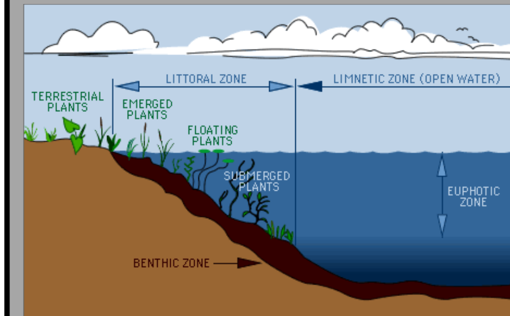
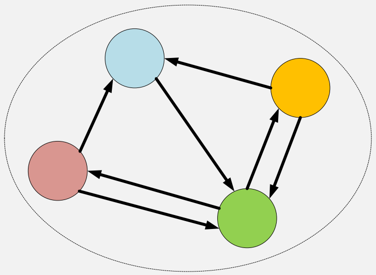




Where Do Systems Come From, and Where Do They Go?

S*Patterns in Model-Based Systems Engineering: Emergence of Purpose, Fitness, Value, Resilience

ISSS2016 Plenary VIII Panel:
Prospects for Scientific Systemic Synthesis

1.2.4

ICTT System Sciences

Bill Schindel
schindel@ictt.com

INCOSE
International Council on Systems Engineering

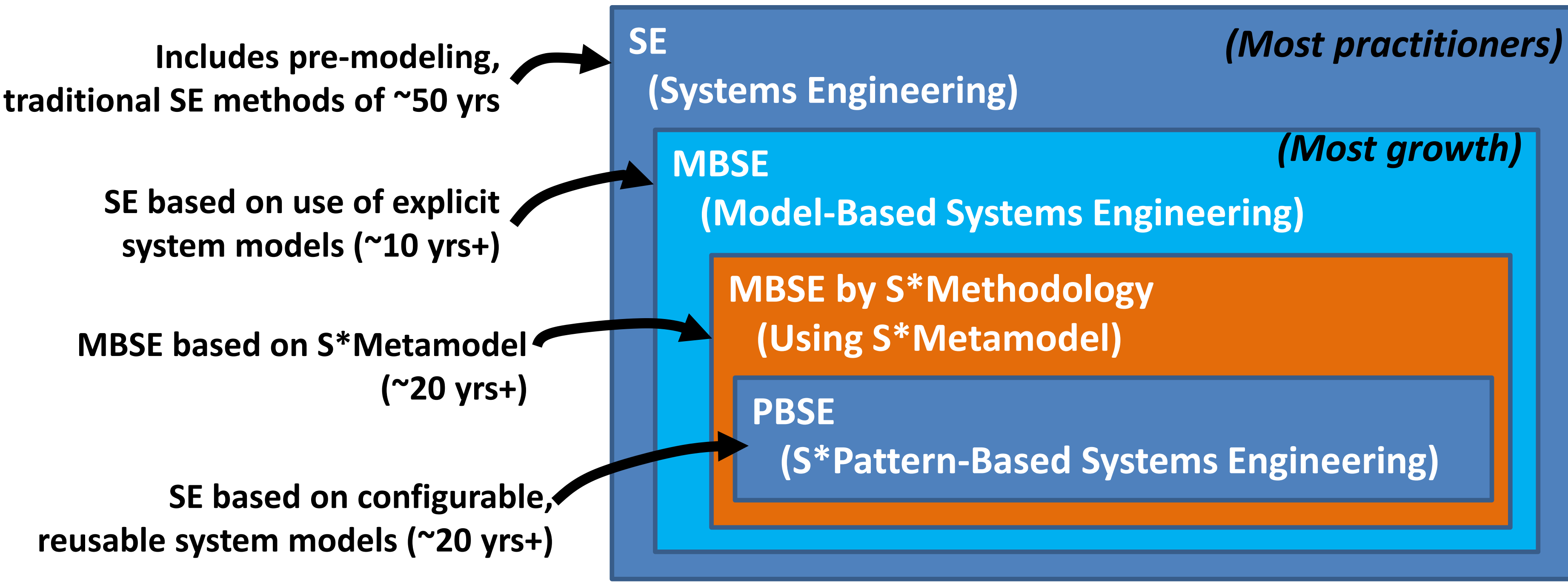
Contents

SOURCES OF THIS PERSPECTIVE

- **A System Engineer's Viewpoint**:
  - 40+ years in engineered systems, founding multiple systems businesses.
  - Aero, Telecom, Automotive, Health Care, Consumer Products, Advanced Manufacturing, Education, all manner of technologies, including living systems.
  - Last twenty years providing systems engineering assistance to Fortune 100 companies, pioneering & introducing Pattern-Based Systems Engineering Methodology, based on S*Metamodel, and recognizing engineering as a social enterprise.
  - Many S*Patterns across many domains, informed by existing or emerging sciences.
- **INCOSE (International Council on Systems Engineering)**:
  - Co-chair of INCOSE MBSE Patterns Working Group.
  - Member, INCOSE Agile Systems Discovery Project lead team.
  - INCOSE MBSE Transformation Lead Team.
  - INCOSE Chapter President, Crossroads of America.
- **ISSS-INCOSE Connections and MOU:**
  - Through INCOSE System Science Working Group (SSWG), met David Rousseau, John Kineman, Len Troncale, Jennifer Wilby.
  - Member of a 2013-14 SSWG MBSE Patterns Project, inspired by Len Troncale.
- **Academics:**
  - Applied Mathematics background in engineering contexts.
  - Short early stint as a young tenured faculty member, math & engineering, before businesses.
  - Just wrapped up 30+ years as trustee, including board academic affairs committee chair, twice chairing successful presidential searches.
  - ASEE series on teaching systems competencies for all engineering undergraduates.

1. A "Phase Change" in Systems Engineering

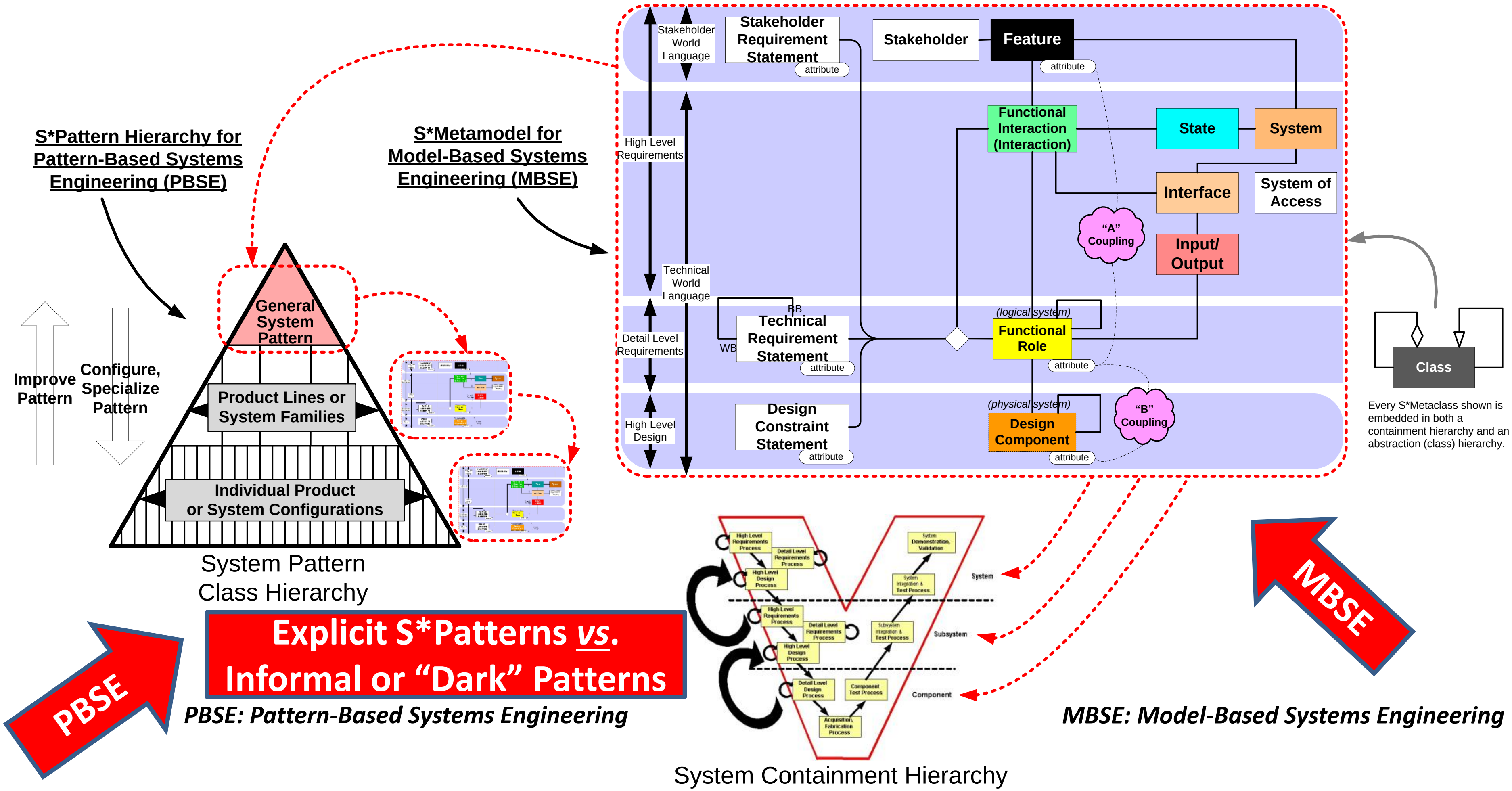
- A change of paradigm, to a model-based foundation:
  - Even the INCOSE Board of Directors has recognized as a strategic objective.
  - The traditional engineering disciplines (ME, ChE, CE, etc.) were closer to such a model-basis when they originated as applications of physical sciences, but SE originated in a different way.
  - And, the 10,000 member INCOSE community is not all doing the same systems engineering!



The S*Metamodel in Systems Engineering

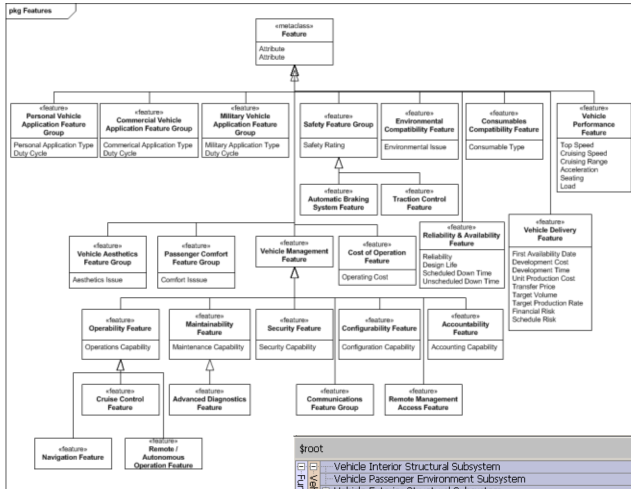
- Until recently, *unlike the other, science-based engineering disciplines*, what many SEs considered the foundation of MBSE "system models" was:
  - not based on natural phenomena from science, . . .
  - but instead the underlying data models of modeling languages & toolsets (perspective contributed by IT world),
  - which is not the same as underlying model of the world they describe.
  - Today, still trailing the burden of some of that history, versus a stronger foundation.
  - Not a good basis for a science-based engineering discipline!
  - Still in flux, but now starting to return to traditional science-based roots in nature and mathematics, and strengthening model-based foundations.

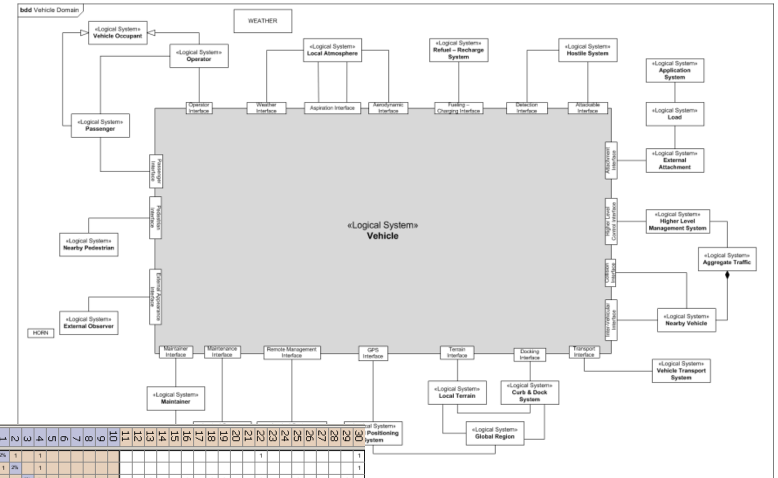
- The S*Metamodel figures into that foundation, as follows . . .

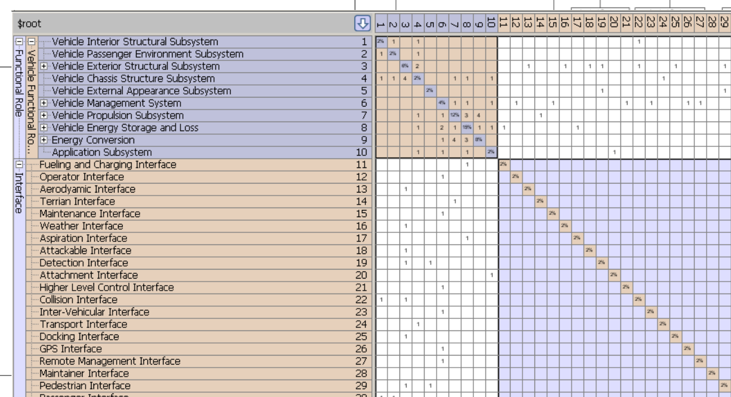


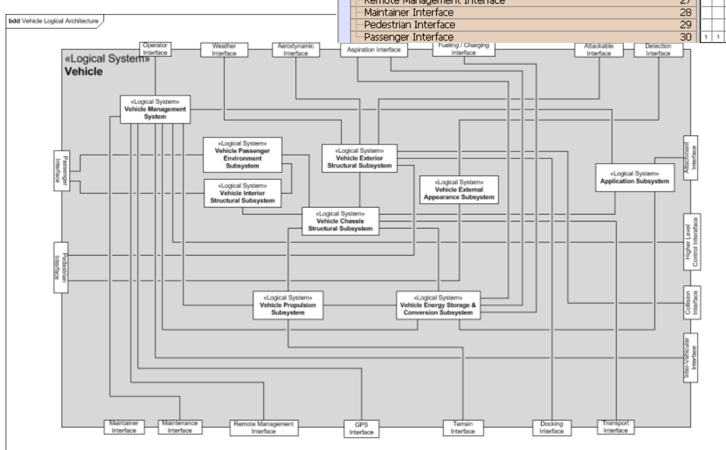
- Metamodel: An underlying relational framework, "model of models".
- S* covers the <u>*smallest model framework necessary for engineering & science purposes*</u>.
- <u>S*Models</u> are system models that conform to the S*Metamodel.
- S* is agnostic as to modeling language (e.g., SysML, UML, OPM, etc.) and modeling tools (can be used with potentially any of them, through profiling, and have mapped into many).
- Above is an <u>informal summary</u> of key subset; the <u>formal</u> S*Metamodel is described in UML.

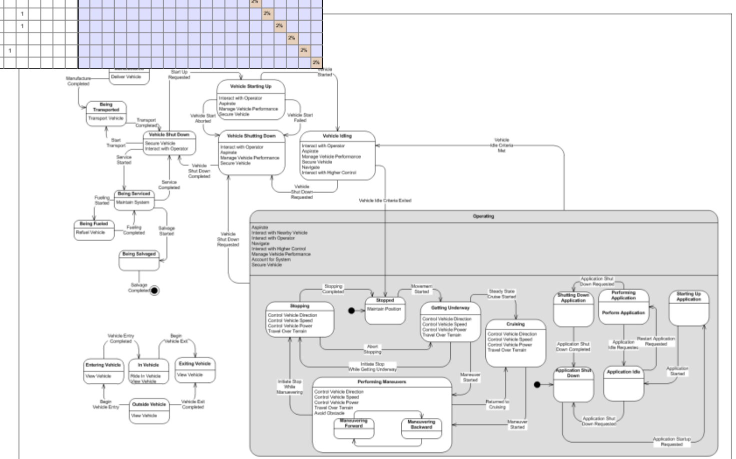
Extracts from Terrestrial Vehicle S*Pattern



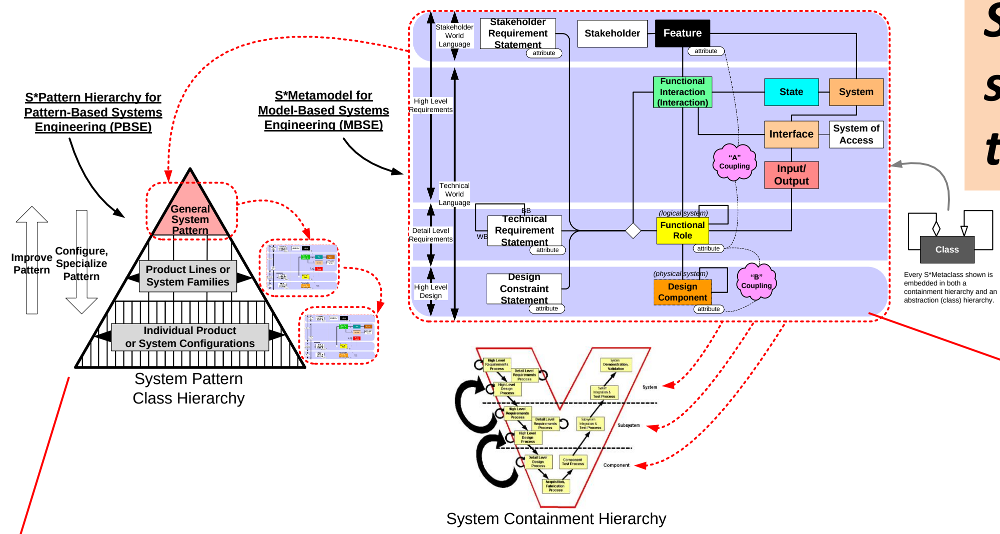








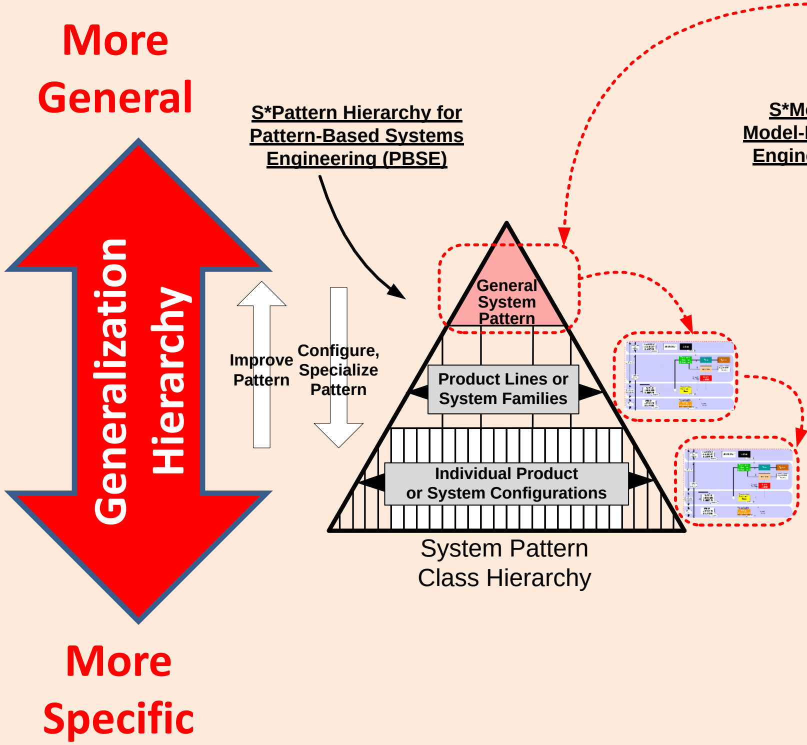
*S*Pattern construction and use over several decades, many domains, technologies, multiple INCOSE WGs.*

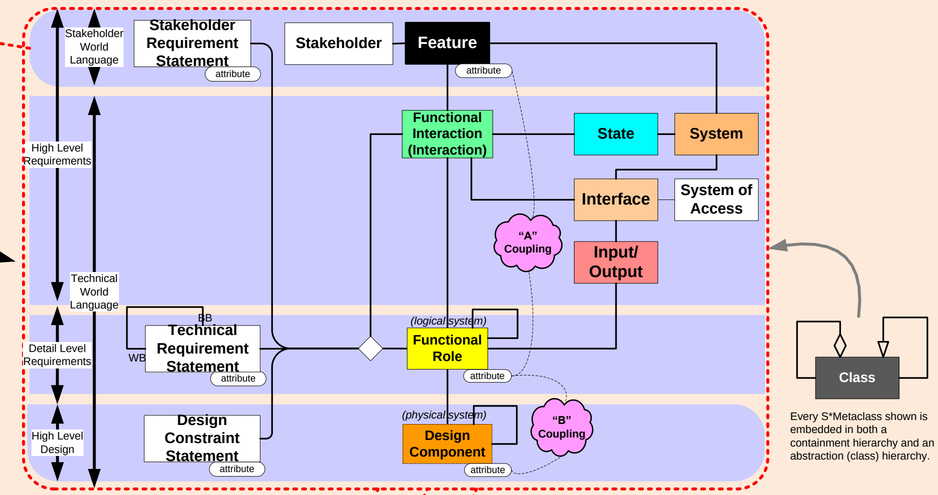


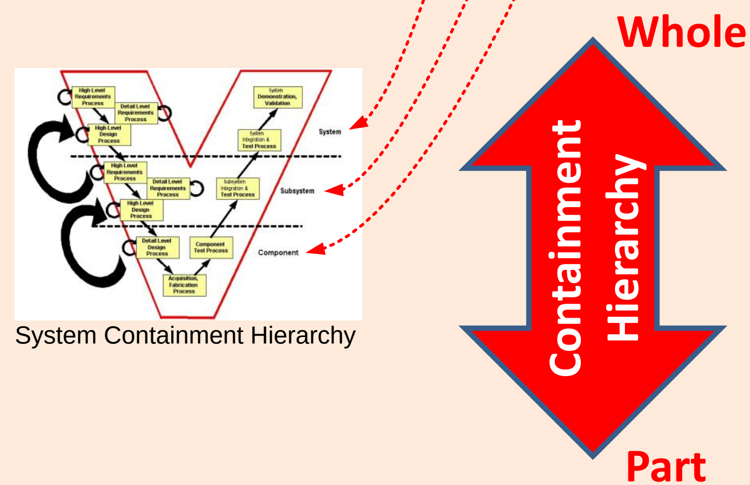
Medical Devices Patterns	Construction Equipment Patterns	Commercial Vehicle Patterns	Space Tourism Pattern
Manufacturing Process Patterns	Vision System Patterns	Packaging Systems Patterns	Lawnmower Product Line Pattern
Embedded Intelligence Patterns	Systems of Innovation (SOI) Pattern	Multiple Consumer Products Patterns	Orbital Satellite Pattern
Product Service System Patterns	Product Distribution System Patterns	Plant Operations & Maintenance System Patterns	Oil Filter Pattern
Life Cycle Management System Patterns	Production Material Handling Patterns	Engine Controls Patterns	Military Radio Systems Pattern
Agile Systems Engineering Life Cycle Pattern	Transmission Systems Pattern	Precision Parts Production, Sales, and Engineering Pattern	Higher Education Experiential Pattern

- Commercially applied across wide range of domains and technologies for 20+ years.
- Used by INCOSE MBSE **Patterns Working Group** and its joint projects with other INCOSE WGs, including **Agile Systems WG**, **Product Line Engineering WG**, & **System of Systems WG**.

Two entirely different hierarchies are involved:





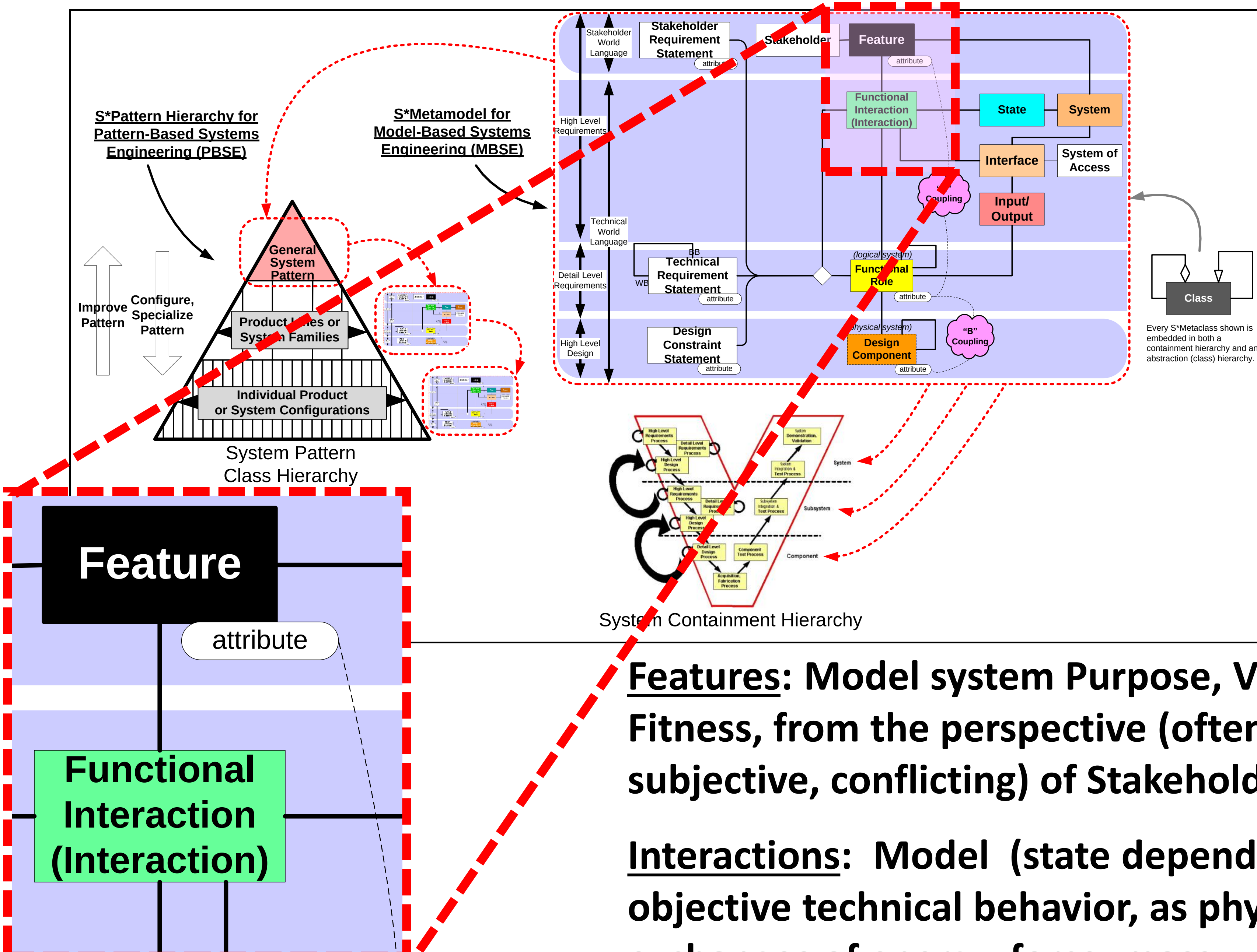


What Is the Smallest Model of a System?

William D. Schindel
ICTT System Sciences
schindel@ictt.com

Abstract. How we represent systems is fundamental to the history of mathematics, science, and engineering. Model-based engineering methods shift the nature of representation of systems from historical prose forms to explicit data structures more directly comparable to those of science and mathematics. However, using models does not guarantee simpler representation--indeed a typical fear voiced about models is that they may be too complex.

Minimality of system representations is of both theoretical and practical interest. The mathematical and scientific interest is that the size of a system's "minimal representation" is one definition of its complexity. The practical engineering interest is that the size and redundancy of engineering specifications challenge the effectiveness of systems engineering processes. INCOSE thought leaders have asked how systems work can be made 10:1 simpler to attract a 10:1 larger global community of practitioners. And so, we ask: What is the smallest model of a system?



<u>Features</u>: Model system Purpose, Value, Fitness, from the perspective (often subjective, conflicting) of Stakeholders.

<u>Interactions</u>: Model (state dependent) objective technical behavior, as physical exchanges of energy, force, mass, information, resulting in change of state.

2. Interactions and the Systems Phenomenon

Systems engineering has passed through a different path than the other engineering disciplines which were better connected to underlying phenomena-based physical sciences . . .

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

Got Phenomena? Science-Based Disciplines for Emerging Systems Challenges

Bill Schindel
ICTT System Sciences
schindel@ictt.com

Abstract. Engineering disciplines (ME, EE, CE, ChE) sometimes argue their fields have "real physical phenomena", "hard science" based laws, and first principles, claiming Systems Engineering lacks equivalent phenomenological foundation. We argue the opposite, and how replanting systems engineering in MBSE/PBSE supports emergence of new hard sciences and phenomena-based domain disciplines.

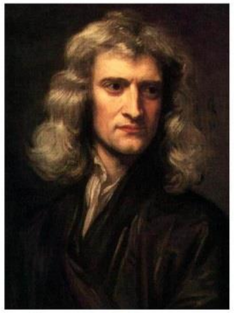
Supporting this perspective is the System Phenomenon, wellspring of engineering opportunities and challenges. Governed by Hamilton's Principle, it is a traditional path for derivation of equations of motion or physical laws of so-called "fundamental" physical phenomena of mechanics, electromagnetics, chemistry, and thermodynamics.

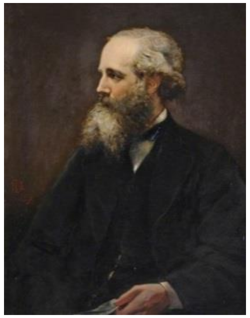
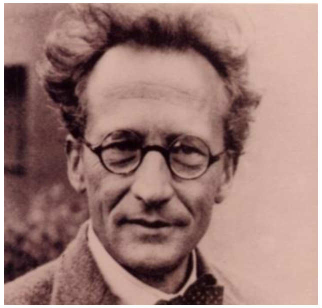
We argue that laws and phenomena of traditional disciplines are less fundamental than the System Phenomenon from which they spring. This is a practical reminder of emerging higher disciplines, with phenomena, first principles, and physical laws. Contemporary examples include ground vehicles, aircraft, marine vessels, and biochemical networks; ahead are health care, distribution networks, market systems, ecologies, and the IoT.

Phenomena-Based Engineering Disciplines

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

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



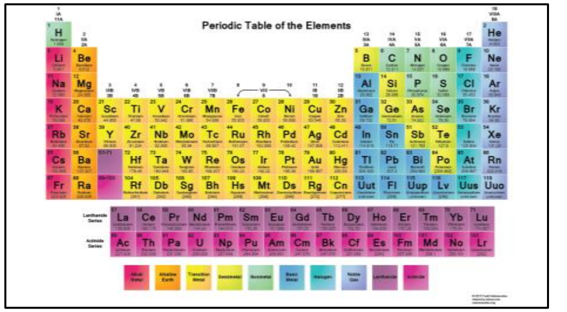
The Traditional Perspective

- 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.

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

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

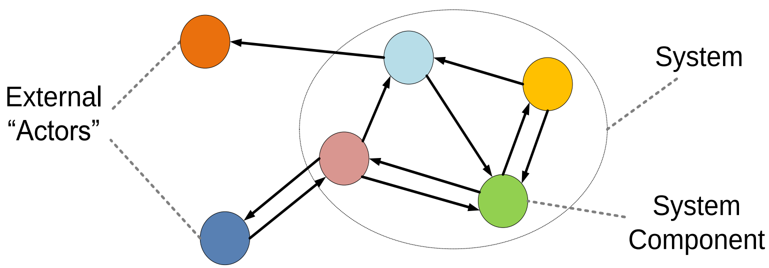
$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

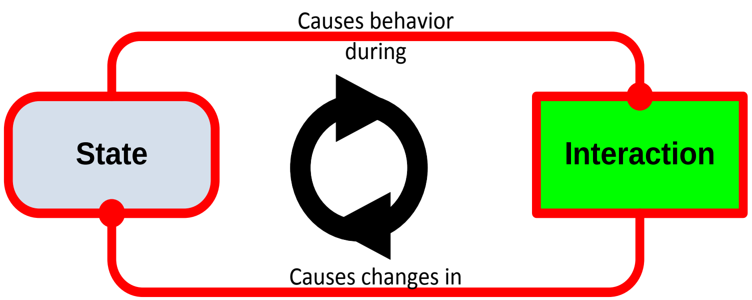


- Instead, Systems Engineering is sometimes viewed as:
  - Emphasizing process and procedure
  - Critical thinking and good writing skills
  - Organizing and accounting for information
- But not based on an underlying “hard science” and “phenomena”.

The System Phenomenon

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



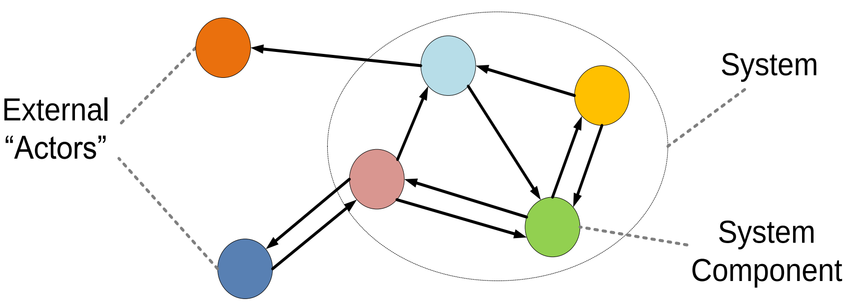


- Where interaction involves the exchange of energy, force, mass, or information, . . .
- Through which one component impacts the state of another component, . . .
- And in which the state of a component impacts its behavior in future interactions.

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:

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

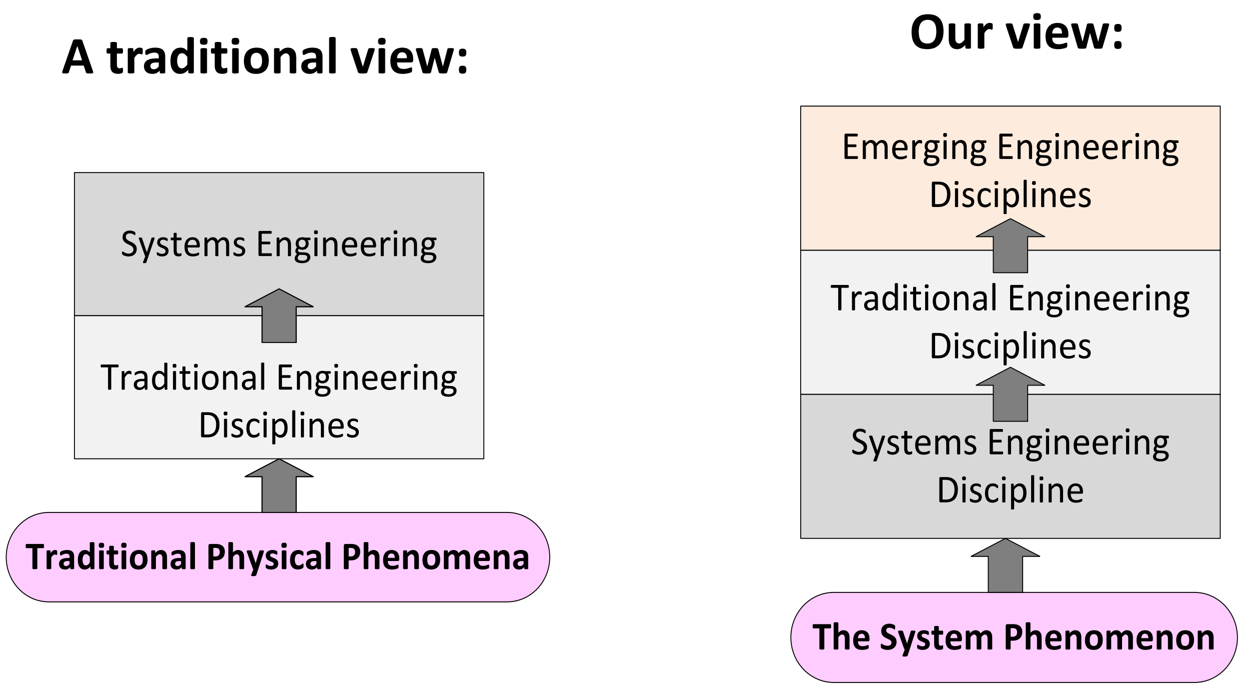


- Reduced to simplest forms, the resulting equations of motion (or if not solvable, empirically observed paths) provide "physical laws" subject to scientific verification.

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.
- Examples:
  - Chemistry, arising out of electron & other interactions
  - The gas laws, arising out of particle & other interactions

The System Phenomenon



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

3. Emergence of Purpose, Value, Fitness in an Ecology of Interactions

Fitness, Value, Innovation, in S*Feature Space

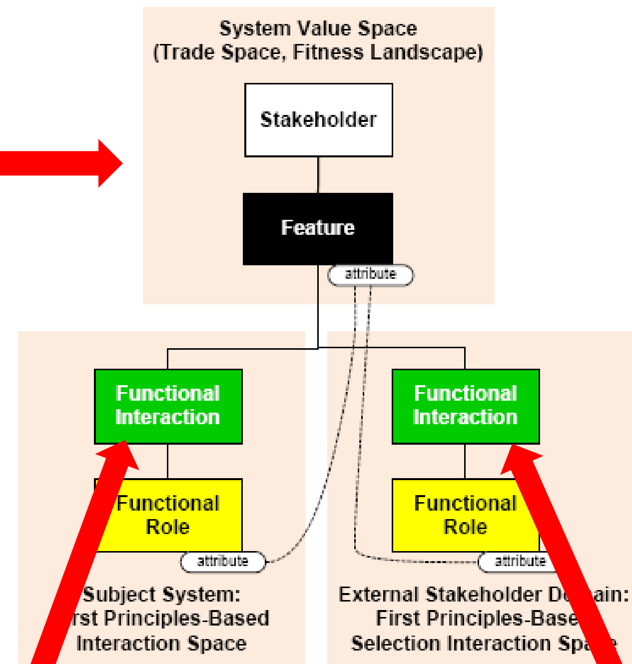


Figure 7: S*Agile Syst ns Engineering Life Cycle Pattern extract, highlightin System Value which is genera d via interactions - the first principles of engineering an science

System Performance Interaction

System Selection (or De-Selection) Interaction

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

Explicating System Value through First Principles:
Re-Uniting Decision Analysis with Systems Engineering

Troy Peterson
Technical Fellow
Chief Engineer
Booz Allen Hamilton
Troy, MI 48084

Bill Schindel
President
ICTT System Sciences
Terre Haute, IN 47803

Abstract. System complexity continues to grow, creating many new challenges for engineers and decision makers. To maximize value delivery, "both" Systems Engineering and Decision Analysis are essential. The systems engineering profession has had a significant focus on improving systems engineering processes. While process plays an important role, the focus on process was often at the expense of foundational engineering axioms and their contribution to system value. As a consequence, Systems Engineers were viewed as process developers and managers versus technical leaders with a deep understanding of how system interactions are linked to stakeholder value.. With the recent shift toward Model Based Systems Engineering (MBSE), Systems Engineering is "getting back to basics," focusing on value delivery via first principles, using established laws of engineering and science. This paper describes how Pattern Based Systems Engineering (PBSE), as outlined within INCOSE's Model Based Systems Engineering (MBSE) initiative, explicates system value through modeling of first principles, re-uniting Systems Engineering and Decision Analysis capabilities.

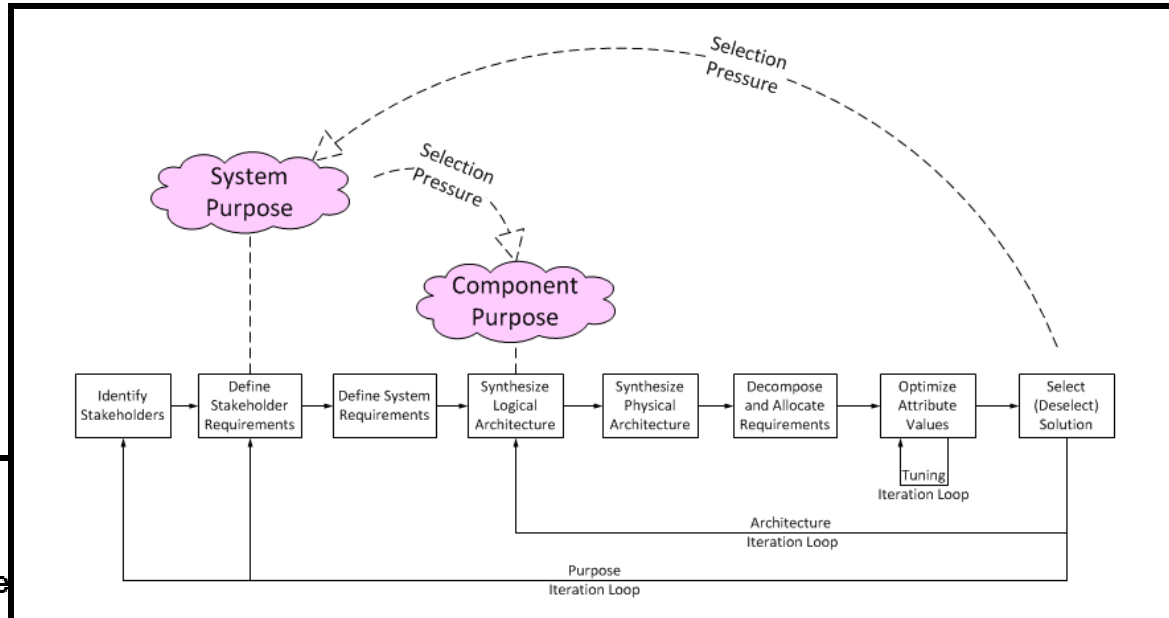
S*Patterns Emphasize <u>*Complete*</u> Stakeholder-Feature Models

- Features: Model system Purpose, Value, Fitness, from the perspective (often subjective, conflicting) of Stakeholders.
- Scope of S*Model includes <u>**all**</u> system stakeholders, and therefore all the values / fitness measures of all of them — even when they conflict.
- Feature Space is the "scoreboard" for all decisions, actions, judgements concerning the subject system--including ethical and other aspects.
- What systems engineers call "trade space", model of value conflicts.
- S*Patterns: Features express <u>selectable</u> options/partitions, configuring system based on capabilities, challenges, situations.
- Features form the basis of system selection, <u>*and*</u> are formed by it.
- Features also express all risks—the only risks are stakeholder risks.
- And, Features also express all the (negative) "Effects", of MBSE version of Failure Modes, Effects, and Criticality Analysis (FEMCA), risk analysis.

4. The System of Innovation (SOI) Pattern:

This pattern models Innovation itself, not just the innovated thing—and it is highly non-linear, iterated, & exploratory.

Includes Purpose-Discovery Loop



Systems of Innovation II:

The Emergence of Purpose

William D. Schindel

ICTT System Sciences

schindel@ictt.com

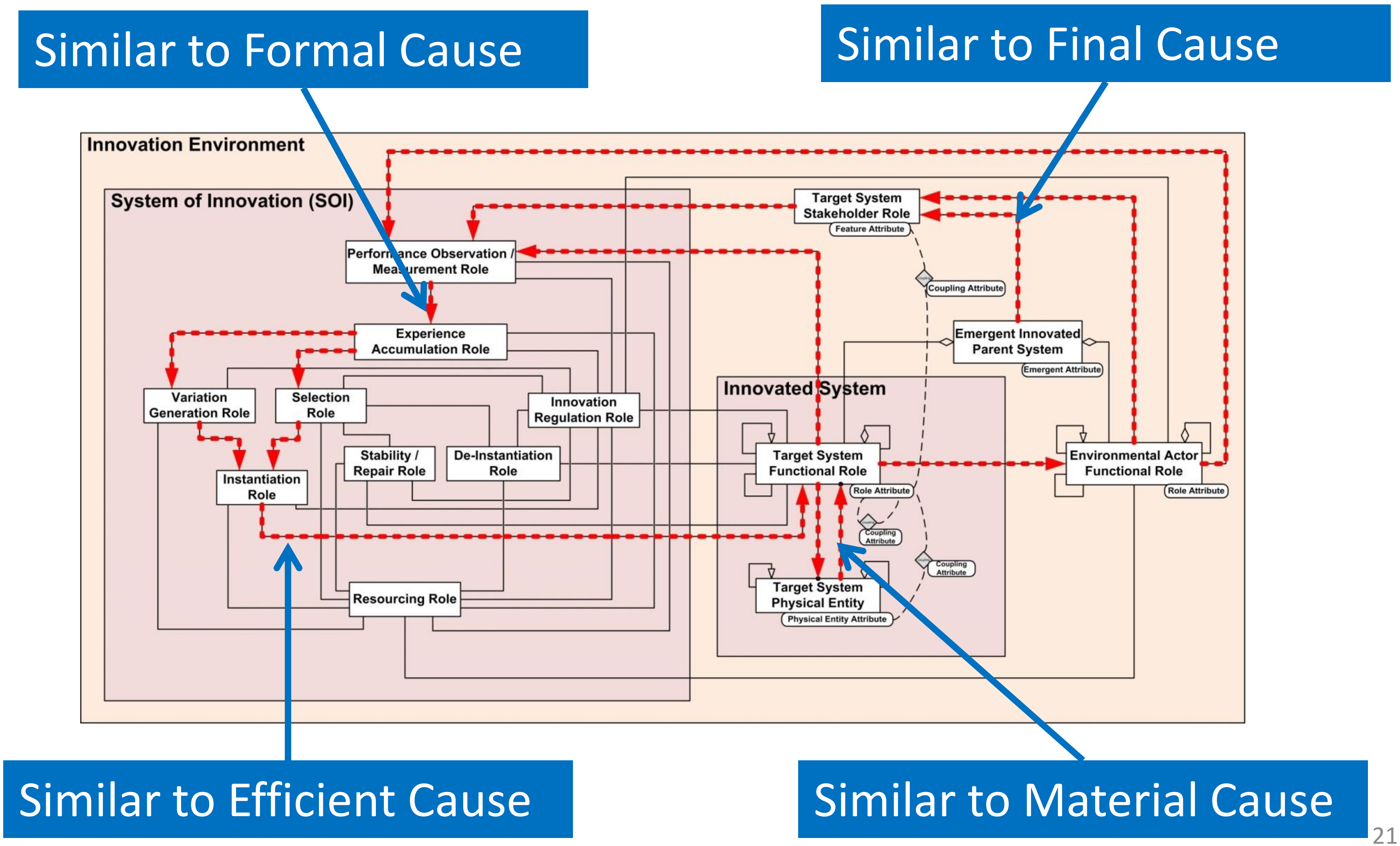
Abstract. Engineers design mindful of the purpose of a system. So, engineering conceptual definitions of the concept of "system" frequently include the idea of purpose.

However, we also use "system" to describe things not human-designed. We might refer to purpose in living systems, as in the immune system, but biologists use "function" to avoid this. What about inanimate natural systems? Do Saturn's rings have a purpose, or function? And what about pathologies, when systems don't work as they "should"? Do all these "systems" terms and concepts serve us well across these different domains, or are some force-fit?

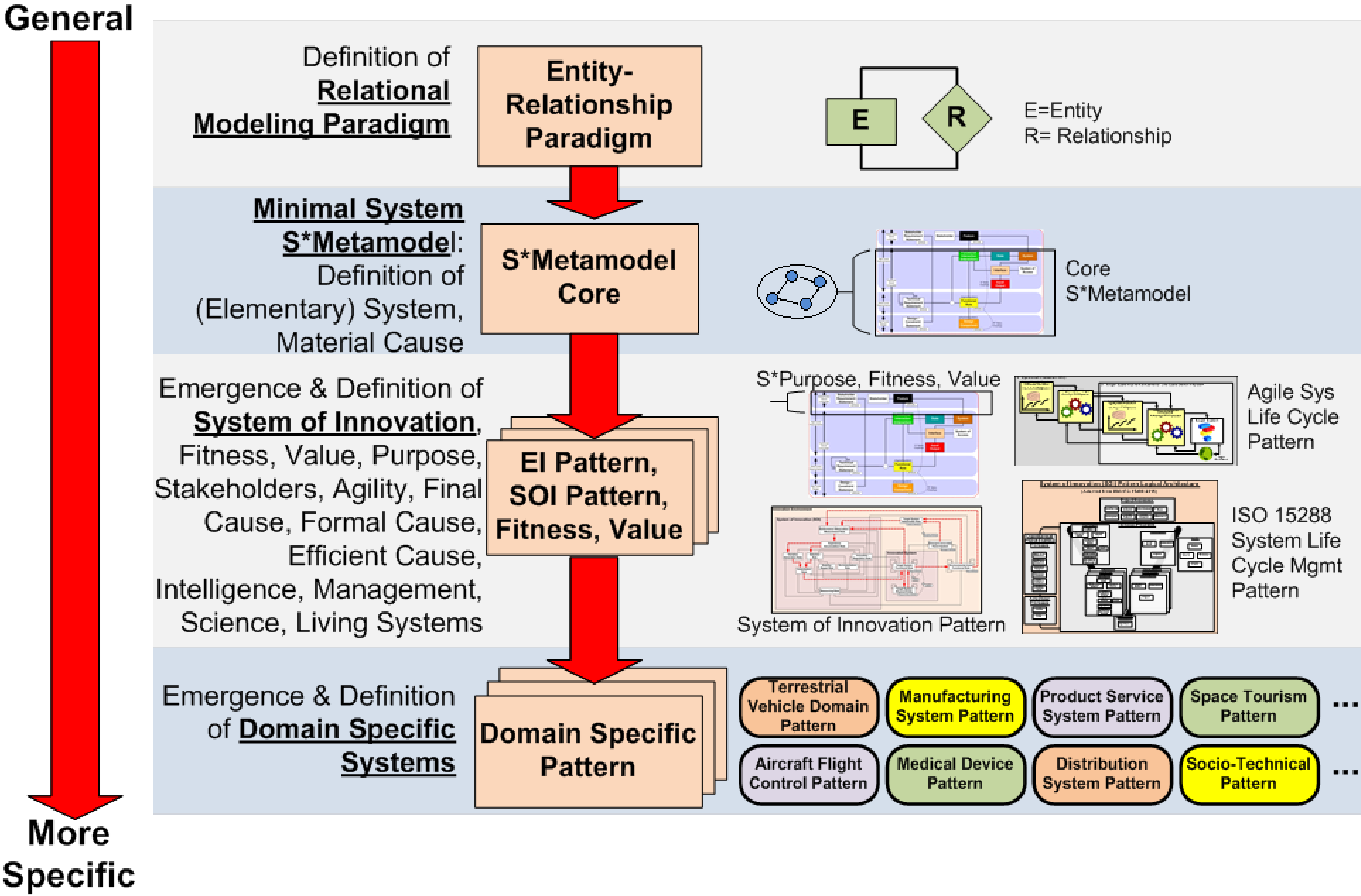
Using the language of Model-Based Systems Engineering (MBSE) and Pattern-Based Systems Engineering (PBSE), this paper describes a framework in which "system" and "purpose" emerge at different levels, apply uniformly, naturally, or not at all, and inform. The framework is the Systems of Innovation (SOI) Pattern. Practical benefits include insights into the nature of innovation across these domains, improving ability to perform innovative systems engineering.

"Pivoting" is not just for entrepreneurs.

The System of Innovation (SOI) Pattern: Feedback Signaling Path in Logical Architecture

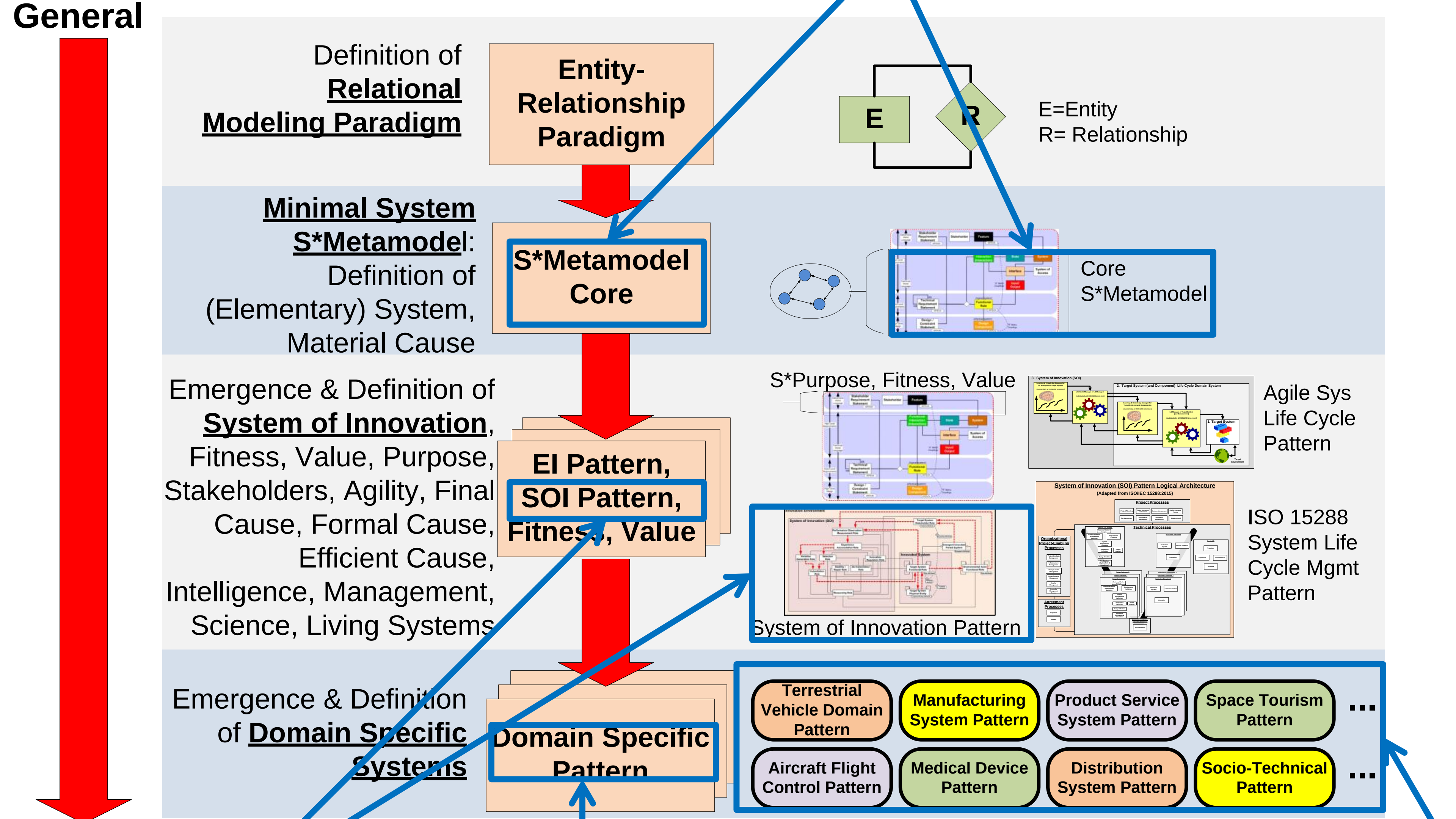


Emergence of Patterns from Patterns: S*Pattern Class Hierarchy



Universal systems nomenclature, domain-independent.

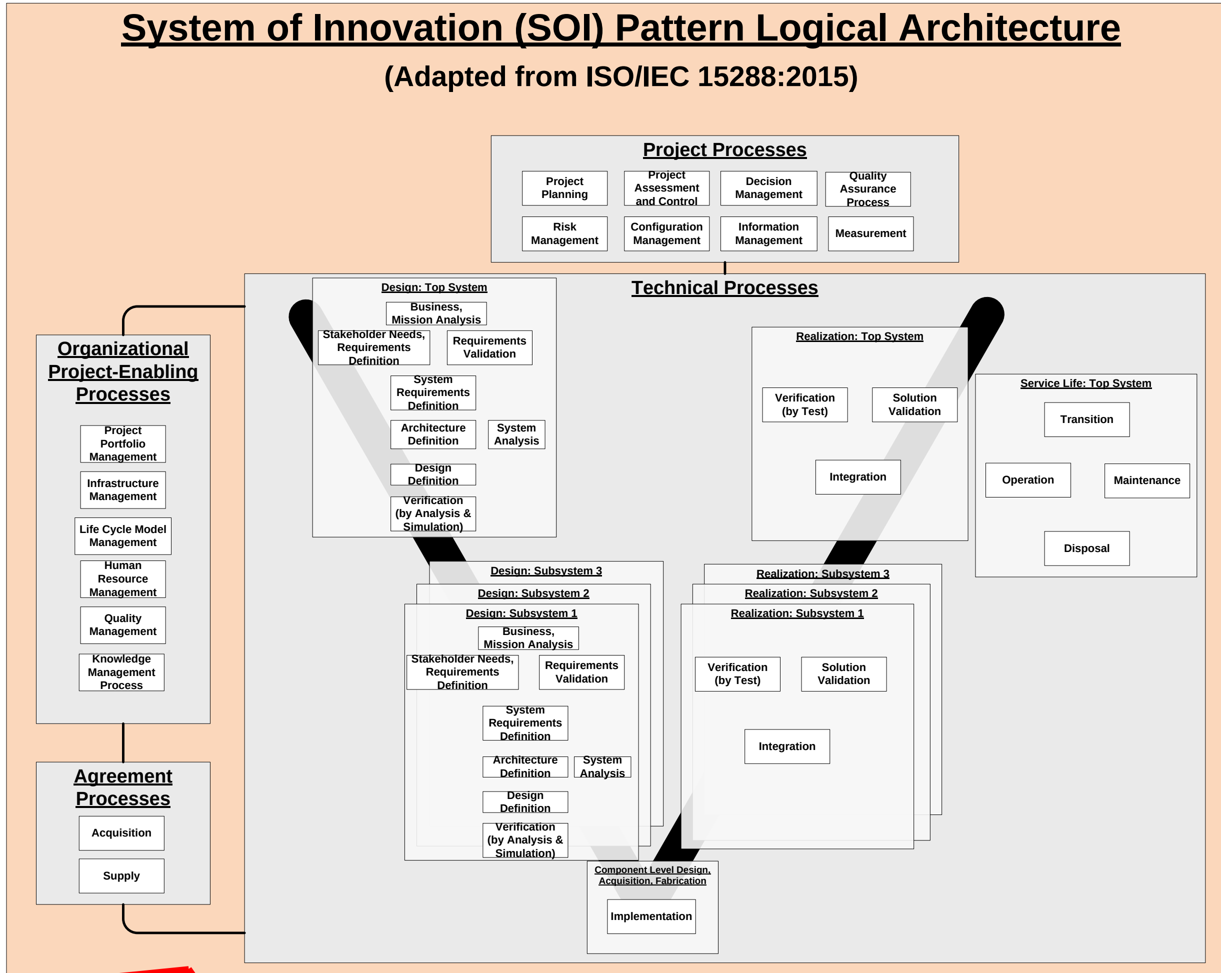
Emergence of Patterns from Patterns: S*Pattern Class Hierarchy

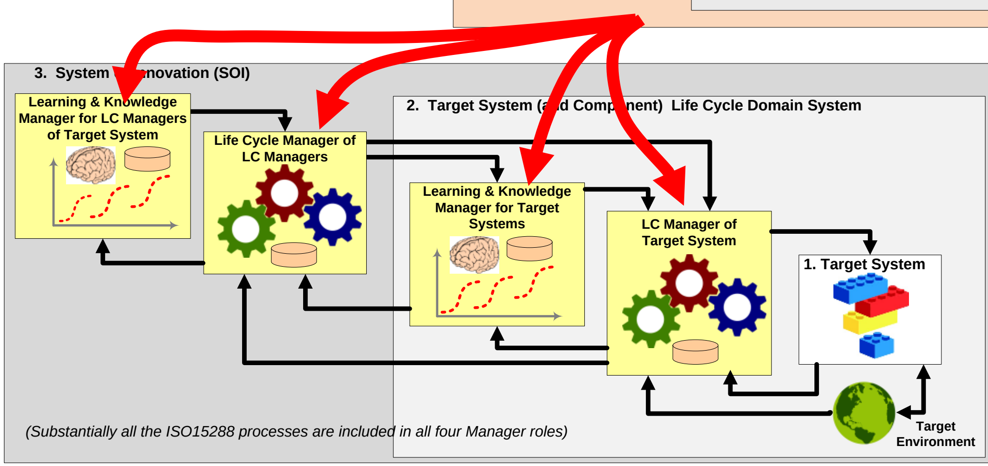


Domain-specific languages, frameworks, ontologies.

Generator of “new systems”; also maintainer, destroyer

ISO15288 and INCOSE SE Handbook describe a framework of ~32 roles of system Life Cycle (LC) Management.

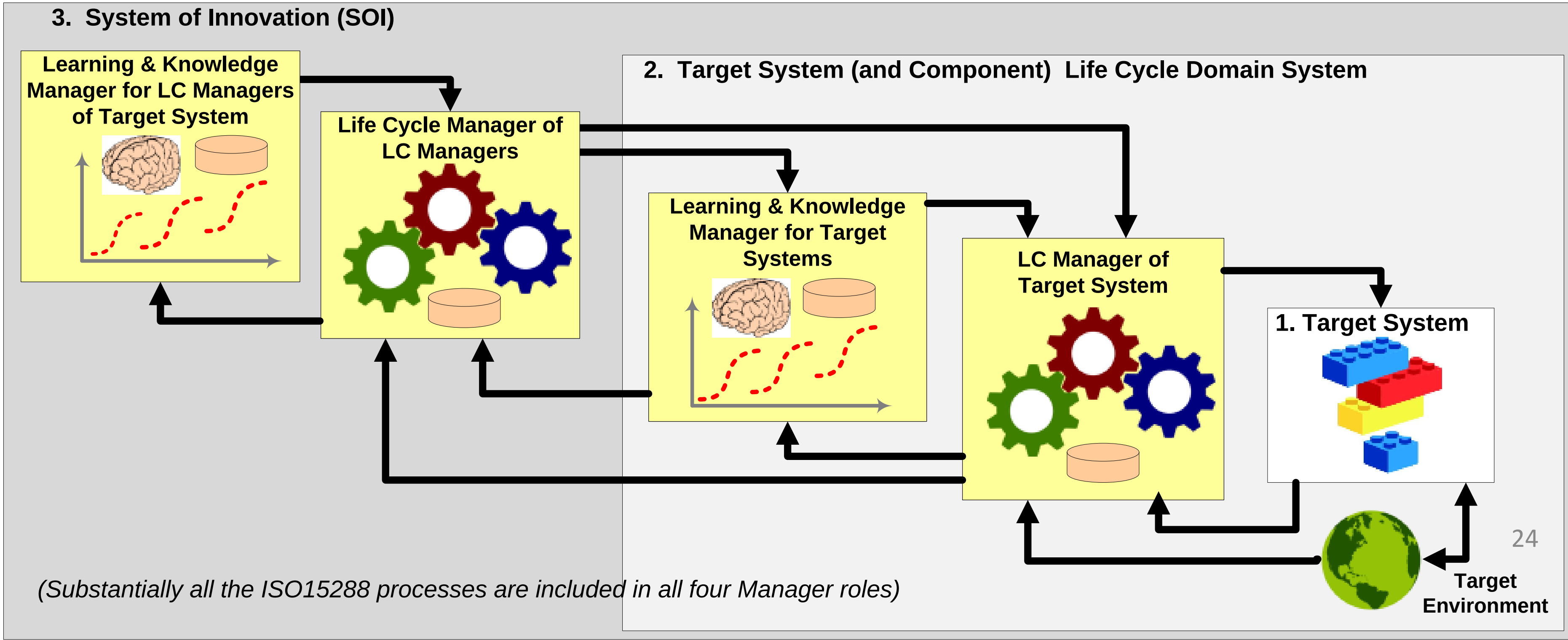


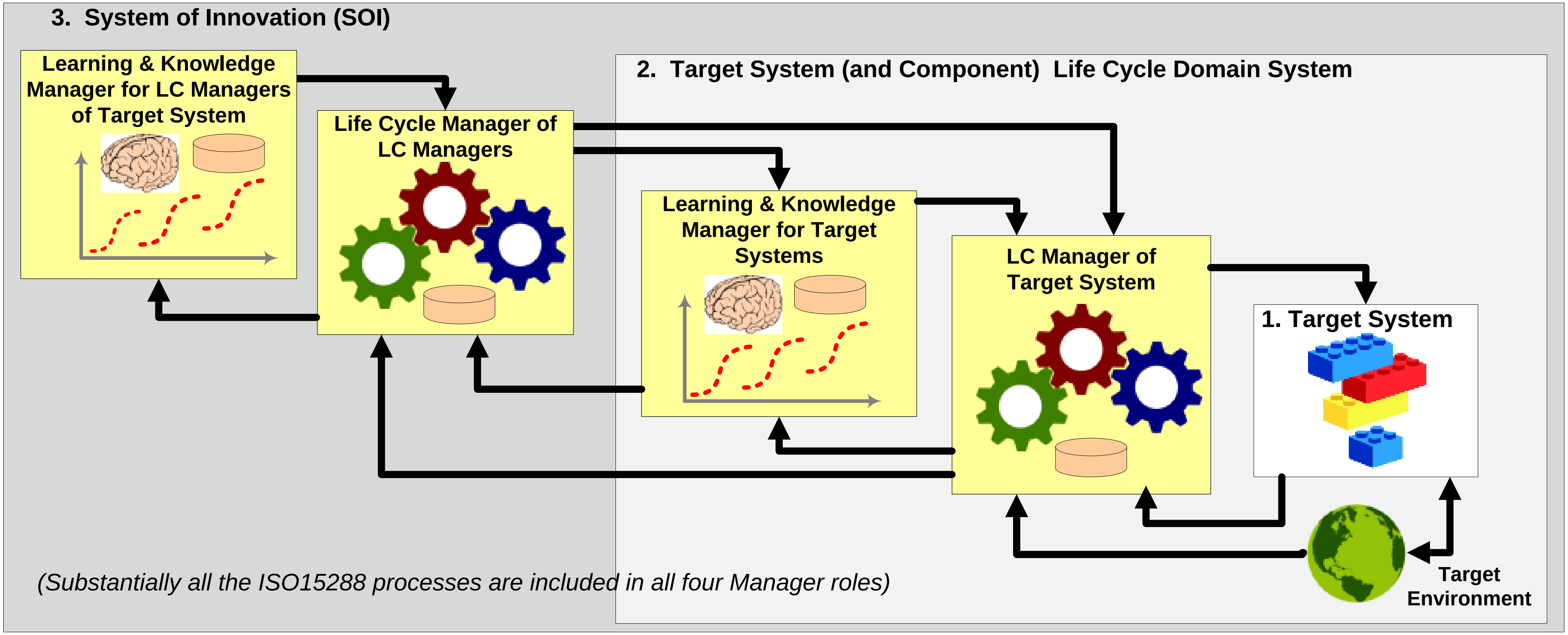


They appear repeatedly, in different ways in the SOI & ASELCM Patterns . . . . . .

INCOSE Agile System Life Cycle Pattern: Application of System of Innovation (SOI) Pattern

- A complex adaptive system reference model for system innovation, adaptation, sustainment, retirement.
- Whether 100% human-performed or automation aided.
- Whether performed with agility or not, 15288 compliant or not, informal, scrum…
- Whether performed well or poorly.
- Includes representation of pro-active, anticipatory systems.





System 1: Target system of interest, to be engineered or improved.

System 2: The environment of (interacting with) S1, including all the life cycle management systems of S1, including learning about S1.

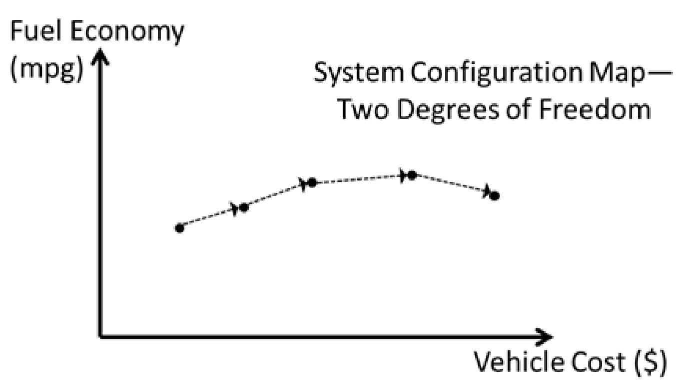
System 3: The life cycle management systems for S2, including learning about S2.

Most of the challenges discussed this week in ISSS sessions are System 2 and System 3 problems, not System 1 problems.

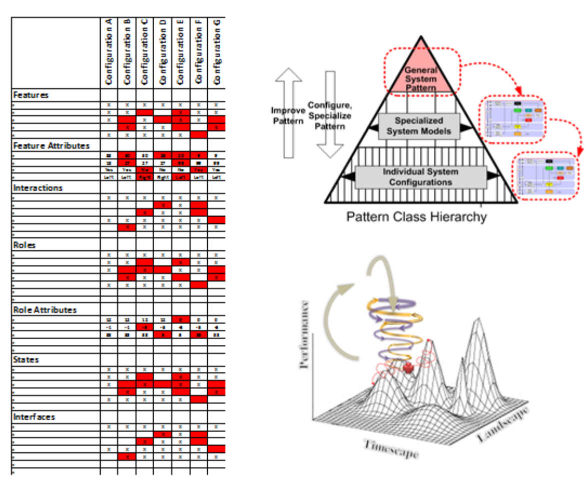
5. Where Do Systems Come From and Go? System Life Cycle Trajectories in S*Space

- 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

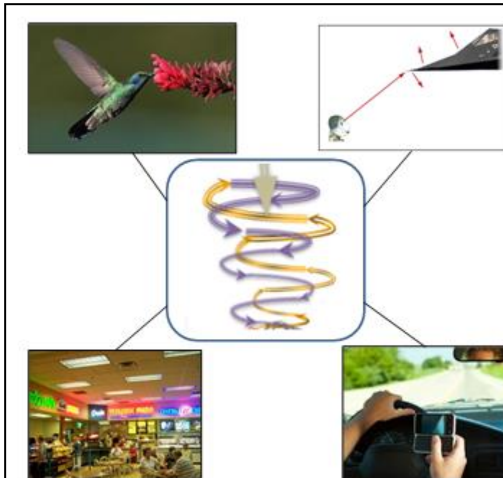
Evolving Systems Over Multiple Life Cycles



Path as a series of system configurations, through iterations of the SE process



"Delta" Descriptions Further Compress Trajectory Representations



Co-Evolution of Interacting Systems

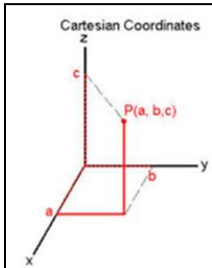
Maps *vs*. Itineraries -- SE Information *vs*. SE Process

Itinerary ≠ Map!

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

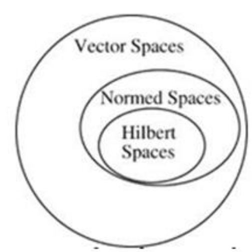
When they eventually did emerge, maps represented a newer idea of the nature of "where".

- 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 and Function spaces (Descartes, Hilbert)
- 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

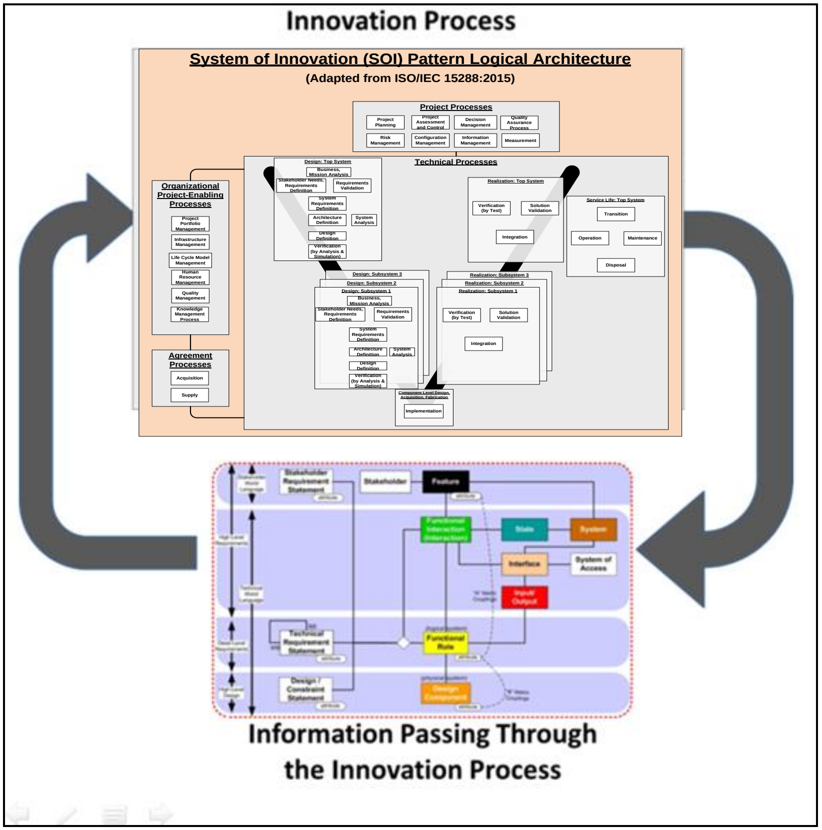
Geometrization of Algebra, by Rene Descartes

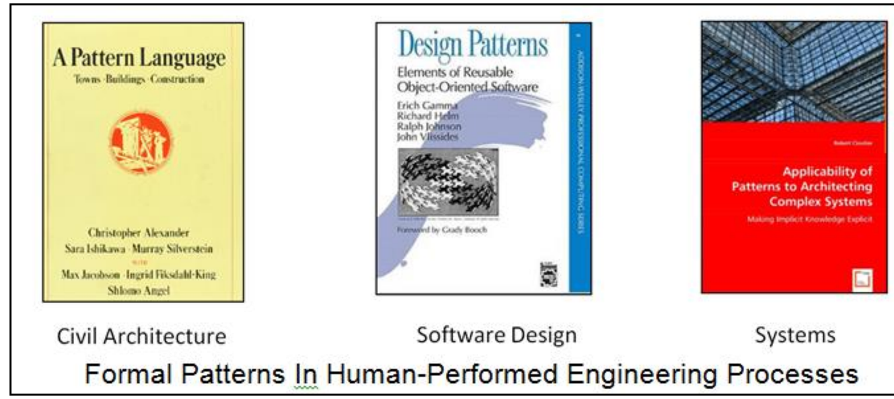


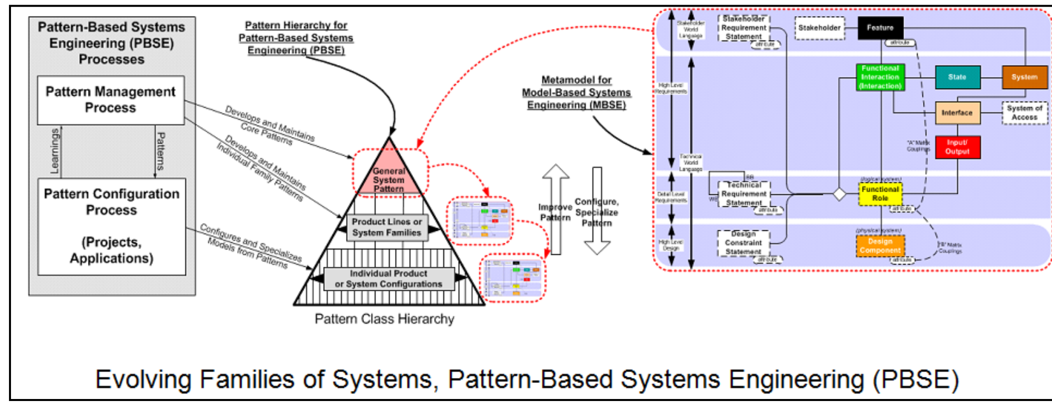
David Hilbert
1862 - 1943

Geometrization of Function Space, by David Hilbert

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

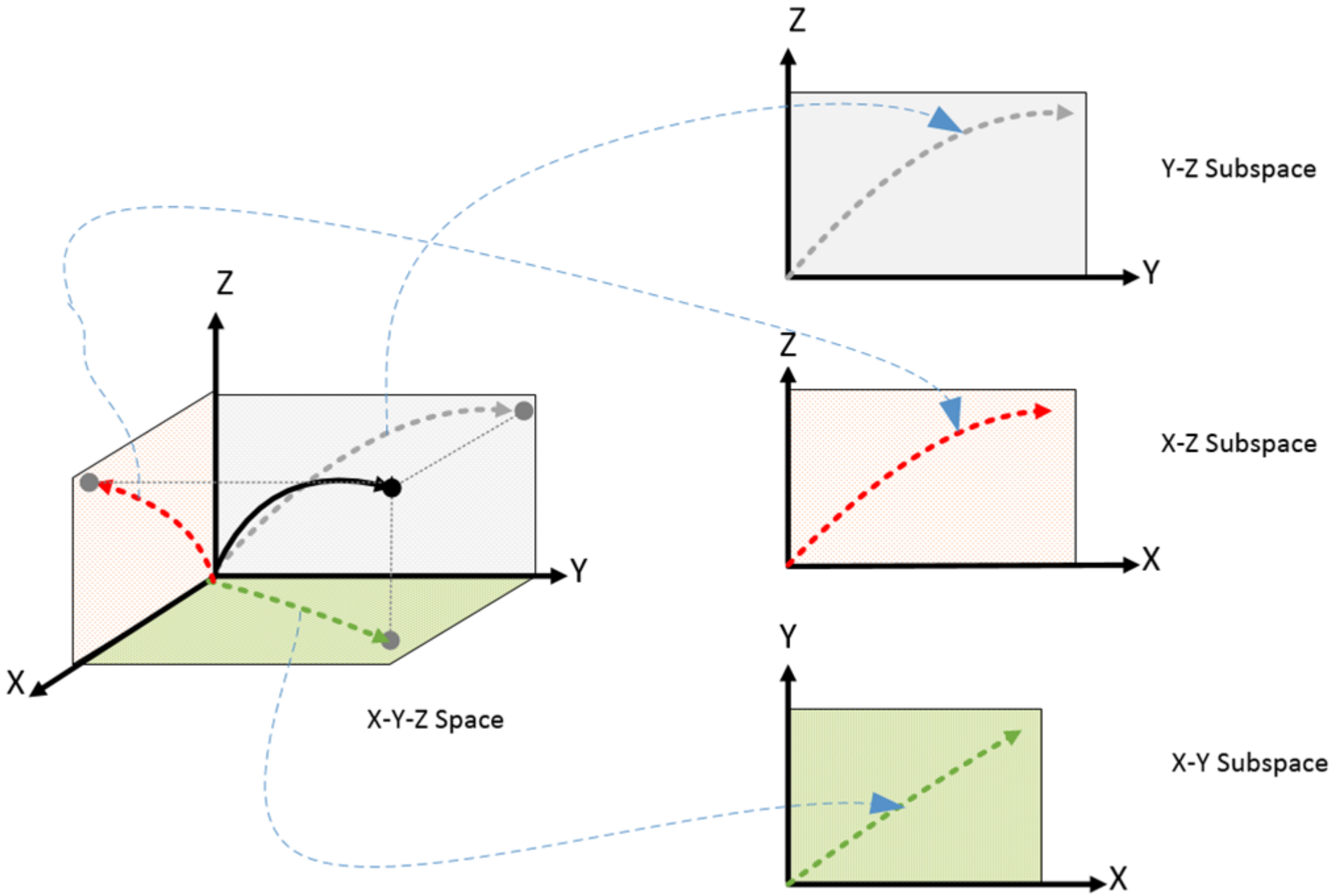




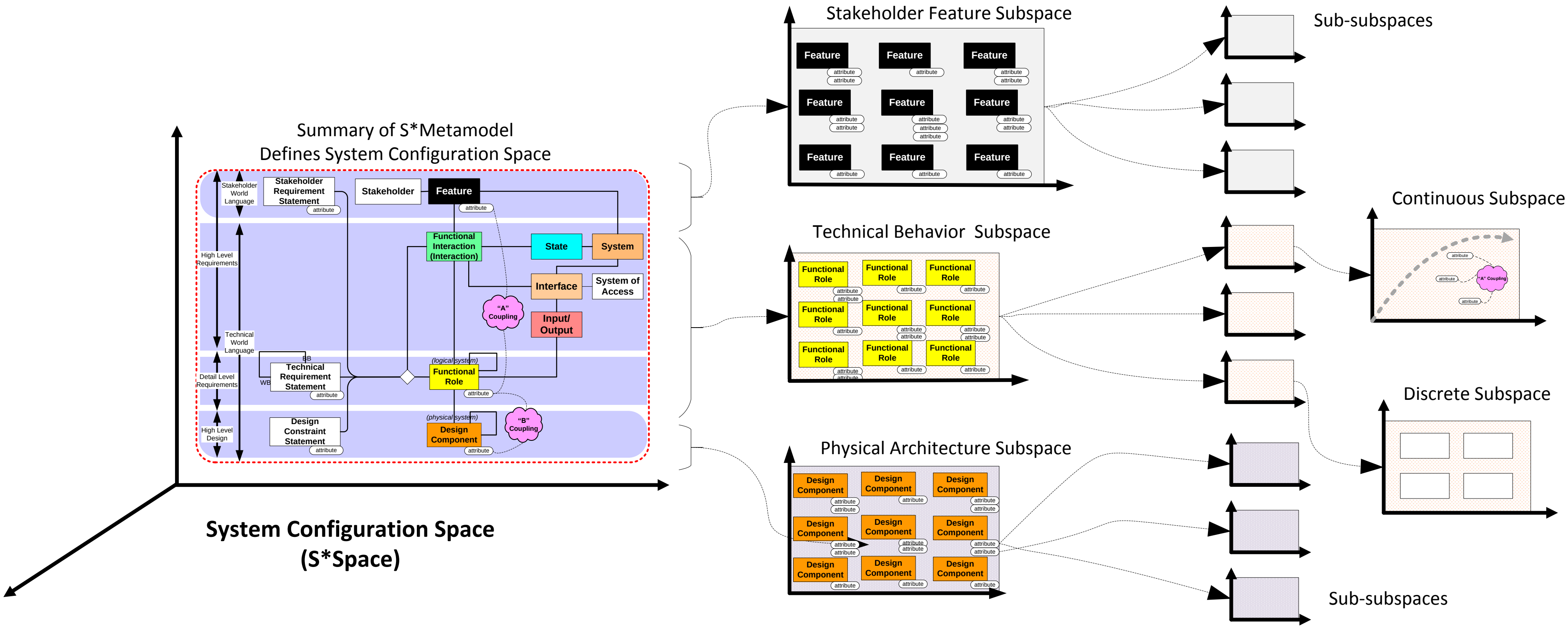


- Model-based Patterns in S*Space.
- Interactions as the basis of all laws of physical sciences.
- Relationships, not procedures, are the fruits of science used by engineers: Newton's laws, Maxwell's Equations.
- Immediate connection to Agility: knowing where you are--starting with better definition of what "where" means. There is a minimal "genome" (S*Metamodel) that provides a practical way to capture, record, and understand—the "smallest model of a system".
- Not giving up process: MBSE/PBSE version of ISO/IEC 15288.

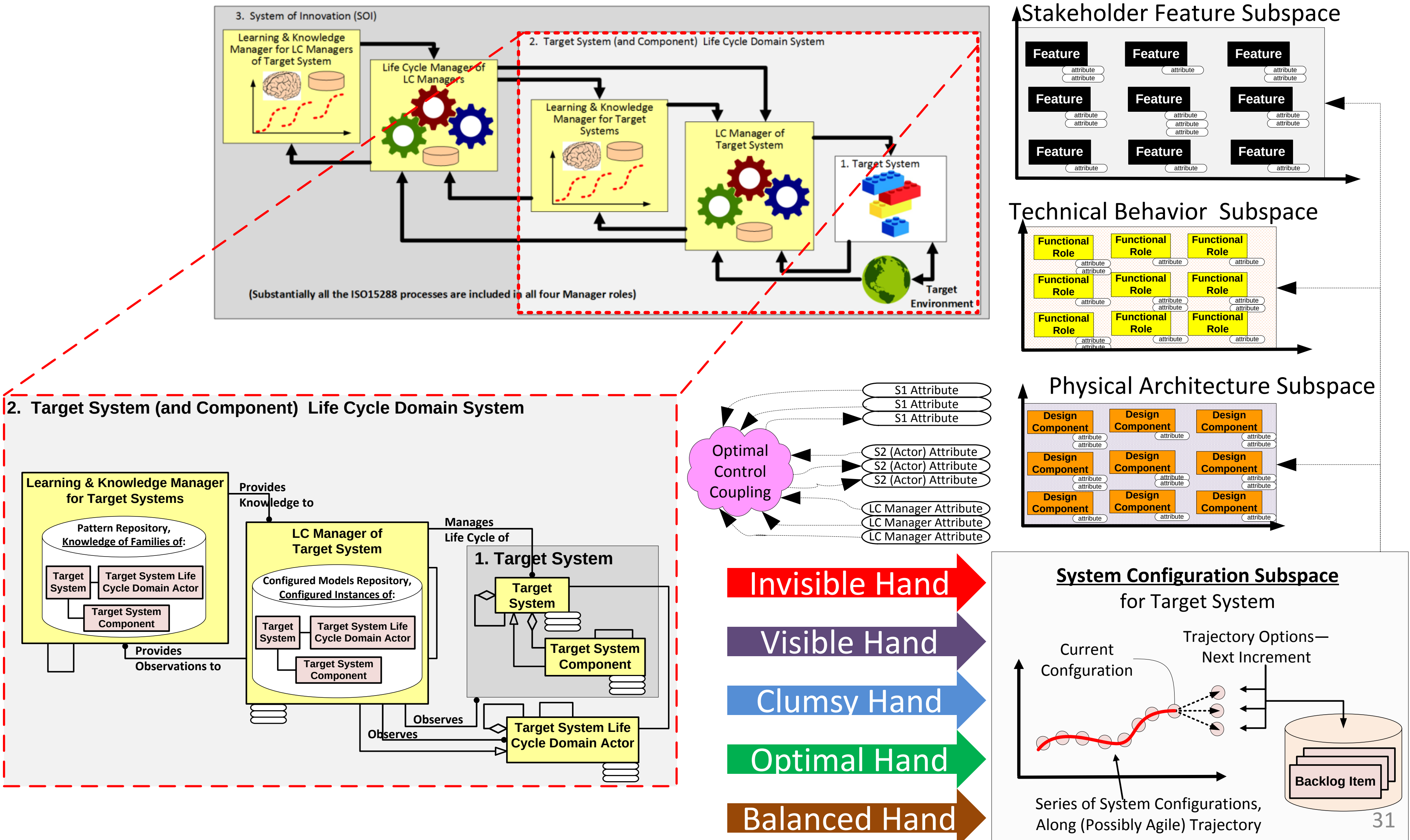
Simple Geometric/Mathematical Idea: Subspace Projections

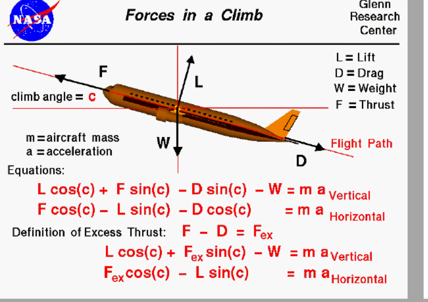


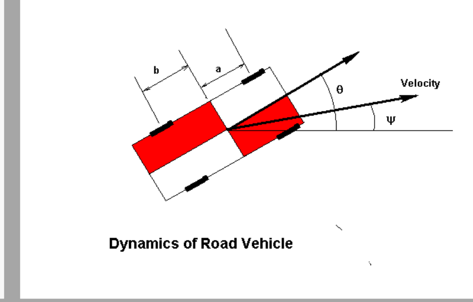
System Life Cycle Trajectories in S*Space, and S*Subspaces

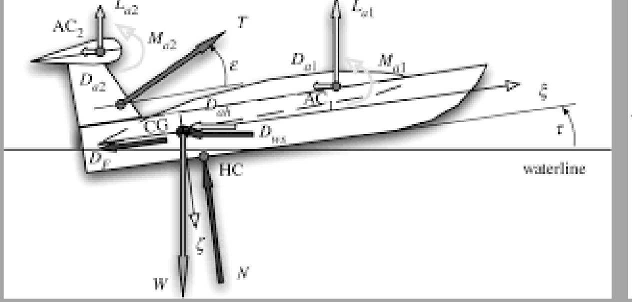


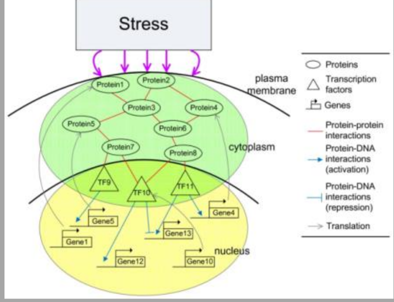
Agility as Optimal Trajectory Control in S*Space: Finding the Best Next Increment "Direction"







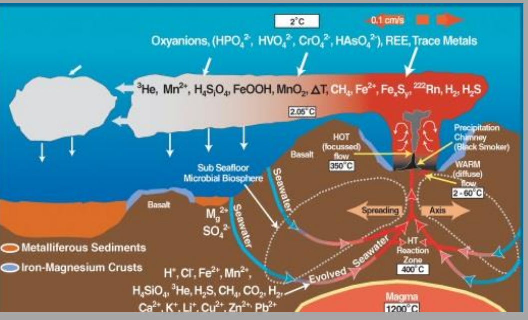




Recent Generations of Science & Engineering (Patterns)

6. Progressively <u>larger scale patterns</u> support larger-scale <u>system sciences</u> and emerging <u>engineering disciplines</u>—including very real higher-level entities, emergent parametrics, forces, states, energies, etc.

Current Challenges Inviting Future Science & Engineering



Conclusions and Invitation

1. Across decades of use over diverse domains, the S*Metamodel has been shown capable of compactly representing minimal S*Models sufficient for the purposes of systems engineering—in particular, in reusable configurable S*Patterns.
2. The System Phenomenon re-connects our understanding to the same modeled physical interactions paradigm that is the underlying historical basis of the laws of the hard sciences.
3. In the tradition of the physical sciences, these larger scale patterns encode what we learn from scientific and other endeavors, providing the basis of larger scale science and engineering disciplines.
4. As several have noted this week, we may not necessarily need more science as it relates to System 1—but we argue that System 2 and System 3 are woefully in need of more attention, as first-class systems in their own right—the interventions are needed there, not just for System 1—and some S2/S3 science is needed.
5. INCOSE and ISSS are especially about System 2 and 3--interested parties are invited to join the INCOSE MBSE Patterns Working Group and participate in the related activities.

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