Bill Schindel, ICTT System Sciences, schindel@ictt.com

V1.6.8

Implications for Future SE Practice as a Discipline:

Initial Elements of a Science of Systems

(workshop version, 2-3 hrs)

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

Page 40

Systems Engineering Foundations

Shoring Up the Theoretical Foundation

FROM

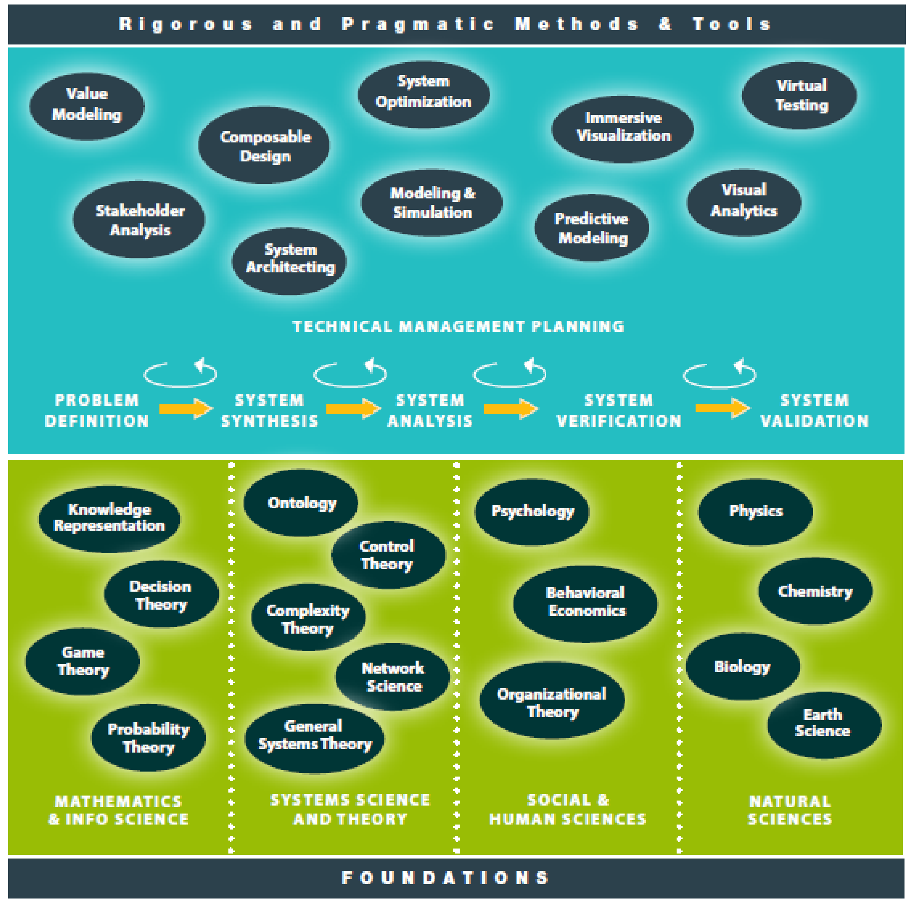
Systems engineering practice is only weakly connected to the underlying theoretical foundation, and educational programs focus on practice with little emphasis on underlying theory.

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.

What foundational elements?
(our subject)

SHORING UP THE
THEORETICAL
FOUNDATION
OF SYSTEMS
ENGINEERING



Systems Theories Across Disciplines

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.

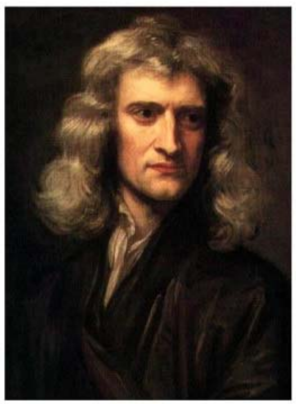
Contents

- Background for a “phase change” in SE
- SE history versus other engineering disciplines
- Recognizing interconnected science & math-based foundation elements for SE
- 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

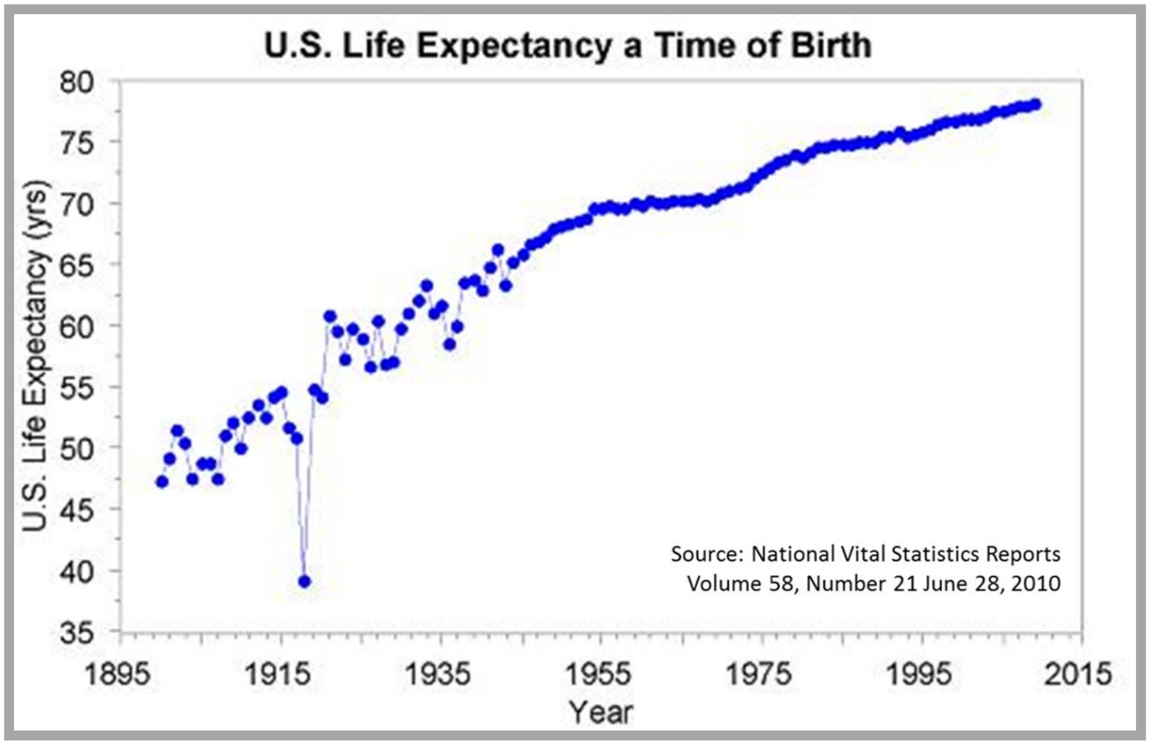
Phase Change #1 Evidence: Efficacy of Phenomena-Based STEM Disciplines

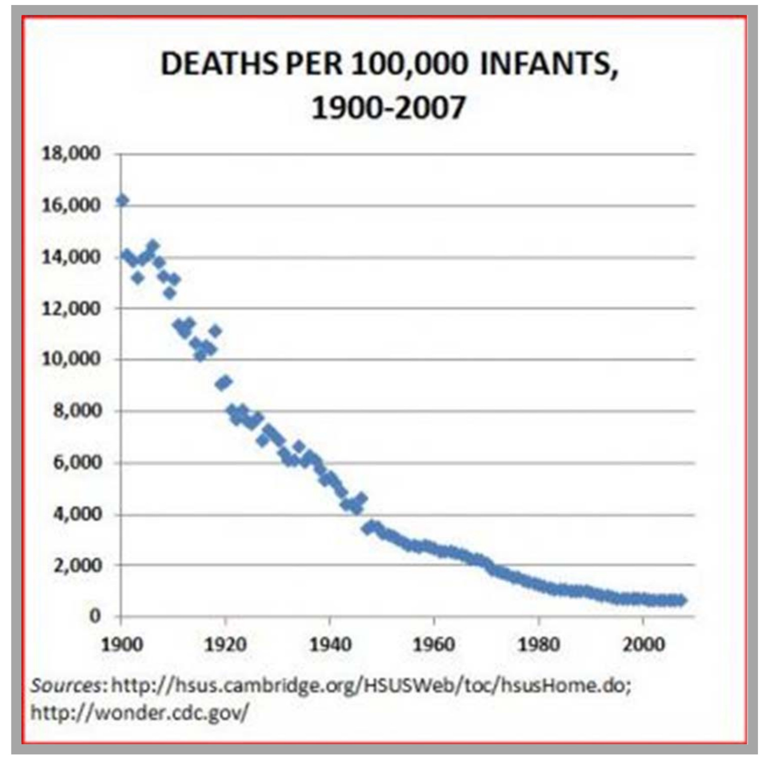



In a matter of a 300 years . . .

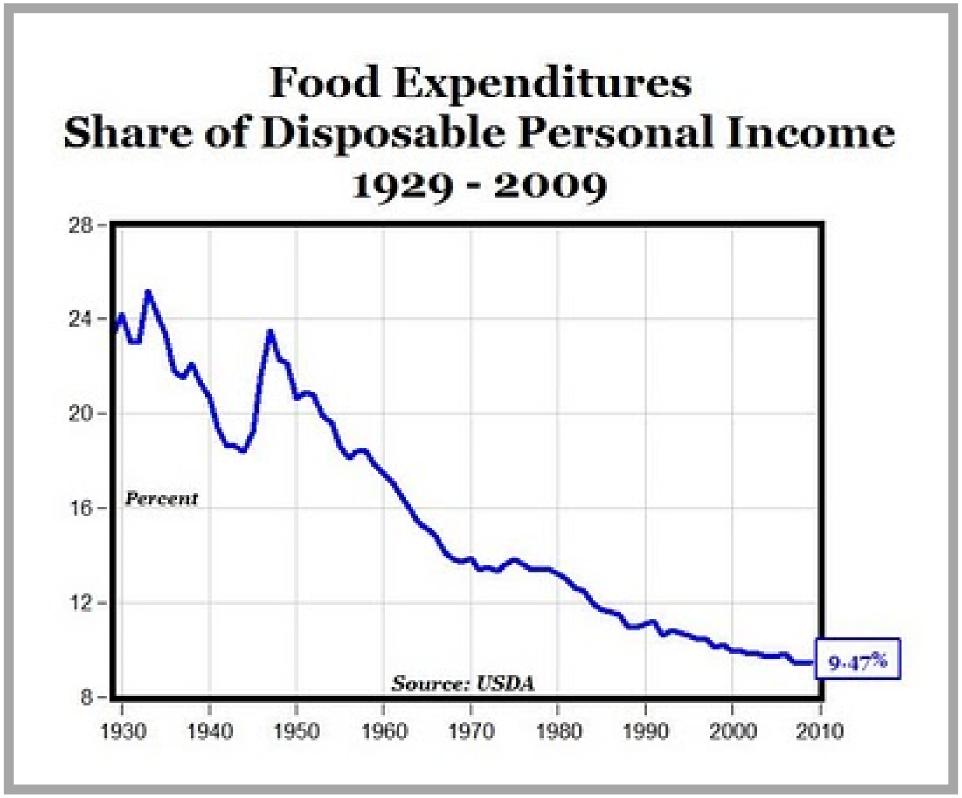
- the accelerating emergence of Science, Technology, Engineering, and Mathematics (STEM) . . .
- has lifted the possibility, nature, quality, and length of life for a large portion of humanity . . .
- while dramatically increasing human future potential.
- By 20th Century close, strong STEM capability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

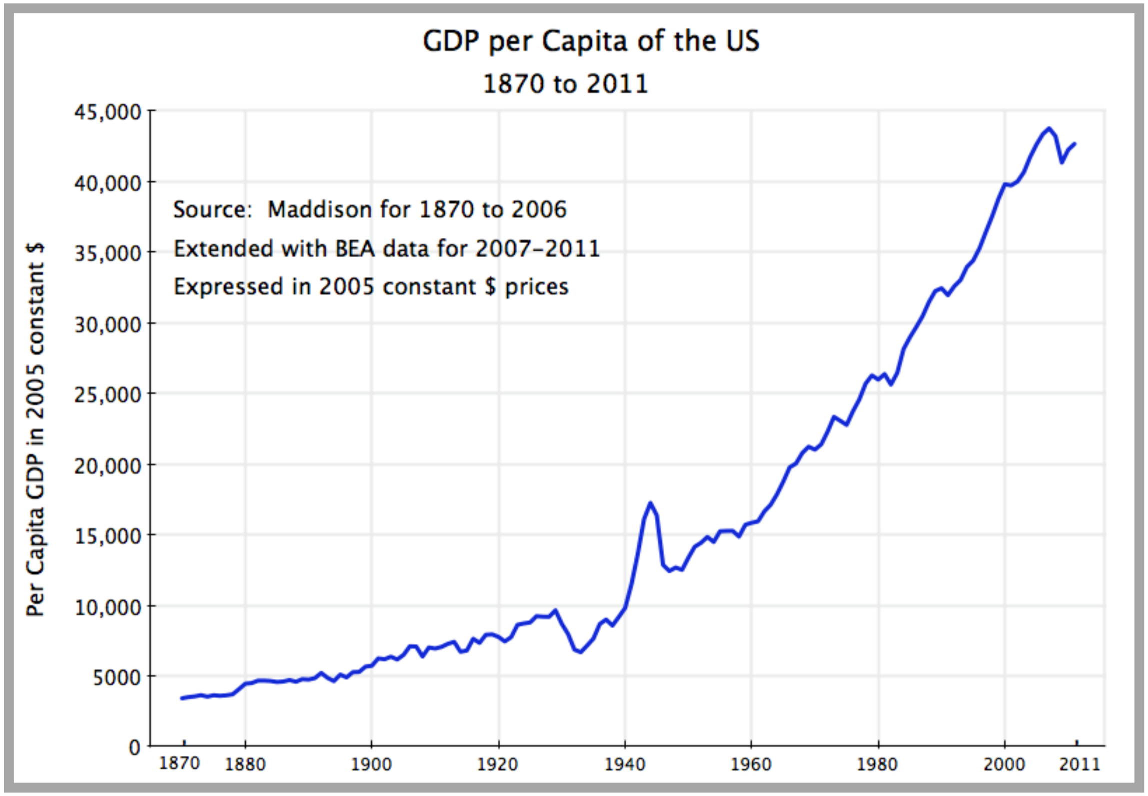
The length of human life has been dramatically extended:



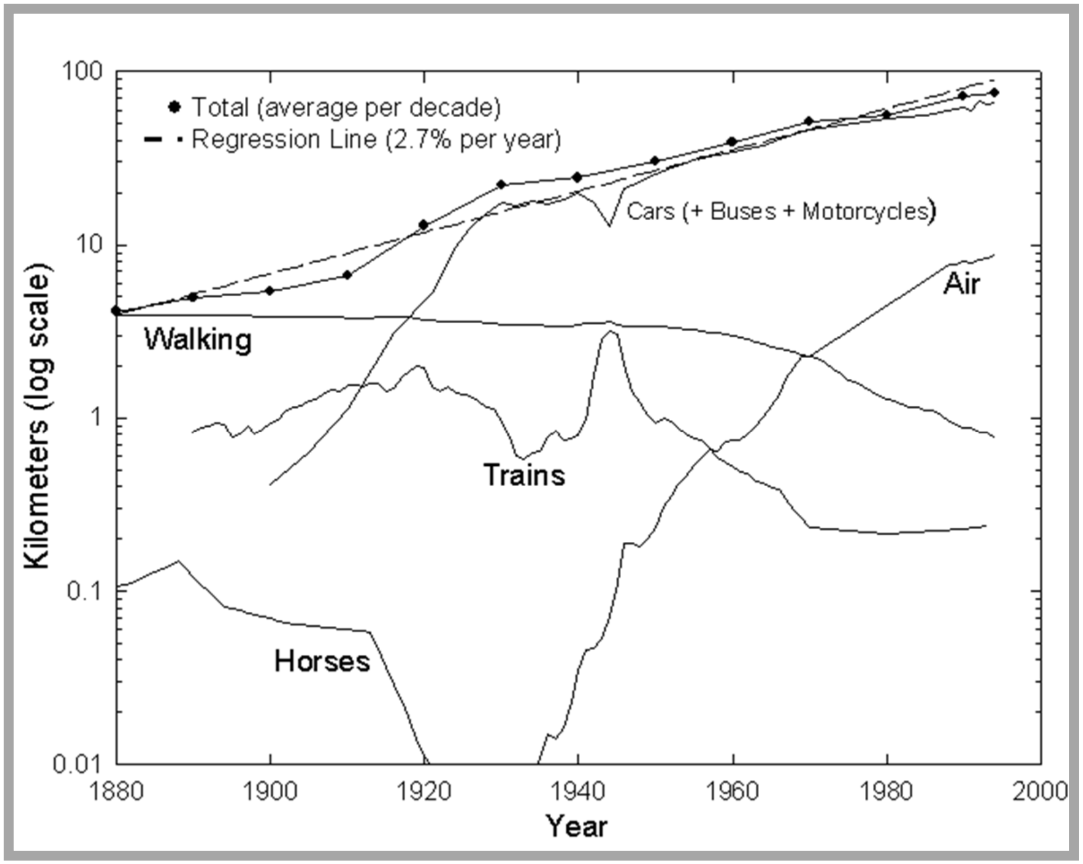


Simply feeding ourselves consumes less labor and time:





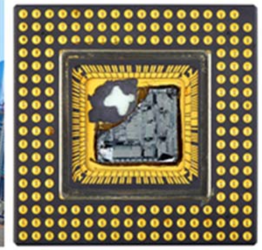
The range of individual human travel has vastly extended:



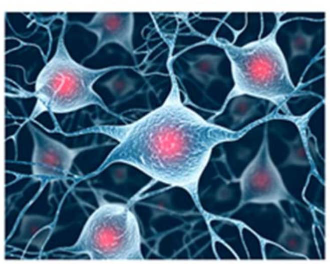
US passenger travel per capita per day by all modes.
Sources of data: Grubler , US Bureau of the Census , US Department of Transportation

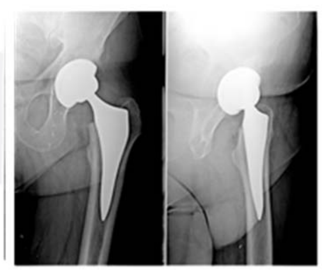
Challenges Have Likewise Emerged



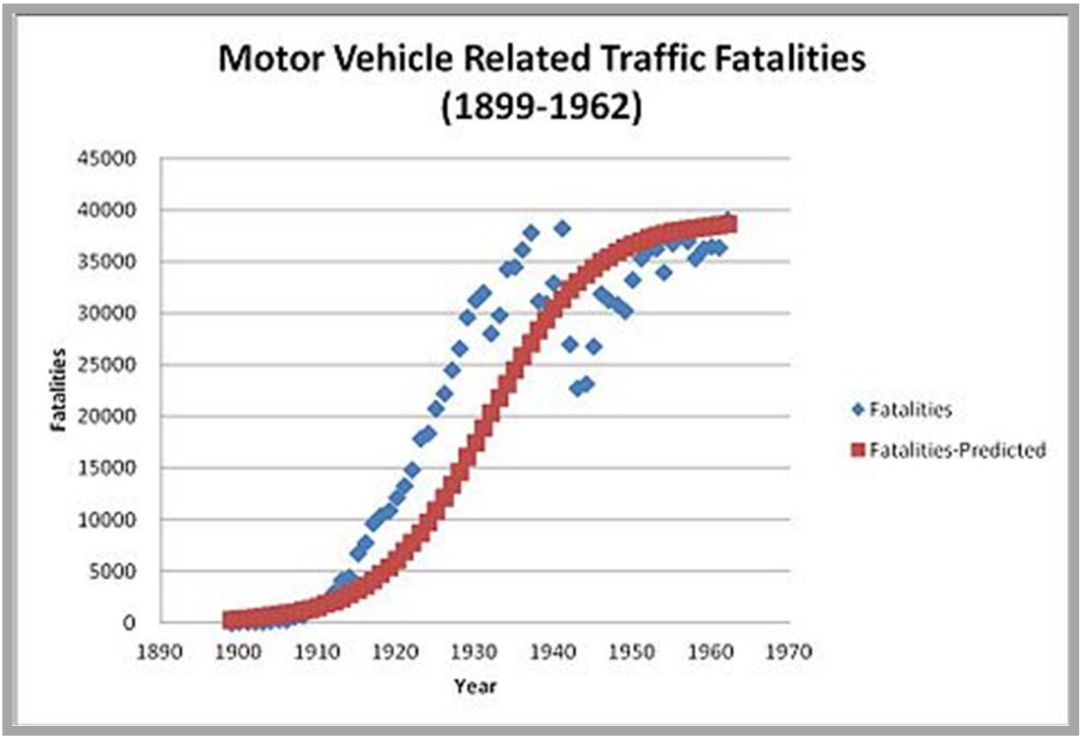


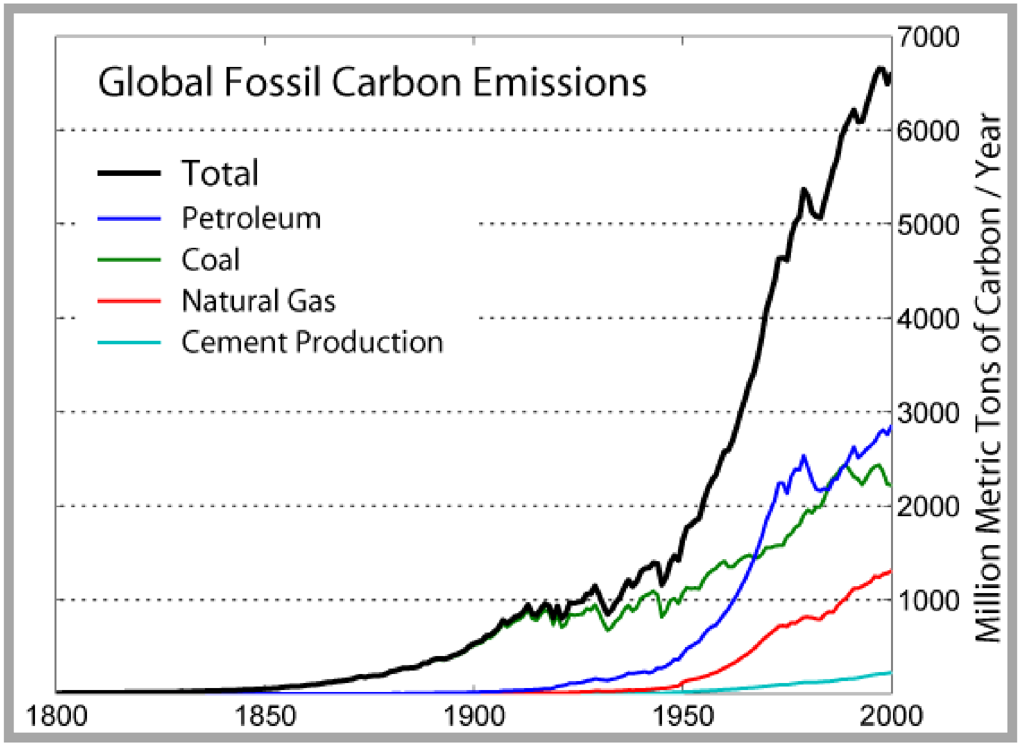

- In recent decades, the human-populated world has become vastly more interconnected, complex, and challenging . . .
- Offering both expanding opportunities and threats.
- From the smallest known constituents of matter and life, to the largest-scale complexities of networks, economies, the natural environment,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





Systems progress has come with challenging side effects:





NHTSA and FHWA data

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

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	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 that amazing progress, as well as challenges.

- How should Systems Engineering be compared to engineering disciplines based on the “hard sciences”, including their impact/effectiveness over three centuries?

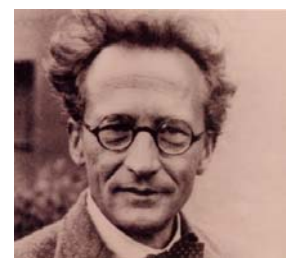
Phenomena-Base Engineering Disciplines

- 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.

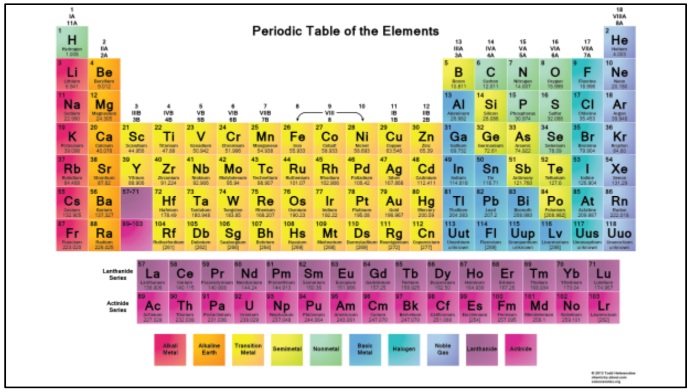






Traditional Perspective on SE—as we know it today

- 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.



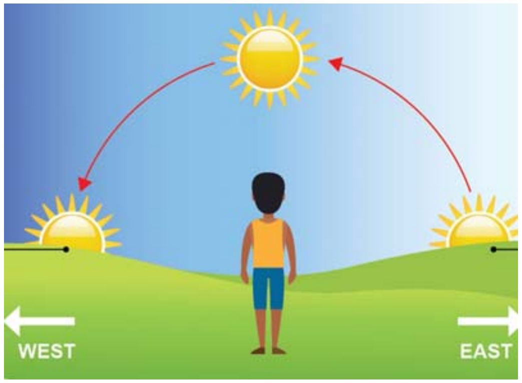
$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

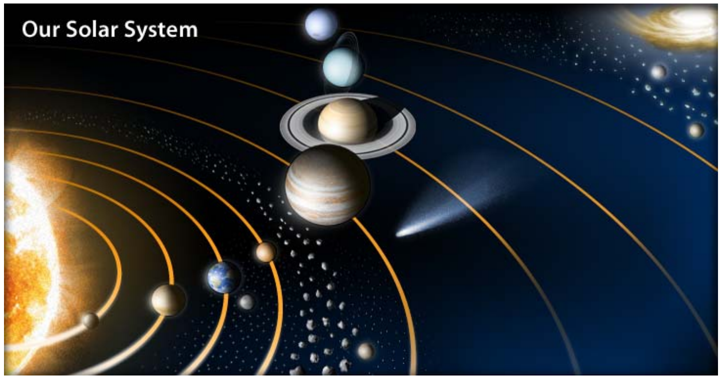
$$\frac{N_b}{N_a} = \left(\frac{g_b}{g_a}\right)\left(e^{-(E_b - E_a)/kT}\right)$$

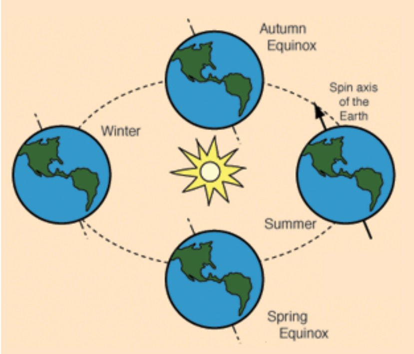
$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

- 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

We expect Sciences to represent, predict and explain

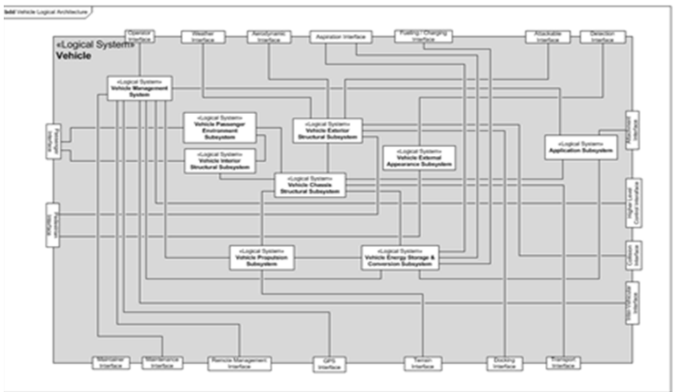






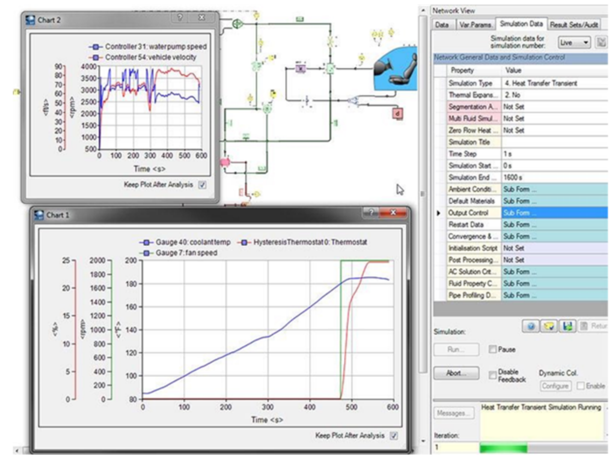
- Predict: For millennia, the evolving passage of sunrise, sunset, Lunar phases, and passage of the seasons has been reliably predicted based on learned, validated patterns, helping feed exploding human population.
- Explain: By the time of Copernicus and Newton, science had provided improved explanations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

Vehicle Logical Architecture



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

Vehicle Thermal Dynamics

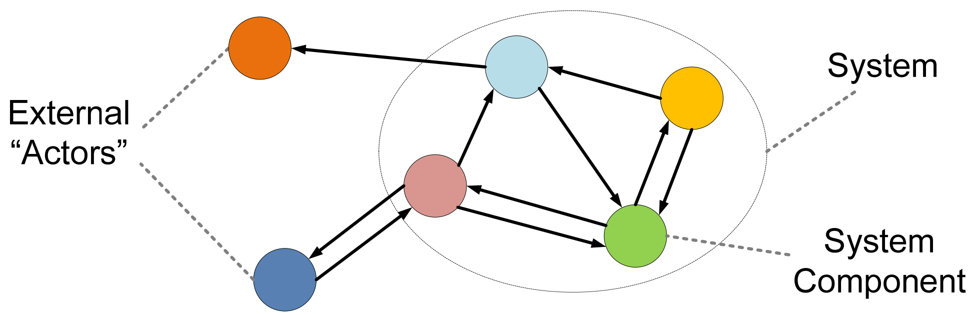


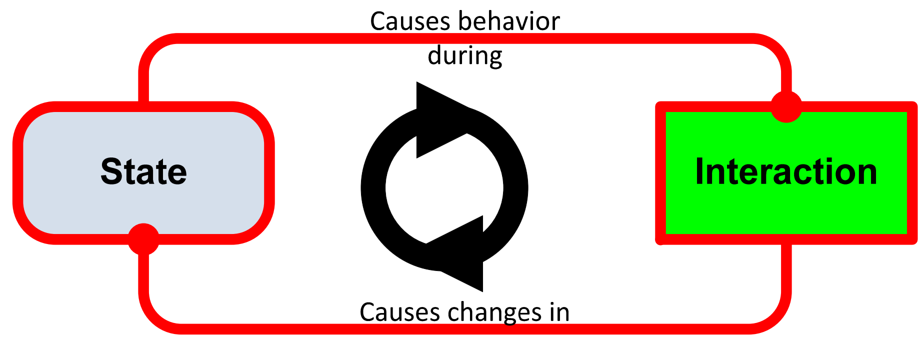
While models are not new to STEM . . .

- <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 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 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 (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.

Formalizing System Representations

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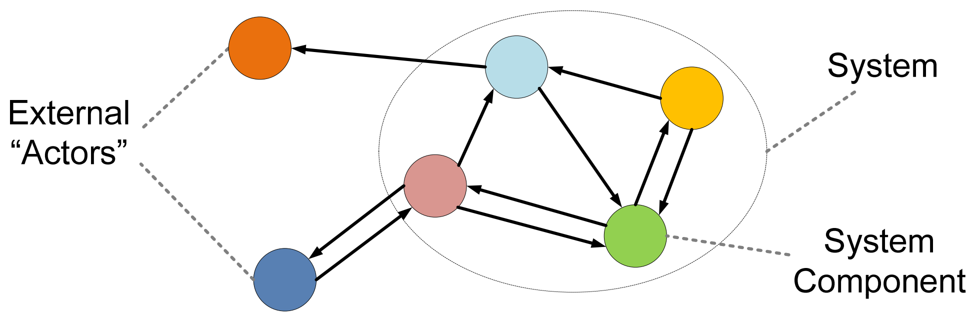

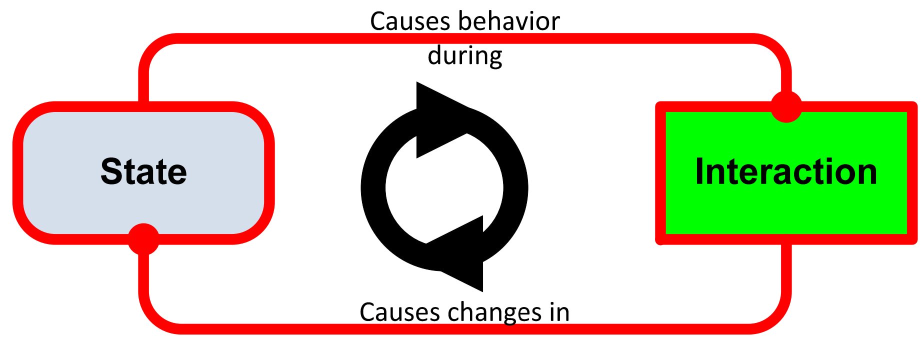

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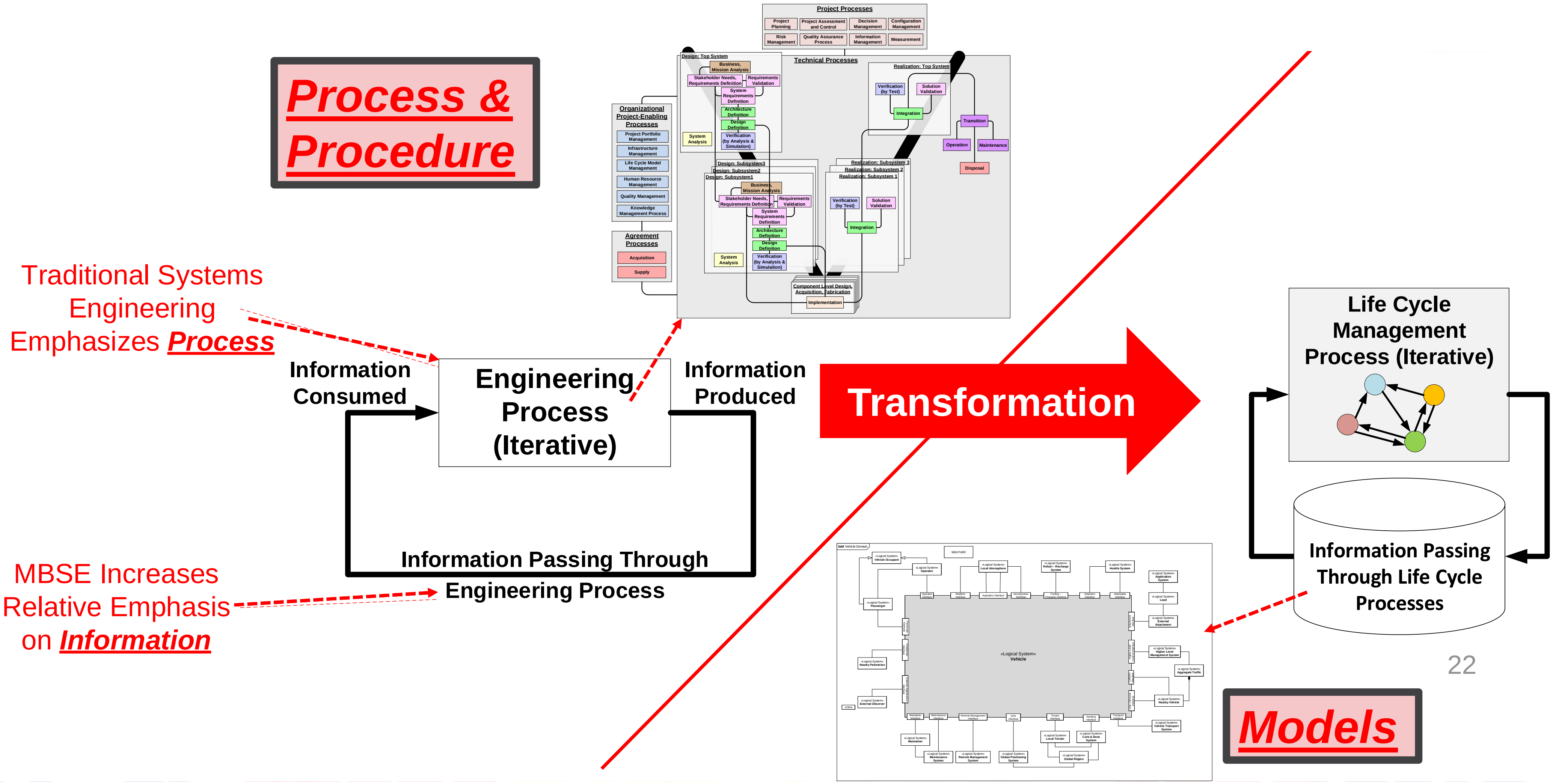
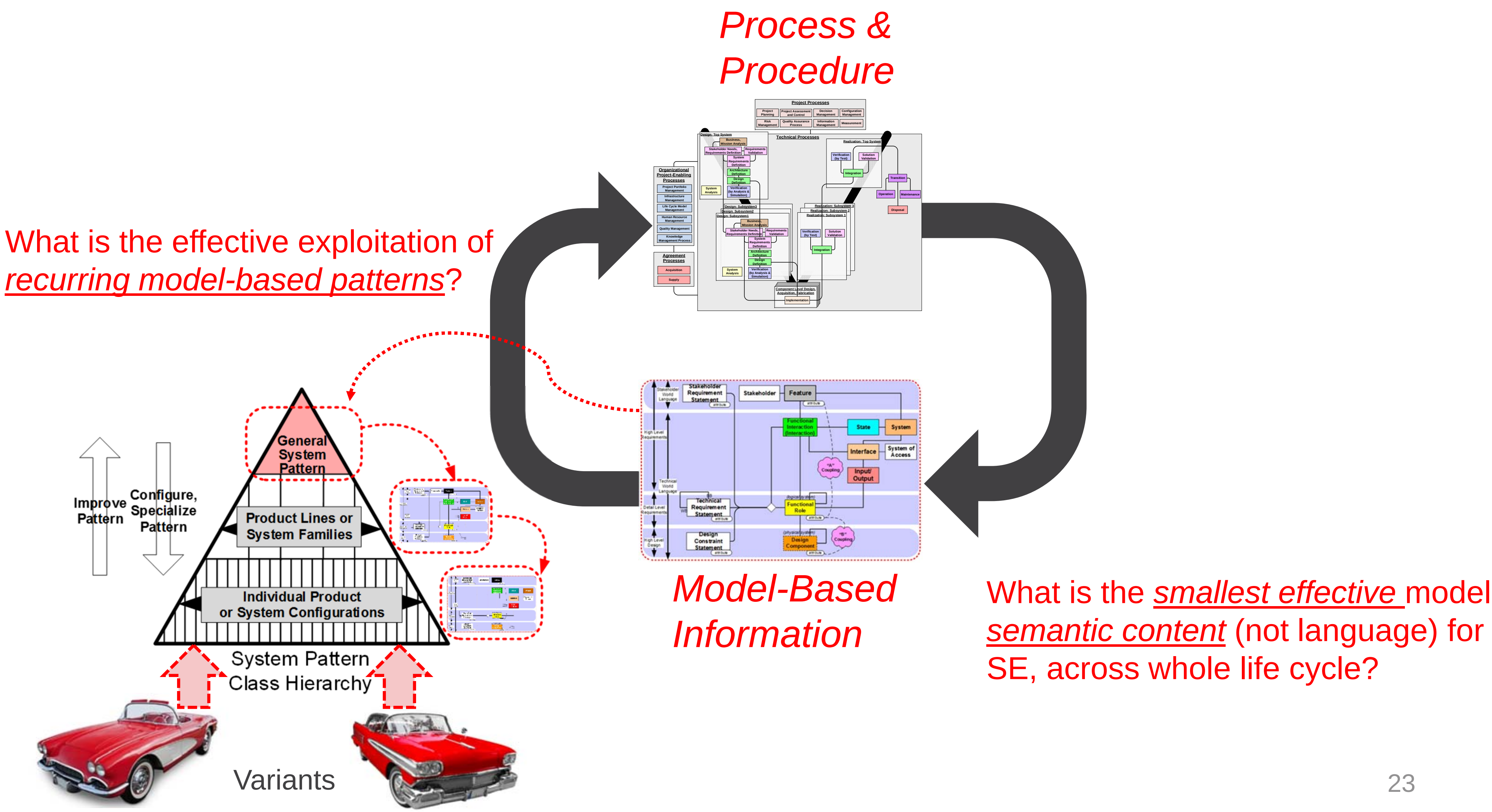
- By "state" we mean a property of a component that impacts its input-output behavior during interactions.
- So, a component's "behavior m… ring interaction—*there is no "naked* …
- The behavior of a system as a w… hole.

Notice that these definitions, and all the material we discuss later, explicitly includes Information based phenomena (e.g., Cyber world).

MBSE, PBSE: A Phase Change in SE Emphasis

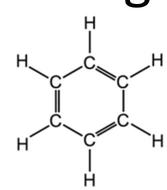


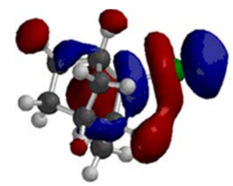

Process &
Procedure
What is the effective exploitation of
recurring model-based patterns?
General
System
Pattern
Product Lines or
System Families
Individual Product
or System Configurations
Improve
Pattern
Configure,
Specialize
Pattern
System Pattern
Class Hierarchy
Variants
Model-Based
Information
What is the smallest effective model
semantic content (not language) for
SE, across whole life cycle?

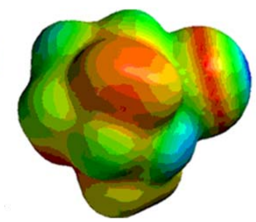
Patterns: At the heart of scientific laws

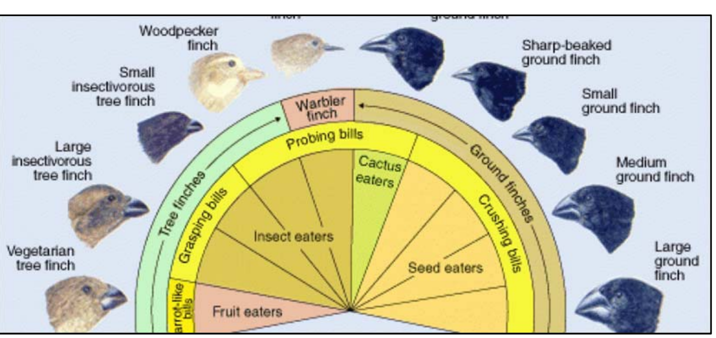
July 18 - 21, 2016

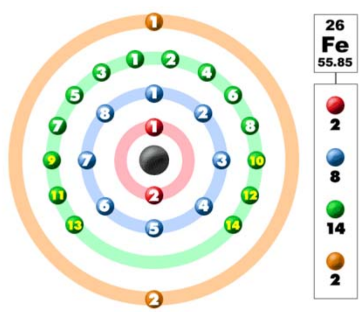
- All “patterns” are recurrences, having both fixed and variable aspects.
- The heart of physical science’s life-changing 300 year success in prediction and explanation lies in recognition, representation, exploitation of recurring patterns.
- Noether’s Theorem & Hamilton’s Principle: Substantial math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

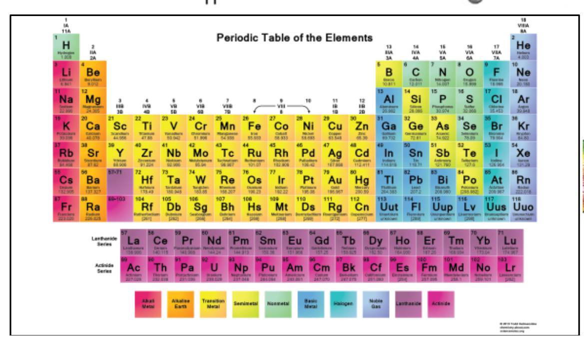


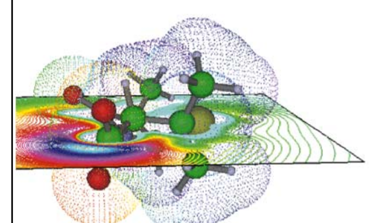












Initial elements of a science of systems

INCOSE

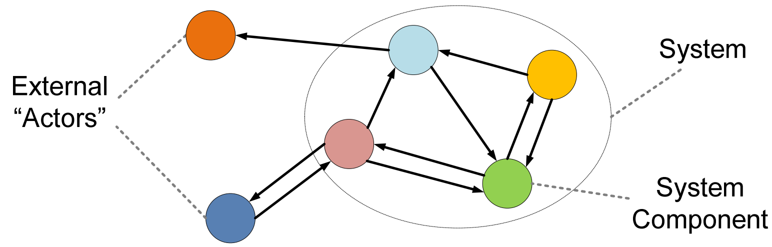
- **The System Phenomenon**: Each of the traditional physical sciences is based on specific physical phenomena (mechanical phenomena, electrical phenomena, chemical phenomena, etc.) and related mathematical representation of the recurring patterns of physical laws and first principles. What is the equivalent "hard science" phenomenon for systems, where is its mathematics, and what are the impacts on future SE practice? In the tradition of the earlier sciences, how are these models validated? How is their uncertainty quantified?

- **The Value 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 are the phenomena, what is the bridge effectively connecting these domains, where is the related mathematics and recurring patterns, and what are the impacts on future SE practice? How are these models validated? How is their uncertainty quantified?

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 phenomena[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])

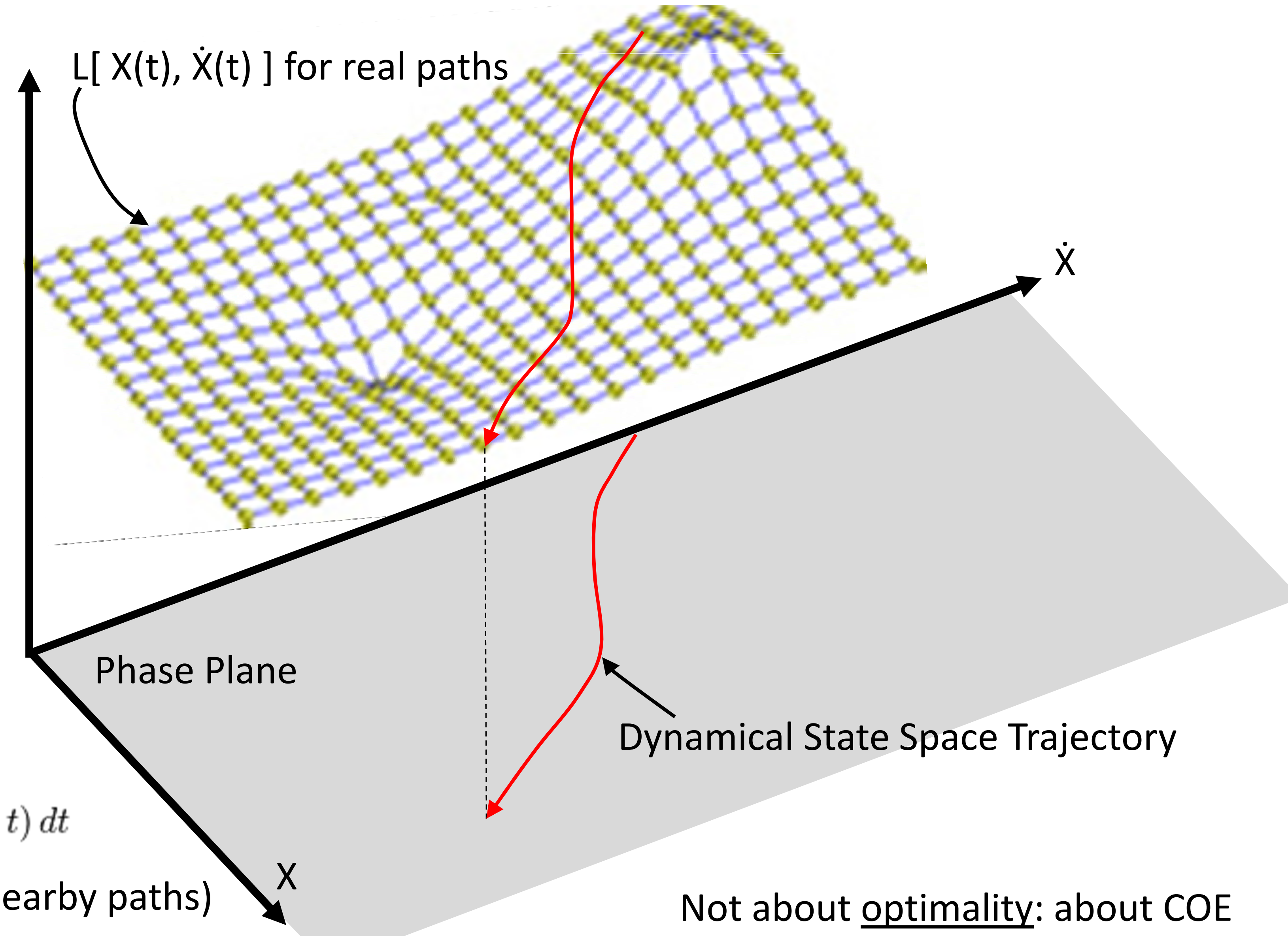
- Reduced to simplest forms, the resulting equations of motion (or if not solvable, simulated/observed paths) provide “physical laws” subject to scientific verification—an amazing foundation across all phenomena.

(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.

William Rowan Hamilton
Ireland, 1805-1865

Hamilton's Principle: Root of Equations of Motion for All[1] Interactive Phenomena (Dynamics)

- Hamilton's Principle: Stated in language of mathematics (calculus of variations, not just heuristics or prose-based 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 Equation, etc.)
  - Patterns arise from the interactions, as well as holistic properties



Action:

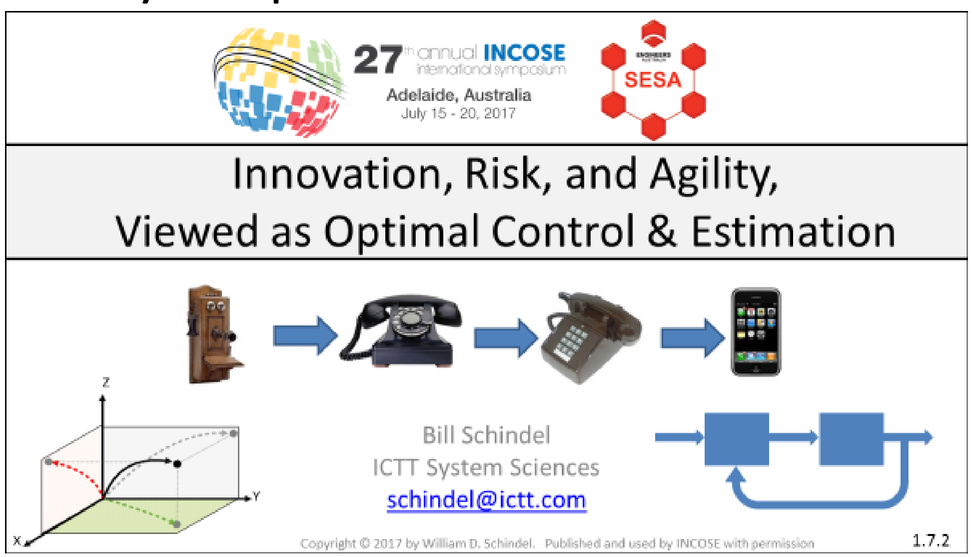
$$\mathcal{S} = \int_{t_1}^{t_2} L(x, \dot{x}, t)\, dt$$

(Stationary wrt nearby paths)

Not about optimality: about COE

Hamilton's Principle

- Applies to random processes as well as deterministic models:
  - For starters: the gas laws. -- And: Learning systems, spin glasses, etc.
- In fact, some of the most interested applications are stochastic:
  - In particular, System 2: the systems of engineering and life cycle management
  - Applying powerful theory of optimal estimation and control in noisy environments



Selection processes, fitness space energy, etc.

Emmy Noether
Germany and USA
1882-1935

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

- The heroic story of Emmy Noether.
- 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.
  - Symmetry and conserved quantities have become central to discovery in the last 100 years of modern physics

Mathematics for the System Phenomenon: Support Beyond Hamilton's Principle

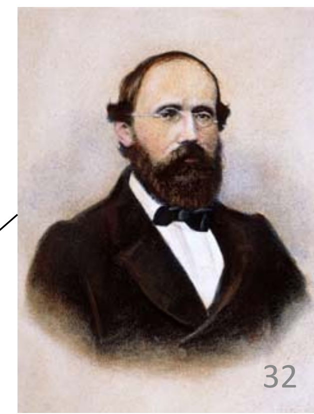
- The System Phenomenon is a more general pattern than the mathematics of Hamilton's Principle :
  - Reviewing the conceptual framework of the System Phenomenon should convince you that it is much more general in scope than the setting for the original formulation of Hamilton's Principle (continuous, 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 mathematical constructions and their discoverers . . .

The System Phenomenon, Beyond Hamilton's Principle

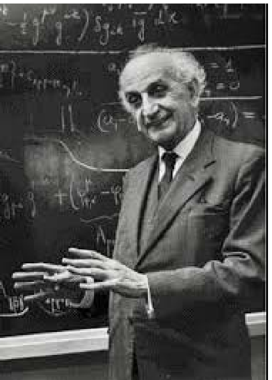
- **<u>Hamilton's Principle</u>**: Was already strong enough to generate all the fundamental phenomena of physics, from Newton through Feynman

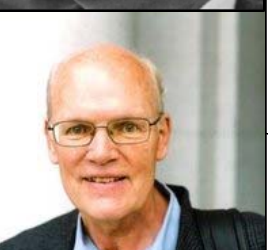
- **<u>Noether's Theorem</u>**: Deeper insight into the connection of Hamilton's principle to Symmetry and Conservation Laws

- **<u>D'Lambert's Principle</u>**: Older than Hamilton, but wider in scope than Hamilton's Principle, adding non-holonomic constraints, dissipative systems



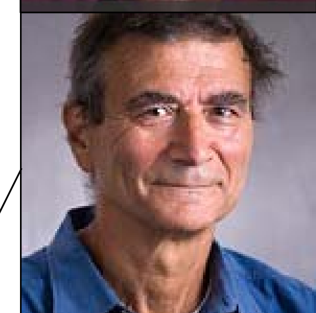
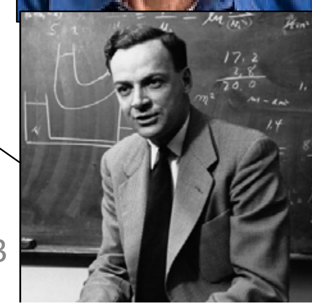
- **<u>Bernhard Riemann</u>**: Embedded Manifold spaces further generalize representation of complex dynamics.



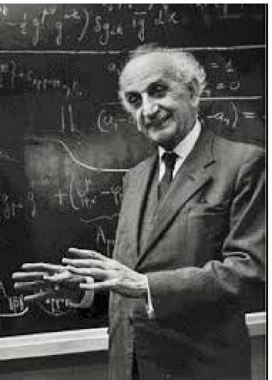


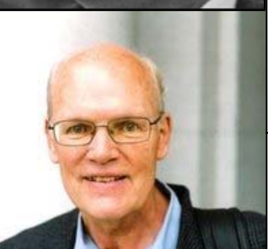

The System Phenomenon, Beyond Hamilton's Principle



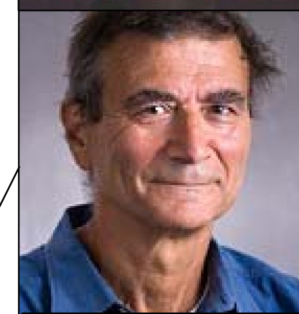
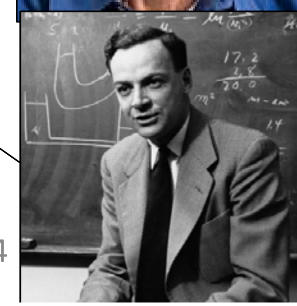
- **Cornelius Lanczos**: Master elucidator of Analytical Mechanics
- **Prigogine, Sieniutycz, Farkas**: Irreversible and large scale thermodynamic systems
- **JE Marsden**, **A Bloch, Marston Morse**: Non-Holonomic Control Systems, Discrete Mechanics; Symbolic Dynamics, Discrete Hamilton's Principle;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






The System Phenomenon, Beyond Hamilton's Principle



- **Cornelius Lanczos**: Master elucidator of Analytical Mecha[nics]
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- **Ed Fredkin**, **Charles Benn[ett]**, **Tomas Toffoli**, **Richard Feynman**: Information Systems and Automata

Notice that these extensions, like all the material we discuss, explicitly includes Information based phenomena (e.g., Cyber world).

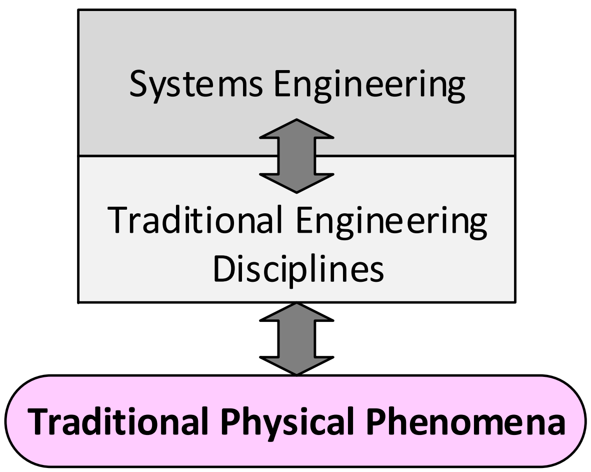
The System Phenomenon

- Each of the so-called “fundamental” phenomena law mathematical expression (Newton, Maxwell, Schrodinger, et al) is derivable from the above.
- 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 Mach 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!

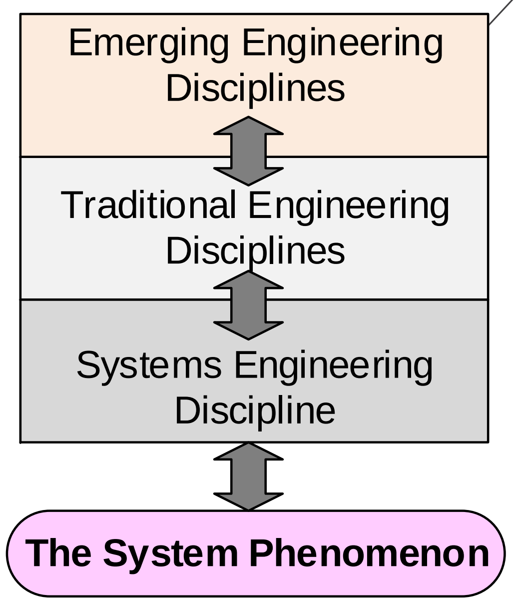
Implications: SE Positioning in the Disciplines

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

Traditional view:



Future view:



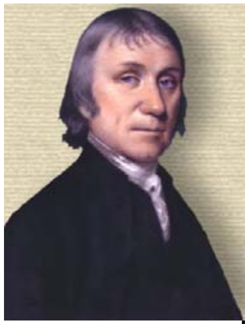
Future

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

Recent

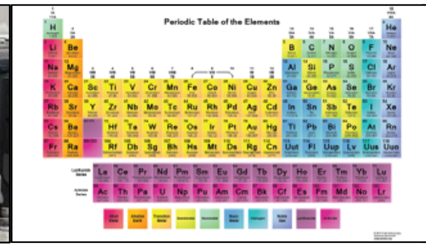
- Ground Vehicles
- Aircraft
- Marine Vessels
- Biological Regulatory Networks

Historical Example 1: Chemistry

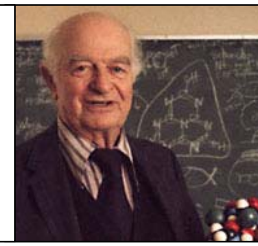


Priestley : Oxygen

Modern Chemist



Periodic Table of the Elements

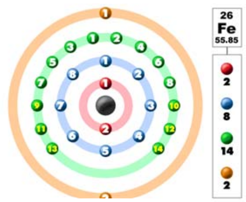


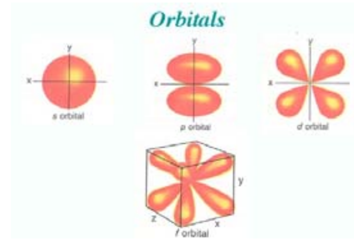
Pauling: Chemical Bond

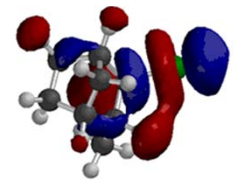
Mendeleev: Periodic Table

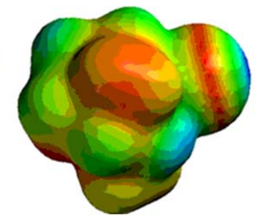
- Chemists, and Chemical Engineers, justifiably consider their disciplines to be based on the “hard phenomena” of Chemistry:
  - A view that emerged from the scientific discovery and verification of laws of Chemistry.
  - Chemical Elements and their Chemical Properties, organized by the discovered patterns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

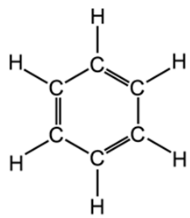
Chemistry, continued

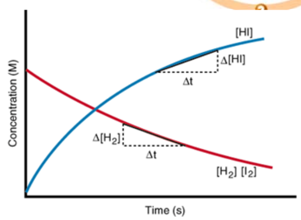


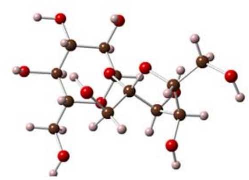


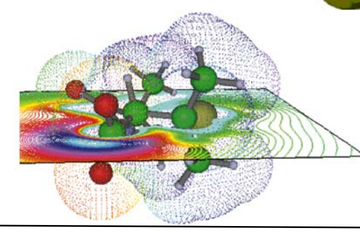








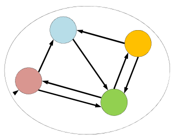




However . . .

- 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 . . .

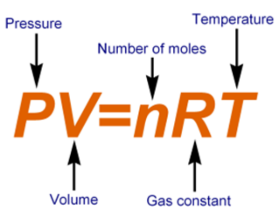
- Chemistry and Chemical Engineering study and apply those <u>system pa</u>tterns.

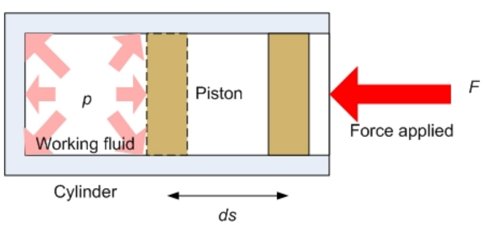
Historical Example 2: The Gas Laws and Fluid Flow

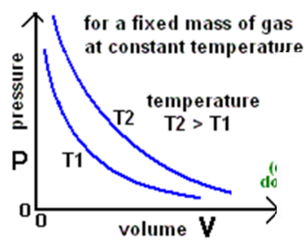
Boyle

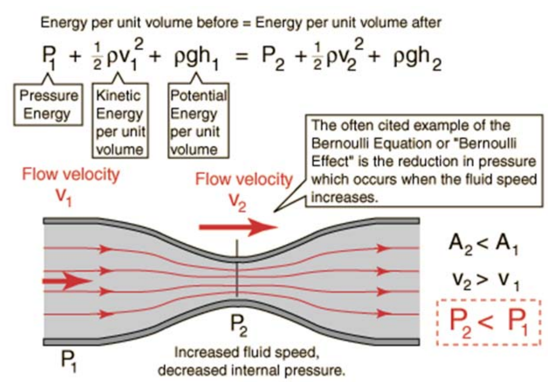
Daniel Bernoulli

- 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.

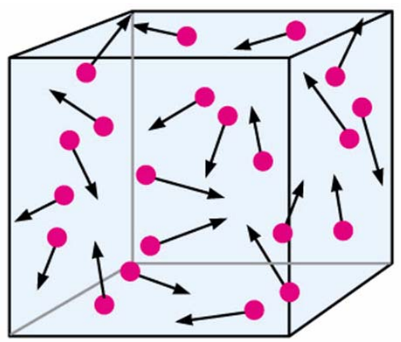


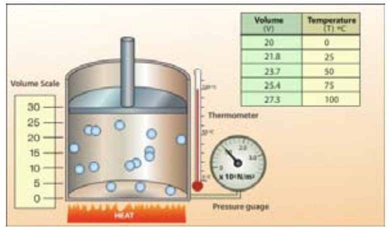


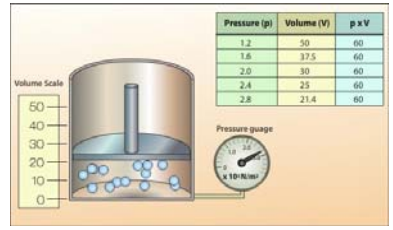




Gas Laws, continued







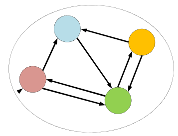
$$\frac{N_b}{N_a} = (\frac{g_b}{g_a})(e^{-(E_b - E_a)/kT})$$

Boltzmann

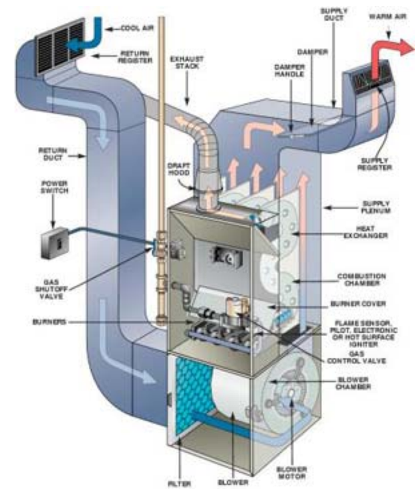
However . . .

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

Gas Laws, continued



So . . .



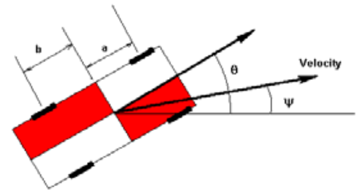
- The “fundamental phenomena” of gases, along with the scientifically-discovered / verified “fundamental laws and first principles” are in fact . . .
- higher level emergent <u>system patterns</u>

  so that . . .

- Mechanical Engineers, Thermodynamicists, and Aerospace Engineers can study and apply those <u>system patterns</u>.

More Recent Historical Examples

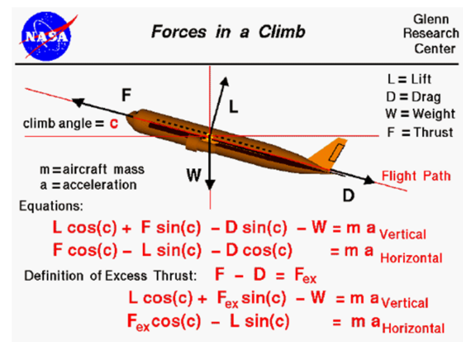
- Ground Vehicles
- Aircraft
- Marine Vessels
- Biological Regulatory Networks

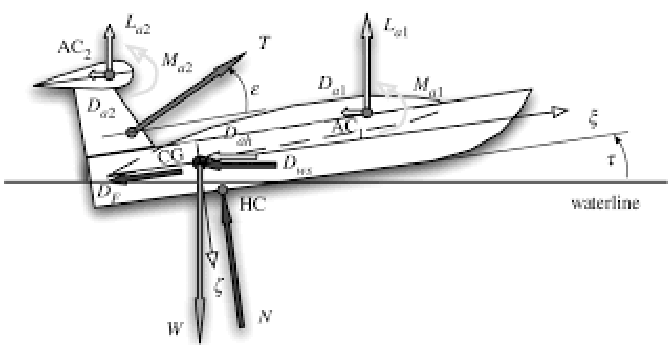


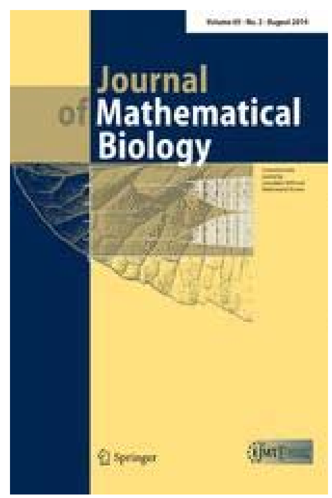
Dynamics of Road Vehicle

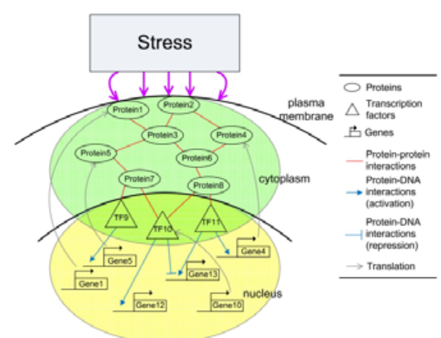
Denoting the angular velocity ω, the equations of motion are:

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



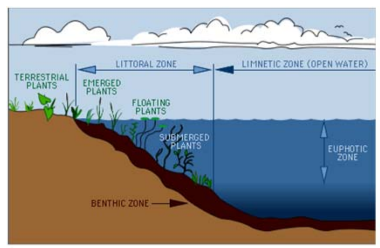


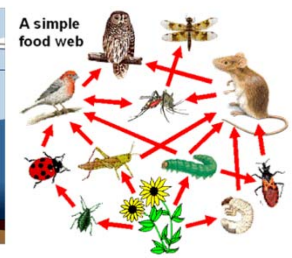


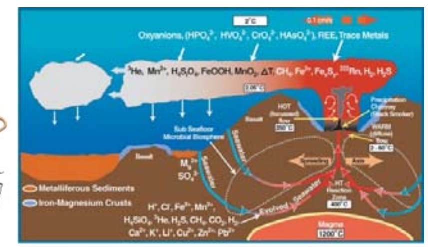


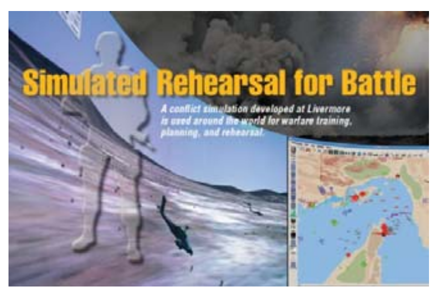
Future Examples

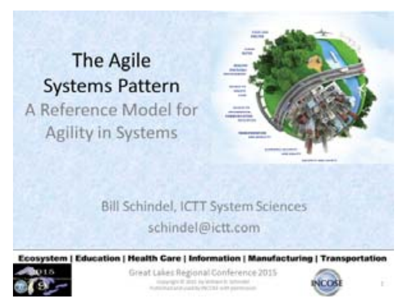
- Utility and other distribution networks
- Biological organisms and ecologies
- Market systems and economies
- Health care delivery, other societal services
- Systems of conflict
- Agile innovation



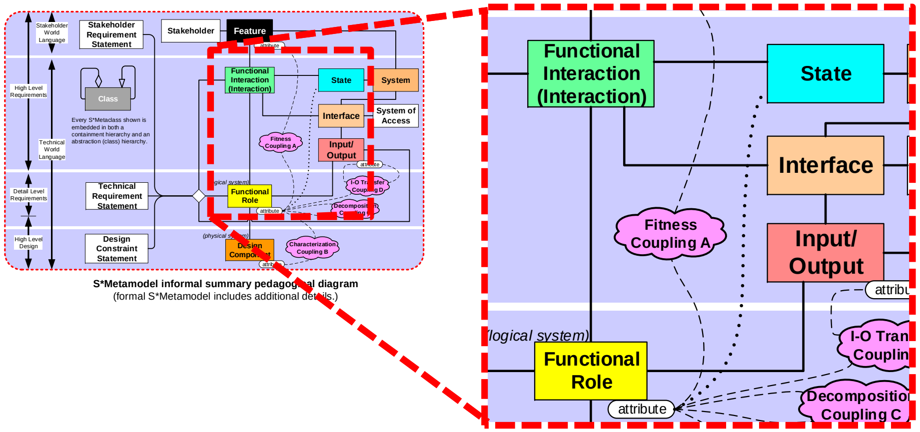








System Phenomenon: Implications for SE practice



- 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

Initial elements of a science of systems

- **The System Phenomenon**: Each of the traditional physical sciences is based on specific physical phenomena (mechanical phenomena, electrical phenomena, chemical phenomena, etc.) and related mathematical representation of the recurring patterns 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? In the tradition of the earlier sciences, how are these models validated? How is their uncertainty quantified?

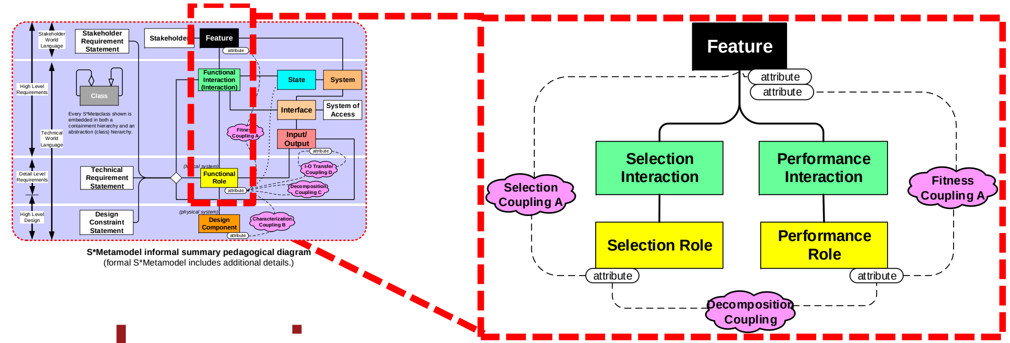
- **The Value Phenomenon**: Engineers know that value is essential to their practice, but its "soft" or subjective nature seems challenging to connect to hard science and engineering phenomena. What are the phenomena, what is the bridge effectively connecting these domains, where is the related mathematics and recurring patterns, and what are the impacts on future SE practice? How are these models validated? How is their uncertainty quantified?

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

- The expression of value in action is always via selection:

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

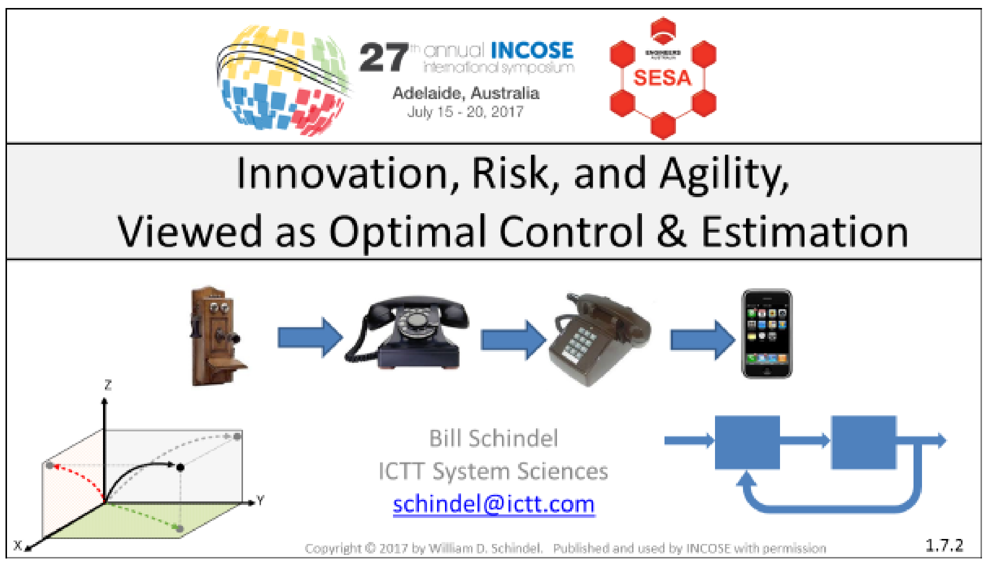
The bridge to value: Innovation Steering Mechanism



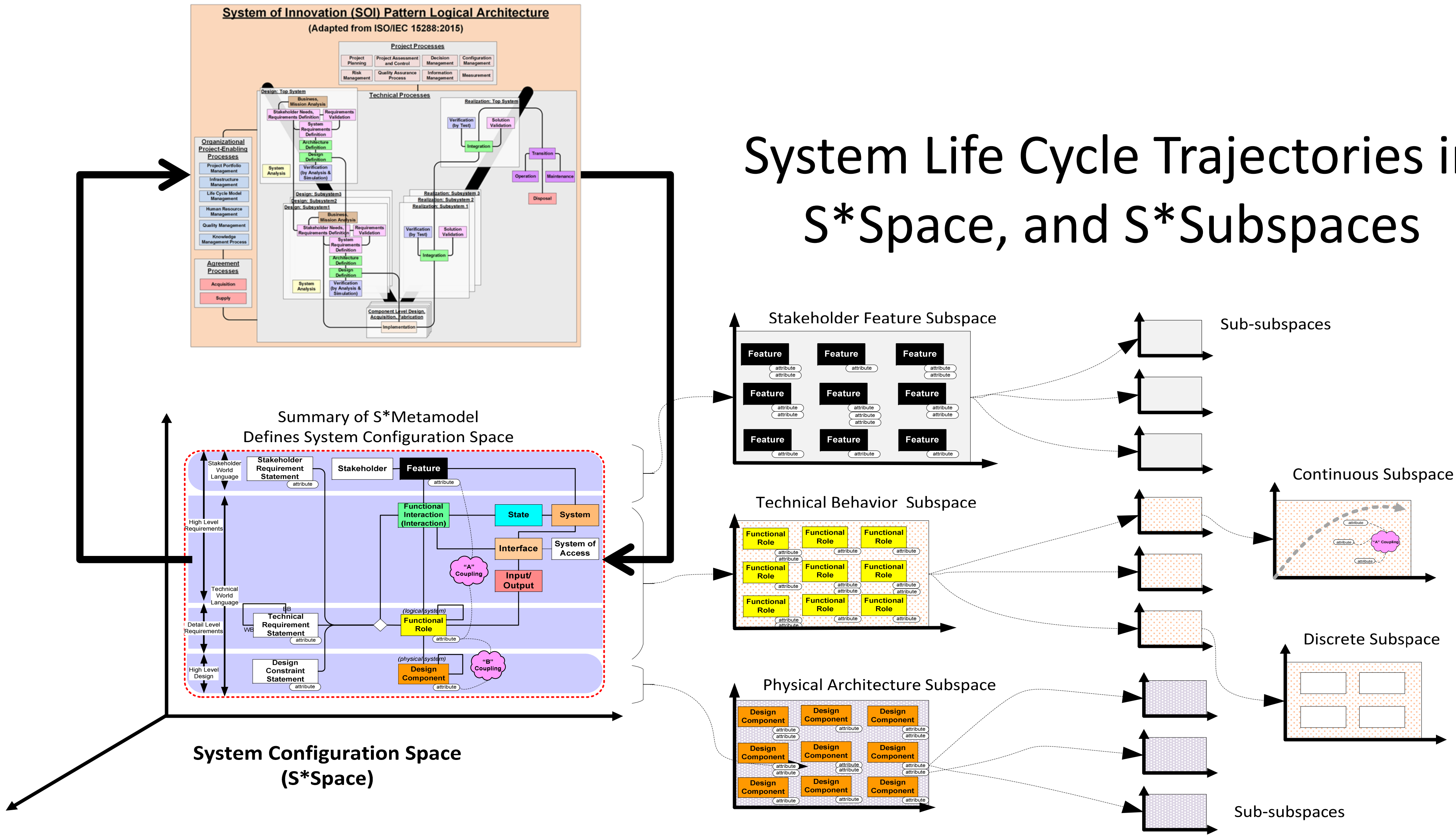
- <u>Interactions</u> connect to Value in two fundamental/different ways:
  - Performance Interactions (real or imagined, present, past, or future) <u>*embody*</u> Value from Performers;
  - Selection Interactions (human or otherwise) <u>*express*</u> the comparative Values of a Selection Agent / Agency of some form.
- Selection is itself an Interaction:
  - Studying downstream system performance effects of selection is feasible
  - Studying the upstream 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



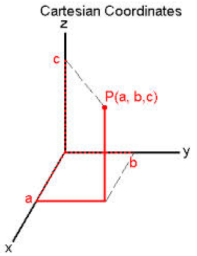
Maps *vs*. Itineraries -- SE Information *vs*. SE Process

Itinerary ≠ Map!

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

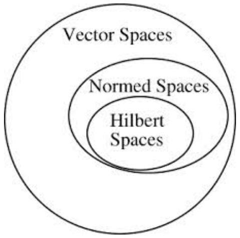
When they eventually did emerge, maps represented a newer idea of the nature of "where".

- 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.



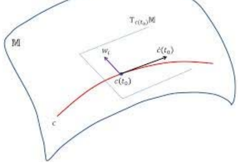
Rene Descartes
1596 - 1650

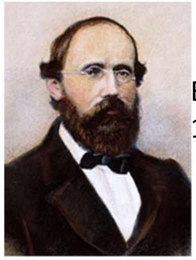
Geometrization of Algebra



David Hilbert
1862 - 1943

Geometrization of Function Space



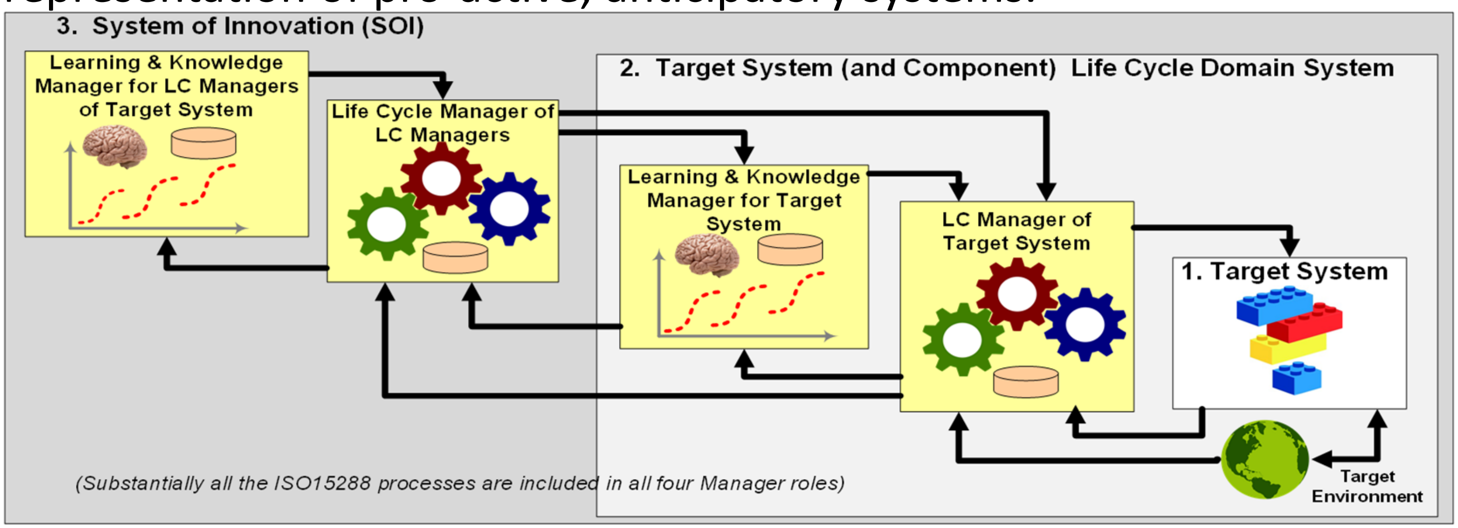


Bernhard Riemann
1826 – 1866

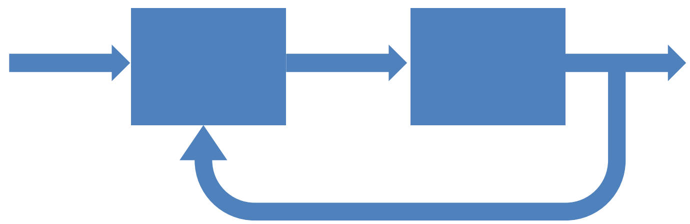
Dynamics on Embedded Manifolds

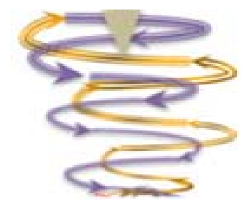
The Guidance System:
Including the System of Innovation In the Model

- A complex adaptive system reference model for system innovation, adaptation, operation/use/metabolism, sustainment, retirement.
- Whether 100% human-performed or automation-aided, various hybrids.
- Whether performed with agility or not, 15288 compliant or not, informal, scrum…
- Familiar example in agile software methods: “WSJF” criteria for picking next increments
- Whether performed well or poorly.
- Includes representation of pro-active, anticipatory systems.



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

Optimal Control and Estimation Problem Frameworks

- Optimal control problem, in continuous deterministic form:

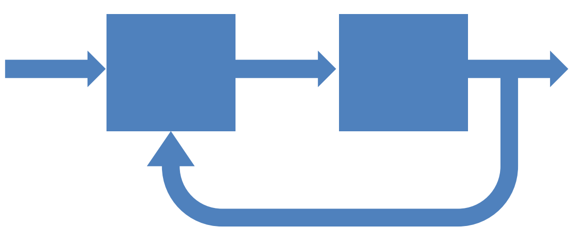
System defined by:

$$\dot{X} = f(X, U)\,, \quad X \in Rn$$

system state X(t) and control U(t);

Find an optimal control U(t) that minimizes:

$$\int_0^T g\big(X(t), U(t)\big)dt$$



Optimal Control and Estimation Problem Frameworks

- Optimal estimation/filtering problem, in discrete time form:

System state X_n, driven by random process W_n :

$$X_{n+1} = \Phi_n X_n + \Gamma_n W_n$$

and monitored through observable Z_n, with that observation corrupted by random process V_n:

$$Zn = H_n X_n + V_n$$

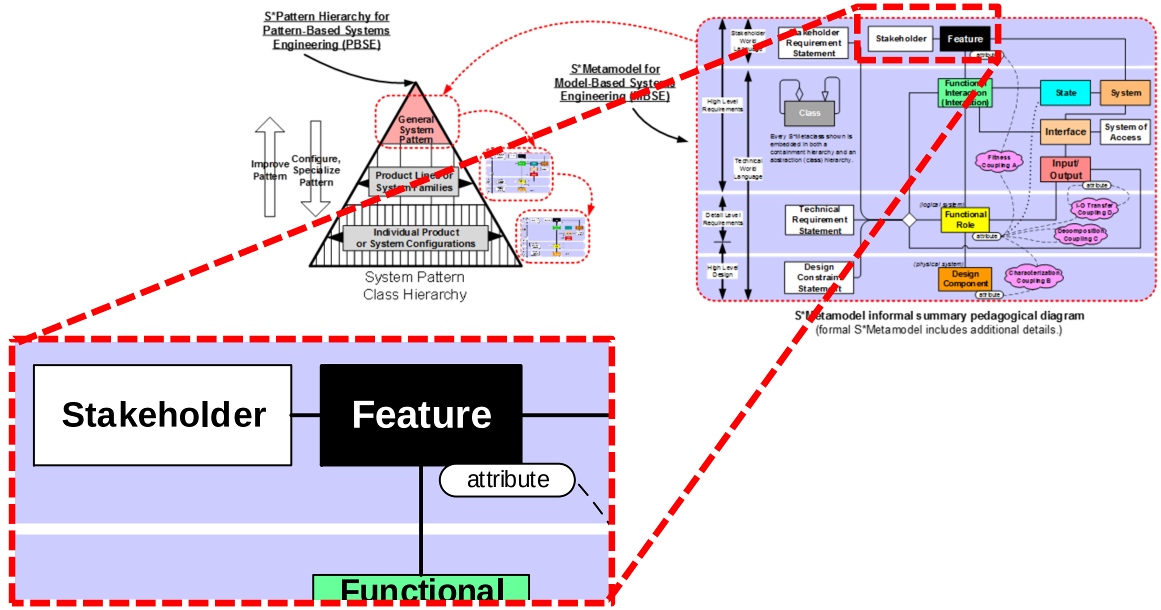
and having $var(W_n) = Q_n$ *and* $var(V_n) = R_n$

Assuming a previous estimated system state $\hat{X}_n$, find an optimal next estimate $\hat{X}_{n+1}$ minimizing $P_{n+1} = var(\hat{X}_{n+1} - X_{n+1})$

Value Phenomenon: Implications for Agile Innovation to Product or Process: Execution as Well As Strategy

- Existing Pattern Configuration Envelopes:
  - Discovering and representing explicit System Patterns (S*Patterns), to increase agility of innovation: Leveraging what we know to lower risk, improve cost, speed of response, time to market, competitiveness;
  - These gains are available within the configurable space (envelopes) of those S*Patterns, by exploiting what "we" already "know";
- Expanding Pattern Configuration Envelopes:
  - Patterns are initially discovered and later expanded in envelope size by the exploratory learning part of the configuration trajectories;
  - Creating new higher level domain specific sciences by agile pattern extraction—the process of science, great success of the last 300 yrs.
  - Underlying patterns as Accelerators; Fields and Attractors.
- Improved intuition, as well as discipline, about direction and decision.
- Potential for automated support of direction analysis decisions.
- Environmental & opponent trajectories; game theory, differential games.
- Applies to innovations in the SOI itself, not just in the Target System

Value Phenomenon: More implications for SE Practice



- Each S*Pattern creates a domain-specific language (DSL), including the "value space", characteristic of that domain.
- We also use the same consistent value space for very "different" things:
  1. Optimization, frontiers, decision-making, trades, selection
  2. "E" of FMEA—effects of failures, penalties, only things that can be at risk, risk management, project management
  3. Partitioning of platform configuration space for covering variant minimization

Implications

- For Systems / Disciplines overall positioning
- For Systems Engineering & Science Practice
- For Engineering Education
- For Systems Engineering Research

Implications: For Systems / Disciplines Overall Positioning

It is not Systems Engineering that lacks its own technical phenomenon-based foundation—instead, it has been providing what are considered the foundations for all the other "hard" disciplines:

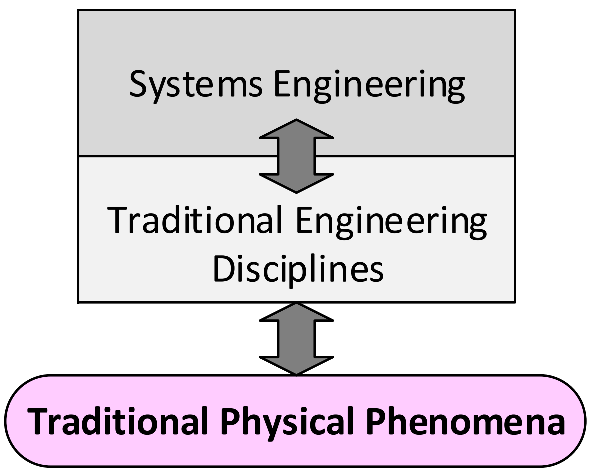
Future:

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

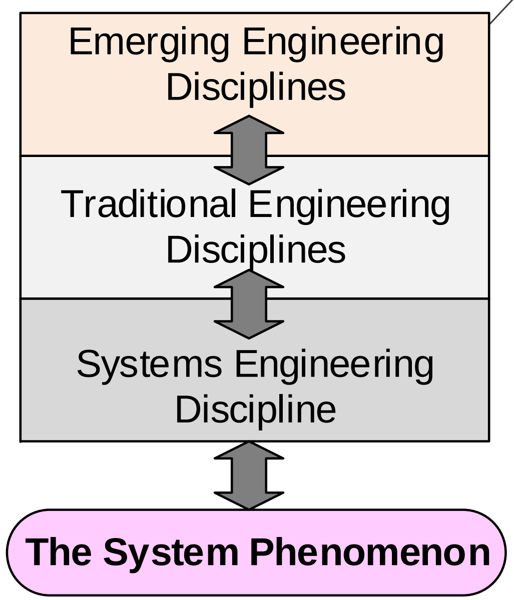
Recent:

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

Traditional view:



Future view:



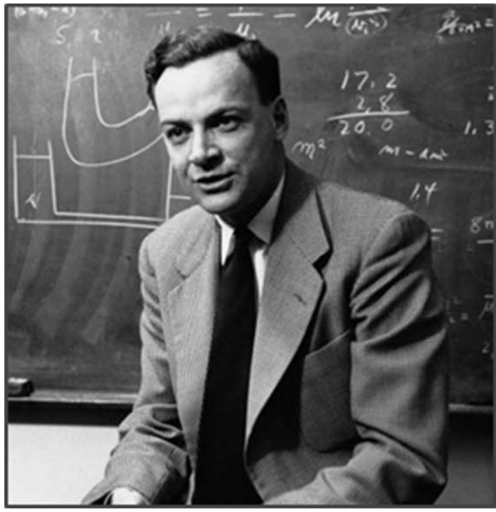
Implications for Engineering & Science Practice

- There are domain-specific phenomena, laws, and other domain pattern elements at each emerging level.
- It is already historical practice to refer to “disciplines” at these different levels—consider the two examples provided.
- Recognizing, formally representing, validating, and exploiting these, instead of re-discovering them repeatedly, can greatly reduce cycle times, risks, and costs, while advancing progress.
- Would you do chemistry without the periodic table?

Implications:
For Engineering & Science Practice

- Since Interactions are the phenomenon center of three centuries of highly impactful science and engineering, they should appear center stage in every system model—for example, much more impactful than unipolar Function alone.
- The basis of those historical sciences' success is model credibility, and the system of Model VVUQ that has grown up for it. This is not as strong in the history of SE as other disciplines—the need is to generate trusted patterns using the principles of scientific model VVUQ, and apply them widely.
- Manage and Use trusted patterns as "foundations" of each progressively emergent domain.

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

Implications:
For Science and Engineering Practice

- Other engineering societies have been establishing the standards for Model Verification, Validation, and Uncertainty Quantification (Model VVUQ)—INCOSE practitioners need to recognize the valid models are not a matter of opinion or approval.

This worked exceedingly well for human progress last three centuries:

- *"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

Today, we might add:

- *It doesn't matter how well-funded your theory is, it doesn't matter who endorses it. If it doesn't agree with experiment, it's wrong.*

Unreproducible experimental results

Lessons for longevity in science advice

Hacks, kludges and retrofits down the ages

How did natural selection give rise to mental illnesses?

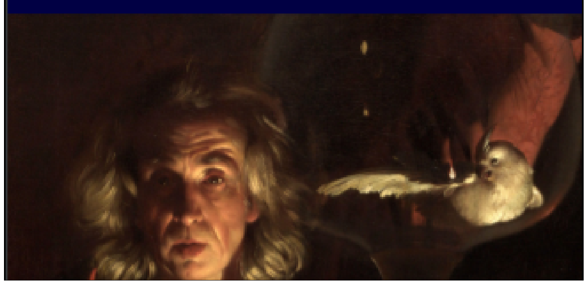
Dizzyingly prolific mathematician Jean Bourgain remembered

Overdue: a US advisory board for research integrity

Research needs an authoritative forum to hash out collective problems, argue C. K. Gunsalus, Marcia K. McNutt and colleagues.

THE IRREPRODUCIBILITY CRISIS OF MODERN SCIENCE

Causes, Consequences, and the Road to Reform



How Bad Is the Government's Science?

Policy makers often cite research to justify their rules, but many of those studies wouldn't r

By Peter Wood and David Randall

April 16, 2018 5:56 p.m. ET

Half the results published in peer-reviewed scientific journals are probably wrong. John Ioannidis, now a professor of medicine at Stanford, made headlines with that claim in 2005. Since then, researchers have confirmed his skepticism by trying—and often failing—to reproduce many influential journal articles. Slowly, scientists are internalizing the lessons of this irreproducibility crisis. But what about government which has been making policy for generations without confirming that the science behind it is valid?

nature > special

nature

International journal of science

Special | 18 October 2018

Challenges in irreproducible research

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Science moves forward by corroboration – when researchers verify others' results. Science advances faster when people waste less time pursuing false leads. No research paper can ever be considered to be the final word, but there are too many that do not stand up to further study.

WORLD VIEW *A personal take on events*

No reproducibility without preproducibility

Instead of arguing about whether results hold up, let's push to provide enough information for others to repeat the experiments, says **Philip Stark**.

From time to time over the past few years, I've politely refused requests to referee an article on the grounds that it lacks enough information for me to check the work. This can be a hard thing to explain.

Our lack of a precise vocabulary — in particular the fact that we don't have a word for 'you didn't tell me what you did in sufficient detail for me to check it' — contributes to the crisis of scientific reproducibility. In computational science, 'reproducible' often means that enough information is provided to allow a dedicated reader to repeat the calculations in the paper for herself. In biomedical disciplines, 'reproducible' often means that a different lab, starting the experiment from scratch, would get roughly the same experimental result.

In 1992, philosopher Karl Popper wrote: "Science may be described as the art of systematic oversimplification — the art of discerning what we may with advantage omit." What may be omitted depends on the discipline. Results that generalize to all universes (or perhaps do not even require a universe) are part of mathematics. Results that generalize to our Universe belong to physics. Results that generalize to all life on Earth underpin molecular biology. Results that generalize to all mice are murine biology. And results that hold only for a particular mouse in a particular lab in a particular experiment are arguably not science.

or analysis is preproducible if it has been described in adequate detail for others to undertake it. Preproducibility is a prerequisite for reproducibility, and the idea makes sense across disciplines.

The distinction between a preproducible scientific report and current common practice is like the difference between a partial list of ingredients and a recipe. To bake a good loaf of bread, it isn't enough to know that it contains flour. It isn't even enough to know that it contains flour, water, salt and yeast. The brand of flour might be omitted from the recipe with advantage, as might the day of the week on which the loaf was baked. But the ratio of ingredients, the operations, their timing and the temperature of the oven cannot.

Given preproducibility — a 'scientific recipe' — we can attempt to make a similar loaf of scientific bread. If we follow the recipe but do not get the same result, either the result is sensitive to small details that cannot be controlled, the result is incorrect or the recipe was not precise enough (things were omitted to disadvantage).

Depending on the discipline, preproducibility might require information about materials (including organisms and their care), instruments and procedures; experimental design; raw data at the instrument level; algorithms used to process the raw data; computational tools used in analyses, including any parameter settings or ad hoc choices; code, processed data and software build environments; or analyses that were

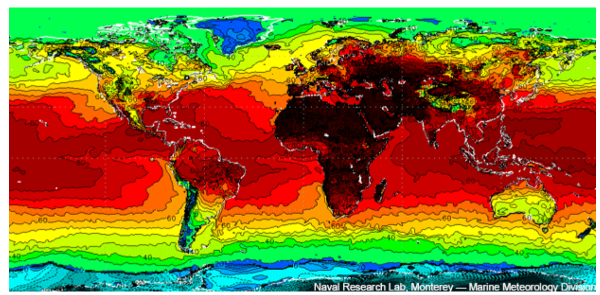
SCIENCE SHOULD BE 'SHOW ME', NOT 'TRUST ME'.

Learned models from STEM (~300 years) offer a most dramatic example of positive collaborative impact of effectively shared & validated models

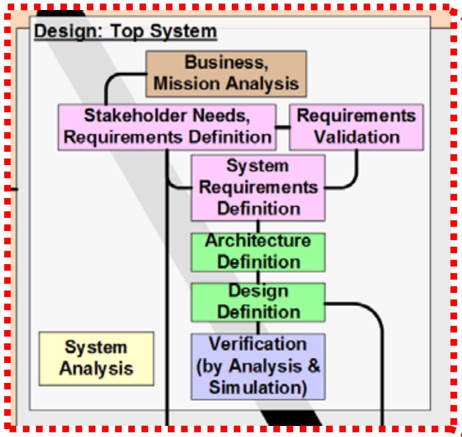
- Effective Model Sharing:
  - We cannot view MBSE as mature if we perform modeling "from scratch", instead of building on what we (*including others*) already know.
  - This is the basis of MBSE Patterns, Pattern-Based Systems Engineering (PBSE), and the work of the INCOSE MBSE Patterns Working Group.
  - S1 Patterns are built directly into future S2 project work of other people—effective sharing only occurs to extent it impacts future tasks performed by others.
  - This sharing may occur across individuals, departments, enterprises, domains, markets, society.
  - It applies not only to models of S1 (by S2), but also models of S2 (by S3).
- Effective Model Validation:
  - Especially when shared, models demand that we trust them.
  - This is the motivation for Model Validation, Verification, and Uncertainty Quantification (Model VVUQ) being pursued with ASME standards committees.
  - Effectiveness of Model VVUQ is essential to MBSE Maturity.
  - Because Model VVUQ adds significantly to the cost of a trusted model, MBSE Patterns are all the more important—the IP of enterprises, industries.

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



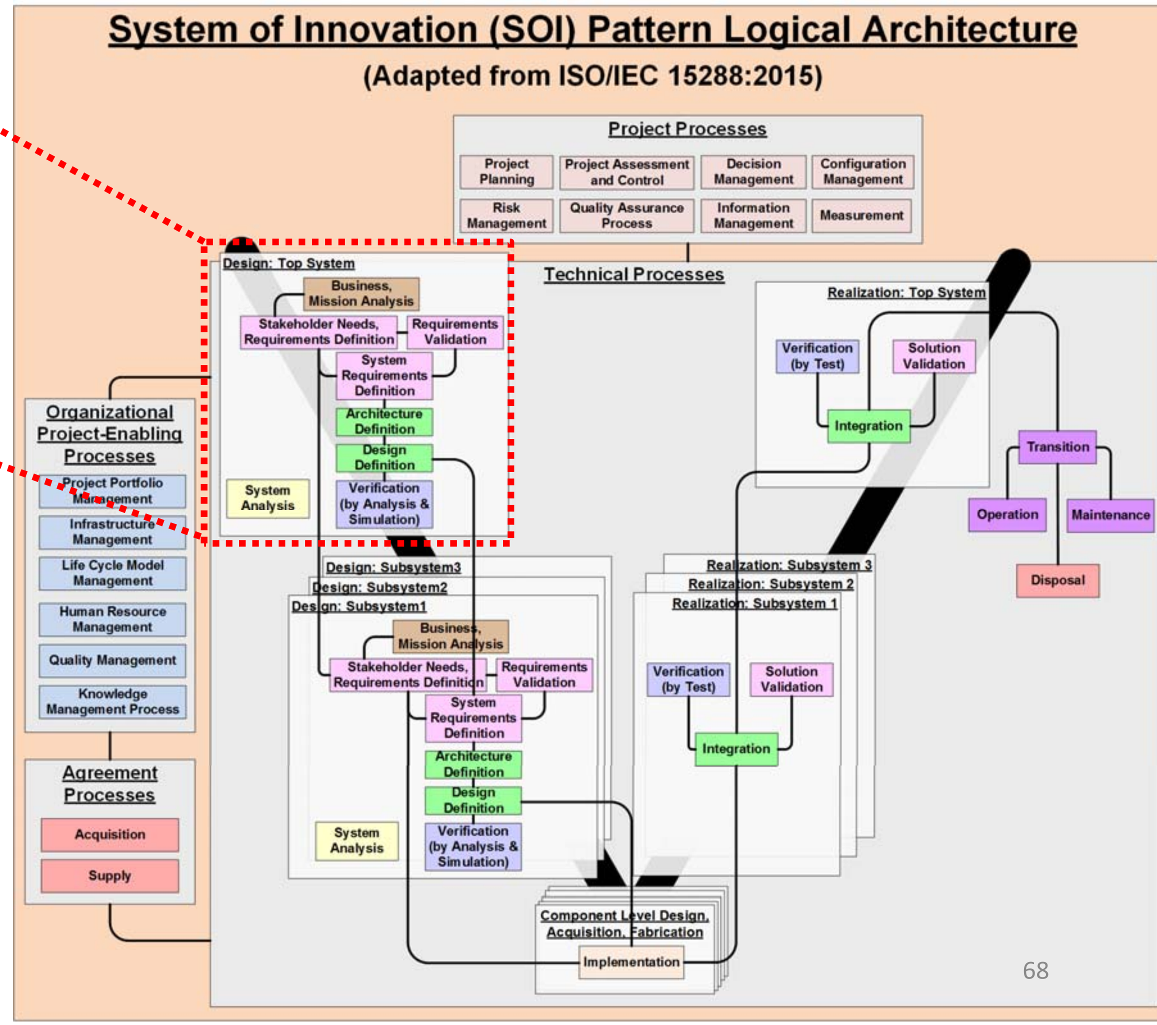
- Related risks require that we characterize the structure of that trust and manage it:
  - The Validation, Verification, and Uncertainty Quantification (VVUQ) ***of the models themselves***.



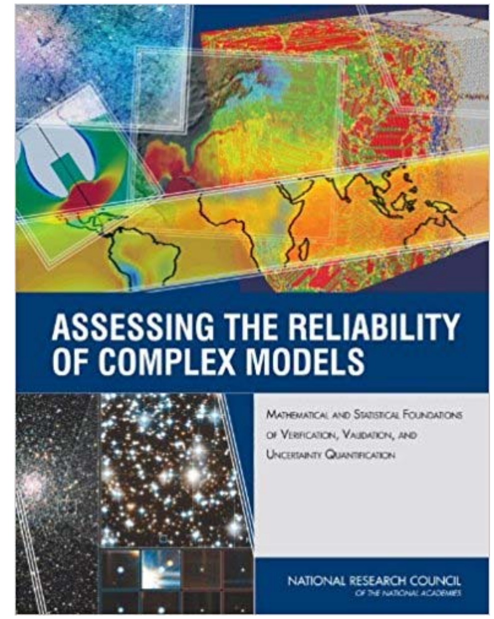
Models trusted--for what purposes?

Potentially for any ISO 15288 processes:

- If there is a net benefit . . .
- Some more obvious than others.
- The INCOSE MB Transformation is using ISO 15288 framework as an aid to migration planning and assessment.
- Notice that ISO 15288 tells us all the things we do if we start with no knowledge of the target system; but…
- *What about what we already know?*



Quantitative Fidelity, including Uncertainty Quantification (UQ)



- There is a large body of literature on a mathematical subset of the UQ problem, in ways viewed as the heart of this work.
- But, some additional systems work is needed, and in progress, as to the more general VVUQ framework, suitable for general standards or guidelines.

General structure of uncertainty / confidence tracing:

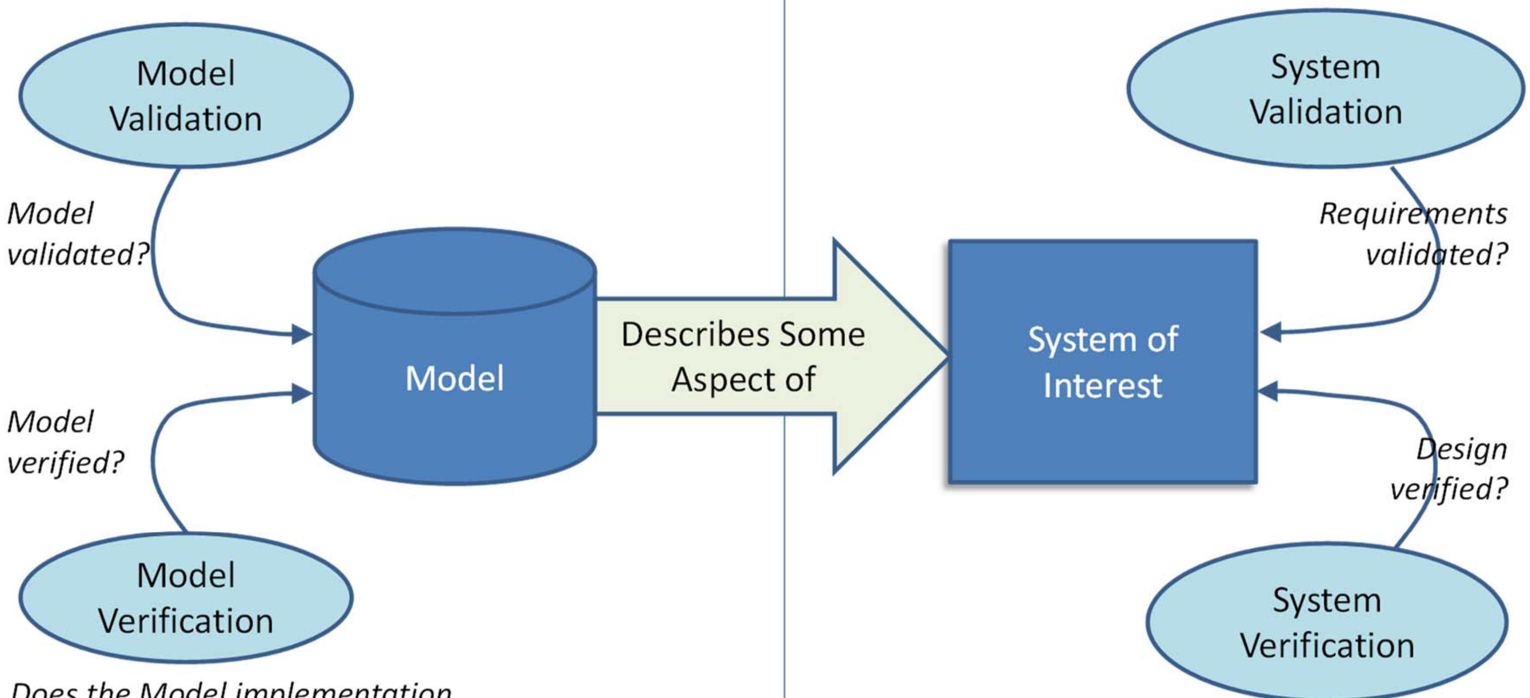
- Do the modeled external Interactions qualitatively cover the modeled Stakeholder Features over the range of intended subject system situations of interest?
- Quantify confidence / uncertainty that the modeled Stakeholder Feature Attributes quantitatively represent the real system concerns of the subject system Stakeholders with sufficient accuracy over the range of intended situation envelopes.
- Quantify confidence / uncertainty that the modeled Technical Performance Attributes quantitatively represent the real system external behavior of the subject system with sufficient accuracy over the range of intended situation envelopes.

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

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

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

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) may be used for system verification or validation (on the right!)

Related ASME activities and resources

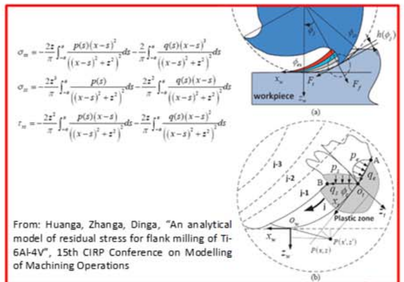
- ASME, has an active set of teams writing guidelines and standards on the Verification and Validation of Computational Models.
  - Inspired by the proliferation of computational models (FEA, CFD, Thermal, Stress/Strain, etc.)
  - It could fairly be said that this historical background means that effort was not focused on what most systems engineers would call "system models"
- Also conducts annual Symposium on Validation and Verification of Computational Models, in May.
- To participate in this work, in 2016 the speaker joined the ASME VV50 Committee on behalf of INCOSE:
  - With the idea that the framework ASME set as foundation could apply well to systems level models; and . . .
  - with a pre-existing belief that system level models are not as different from discipline-specific physics models as believed by systems community.
- Also invited sub-team leader Joe Hightower (Boeing) to address the INCOSE IW2017 MBSE Workshop, on our related ASME activity.

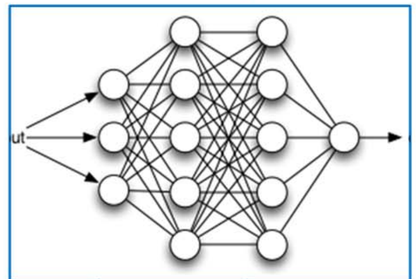
Physics-Based Model

- Predicts the external behavior of the System of Interest, visible externally to the external actors with which it interacts.
- Models internal physical interactions of the System of Interest, and how they combine to cause/explain externally visible behavior.
- Model has both external predictive value and phenomena-based internal-to-external explanatory value.
- Overall model may have high dimensionality.

Data Driven Model

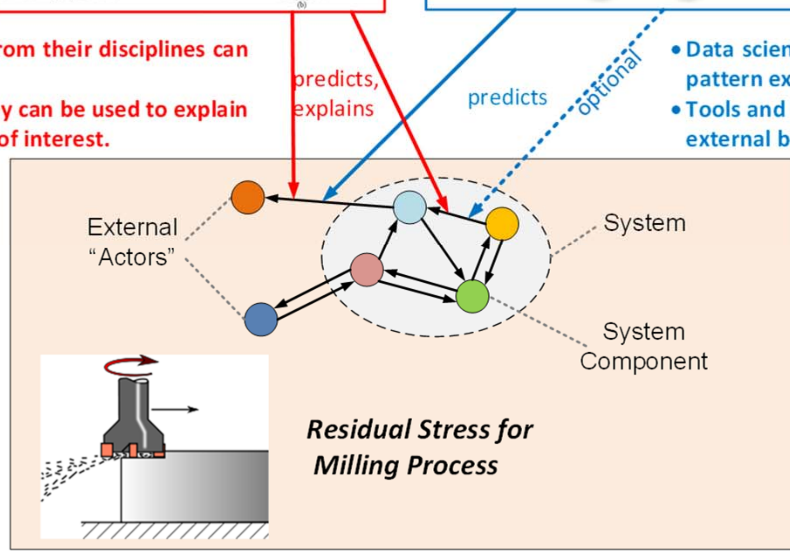
- Predicts the external behavior of the System of Interest, visible to the external actors with which it interacts.
- Model intermediate quantities may not correspond to internal or external physical parameters, but combine to adequately predict external behavior, fitting it to compressed relationships.
- Model has external predictive value, but not internal explanatory value.
- Overall model may have reduced dimensionality.





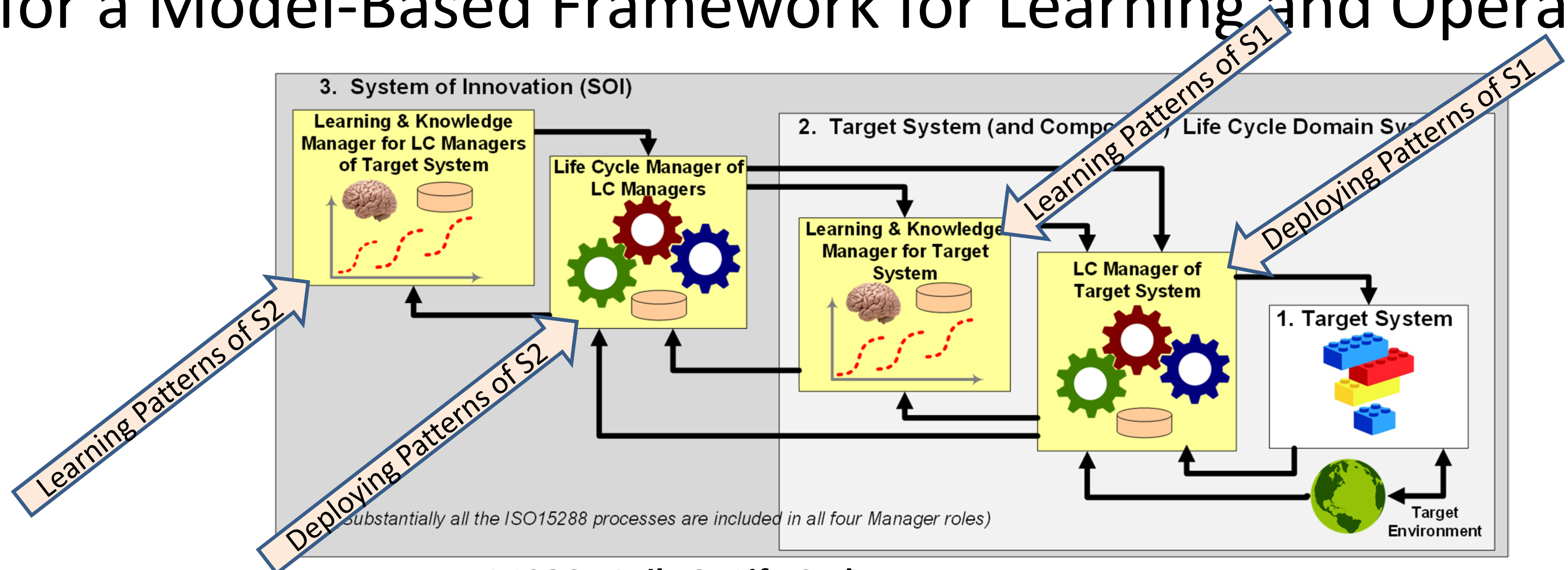
- Physical scientists and phenomena models from their disciplines can apply here.
- The hard sciences physical laws, and how they can be used to explain the externally visible behavior of the system of interest.

- Data scientists and their math/IT tools can apply here (data mining, pattern extraction, cognitive AI tooling).
- Tools and methods for discovery / extraction of recurring patterns of external behavior.



Real Target System Being Modeled

Increased Cost of Credibility of a Model: Creates Pressure for a Model-Based Framework for Learning and Operating



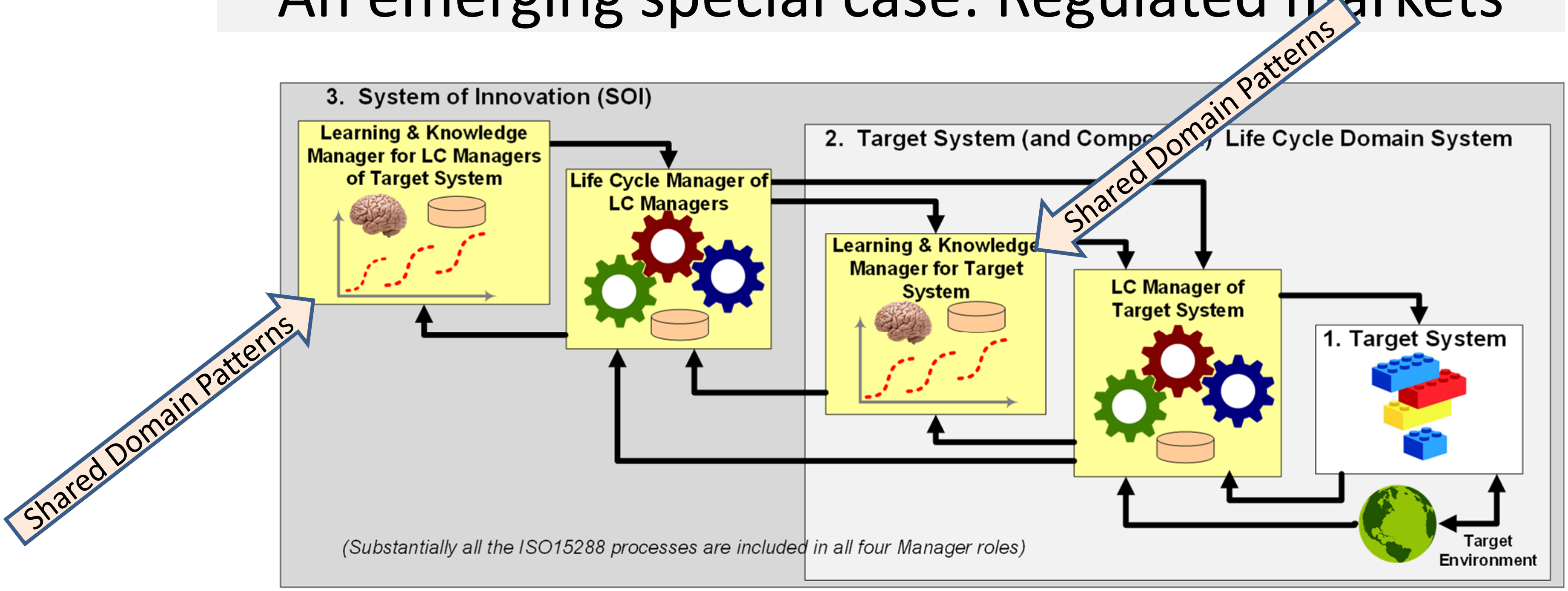
INCOSE Agile SE Life Cycle Management Pattern

System 1: The 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

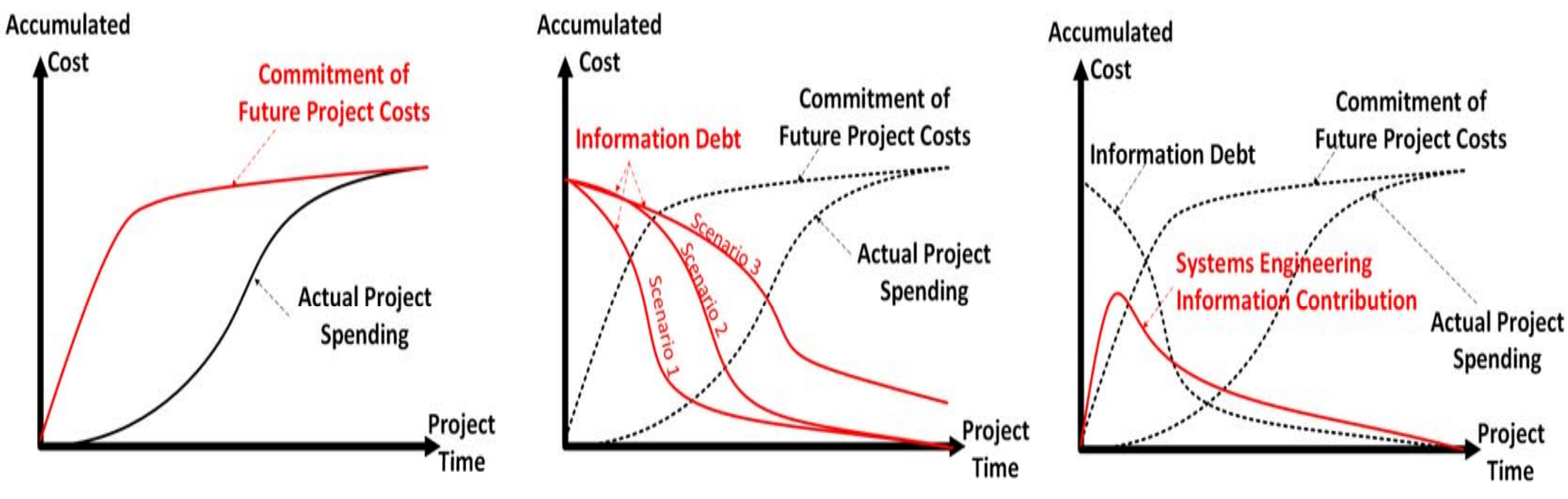
System 3: The life cycle management systems for System 2

An emerging special case: Regulated markets



- Trusted shared MBSE Patterns for <u>classes</u> of systems: Address rising cost of trusted models
- Configurable for vendor-specific systems, including proprietary aspects
- With Model VVUQ frameworks lowering the cost of model trust for increasingly complex and accelerating regulatory submissions and analyses
- Vision: Application to situations such as the Boeing 737 MAX design, analysis, submission (vision of V4 Institute, semantic technologies, etc.)

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

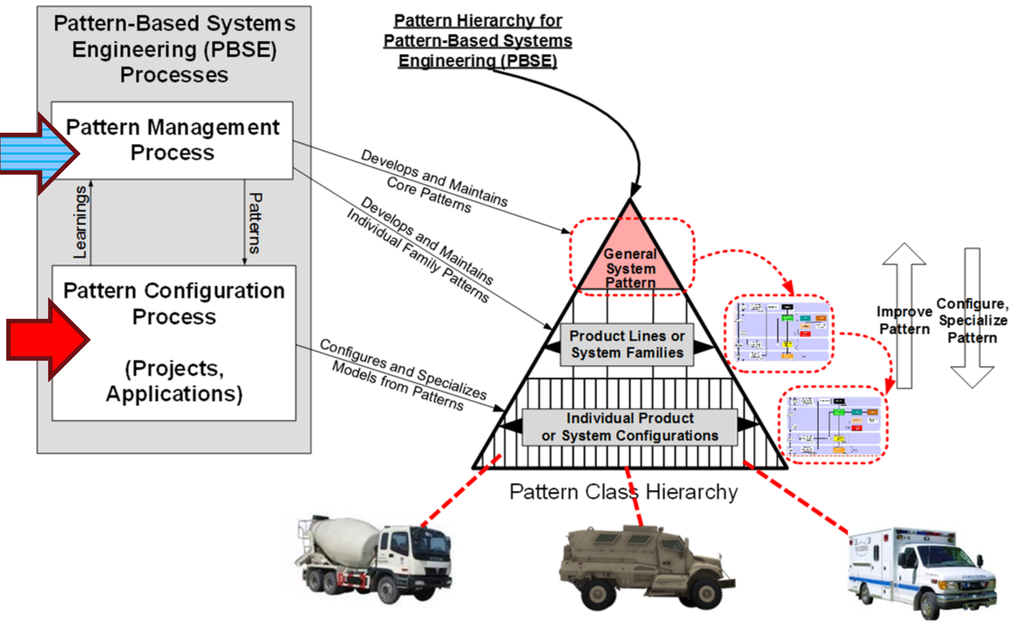


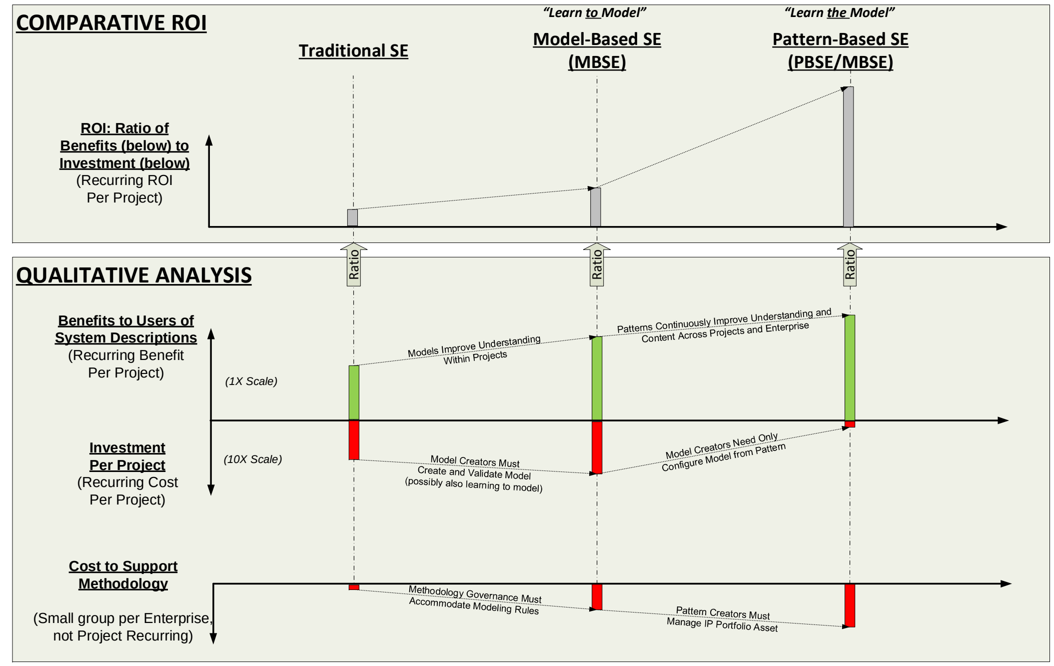
(a) When Project Costs Are Committed versus Incurred

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

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

Payoff: Rapidly Configuring Trusted Models from 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) Project
- Thereafter, S*Pattern becomes the point of accumulation of future group learning-- the "muscle memory" that is automatically consulted in each future project.

Cultural challenges

- Everyone / every project wants to build their own models:
  - Condemned to learning the same lessons, making the same mistakes, low-grade learning curves
  - Innovation with the brakes on
- Incommensurability of personal or local paradigms:
  - T. Kuhn on incommensurable frameworks in technical communities
  - Reference frameworks, ontologies, beliefs, world views
  - My way or our way?

Trust Phenomenon: Implications

- Learn about and apply the existing body of theory and practice for V&V of models.
- System 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 trusted patterns more justifiable, and the sharing of patterns more attractive
- The effective learning location to place patterns is squarely in the path of project start-up, based on configuring project models from patterns
- VVUQ of models is connected to model intended uses, risks
- Consider joining related community activities of ASME Model V&V Committee, INCOSE Patterns Working Group, V4 Institute

Implications:
For Engineering Education

"Tiny" system models (including interactions, value) build system skills for undergraduate engineering students across disciplines—not just for SE majors.

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

Mario Simoni
Rose-Hulman Institute of Technology
5500 Wabash Ave, Terre Haute, IN 47803
(812) 877-8341
simoni@rose-hulman.edu

Eva Andrijcic
Rose-Hulman Institute of Technology
5500 Wabash Ave, Terre Haute, IN 47803
(812) 877-8893
andrijci@rose-hulman.edu

Bill Kline
Rose-Hulman Institute of Technology
5500 Wabash Ave, Terre Haute, IN 47803
(812) 877-8136

Ashley Bernal
Rose-Hulman Institute of Technology
5500 Wabash Ave, Terre Haute, IN 47803
(812) 877-8623

ASEE

Paper ID #19345

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

Dr. William A Kline, Rose-Hulman Institute of Technology

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.

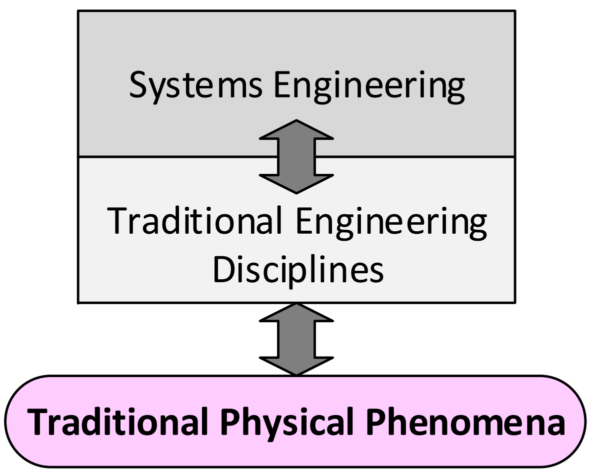
Mr. William D. Schindel, ICTT System Sciences

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

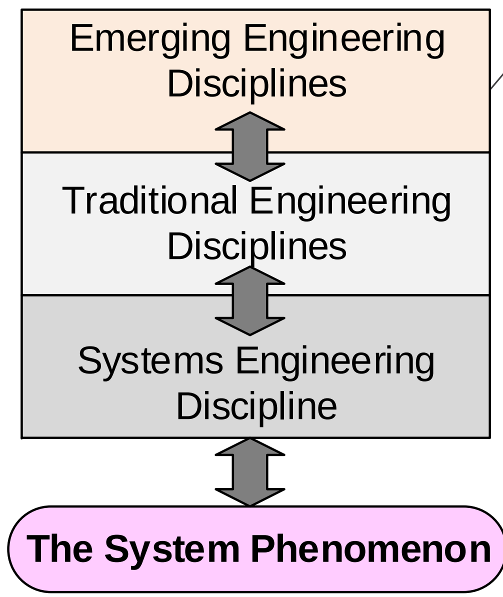
Implications:
For Targeting Systems Engineering Research

Recall our earlier discussion:

Traditional view:



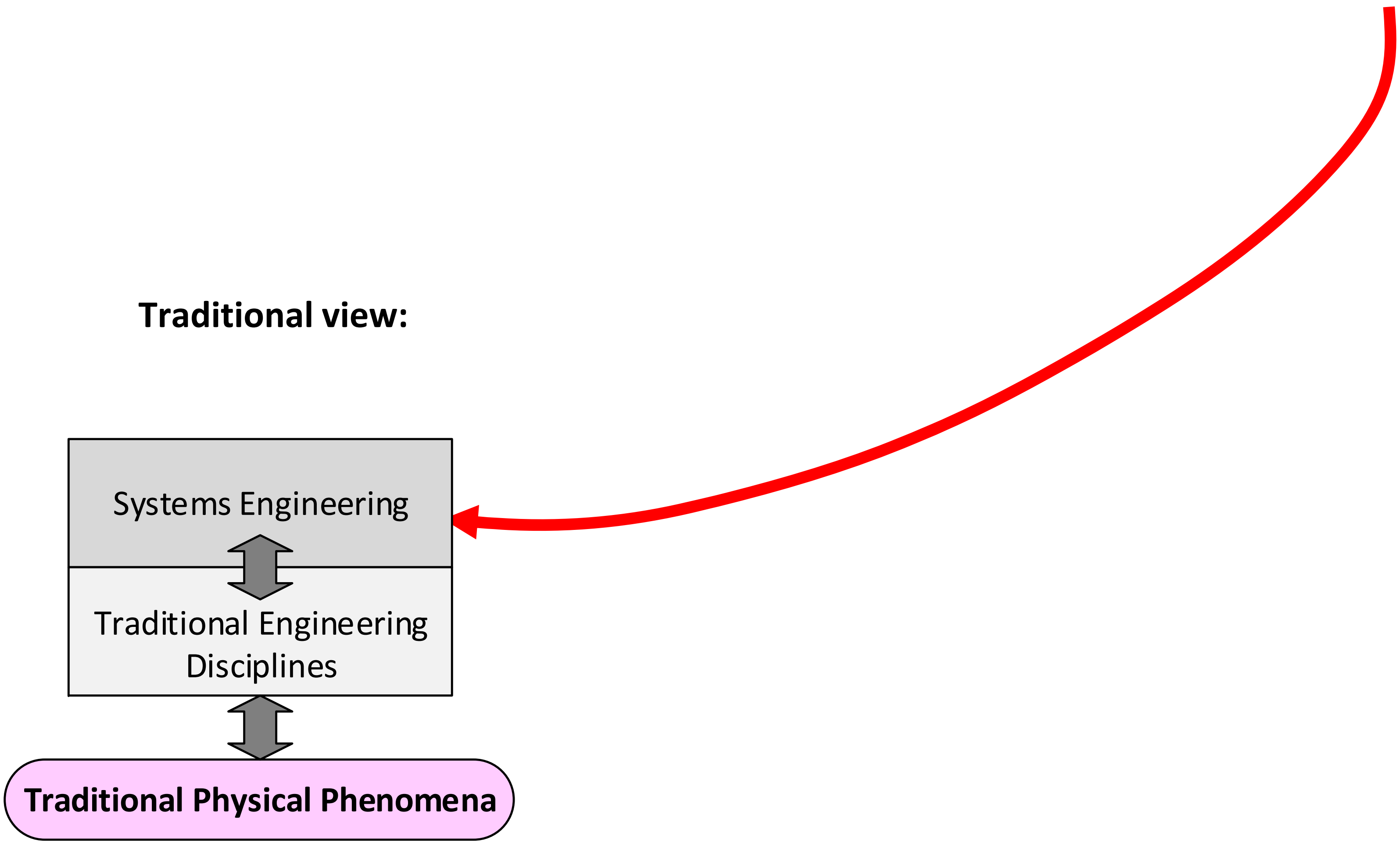
Future view:



- 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

Historical Systems Engineering Research Attention

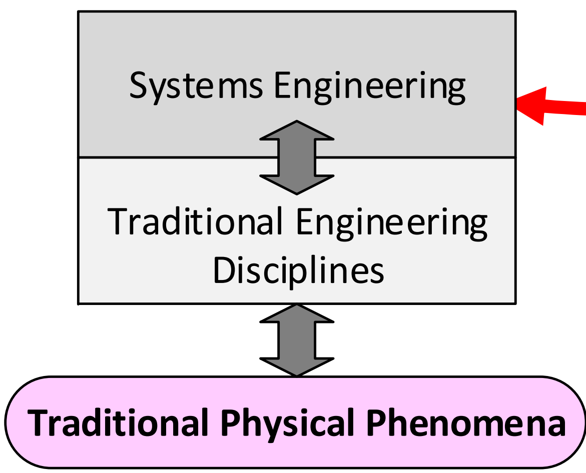
Traditional view:



Historical “System Foundations” Research Attention

We assert this is focusing on the wrong place.

Traditional view:



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
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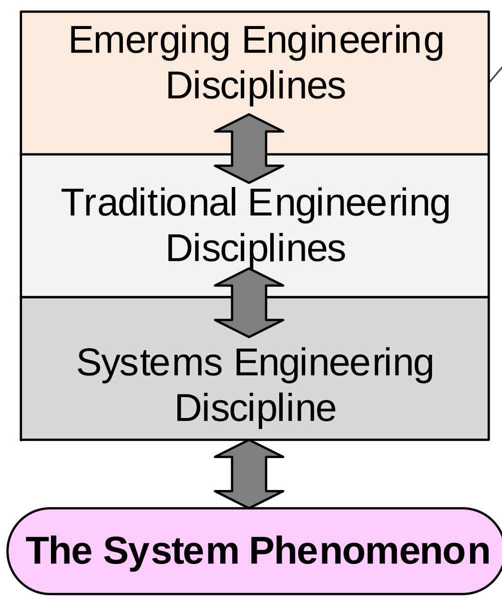
Future view:



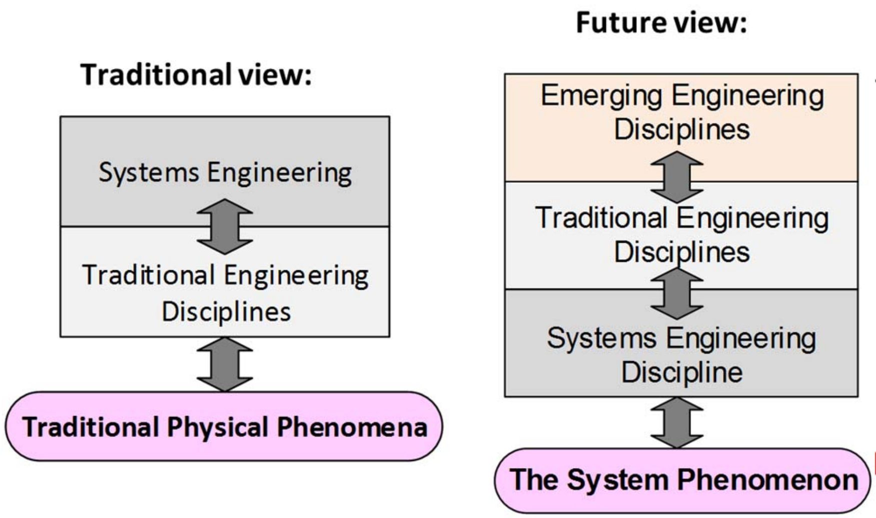
A great deal of math/science already exists here, from 300 years of progress. Better we should be <u>learning it</u> and <u>using it</u> than searching for a replacement.

What are the incentives to the SE research community, and its funders, to consider this message?

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.

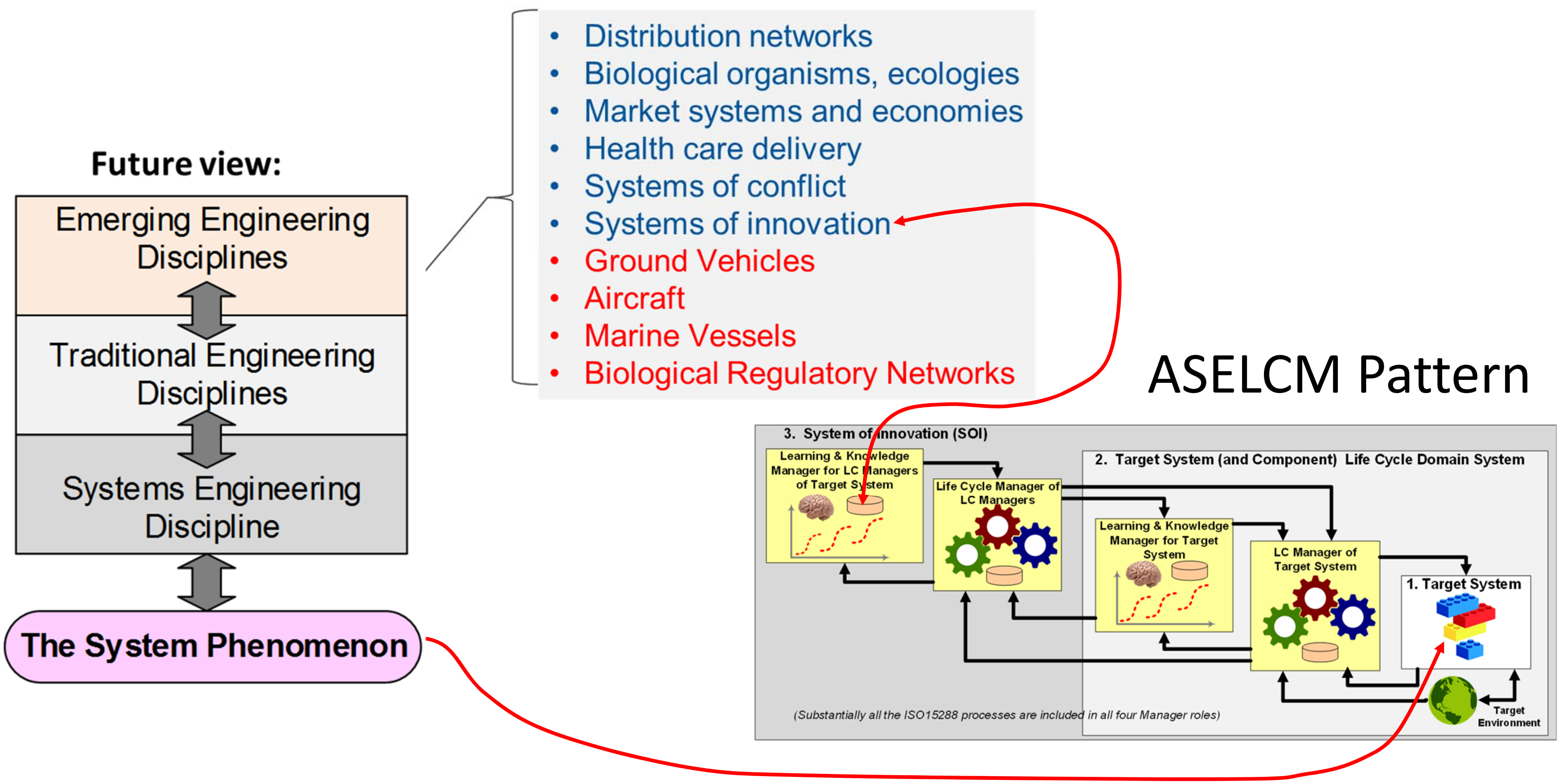
- Distribution networks
- Biological organisms, ecologies
- Market systems and economies
- Health care delivery
- Systems of conflict
- Systems of innovation
- Ground Vehicles
- Aircraft
- Marine Vessels
- Biological Regulatory Networks

Not all SE research is on foundations, but, there is foundation research work to do at each emerging domain level. What are the patterns of interactions (phenomena)? states? values? couplings?



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.

- Notice that the emergent higher patterns include System of Innovation (ASELCM System 2).
- That system is an arguably better target for additional SE research than System 1:



Q&A, Discussion

Reference Starting Points—Including Bibliographies

The System Phenomenon

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The Value Phenomenon

https://www.researchgate.net/publication/281688634_Systems_of_Innovation_II_The_Emergence_of_Purpose

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The INCOSE Patterns Working Group

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