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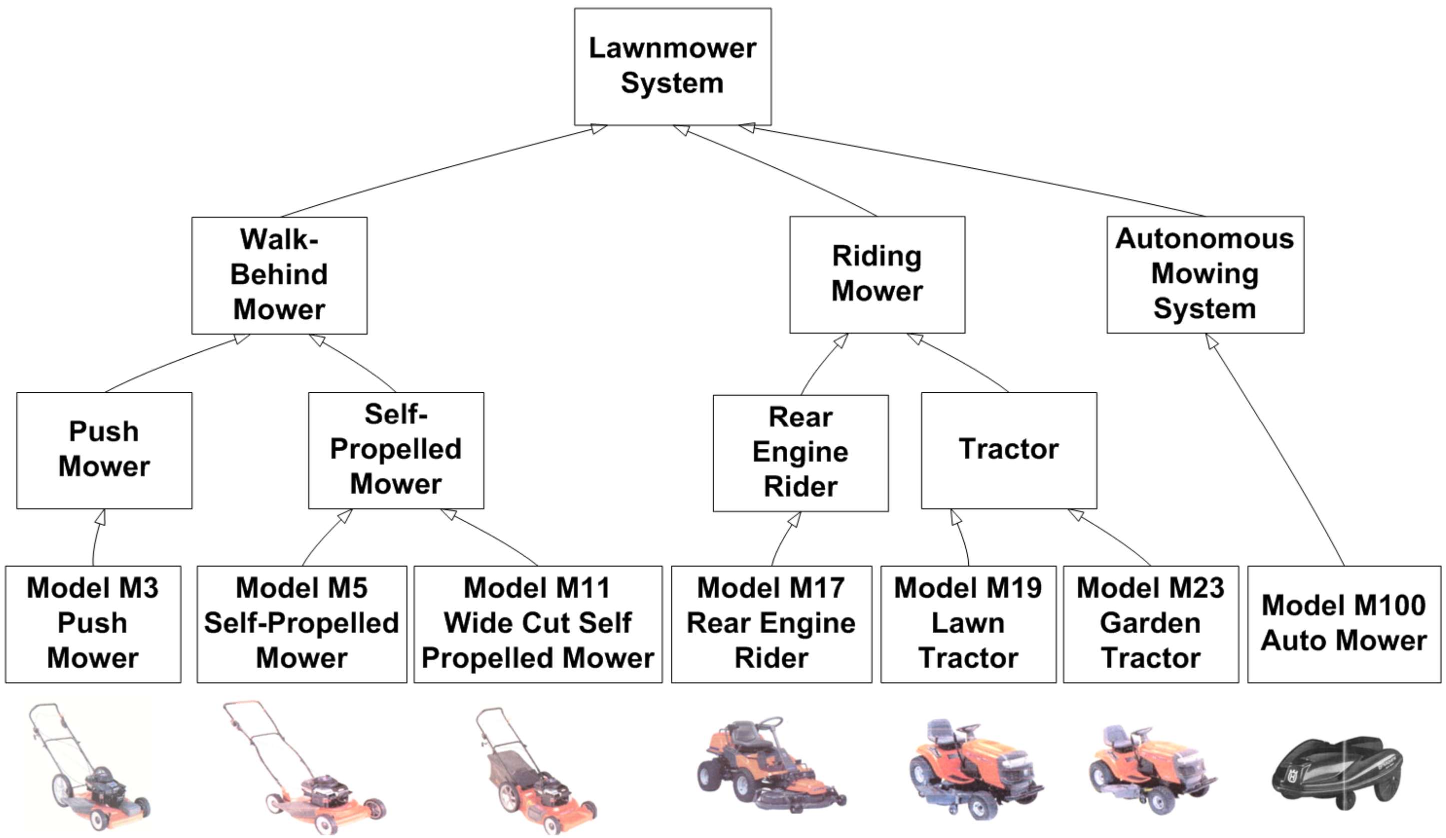
Introduction to Pattern-Based Systems Engineering (PBSE)



Abstract

Complexity of the human-engineered world is growing faster than human capacity to deal with that complexity. It is becoming easier to create a system more complex than we can readily understand. INCOSE thought leaders have been calling for a 10:1 reduction in the effort to address 10X more complex systems, using people from a 10X larger global community than the “systems expert” group INCOSE currently reaches.

For 300 years, humankind has drawn upon science and mathematics to make a complex natural world simple enough to advance civilization. At the heart of this revolution are the detection, representation, and exploitation of “patterns” (repeating regularities) in the world around us. Pattern-Based Systems Engineering (PBSE) applies this approach to increase the power of systems engineering to address greater complexity while reducing the load on the people who perform it.

This webinar will review the PBSE approach as an extension of Model-Based Systems Engineering (MBSE). Existing modeling languages and tools can be used to create S* Patterns, which are re-usable, configurable S* Models, which describe the Requirements, Design, Failure Modes, Verification, or other aspects of systems, in the tradition of science and mathematics. Among the patterns which emerge are product patterns, manufacturing and distribution patterns, patterns of intelligence, and the pattern of innovation in the natural and human-engineered world. This approach has been applied to aerospace, automotive, telecommunication, medical and health care, consumer product, and advanced manufacturing domains, with significant impact on their ability to address growth in complexity.

Contents

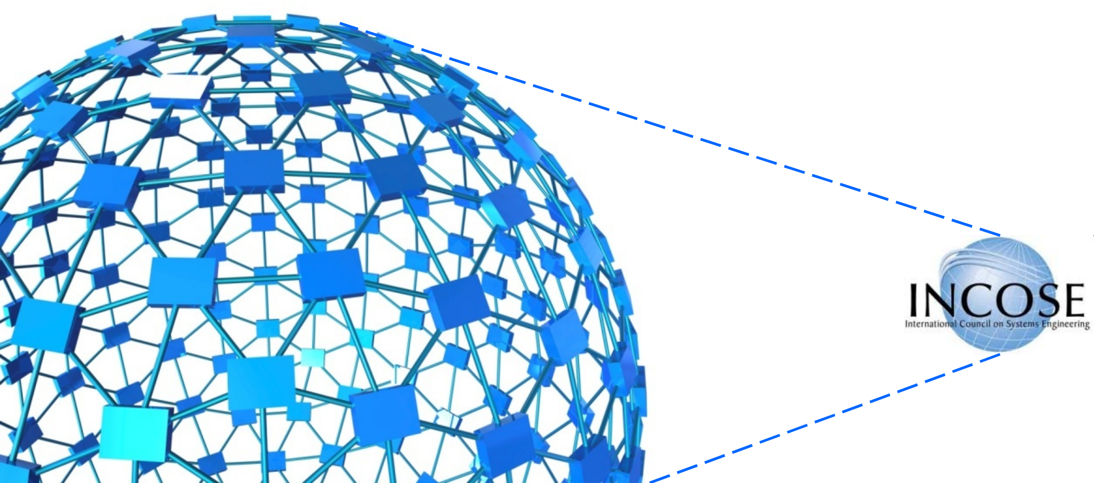
The Need, Call-to-Arms, and Vision

– INCOSE thought leaders have discussed the growing need to address 10:1 more complex systems with 1:10 reduction in effort, using people from a 10:1 larger community than the "systems expert" group INCOSE currently reaches.

– Many SE efforts are in some way concerned with growing complexity, but none give evidence of the sweeping order-of-magnitude improvements demanded by this call-to-arms.

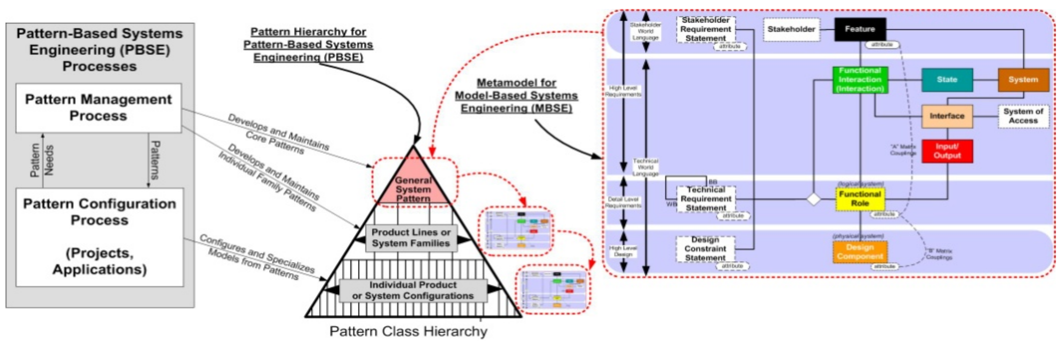
– This talk is about a way to achieve this order-of-magnitude improvement:

  - Using Pattern-Based Systems Engineering (PBSE)—an extension of Model-Based Systems Engineering (MBSE).



Concept Summary: Pattern-Based Systems Engineering (PBSE)

- The PBSE approach respects the systems engineering tradition, body of knowledge, and historical lessons, while providing a high-gain path forward.
- 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). The Pattern includes not only the Platform, but all the extended system information (e.g., requirements, risk analysis, design trade-offs & alternatives, decision processes, etc.):



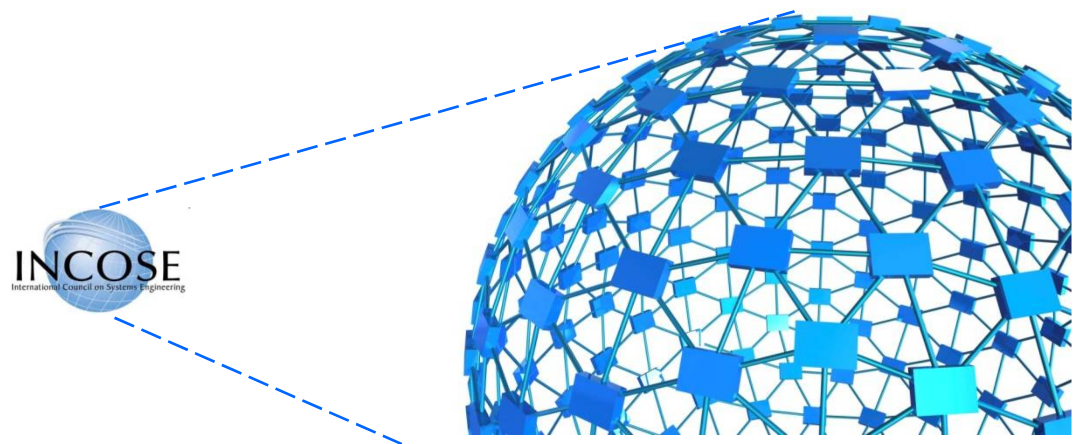
- By including the appropriate S* Metamodel concepts, these can readily be managed in (SysML or other) preferred modeling languages and tools—the ideas involved here are not specific to a modeling language or specific tool.
- The order-of-magnitude changes have been realized because projects that use PBSE rapidly start from an existing Pattern, gaining the advantages of its content, and feed the pattern with what they learn, for future users.
- The "game changer" here is the shift from "learning to model" to "learning the model", freeing many people to rapidly configure, specialize, and apply patterns to deliver value in their model-based projects.

Status of PBSE

- The major aspects of PBSE have been defined and practiced for years across a number of enterprises and domains, but with limited INCOSE community awareness:

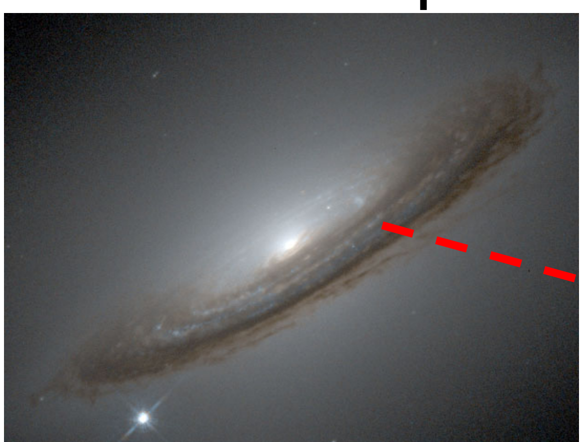
Medical Device Patterns	Construction Equipment Patterns	Commercial Vehicle Patterns	Space Tourism Pattern
Manufacturing Process Patterns	Vision System Patterns	Packaging System Patterns	Lawnmower Pattern
Embedded Intelligence Patterns	Systems of Innovation (SOI) Pattern	Baby Product Pattern	Orbital Satellite Pattern
Development Process Patterns	Production Material Handling Patterns	Engine Controls Patterns	Military Radio Systems Pattern

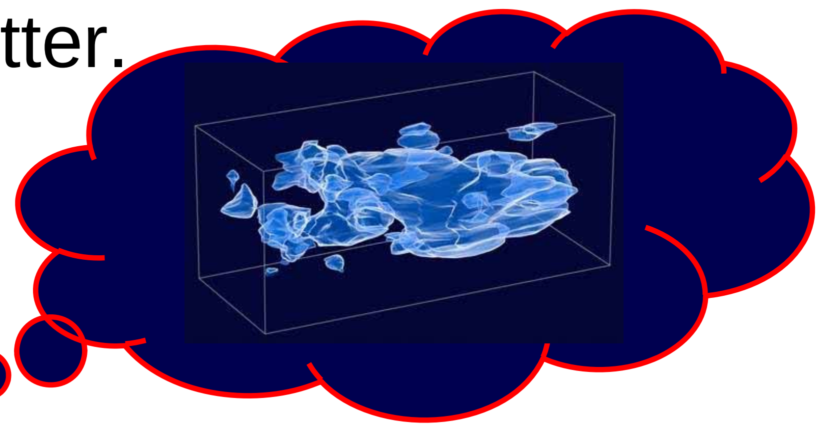
- This talk is more about INCOSE community awareness and capability than about technically establishing a new method—although it will look new to INCOSE practitioners.
- We recognize that the human change aspect can be the most challenging – but are not suggesting that we also have to create new technical methods. We are introducing PBSE to a larger community.



Dark Matter

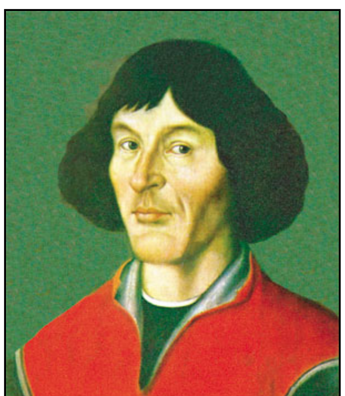
- Some cosmologists believe “Dark Matter” exists:
  - Is invisible (optically),
  - Exerts gravitational force on the rest of matter,
  - Is a major & widespread component of the universe.
- Otherwise unexplained behavior of the universe seems explained by Dark Matter.

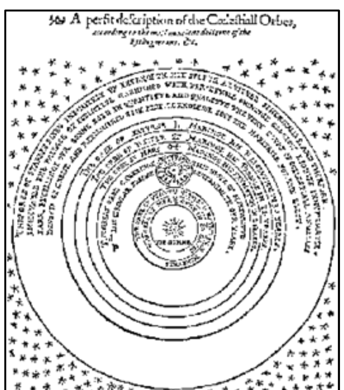


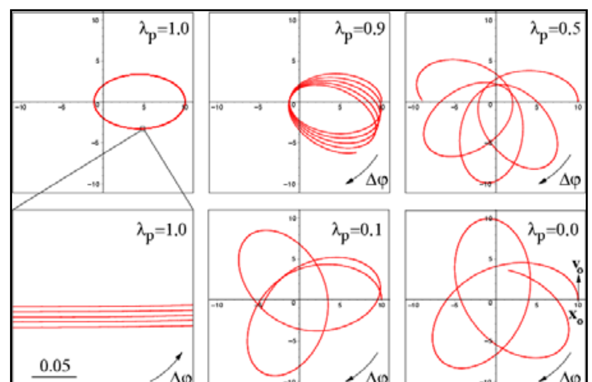


Science Seeks Models

- Will Dark Matter become fully accepted by the scientific community to explain the patterns of observed behavior?
  - It is still early to say.
- Earlier, the Copernican Revolution required <u>generations</u> to be the accepted explanation of planetary behavior patterns:
  - Others after Copernicus (Galileo, Brahe, Kepler, Newton) were aided by finding <u>improved methods of representation</u> to better explain <u>regularities of observed behavior</u>.

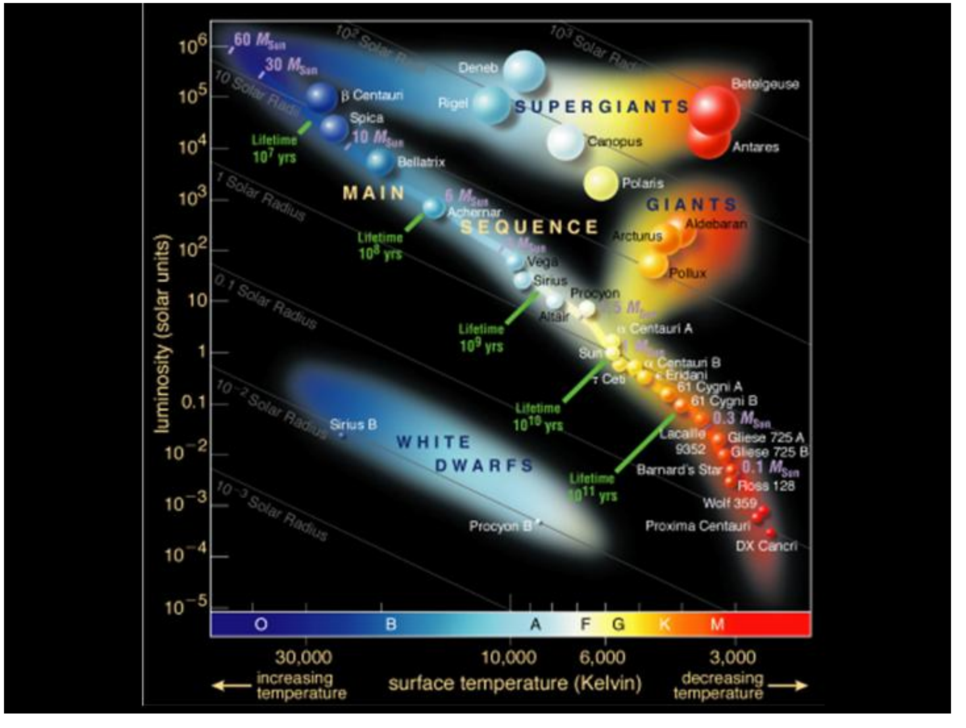






One-off Models versus Family Patterns

- These improved understandings depended not just on better Models of individual situations, but also on . . .
- Representation of Families, helping to understand different types of behavior, organizing the universe further into “types”:



The systems engineering connection

- *Discovering regularities and how to represent them* has been at the heart of science and engineering progress:
  - The INCOSE System Sciences Working Group (SSWG) bridges the interests of engineering and science.
  - Next meeting will be at IW2012.
  - https://sites.google.com/site/syssciwg/
- *Ability to manage risk and adapt* are related to our *awareness* and *understanding* of the *regularities* (patterns) around us:
  - Whether in the systems we engineer, or the markets and operational environments in which their life cycle unfolds.
  - They exert "forces" on us, whether are aware of them or not.

What repeating regularities are of interest?

- Smaller-Scale Regularities:
  - Patterns of Stakeholder Features (e.g., in vehicles, energy systems, etc.)
  - Patterns of Requirements
  - Patterns of Design Solutions
  - Patterns of Failure Modes and Effects
  - Patterns of Functional Roles, Interactions, States
  - Patterns of Interfaces, Input-Outputs, and Access
  - Patterns of Technologies

- Larger-Scale Regularities:
  - Patterns of how all the above are related to each other
  - Patterns in couplings across systems, domains, SOS's
  - Systems of Material Handling, Production, Distribution, Sustainment
  - Systems of Innovation
  - Patterns of Systems Pathologies

INCOSE SSWG

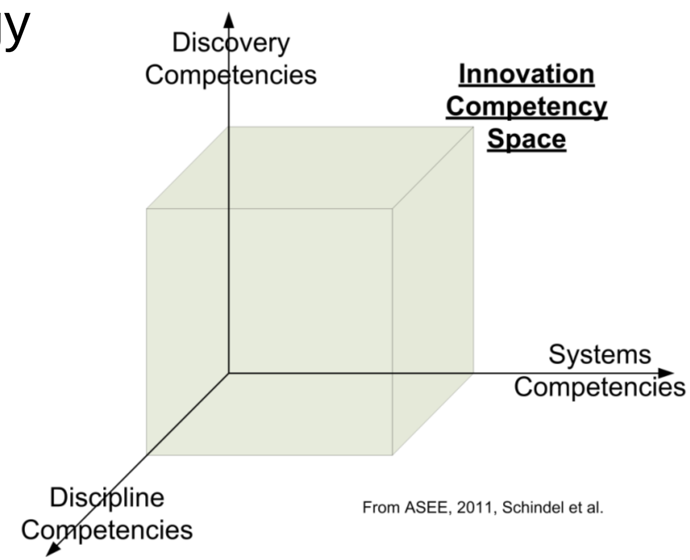
Is this “just of academic interest”?

- Hardly! Lack of awareness of these regular patterns leaves products, programs, enterprises at serious risk:
  - Re-experiencing the same mis-steps and reworks;
  - Just because we have made one system work, how do we know what will happen when we deploy more of them, as markets, conditions, & technologies evolve?
  - Just because our system has human experts on hand today, how do we know what will happen when they move on?
- Example cases and responses:
  - FDA push to the pharmaceutical manufacturing industry to improve the science-based understanding of underlying process transformations, provable ranges, and control strategies, etc.
  - The generation of system requirements families for globally-deployed product families and their production, distribution, and support systems.
  - The generation of system verification plans from underlying patterns of system requirements.
  - The use of System Patterns to generate Risk Analyses (e.g., FMEAs, etc.) for a variety of domain systems.

“Chance favors the prepared mind”

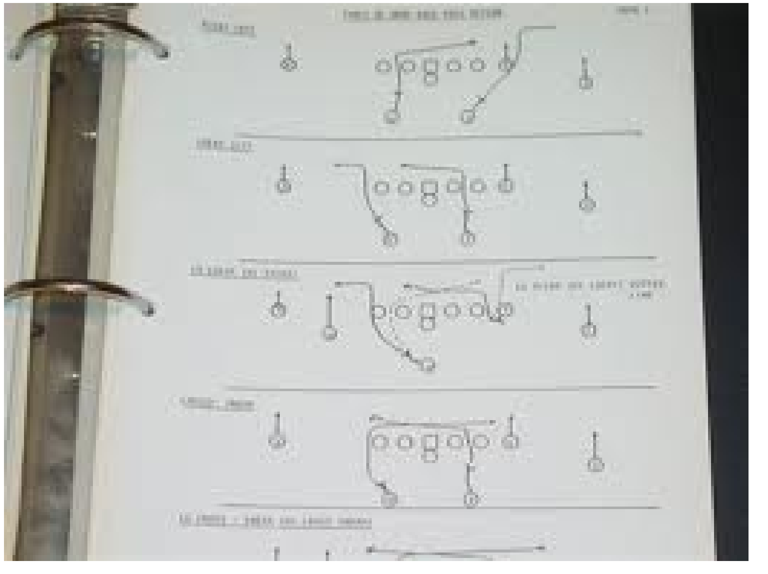
- Louis Pasteur

- Explicit patterns help us organize what we know--as well as what we don’t.
- Explicit preparation for:
  - System & program risks
  - Market & competitive shifts
  - New science & technology
  - Life cycle extensions
- Adaptability!



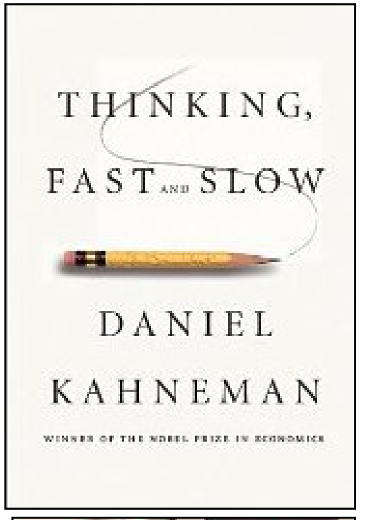
Adaptation Response Time

- Explicit pattern awareness helps us to:
  - Recognize the situation has changed.
  - Know the best alternate pattern configuration.

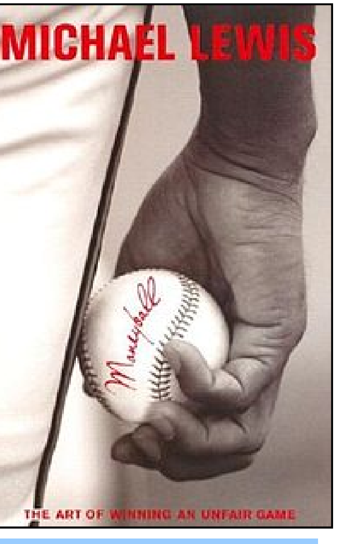


Irrationality: Human beings' behaviorally-preferred mode?

- A broad issue across human life:
  - The science of irrationality
  - Daniel Kahneman, Nobel Laureate, "Thinking, Fast and Slow")
  - "Moneyball", Oakland A's, Billy Beane.



- Engineering teams more rational than others?
  - Ever encounter a bad decision?
  - A significant fraction of requirements are left unstated



- Patterns existing in Nature do not mean the patterns are recognized by humans

One way people cope . . .

- “Domain experts” internalize patterns:
  - These human experts influence our projects, using their experience, intuition, informed judgment.

System Patterns: Dark and Visible

- The regularities are “out there”, whether we represent them or not:
  – In particular, they impact our ability to deal with uncertainty and adaptability.
- We use the term <u>Dark Pattern</u> to refer to system regularities that have <u>not</u> been explicitly represented:
  – They are in a sense “invisible”, but still impact our systems, customers, programs, enterprises, institutions, and society.
- By contrast, when we represent those System Patterns formally, they become “visible”, as <u>Explicit Patterns</u>:
  – Our method for doing this is Pattern-Based Systems Engineering (PBSE);
  – PBSE is an extension of Model-Based Systems Engineering (MBSE);
  – PBSE creates and applies configurable, re-usable models, called <u>Patterns</u>;
  – They typically include much more than just the “subject system”.

How many patterns are Dark?

- Most systems programs involve Patterns, such as:
  - Patterns of available technologies and parts
  - Patterns of candidate solution architectures
  - Patterns of interfaces
  - Patterns of system states or modes
  - Patterns of customers, or market expectations
  - Patterns of competitive offerings
  - Patterns of system failures modes and effects
- Most systems engineering efforts—even model-based--still occur without use of explicit Pattern-Based methods:
  - This is the world of Dark Patterns.
  - Example: Nearly universally missed requirements.
- Explicit Patterns prepare us to adapt by describing key objects, relationships, and variables—including multiple types of risk.

Representing System Patterns

- What is the smallest amount of information we need to represent these regularities?
  - Some people have used prose to describe system regularities.
  - This is better than nothing, but usually not enough to deal with complex systems.
- We use S* Models, which are the minimum model-based information necessary:
  - This is not a matter of modeling language—your current favorite language and tools can readily be used for S* Models.
  - The minimum underlying information classes are summarized in the S* Metamodel, for use in any modeling language.
- The resulting system model is made configurable and reusable, thereby becoming an S* Pattern.

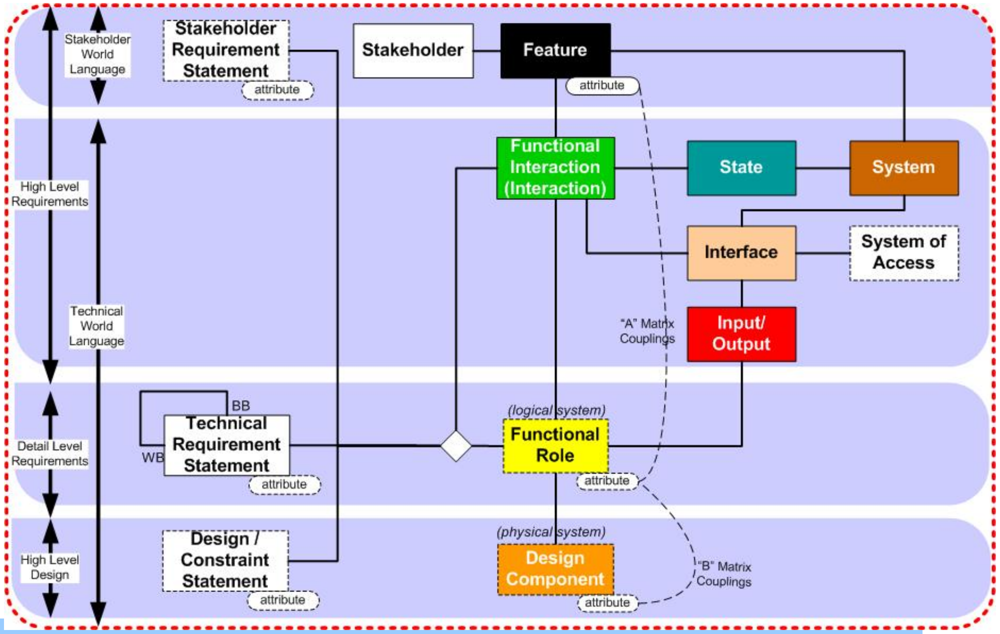
Constructing an efficient representation

- A <u>metamodel</u> is a model of other models;
  - Sets forth how we will represent Requirements, Designs, Verification, Failure Analysis, Trade-offs, etc.;
  - We utilize the (language independent) S* Metamodel from Systematica™ Methodology:

- The resulting system models may be expressed in SysML™, other languages, DB tables, etc.

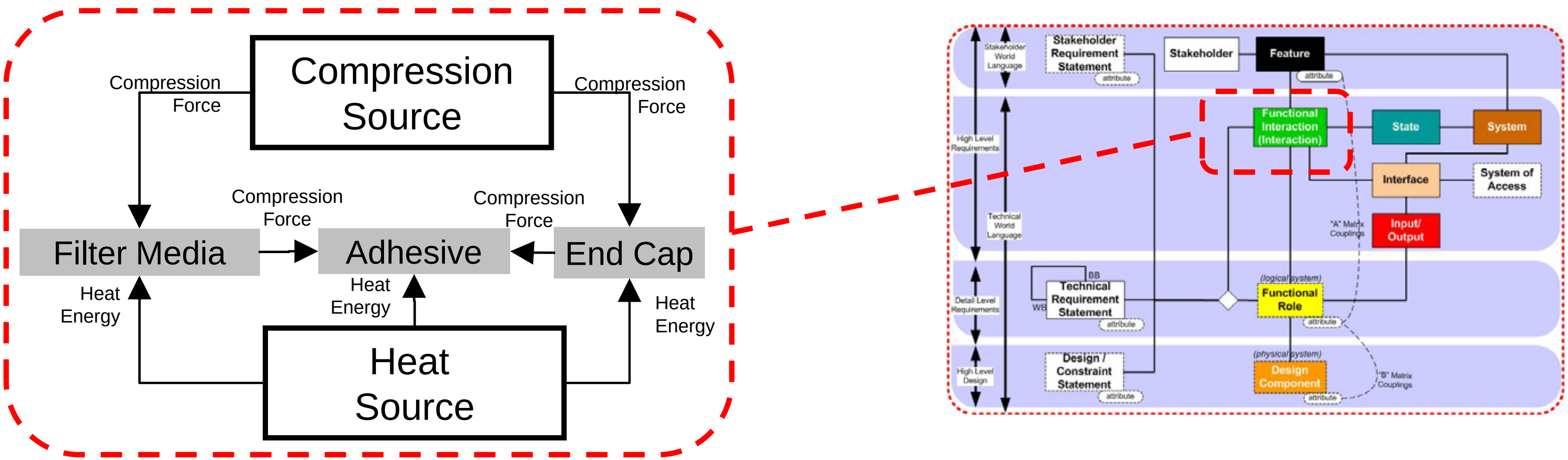
- Has been applied to systems engineering in aerospace, transportation, medical, advanced manufacturing, communication, construction, other domains.

Simple summary of detailed S* Metamodel.



Physical Interactions: At the heart of S* models

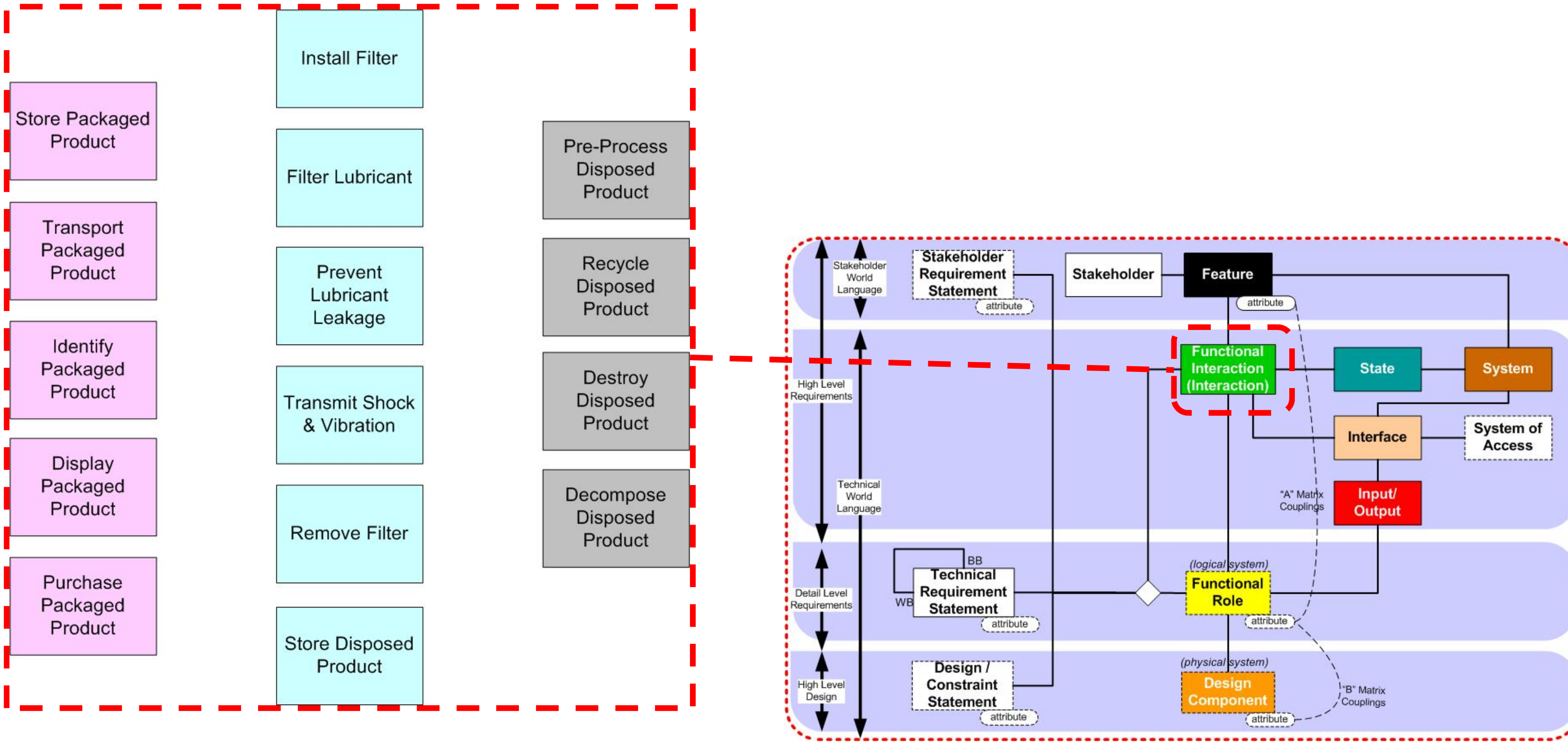
- S* models represent Interactions as explicit objects:
  - Goes to the heart of 300 years of natural science of systems as a foundation for engineering, including emergence.
  - All functional requirements are revealed as external interactions [Schindel].



- Other Metamodel parts: See the References.

Physical Interactions: At the heart of S* models

- S* models represent <u>Physical Interactions</u> as explicit objects:
  - Example: Pattern of Oil Filter Interactions:



Pattern-based systems engineering (PBSE)

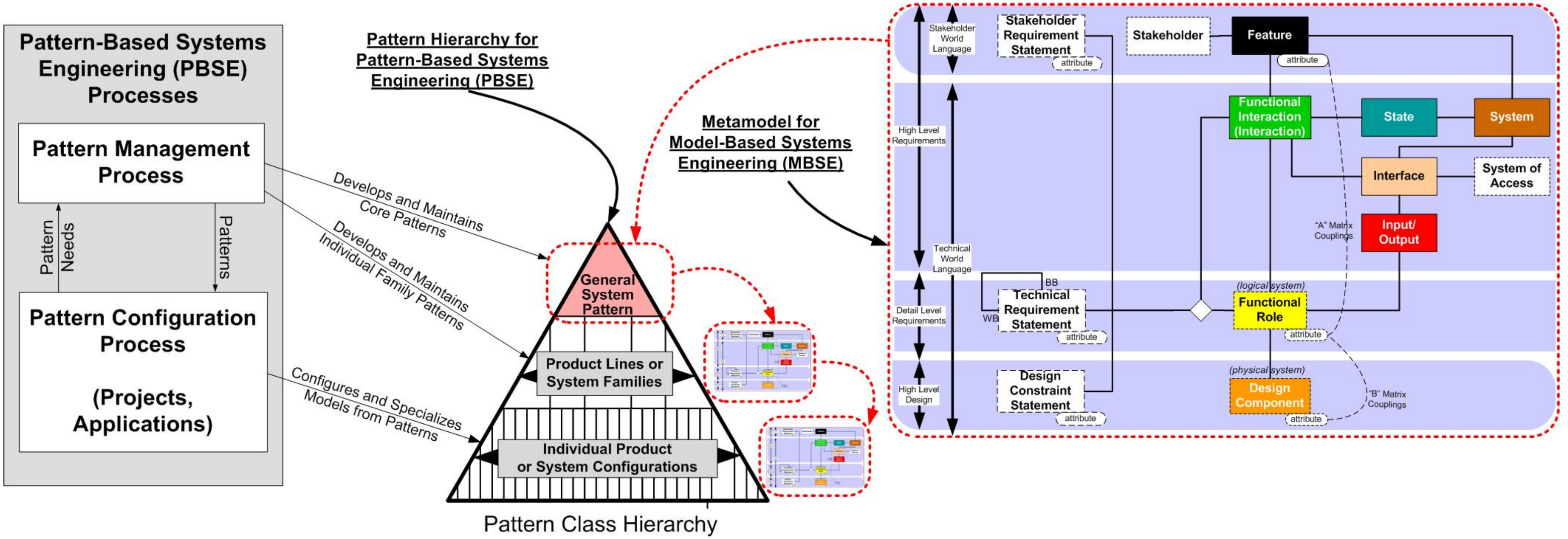
- Model-based Patterns:
  - In this approach, Patterns are reusable, configurable S* models of families (product lines, sets, ensembles) of systems.
- These Patterns are ready to be configured to serve as Models of individual systems in projects.
- Configured here is specifically limited to mean that:
  - Pattern model components are populated / de-populated, and
  - Pattern model attribute (parameter) values are set

. . . both based on configuration rules that are part of the Pattern.

- Patterns are based on the same Metamodel as "ordinary" Models

Pattern-based systems engineering (PBSE)

- Pattern-Based Systems Engineering (PBSE) has two overall processes:
  - **Pattern Management Process**: Generates the underlying family model, and periodically updates it based on application project discovery and learning;
  - **Pattern Configuration Process**: Configures the pattern into a specific model for application in a project.

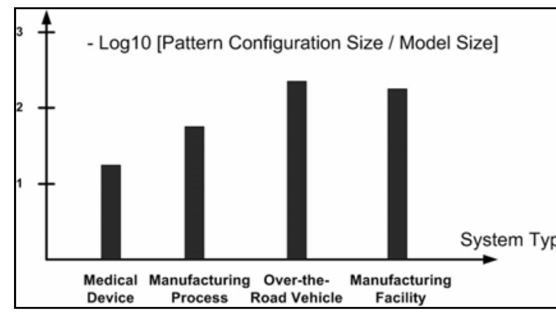


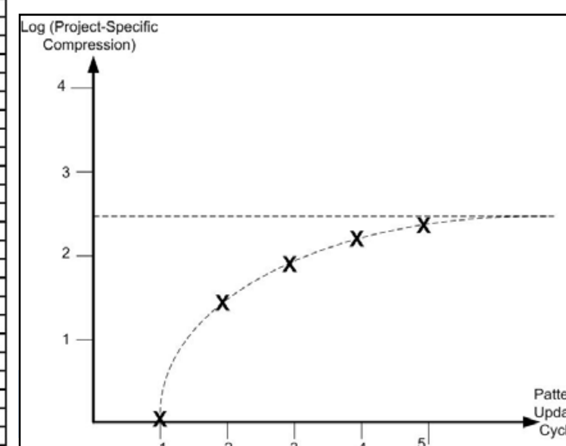
Pattern configurations

- A table of configurations illustrates how patterns facilitate compression;
- Each column in the table is a compressed system representation with respect to ("modulo") the pattern;
- The compression is typically very large;
- The compression ratio tells us how much of the pattern is variable and how much fixed, across the family of potential configurations.

Lawnmower Product Line: Configurations Table

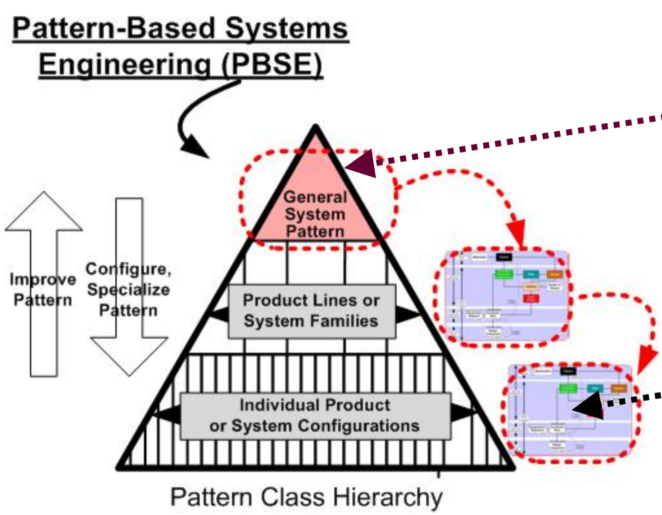
		Units	Walk-Behind Push Mower Push Mower	Walk-Behind Mower Self-Propelled	Walk-Behind Self-Propelled Wide Cut	Riding Rider Rider	Riding Tractor Lawn	Riding Mower Tractor Garden	Autonomous Autonomous Auto Mower
	Model Number		M3	M5	M11	M17	M19	M23	M100
	Market Segment		Sm Resident	Med Resident	Med Resident	Lg Resident	Lg Resident	Home Garden	High End Suburban
Power	Engine Manufacturer		B&S	B&S	Tecumseh	Tecumseh	Kohler	Kohler	Elektroset
	Horsepower	HP	5	6.5	13	16	18.5	22	0.5
Production	Cutting Width	Inches	17	19	36	36	42	48	16
	Maximum Mowing Speed	MPH	3	3	4	8	10	12	2.5
	Maximum Mowing Productivity	Acres/Hr			1.6				
	Turning Radius	Inches	0	0	0	0	126	165	0
	Fuel Tank Capacity	Hours	1.5	1.7	2.5	2.8	3.2	3.5	2
	Towing Feature						x	x	
	Electric Starter Feature				x	x	x	x	
	Basic Mowing Feature Group		x	x	x	x	x	x	x
Mower	No. of Anti-Scalping Rollers		0	0	1	2	4	6	0
	Cutting Height Minimum	Inches	1	1.5	1.5	1.5	1	1.5	1.2
	Cutting Height Maximum	Inches	4	5	5	6	8	10	3.8
	Operator Riding Feature					x	x	x	
	Grass Bagging Feature		Optional	Optional	Optional	Optional	Optional	Optional	
	Mulching Feature		Standard	Factory Installed	Dealer Installed				
	Aerator Feature					Optional	Optional	Optional	
	Autonomous Mowing Feature								x
	Dethatching Feature					Optional	Optional	Optional	
Physical	Wheel Base	Inches	18	20	22	40	48	52	16
	Overall Length	Inches	18	20	23	58	56	68	28.3
	Overall Height	Inches	40	42	42	30	32	36	10.3
	Width	Inches	18	20	22	40	48	52	23.6
	Weight	Pounds	120	160	300	680	705	1020	15.6
	Self-Propelled Mowing Feature			x	x	x	x	x	x
	Automatic TransmFeature							x	
Financials	Retail Price	Dollars	360	460	1800	3300	6100	9990	1799
	Manufacturer Cost	Dollars	120	140	550	950	1800	3500	310
Maintenance	Warranty	Months	12	12	18	24	24	24	12
	Product Service Life	Hours	500	500	600	1100	1350	1500	300
	Time Between Service	Hours	100	100	150	200	200	250	100
Safety	Spark Arrest Feature		x	x	x	x	x	x	





Checking holistic alignment to a pattern

- Gestalt Rules express what is meant by holistic conformance to a pattern:
  - Expressing regularities of whole things, versus same “parts”

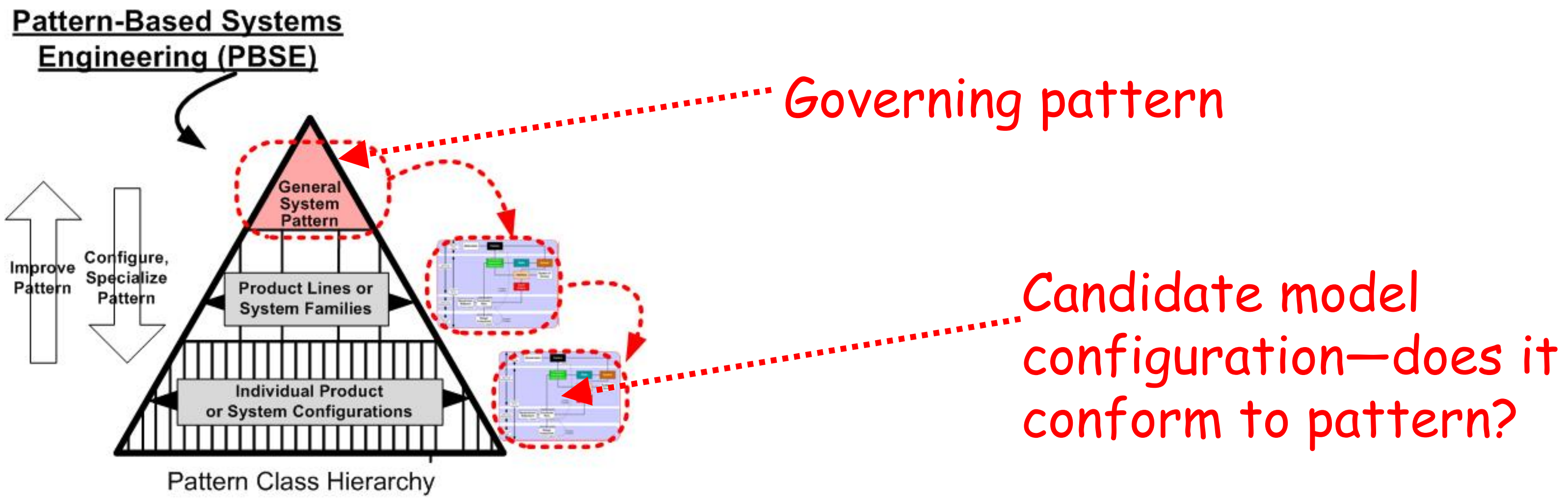


Governing pattern

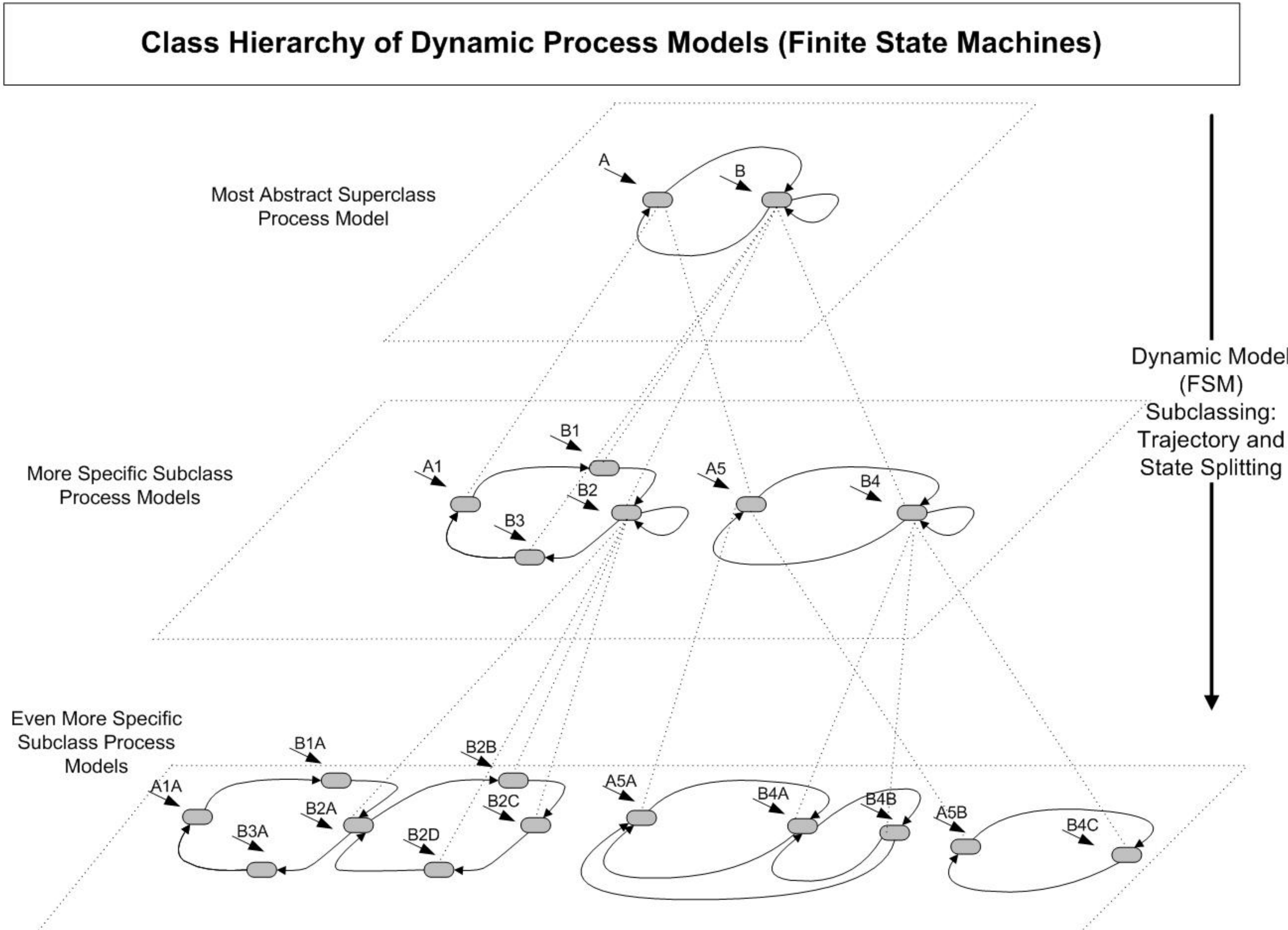
Candidate model configuration—does it conform to pattern?

The Gestalt Rules

1. Every component class in the candidate model must be a subclass of a parent superclass in the pattern—no “orphan classes”.
2. Every relationship between component classes must be a subclass of a parent relationship in the pattern, and which must relate parent superclasses of those same component classes—no “orphan relationships”.
3. Refining the pattern superclasses and their relationships is a permissible way to achieve conformance to (1) and (2).

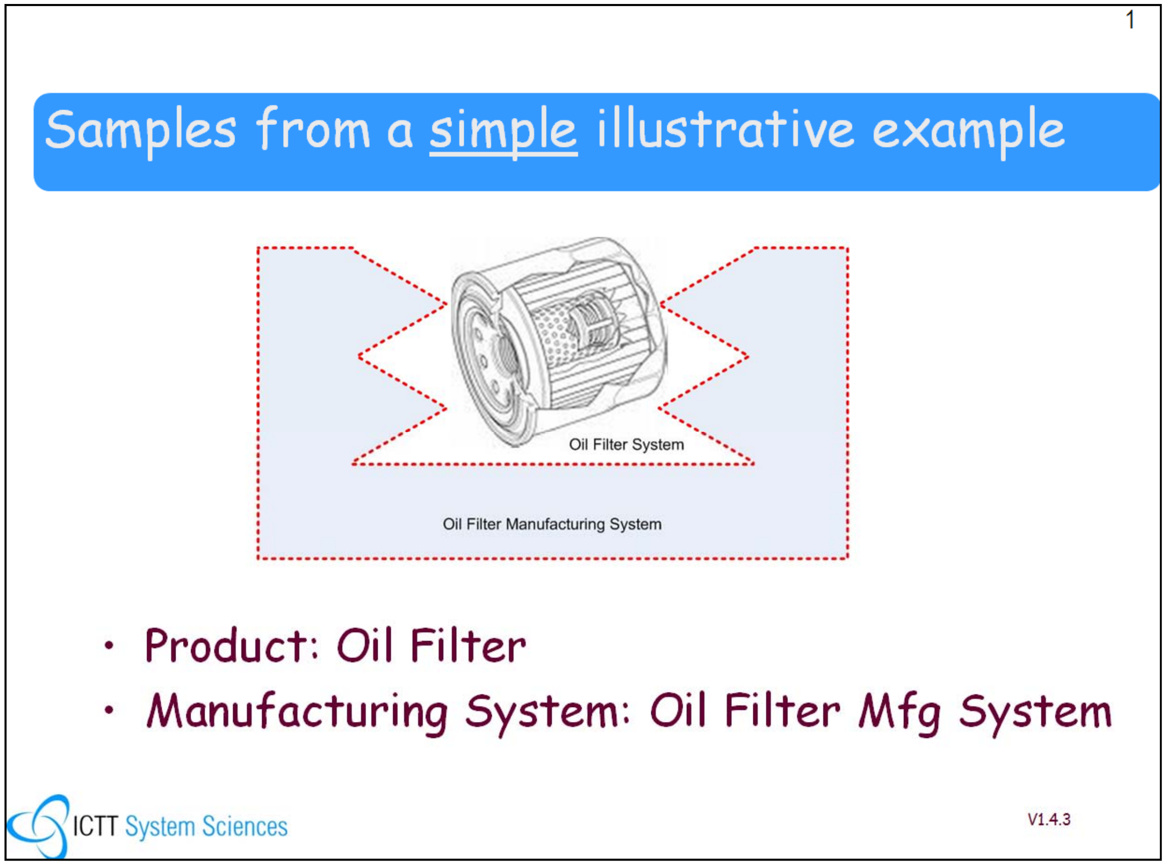


Example: State Model Pattern—illustrates how *visual* is the "class splitting" and "relationship rubber banding" of the Gestalt Rules



Extended example details

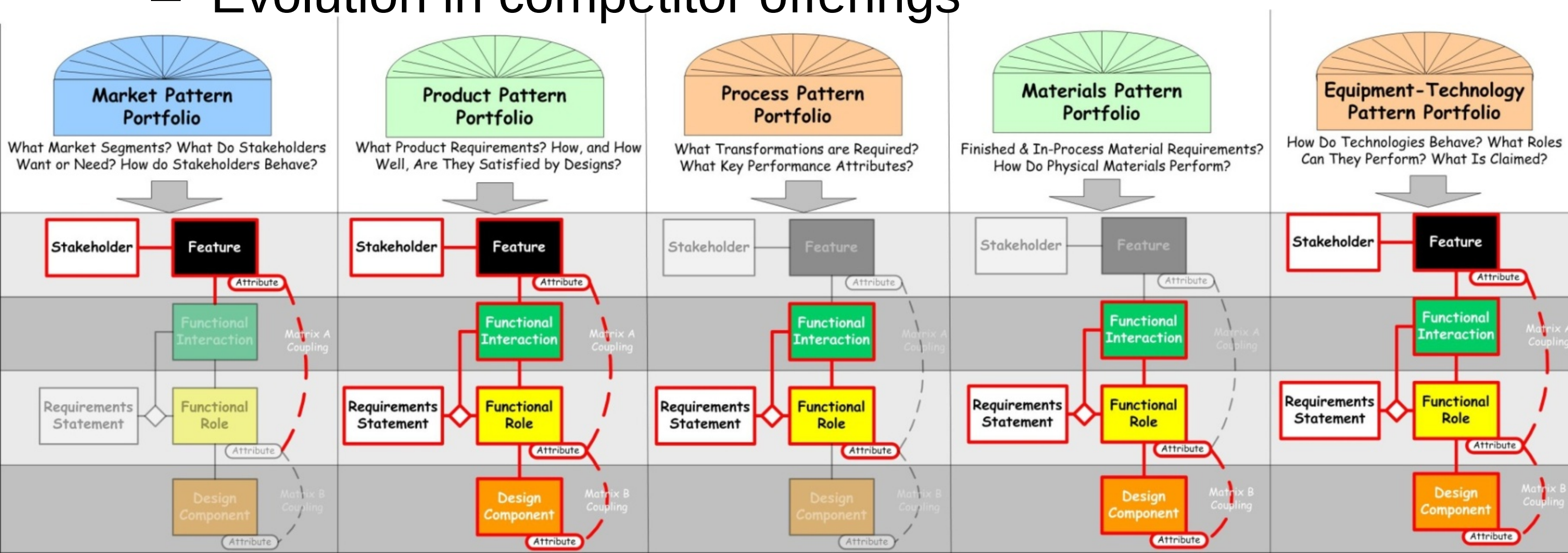
- See:



INCOSE
International Council on Systems Engineering

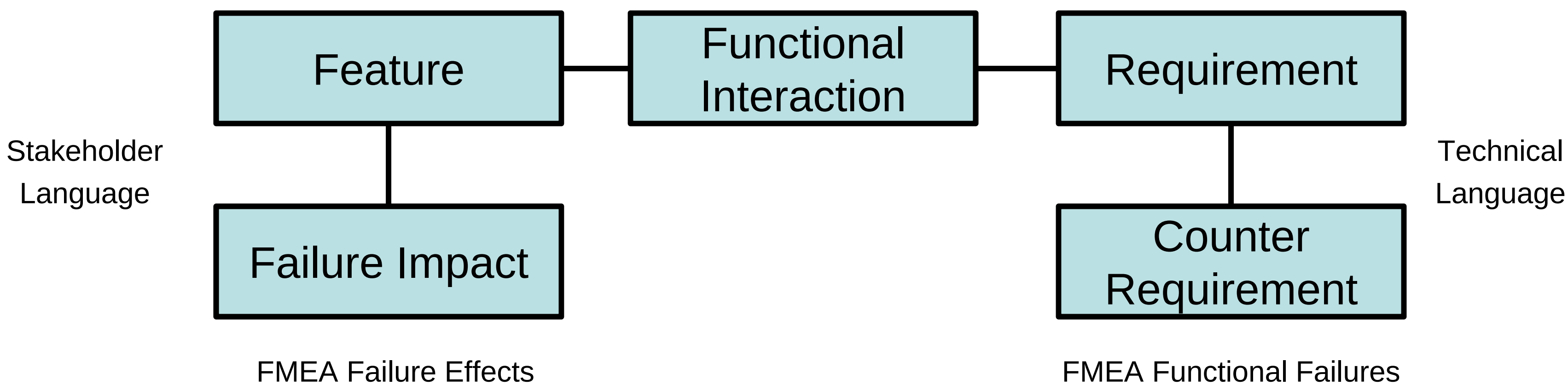
Leveraging adaptability to tame uncertainty

- Patterns express “envelopes” around “point situations”.
- Patterns help us discover, explore, and record what we may have to adapt to, along with adaptation plans:
  - Evolution in available technologies and parts
  - Evolution in system requirements, interfaces, modes, etc.
  - Evolution in the larger systems in which we operate
  - Evolution in customer or market expectations
  - Evolution in competitor offerings



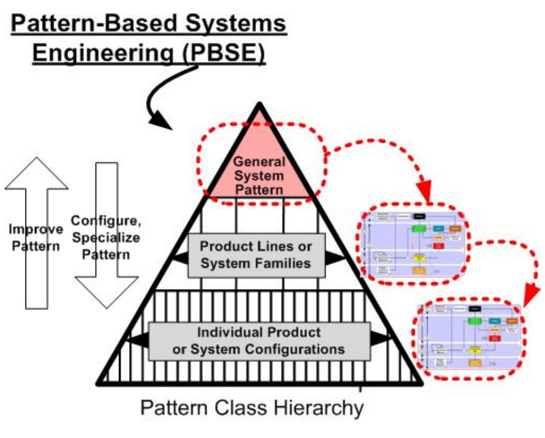
Leveraging adaptability to tame uncertainty

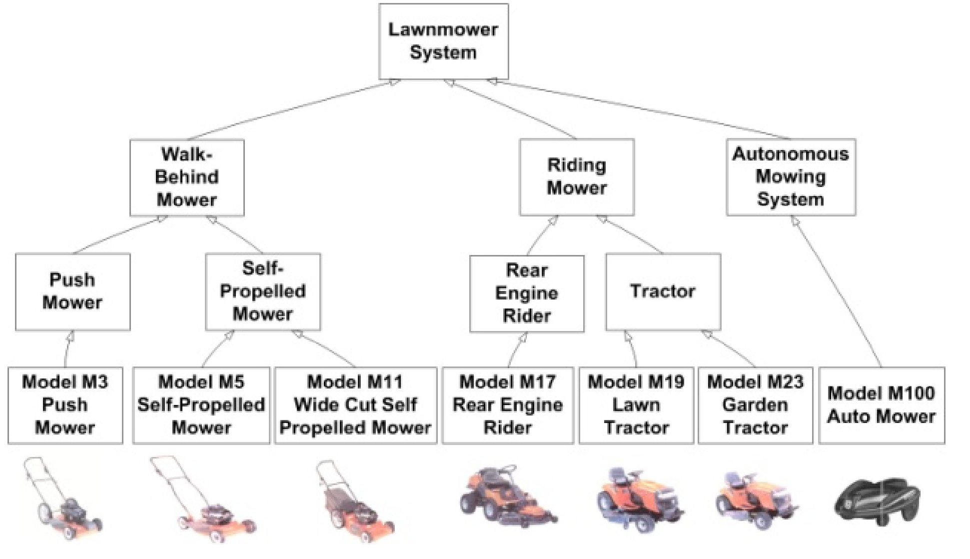
- Patterns also express risks and mitigations for:
  - Patterns of system failure modes and effects (d-FMEA)
  - Patterns of operator failure modes and effects (a-FMEA)
  - Patterns of production & distribution failures (p-FMEA)



Leveraging adaptability to tame uncertainty

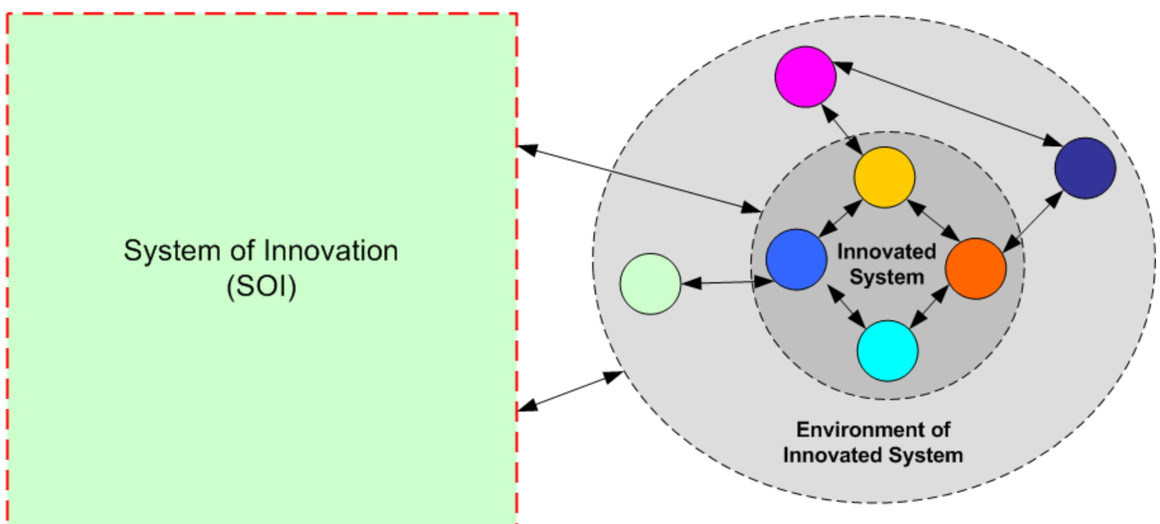
- Descriptions of SE processes typically appear to describe engineering a "new" system "from scratch" [e.g., ISO 15288, INCOSE SE Handbook]:
  - However, real projects are often concerned with engineering similar (but different) systems across different product generations, applications, configurations, or market segments.
  - Patterns provide the IP basis to make Platform Management a discipline, not just an attractive idea:





Leveraging adaptability to tame uncertainty

- The science behind the emergence of re-usable building blocks in natural innovation:
  - The Systems of Innovation Project of the INCOSE System Science Working Group
  - Next workshop will be at IS2012.
  - https://sites.google.com/site/syssciwg/projects/o-systems-of-innovation



Conclusions

1. Patterns abound in the world of systems engineering.
2. These patterns extensively impact our projects, whether we take advantage of them as Explicit Patterns, or we are negatively impacted by Dark Patterns.
3. Pattern-Based Systems Engineering (PBSE) offers specific ways to extend MBSE to exploit Patterns.
4. MBSE comes first—Patterns without Models is like orbital mechanics before Newton.
5. We've had good success applying pattern-based methods in mil/aerospace, automotive, medical/health care, advanced manufacturing, and consumer product domains.

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