Dynamic Visualization of Complex Systems:

Extending the Impact of Model Based Systems Engineering

Troy A. Peterson
Fellow & Chief Engineer
Booz Allen Hamilton

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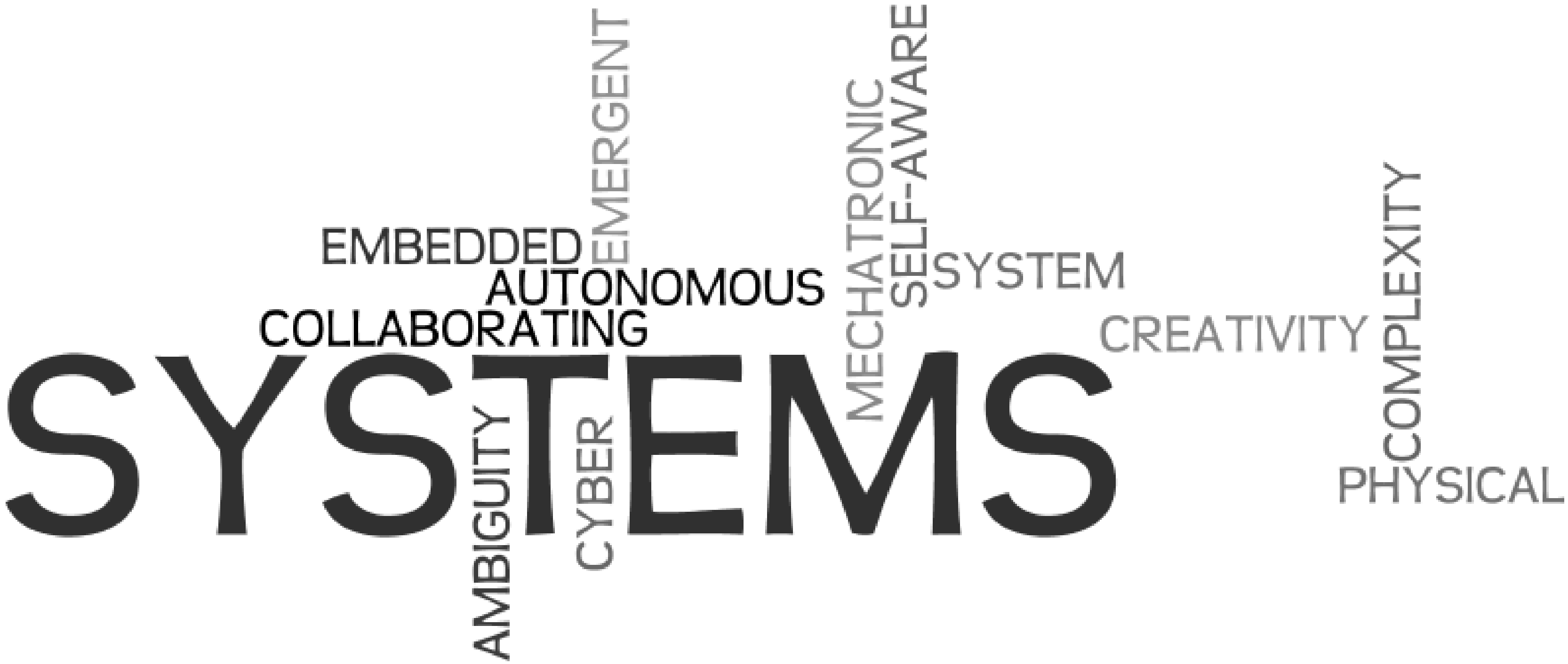
Complexity in Systems



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Understanding empowers innovation

- *"Scientists investigate that which already is; engineers create that which has never been."*

Albert Einstein

The essence of a system - Interactions

- *Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems*.

INCOSE

in·no·va·tion

in·no·va·tion (ĭn′ə-vā′shən) *noun*
1. The act of introducing something new.

en·gi·neer·ing

en·gi·neer·ing (ĕn′jə-nîr′ĭng) *noun*
Abbr. **e.**, **E.**, **eng.**
1. **a.** The application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems. **b.** The profession of or the work performed by an engineer.

sys·tem

sys·tem (sĭs′təm) *noun*
Abbr. **syst.**
1. A group of interacting, interrelated, or interdependent elements forming a complex whole.

in·ter·ac·tion

in·ter·ac·tion (ĭn′tər-ăk′shən) *noun*
1. **a.** The act or process of interacting. **b.** The state of undergoing interaction.

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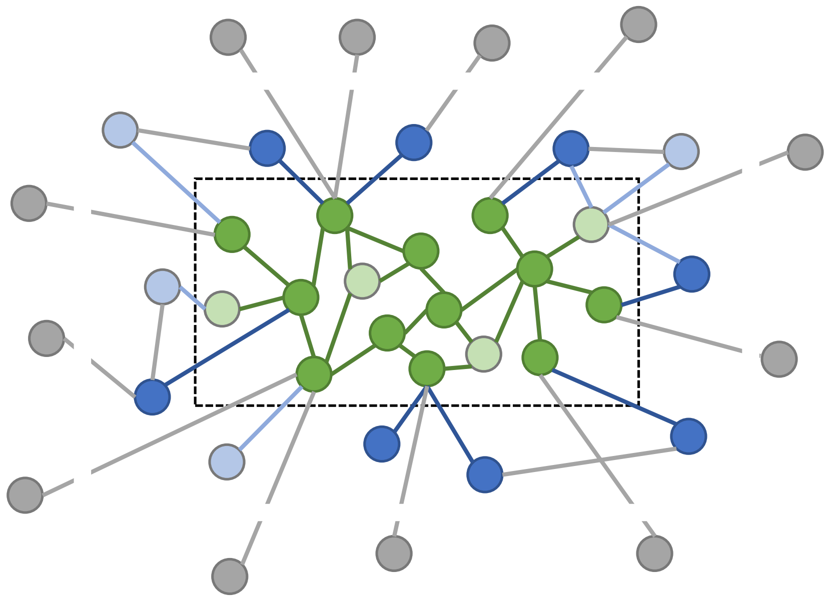
Interaction Density



System Elements & Interactions

System External Elements & Interactions

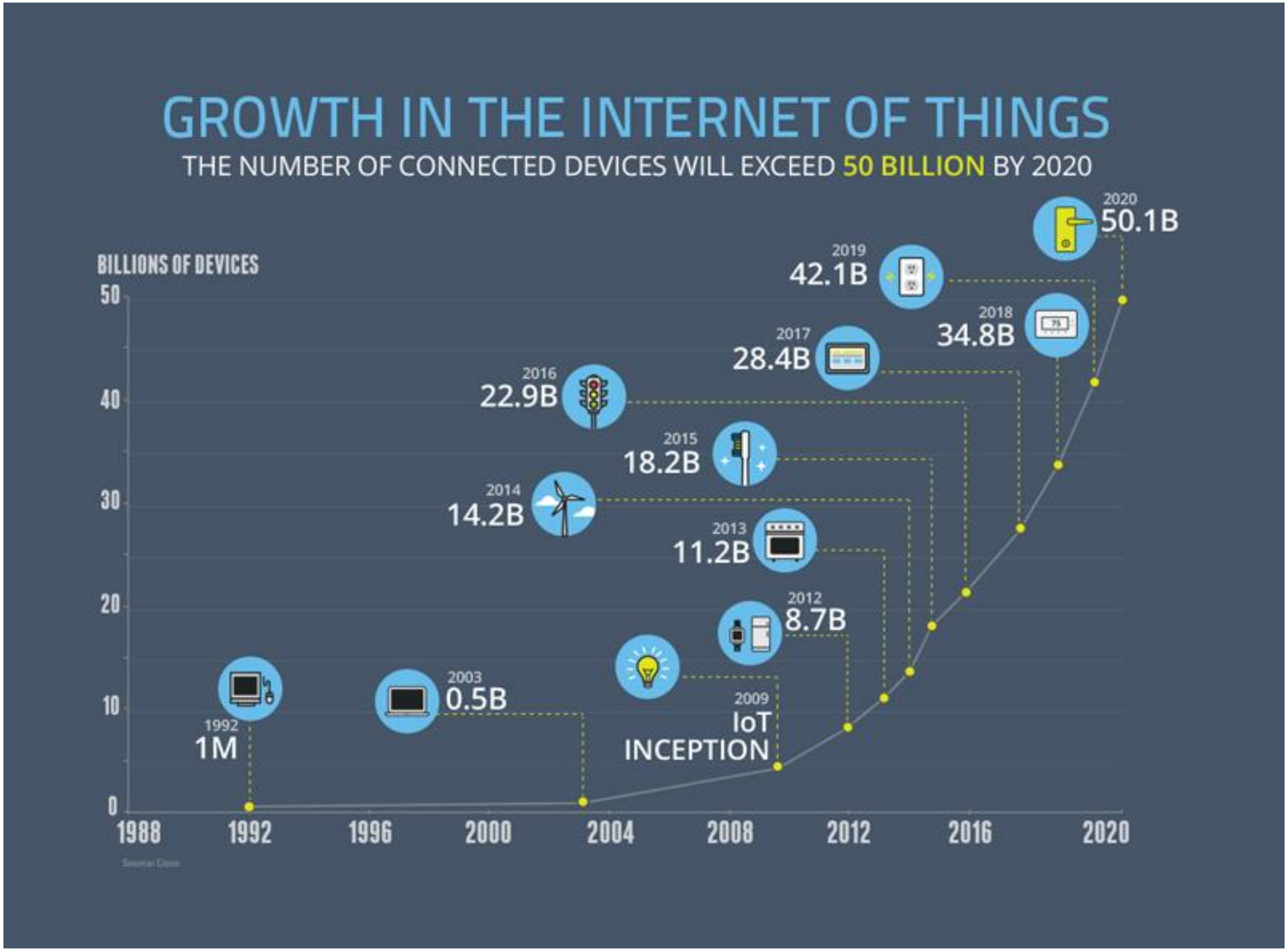
Increased Density of System Elements & Interactions

Increased Density of System External Elements & Interactions

Increased Interactions Between External Elements

Expanding System Domain Boundary Increasing Interactions

Internet of Things



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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],

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

Rethinking System Conceptualization

- Interconnectedness and the rise of Cyber Physical Systems
- The National Science Foundation (NSF) describes Cyber-Physical Systems (CPS) as “engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components”
- They tightly intertwine computational elements with physical entities across domains
- The rapid increase in Cyber-Physical Systems is changing the way we develop, manage and interact with systems.
- The NSF notes that CPS challenges and opportunities are both significant and far-reaching. To address these challenges the NSF is calling for methods to conceptualize and design for the deep interdependencies inherent in Cyber-Physical Systems.

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Systems Engineering Transformation

- While complex systems transform the landscape, the Systems Engineering discipline is also experiencing a transformation - to a model-based discipline.

- While Model Based Systems Engineering (MBSE) shows significant promise, it’s still in a formative stage and very few subject matter experts understand formalized systems languages or have ready access to MBSE related tools.

- Key enablers to managing system complexity
  - Applying MBSE to provide explicit integrated system models
  - Expressing system models to deepen our understanding
  - Leverage methods to reach the larger community of stakeholders

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Model Based Systems Engineering

- Model Based Systems Engineering (MBSE) provides organizations a timely opportunity to address the rapid growth in complexity
- 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
- The Object Management Group’s MBSE wiki notes that “Modeling has always been an important part of systems engineering to support functional, performance, and other types of engineering analysis.”
- The application of MBSE has increased dramatically in recent years enabled by the continued maturity of modeling languages such as SysML and significant advancements made by tools vendors

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- MBSE is often discussed as being composed of three fundamental elements – tool, language and method.
  - While there are differences between tools most are very capable and can be used to make significant improvements in managing the complexity of systems today.
  - Many modeling languages also exist to express system representations. MBSE practitioners often use the System Modeling Language (SysML).
  - The third element, method, has not always been given proper consideration, because the language and tool are relatively method independent, it is methodology which further differentiates the effectiveness of any MBSE approach.

Content – Process – Automation

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MBSE: Pattern Based Systems Engineering

- As a Model-Based Systems Engineering (MBSE) methodology, Pattern-Based Systems Engineering (PBSE) is tool and language neutral and offers a strong underlying ontology and metamodel.
- At the heart of the PBSE metamodel is a focus on interactions which are also at the heart of complex systems and the basis of the physical sciences.
- PBSE can address 10:1 more complex systems with 10:1 reduction in modeling effort, using people from a 10:1 larger community than the “systems expert” group, producing more consistent and complete models sooner. These dramatic gains are possible because projects using PBSE get a “learning curve jumpstart” from an existing pattern

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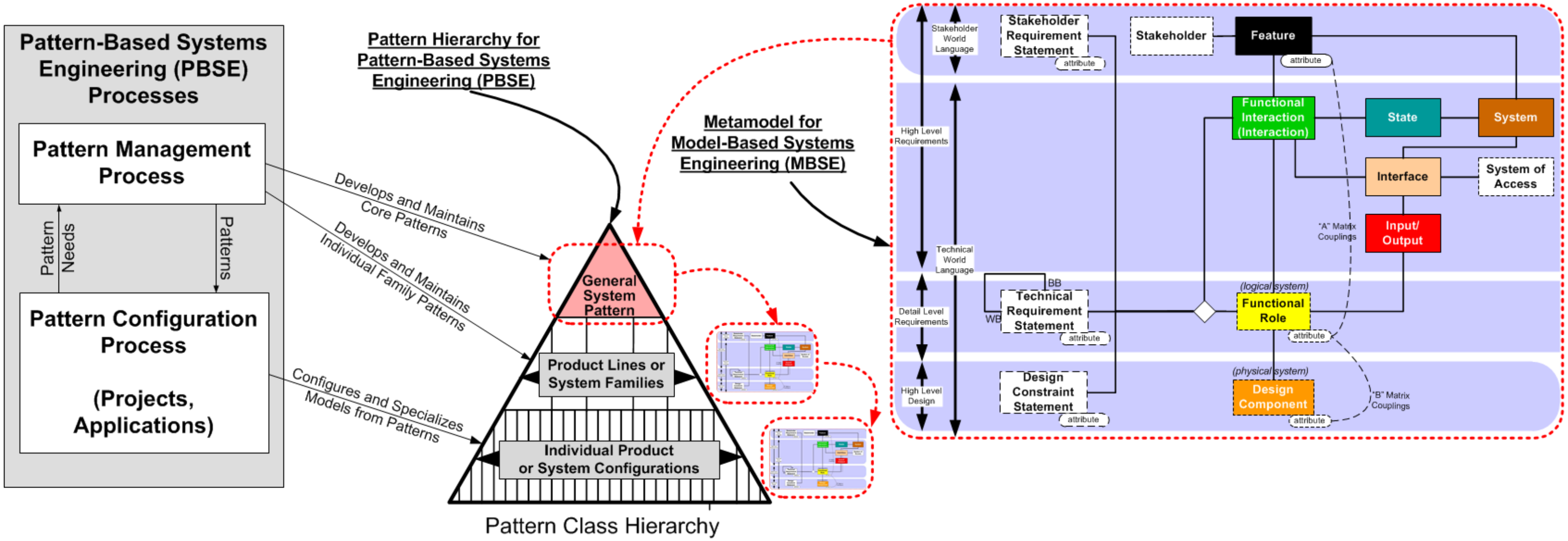
MBSE: Pattern Based Systems Engineering

- PBSE is leveraged as the MBSE methodology due to the impact it has had in helping teams focus on interactions, improve platform management as well as its data compression characteristics and strong underlying metamodel. To increase awareness of the PBSE approach, INCOSE has recently started a Patterns Challenge Team within the INCOSE MBSE Initiative and it is a recognized methodology on INCOSE's MBSE wiki.



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

INCOSE PBSE Content: http://www.omgwiki.org/MBSE/doku.php?id=mbse:patterns:patterns

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Model Expression

- The Systems Modeling Language (SysML) has proven to be a significant enabler to advance MBSE methods given its flexibility and expressiveness.
- The flexibility of the language and advances in tools also permits easy construction of allocation tables and dynamic tabular representations.
- While SysML provides clarity and consistency, unfortunately, the number of people who know and SysML is still relatively small which has led to some criticism and limited widespread acceptance.
- To bring the full power of MBSE to the larger community system models in SysML can also be represented in a more intuitive form. Not as a replacement to the rich detail provided by the SysML but as a complementary product to conceptualize and design for the deep inter-dependencies inherent in systems today.

Model Expression and Learning

- The objective of model expression is to maximize our ability to translate system data and information into knowledge we can use to improve the trajectory of our programs.
- To improve program and system performance we need to deepen the understanding of system models for the larger community of development stakeholders.
- To ensure we can extend the power of MBSE and SysML to a much larger community it's worthwhile to first consider how we think and interact with information.
  - "Vision trumps all other senses. We are incredible at remembering pictures." [8]
  - Research has shown repeatedly that we are wonderful at encoding images but not especially good with arbitrary information
  - Our brains are designed for spatial information and our image recognition is very durable.

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Exercise

Pretend your life depends upon remembering the sequence of numbers I am about to share with you

- Do not write them down
- Your results will not be scored
- Everyone passes

Each number will be displayed in a green circle. #

Please commit to memory the numbers which follow

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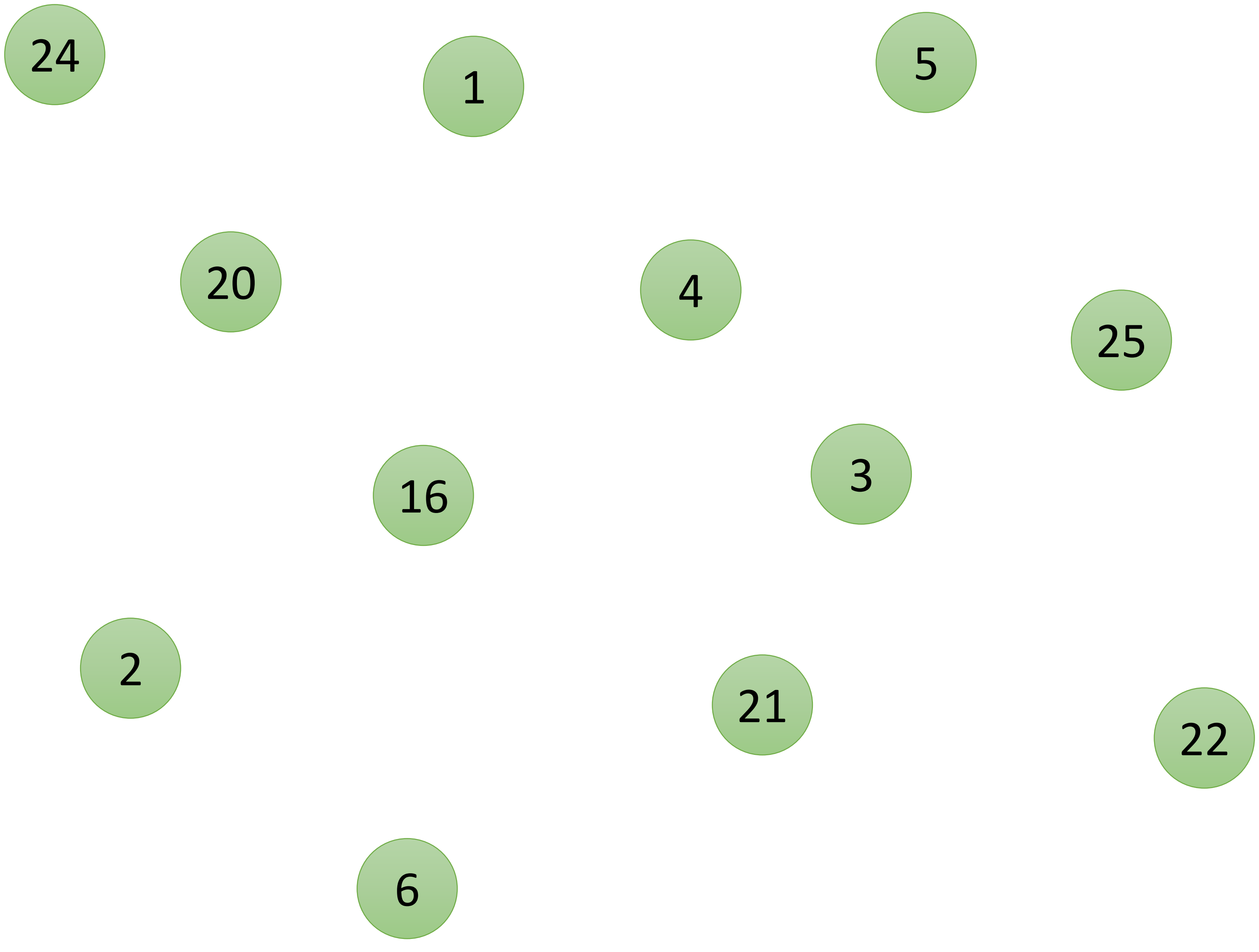
24

Write down as many as you can remember

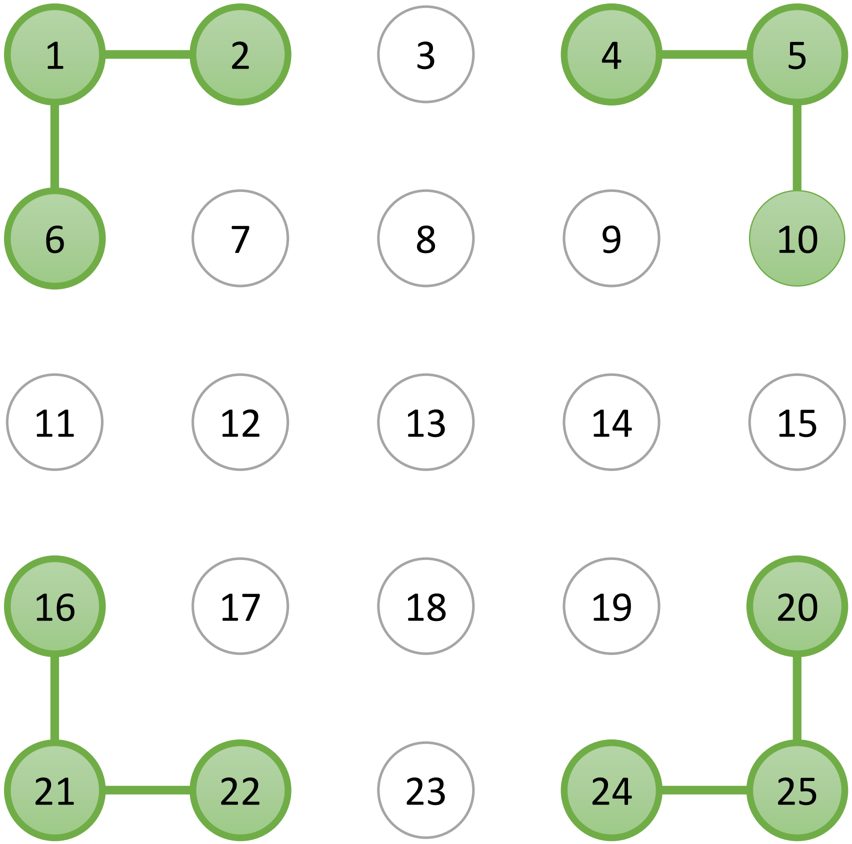
How well did you do?

Let’s try another view


24
1
5
20
4
25
16
3
2
21
22
6

Any better?

One last try?


1
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22
23
24
25

Could you reproduce the numbers now?

How would you do it?

Do you think of the numbers or the pattern?

Information Encoding and Allocations

- Just as a computer needs information coded properly in bits – we need images.
- Long strings of numbers are very easy for a computer to recall but spatial information and associations can be far more challenging for a computer. This is true even with the great strides made in machine learning and artificial intelligence.
- As our developments become more digital we need to appropriately allocate activities.
  - Let machines handle what they do well, for instance, storing and reproducing information
  - Focus our attention on leveraging our amazing cognitive ability to compare, contrast, associate, integrate and synthesize information

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Model Expression

- Use of different representations of the same information is not a new concept. Architects, engineers and others often provide multiple views of the same elements to provide users of their products as much clarity as possible.
- To represent form engineers often use left, right, top, bottom, exploded, isometric, cut-out and perspective drawings.
- To represent function we also use several views; this notion is a key tenant of SysML, UML, DODAF and other languages and frameworks.
- In particular, SysML defines nine diagrams, all of which are useful and depict important information about the structure and behavior of a system.

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Exercise: Can you name this system?

Perspective matters

Different views communicate different things

Some views can tell us interesting things very quickly

The Larger Stakeholder Community

- Many SMEs are required to engineer systems.
- Each SME has tools, languages and methods that they use to model and design systems.
- These languages are often not natural or intuitive to others outside their domain.
- We need to have representations which bridge over roles, domains and areas of functional expertise.
- Graph Theory can provide a means to reach this larger community without significantly sacrificing the power and expressivity of SysML's semantics.
- It can also expose us to new ways of viewing, analyzing and understanding the complex systems we design. Coupled with dynamic visualization we can explore, query and learn the model

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Graph Theory Overview

- The application of graph theory has proven very effective in the design, analysis, management, and integration of complex systems.
- More specifically, it enables the user to model, visualize, and analyze the interactions among the entities of any system.
- Derivatives of Graph Theory, such as Network Analysis and Design Structure Matrix (DSM), are enabled by and support the application of Model Based Systems Engineering (MBSE).
- Both DSM, as a matrix-based system modeling representation, and Network Analysis, as a graphical node and line representation, can be generated from SysML models.
- These representations offer a complementary way to visualize and analyze systems models.

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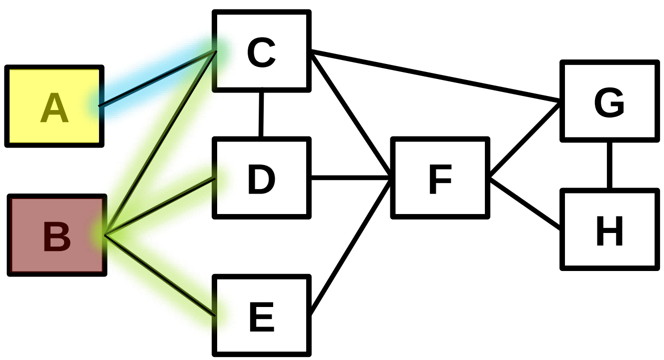
A powerful paradigm and method to analyze systems

- The diagrams below provide two different views of a generic system with relationships as shown
- For systems, relationships may be interactions of force, information, energy or mass flow
- These diagrams can be powerful in providing understanding of how systems elements interact



Network View

Lines indicate connectivity between elements

	A	B	C	D	E	F	G	H
A			X					
B			X	X	X			
C	X	X		X		X	X	
D		X	X			X		
E		X				X		
F			X	X	X		X	X
G			X			X		X
H							X	

Matrix View

X's indicate connectivity between elements

The network view is intuitive and good for understanding very large data sets
The matrix view provides a compact visual and enables holistic systems modeling

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Design Structure Matrix Overview

Design Structure Matrix (DSM)

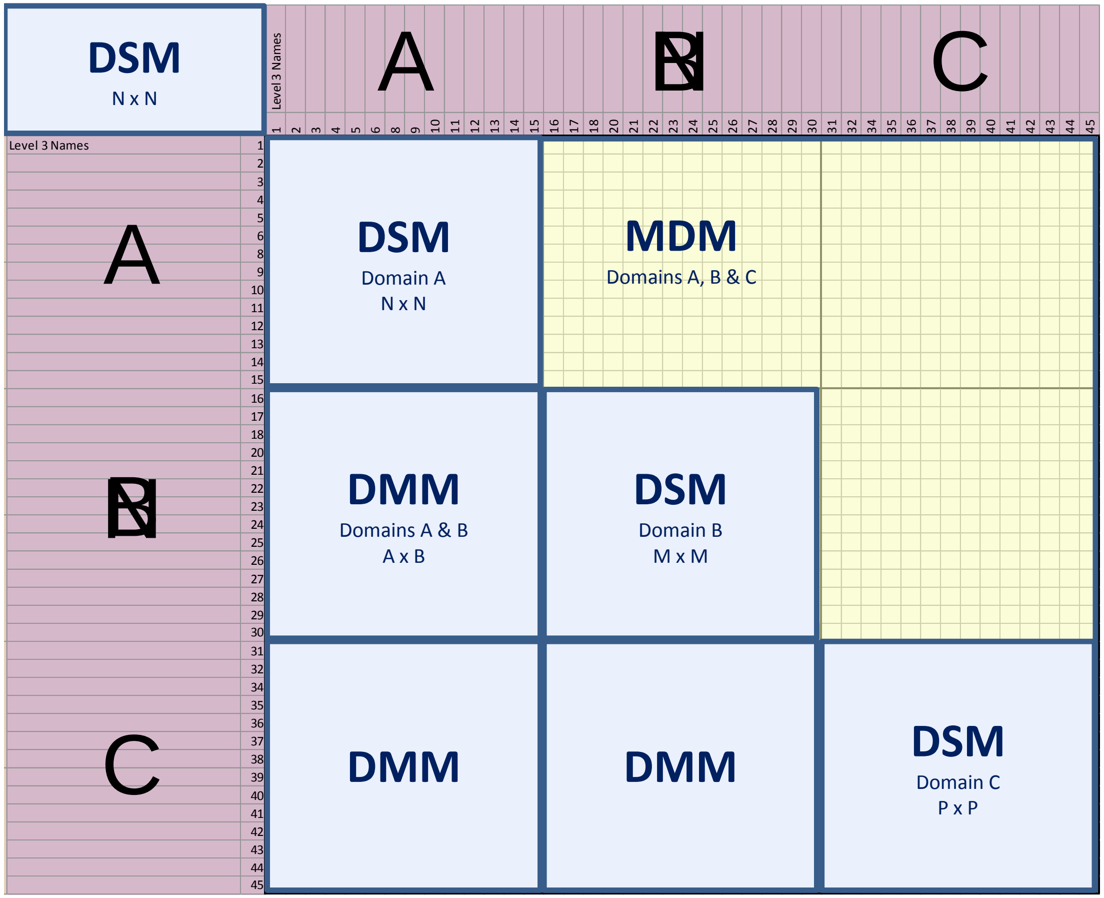
- Square matrix- N x N or N^2
- Analyze dependencies within a domain
- Used for products, process and Organizations
- Binary marks “(1” or “X”) show existence of a relation
- Numerical entries are weights of relation strength
- Can be directed or undirected (symmetrical)

Multi Domain Matrix (MDM)

- Square matrix - N x N or N^2
- Analyze dependencies across domain
- Combination of DSMs and DMMs
- Especially helpful for DSMs > 1000 elements

Domain Mapping Matrix (DMM)

- Normally rectangular matrix – N x M
- Mapping between two domains



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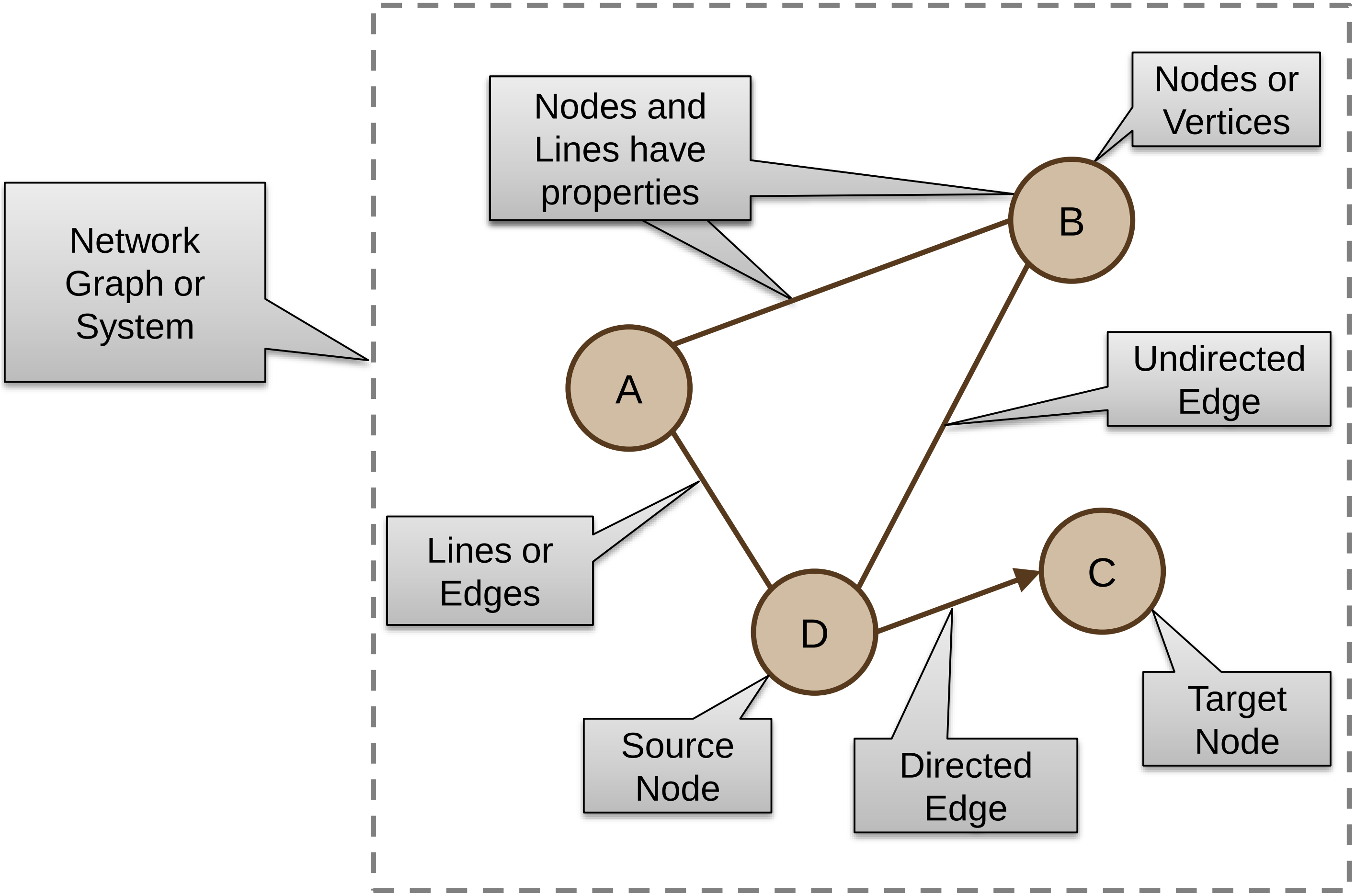
Graph / Network Overview



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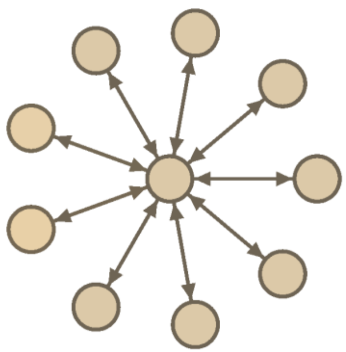
Graph and DSM Patterns

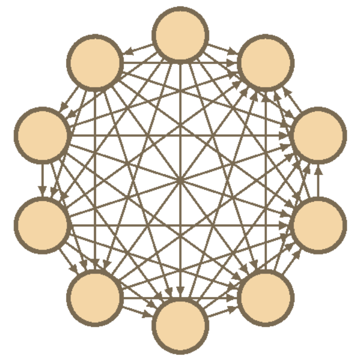


Layout: Concentric

$root	1	2	3	4	5	6	7	8	9	10
Element 1 1	10%									1
Element 2 2		10%								1
Element 3 3			10%							1
Element 4 4				10%						1
Element 5 5					10%					1
Element 6 6						10%				1
Element 7 7							10%			1
Element 8 8								10%		1
Element 9 9									10%	1
Element...10	1	1	1	1	1	1	1	1	1	10%

Sample System

- Symmetrical
- Layered System – Every system uses and feeds element 10

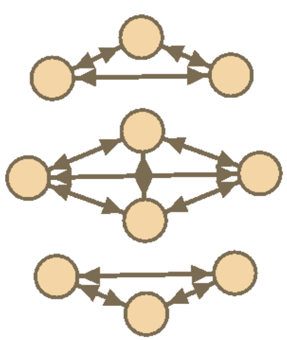


Layout: Circular

$root	1	2	3	4	5	6	7	8	9	10
Element 1 1	10%									
Element 2 2	1	10%								
Element 3 3	1	1	10%							
Element 4 4	1	1	1	10%						
Element 5 5	1	1	1	1	10%					
Element 6 6	1	1	1	1	1	10%				
Element 7 7	1	1	1	1	1	1	10%			
Element 8 8	1	1	1	1	1	1	1	10%		
Element 9 9	1	1	1	1	1	1	1	1	10%	
Element 10 10	1	1	1	1	1	1	1	1	1	10%

System

- Non symmetrical
- Layered System – every system uses or feeds every system below it

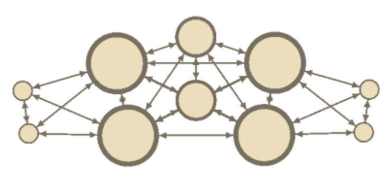


Layout: ForceAtlas2

$root	1	2	3	4	5	6	7	8	9	10
Element 1 1	10%	1	1							
Element 2 2	1	10%	1							
Element 3 3	1	1	10%							
Element 4 4				10%	1	1	1			
Element 5 5				1	10%	1	1			
Element 6 6				1	1	10%	1			
Element 7 7				1	1	1	10%			
Element 8 8								10%	1	1
Element 9 9								1	10%	1
Element 10 10								1	1	10%

System

- Symmetrical
- Non-Overlapping clusters



Layout: Yifan Hu

$root	1	2	3	4	5	6	7	8	9	10
Element 1 1	10%	1	1	1						
Element 2 2	1	10%	1	1						
Element 3 3	1	1	10%	1	1	1	1	1		
Element 4 4	1	1	1	10%	1	1	1	1		
Element 5 5			1	1	10%	1	1	1		
Element 6 6			1	1	1	10%	1	1		
Element 7 7			1	1	1	1	10%	1	1	1
Element 8 8			1	1	1	1	1	10%	1	1
Element 9 9							1	1	10%	1
Element 10 10							1	1	1	10%

System

- Symmetrical
- Overlapping clusters

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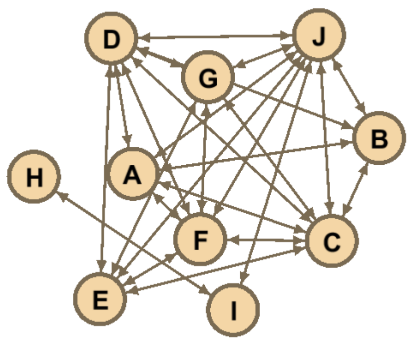
Graph and DSM Patterns and Algorithms

Unorganized



$root		1	2	3	4	5	6	7	8	9	10
System	Element D 1	10%	1		1		1	1	1	1	1
	Element A 2	1	10%		1			1	1	1	
	Element H 3			10%		1					
	Element F 4	1	1		10%		1		1	1	1
	Element I 5			1		10%			1		
	Element E 6	1			1		10%		1	1	1
	Element B 7	1	1					10%	1	1	
	Element J 8	1	1		1	1	1	1	10%	1	1
	Element C 9	1	1		1		1	1	1	10%	1
	Element G 10	1			1		1		1	1	10%

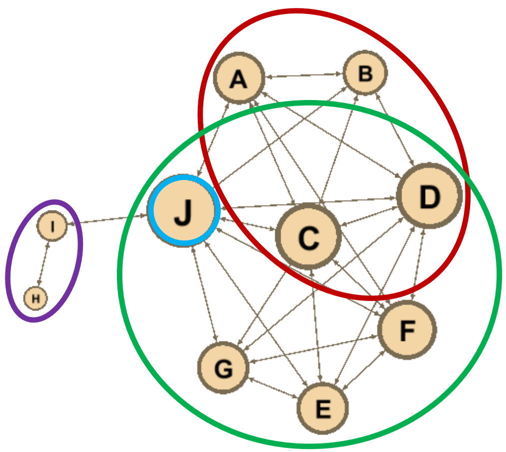
Network Graph

- Randomly generated

DSM

- Randomly ordered

Organized



$root		1	2	3	4	5	6	7	8	9	10
System	Element H 1	10%	1								
	Element I 2	1	10%								1
	Element A 3			10%	1	1	1		1		1
	Element B 4			1	10%	1	1				1
	Element C 5			1	1	10%	1	1	1	1	1
	Element D 6			1	1	1	10%	1	1	1	1
	Element E 7					1	1	10%	1	1	1
	Element F 8			1		1	1	1	10%	1	1
	Element G 9					1	1	1	1	10%	1
	Element J 10		1	1	1	1	1	1	1	1	10%

Network Graph

- Nodes sized by degree
- Arranged by cluster

DSM

- Layered
- Change propagator, Element J, clearly shown at the bottom
- Clustered, showing both overlapping non-overlapping and clusters

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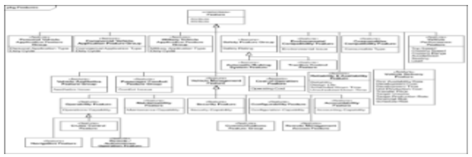
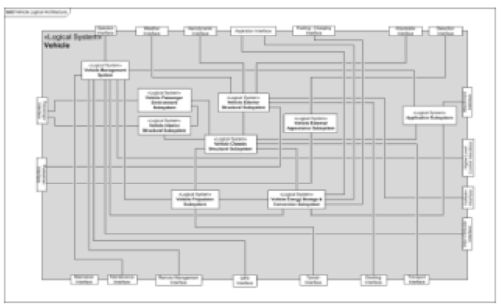
Pattern Based Systems Engineering (PBSE) MD

Vehicle MDM

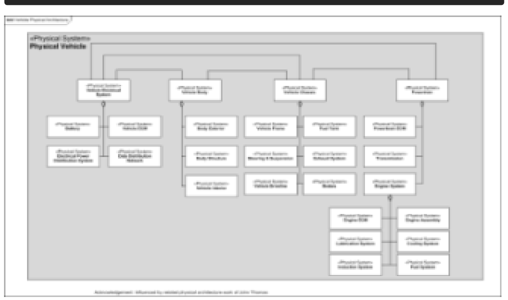
Features

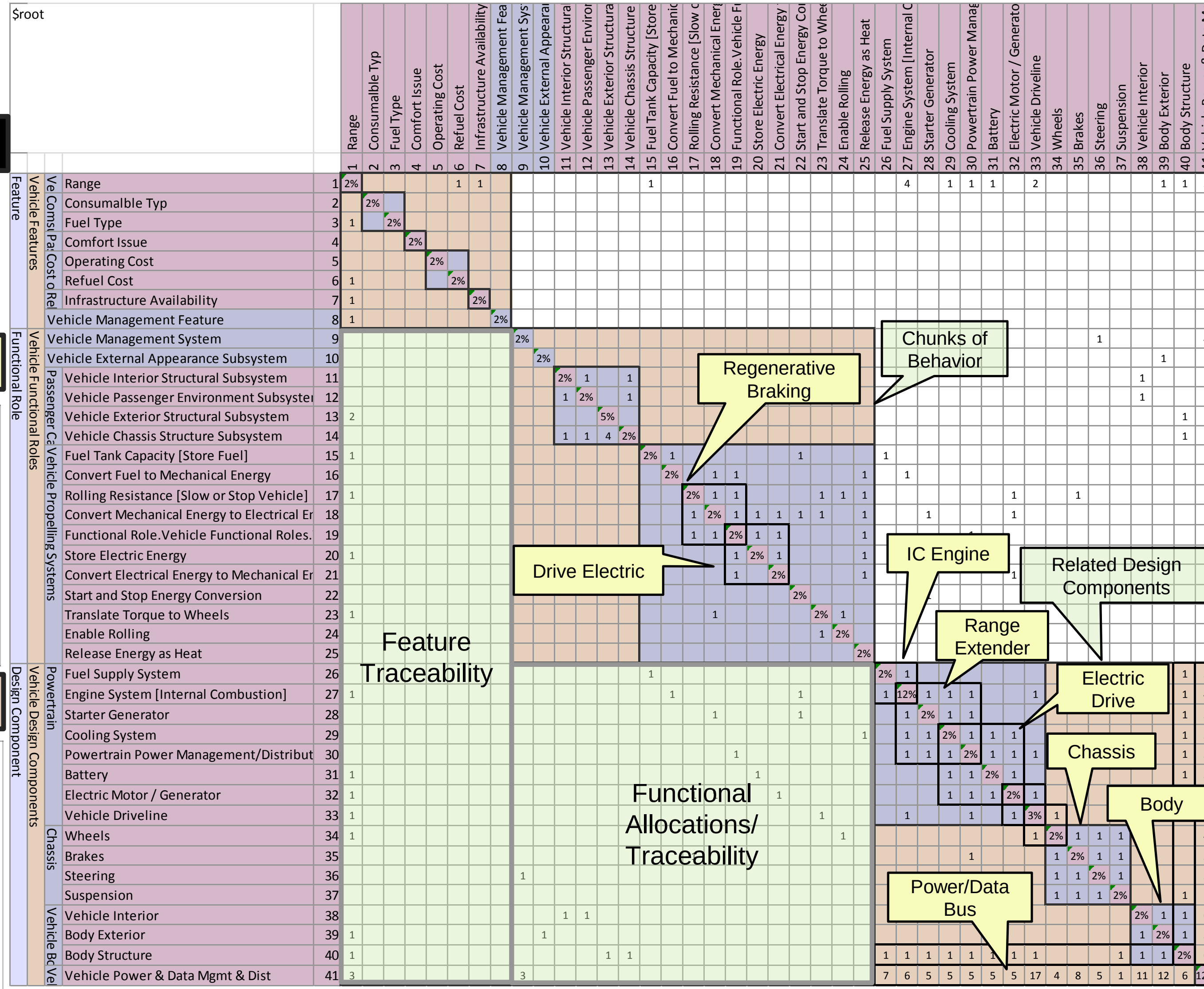


Functional Roles



Design Components





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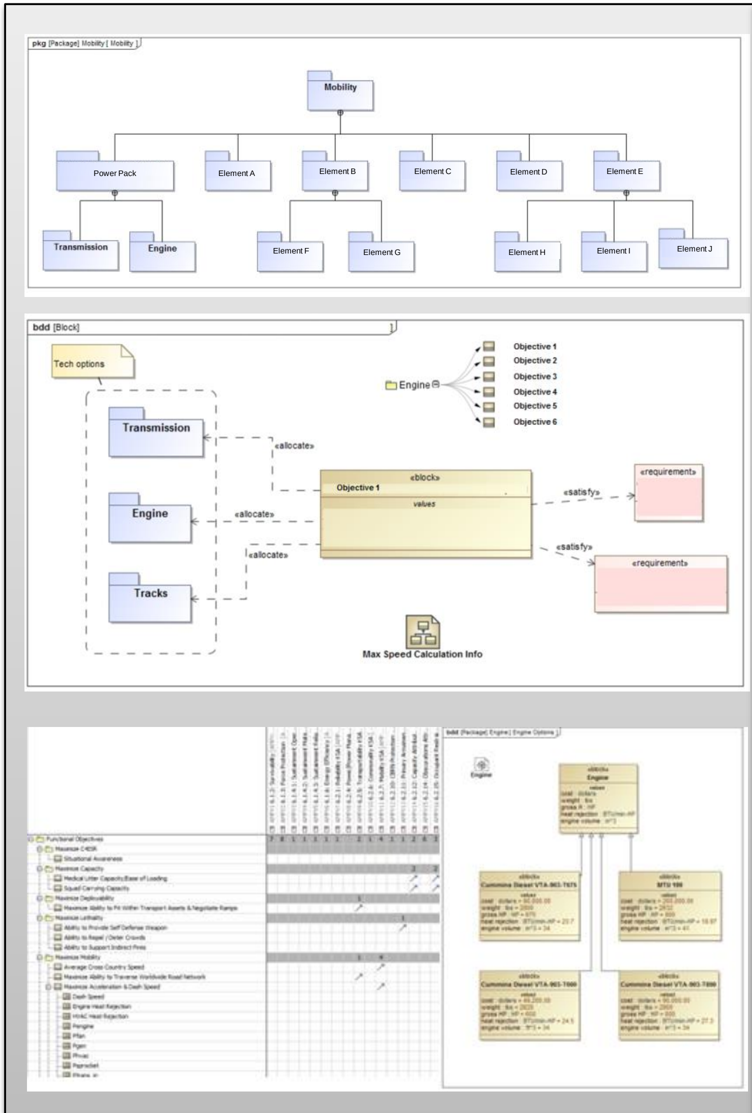
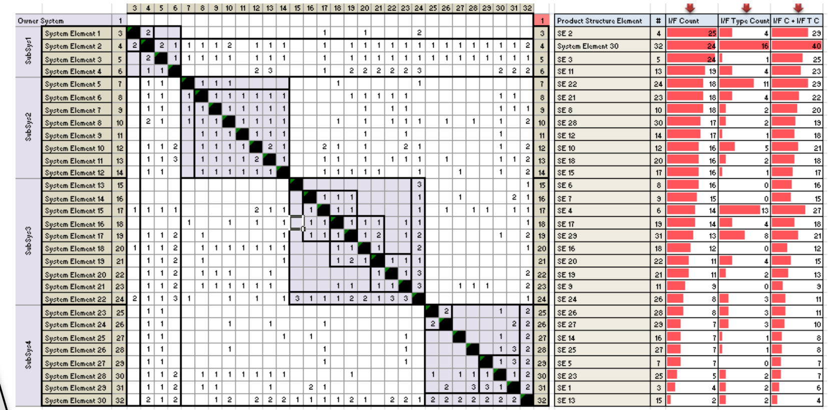
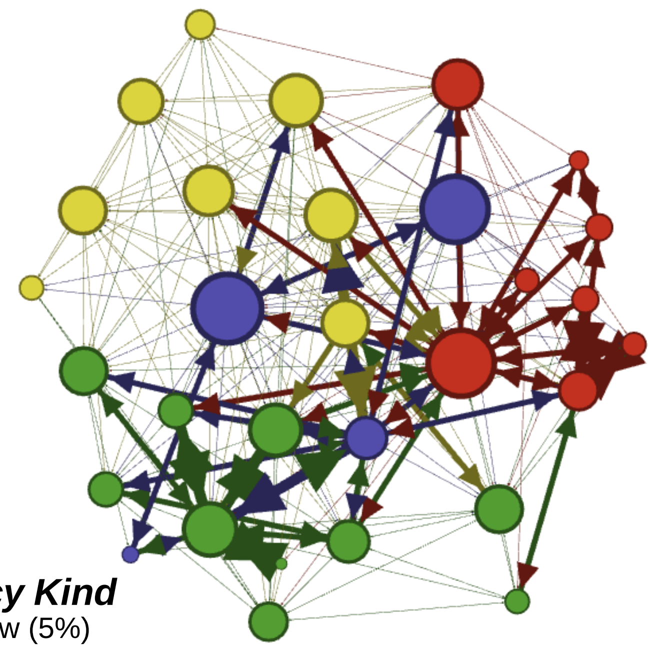
Model Expressed in SysML, DSM and Graph



Use MBSE system descriptive models to generate DSM and Graph views





Dependency Kind

- Mass Flow (5%)
- Force (24%)
- Energy (26%)
- Data (45%)

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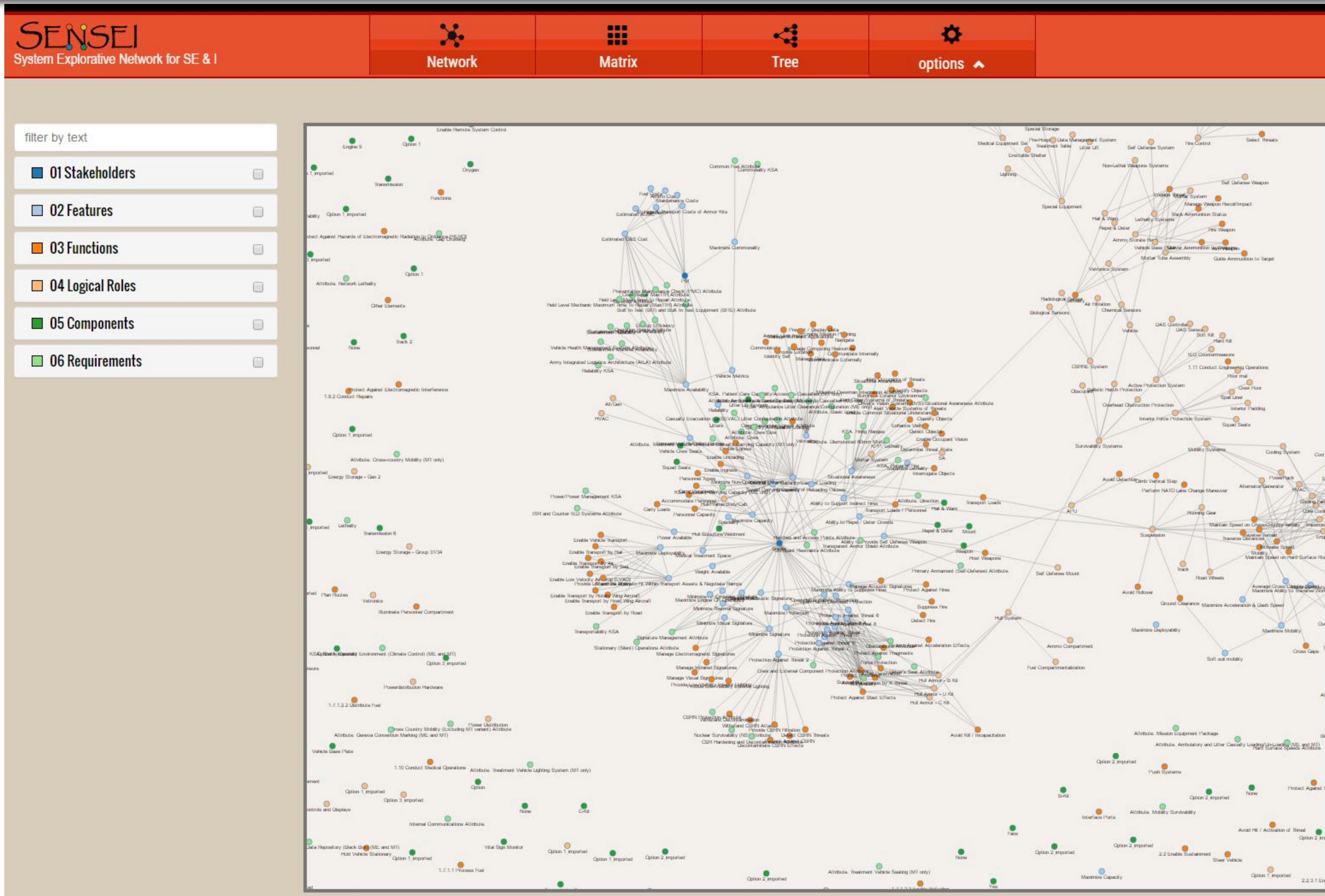
Dynamic Visualization - Network



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Conclusions

- As systems become more and more complex they provide both incredible opportunity and risk.
- The benefits of Model Based Systems Engineering approaches are a powerful way to model, understand and manage the evolution of systems.
- Translating detailed models into simple system representations (graphs and matrices) and providing dynamic visualizations can extend the full power of model based methods to the larger engineering community and deepen our understanding
- When coupled with an understanding of how we learn models have an excellent opportunity to help development teams and leadership gain insights, build intuition and speed the innovation

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Troy Peterson Bio

Troy Peterson

Booz Allen Fellow
Chief Engineer
peterson_troy@bah.com
313.806.3929

Troy Peterson is a Booz Allen Fellow and Chief Engineer instituting capabilities to manage complexity, engineer resiliency and speed innovation. As a Fellow, Troy operates as a firm-wide resource to help colleagues and clients confront systems challenges.

Troy has led several international projects and large teams in the delivery of complex systems. His experience spans commercial, government and academic environments across all product life cycle phases. Recent engagements include Contingency Basing, the Ground Combat Vehicle (GCV), Mine Resistant Ambush Protected (MRAP) vehicle and developing engineering capability within organizations responsible for research, development, acquisition and system of systems engineering and integration.

Troy's impact has led to his appointment to six different boards to improve engineering education and method application. He frequently speaks at leading engineering conferences and was recently appointed by INCOSE as the lead for transforming Systems Engineering to model based discipline.

Prior to joining Booz Allen, Troy worked at Ford Motor Company and as an entrepreneur operating a design and management consulting business. Troy received his B.S. in Mechanical Engineering from Michigan State University, his M.S. in Technology Management from Rensselaer Polytechnic Institute, and an advanced graduate certificate in Systems Design and Management from the Massachusetts Institute of Technology (MIT). He holds INCOSE Systems Engineering, PMI Project Management, and ASQ Six Sigma Black Belt certifications.

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Abstract

Understanding Systems through Graph Theory and Dynamic Visualization

As today's Cyber Physical Systems (CPS) become more and more complex they provide both incredible opportunity and risk. In fact, rapidly growing complexity is a significant impediment to the successful development, integration, and innovation of systems. Over the years, methods to manage system complexity have taken many forms. Model Based Systems Engineering (MBSE) provides organizations a timely opportunity to address the complexities of Cyber Physical Systems. MBSE tools, languages and methods are having a very positive impact but are still in a formative stage and continue to evolve. Moreover, the Systems Modeling Language (SysML) has proven to be a significant enabler to advance MBSE methods given its flexibility and expressiveness. While the strengths of SysML provide clarity and consistency, unfortunately the number of people who know SysML well is relatively small. To bring the full power of MBSE to the larger community, system models represented in SysML can be rendered in a more intuitive form. More specifically, Graph Theory has proven to be very effective in the design, analysis, management, and integration of complex systems. Network Analysis and Design Structure Matrix, both variants of Graph Theory, enable users to model, visualize, and analyze the interactions among the entities of any system. Use of MBSE and Graph Theory together to create dynamic visualization can help teams gain insights, build intuition and ultimately help speed the innovation process.

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