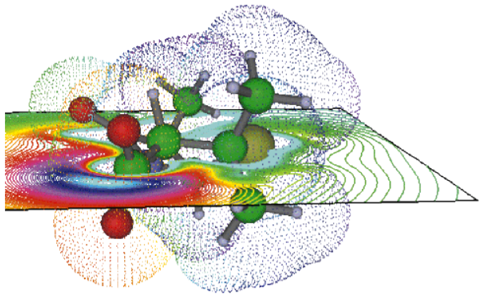

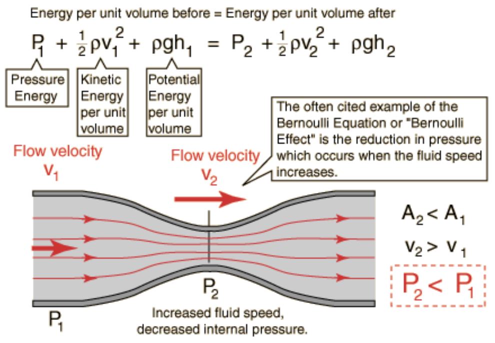

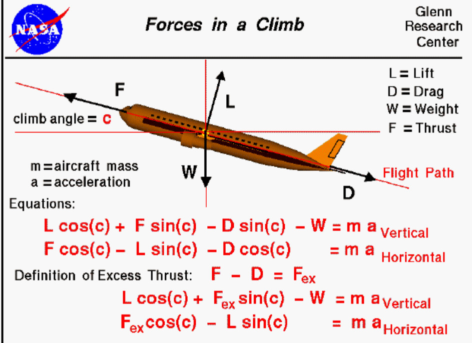

Got Phenomena?

Science-Based Disciplines for Emerging Systems Challenges

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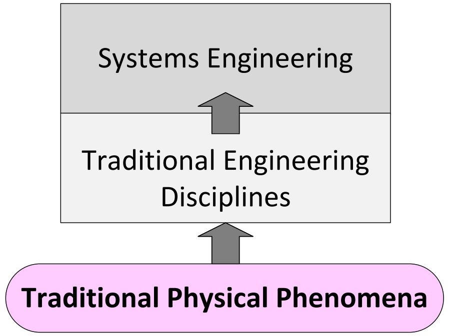
V1.4.2

26 annual INCOSE international symposium
Edinburgh, UK
July 18 - 21, 2016

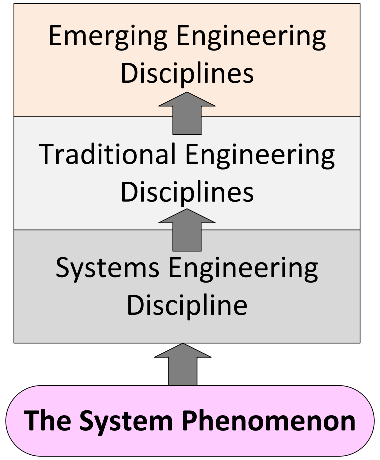
Abstract

- Specialists in individual engineering disciplines (ME, EE, CE, ChE, etc.) sometimes argue their fields have "real physical phenomena", physical laws based in the "hard sciences", and first principles, often claiming that Systems Engineering lacks the equivalent phenomena foundation. This talk will explain why the opposite is true, and how "re-planting" systems engineering in MBSE / PBSE supports the emergence of new hard science phenomena-based domain disciplines, based on higher level system patterns.
- The importance of this perspective is not just philosophical, but a reminder that there are ever-higher levels of systems with their own emergent phenomena, first principles, and physical laws. Recent successes include ground vehicles, aircraft, marine vessels, and biochemical networks. Those of future interest include distribution networks, biological organisms and ecologies, market systems and economies, health care delivery or other societal service systems, military conflict systems, and agile innovation.
- The intended audience is anyone facing these higher-level systems challenges, and the objective is improved awareness of Systems Phenomenon tools of science and engineering addressing them.

A traditional view



Our view



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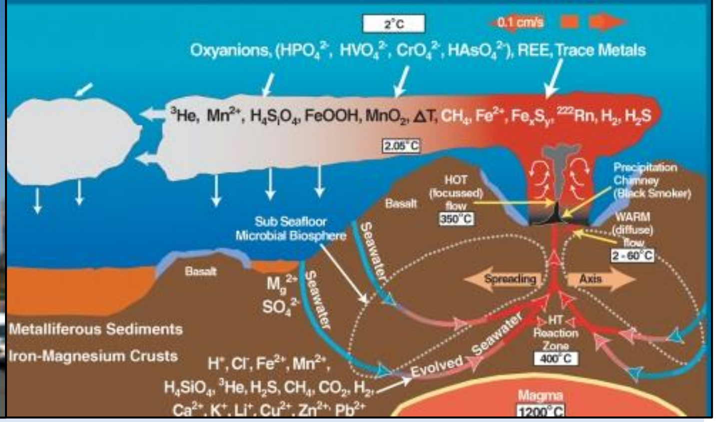

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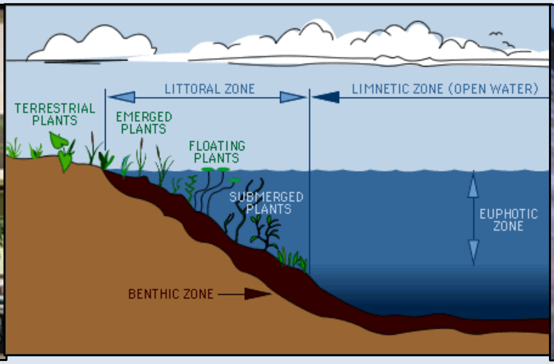
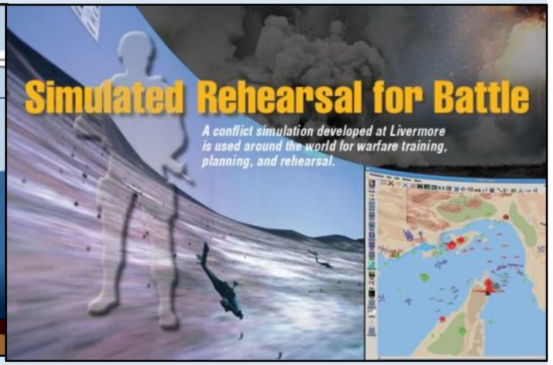
<u>**Systems**</u>: Big, Complex, and Challenging

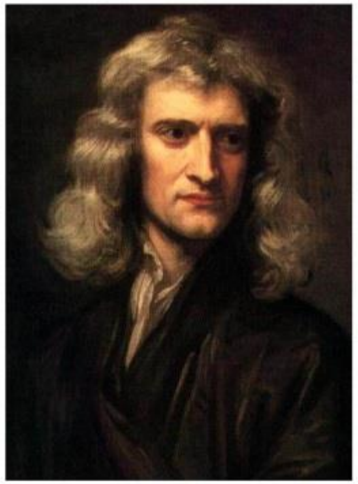




- Engineers and scientists are increasingly concerned with understanding or designing large, complex systems.
- Is current Systems Engineering up to this challenge?

Two "Phase Changes" in Technical Disciplines

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



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

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

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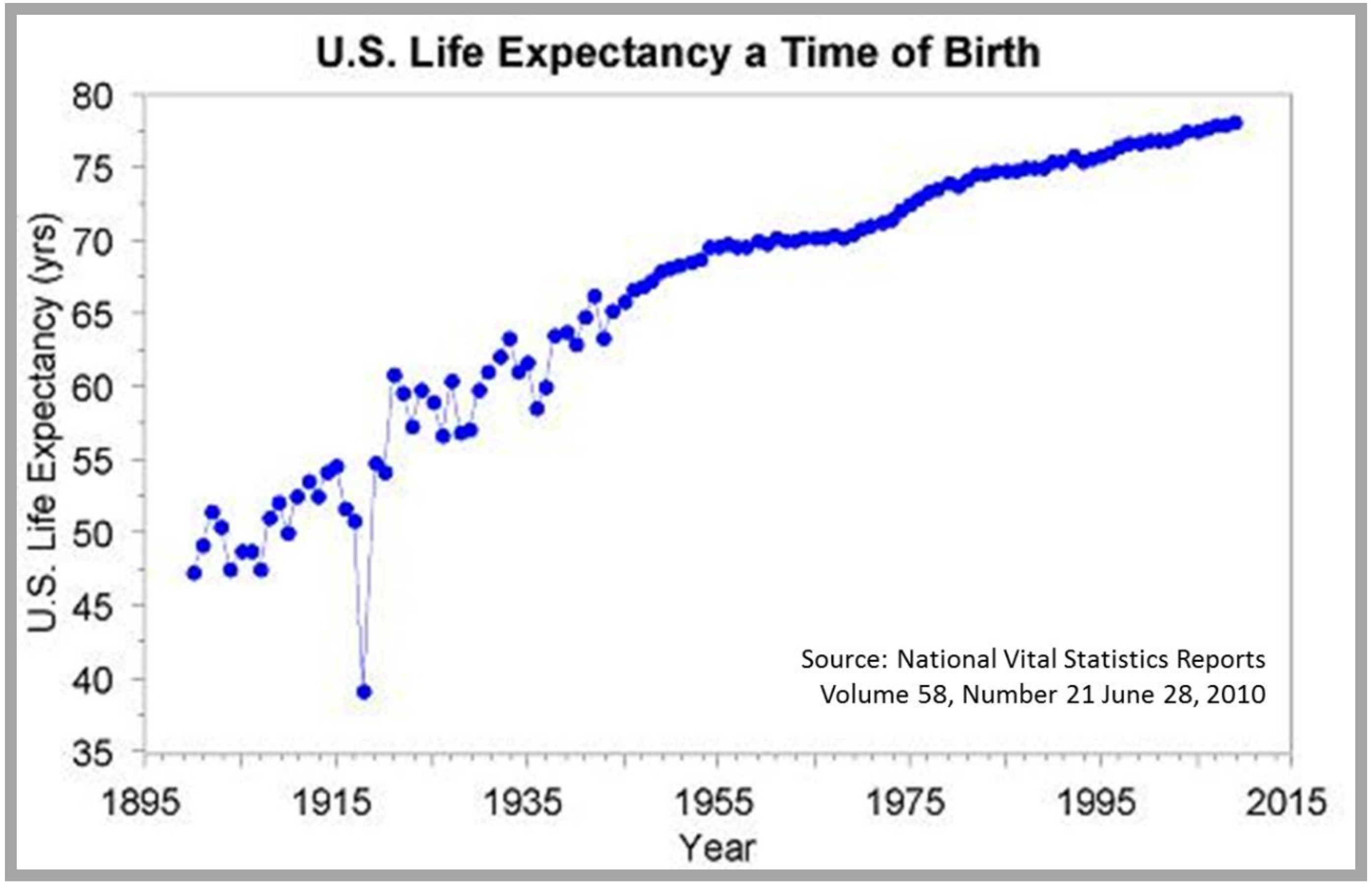
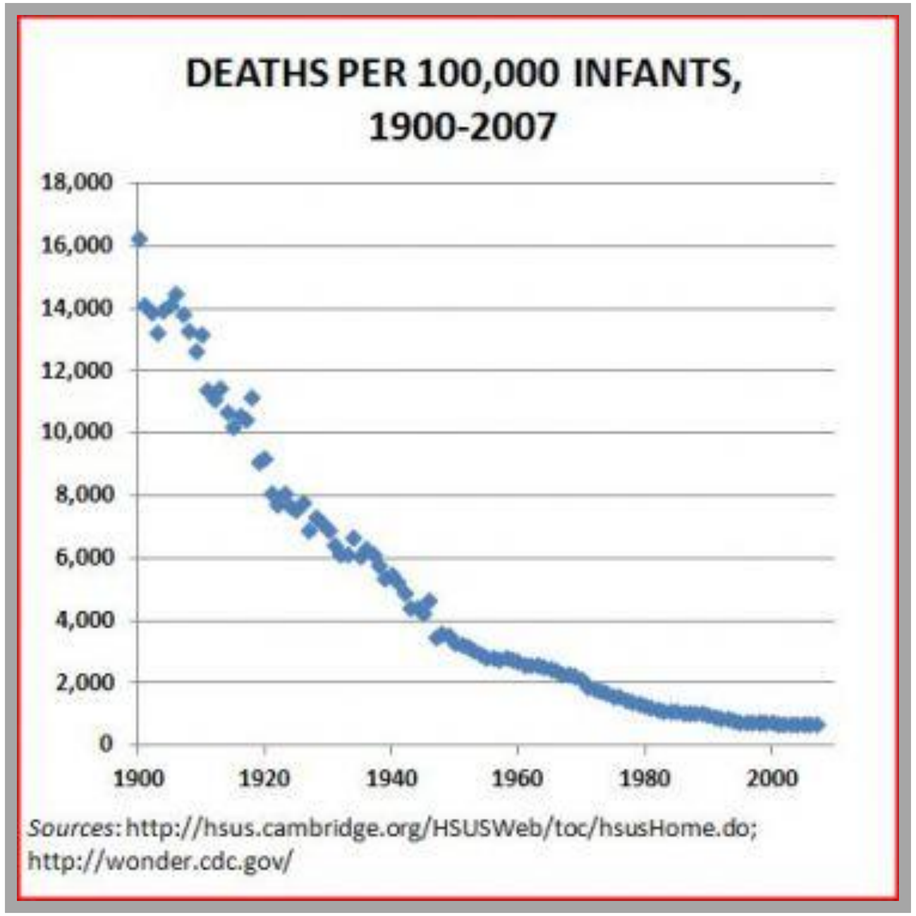
In a matter of a 300 years . . .

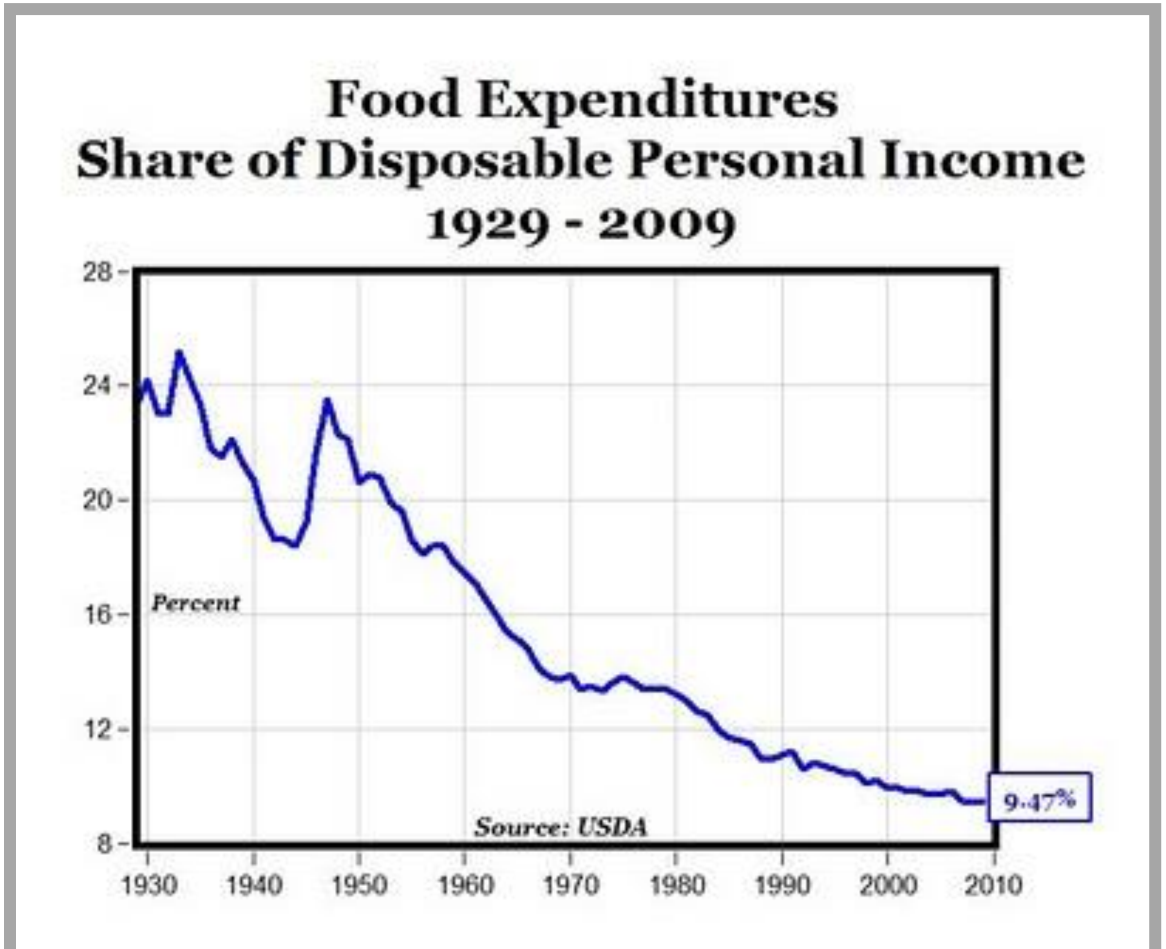
- the accelerating emergence of Science, Technology, Engineering, and Mathematics (STEM) . . .
- has lifted the possibility, quality, and length of life for a large portion of humanity . . .
- while dramatically increasing human future potential.
- By 20th Century close, strong STEM capability was recognized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

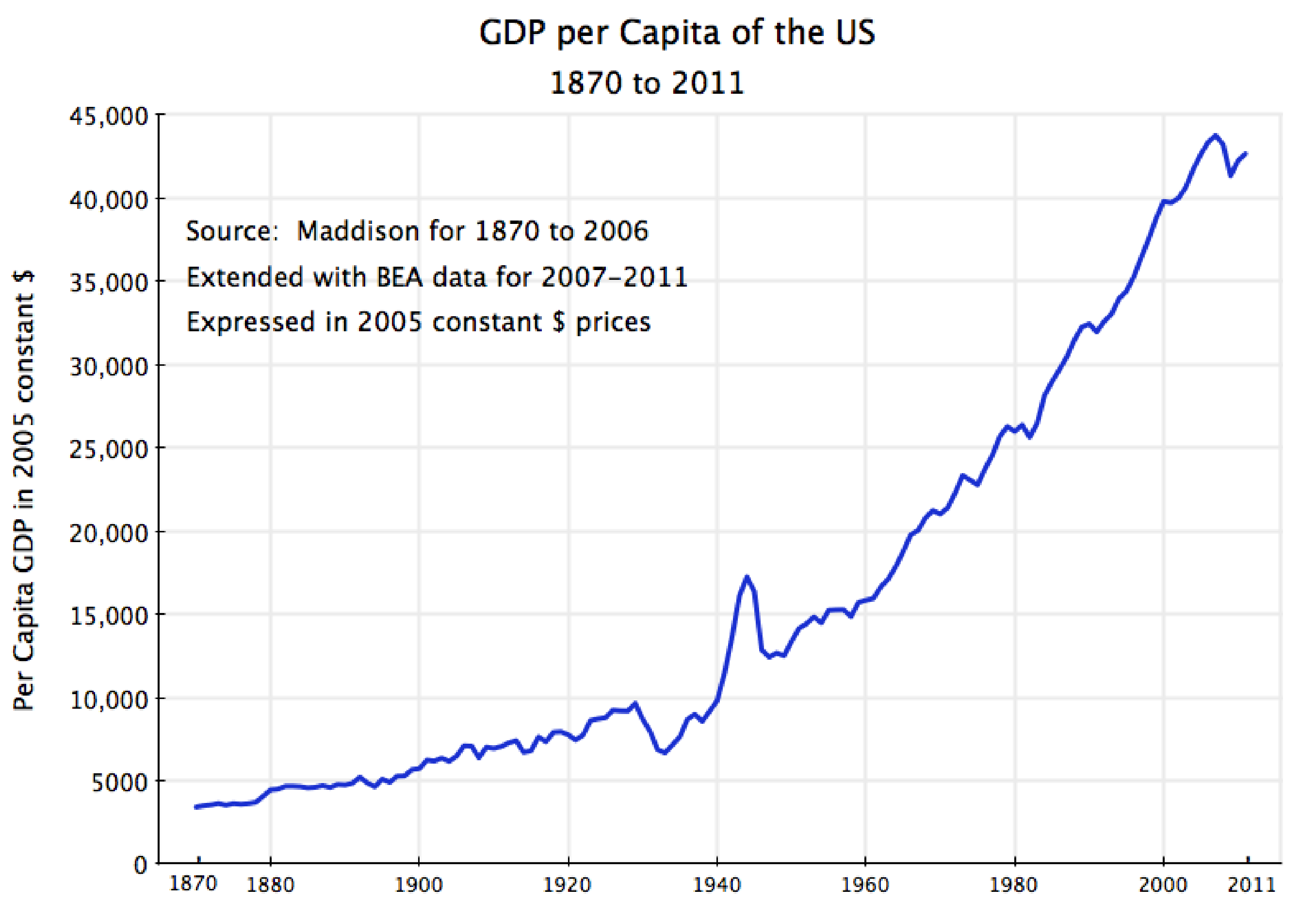
The length of human life has been dramatically extended:



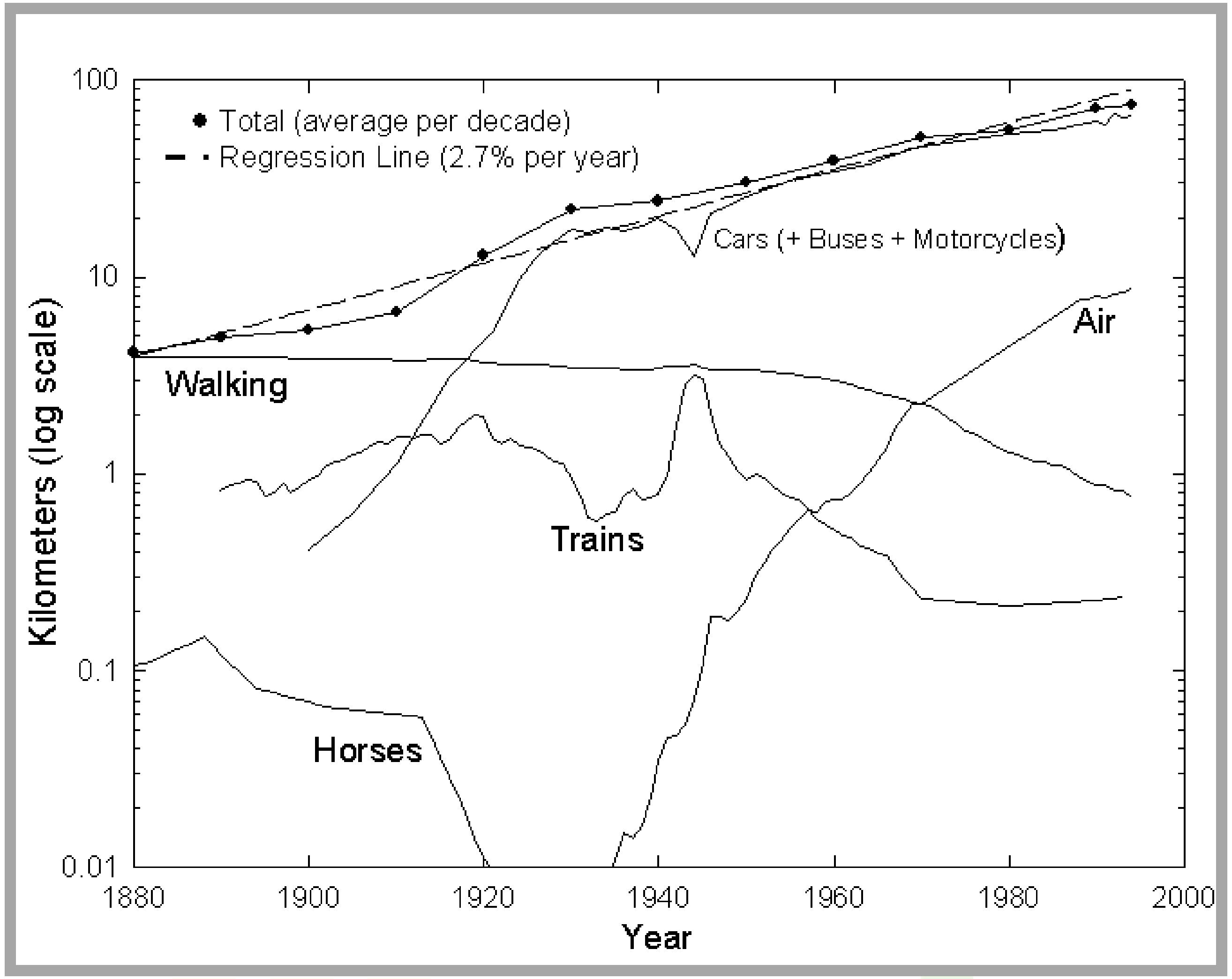


Simply feeding ourselves consumes less labor and time:





The range of individual human travel has vastly extended:

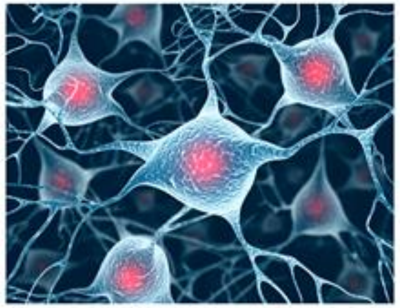


US passenger travel per capita per day by all modes.
Sources of data: Grubler , US Bureau of the Census , US Department of Transportation

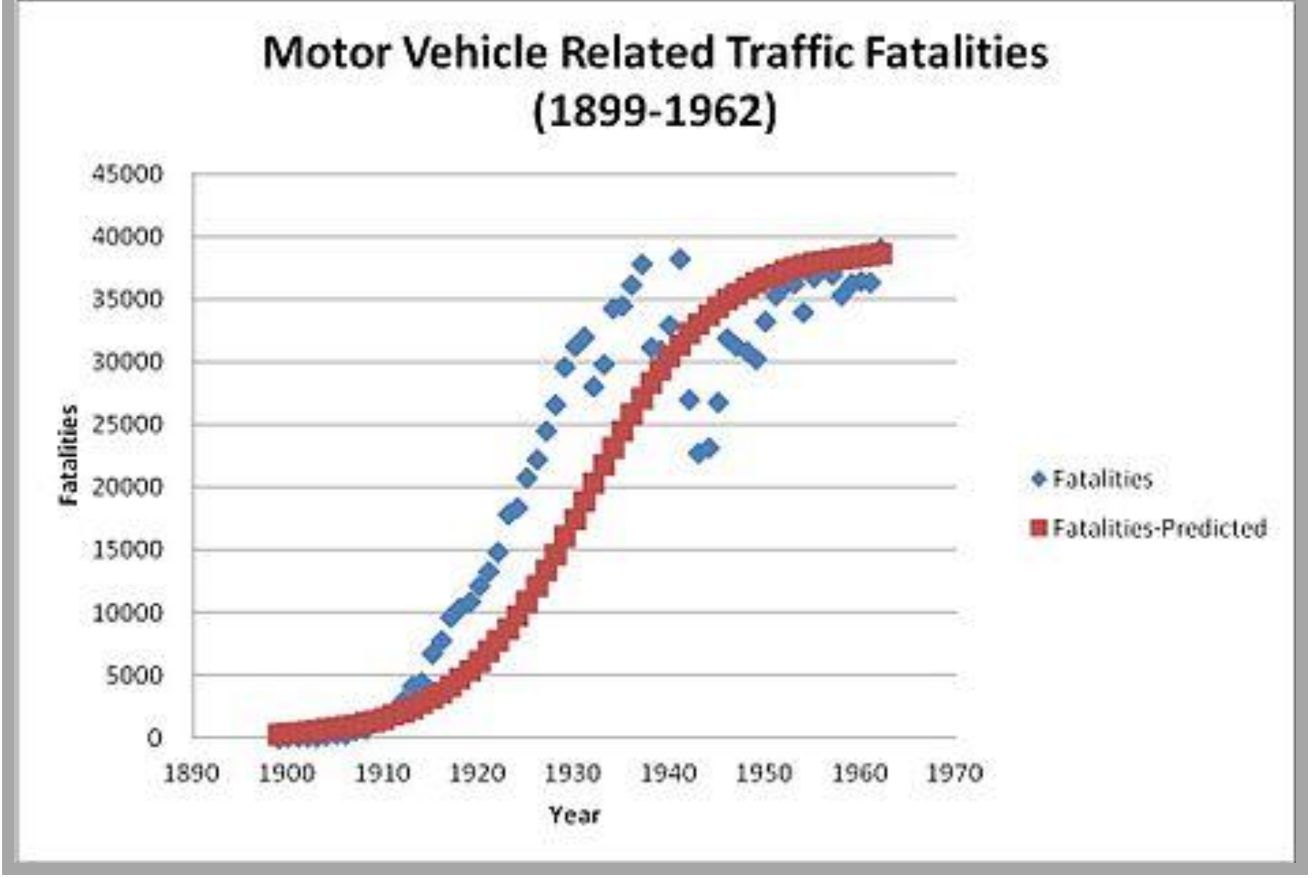
Challenges Have Likewise Emerged

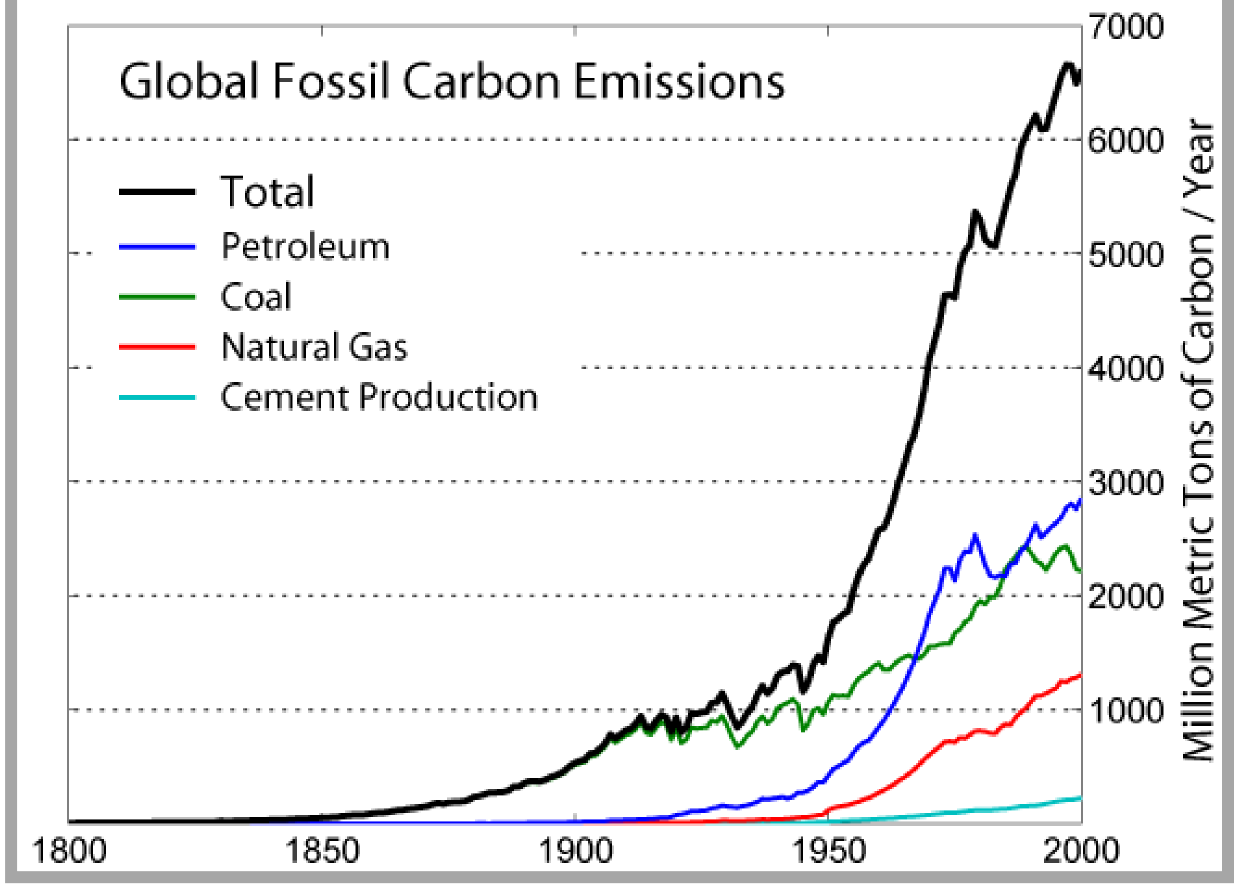



- In recent decades, the human-populated world has become vastly more interconnected, complex, and challenging . . .
- Offering both expanding opportunities and threats.
- From the smallest known constituents of matter and life, to the largest-scale complexities of networks, economies, the natural environment,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



Systems progress has come with challenging side effects:





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

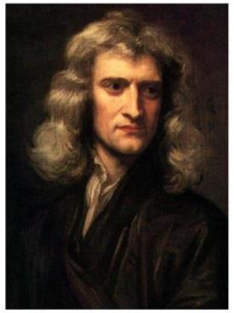
- The “hard sciences”, along with the “traditional” engineering disciplines and technologies based on those sciences, may be credited with much of this amazing progress, as well as challenges.

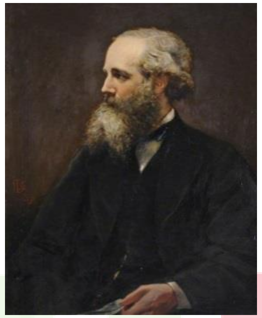
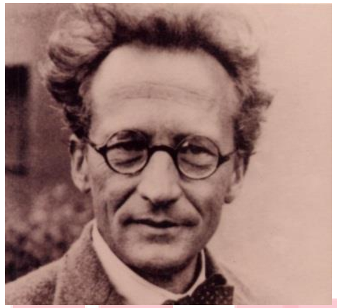
- How should Systems Engineering be compared to engineering disciplines based on the “hard sciences”?

Phenomena-Base Engineering Disciplines

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

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



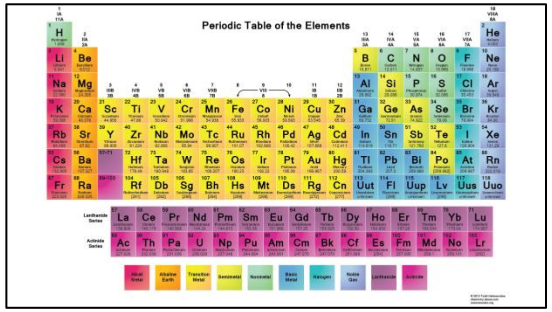
The Traditional Perspective

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

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

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

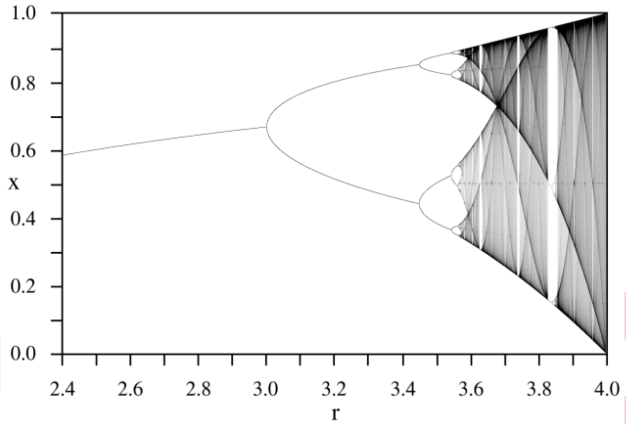
$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

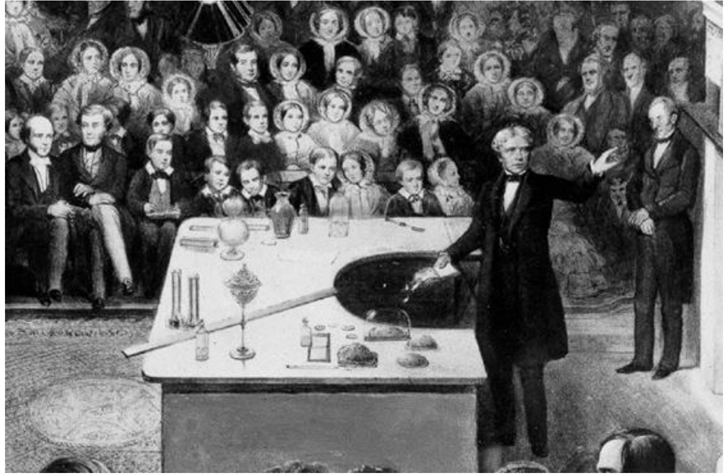


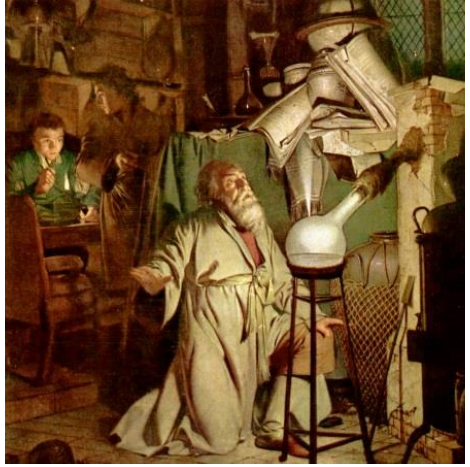
- Instead, Systems Engineering is sometimes viewed as:
  - Emphasizing process and procedure
  - Critical thinking and good writing skills
  - Organizing and accounting for information
- But not based on an underlying “hard science”

Traditional Perspective, continued

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







However . . .

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

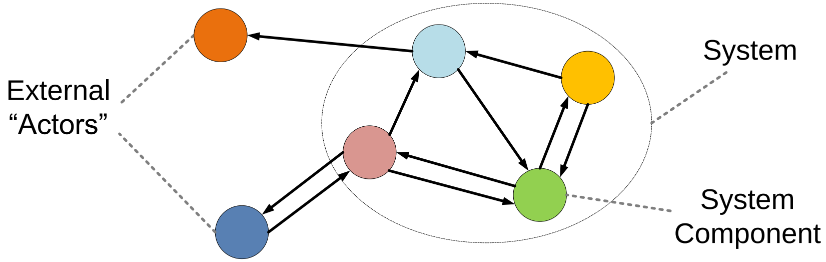
MBSE, PBSE: A Phase Change in Systems Engineering

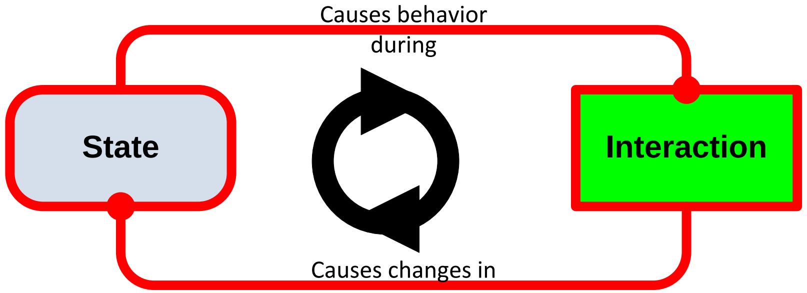
While models are not new to STEM . . .

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

The System Phenomenon

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



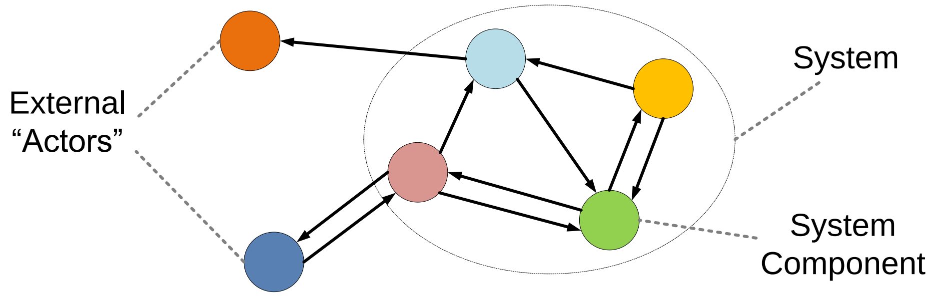


- Where interaction involves the exchange of energy, force, mass, or information, . . .
- Through which one component impacts the state of another component, . . .
- And in which the state of a component impacts its behavior in future interactions.

The System Phenomenon

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

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



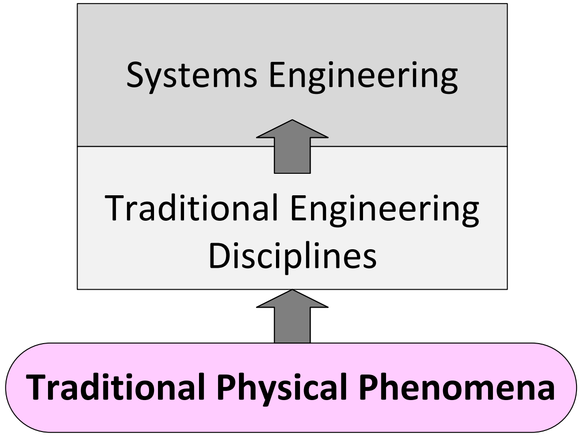
- Reduced to simplest forms, the resulting equations of motion (or if not solvable, empirically observed paths) provide "physical laws" subject to scientific verification.

The System Phenomenon

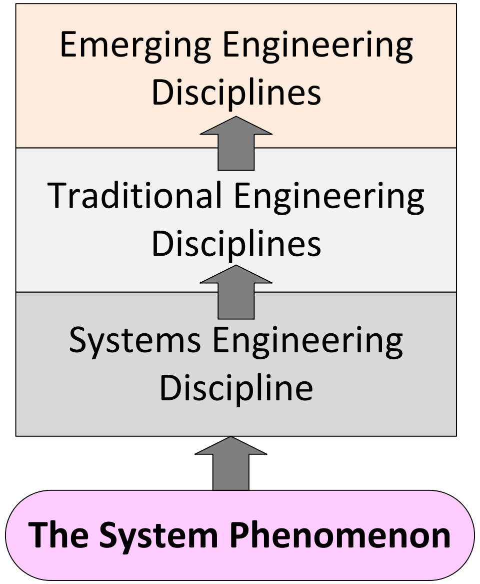
- Instead of Systems Engineering lacking the kind of theoretical foundation that the “hard sciences” bring to other engineering disciplines, . . .
  - It turns out that all those other engineering disciplines’ foundations are themselves dependent upon the System Phenomenon.
  - The underlying math and science of systems provides the theoretical basis already used by all the hard sciences and their respective engineering disciplines.
  - It is not Systems Engineering that lacks its own foundation—instead, it has been providing the foundation for the other disciplines!

The System Phenomenon

A traditional view:

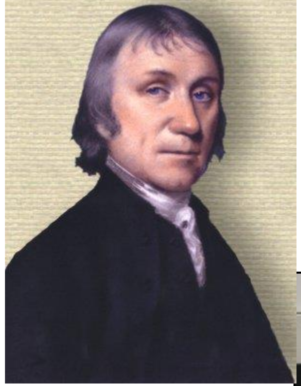


Our view:



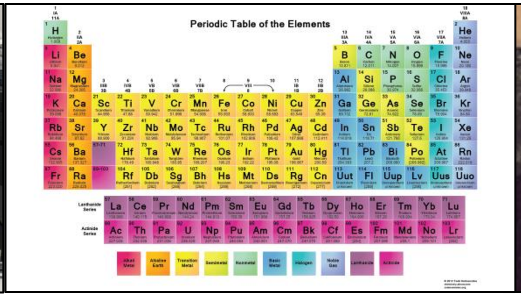
– It is not Systems Engineering that lacks its own foundation—instead, it has been providing the foundation for the other disciplines!

Historical Example 1: Chemistry

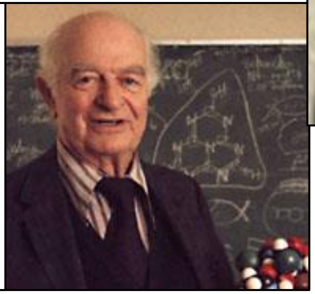

Priestley : Oxygen


Mendeleev: Periodic Table


Modern Chemist

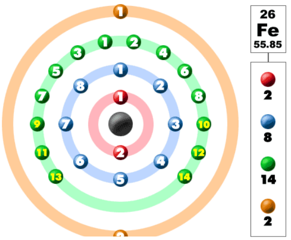


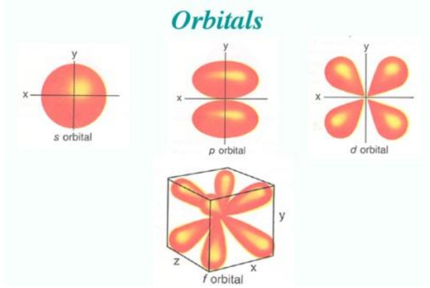
Periodic Table of the Elements

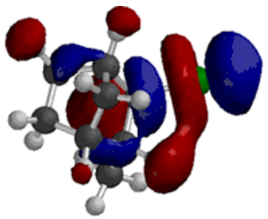

Pauling: Chemical Bond

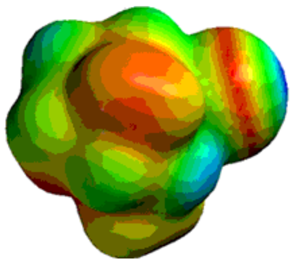
- Chemists, and Chemical Engineers, justifiably consider their disciplines to be based on the "hard phenomena" of Chemistry:
  - A view that emerged from the scientific discovery and verification of laws of Chemistry.
  - Chemical Elements and their Chemical Properties, organized by the discovered patterns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

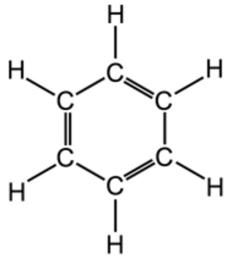
Chemistry, continued

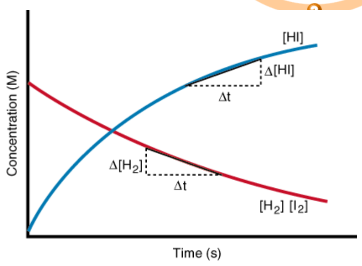


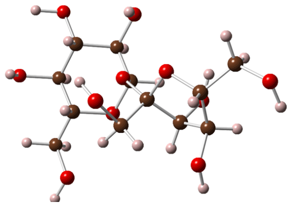


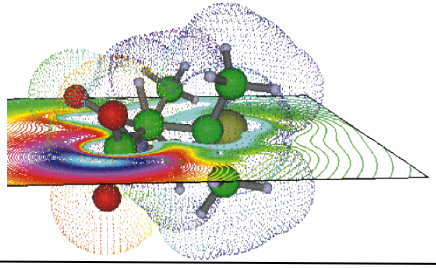








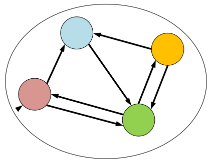




However . . .

- All those chemical properties and behaviors are emergent consequences of <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 system patterns

  and . . .

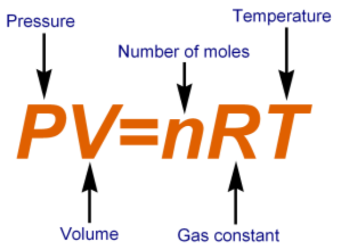
- Chemistry and Chemical Engineering study and apply those system patterns.

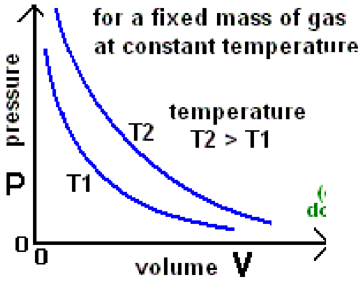
Historical Example 2: The Gas Laws and Fluid Flow

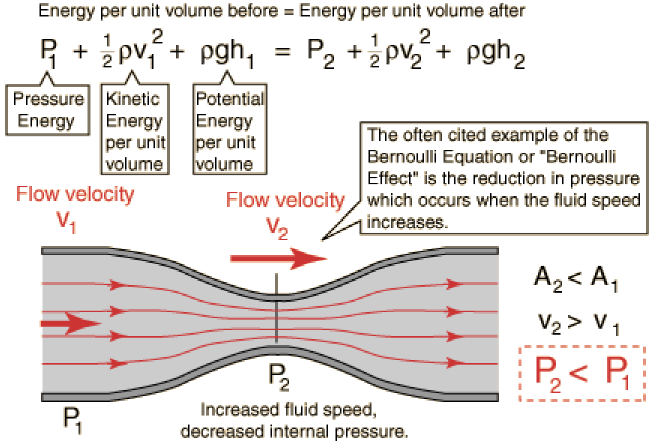
Boyle

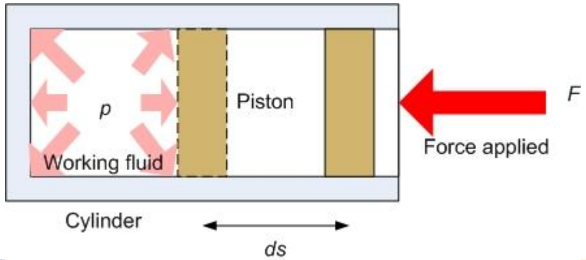
Daniel Bernoulli

- 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.

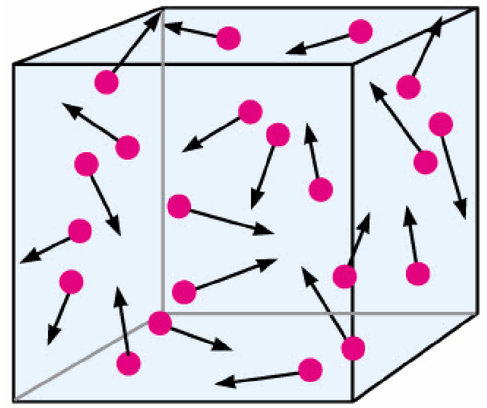


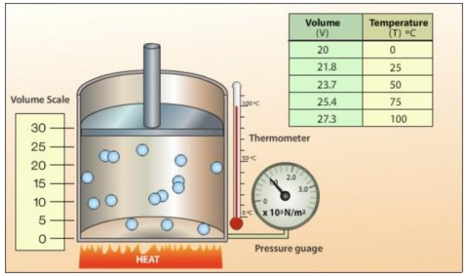


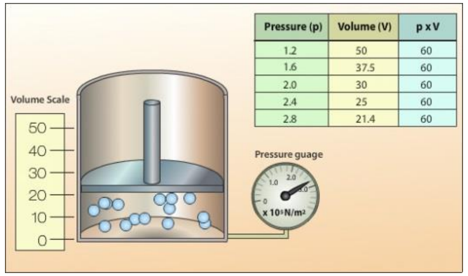




Gas Laws, continued







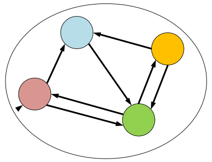
Boltzmann

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

However . . .

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

Gas Laws, continued

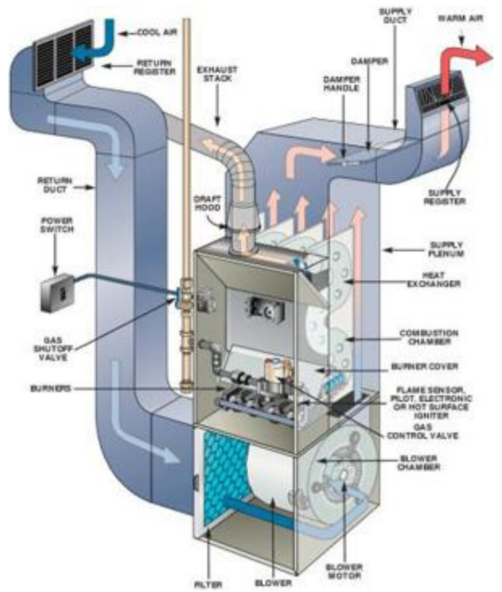


So . . .

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

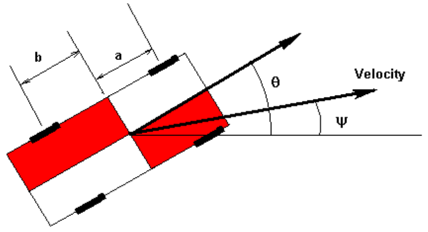
  so that . . .

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



More Recent Historical Examples

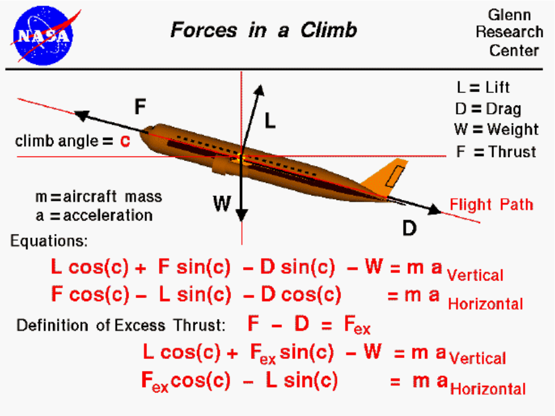
- Ground Vehicles
- Aircraft
- Marine Vessels
- Biological Regulatory Networks

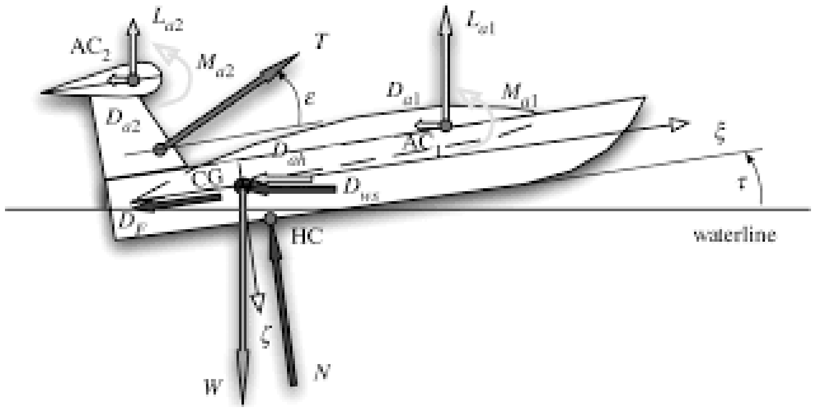


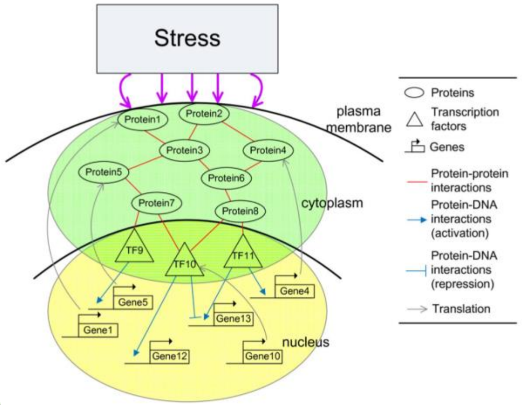
Dynamics of Road Vehicle

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 Applications

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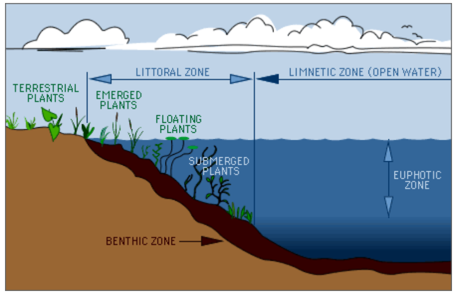
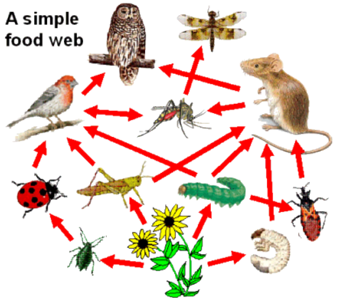
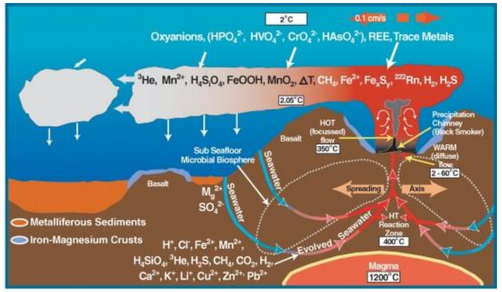
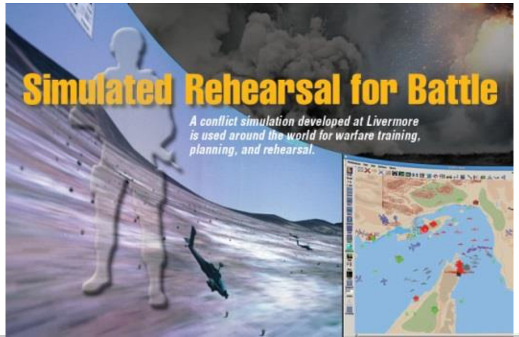
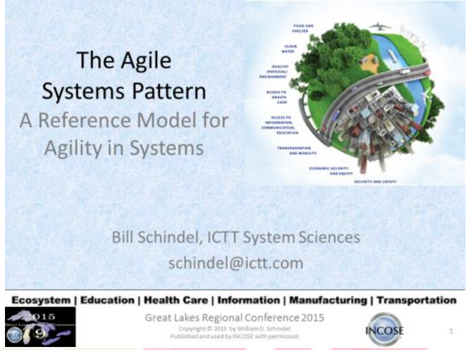
- Utility and other distribution networks
- Biological organisms and ecologies
- Market systems and economies
- Health care delivery, other societal services
- Systems of conflict
- Agile innovation





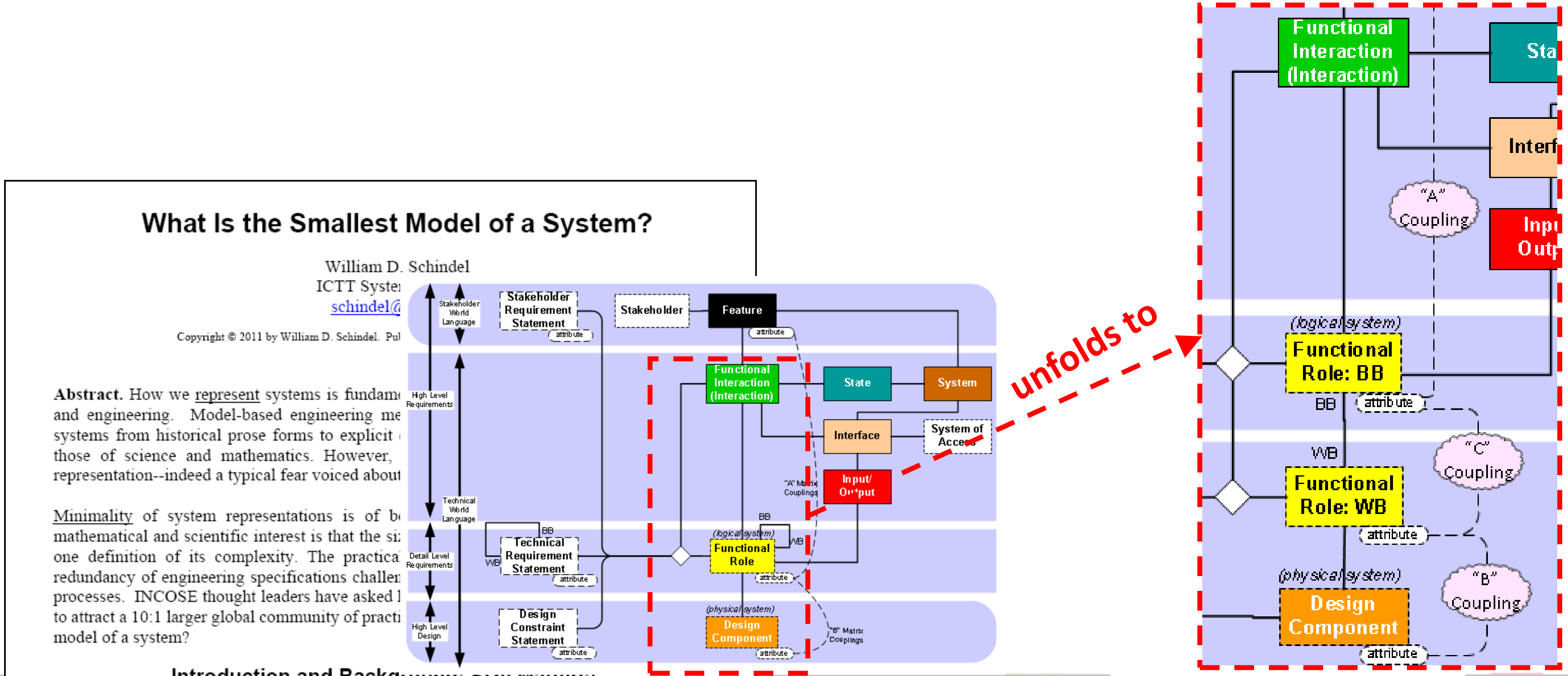






Strengthening the Foundations of MBSE

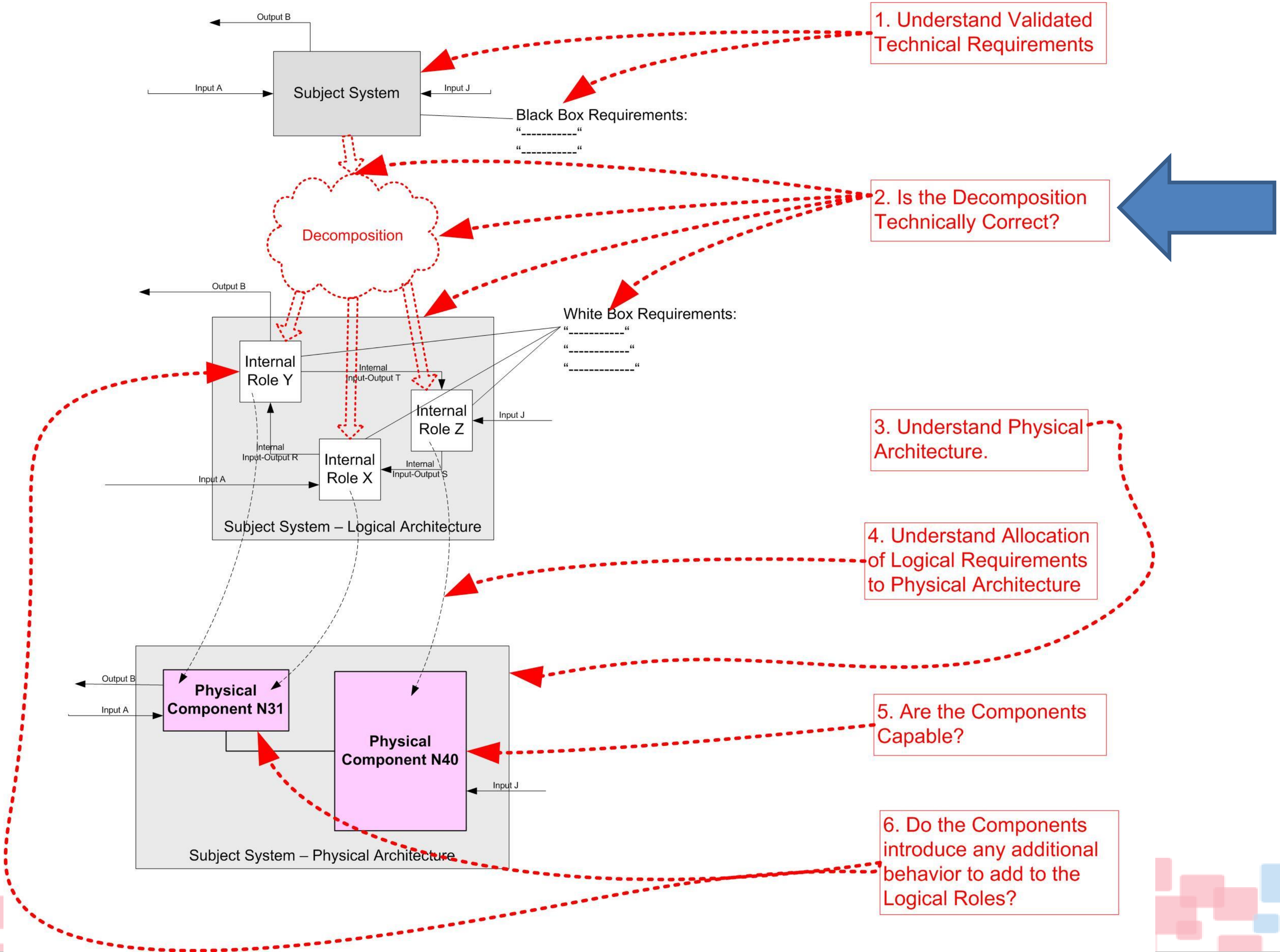
- Model-Based Systems Engineering requires a strong enough underlying Metamodel and Systems Science to equip it for the challenges and opportunities of these higher level systems.
- Example: The model framework of behavior emerging from interactions is at the center of the S*Metamodel framework:



An illustration of Related SE Impact: Design Review

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

Six Questions for Design Review:



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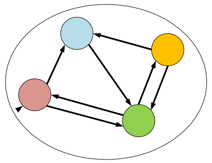

What You Can Do

- Practice expressing your systems' requirements and designs using models that explicitly represent their <u>interactions</u>:
  - The S*Metamodel provides a framework; see examples and references

- For the higher level systems challenging your efforts, look for opportunities to discover, express, and verify hard system patterns (repeatable parameterized models) of their higher level "phenomena":
  - See the S*Patterns examples and references

- Help INCOSE make progress: Participate in the INCOSE Patterns Working Group on a related project on this subject:

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

Selected References

1. INCOSE MBSE Initiative Patterns Working Group web site, at http://www.omgwiki.org/MBSE/doku.php?id=mbse:patterns:patterns
2. "Pattern-Based Systems Engineering (PBSE), Based On S*MBSE Models", INCOSE PBSE Working Group, 2015: http://www.omgwiki.org/MBSE/doku.php?id=mbse:patterns:patterns_challenge_team_mtg_06.16.15
3. Pauling, L., *The Nature of the Chemical Bond and the Structure of Molecules and Crystals: An Introduction to Modern Structural Chemistry,* 3rd edition, Cornell University Press; 1960.
4. Cardwell, D.S.L. *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age*. London: Heinemann, 1971.
5. Sussman, G, and Wisdom, J., *Structure and Interpretation of Classical Mechanics,* Cambridge, MA: MIT Press, 2001.
6. Levi, M., *Classical Mechanics with Calculus of Variations and Optimal Control*, American Mathematical Society, Providence, Rhode Island, 2014.
7. Schindel, W., "What Is the Smallest Model of a System?", *Proc. of the INCOSE 2011 International Symposium*, International Council on Systems Engineering (2011).
8. Schindel, W., "System Interactions: Making The Heart of Systems More Visible", *Proc. of INCOSE Great Lakes Regional Conference*, 2013.
9. Schindel, W., "Got Phenomena? Science-Based Disciplines for Emerging System Challenges", accepted to appear in *Proc. of INCOSE 2016 International Symposium*, International Council on Systems Engineering, 2016. (Includes larger bibliography)