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

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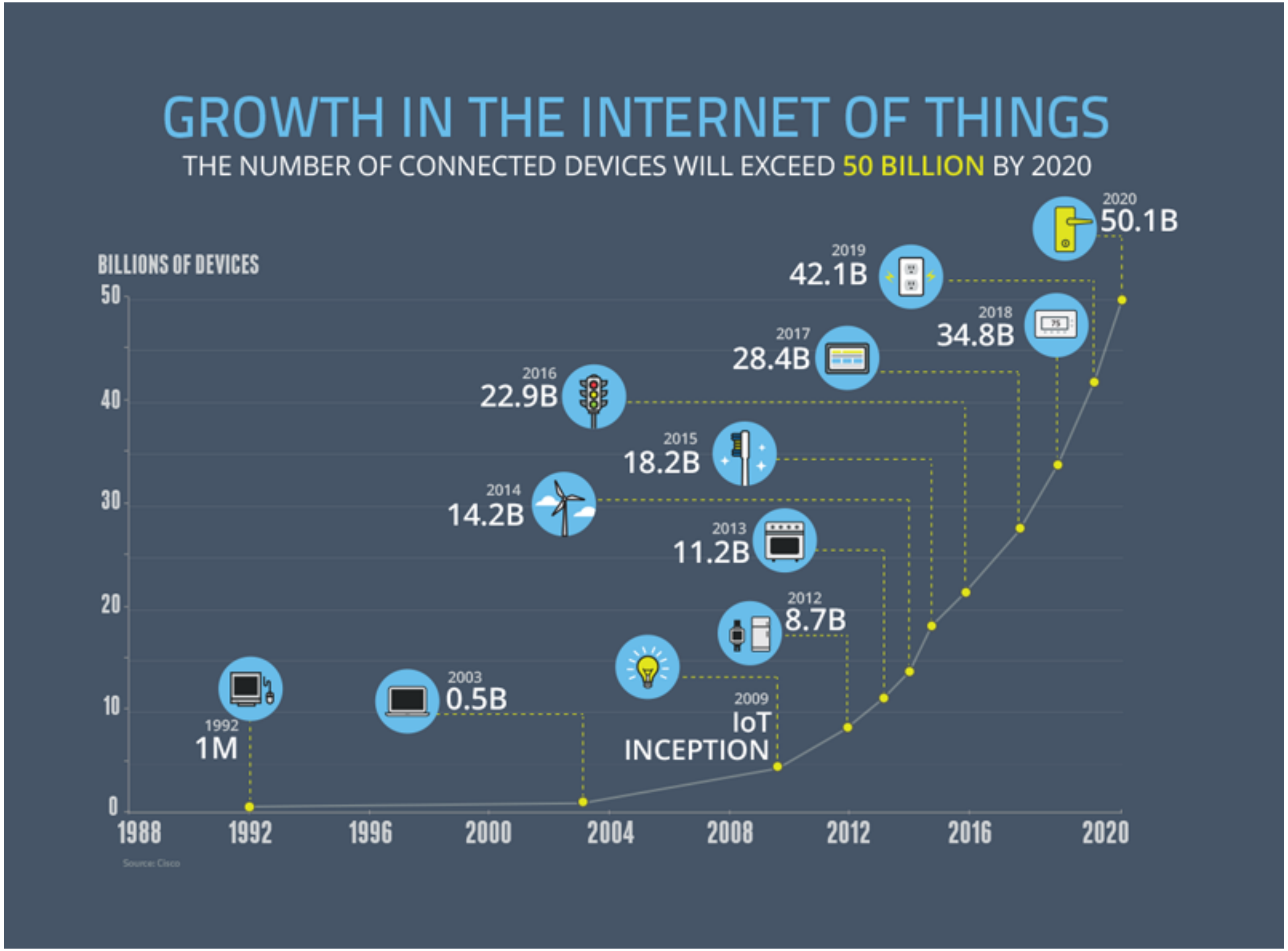
EMERGENT
MECHATRONIC
SELF-AWARE
EMBEDDED
AUTONOMOUS
SYSTEM
COLLABORATING
CREATIVITY
COMPLEXITY
SYSTEMS
AMBIGUITY
CYBER
PHYSICAL


GROWTH IN THE INTERNET OF THINGS
THE NUMBER OF CONNECTED DEVICES WILL EXCEED 50 BILLION BY 2020
BILLIONS OF DEVICES
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2020
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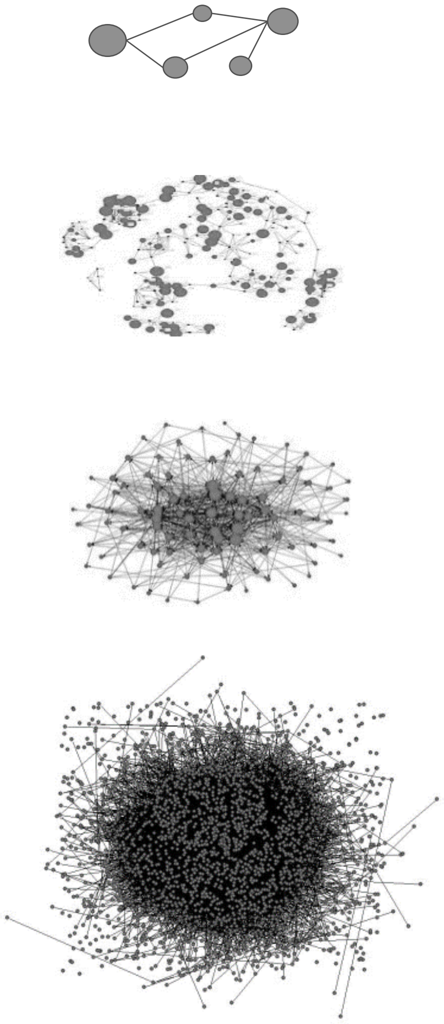
Source: Cisco

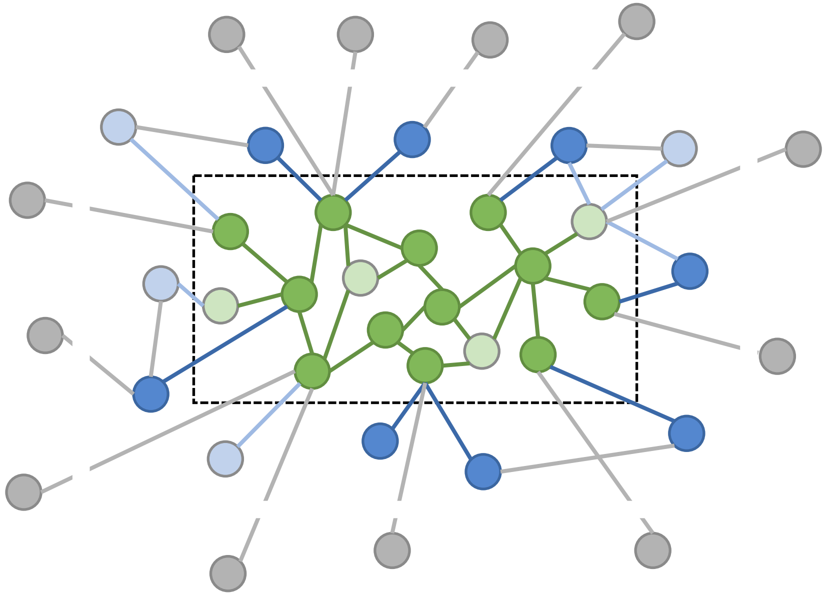
Contextual Complexity Impacting Systems and Decisions

- Contextual Volatility, Uncertainty, Complexity and Ambiguity
- Product customization and rapid rates of change
- Time pressure from faster business and product cycles
- Global Competition and Asymmetrical threats
- System of System level complexity
- Environmental variety & mission needs
- Extending aging legacy systems
- Pace technological evolution
- Extreme cost pressures



System Engineering (SE) Complexity

As systems become more and more interconnected internal and external interactions increase dramatically



System Elements & Interactions

System External Elements & Interactions

Increased Density of System Elements & Interactions

Increased Density of System External Elements & Interactions

Increased Interactions Between External Elements

Expanding System Domain Boundary Increasing Interactions

Decision Analysis (DA) Complexity

- Rapid contextual change and increased systems complexity has increased the risk and uncertainty for decision makers
  - Apparently "simple" decisions first may have significant strategic, social, political and economic impact.
  - Increased number of stakeholders and associated external considerations, policy, environment etc.
  - Challenges extend beyond the technical domain
  - Number of objectives and conflict between them
  - Amount and complexity of information to process
  - Continuous evolution and new …ilities
  - Nonlinear interactions

Complexity – Is this all new?

"Today more and more design problems are reaching insoluble levels of complexity."

"At the same time that problems increase in quantity, complexity and difficulty, they also change faster than before."

"Trial-and-error design is an admirable method. But it is just real world trial and error which we are trying to replace by a symbolic method. Because trial and error is too expensive and too slow."

Christopher Alexander,
Notes on the Synthesis of Form[1],

1. Christopher Alexander, "Notes on the Synthesis of Form" Harvard University Press, Cambridge Massachusetts, 1964

INCOSE Vision 2025 points to the coupling of SE and DA

“Trends of Emerging System Properties Inter-connectivity and interdependence are characteristics that, by themselves provide no instrinsic value. **Value is gained by building systems with these characteristics to address stakeholder desires.** “

“**Technical and programmatic sides of projects are poorly coupled hampering effective project risk-based decision making**.- Five Systmes Enginering Challenges, *Adapted from Todd Bayer, Jet Propulsion Laboratory”*

“The expected competencies of a systems engineer will be more consistently defined and broadened to support the expanded systems engineering roles… **mastery of systems engineering foundations and methods related to knowledge representation, decision analysis, stakeholder analysis, and complex system understanding;….**

Summary: Supported by a more encompassing foundation of theory and **sophisticated model-based methods and tools allowing a better understanding of increasingly complex systems and decisions in the face of uncertainty.**

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Vision25 Systems Engineering

INCOSE International Council on Systems Engineering

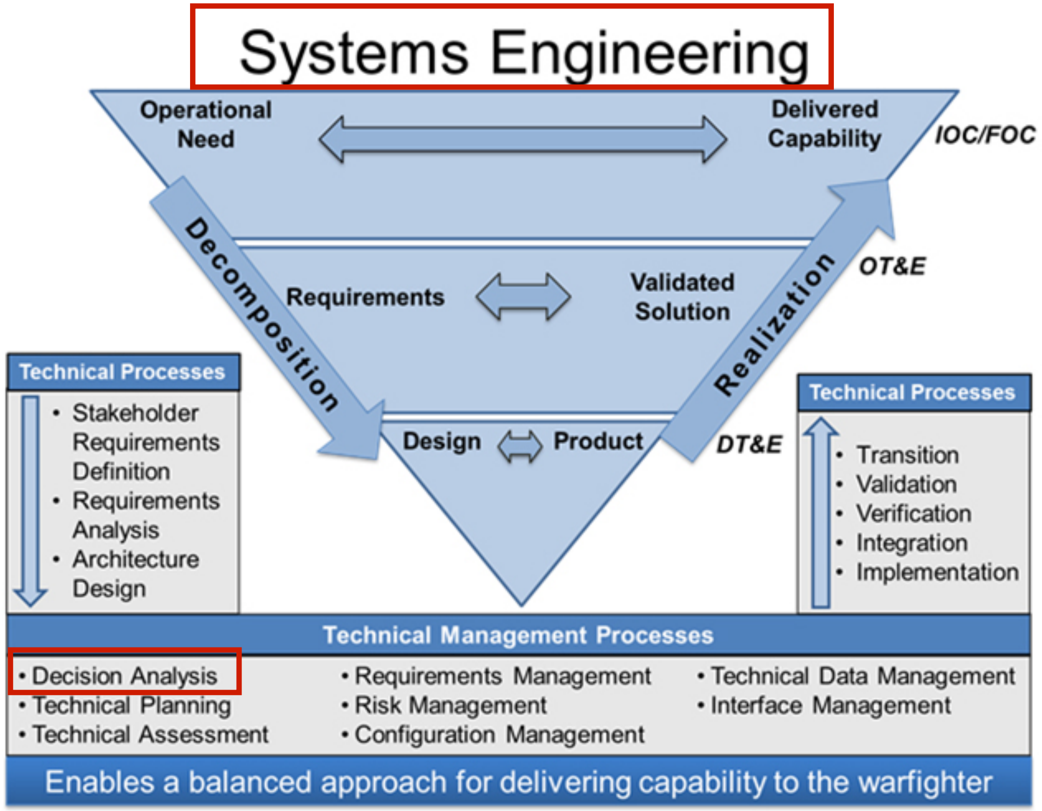
Systems Engineering (SE) & Decision Analysis (DA)

- ***Systems Engineering*** provides an overarching methodology to systematically innovate
- ***Decision Analysis*** provides a systematic approach to think through and analyze complex problems or opportunities throughout the innovation process
- An essential aspect of ensuring our methods are successful is to better couple the decision making and innovation processes and related models

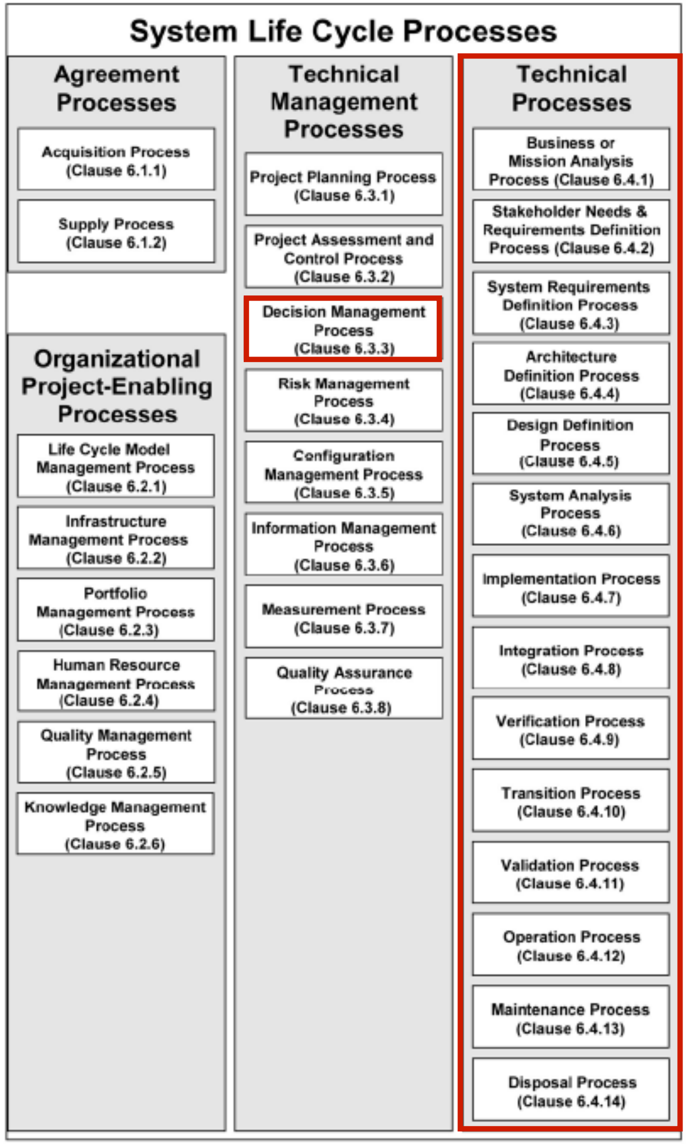
SE & DA - History and an Expanded Stakeholder View

- Maturation and integration of SE and DA is being actively worked in many forums (INCOSE, INFORMS, PMI and others)
- The Council of Engineering Systems Universities (CESUN) noted:
  - *As many engineers began to delve deeper and deeper into science, some others stressed the design perspective and explored how to solve the problems arising from greater technical complexity.* ***Operations research, systems and decision analysis, industrial engineering, systems engineering—these all contributed to the expansion of engineering—but*** *at a certain point there was a recognition that some of the greatest challenges were precisely where the technical systems had their interfaces with people, policies, regulations, culture, and behavior.* http://cesun.mit.edu/about/purpose
- This excerpt also calls out the expanded and new view at the "…interfaces with people, policies, regulations, culture and behavior."
- This perspective brings with it a diverse set of stakeholders and an expanded view of value

Systems Engineering & Decision Analysis



Defense Acquisition University
Figure 4.1.F2. Systems Engineering Processes



ISO/IEC/IEEE 15288
Systems and software engineering
System life cycle processes

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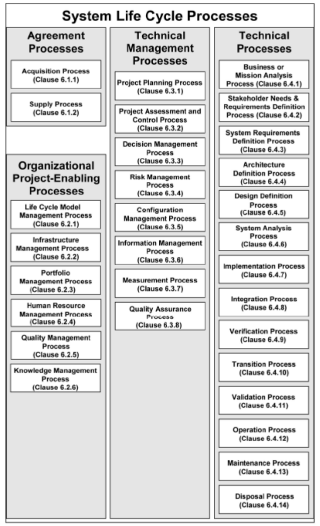
Models of Process vs Models of Systems

- Process integration is helpful, but alone it is not sufficient
- Much of the integration effort of SE and DA has been focused on process – the infrastructure for information about the system of interest
- Integration has not been however, as focused on the information that passes through the process about the system of interest
- There is a need in connecting the disciplines, both more deeply and in a more explicit way to ensure value delivery



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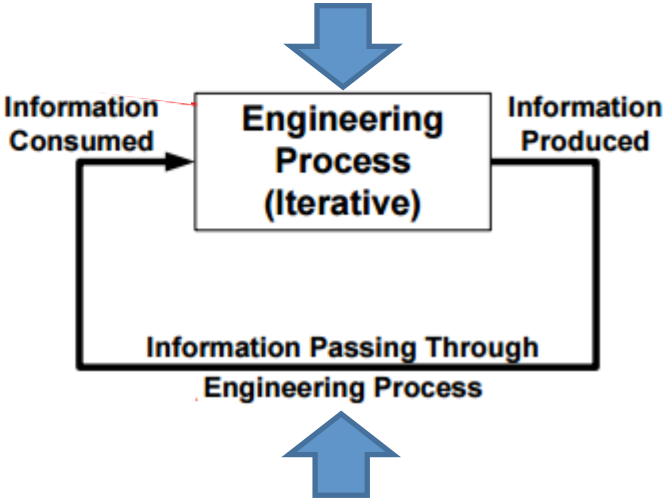


Target System / SOI

Getting Back to Basics

- With the recent shift toward Model Based Systems Engineering (MBSE), the Systems Engineering discipline is "getting back to basics"
- A focus on modeling the Target System/System of Interest
- A paradigm more aligned with the genesis of classical mechanics, beginning with Newtonian interactions and their emergent properties, so that the whole is greater than the sum of the parts
- Back to the foundational engineering axioms built upon first principles and established laws of science and engineering
- With MBSE we much use our models to explicate how first principles of engineering and science provide stakeholder value

Symbolic Method

"Trial-and-error design is an admirable method. But it is just real world trial and error which we are trying to replace by a symbolic method. Because trial and error is too expensive and too slow."

- To fully integrate SE and DA the third bullet from Alexander makes an important observation about the use of *"…symbolic method. Because trial and error is too expensive and slow."*

- This brings us first to the use of models and model based systems engineering (the symbolic part)

Model Based Systems Engineering

- INCOSE defines Model-Based Systems Engineering (MBSE) as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases…" INCOSE SE Vision 2020

- MBSE is often discussed as being composed of three fundamental elements – tool, language and method.

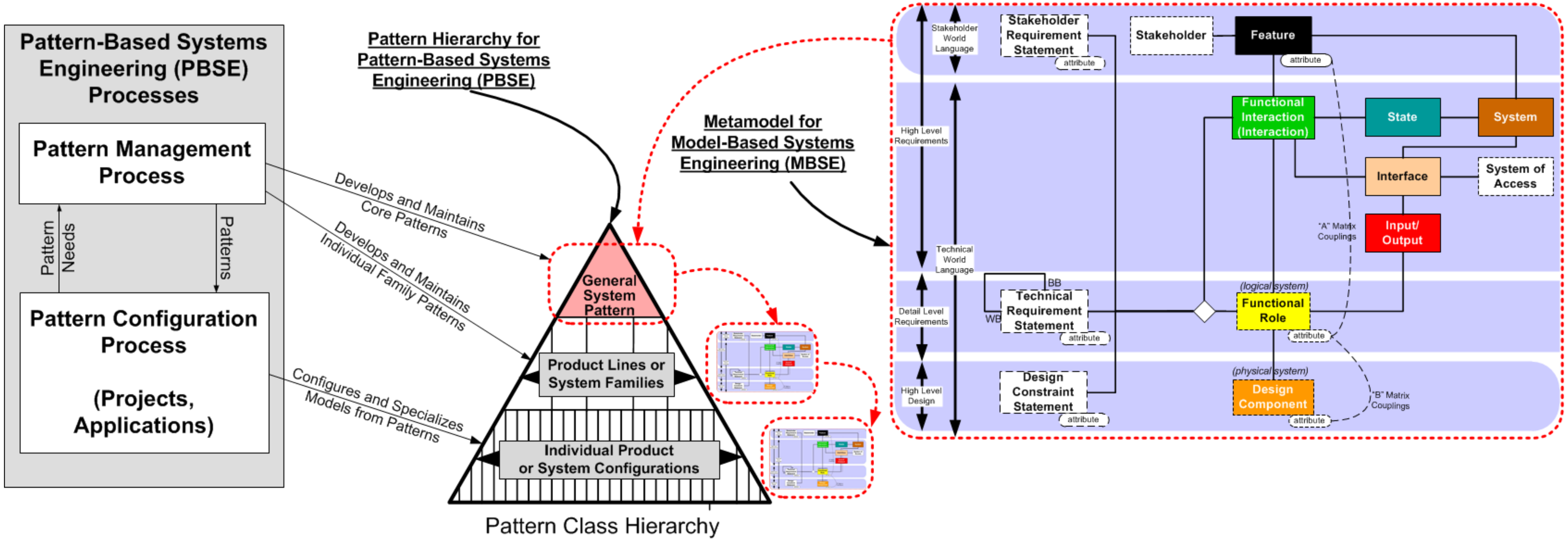
- For this briefing we remain neutral to language and tool and focus in on the content and method which can be expressed in any language or tool

Patten Based Systems Engineering

- As a Model-Based Systems Engineering (MBSE) methodology, Pattern-Based Systems Engineering (PBSE) addresses complex systems, with a reduction in modeling effort.
- Gains are possible because projects using PBSE get a "learning curve jumpstart" from an existing model-based pattern and its previous users, rapidly gaining the advantages of its content.
- The term "pattern" appears repeatedly in the history of design, such as civil architecture, software design and systems engineering. While these are all loosely similar in the abstract the PBSE methodology referred to by this paper, based on S*Models and S*Patterns which are distinguished by:
  - S*Patterns are Model-Based: Patterns represented by formal system models, and specifically those which are re-usable, configurable models based on the underlying S*Metamodel.
  - Scope of S*Patterns: Patterns which will usually cover entire systems, not just smaller-scale element design patterns within them. For this reason, the typical scope of an S*Pattern applications may be thought of as re-usable, configurable models of whole domains or platform.

Pattern Based Systems Engineering

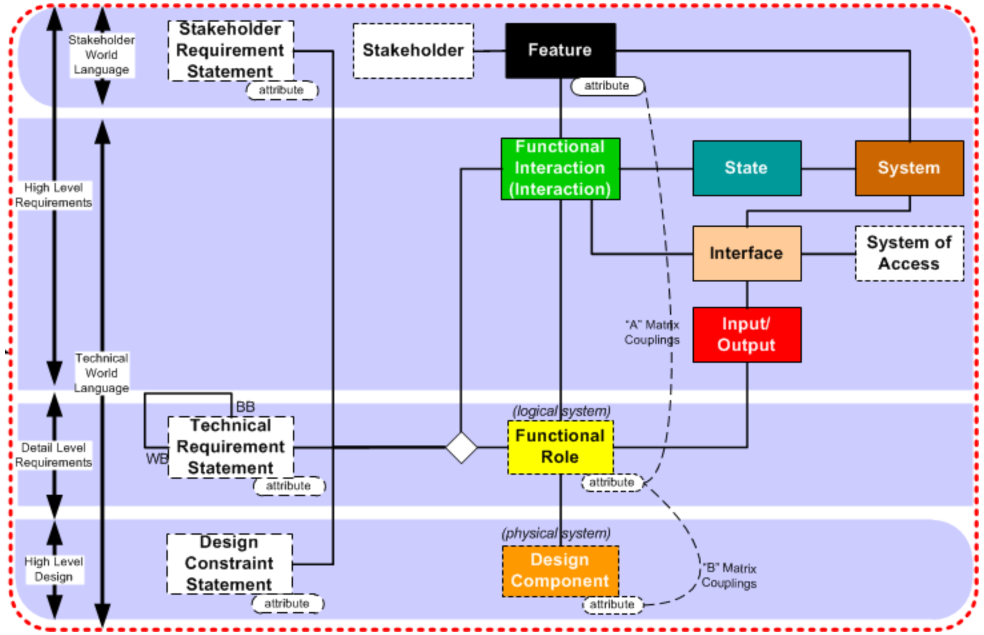
- Fundamental to PBSE is the use of the S*Metamodel, a relational / object information model intended to describe the "smallest possible model" necessary for the purposes of performing systems engineering or science.
- It provides the semantics to describe requirements, designs, and other information such as verification, failure analysis, etc.
- Specifically, an S*Pattern is a re-usable, configurable S*Model of a family of systems (product line, set, ensemble etc.)



A summary view of the S* metamodel and Pattern Hierarchy and Process

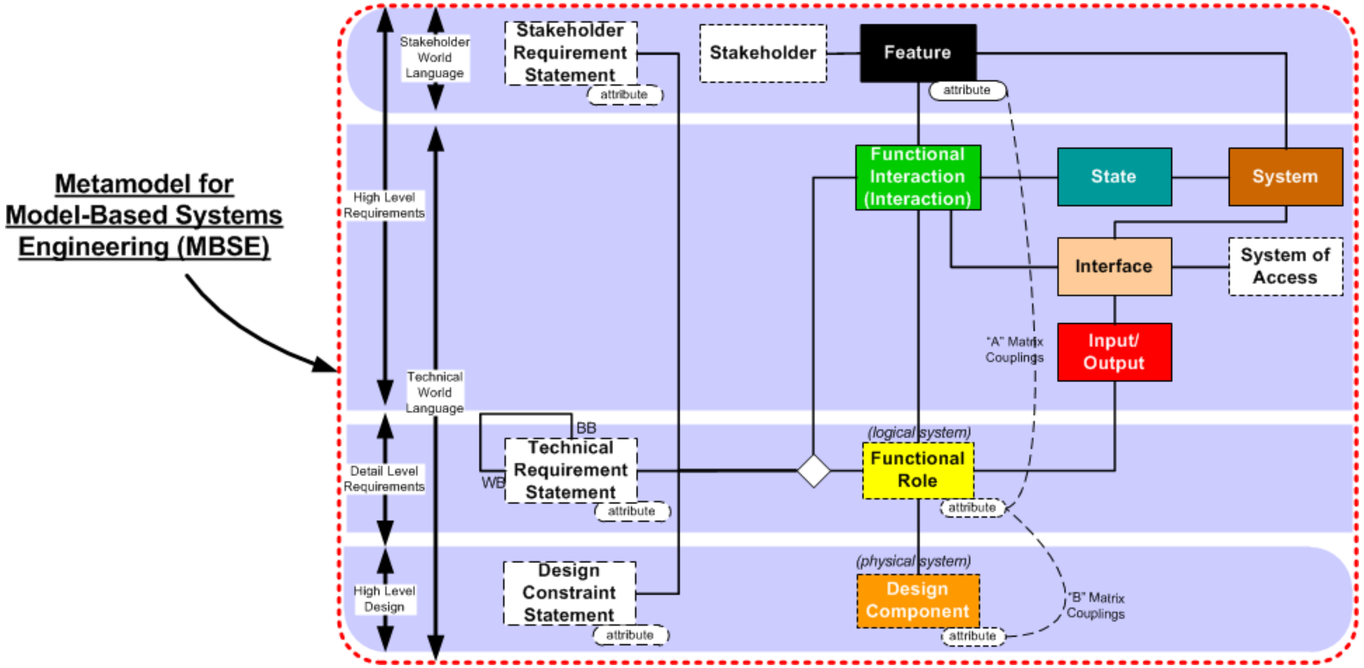
PBSE & First Principles

- Interactions are at the heart of the S* Metamodel
- The S*Metamodel is focused on the very physical Interactions that are the basis / first principles of all the observed laws of the physical sciences, and which we assert are at the heart of the definition of System (a collection of interacting components).



Patten Based Systems Engineering

- The S*Model
  - **<u>An S* Model</u>** is a description of all those important things, and the relationships between them.
  - Typically expressed in the "views" of some modeling language (e.g., SysML™).



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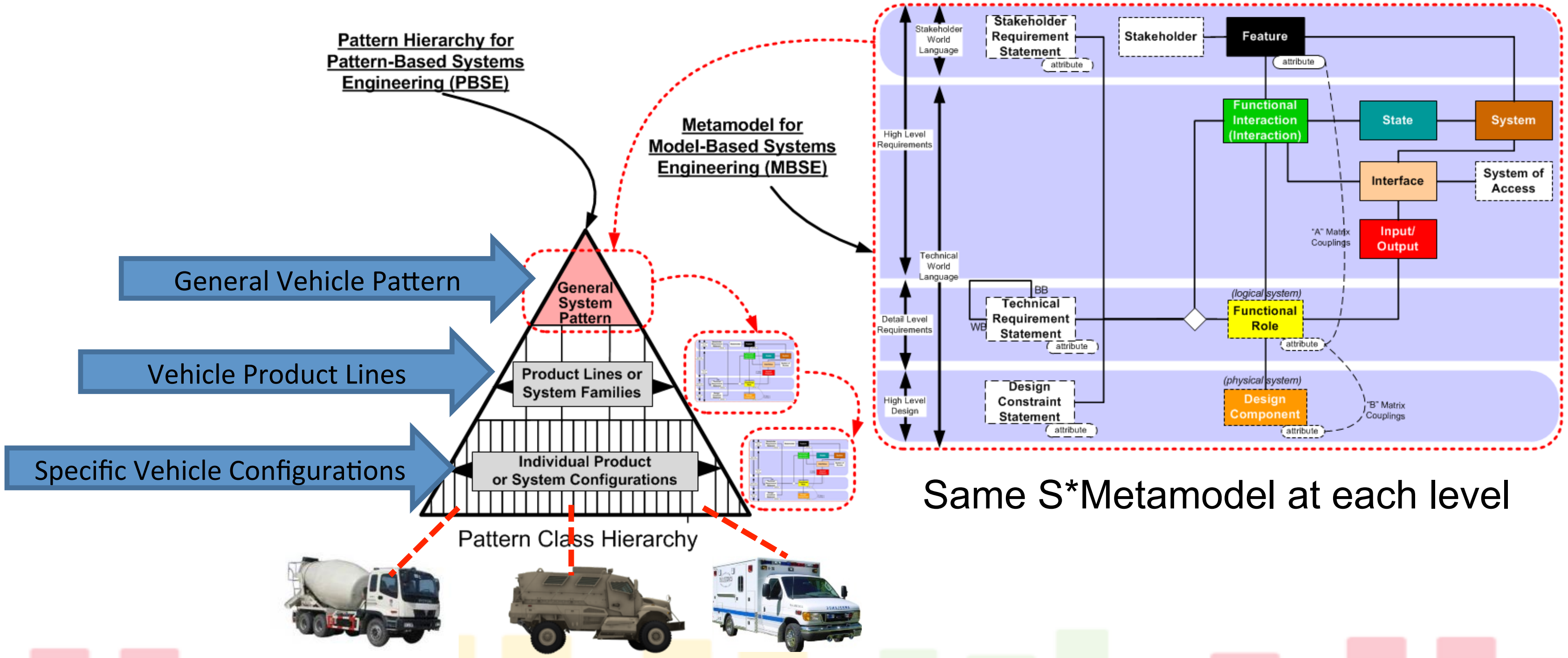
- An **S* Pattern** is a configurable, re-usable S* Model. It is an extension of the idea of a Platform (which is a configurable, re-usable design) or Enterprise / Industry Framework.
- The Pattern includes not only the physical Platform information, but all the extended system information (e.g., pattern configuration rules, requirements, risk analysis, design trade-offs & alternatives, decision processes, etc.):

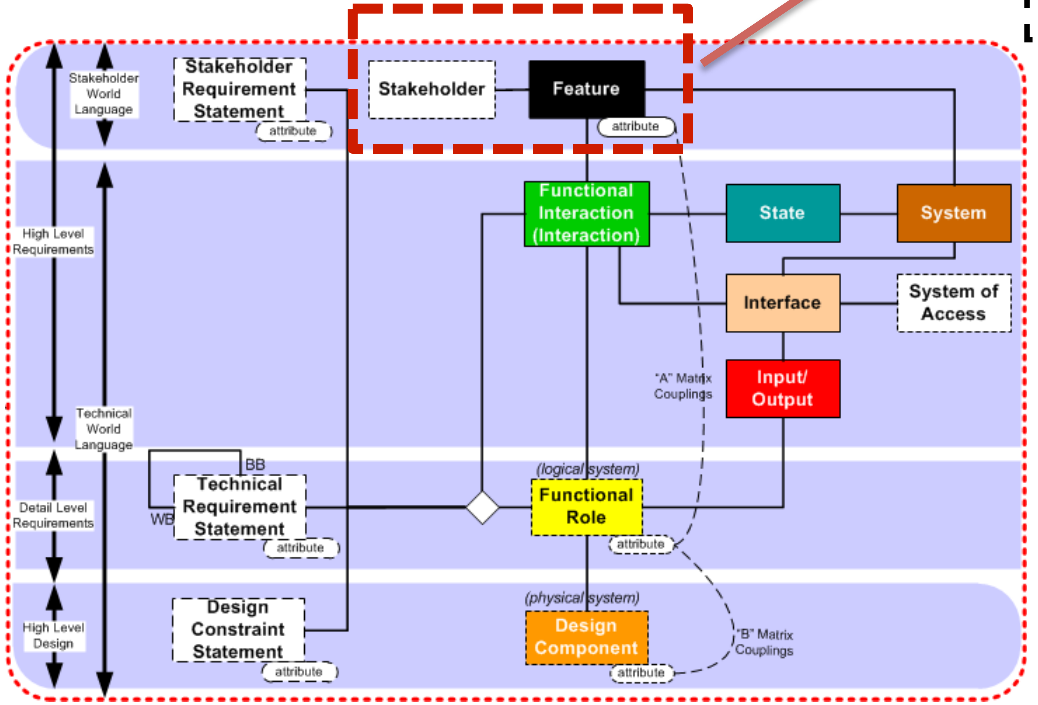


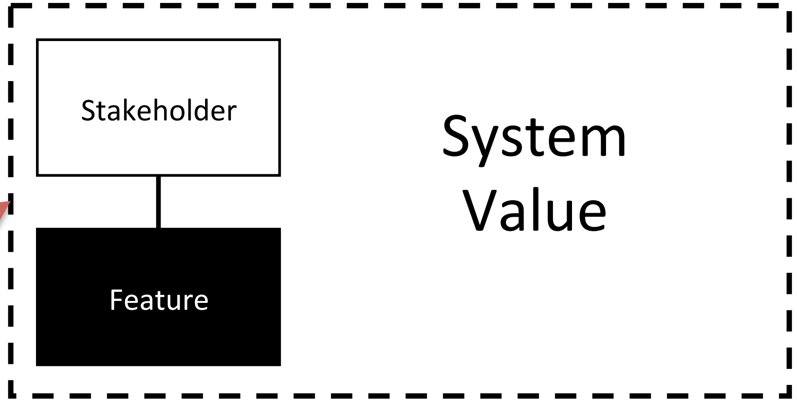
Same S*Metamodel at each level

System Value Space

Stakeholder:

A person or other entity with something at stake in the life cycle of a system. Example: Vehicle Operator; Vehicle Owner; Pedestrian





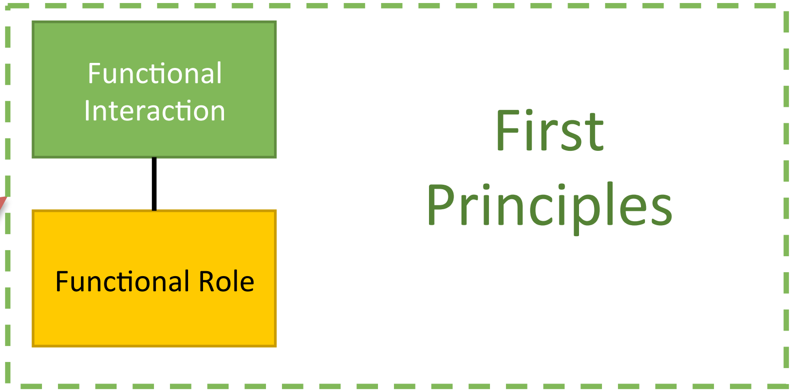
Feature:

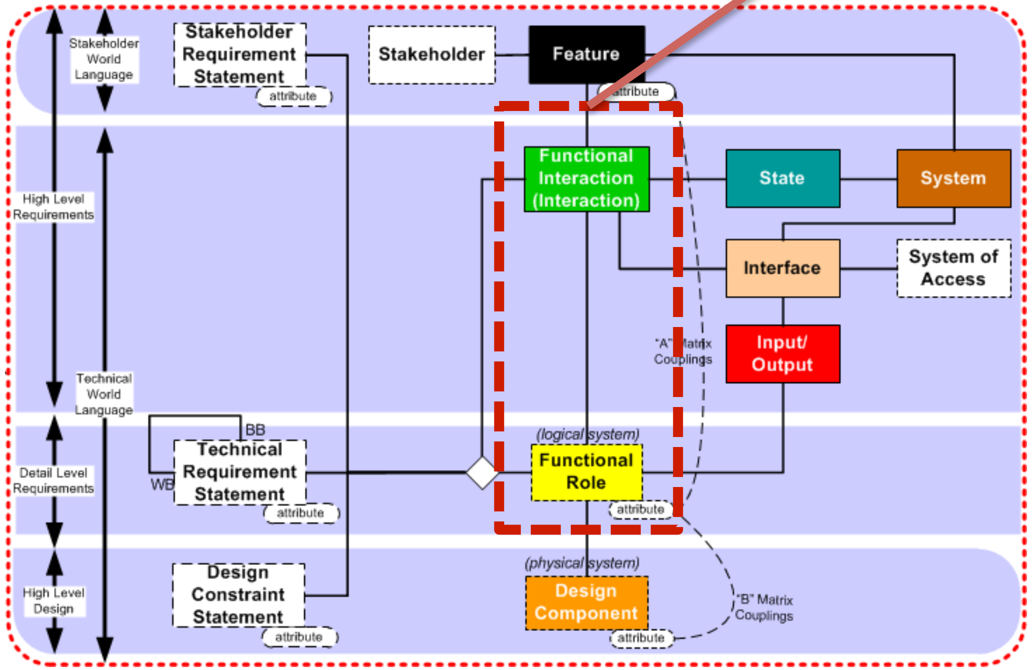
A behavior of a system that carries stakeholder value. Example: Automatic Braking System Feature; Passenger Comfort Feature Group

First Principles Space

Functional Interaction (Interaction):

An exchange of energy, force, mass, or information by two entities, in which one changes the state of the other. Example: Refuel Vehicle; Travel Over Terrain



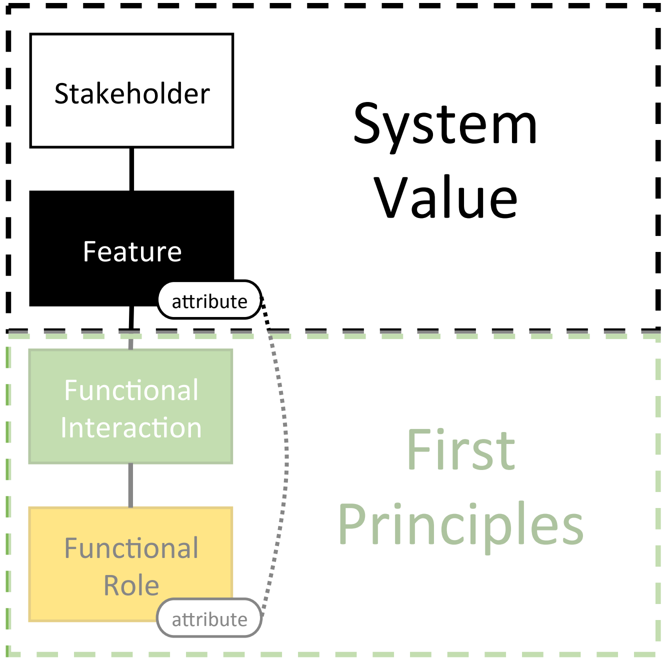


Functional Role (Role):

The behavior performed by one of the interacting entities during an Interaction. Example: Vehicle Operator; Vehicle Passenger Environment Subsystem

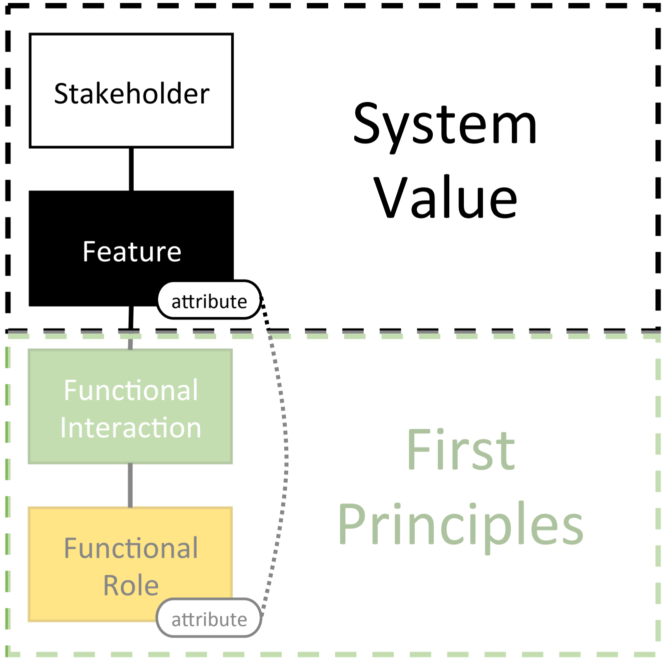
System Value – Stakeholder Features

- Values are what we care about. As such, they should be the driving force for our decision making[23]
- Determine what you want; then figure out how to get it, vice what are the options then pick the best alternative.
- Stakeholders include all classes of stakeholders and not just those who may purchase or use a product or system of interest.
- Features and their associated attributes contain the value space for a system of interest codified as formalized stakeholder needs/values.



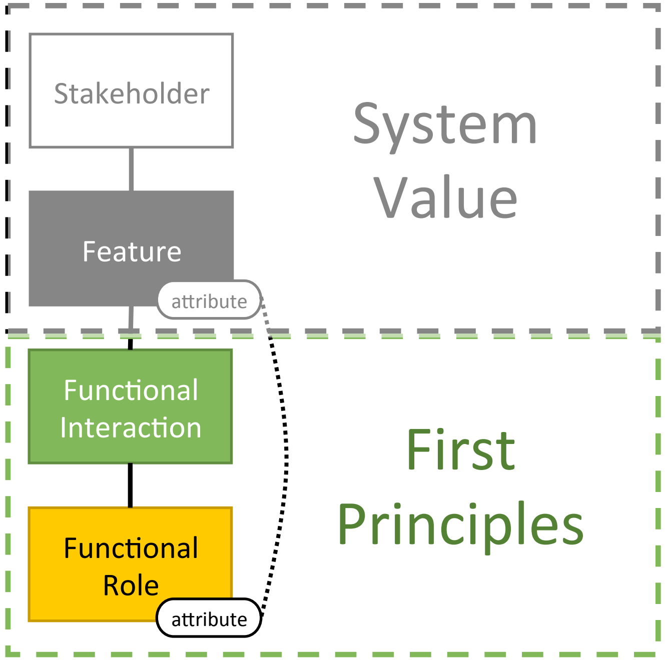
System Value – Stakeholder Features

- Since feature space contains the full complement of stakeholder values (the fitness landscape) it contains the entire trade space for design and development
- Feature space includes the full breadth and hierarchical depth of value including objectives and measures, weights and rationale prescribed in my texts focused on Decision Analysis.
- With Stakeholders and their Features well understood the Features are used to configure systems that conform to the selections and the dialing in of their associated attributes.
- Feature space is where selection-based decision analysis occurs, it's used as the basis of analysis and defense of all decision-making including optimization and trade-offs[23].



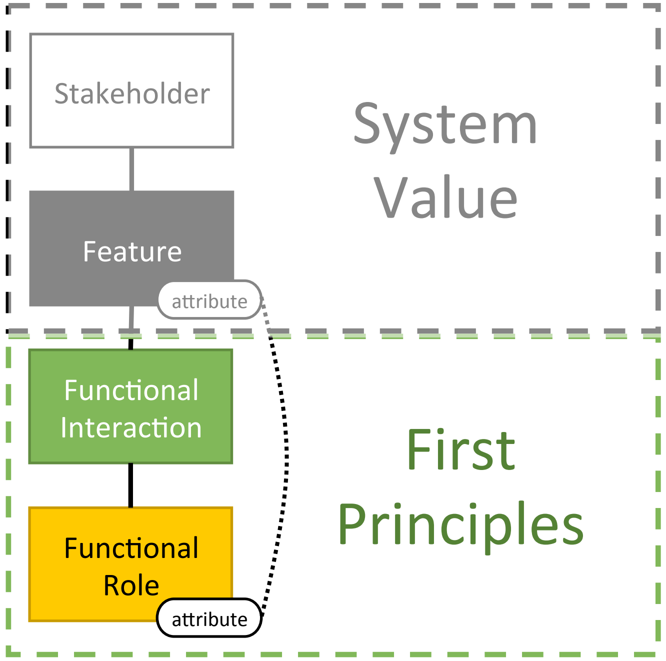
First Principles – Functional Interactions

- Functional Interactions are what define a system (a group of interacting, elements forming a complex whole) and through which the system delivers value.
- Functional interactions involve the exchange of forces, mass, energy or information. When we think of these fundamental exchanges, it brings to mind physics, chemistry, mechanics and many other engineering, science, or mathematics principles
- An identified Functional Interaction may be implemented by various combinations of functional roles.



First Principles – Functional Interactions

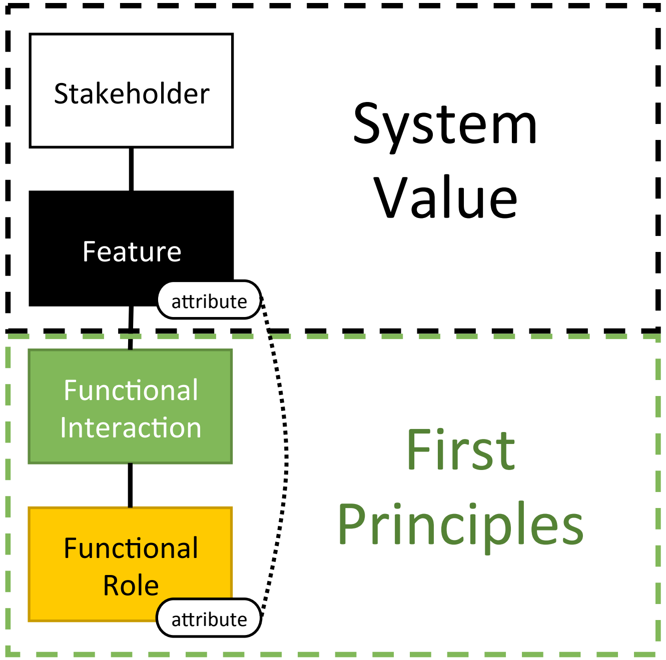
- ME, EE, CE, ChE, etc. are known for use of physical laws based in the "hard sciences", and first principles.
- Systems Engineering has an equivalent phenomena foundation. MBSE / PBSE supports hard science, first principle based (phenomena-based) domain disciplines, based on higher level system patterns.
- Attend "Got Phenomena"[25] briefing which will explain how systems engineering in MBSE / PBSE supports the emergence of new hard science phenomena-based domain disciplines, based on higher level system patterns i.e. ground vehicles, aircraft, marine vessels, and biochemical networks.



25: W. Schindel, "Got Phenomena? Science-Based Disciplines for Emerging Systems Challenges" in proceedings of INCOSE International Symposium, July 2016

Parameterization

- Just as Feature Attributes parameterize stakeholder values, Functional Role Attributes parameterize technical behavior.
- The coupling of these attributes provides a model based approach to coupling the first principles of engineering and science with stakeholder value.
- It's through this coupling that Pattern Based Systems Engineering explicates system value through first principles.

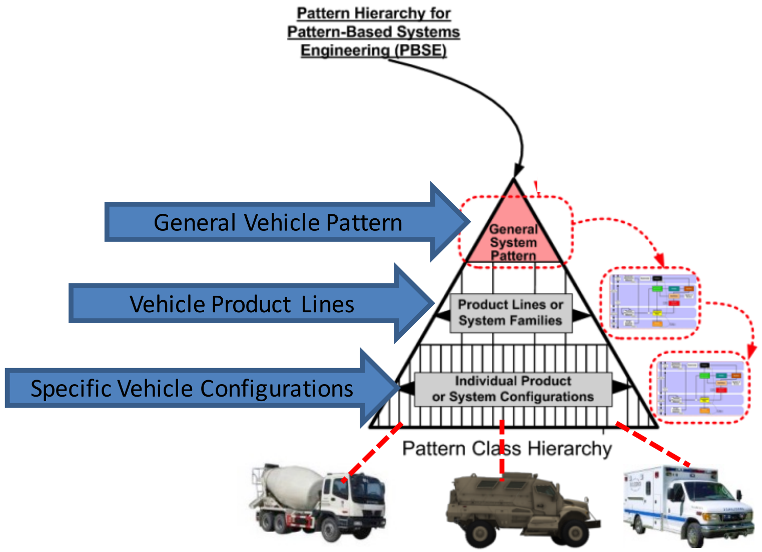


Configuration

- S*Models are intended to establish modeled Feature sets for all Stakeholders. These Features are then used to configure the pattern for individual applications/ product configurations. Feature selection becomes a proxy for configuring the rest of an S*Pattern

- Features and their Attributes (parameters) characterize the value space of system stakeholders, the resulting Feature Configuration Space becomes the formal expression of the trade space used as the basis of analysis and defense of all decision-making.

- Producing a “configured model” is limited to two transformation operations:
  - 1. Populate individual classes, relationships and attributes
  - 2. Adjust value attributes



Vision 2025 –Composable Designs & Configurability

- "Composable design methods will leverage reuse and validated patterns to configure and integrate components into system solutions. Decision support methods will support more rapid analysis of a large number of alternative designs, and optimization of complex systems with multiple variables and uncertainty."

- "The theoretical foundation will build on systems science to expand our understanding of the system under development and of the environment in which it operates. The foundations will encompass the mathematics of probability theory, decision theory and game theory to ensure methods that lead to the selection of a system design that maximizes value under uncertainty."

Decision Support

Leveraging Information and Analysis for Effective Decision Making

FROM	TO
Systems engineers explore a limited number of design alternatives primarily based on deterministic models of performance, physical constraints, cost and risk.	Systems engineers rapidly explore a broad space of alternatives to maximize overall value, based on a comprehensive set of measures including performance, physical constraints, security, resilience, cost and risk.

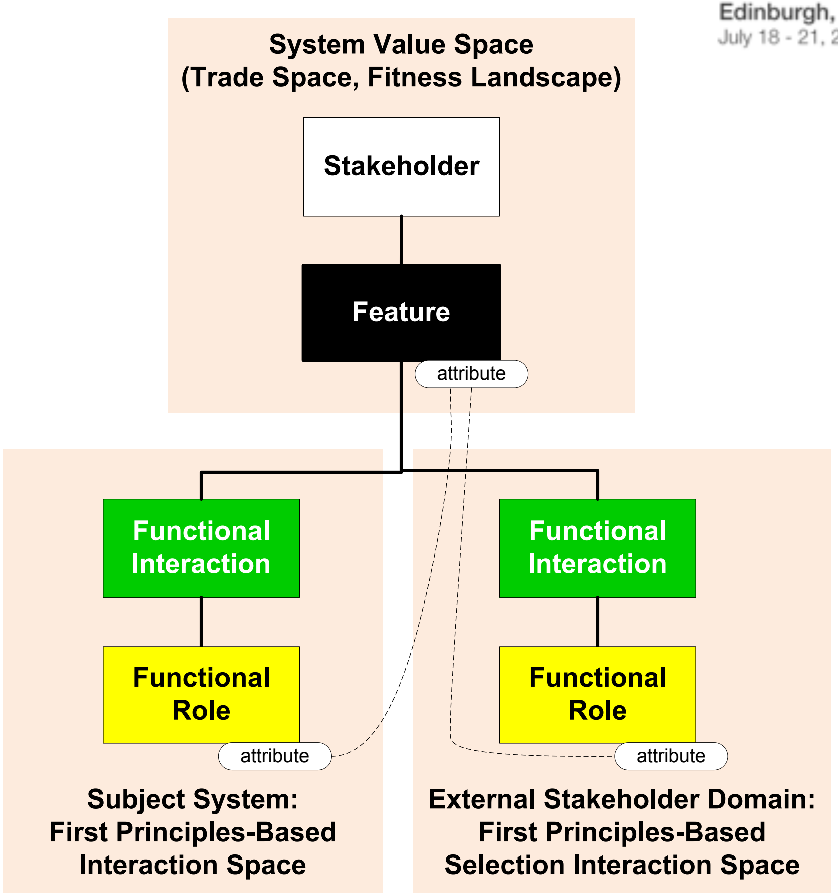
Extending Symbolic Method to Speed Up Trial and Error

"Trial-and-error design is an admirable method. But it is just real world trial and error which we are trying to replace by a symbolic method. Because trial and error is too expensive and too slow."

- To fully integrate SE and DA the third bullet from Alexander makes an important observation about the use of *"…symbolic method. Because trial and error is too expensive and slow."*
- This brings us first to the use of models and model based systems engineering (the symbolic part) and then to the Agile Systems Engineering Life Cycle Pattern (the sped-up "trial and error" part).

System Value, First Principle & Selection Interactions

- In the ASELCM Pattern, these selections are as explicit as the (other) interactions of the system of interest.
- Every trade off or decision which sets the direction of a system design is a value judgment (selection interaction) from the perspective of one or more stakeholders.
- System value is measured by the selection interactions of stakeholders or their representatives; these are expressed explicitly as Features.



Agile Systems Engineering Life Cycle

- INCOSE is currently executing the 2015-16 Agile Systems Engineering Life Cycle Model (ASELCM) Project. Working across a series of North American and European enterprises and industries, this discovery project is articulating and validating the ASELCM Pattern, in the form of a formal S*Pattern.

- The ASELCM Pattern explicates the points summarized in this paper, including:
  - The deeper re-integration of DA and SE, with the decisions shared between “internal” decision-makers and agile-measured “external” stakeholder representatives, whose selection behaviors are studied as a faster and surer path to good decisions.
  - The use of explicit MBSE Models to express life cycle system requirements, design, generated from MBSE Patterns by configuration and reconfiguration, as the environment changes in non-deterministic ways, and as a point of accumulation of learning.

http://www.incose.org/ChaptersGroups/WorkingGroups/knowledge/agile-systems-se

PBSE Benefits

- Strong expression of fitness landscapes as the basis for selection, trades, improvements, decisions, innovations, configuration, and understanding of risk and failure.
- Explication of the system phenomenon as a real world-based science and math foundation for systems engineering, amenable to systems science, connected to historical math/science models of other engineering disciplines, and encouraging discovery and expression
- A detailed MBSE approach to Platform Engineering and Management for system families and product lines.
- Compatibility with contemporary modeling language standards and tools.
- Deeper support for federated data across differing information systems, for integration with emerging open systems life cycle standard technologies.

Conclusions

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- System complexity and interconnectedness continues to rapidly increase making systems development extremely challenging.
- The context in which developed systems operate is continually changing altering the fitness and value delivered systems provide.
- Our traditional development activities must be revisited and enhanced to manage significant complexity. An important aspect is to better integrate DA and SE.
- We need to leverage “symbolic method” – this leads us to modeling methods and the promise provided by MBSE
- PBSE is particularly well suited MBSE methodology to model complex systems.
- Focus on interactions - how systems fundamentally provide value. Couple the first principles of engineering and science (expressed as Functional Interactions) to system value, (expressed by Stakeholders as Features)
- Explicate system value through explicit modeling of interaction/first principles to better uniting the SE and DA capabilities.

Biographies

Troy Peterson is Vice President of System Strategy, Inc. (SSI) Prior to joining SSI Troy was a Booz Allen Fellow and Chief Engineer, he worked at Ford Motor Company and operated his own engineering consulting business. He serves on the MSU Mechanical Engineering Department Advisory Board and INCOSE's Corporate Advisory Board. He's a past president of INCOSE's Michigan Chapter and he co-leads the Patterns Challenge Team of the INCOSE MBSE Initiative. Troy is also INCOSE's AD for Systems Engineering Transformation

William D. (Bill) Schindel is president of ICTT System Sciences. His engineering career began in mil/aero systems with IBM Federal Systems, included faculty service at Rose-Hulman Institute of Technology, and founding of three systems enterprises. Bill co-led a 2013 project on the science of Systems of Innovation in the INCOSE System Science Working Group. He co-leads the Patterns Challenge Team of the INCOSE MBSE Initiative

Abstract

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

System complexity continues to grow, creating many new challenges for engineers and decision makers. To maximize value delivery, amidst this complexity, "both" Systems Engineering and Decision Analysis capabilities are essential. For well over a decade 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 shepherds which diluted their technical influence on programs. With the recent shift toward Model Based Systems Engineering (MBSE) the Systems Engineering discipline is "getting back to basics," focusing on value delivery via foundational engineering axioms built upon first principles, using established laws of engineering and science. This paper will share how Pattern Based Systems Engineering (PBSE), as outlined within INCOSE's Model Based Systems Engineering (MBSE) initiative, is a methodology which explicates system value through an understanding and explicit modeling of first principles, better re-uniting Systems Engineering and Decision Analysis capabilities.

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Backup

Definitions of some S* Metamodel Classes

- **System**: A collection of interacting components. Example: Vehicle; Vehicle Domain System.
- **Stakeholder**: A person or other entity with something at stake in the life cycle of a system. Example: Vehicle Operator; Vehicle Owner; Pedestrian
- **Feature**: A behavior of a system that carries stakeholder value. Example: Automatic Braking System Feature; Passenger Comfort Feature Group
- **Functional Interaction (Interaction):** An exchange of energy, force, mass, or information by two entities, in which one changes the state of the other. Example: Refuel Vehicle; Travel Over Terrain
- **Functional Role (Role):** The behavior performed by one of the interacting entities during an Interaction. Example: Vehicle Operator; Vehicle Passenger Environment Subsystem
- **Input-Output:** That which is exchanged during an interaction (generally associated with energy, force, mass, or information). Example: Fuel, Propulsion Force, Exhaust Gas

Definitions of some S* Metamodel Classes

- **<u>System of Access:</u>** A system which provides the means for physical interaction between two interacting entities. Examples: Fueling Nozzle-Receptacle; Grease Gun Fitting; Steering Wheel; Dashboard; Brake Peddle
- **<u>Interface:</u>** The association of a System (which “has” the interface), one or more Interactions (which describe behavior at the interface), the Input-Outputs (which pass through the interface), and a System of Access (which provides the means of the interaction). Examples: Operator Interface; GPS Interface
- **<u>State:</u>** A mode, situation, or condition that describes a System’s condition at some moment or period of time. Example: Starting; Cruising; Performing Maneuvers
- **<u>Design Component:</u>** A physical entity that has identity, whose behavior is described by Functional Role(s) allocated to it. Examples: Garmin Model 332 GPS Receiver; Michelin Model 155 Tire
- **<u>Requirement Statement:</u>** A (usually prose) description of the behavior expected of (at least part of) a Functional Role. Example: “The System will accept inflow of fuel at up to 10 gallons per minute without overflow or spillage.”