Systems Engineering: Bridging Industry, Government and Academia

Pattern-Based Systems Engineering: An Extension of Model-Based SE

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INCOSE 2005 TIES 4

INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

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- Introductions
- Model-based systems engineering
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- Results and implications
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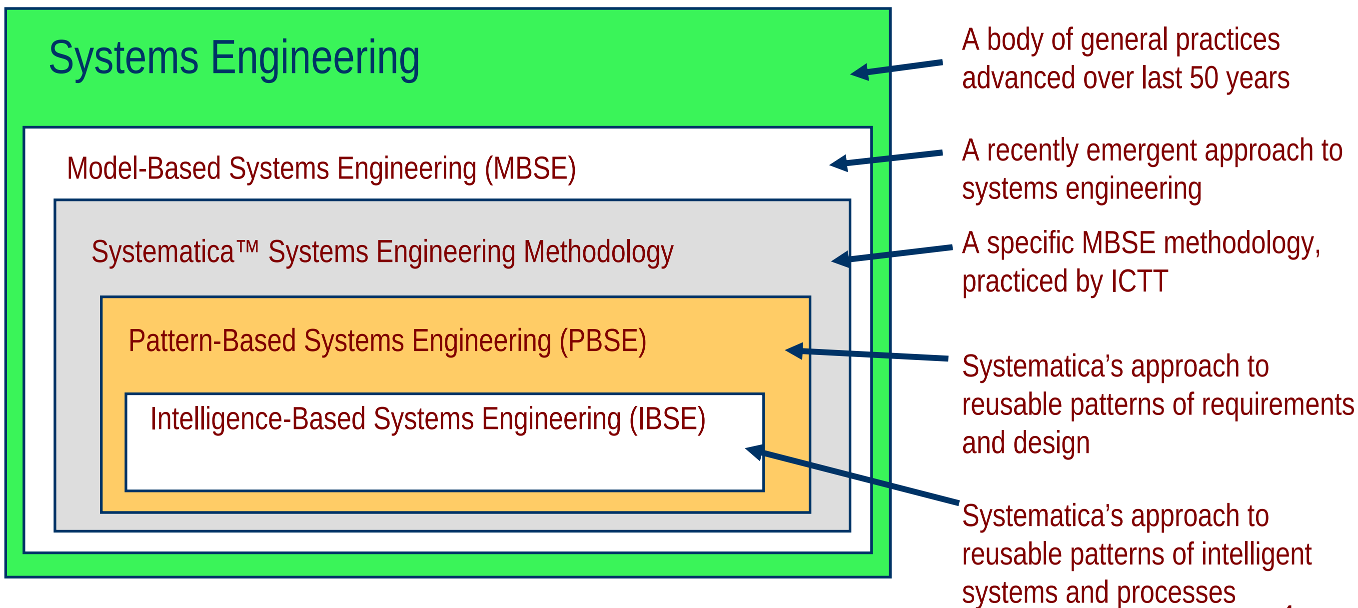
ICTT

- Specialists in Systems Engineering professional services:
  - www.ictt.com
  - Indiana home office
- Originated over twenty years ago as a business-academic joint venture with Rose-Hulman Institute of Technology:
  - www.rose-hulman.edu
- National historical client and partner base:
  - The world's largest system companies; the world's most complex systems

Summary of approach

Systematica™ Do more with less

- Systematica™ Methodology, at three levels of sophistication:
  - Model-Based Systems Engineering (MBSE)
  - Pattern-Based Systems Engineering (PBSE)
  - Intelligence-Based Systems Engineering (IBSE)



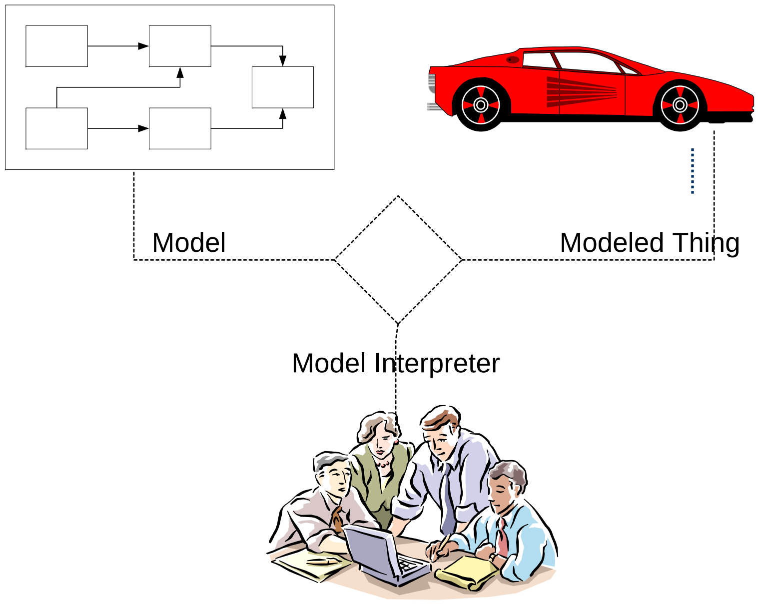
Model-Based Systems Engineering (MBSE)

Heinz Stoewer's INCOSE 2005 Symposium opening:

- "The future of systems engineering is model-based"

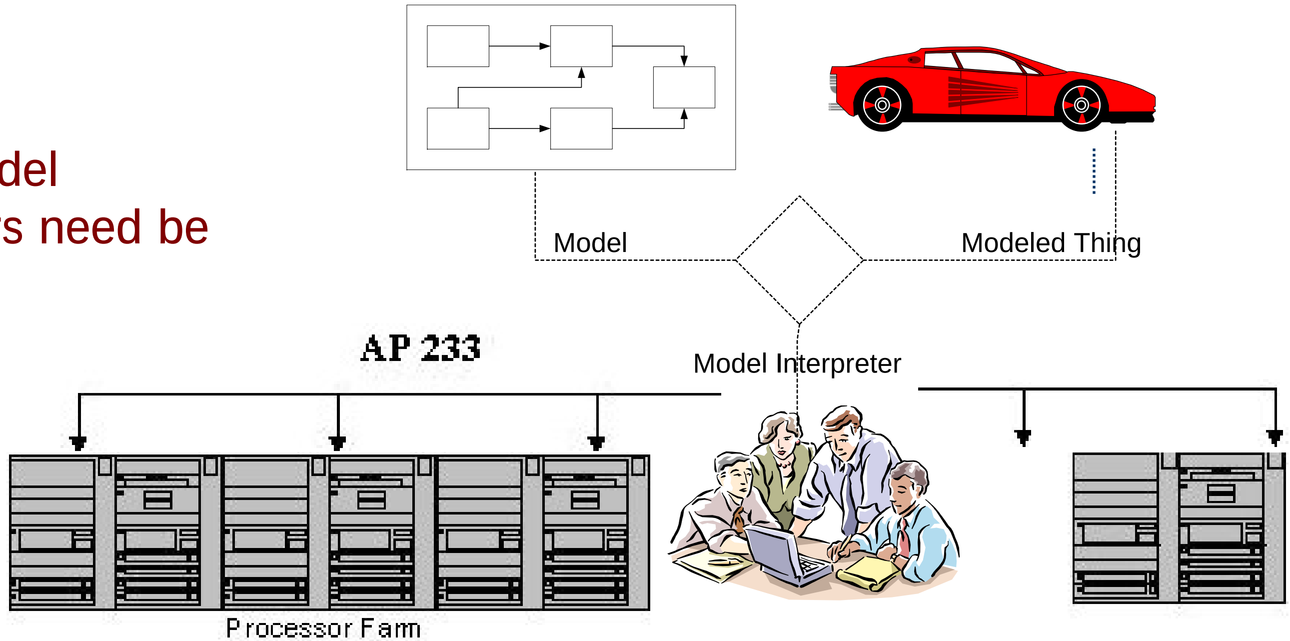
Model-based systems engineering

- Model-based systems engineering is an emerging approach to systems engineering:
  - See www.incose.org
- Uses explicit models where traditional SE used informal, intuitive, natural language prose (e.g., English) of documents



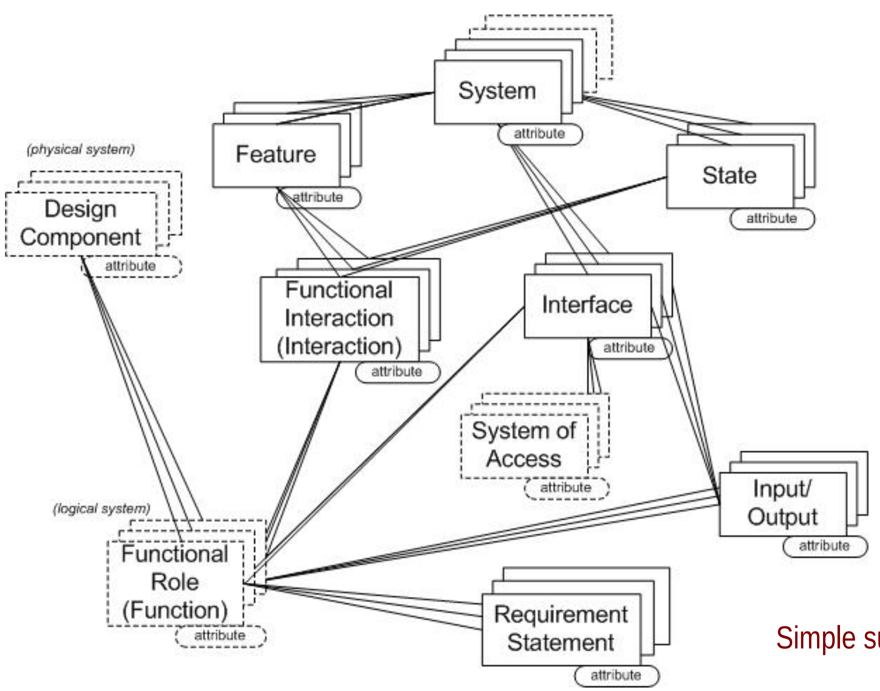
Model-based systems engineering

- Model-based systems engineering is an emerging approach to systems engineering:
  - See www.incose.org
- Uses explicit models where traditional SE used informal, intuitive, natural language prose (e.g., English) of documents
- Not all model interpreters need be human



The Systematica approach to MBSE

- Uses <u>models</u> ("blueprints" or data structures) not just traditional prose, to specify <u>requirements</u> *and* <u>design</u> of complex systems--*explicitly*.
- Language independent—expressed in many languages (UML, SysML, IDEF, ….)
- Uses *Systematica Metamodel*:



The minimum set of ideas necessary to express all concepts of system requirements and design, independent of language, domain, or technology

Simple summary of detailed Systematica Metamodel.

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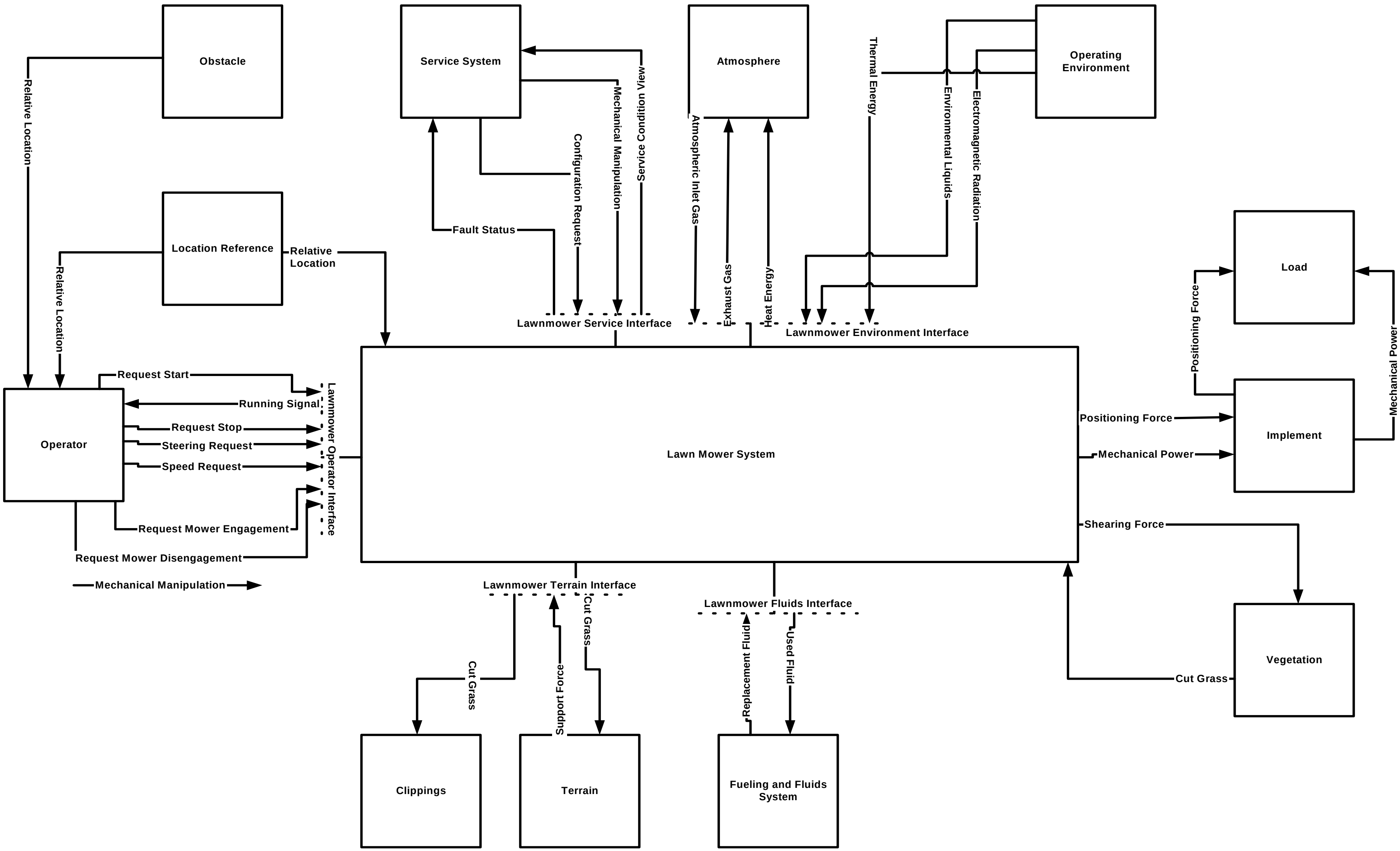
Simple example—domain model



Simple example--feature model

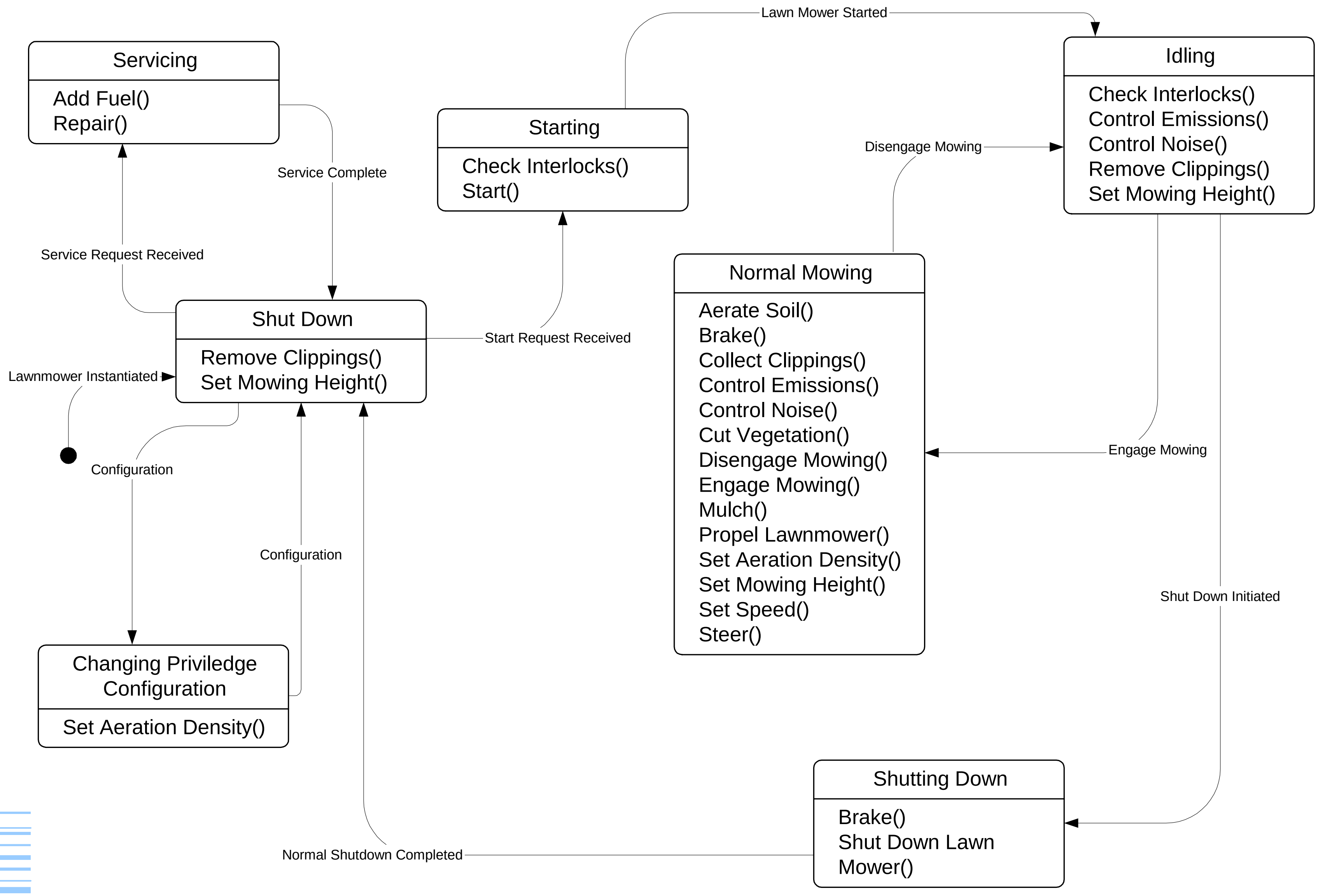
Feature	Feature Definition	Feature Attributes
Aerator Feature	The feature creating a healthier base for future vegetation growth by generating aeration vents in soil being mowed.	Lawn Health
Automatic Starter Feature	The feature making it easy to start the mower without using muscle power.	Starting Effort; Starting Reliability; Starting Time
Automatic Transmission Feature	The feature simplifying machine operation as experienced by operator, while optimizing speed and torque for traction, mowing, and other work.	Operational Simplicity; Fuel Economy
Autonomous Mowing Feature	Provides automatic mowing without an operator, except for set-up, using robotic automatic mowing schedule and guidance. Yard owner is spared from pushing, following, or riding a mower while maintaining an attractive yard.	Operational Time Savings
Basic Mowing Feature	The basic feature set for mowers, prior to adding advanced features. Makes local terrain vegetation height uniform and attractive, enhancing its value.	Lawn Appearance; Fuel Economy; Operator Effort; Mowing Time; Mowing Service Availability
Dethatching Feature	The feature creating a more attractive and healthier base for future vegetation growth and use of land, by dethatching vegetation during mowing.	Lawn Health
Grass Bagging Feature	The feature making for a clean appearance and healthy condition in the region mowed. Collects clippings in a receptacle for easy movement of these away from the region being mowed.	Clippings Capacity; Operator Effort; Lawn Appearance
Maintenance Feature Group	A group of features facilitating easy preventive maintenance, fault diagnosis, removal of parts, repair, and replacement. Reduces the overall cost of ownership of the product, by minimizing the cost of service.	Maintenance Effort; Maintenance Complexity
Mulching Feature	The feature covering vegetation clippings to mulch and spreading them onto the mowed terrain. Creates a healthy base encouraging future growth of vegetation.	Lawn Health
Operator Riding Feature	The feature reducing lawnmower operator fatigue by allowing the operator to ride instead of walking behind the lawnmower during operation.	Operator Fatigue; Mowing Rate
Self-Propelled Mowing Feature	The feature reducing lawnmower operator fatigue by propelling the mower without requiring human muscle power for propulsion.	Operator Fatigue; Mowing Rate
Spark Arrest Feature	The feature increasing fire safety and conformance to regulations on spark emissions. Minimizes emission of sparks from exhaust.	Mean Time Between Events
Towing Feature	The feature supporting towing of attachments behind mowing system, creating additional applications for mower, increasing its value and flexibility.	Towing Capacity

Simple example--functional interaction model

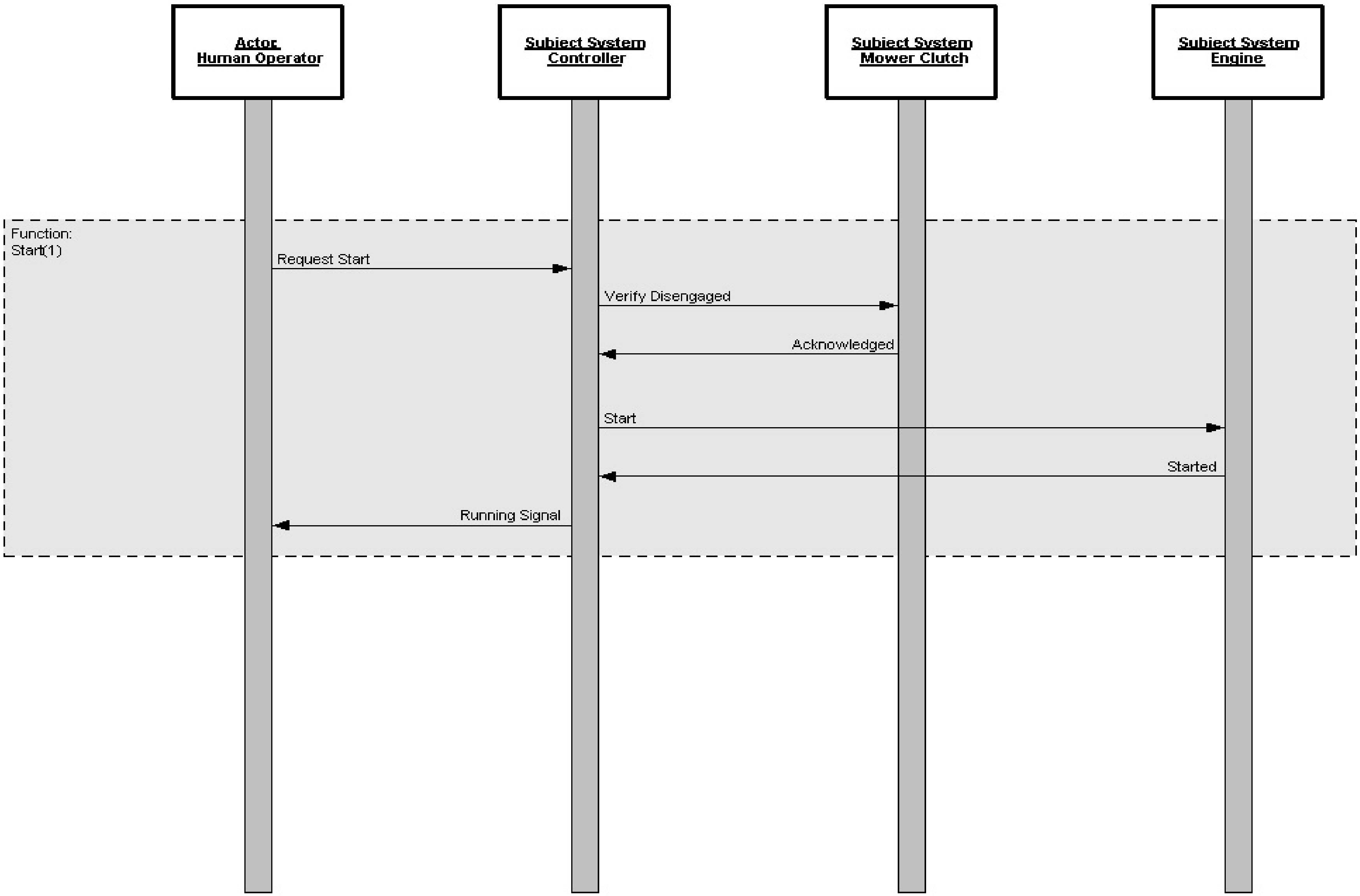
Feature	Functional Interaction	Functional Interaction Definition
Basic Mowing Feature	Cut Vegetation	Shear vegetation to pre-set height, routing clippings for storage, spreading, or mulching.
	Add Fuel	Add chemical, electrical, or other energy to the Lawn Mower System.
	Steer	Control the direction of forward/reverse motion of the mowing system over the terrain, based upon operator request.
	Brake	Reduce the rate of forward/reverse movement of the mowing system over the terrain, or maintain fixed current position.
	Set Speed	Set the rate at which the mowing system moves over the terrain.
	Set Mowing Height	Adjust height at which vegetation will be cut, based upon operator preference.
	Shut Down Lawnmower	Place the Lawnmower in an "off" state for storage, service, or other non-operational situation
	Control Emissions	Maintains gaseous and particulate emissions at less than regulation and standards.
	Start	The interaction between a managed system and a management system that places the system in a state of sustained operation ready to generate production services.
	Control Noise	Maintain machine noise less than level required by regulation and standards.
	Check Interlocks	Checks safety interlocks required to be met in order to allow machine operations such as start, engage, move, etc. This enhances safety.
	Disengage mowing	Turns off vegetation cutting process in a running mower system without shutting down the whole system.
	Engage Mowing	Starting mowing (vegetation cutting) process in a running mower.
Aerator Feature	Aerate Soil	Generate aeration holes in terrain being mowed to preset aeration hole density.
	Set Aeration Density	Operator sets the density at which a later soil aeration process will place aeration holes into the soil.
Automatic Starter Feature	Automatic Start	A mowing system automatically starts without muscle power from the operator.
Automatic Transmission Feature	Shift	The transmission or other form of power converter is changed in torque and speed conversion rations, as a function of machine speed and load, to maintain optimal torque and speed for the operation in progress.
	Determine Shirt Point	The operator, or an internal automatic transmission controller, determines when speeds are reached (during either acceleration or deceleration) that require (up or down) shifts of the machine transmission.

Feature	Functional Interaction	Functional Interaction Definition
Grass Bagging Feature	Collect Grass Clippings	Collect cut vegetation from the mowing process into a bag or other receptacle, for later removal.
	Remove Clippings	Remove cut vegetation that has been temporarily stored during mowing, for transport to other location.
Autonomous Mowing Feature	Steer	Control the direction of forward/reverse motion of the mowing system over the terrain, based upon operator request.
	Timed Autostart	The mowing system is started up without operator interaction, based upon a preset mowing schedule.
	Auto Return	An autonomous mowing system automatically navigates to its off-duty charging location at the end of a mowing cycle.
	Add Fuel	Add chemical, electrical, or other energy to the Lawn Mower System.
	Configure Autonomous Operation	Operator sets up the configuration of an autonomous mowing system, setting mowing schedule, height, and other attributes.
	Safety Shutdown	An autonomous mowing system detects a condition that requires it to automatically shut down, for safety reasons.
Dethatching Feature	Dethatch	Separate ground vegetation, leaving it in untangled (dethatched) state.
Maintenance Feature Group	Repair	Service operations performed on the lawnmower, including preventive maintenance, fault diagnosis, and repair.
Mulching Feature	Mulch	Process vegetation cuttings from the mowing operation, into a mulch coating spreadable to the terrain.
Operator Riding Feature	Support Operator	For riding mowers, the operator is supported in a position and posture intended to maximize comfort and controllability while minimizing fatigue.
Self-Propelled Mowing Feature	Propel Lawnmower	Drive the lawnmower over the terrain using either internal power source or external operator muscle power.
Spark Arrest Feature	Control Emissions	Maintain gaseous and particulate emissions at less than regulation and standards.
Towing Feature	Tow	The lawnmowing system pulls an attached piece of equipment.

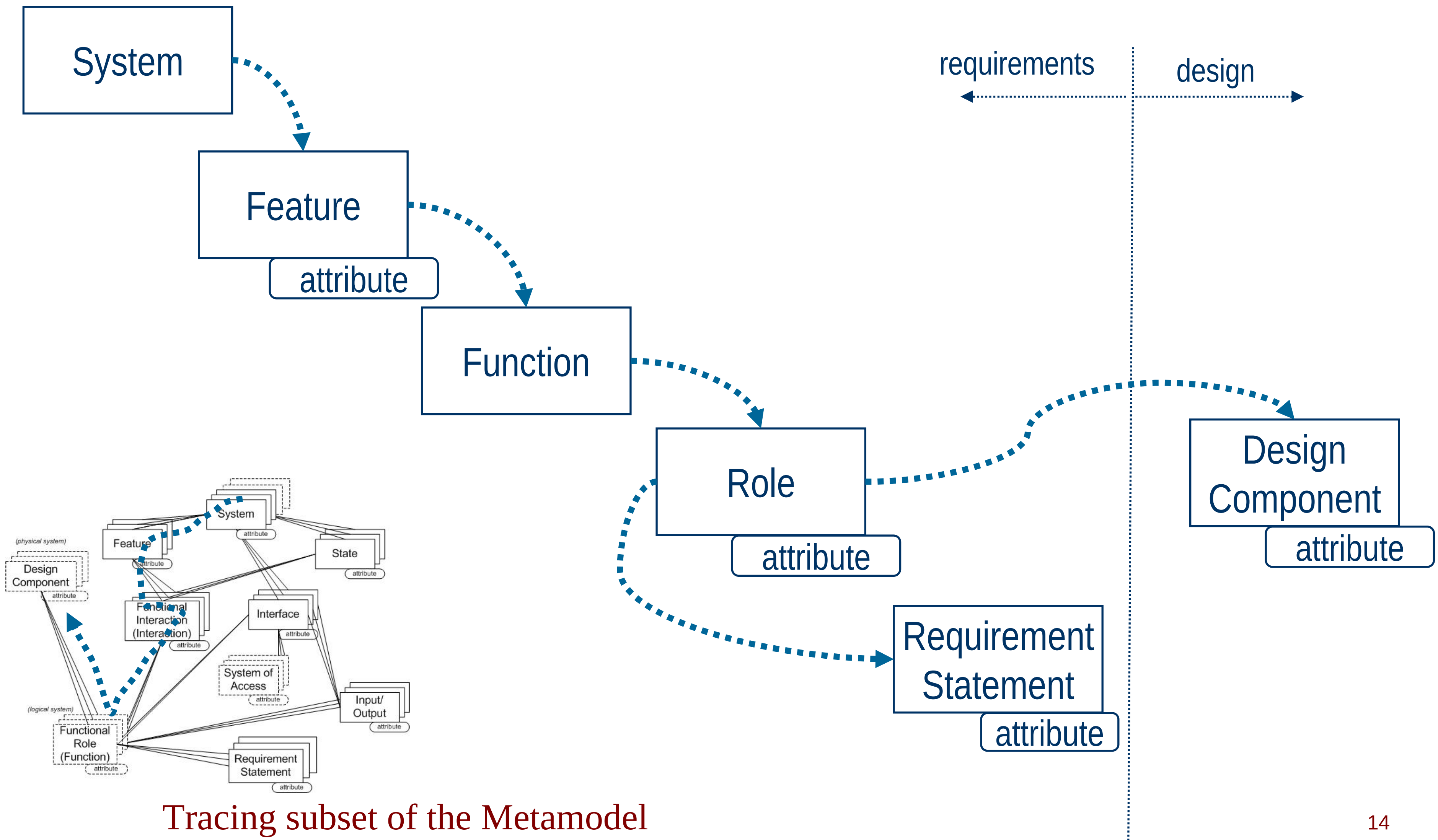
Simple example—state model



Simple example--detail function interaction model

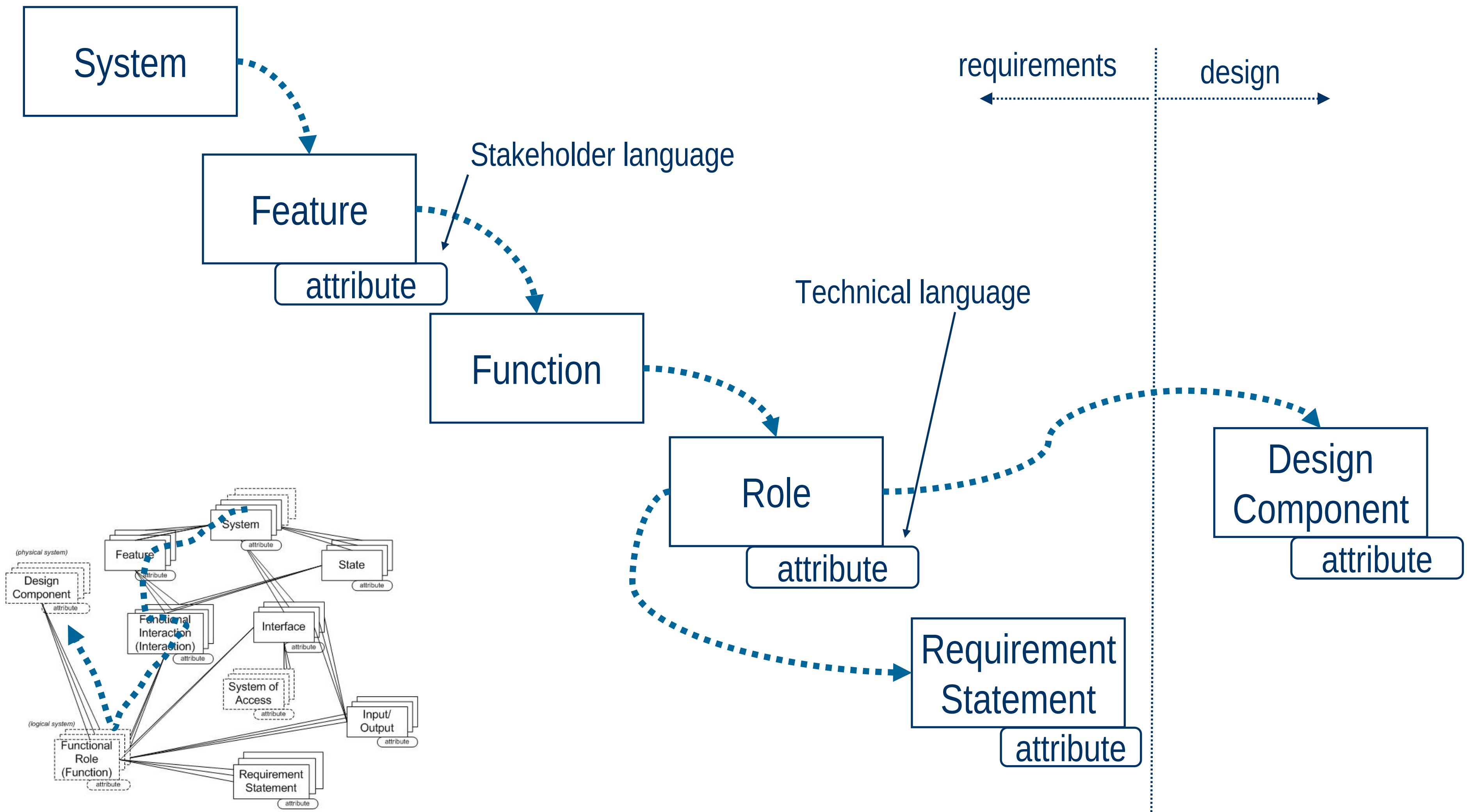


Attribute Couplings



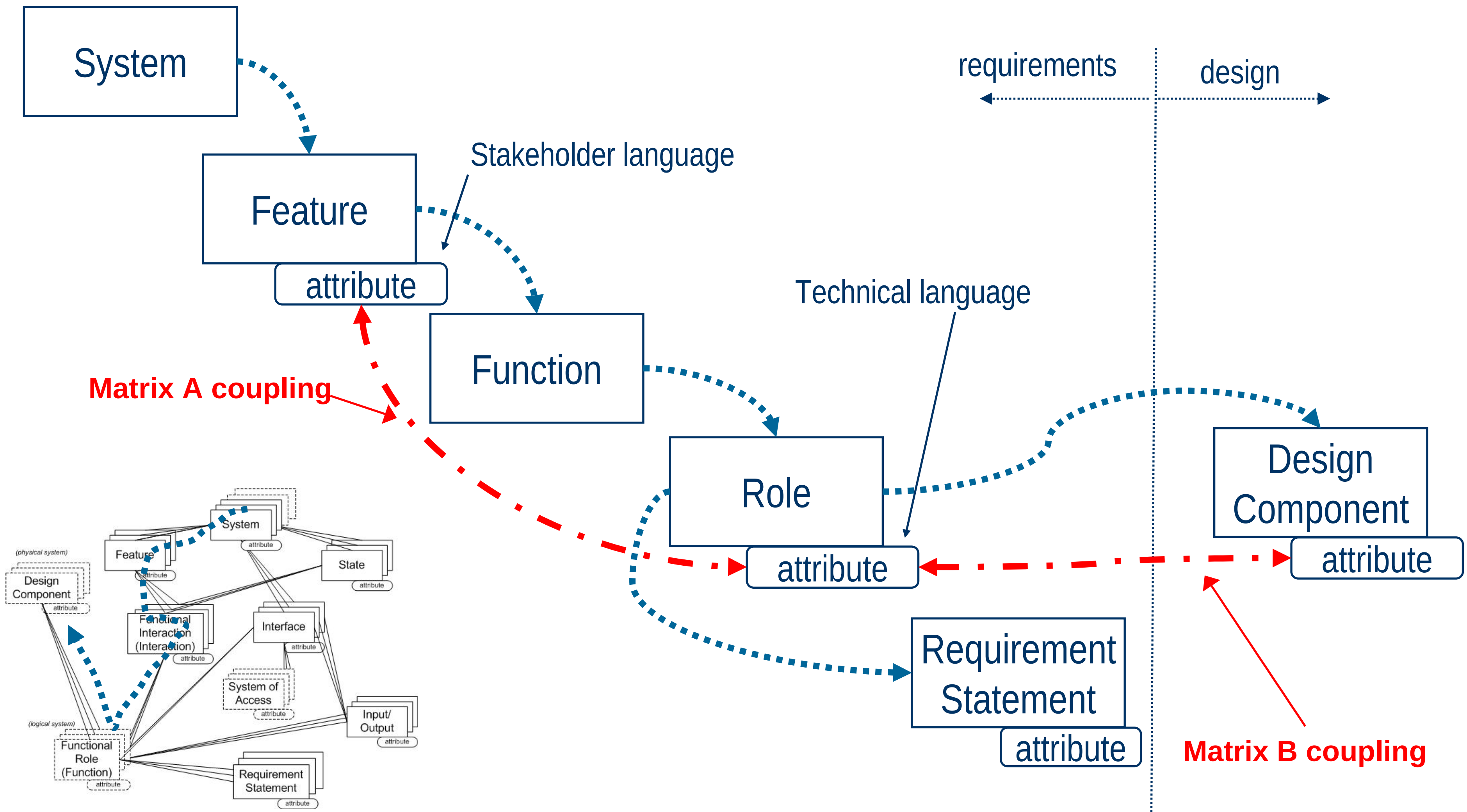
Tracing subset of the Metamodel

Metamodel Expresses Attribute Couplings



Tracing subset of the Metamodel

Stakeholder-Technical Coupling Matrix A



Tracing subset of the Metamodel

Matrix A: “X” couplings can be modeled.

			Feature F1				**Feature F2**		
Matrix A: Feature-Role Attribute Mapping			Feature Attribute FA1	Feature Attribute FA2	Feature Attribute FA3		Feature Attribute FA4	Feature Attribute FA5	Feature Attribute FA6
Function Role R1									
	Technical Role Attribute X1				X				
	Technical Role Attribute X2		X		X			X	
	Technical Role Attribute X3			X					
Function Role R2									
	Technical Role Attribute X4		X						X
	Technical Role Attribute X5						X		X
	Technical Role Attribute X6							X	
Function Role R3									
	Technical Role Attribute X7			X					X
	Technical Role Attribute X8						X		

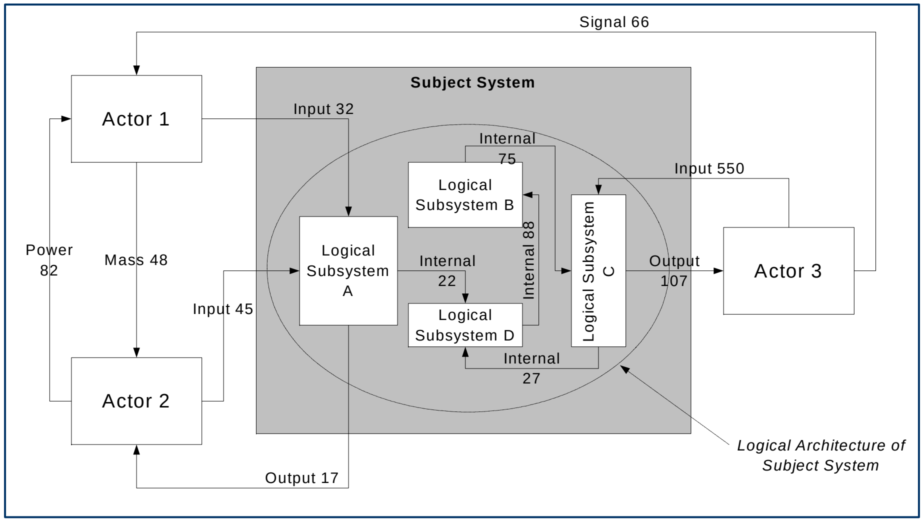
Matrix B: “X” couplings can be modeled.

			Physical Component C1				**Physical Component C2**		
Matrix B: Role-Physical Component Attribute Mapping			Physical Component Attribute CA1	Physical Component Attribute CA2	Physical Component Attribute CA3		Physical Component Attribute CA4	Physical Component Attribute CA5	Physical Component Attribute CA6
Function Role R1									
	Technical Role Attribute X1		X						
	Technical Role Attribute X2		X		X			X	
	Technical Role Attribute X3			X					
Function Role R2									
	Technical Role Attribute X4				X		X		
	Technical Role Attribute X5						X		X
	Technical Role Attribute X6							X	
Function Role R3									
	Technical Role Attribute X7			X			X		
	Technical Role Attribute X8								X

These couplings “explicate” many of the pattern “forces/problems” to be balanced, as intuited by C. Alexander and other patterns workers.

For examples of requirements statements connection, see INCOSE 2005 best paper award: "Requirements Statements Are Transfer Functions: An Insight from Model-Based Systems Engineering" , B. Schindel

Functional analysis and logical architecture



Requirements Statements	Allocated To
Requirements statement XXX.	Logical Subsystem C
Requirements statement YYY.	Logical Subsystem B
Requirements statement ZZZ.	Logical Subsystem D
Requirements statement XYZ	Logical Subsystem A
Requirements statement XXYY	Logical Subsystem D
Requirements statement XYYZ	Logical Subsystem C

- The logical subsystems can be further described by allocating requirements statements to them.
- These requirements statements are frequently not mathematical.
  - But, in MBSE, they become the generalization of mathematical relationships.
  - These statements become the description of the relationship of mapping of inputs to outputs, for a given block.
  - This embeds traditional prose SE methods in a model-based framework, giving new meaning and structure to prose requirements statements.

Pattern-Based Systems Engineering (PBSE)

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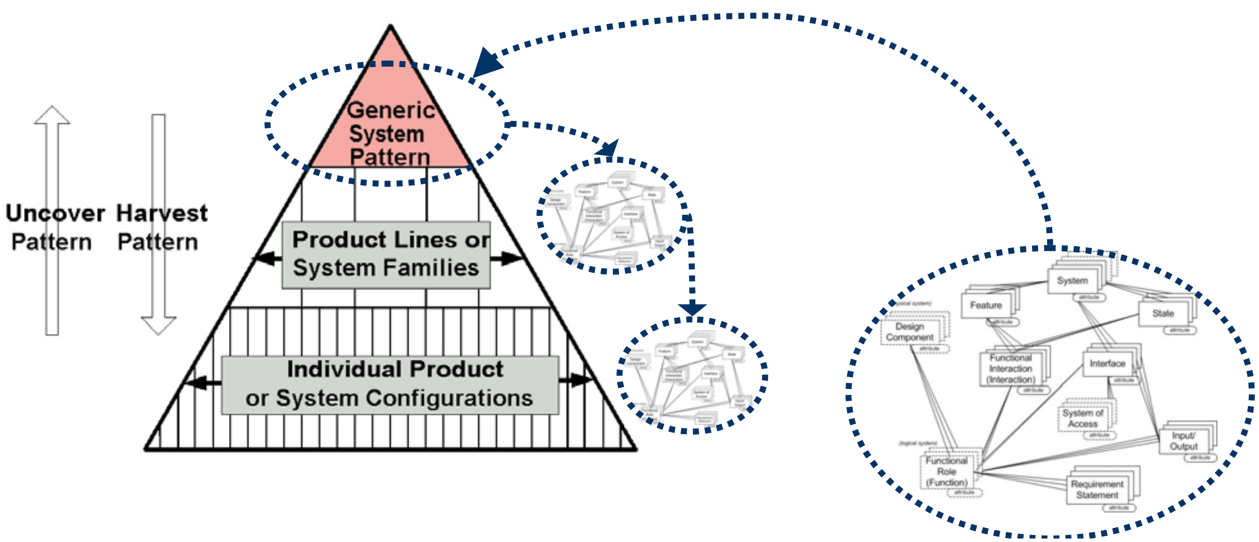
- Our approach:
  - Patterns are reusable, configurable models (created as in MBSE)
  - These patterns can describe *requirements alone* (patterns of requirements), or also *design patterns* that satisfy those requirements
  - The key to re-usable designs is understanding re-usable requirements—there would be no re-use of design components if there were not repeating requirements for them
- Word of warning: Not all patterns workers agree with these points
- Attempting to use Patterns without basing them on Models is like attempting to do orbital mechanics without mathematics:
  - You may make progress, but will miss much of the power of patterns (Galileo vs. Kepler vs. Newton)
  - However, much of current "patterns" work in engineering is without the benefit of a model-based foundation
  - Valuable patterns sessions in this conference include: C. Haskins, et al
  - Historical patterns references include: C. Alexander, J. Coplien, et al

Pattern-Based Systems Engineering (PBSE)

- An example of what models do for patterns:
  - *System* patterns are inherently *relational* — models express these relationships *explicitly*
  - Gestalt Rules™ provide powerful means for checking proposed specifications against applicable patterns, for conformance and exceptions
- But patterns also help models tremendously:
  - Instead of all your engineers being required to learn how to model, you can teach many of them the standard patterns (re-usable models) that describe your core business IP
  - Much better human resource leverage—a powerful way to introduce model-based engineering into your organization

Pattern-based systems engineering (PBSE)

- "Uncovers" and models framework of common corporate system architecture patterns of *requirements and design* – using MBSE models of those patterns.
- This reusable pattern framework is then applied as individual configuration products, manufacturing systems, or development processes are "harvested".
- Reduces cost of development, increases productivity and quality, lowers time to market, reduces rework, leverages expertise:



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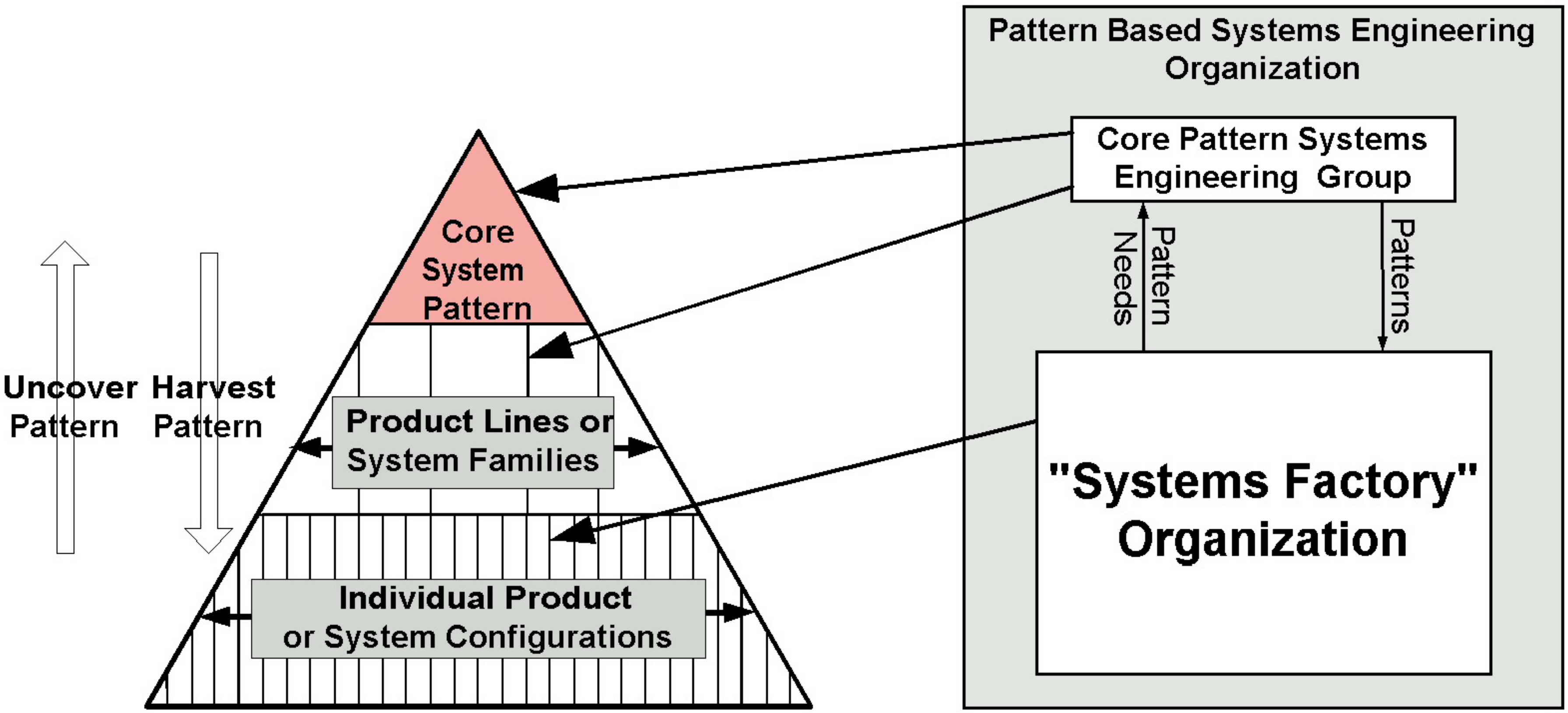
Reusable patterns, configurable and specializable, that include both *requirements and design*.

Pattern-based systems engineering: The operational vision



Product line example

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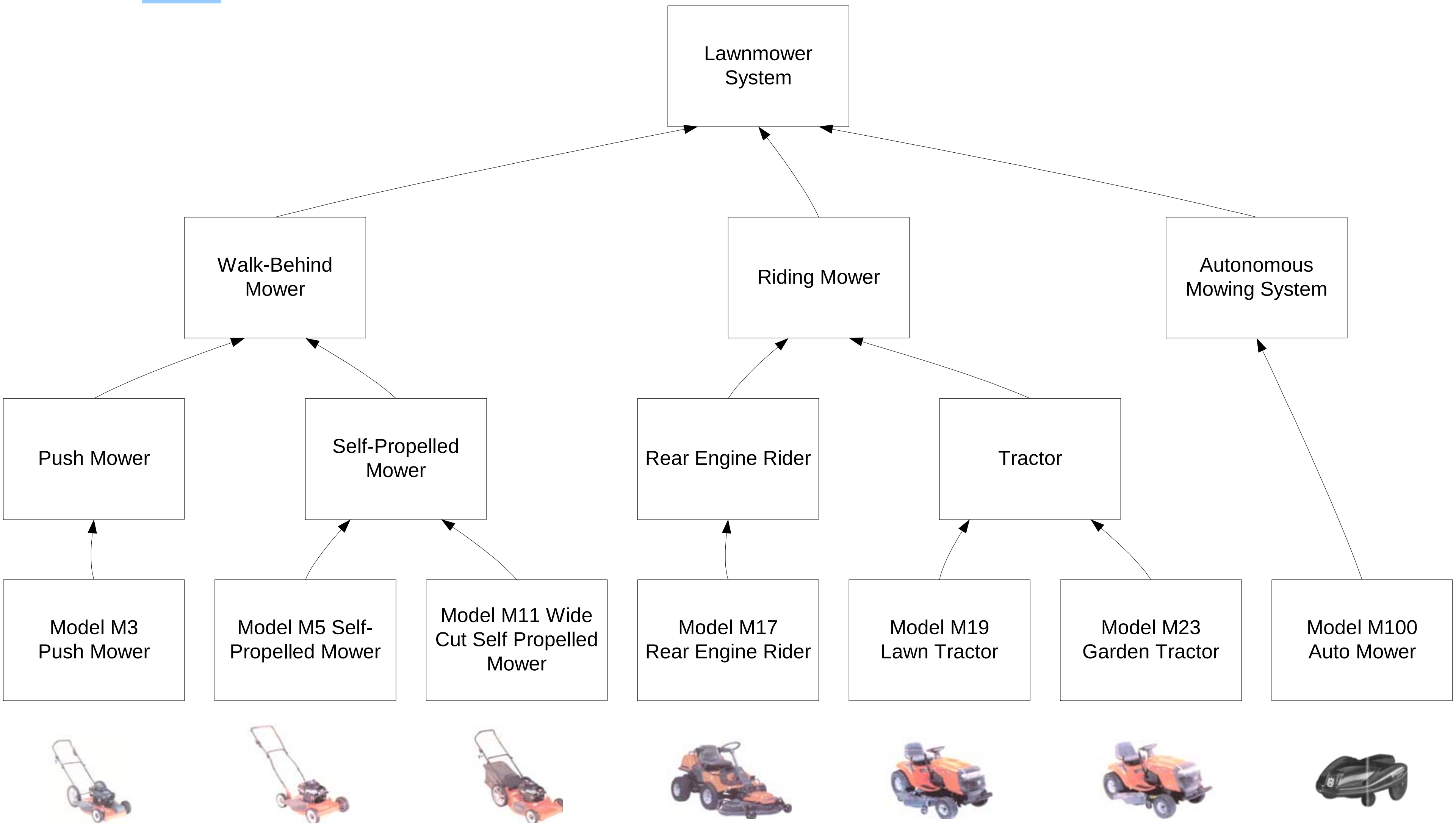

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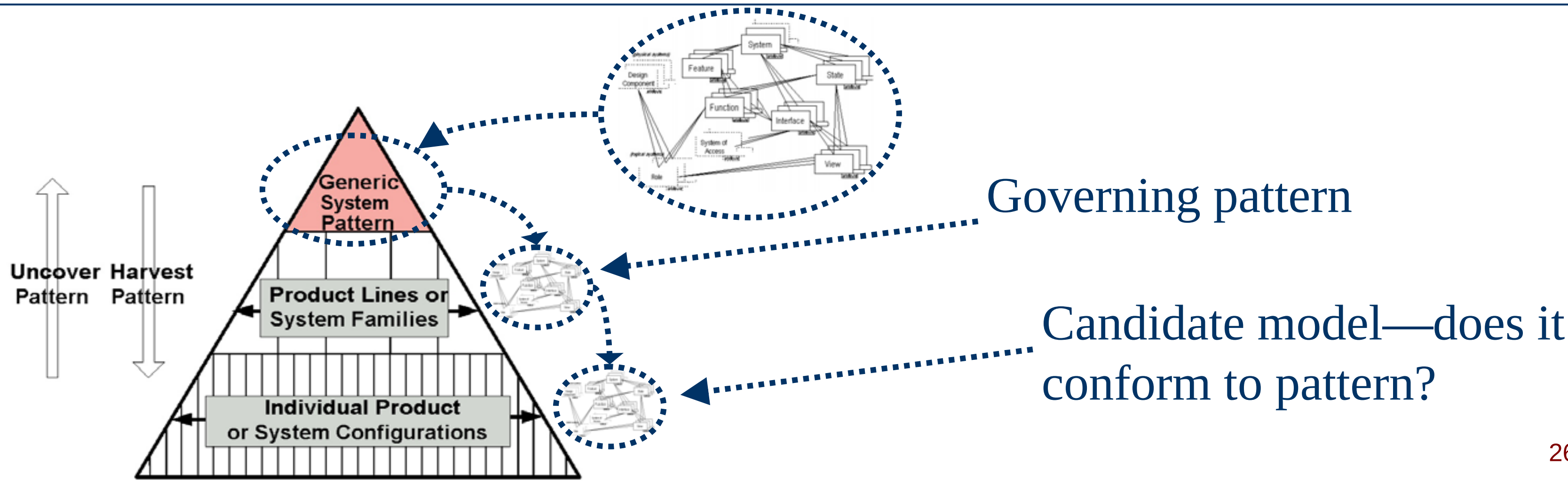
Lawnmower Product Line: Configurations Table

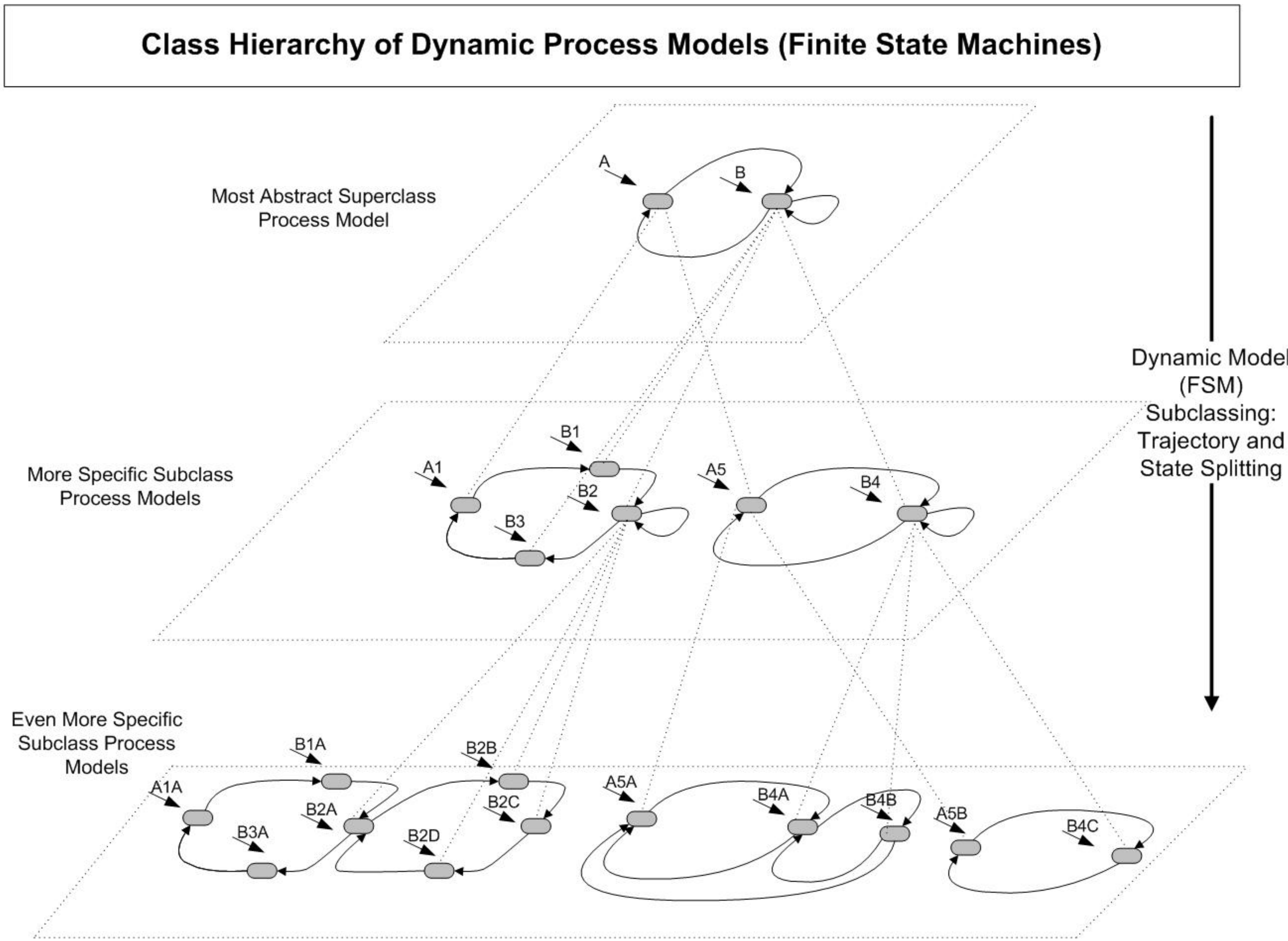
		Units							
			Walk-Behind Mower	Walk-Behind Mower	Walk-Behind Mower	Riding Mower	Riding Mower	Riding Mower	Autonomous Mowing System
			Push Mower	Self-Propelled Mower	Self-Propelled Mower	Rear Engine Rider	Tractor	Tractor	Autonomous Mowing System
			Push Mower	Self-Propelled	Wide Cut Self Propelled Mower	Rear Engine Rider	Lawn Tractor	Garden Tractor	Auto Mower
	Model Number		M3	M5	M11	M17	M19	M23	M100
	Market Segment		Small Residential	Medium Residential	Medium Residential	Large Residential	Large Residential	Home Garden	High End Suburban
Power	Engine Manufacturer		Briggs & Stratton	Briggs & Stratton	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	Number 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
	Fully Automatic Transmission Feature							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	

The Gestalt Rules for pattern conformance

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



Results

- Systems engineering applications of Patterns in:
  - Health care systems (pharmaceuticals, medical devices, etc.)
  - Automotive and heavy equipment
  - Manufacturing systems
  - Mil/aero systems
  - Consumer products
  - Telecom systems
  - Business processes—including the SE process itself

Further implications

- People:
  - Greatly improved understanding across teams, through “explication”
  - Greatly leverages the abilities of pattern-makers across larger teams
- Tools:
  - Greatly improved value from existing tools by structuring data to fit the metamodel
- Inspectability:
  - MBSE makes the model completeness and pattern conformance much easier to inspect/audit by manual or automated means
- Management by measurement:
  - MBSE makes metrics much more possible and meaningful
  - Revolutionizes the gate process
- Gestalt Rules:
  - Explicate the process of identifying and managing IP

Suggestions

- Understand models before patterns:
  - Don't confuse methodology or metamodels with modeling languages
- Models are good—patterns even better
- Requirements patterns are valuable, even before design patterns
- Don't forget that we are still early in the development of systems engineering as an engineering discipline

Thank you!

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References

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