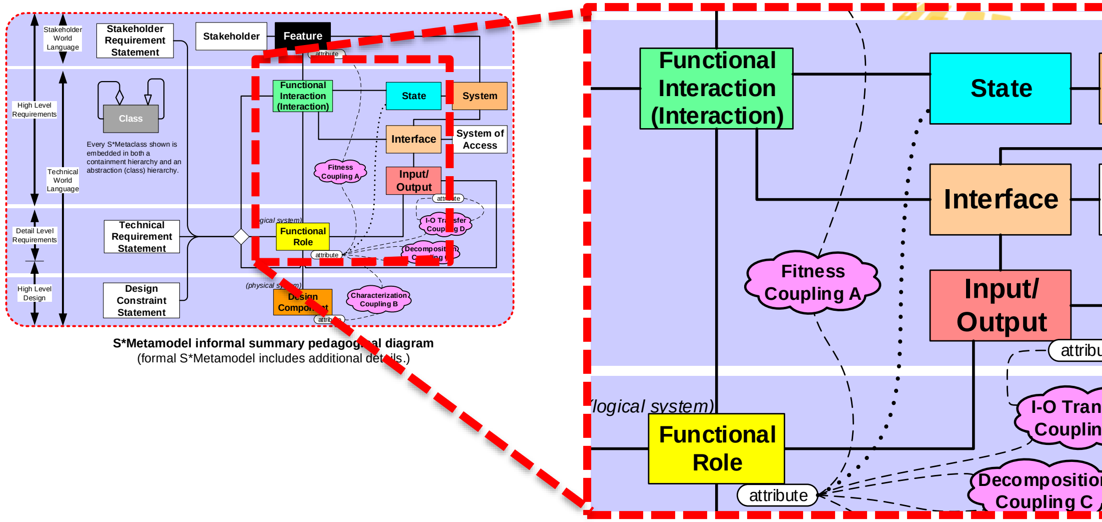
See Attachment I for more.

Implications for Practitioners, Educators, Researchers

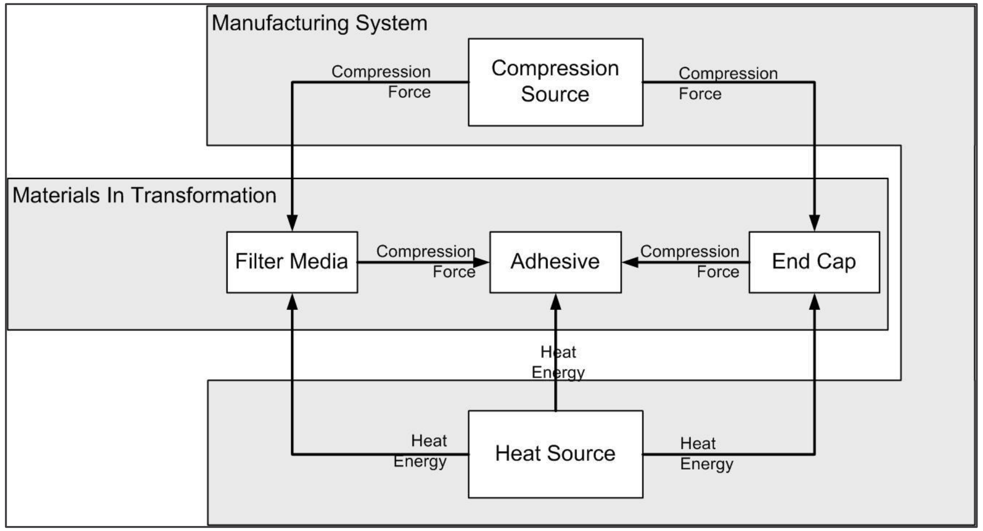
1. Representing the System Phenomenon
2. The burden of model credibility
3. Systems education for all engineers
4. Systems research frontiers, needs, and opportunities

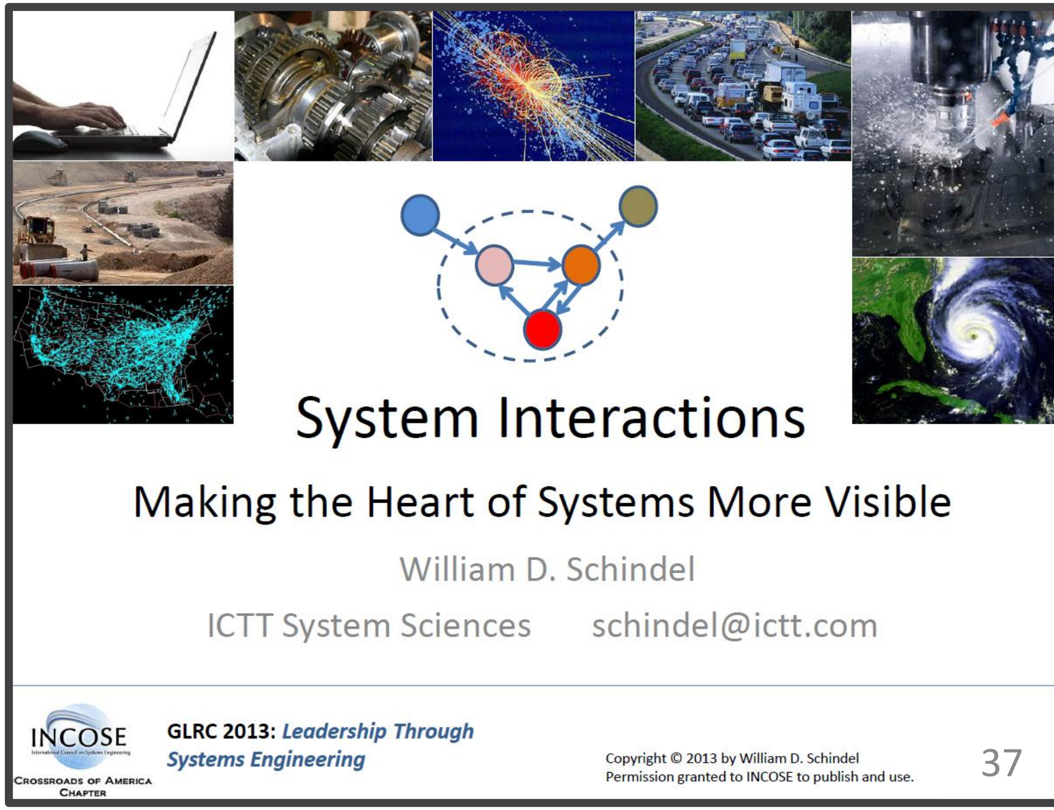
1. Practitioners: Representing the System Phenomenon

- Interactions are the phenomenon-based 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, also present.
- “Naked behavior” does not exist in Nature.



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

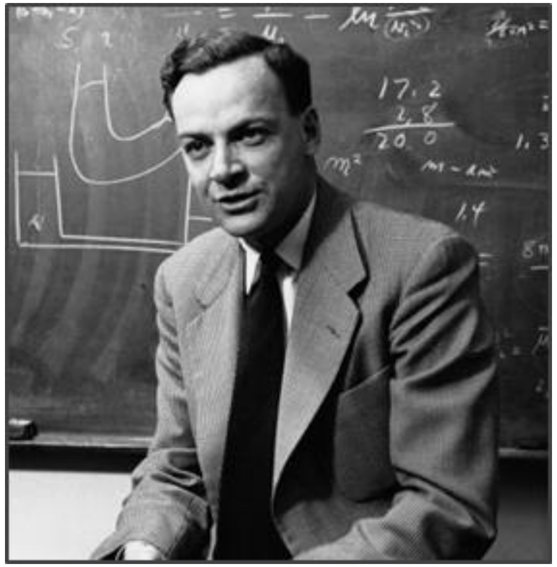




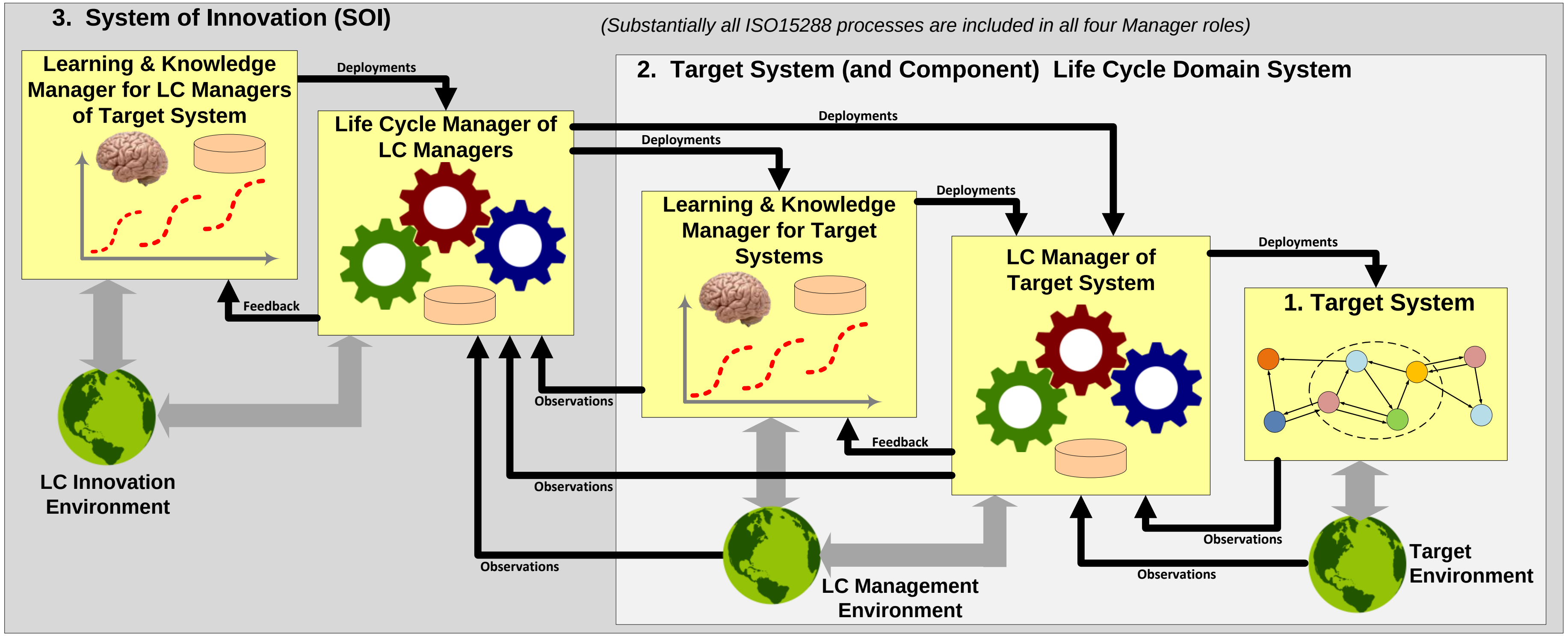
2. Practitioners: The burden of model credibility

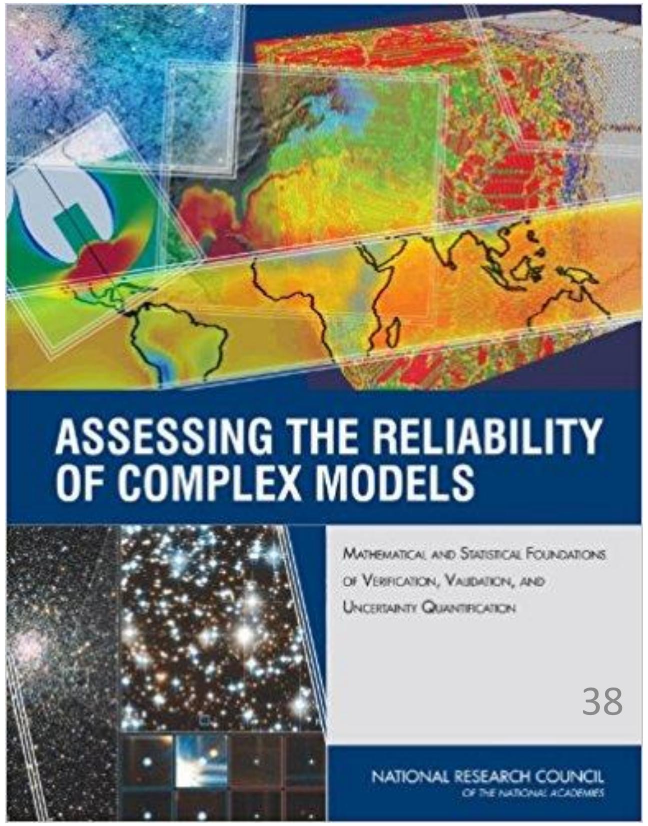
"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong."

– Richard P. Feynman



(MBSE Models are not exempt. See current ASME VVUQ work joined by INCOSE, FAA, FDA, NRC. Leverage of trusted shared Patterns.)





3. 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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Bill Kline is Professor of Engineering Management and Associate Dean of Innovation at Rose-Hulman. His teaching and professional interests include systems engineering, quality, manufacturing systems, innovation, and entrepreneurship. As Associate Dean, he directs the Branam Innovation Center which houses campus competition teams, maker club, and projects.

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.

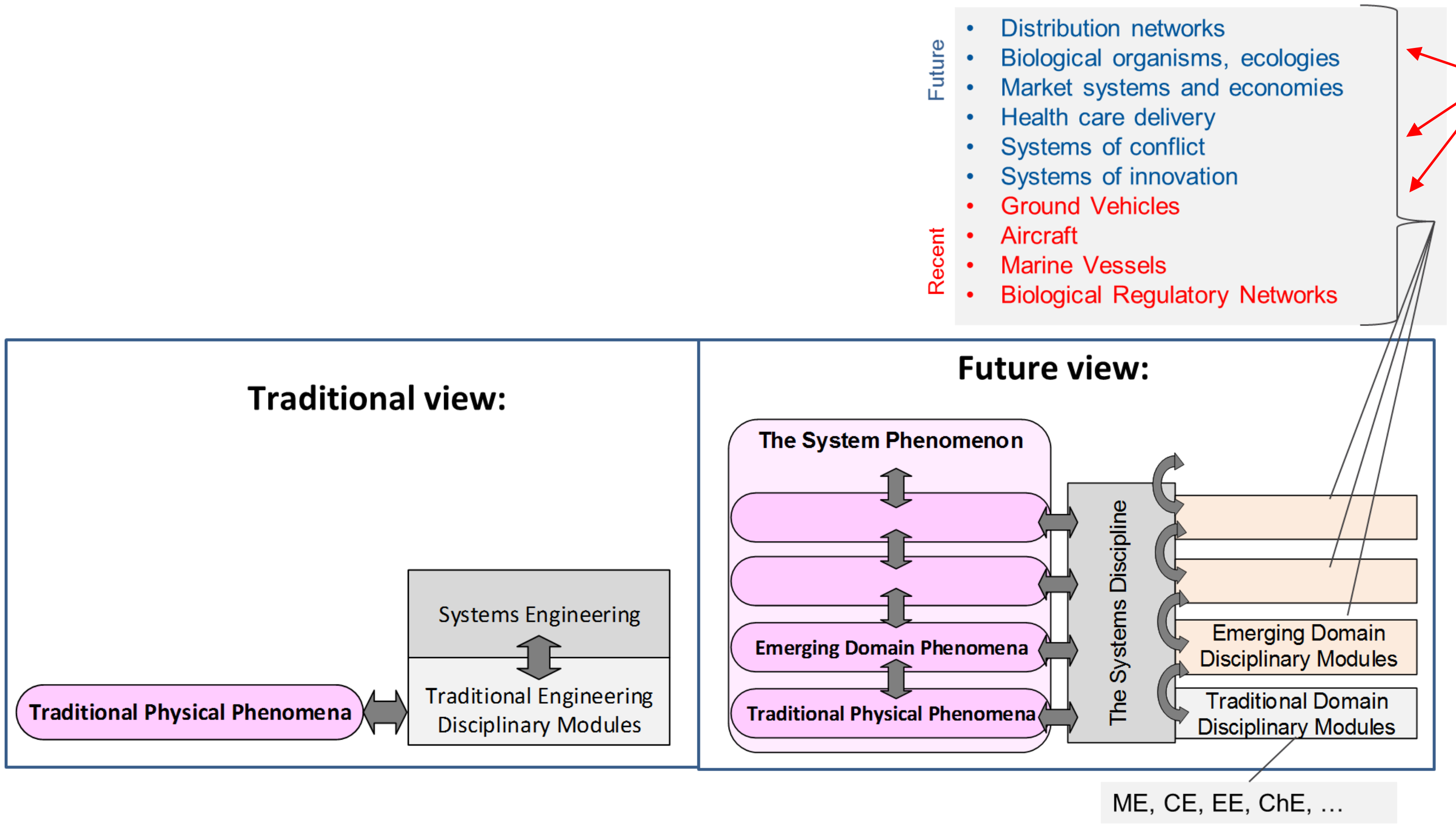
Bill is a Phi Beta Kappa graduate of Illinois College and a Bronze Tablet graduate of University of Illinois at Urbana Champaign where he received a Ph.D. degree in Mechanical Engineering.

Mr. William D. Schindel, ICTT System Sciences

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

4. Systems research frontiers, needs, and opportunities

Abstract Theories of Systems: A great deal of math/science already exists here (even if overlooked) from 300 years of progress. Better we should be learning it and using it than searching for a replacement. Better to invest more systems research in the emerging domains' system phenomena.



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 system domain patterns and their related mathematics, and apply them for the good of each domain.

Q&A, Discussion

Reference Starting Points—Including Bibliographies

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The Value Phenomenon

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The INCOSE Patterns Working Group

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The INCOSE ASELCM (System of Innovation) S*Pattern

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