Got Phenomena?

Science-Based Disciplines for Emerging Systems Challenges

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Ecosystem | Education | Health Care | Information | Manufacturing | Transportation

V1.2.5

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.

Contents

Systems: Big, Complex, and Challenging

- This conference is particularly concerned with the big, complex, challenging systems of the Great Lakes Region, and the rest of the globe.
- Is Systems Engineering up to this challenge?

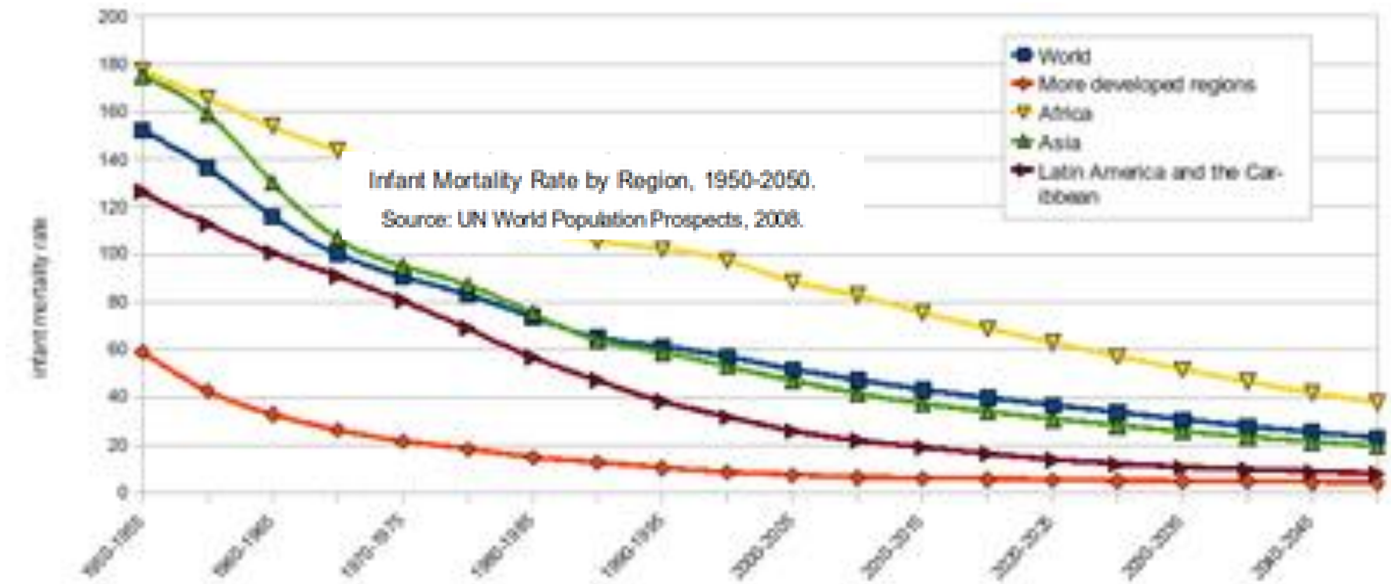
Science, Technology, Engineering, and Mathematics —300 Years of Impact

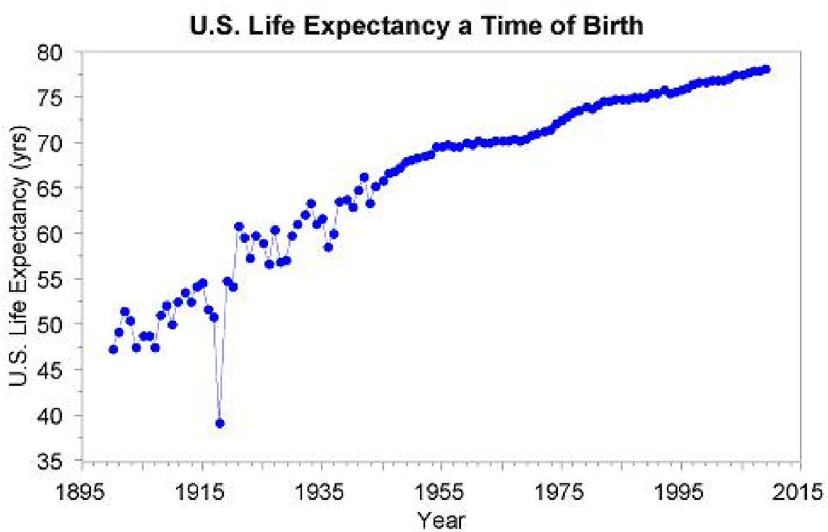



In a matter of a 300 years . . .

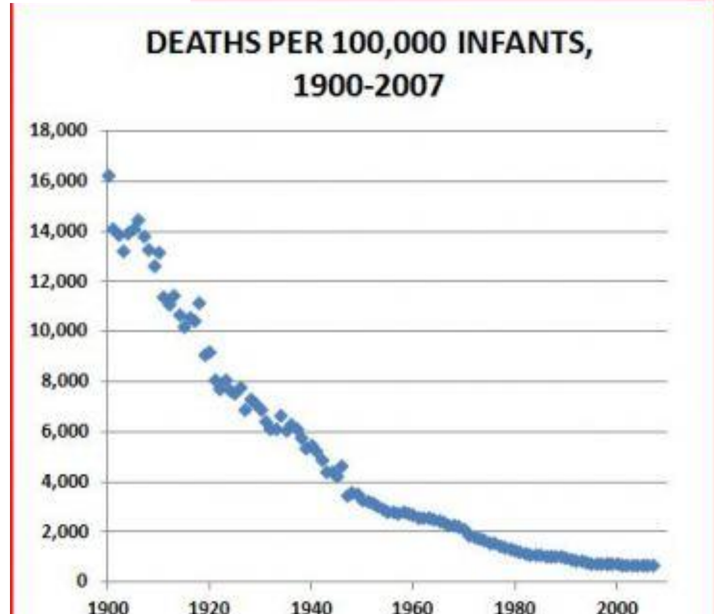
- the accelerating emergence of Science, Technology, Engineering, and Mathematics (STEM) . . .
- has lifted the possibility, quality, and length of life for a large portion of humanity . . .
- while dramatically increasing human future potential.
- By 20th Century close, strong STEM capability was recognized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

The length of human life has been dramatically extended.



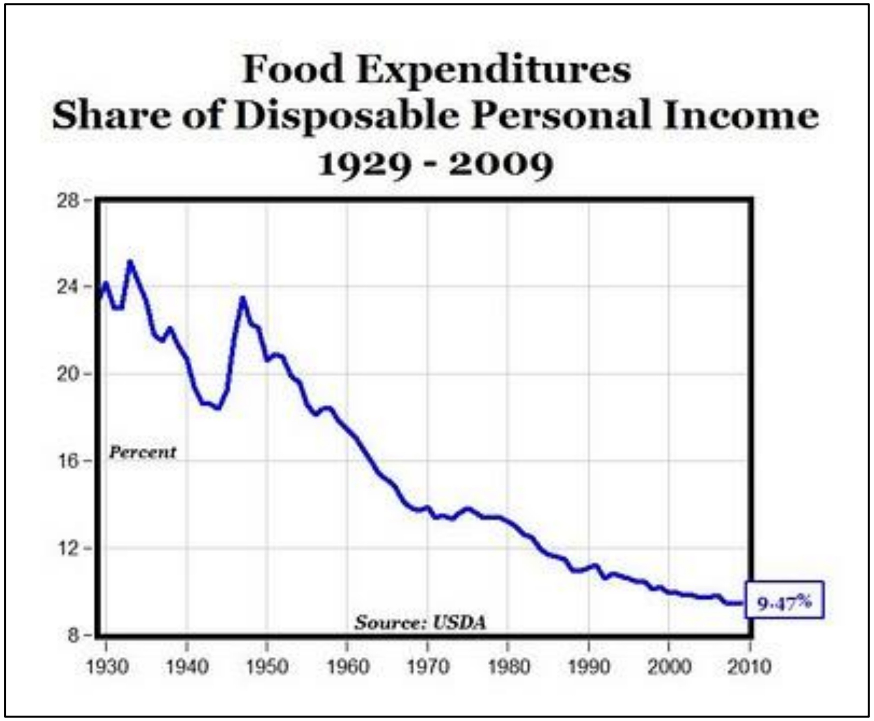


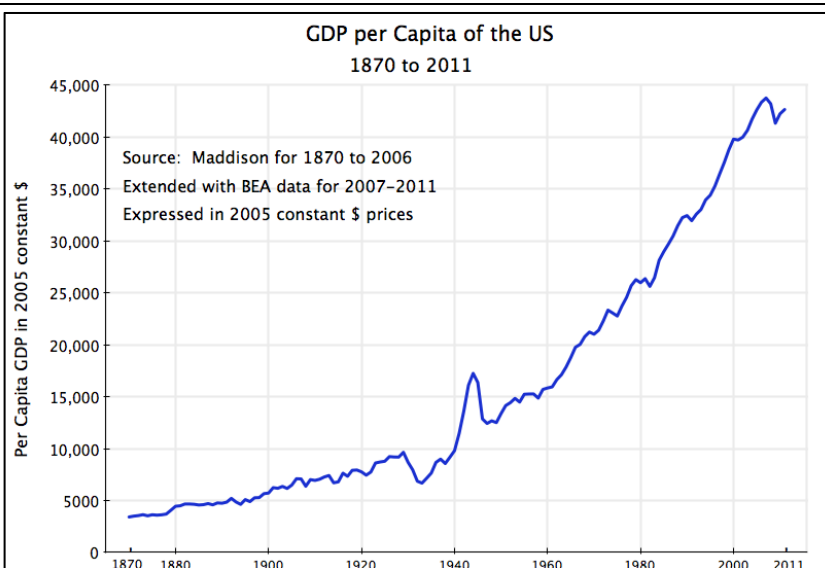
Life expectancy at birth in the U.S., 1900–2009 (source: Centers for Disease Control)

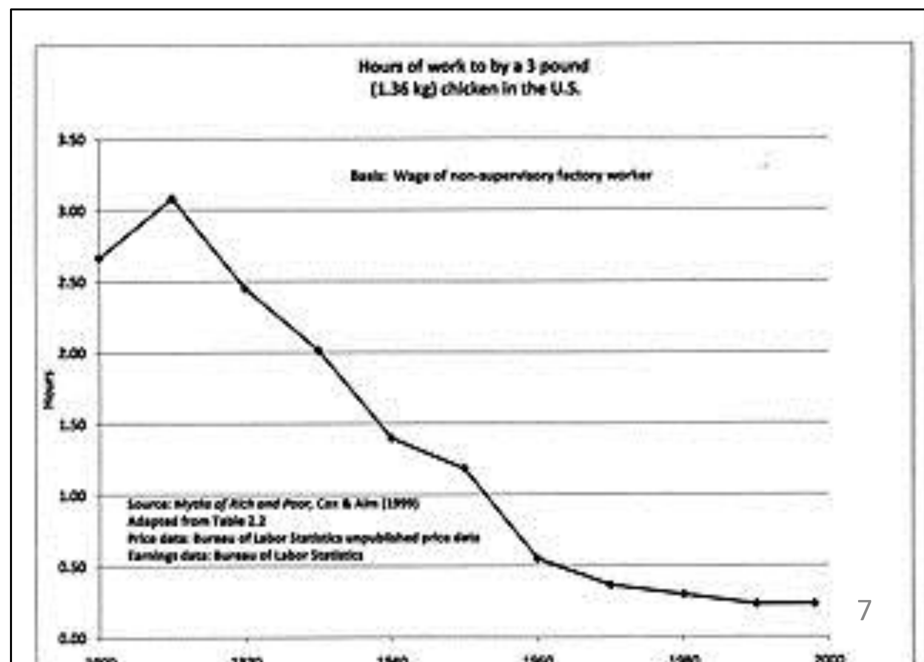


Sources: http://hsus.cambridge.org/HSUSWeb/toc/hsusHome.do; http://wonder.cdc.gov/

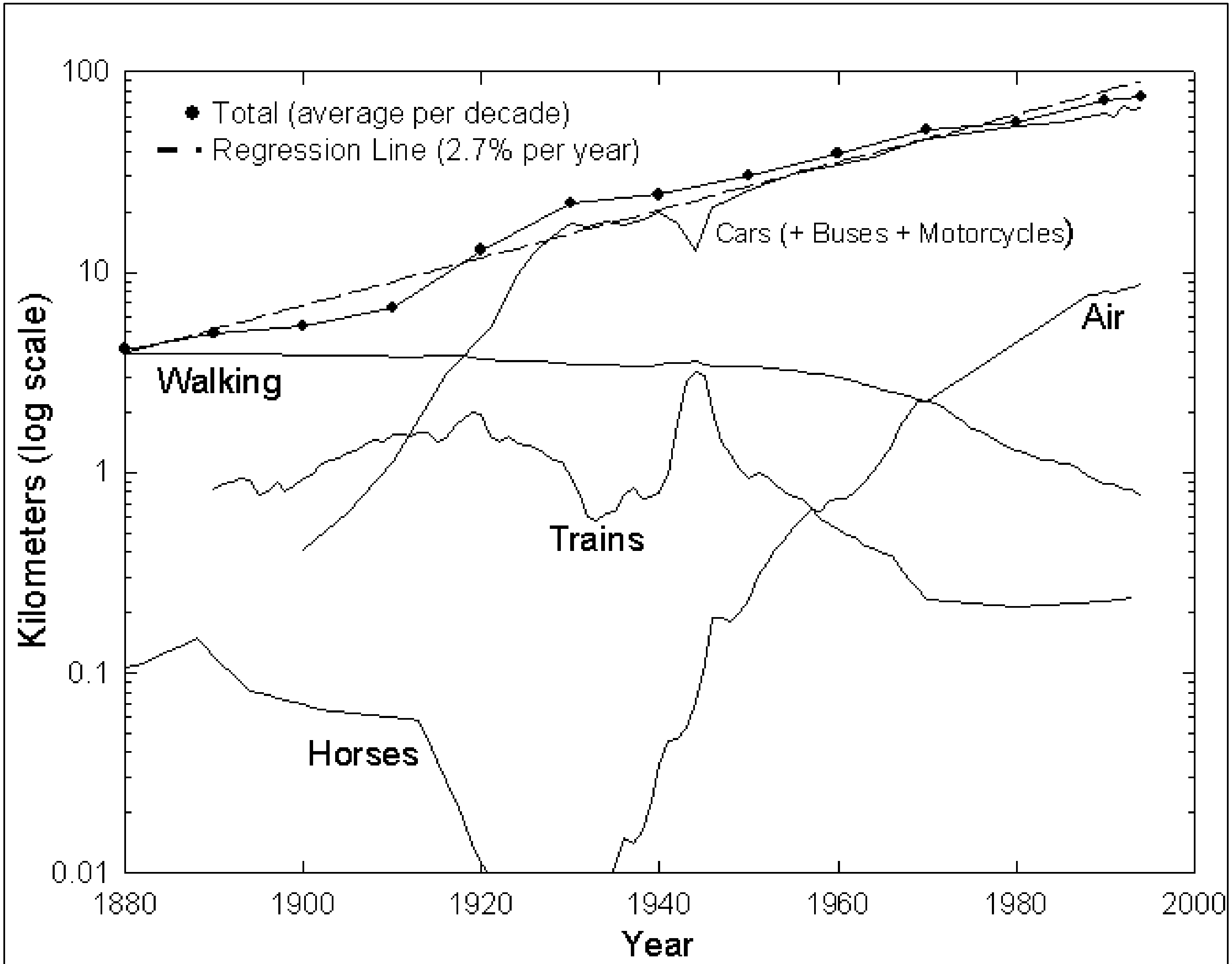
Simply feeding ourselves consumes less labor and time.







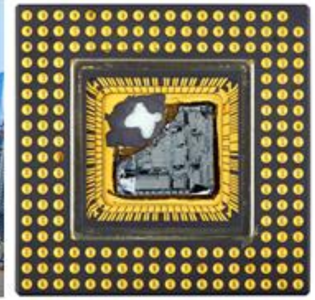
The range of individual human travel has vastly extended.



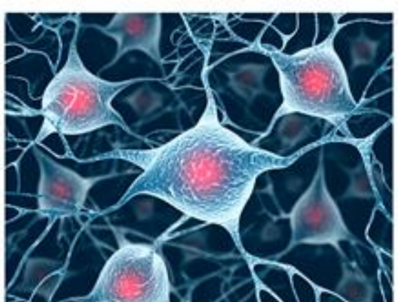
US passenger travel per capita per day by all modes.
Sources of data: Grubler , US Bureau of the Census , US Department of Transportation .

Challenges Have Likewise Emerged

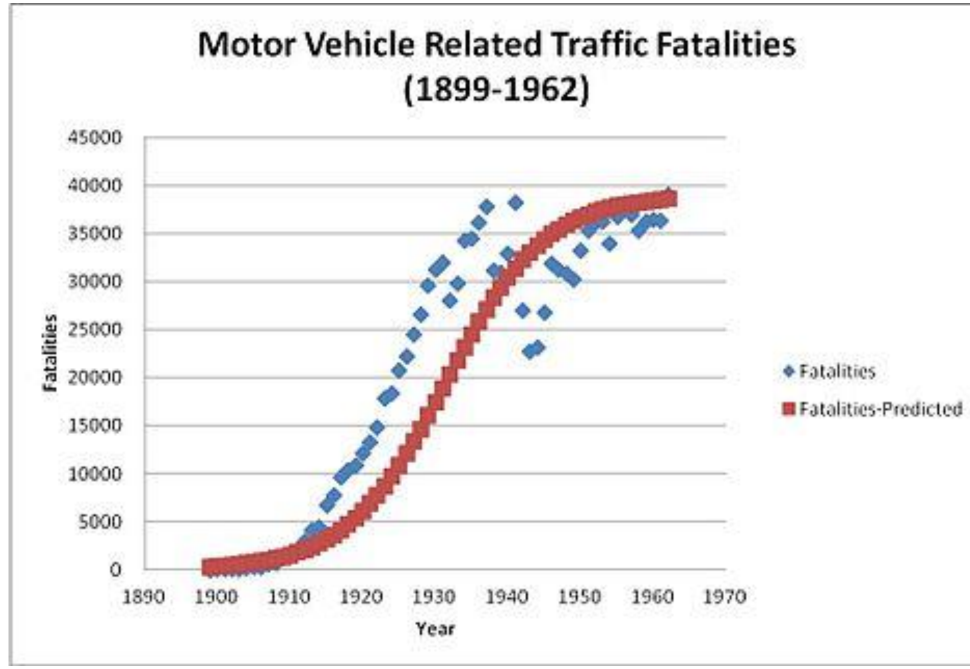


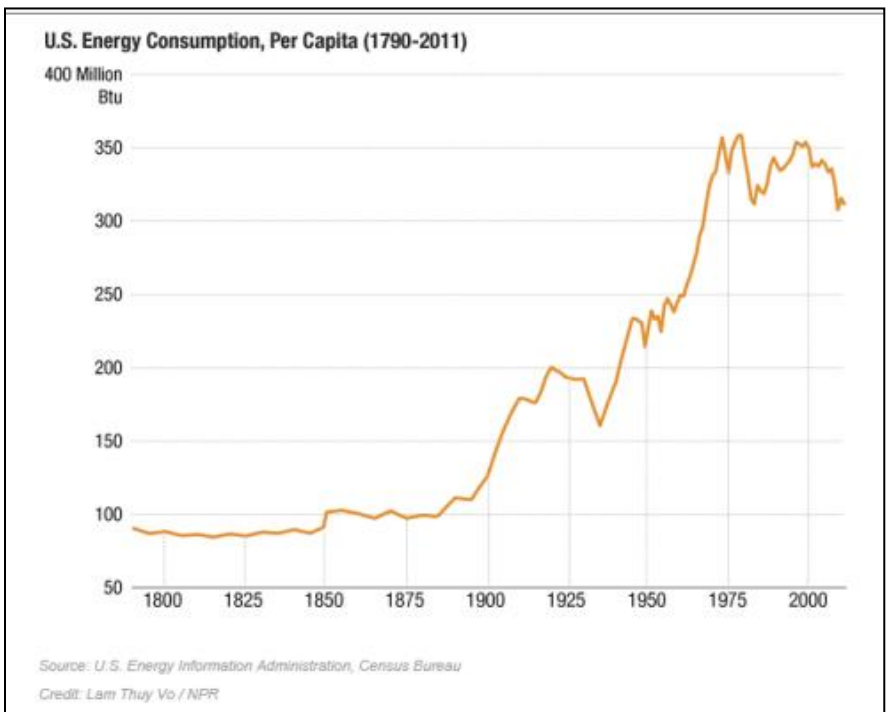


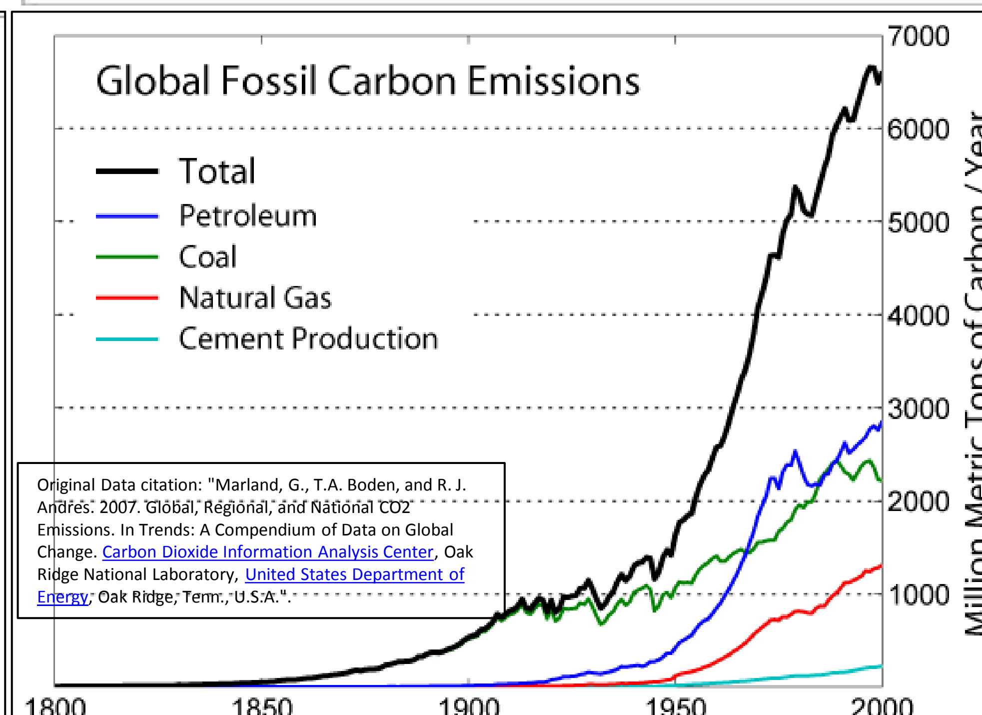

- In recent decades, the human-populated world has become vastly more interconnected, complex, and challenging . . .
- Offering both expanding opportunities and threats.
- From the smallest known constituents of matter and life, to the largest-scale complexities of networks, economies, the natural environment,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



Increased mobility, more available energy have come with challenging side effects.







Emergence of Science and Engineering

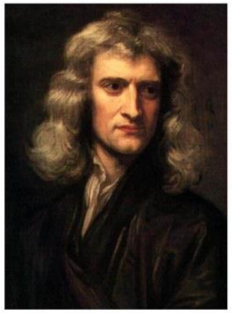
- The “hard sciences”, along with the engineering disciplines and technologies based on those sciences, may be credited with much of this amazing progress, as well as challenges.

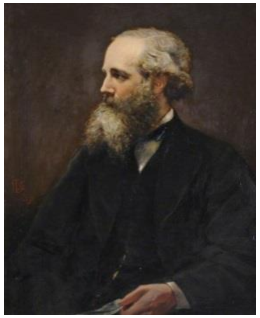
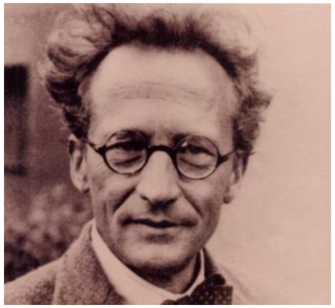
- How should Systems Engineering be compared to engineering disciplines based on the “hard sciences” ?

Phenomena-Base Engineering Disciplines

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

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



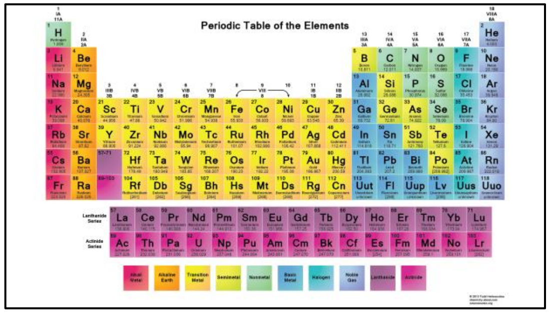
The Traditional Perspective

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

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

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

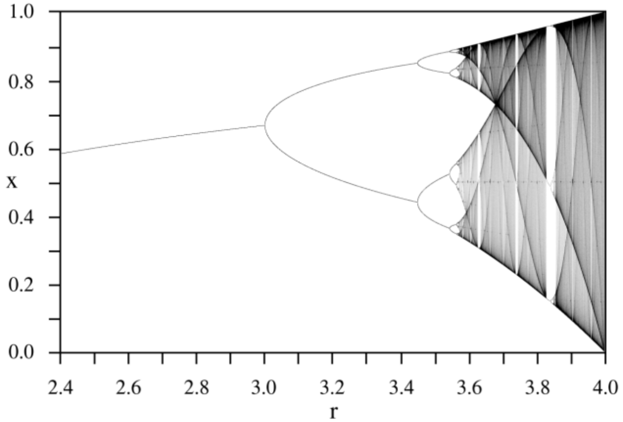
$$H(t)|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle$$

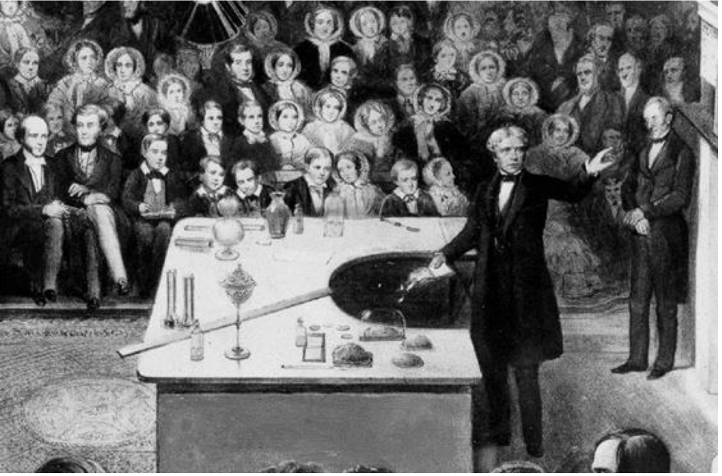
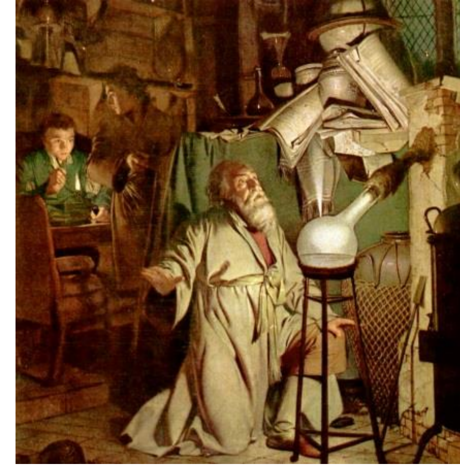


- Instead, Systems Engineering is sometimes viewed as:
  - Emphasizing process and procedure
  - Critical thinking and good writing skills
  - Organizing and accounting for information
- But not based on an underlying "hard science"

Traditional Perspective, continued

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



However . . .

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

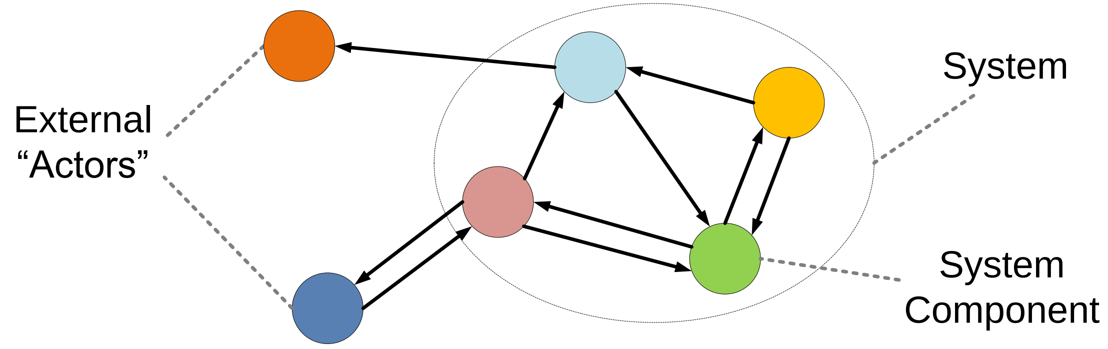
MBSE, PBSE: A Phase Change in Systems Engineering

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

The System Phenomenon

- "Phenomena" of the hard sciences are in each case instances of the 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

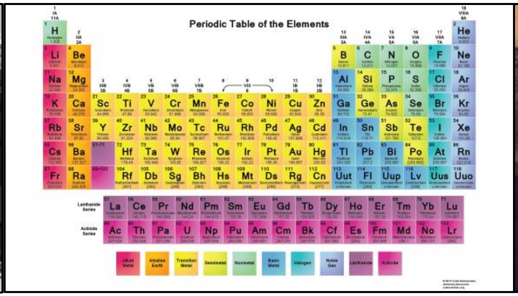
- Instead of Systems Engineering lacking the kind of theoretical foundation that the "hard sciences" bring to other engineering disciplines, . . .
  - It turns out that all those other engineering disciplines' foundations are themselves dependent upon the System Phenomenon.
  - The underlying math and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

Historical Example 1: Chemistry

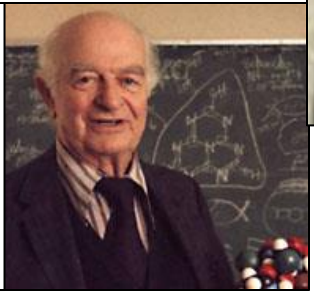
Priestley : Oxygen

Mendeleev: Periodic Table

Modern Chemist

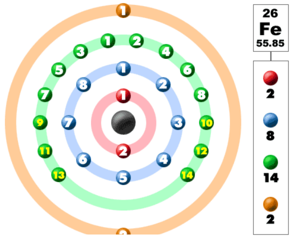


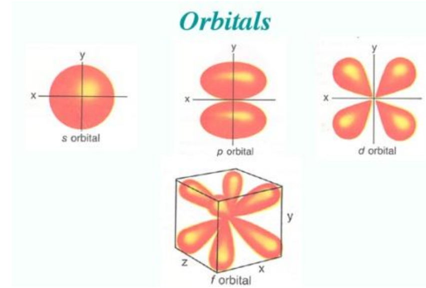
Periodic Table of the Elements

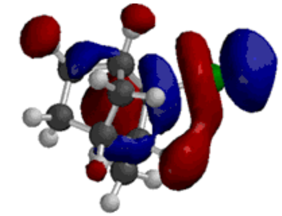


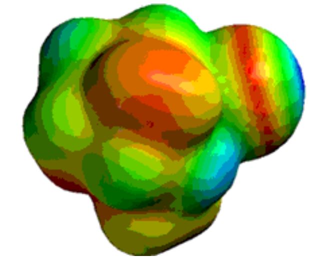
Pauling: Chemical Bond

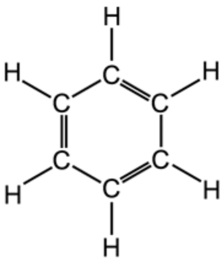
- Chemists, and Chemical Engineers, justifiably consider their disciplines to be based on the “hard phenomena” of Chemistry:
  - A view that emerged from the scientific discovery and verification of laws of Chemistry.
  - Chemical Elements and their Chemical Properties, organized by the discovered patterns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

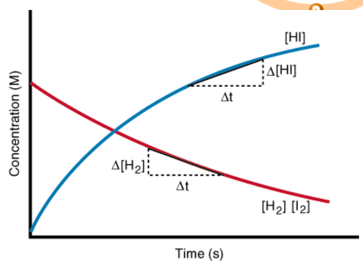


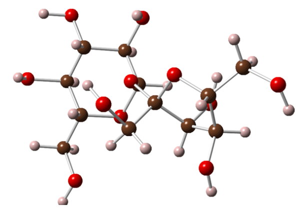


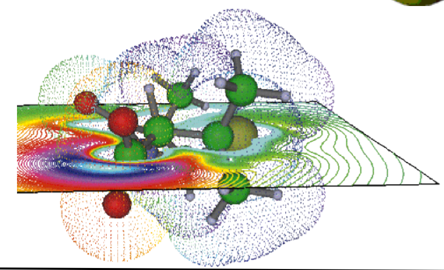






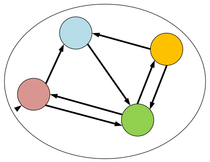






However . . .

- 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.



So . . .

- The "fundamental phenomena" of Chemistry, along with the scientifically-discovered / verified "fundamental laws / first principles" are in fact . . .
- Higher level emergent system patterns

  and . . .

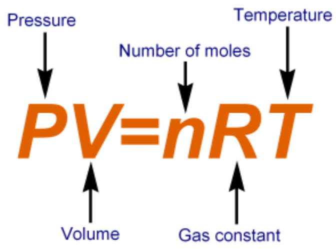
- Chemistry and Chemical Engineering study and apply those system patterns.

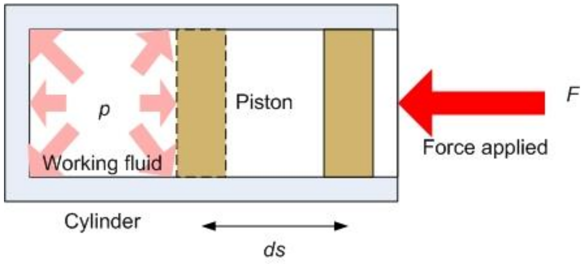
Boyle

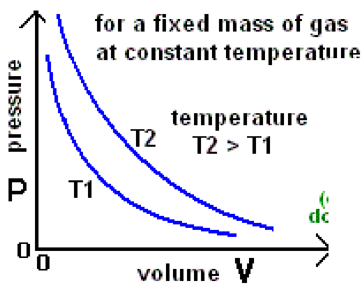
Historical Example 2: The Gas Laws and Fluid Flow

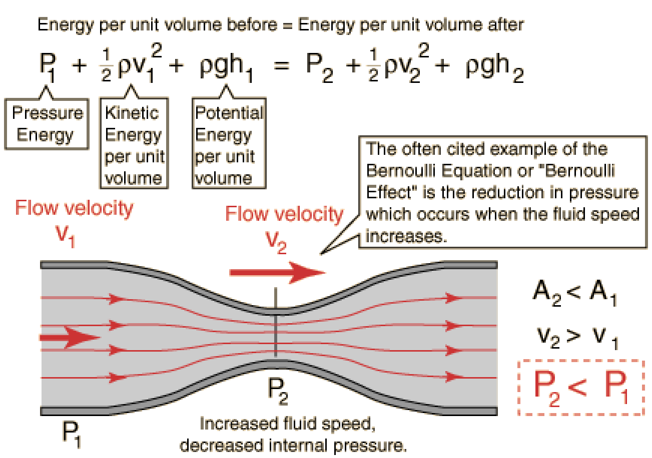
Daniel Bernoulli

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

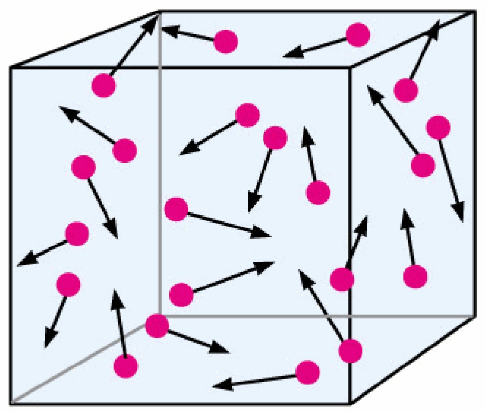


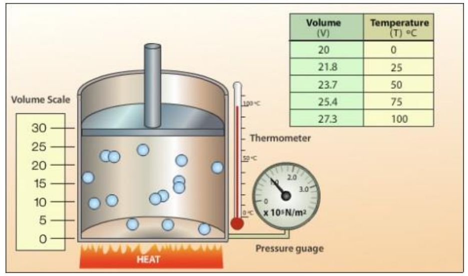




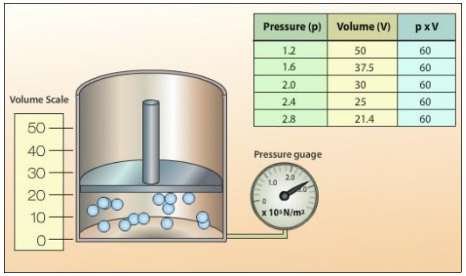


Gas Laws, continued





Volume (V)	Temperature (T) °C
20	0
21.8	25
23.7	50
25.4	75
27.3	100



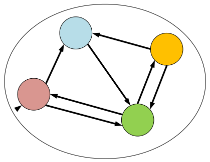
Pressure (p)	Volume (V)	p x V
1.2	50	60
1.6	37.5	60
2.0	30	60
2.4	25	60
2.8	21.4	60

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

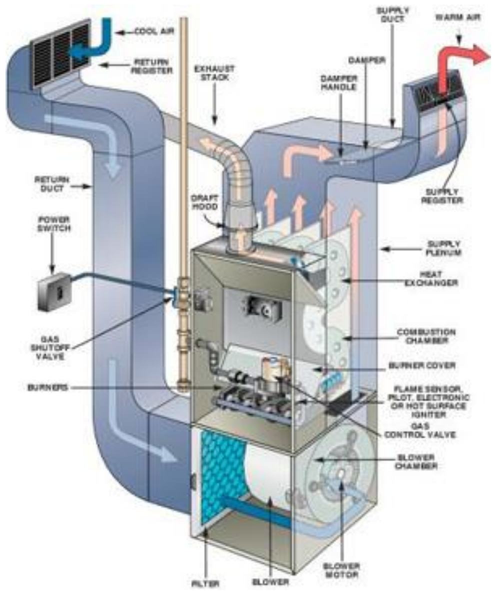

Boltzmann

However . . .

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



So . . .



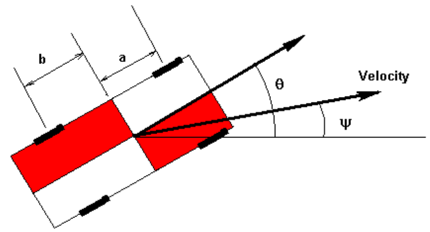
- The “fundamental phenomena” of gases, along with the scientifically-discovered / verified “fundamental laws and first principles” are in fact . . .
- higher level emergent <u>system patterns</u>

  so that . . .

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

More Recent Historical Examples

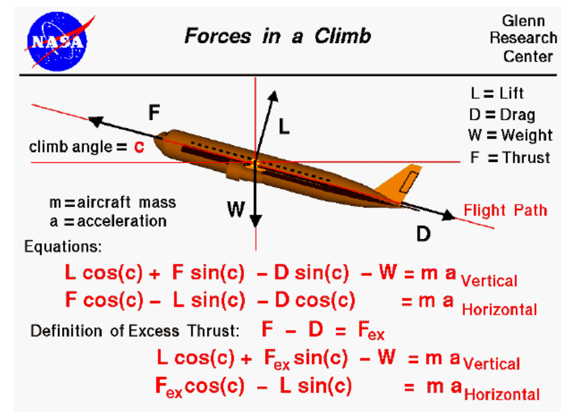
- Ground Vehicles
- Aircraft
- Marine Vessels
- Biological Regulatory Networks

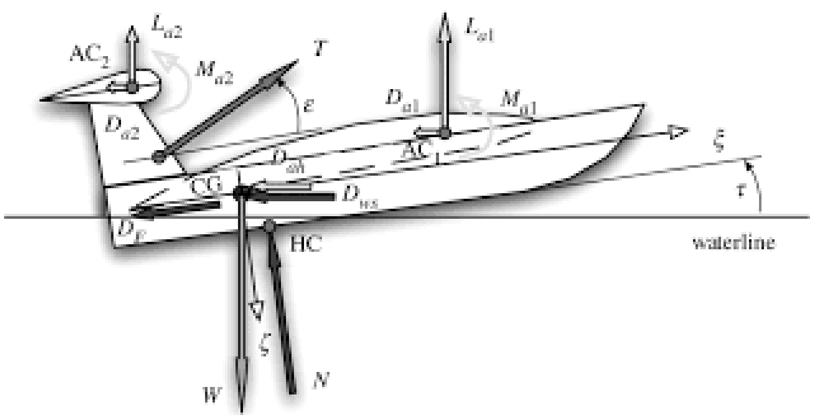


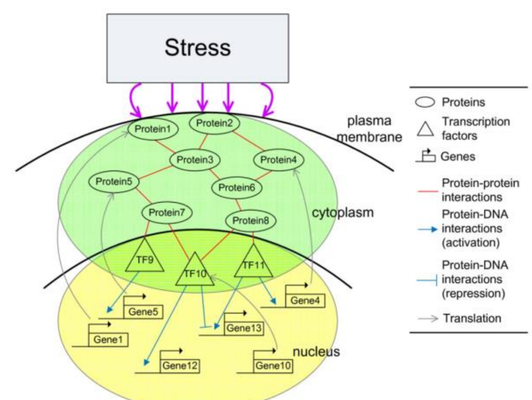
Dynamics of Road Vehicle

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

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

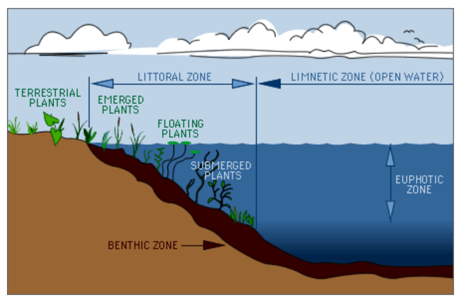


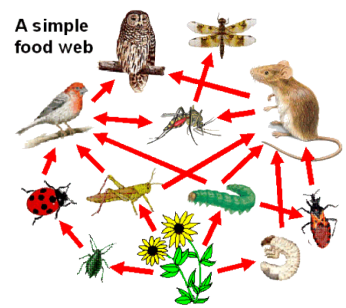


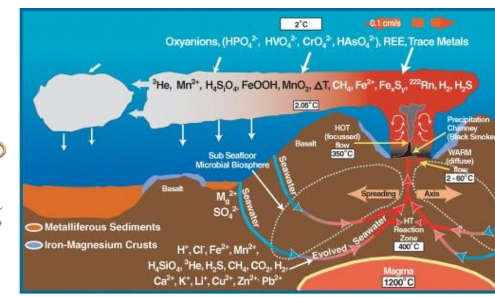


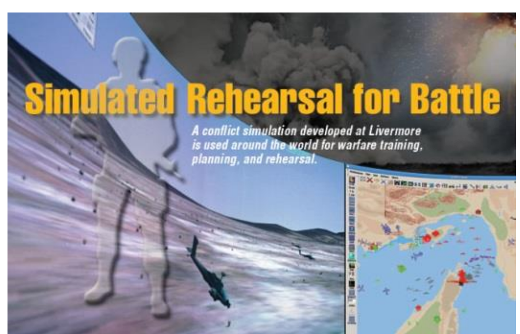
Future Applications

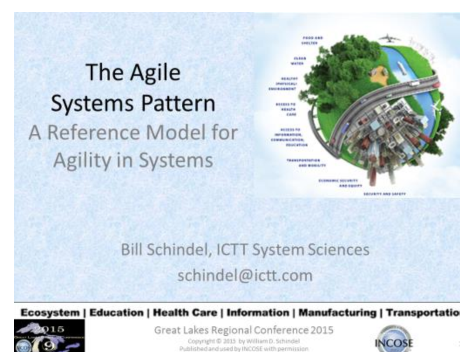
- Utility and other distribution networks
- Biological organisms and ecologies
- Market systems and economies
- Health care delivery, other societal services
- Systems of conflict
- Agile innovation





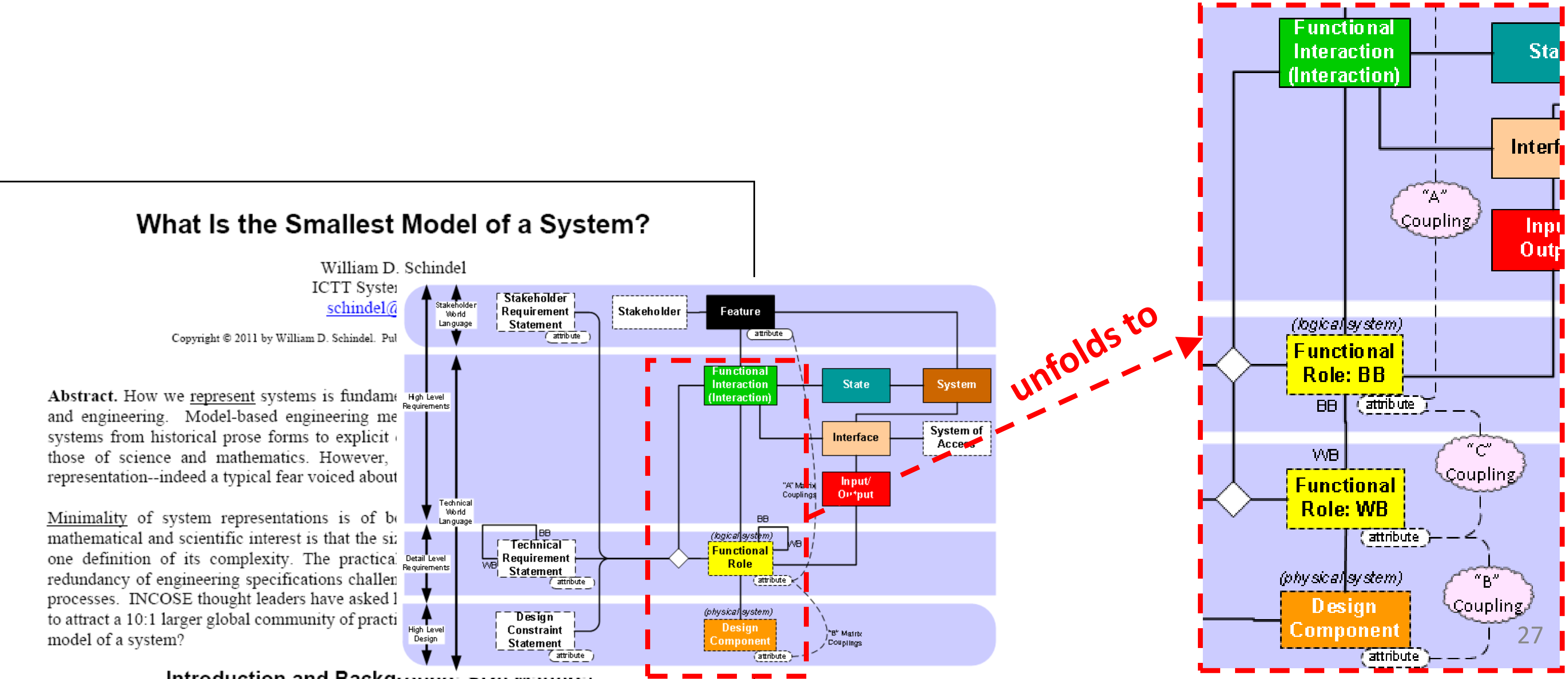


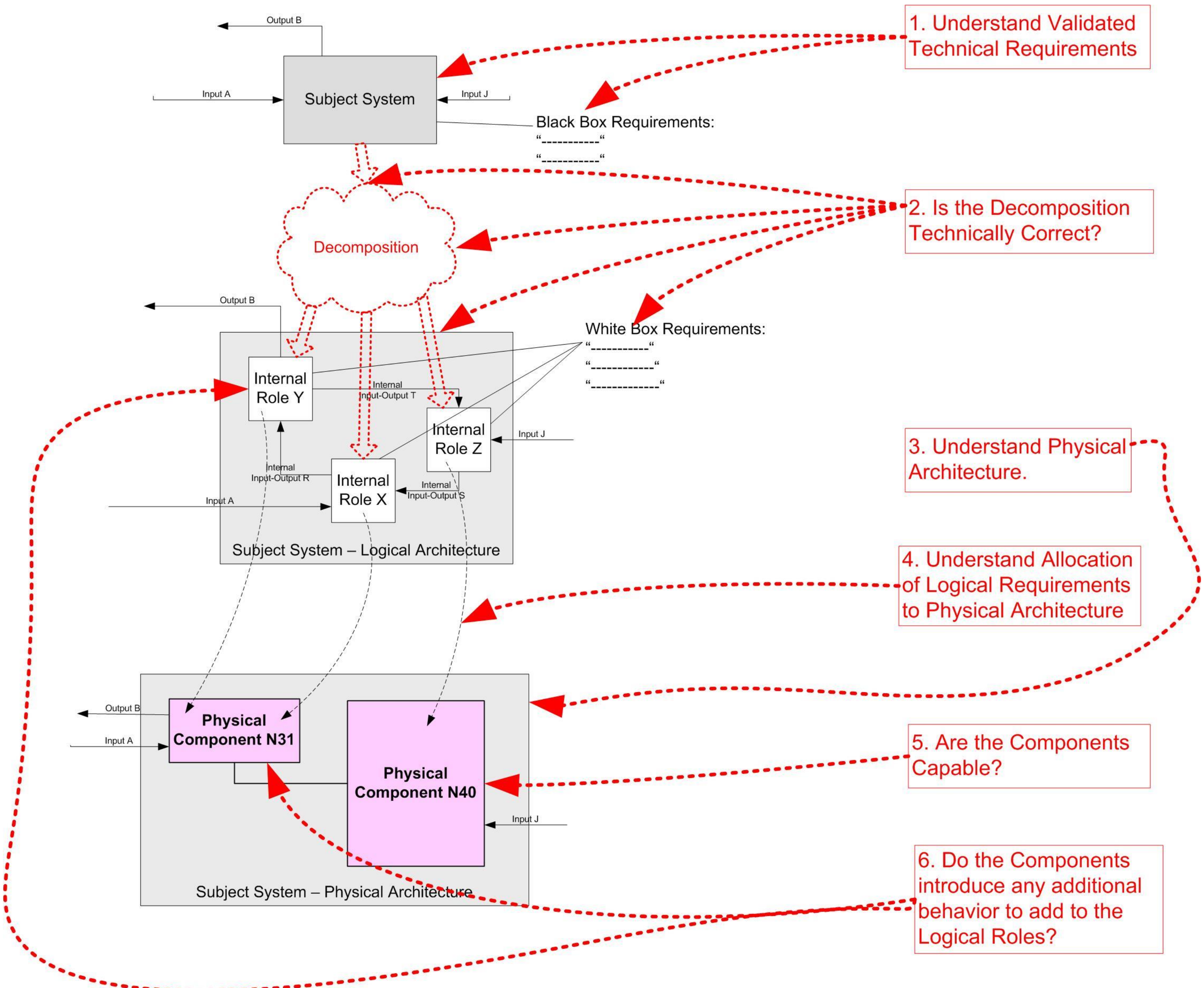




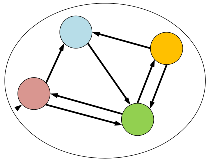
Strengthening the Foundations of MBSE

- 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:





1. Understand Validated Technical Requirements
Output B
Input A
Subject System
Input J
Black Box Requirements:
"-----------"
"-----------"
2. Is the Decomposition Technically Correct?
Decomposition
Output B
White Box Requirements:
"-----------"
"------------"
"-------------"
Internal Role Y
Internal Input-Output T
Internal Role Z
Input J
Internal Input-Output R
Internal Role X
Internal Input-Output S
Input A
Subject System – Logical Architecture
3. Understand Physical Architecture.
4. Understand Allocation of Logical Requirements to Physical Architecture
Output B
Input A
Physical Component N31
Physical Component N40
Input J
5. Are the Components Capable?
Subject System – Physical Architecture
6. Do the Components introduce any additional behavior to add to the Logical Roles?



What You Can Do

- Practice expressing your systems' requirements and designs using models that explicitly represent their interactions:
  - 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

References

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