National Aeronautics and Space Administration

Engineering Elegant Systems: Principles of System Engineering

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Michael D. Watson, Ph.D.

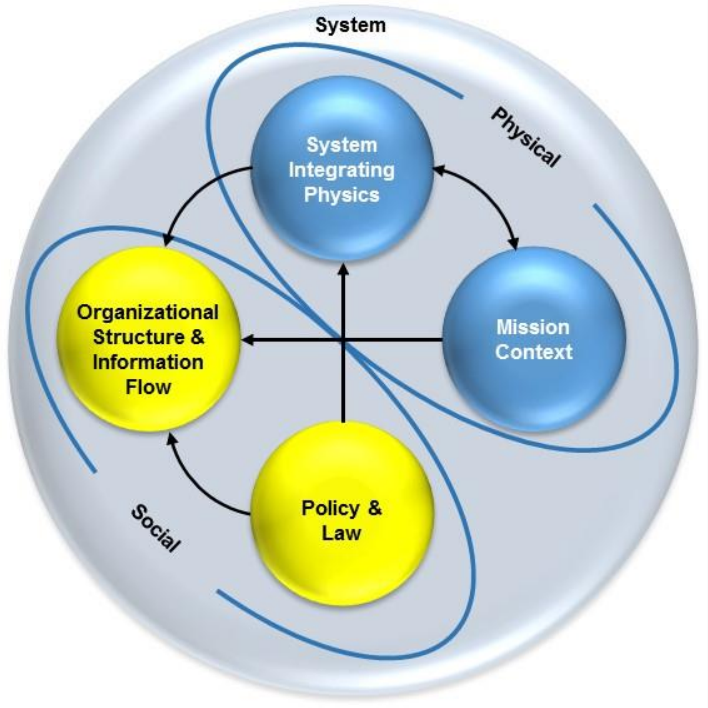
<u>Consortium Team</u>
UAH
George Washington University
Iowa State
MIT
Texas A&M
University of Colorado at Colorado Springs (UCCS)
University of Dayton
Missouri University of S&T
University of Michigan
Shafer Corporation
AFRL Wright Patterson

Space Launch System

Outline

- **Understanding Systems Engineering**

- **Systems Engineering Domain**
  - Primary
    - System Design and Integration
    - Discipline Integration
  - Supporting
    - Processes



- **Products**
  - Engineering Elegant Systems: Theory of Systems Engineering
  - Engineering Elegant Systems: The Practice of Systems Engineering

- **Summary**

Understanding Systems Engineering

Motivation

- **System Engineering of Complex Systems is not well understood**

- **System Engineering of Complex Systems is Challenging**
  - System Engineering can produce elegant solutions in some instances
  - System Engineering can produce embarrassing failures in some instances
  - Within NASA, System Engineering does is frequently unable to maintain complex system designs within budget, schedule, and performance constraints

- **"How do we Fix System Engineering?"**
  - Michael D. Griffin, 61st International Astronautical Congress, Prague, Czech Republic, September 27-October 1, 2010
  - Successful practice in System Engineering is frequently based on the ability of the lead system engineer, rather than on the approach of system engineering in general
  - The rules and properties that govern complex systems are not well defined in order to define system elegance

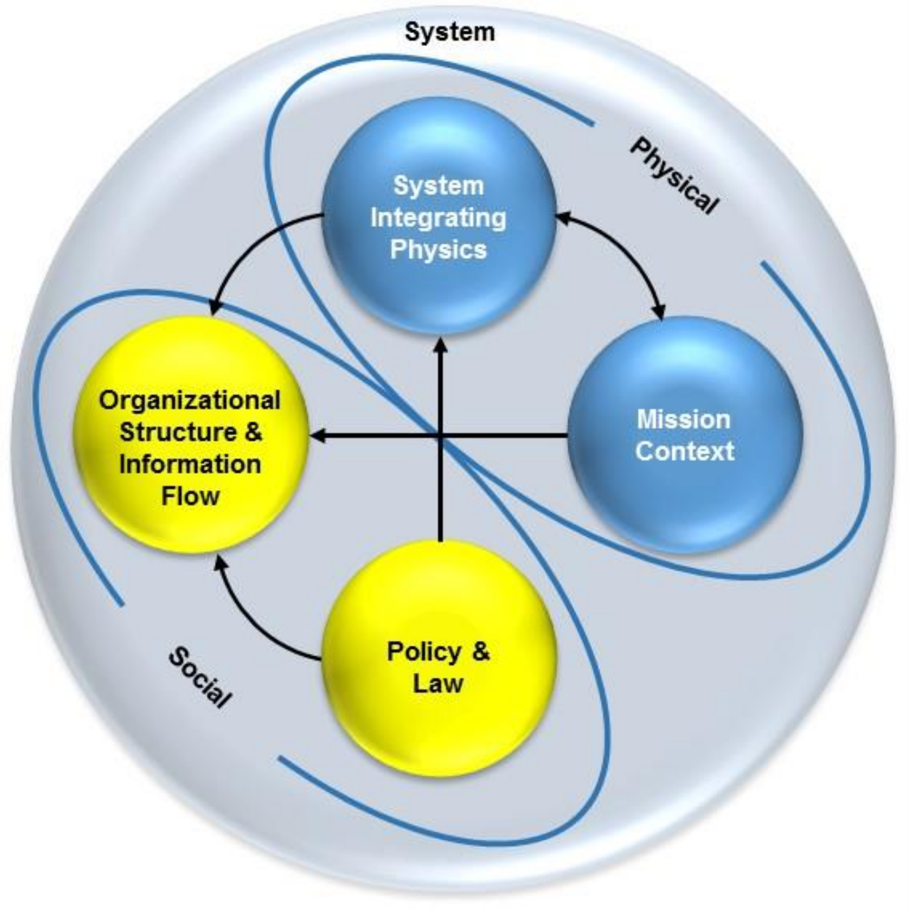
- **4 characteristics of system elegance proposed as:**
  - System Effectiveness
  - System Efficiency
  - System Robustness
  - Minimizing Unintended Consequences

Understanding Systems Engineering

- **Definition – System Engineering is the engineering discipline which integrates the system functions, system environment, and the engineering disciplines necessary to produce and/or operate an elegant system.**

- **Primary Focus**
  - System Design and Integration
    - Identify system couplings and interactions
    - Identify system uncertainties and sensitivities
    - Identify emergent properties
    - Manage the effectiveness of the system
  - Engineering Discipline Integration
    - Manage flow of information for system development and/or operations
    - Maintain system activities within budget and schedule

- **Supporting Activities**
  - Process application and execution



System Engineering Postulates

- Postulate 1: Systems Engineering is product specific.
- Postulate 2: The Systems Engineering domain consists of subsystems, their interactions among themselves, and their interactions with the system environment
- Postulate 3: The function of Systems Engineering is to integrate engineering disciplines in an elegant manner
- Postulate 4: Systems Engineering influences and is influenced by organizational structure and culture
- Postulate 5: Systems Engineering influences and is influenced by budget, schedule, policy, and law
- Postulate 6: Systems Engineering spans the entire system life-cycle
- Postulate 7: Understanding of the system evolves as the system development or operation progresses

System Engineering Hypotheses

- Hypothesis 1: If a solution exists for a specific context, then there exists at least one ideal Systems Engineering solution for that specific context
- Hypothesis 2: System complexity is greater than or equal to the ideal system complexity necessary to fulfill all system outputs
- Hypothesis 3: Key Stakeholders preferences can be accurately represented mathematically

Systems Engineering Principles

- **Principle 1: Systems engineering is driven by the characteristics of the specific system**
- **Principle 2: Complex Systems build Complex Systems**
- **Principle 3: The focus of systems engineering during the development phase is a progressively deeper understanding of the interactions, sensitivities, and behaviors of the system**
  - *Sub-Principle 3(a): Requirements are specific, agreed to preferences by the developing organization*
  - *Sub-Principle 3(b): Requirements are progressively defined as the development progresses*
  - *Sub-Principle 3(c): Hierarchical structures are not sufficient to fully model system interactions and couplings*
  - *Sub-Principle 3(d): A Product Breakdown Structure (PBS) provides a structure to integrate cost and schedule with system functions*
- **Principle 4: Information Theory is a fundamental mathematical concept of systems**
- **Principle 5: Systems engineering has an essential role during operations and decommissioning**
- **Principle 6: Systems engineering influences and is influenced by organizational structure and culture**
- **Principle 7: Systems engineering maps and manages the discipline interactions within the organization that represent the interactions of the system**
- **Principle 8: Decision quality depends on the system knowledge represented in the decision making process**
- **Principle 9: Both Policy and Law must be properly understood to not over constrain or under constrain the system implementation**
- **Principle 10: Systems engineering decisions are made under uncertainty accounting for risk**

System Engineering Domain

Goal: Engineer the System Interactions and the Engineering Discipline Interactions to produce an Elegant (efficient, effective, robust, intentional) System

Methods of System Integration

Goal: Techniques to Enable Integrated System Design and Assessments by the Systems Engineer

System Physics and System Integrating Physics

Goal: Utilize the key system physics to produce an elegant system design

System Integrating Physics

- **Consortium is researching the significance of identifying and using the System Integrating Physics for Systems Engineering**
  - First Postulate: Systems Engineering is Product Specific.
  - States that the Systems are different, and therefore, the Integrating Physics for the various Systems is different
- **SLS is the complex system control for the Consortium**
  - Thermodynamic System
  - Other Thermodynamic Systems
    - Crew Modules
    - Fluid Systems
    - Electrical Systems
    - Power Plants
    - Automobiles
    - Aircraft
    - Ships
- **Not all systems are integrated by their Thermodynamics**
  - Optical Systems
  - Logical Systems
    - Data Systems
    - Communication Systems
  - Biological Systems
- **System Integrating Physics provides the engineering basis for the System Model**

System Integrating Physics

- **What is the Integrating Physics for the System?**
  - SLS – Propulsion Exergy: $\Delta \boldsymbol{m}_{\boldsymbol{propellant}} \left(\boldsymbol{h}_{\boldsymbol{prop}} + \frac{\boldsymbol{V}_{\boldsymbol{e}}^{2}}{2} \right) - \boldsymbol{X}_{\boldsymbol{des}} = \Delta \boldsymbol{KE}_{\boldsymbol{vehicle}} + \Delta \boldsymbol{PE}_{\boldsymbol{vehicle}}$
    - Mass is an input to the equation
    - System Exergy provides a useful work metric
  - MPCV
    - Life Support System Exergy: $\sum \left(1 - \frac{T_{cabin}}{T_{equipment}}\right) Q_{equipment} + \sum_{\boldsymbol{process}} \Delta \boldsymbol{m}_{\boldsymbol{air}} \left(\boldsymbol{h}_{\boldsymbol{process}} - T_{cabin} \left(\boldsymbol{s}_{process} - \right.\right.$

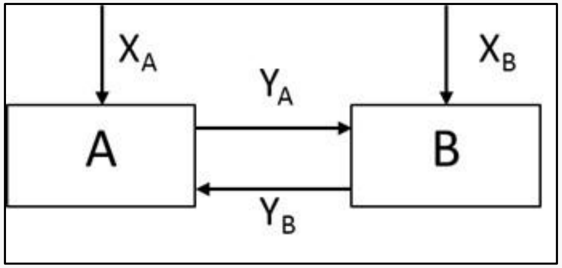
2 Relationships

System Design and Optimization

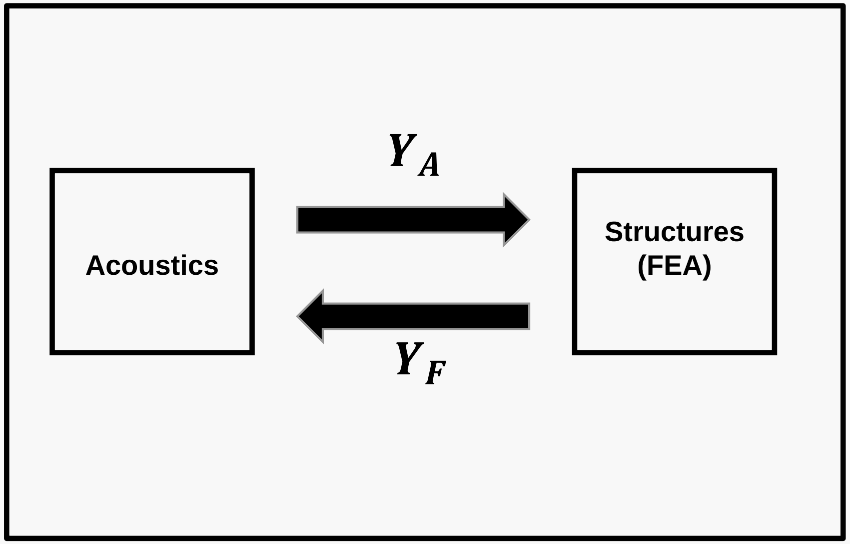
Goal: Apply system design and optimization tools to understand and engineer system interactions

Multidisciplinary Coupling Assessment (MCA)

- **Investigating Multidisciplinary Coupling Assessment (MCA) as a technique to analysis integrated system behavior coupling**
  - Based on Multidisciplinary Design Optimization (MDO) techniques
  - Seeks to identify system couplings and their relationships to allow optimization/mitigation during design
    - Quicker assessment of the couplings
    - Significantly smaller effort to produce understanding of coupling and assess design options
- **SLS is the system control for the analysis**
  - Selected Ares I Thrust Oscillation as a representative case to compare across the Ares I Integrated Stack (i.e., Ares I and MPCV)
- **MCA is a form of the system model focusing on the coupled behaviors of the system as a whole**



ASI Method



Engineering Statistics

Goal: Utilize statistical methods to understand system uncertainties and sensitivities

Systems Engineering makes use of Frequentist Approaches, Bayesian Approaches, Information Theoretic Approaches as appropriate

Optimal Sensor Information Configuration

- **Applying Akaike Information Criteria (AIC) corrected (AICc) to assess sensor coverage for a system**

$$AICc(F) = -2\left(I^{KL}(F|G)\right) + 2K + \frac{2K(K+1)}{n-K-1}$$

- **Two Views of Information Content**
  - AIC Information
    - Information is viewed as the number of meaningful parameters
      - Parameters with sufficient measurements to be reasonable estimates
  - Fisher Information Matrix
    - Defines information as the matrix of partial second derivatives
      - Information is the amount of parameters with non zero values (so provides an indication of structure)
      - This value converges to a maximum as the number of parameters goes to infinity
      - Does not contain an optimum, always increases with added parameters

- **AIC/AICc has an adjustment factor to penalize sensor arrangements where: number of sensors < 3x(number of measurements)**

- **Provides an optimization tool for use with System Models**

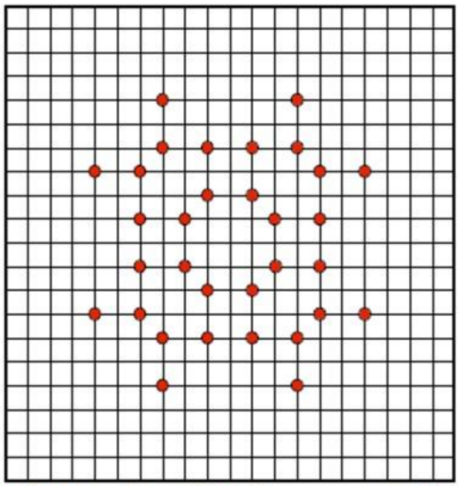
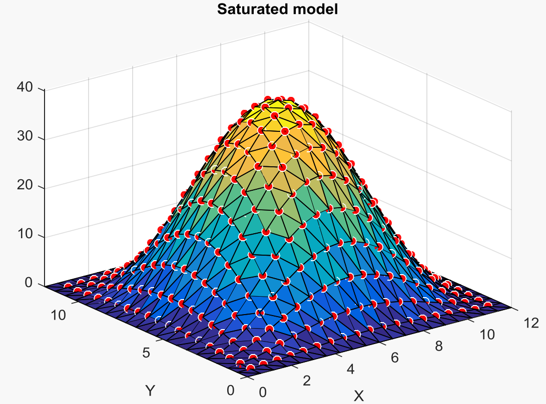


Figure 1a. *$NDOF_{minimum}$ results using Method 1 - $M^{1/2}$ weighting*



System State Variables

Goal: Utilize system state variables to understand the interactions of the system in relation to system goals and system execution

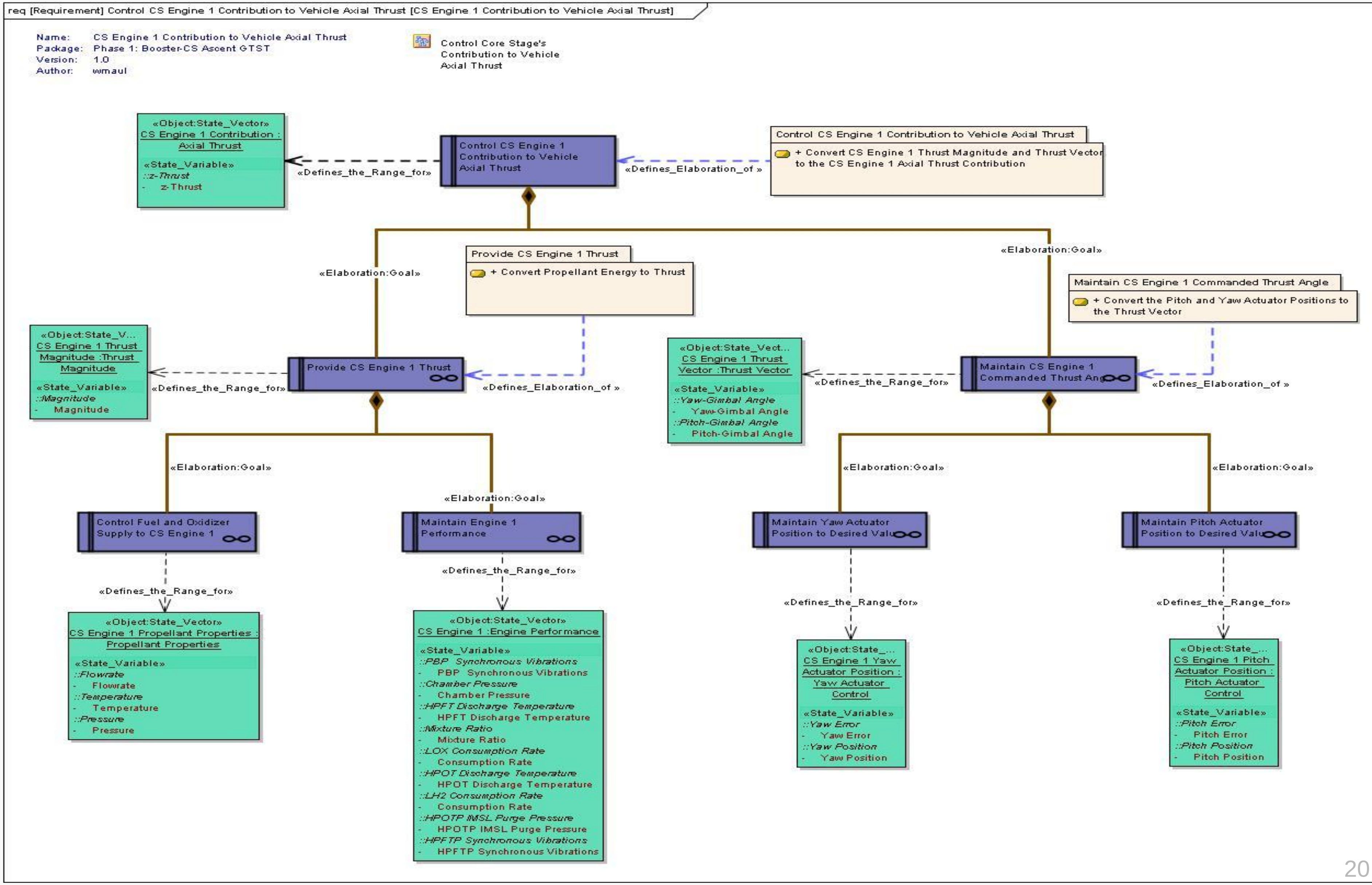
System State Models

- **System Stage Models represent the system as a whole in terms of the hardware and software states that the system transitions through during operation**

- **Goal Function Tree (GFT) Model**
  - "Middle Out" model of the system based on the system State Variables
  - Shows relationship between system state functions (hardware and software) and system goals
  - Does not contain system physical or logical relationships and is not executable

- **System State Machine Model**
  - Models the integrated State Transitions of the system as a whole (i.e., hardware states and software states)
  - Confirms system functions as expected
    - Checks for system hazardous, system anomalies, inconsistent state progression, missing states, improper state paths (e.g., short circuits in hardware and/or software design)
    - Confirms that the system states progress as stated in the system design
  - Executable model of system

Core Stage Engine Control Goal Function Tree (GFT)

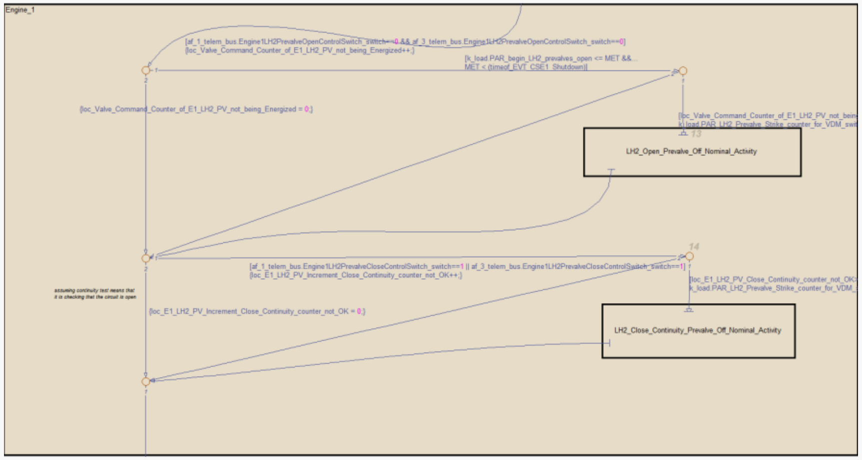


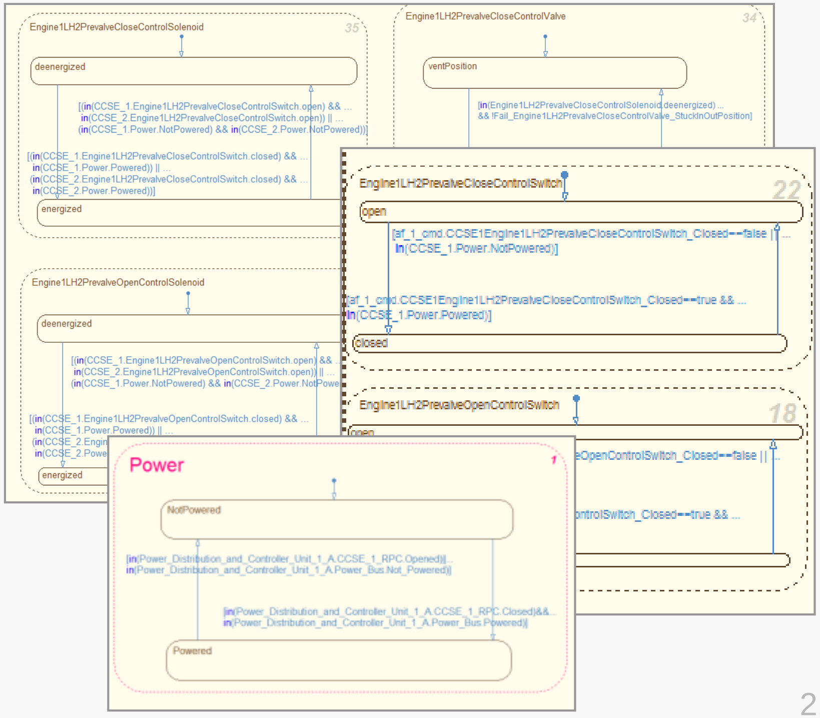
System State Machine Model

- **The state analysis model is split into two main components:**
  - Manager software model
  - System Plant

- **Modeled using MATLAB Stateflow**
  - Allows the software model to look like the SysML Activity Diagrams
  - Allows the SystembPlant to be modeled as State Machines
  - Allows those two models to interact with each other within the MATLAB environment
    - Facilitates the ability to generate custom analysis tools

- **Reads in command sequence to execute model**



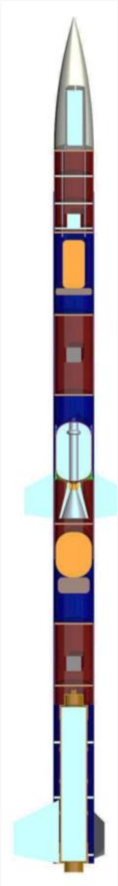


System Value

Goal: Utilize system state variables to understand the interactions of the system in relation to system goals and system execution

System Cost Model

- **System Cost Models are an important tool in both Development Phase and Production and Operations Phase cost control**
  - Unit Cost is critical to understand system cost
    - Product Breakdown Structure (PBS) provides unit cost
    - Work Breakdown Structure (WBS) provides common labor structure and can mask unit cost
  - Parametric models do not properly predict cost
    - Based on historical data
      - Accurate prediction based on following the same methods and approach as the historical program (NAFCOM using Titan IV)
    - Mass Based parametrics do not properly reflect System Integrating Physics and can have inverted relationships
      - Predicts higher cost for higher mass, the inverse is often more true
  - The cultural impact of cost models is important
    - Does the knowledge of the predicted cost bias decision making?
      - Does the predicted cost create a minimum cost mind set or a maximum cost mind set?
    - Is the only result of the cost prediction to forecast what the system will not cost??



System Value Model

- **A System Value Model is a mathematical representation of Stakeholders Preferences (Expectations) for the system**
  - The basic structure is straight forward
  - The sociology/psychology of representing the Preferences can be a challenge

- **The System Value Model is the Basis of System Validation!!!**
  - The Requirements and Design Models form the basis of System Verification
  - The System Value Model forms the basis of System Validation

- **Constructing an SLS Value Model to compare to System Validation results**
  - Can expand to Integrated Stack with input from MPCV and GSDO

- **System Value model also provides basis for a measure of System Robustness**
  - How many mission types are supported by the system?

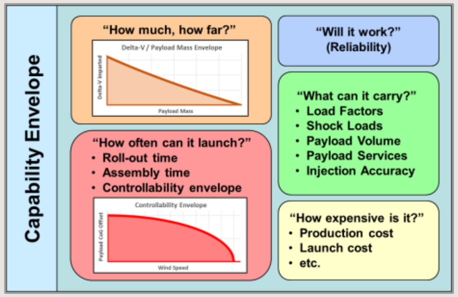
	Status	Gradient	Value
Efficiency	90%	150,000	135,000
Weight	700	-130	-91,000
Reliability	1500	2	3,450
Maintainability	7.8	-340	-2,652
Maintenance Cost	500	-1	-250
Support Equipment	12	-15	-180
Manufacturing Cost	700	-1	-700
Design Value			$ 43,668

$$\pi = f_{aircraft} \quad x_1, x_2 \ldots, x_n$$

$$v_e = \sum_{j=1}^{m} \left(\sum_{i=1}^{n} \frac{\partial \pi}{\partial x_i} \cdot \frac{\partial x_i}{\partial y_j} y_j \right)$$

$$v_t = \sum_{k=1}^{p} \left(\sum_{j=1}^{m} \frac{\partial v_e}{\partial y_j} \cdot \frac{\partial y_j}{\partial z_k} z_k \right)$$

Mapping System Capability to Value



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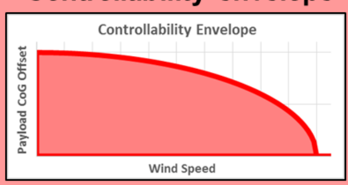
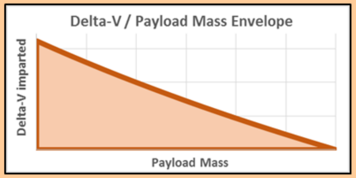
Mission A	Mission B	Mission C
• 20,000 m/s dV required	• 15,000 m/s dV required	• 32,000 m/s dV required
• Value = $50000 * m	• Value = $30000 * m	• Value = $80000 * m
• Demand = 25% of total	• Demand = 60% of total	• Demand = 15% of total

"How often can it launch?"
- **Roll-out time**
- **Assembly time**
- **Controllability envelope**



"How much, how far?"



"How expensive is it?"
- Production cost
- Launch cost
- etc.

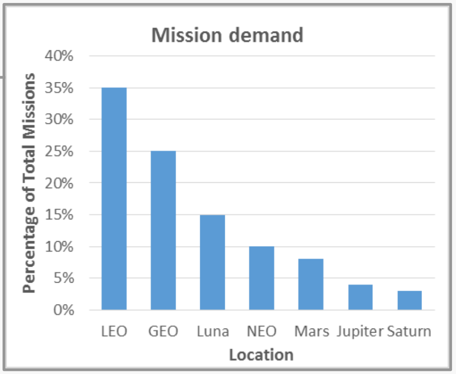
Missions Attempted

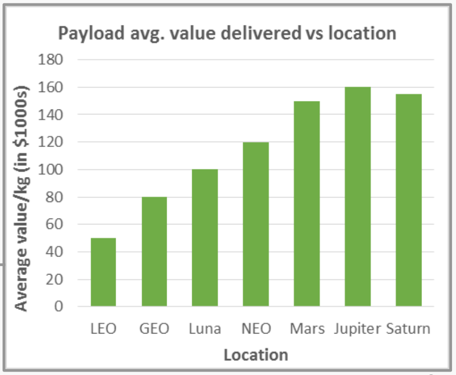
"Will it work?" (Reliability)

"What can it carry?"
- Load Factors
- Shock Loads
- Payload Volume
- Payload Services
- Injection Accuracy

Missions Succeeded

Total Value Delivered by Launch Vehicle

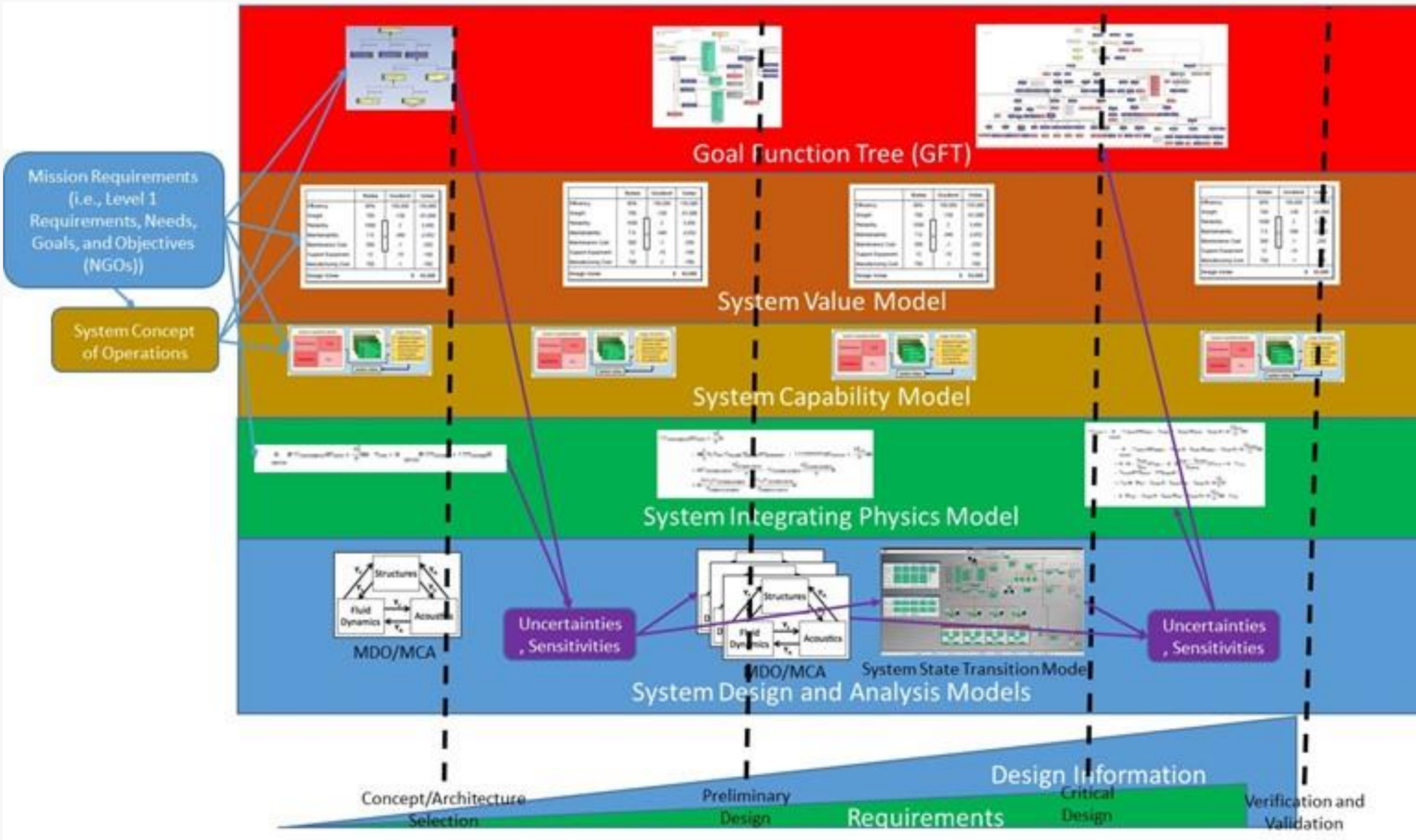




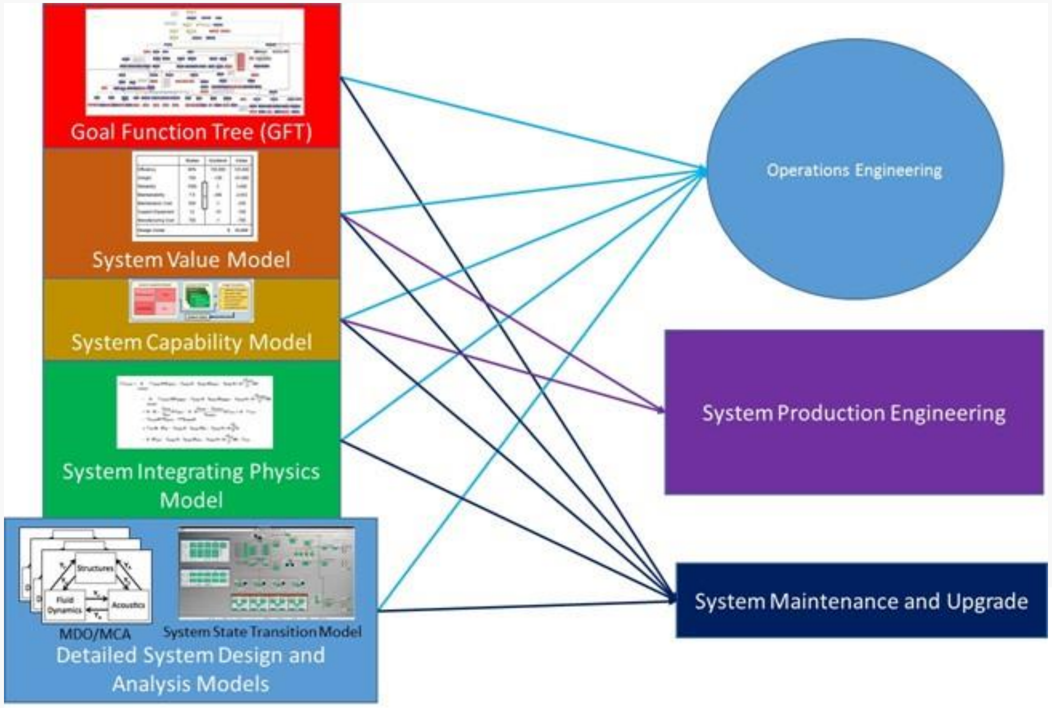
Methods of System Integration

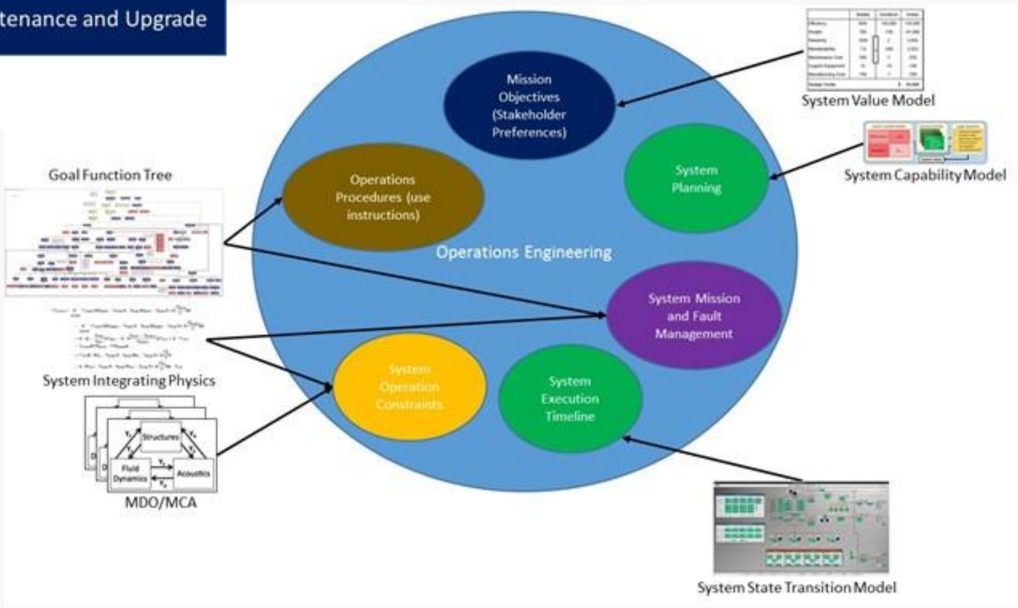
Goal: System Design and Analysis

System Design and Integration



System Operations





Methods of Engineering Discipline Integration

Goal: Understand How Organizational Structures influence Design and Operations Success of Complex Systems

Sociology of Systems Engineering

Goal: Understand the Relationship of Sociological Factors and Cognitive Abilities to Successful System Engineering

Sociological Concepts in Systems Engineering

- **Specification of Ignorance is important in the advancement of the understanding of the system**
- **Consistent use of Terminology is important for Communication within the Organization**
- **Opportunity Structures**
  - Provide opportunity to mature ideas
    - Task teams, working groups, communities of practice, etc.
- **Socially Expected Durations will exist about the project**
- **Both Manifest and Latent Social Functions exist in the organization**
- **Social Role Sets**
  - Individuals have a set of roles for their position
- **Cultural Subsets will form**
  - i.e., disciplines can be a subset within the organization
  - Insider and Outsider attitudes can form
    - Be Aware of the Self-Fulfilling Prophecy, Social Polarization
- **Reconsiderations Process (i.e., Reclama Process)**
  - Provides ability to manage social ambivalence
  - Must be able to recognize social beliefs that may be contributing to the disagreement
  - Helps to avoid putting people in to social dysfunction or complete social anomie
    - Conformity
    - Innovation
    - Ritualism
    - Retreatism
    - Rebellion

Unintended Consequences

- **Unintended Consequences are the result of human mistakes.**
  - Physics do not fail, we do not recognize the consequences.

- **Based on cognitive science, followed the work of Robert K. Merton in classifying unintended consequences.**
  - “The Unanticipated Consequences of Social Action”, 1936

- **Classification**
  - Ignorance (limited knowledge of the problem)
  - Historical Precedent (confirmation bias)
  - Error (mistakes in calculations, working from habit)
  - Short Sightedness (imperious immediacy of interest, focusing on near term and ignoring long term consequences)
  - Cultural Values (cultural bias in what can and cannot happen)
  - Self Defeating Prophecy (by stating the hypothesis you induce a set of conditions that prevent the hypothesis outcome)

Cognitive Science

- **Research Goal: Identify some of the key cognitive and organizational challenges in engineering complex systems and the implications to Systems Engineering**
  - University of Michigan, Design Science
    - Topic: Cognitive Science Perspective of Systems Thinking
      - Mapping Engineering Terminology to Cognitive Science Terminology to provide a scientific basis for the engineering cognitive concepts
      - Investigating Mediated Learning as a method to teach system thinking

Cognitive Competencies from Frank, 2012	Related Concepts from Cognitive Psychology
Understand the whole system and see the big picture	Sensemaking; information integration; mental model formation; generalization
Understand interconnections	Induction; classification; similarity; information integration
Understand system synergy	Deductive inference
Understand the system from multiple perspectives	Perspective taking (direct mapping)
Think creatively	Creativity (direct mapping)
Understand systems without getting stuck on details	Abstraction; subsumption
Understand the implications of proposed change	Hypothetical thinking
Understand a new system/concept immediately upon presentation	Categorization; conceptual learning; inductive learning/inference
Understand analogies and parallelism between systems	Analogical thinking (direct mapping)
Understand limits to growth	Information integration
Ask good (the right) questions	Critical thinking
(Are) innovators, originators, promoters, initiators, curious	Inquisitive thinking
Are able to define boundaries	Functional decomposition
Are able to take into consideration non-engineering factors	Conceptual combination
Are able to “see” the future	Prospection
Are able to optimize	Logical decision-making

Decision Making Information Flow

Goal: Understand the Decision Making Relationship to Information Flow in the System Development and Operations Organizations

Information Theory
Decision Making Processes
Biased Information Sharing

Information Flow

- **Information Flow through a program/project/activity is defined by Information Theory**
  - Organizational communication paths
  - Board Structure
- **Decision Making follows the First Postulate**
  - Decision Process is specific to the decision being made
  - Tracked 3 SLS CRs, with 3 separate task team processes, all had equally rated effectiveness

SLS SE&I MANAGEMENT STRUCTURE

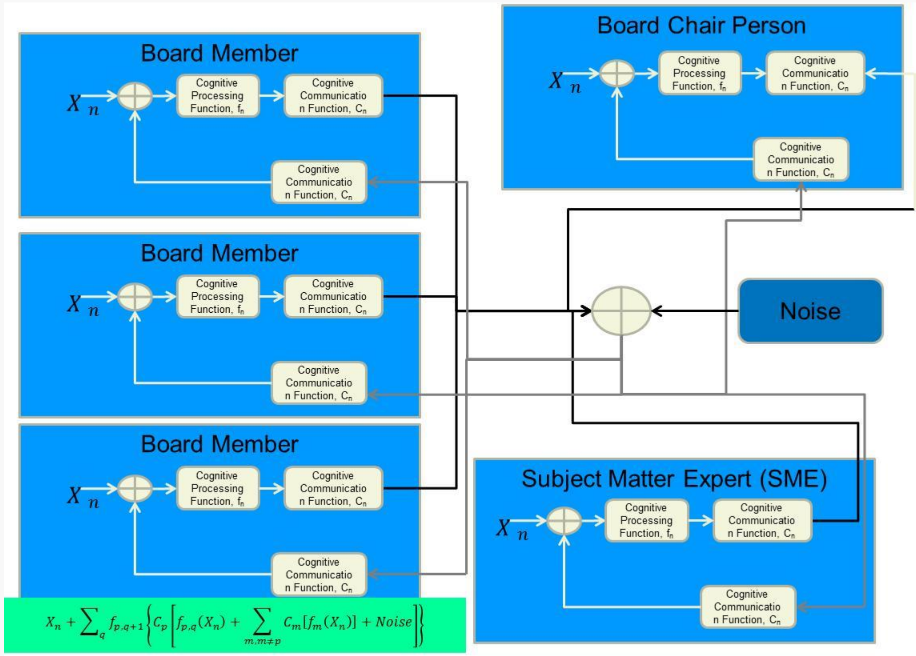
June 9, 2014 version

( ) = OPR [ ] = ORGANIZATIONS MAPPED TO DISCIPLINE

SLS PROGRAM OFFICE ORGANIZATION	CHIEF ENGINEERS OFFICE ORGANIZATION	Systems Engineering (EV01) [EV70, EE12]	Vehicle Management (EV40) [EV40]	Structures & Environments (StE) (EV30) [EV30, ER40, ES21, ES22]	Propulsion (ER01) [ALL ER EXCEPT ER40]	Production (EM01) [ALL EM]	Integrated Avionics and Software (ES01) [ALL ES EXCEPT ES21,ES22]	Operations (EO01) [ALL EO, ES10]	Test (ET01) [ALL ET]	S&MA (QD01) [ALL QD]
SLS Program Manager SLS Program Deputy Manager SLS Associate Program Manager Assistant PM Procurement	Program Chief Engineer Program Deputy Chief Engineer SE&I Technical Manager Assistant CE for Affordability Tech. Assist. Cross Program Integ. Tech. Assist. Ext. Interface Integ.	LSE: EV01 Alt: EV70 Alt: EV73	DLE: EV40 Alt: EV40	DLE: EV30 Alt: EV30	DLE: ER01 Alt: ER51 Alt: ER24	DLE: EM03 Alt: EM03 Alt: EM03	DLE: ES30 Alt: ES01	DLE: EO04 Alt: EO04	DLE: ET10 Alt: ET10	Program CSO Deputy CSO QD02 SE&I S&MA Lead QD35
Stages Element Manager Stages Deputy Element Manager - Avionics Manager - Core Stage Manager - Integration Manager	Stages Chief Engineer Stages Deputy Chief Engineer Stages Deputy CE - Avionics Stages Deputy Chief Engineer - Test	EV70 Alt: EV71	EDLE: EV41	EDLE: EV34	EDLE: ER22	EDLE: EM03 Alt: EM32	EDLE: ES12	EDLE: EO40	EDLE: ET10	QD33
Booster Element Manager Booster Deputy Element Manager - Control Systems Manager - Assem & Struct Systems Manager - Motor/BSM ASM - Booster CEI/Interface Mgr	Booster Chief Engineer Booster Deputy Chief Engineer	ER50	EDLE: EV40	EDLE: ER40	EDLE: ER51	EDLE: EM03	EDLE: ES12	EDLE: EO40		QD31
Engines Element Manager Engines Deputy Element Manager	Engines Chief Engineer Engines Deputy Chief Engineer	ER20	EDLE: EV43	EDLE: ER41	EDLE: ER21	EDLE: EM03	EDLE: ES12	EDLE: ER21		QD32
Spacecraft/Payload Integration and Evolution (SPIE) Office Manager SPIE Deputy Manager	SPIE CE SPIE Deputy CE	EV70 Alt: EV70	EDLE: EV41	EDLE: EV30	EDLE: ER23	EDLE: EM03	EDLE: ES10	EDLE: EO40	EDLE: ET30	QD22
	SPIE CE SPIE Deputy CE				EDLE: ER01 Alt: ER21	EDLE: EM03				QD31

- **Margin is maintained by the Organization, not in the margin management tables**
  - Biased Information Sharing
  - Margin Management is focused on Managing the Disciplines (informed by the System Integrating Physics)
- **SLS Organizational Structure was defined by the LSE as a recommendation to the Chief Engineer and the Program Manager**

Decision Structure Information Flow



Information Theory Model

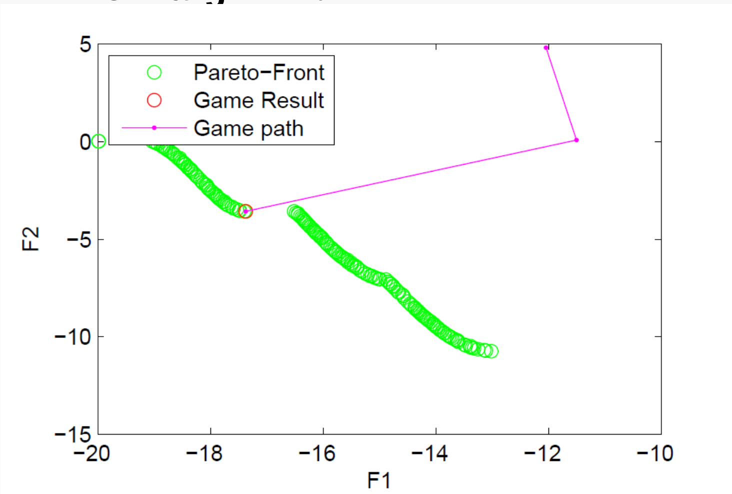
- Information Theory can be used to understand decision making structures and information flow
- $\bar{I} = H = -\sum_n p_n \log p_n$

Practitioner's Guidance

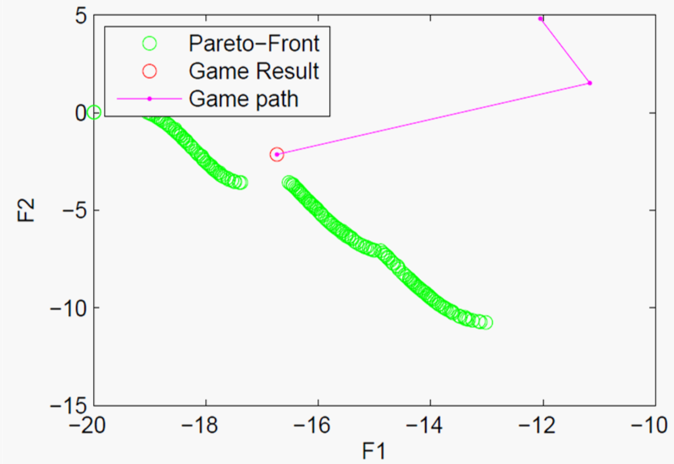
- Understand and define the scope of each needed decision body
- Ensure that each decision body has all affected or contributing disciplines represented, including understanding of the types and magnitudes of uncertainties affecting decisions within that decision body's scope, but no more
  - $H(p_1, p_2, \dots, p_n, q_1, q_2, \dots q_m) \geq H(p_1, p_2, \dots, p_n)$
- Minimize the number of decision bodies based on scope. The efficiency of the structure decreases with distributed and overlapping scopes.
  - $H(S, D, X, Y, Z) \leq H(S) + H(D) + H(X) + H(Y) + H(Z)$

Simulation Results

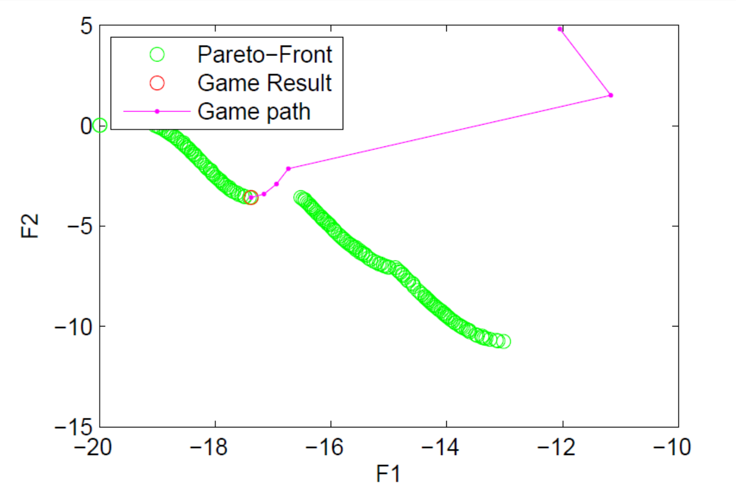
No margin : $m = 1$



Static margin, m= 1.3



Descending margin, m=1.3−.1$*i$ until m=1



- No margin condition reaches optimality quickest
- Descending margin still reaches optimal, but requires more iterations
- Margins are an issue
  - Interviews highlight real-world consequences
  - Simulations quantify extent of the problem
  - Still possible to achieve optimal design with descending margin, but takes additional time to achieve

Policy and Law Assessments

Goal: Understand How Policy and Law Constrain the Design and Operations of a System and How the System Engineer Should Interpret These Constraints

Space Policy and Systems Engineering

Impact of Government Oversight Time Allocation Study

- Motivation: Industry and government leaders agree that government oversight leads to cost growth, but there is less agreement on how much and through what mechanisms.

> *"There is suggestive evidence that the cost of government-driven mission assurance and current Federal Acquisition Regulations (FAR) increase costs by factors of 3-5 times, not just 20- 30%"*
>
> -Dr. Scott Pace, National Security Space Launch Programs - Testimony to Senate Committee on Defense Appropriations, Dirksen Senate Office Building 192, March 5 2014.

- Research:
  - Developed an empirical basis for measuring the extent and nature of the impact of oversight
  - Non-invasive "Time Allocation Study:" Statistically valid aggregated observations of how engineers actually spend their time throughout a product's life cycle.
    - Part One: Collect time-recall diaries to develop a composite list of activities performed
    - Part Two: Survey Population over several months at random times per day to accurately observe amount of time spent on activities

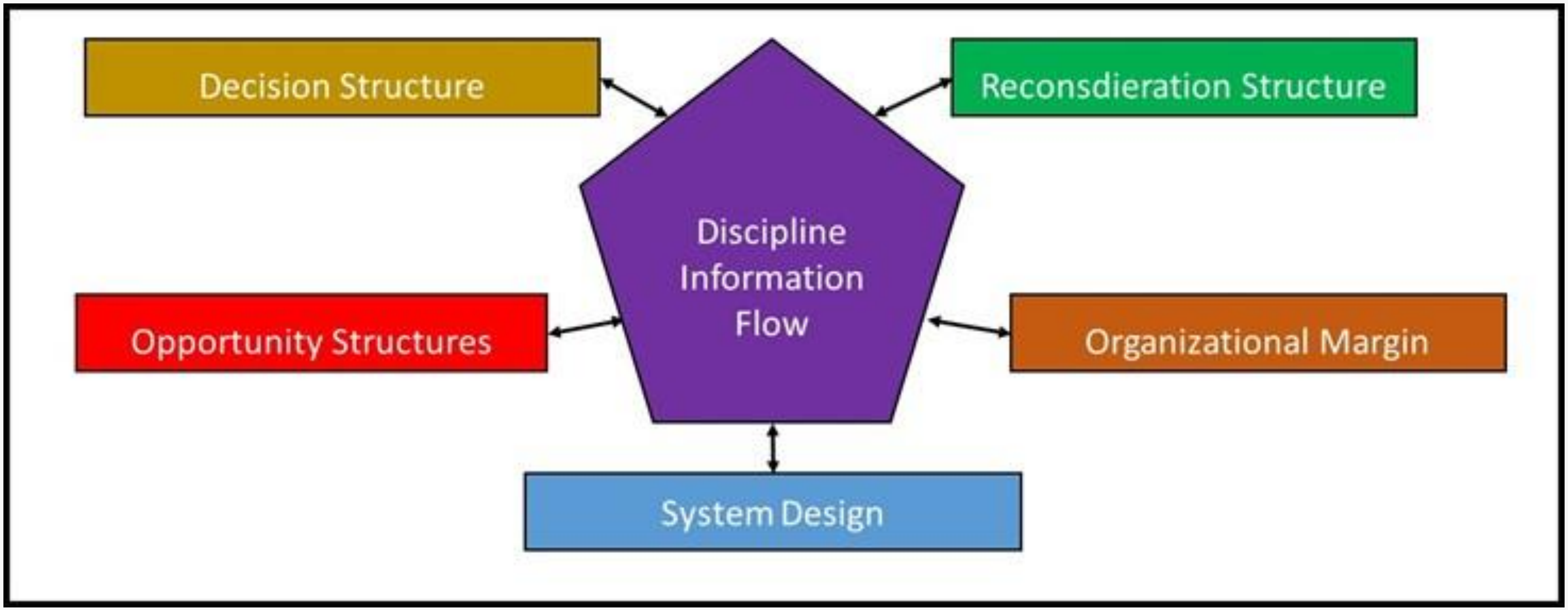
Space Policy Implication on Engineering Decisions

- For Example
  - Capability driven solutions have soft schedule limits
    - SLS
    - Constellation
  - International agreements have harder schedule limits
    - Apollo-Soyuz
    - International Space Station
  - Political implications should be considered at the end of the decision process, not at the beginning

Methods of Discipline Integration

Goal: Integrate the Disciplines during System Development and Operations

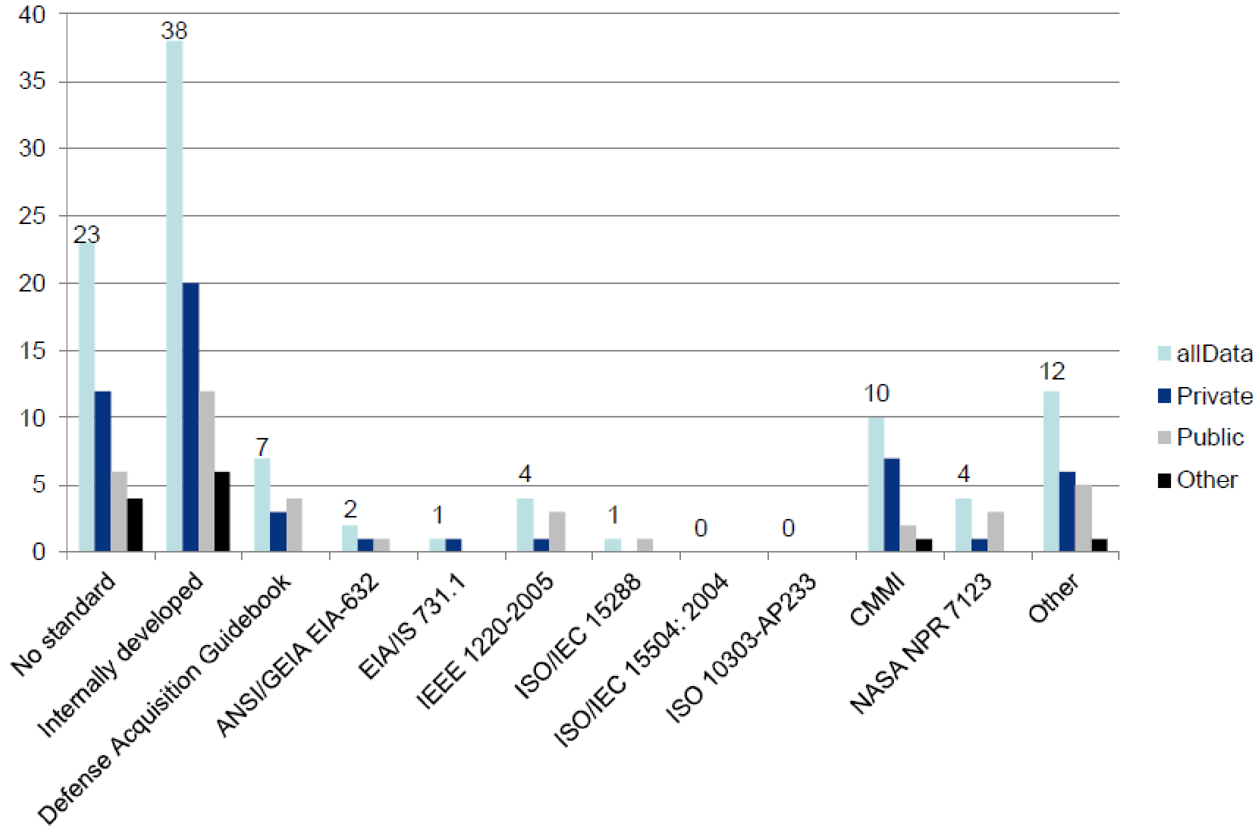
System Development and Operations



System Engineering Supporting Activities

Process Application and Execution for the Specific System

System Engineering Standards in Practice



UAH SE Consortium - Comparing the Relationship between Systems Engineering Process and Project Success in Commercial and Government Research and Development Efforts, 2012 – 2014.

ORIGINAL NASA STUDY AND
NEW STUDY COMMERCIAL FOCUSED PROJECTS

Correlation of 0.4 or greater noted Project Success and System Engineering Processes

	1. Stakeholder Expectations Definition	2. Technical Requirements Definition	3. Logical Decomposition	4. Design Solution	5. Product Implementation	6. Product Integration	7. Product Verification	8. Product Validation	9. Product Transition	10. Technical Planning	11. Requirements Management	12. Interface Management	13. Technical Risk Management	14. Configuration Management	15. Technical Data Management	16. Technical Assessment	17. Decision Analysis
Technical success relative to initial req.									.4	.4							.4
Technical success relative to similar projects						.7	.6		.6								
On schedule relative to original project plan			.4							.6		.4					
On schedule relative to similar projects										.4		.4					
On budget relative to original project plan										.5		.5	.5	.4			
On budget relative to similar projects										.4			.4				
Satisfaction with project management process		.5		.5						.5							
Overall project success (organization view)						.6			.5								
Overall project success (stakeholder view)						.4							.5				

Agriculture
Aerospace
Defense and security
Transportation
Communications
Electronics
Energy
Infrastructure

Processes with > 3 Correlations ≥ .4

Processes with < 3 Correlations ≥ .4

Original Study Correlations

UAH SE Consortium - Comparing the Relationship between Systems Engineering Process and Project Success in Commercial and Government Research and Development Efforts, 2012 – 2014.

ORIGINAL NASA STUDY AND NEW STUDY GOVERNMENT FOCUSED PROJECTS: CHECK

Correlation of 0.4 or greater noted Project Success and System Engineering Processes

	1. Stakeholder Expectations Definition	2. Technical Requirements Definition	3. Logical Decomposition	4. Design Solution	5. Product Implementation	6. Product Integration	7. Product Verification	8. Product Validation	9. Product Transition	10. Technical Planning	11. Requirements Management	12. Interface Management	13. Technical Risk Management	14. Configuration Management	15. Technical Data Management	16. Technical Assessment	17. Decision Analysis
Technical success relative to initial req.	.5		.6				.4		.5		.5	.4	.5			.4	.5
Technical success relative to similar projects	.5		.6	.5	.5		.5			.5	.4					.5	.5
On schedule relative to original project plan	.4	.5								.4						.5	
On schedule relative to similar projects	.5	.4			.4					.5			.5			.5	.5
On budget relative to original project plan	.4						.4			.6						.6	.4
On budget relative to similar projects	.4	.4					.5			.5						.5	
Satisfaction with project management process	.5	.5			.4		.4			.6			.6			.6	.6
Overall project success (organization view)	.5					.5		.5	.5								
Overall project success (stakeholder view)	.6				.4					.4						.5	.4

Processes with > 3 Correlations ≥ .4

Processes with < 3 Correlations ≥ .4

Original Study Correlations

Products

Products

- **“Engineering Elegant Systems: Theory of Systems Engineering”**
- **“Engineering Elegant Systems: The Practice of Systems Engineering”**
- **Each research task individually publishes results (18 journal and conference papers)**
- **Conference on Systems Engineering Research (CSER) 2016**
  - 9 Papers on consortium research
    - “NASA Systems Engineering Research Consortium: Defining the Path to Elegance in Systems”, Michael D. Watson, Phillip A. Farrington, MSFC, University of Alabama in Huntsville
    - “A New Cognitive Framework for Understanding Engineering Systems Thinking”, Melissa T. Greene, University of Michigan
    - “A Novel Approach to Measuring the Time-Impact of Oversight Activities on Engineering Work”, Samantha Marquart, Dr. Zoe Szajnfarber, George Washington University
    - “Systems Engineering Processes in NASA and Commercial Projects”, Paul J. Componation, Kathryne Schomberg, Susan Ferreira, Jordan L. Hansen, University of Texas – Arlington, Iowa State University
    - “The Representations and Practices of the Discipline of Systems Engineering”, Stephen B. Johnson, University of Colorado at Colorado Springs
    - “A Capability-Based Framework for Supporting Value-Driven Design”, R. Price, R. Malak, Texas A&M University
    - “Use of Akaike’s Information Criterion to Assess the Quality of the First Mode Shape of a Flat Plate”, John H. Doty, University of Dayton
    - “A Multidisciplinary Coupling Analysis Method to Support Investigation of Ares 1 Thrust Oscillation”, D. Kis, M. Poetting, C. Wenger, and C. L. Bloebaum, Iowa State University
    - “Uses of Exergy in Systems Engineering”, Andrew Gilbert, Dr. Bryan Mesmer, Dr. Michael D. Watson, University of Alabama in Huntsville, MSFC

Summary

- **Discussed approach to Engineering an Elegant System**
- **Discussed Systems Engineering Framework**
  - System Integration
  - Engineering Discipline Integration
- **Discussed Systems Engineering Postulates, Hypotheses, and Principles**
- **Discussed several methods and tools for conducting integrated system design and analysis**
  - System Integration
    - System Integrating Physics
    - System Design and Optimization
    - Engineering Statistics
    - State Variable Analysis
    - System Value
  - Discipline Integration
    - Sociological Principles and Cognitive Science
    - Decision Making
    - Policy and Law Application
  - Processes Application

Backup

Consortium

- **Research Process**
  - Multi-disciplinary research group that spans systems engineering areas
  - Selected researchers who are product rather than process focused

- **List of Consortium Members**
  - Schafer Corporation: Michael D. Griffin, Ph.D.
  - Air Force Research Laboratory – Wright Patterson, Multidisciplinary Science and Technology Center: Jose A. Camberos, Ph.D., Kirk L. Yerkes, Ph.D.
  - George Washington University: Zoe Szajnfarber, Ph.D.
  - Iowa State University: Christina L. Bloebaum, Ph.D., Michael C. Dorneich, Ph.D.
  - Massachusetts Institute of Technology: Maria C. Yang, Ph.D.
  - Missouri University of Science & Technology: David Riggins, Ph.D.
  - NASA Langley Research Center: Anna R. McGowan, Ph.D., Peter A. Parker, Ph.D.
  - Texas A&M University: Richard Malak, Ph.D.
  - Tri-Vector Corporation: Joey Shelton, Ph.D., Robert S. Ryan
  - The University of Alabama in Huntsville: Phillip A. Farrington, Ph.D., Dawn R. Utley, Ph.D., Laird Burns, Ph.D., Paul Collopy, Ph.D., Bryan Mesmer, Ph.D., P. J. Benfield, Ph.D., Wes Colley, Ph.D.
  - The University of Colorado – Colorado Springs: Stephen B. Johnson, Ph.D.
  - The University of Dayton: John Doty, Ph.D.
  - The University of Michigan: Panos Y. Papalambros, Ph.D.
  - The University of Texas, Arlington: Paul Componation, Ph.D.

- **Previous Consortium Members**
  - Stevens Institute of Technology – Dinesh Verma
  - Spaceworks – John Olds (Cost Modeling Statistics)
  - Alabama A&M – Emeka Dunu (Supply Chain Management)
  - George Mason – John Gero (Agent Based Modeling)
  - Oregon State – Irem Tumer (Electrical Power Grid Robustness)
  - Arkansas – David Jensen (Failure Categorization)

25 graduate students and 3 undergraduate students supported to date

Exergy: Integrating Physics of Thermodynamic Systems

- **Exergy – In thermodynamics, the useful work potential provided by a system in a specific environment**
  - Includes 1st Law of Thermodynamics conversation relationships
    - Conservation of Mass: $M_{in} = M_{out}$
    - Conservation of Energy: $E_{in} – E_{out} = \Delta E_{system}$

  - Includes Second Law Balance relationship
    - Entropy Balance: $S_{in} - S_{out} + S_{generated} = \Delta s_{system}$

  - Exergy(X):
    - $E_{in} – E_{out} – T_0(S_{in} - S_{out} + S_{generated}) = \Delta E_{system} – T_0 \Delta s_{system}$
    - $E_{in} – E_{out} – T_0(S_{in} - S_{out}) + T_0 S_{generated} = \Delta X_{system}$
    - $E_{in} – E_{out} – T_0(S_{in} - S_{out}) + X_{destroyed} = \Delta X_{system}$
    - Where, the energy and entropy changes are referenced to the system environment state (E_0, S_0), and not zero.
    - Heat transfer is limited by the Carnot limits, $(1-T_0/T_k)\ Q_k$

Exergy Equations for a Rocket

- **Exergy – In thermodynamics, the useful work potential provided by a system in a specific environment**

- $$\Delta m_{propellant}\left((h_{prop}-h_o)+\frac{V_e^2}{2}\right)-X_{des}=\Delta KE_{vehicle}+\Delta PE_{vehicle}$$

- $$\eta_{exergy}=\eta_{exergy}=1-\frac{X_{des}}{X_{expended}}=1-\frac{X_{des}}{\sum_{i=1}^{nstage}\Delta mprop\left(h_{prop}+\frac{V_e^2}{2}\right)}$$

- $$X_{des}=\Delta m_{propellant}\left(h_{prop}+\frac{V_e^2}{2}\right)-\Delta KE_{vehicle}-\Delta PE_{vehicle}$$

Square Plate Models and Sensor Recommendations

- **Fischer Information Matrix**
  - CDF, every sensors adds value
  - Look for knee in curve which is fai
  - Large uncertainty

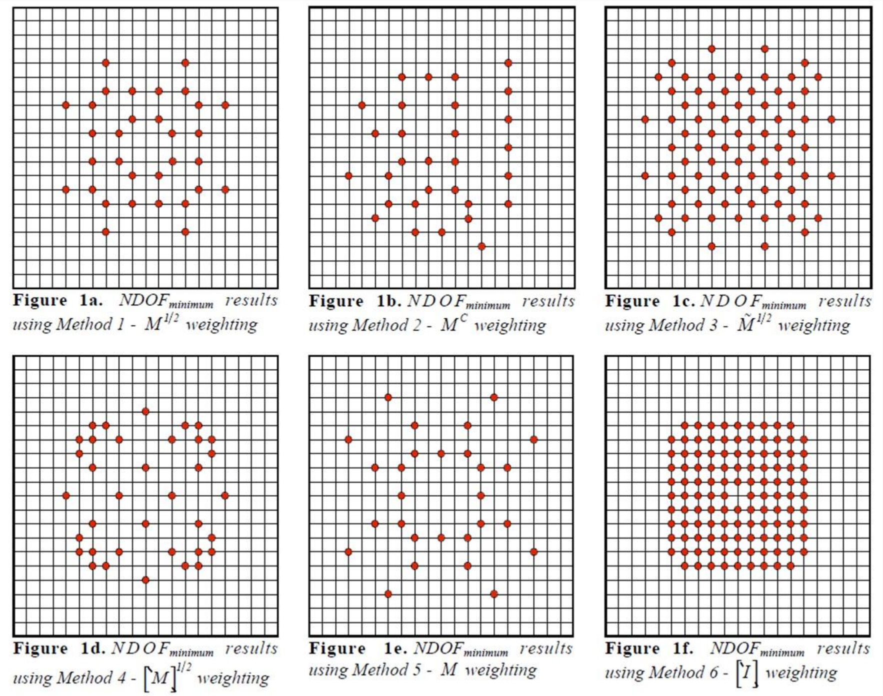


Figure 1a. $NDOF_{minimum}$ results using Method 1 - $M^{1/2}$ weighting

Figure 1b. $NDOF_{minimum}$ results using Method 2 - M^{C} weighting

Figure 1c. $NDOF_{minimum}$ results using Method 3 - $\tilde{M}^{1/2}$ weighting

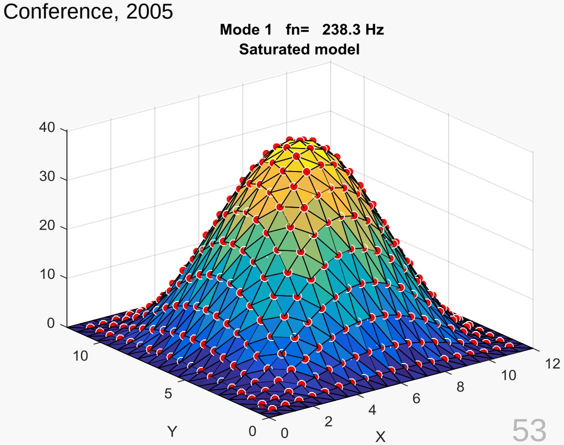
Figure 1d. $NDOF_{minimum}$ results using Method 4 - $\lceil M \rceil^{1/2}$ weighting

Figure 1e. $NDOF_{minimum}$ results using Method 5 - M weighting

Figure 1f. $NDOF_{minimum}$ results using Method 6 - $\lceil I \rceil$ weighting

Lollock, J. A., Cole, T. R., “The Effect of Mass-Weighting on the Effective Independence of Mode Shapes”. AIAA Structures, Structural Dynamics, & Materials Conference, 2005

- **AICc**
  - Plots optimal based on
    - Mode Shapes to detect
    - Uses sensor at every node as truth reference
  - Too few sensor do not provide sufficient information
  - Too many provide too little additional information to be worth the value of the additional sensor



Maximum Likelihood Estimate (MLE)

- **Maximum Likelihood Estimate (MLE) forms a basis to select a model which best fits the available data parameters**

  - This is not a statistical analysis of the data

  - This is a statistical estimate of the best model to fit the given data

$\mathcal{L}(\theta|data, model)$

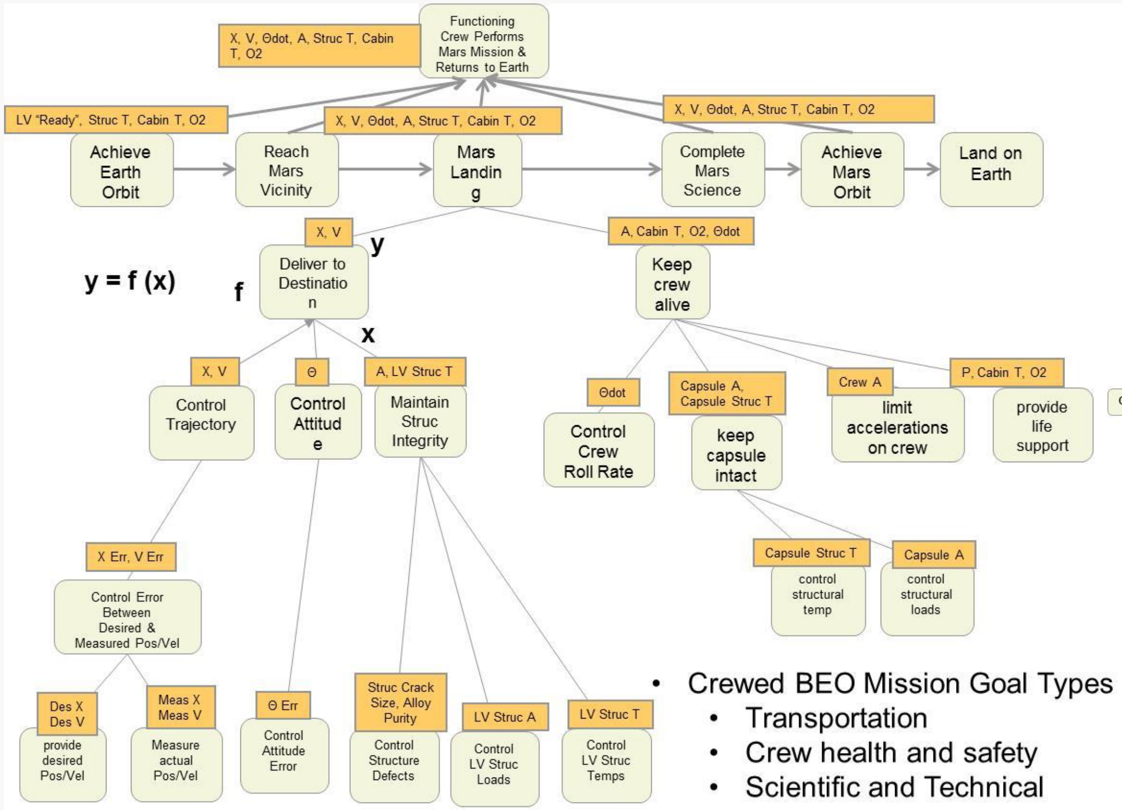
Where the model is the specific equation of the physical phenomena,
data (x) is the dataset the model is being evaluated for fit,
and θ is the set of data parameters in the model

  - The likelihood of the individual data entries fitting the associated parameters is the product of the likelihood functions

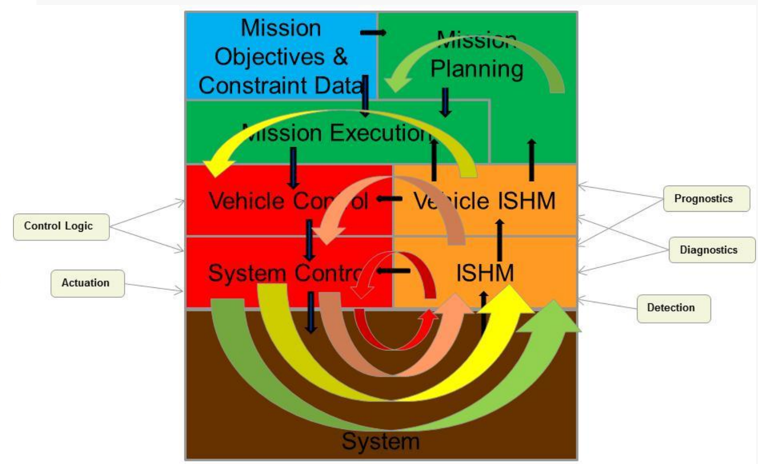
    – $\mathcal{L}(\theta|x, model) = \prod_i \mathcal{L}_i(\theta|x_i, model)$ and is often evaluated as the log likelihood:

    – $\ln(\mathcal{L}(\theta|x, model)) = \sum_i \ln(\mathcal{L}_i(\theta|x_i, model))$

Mars Mission simplified GFT Example



- Crewed BEO Mission Goal Types
  - Transportation
  - Crew health and safety
  - Scientific and Technical

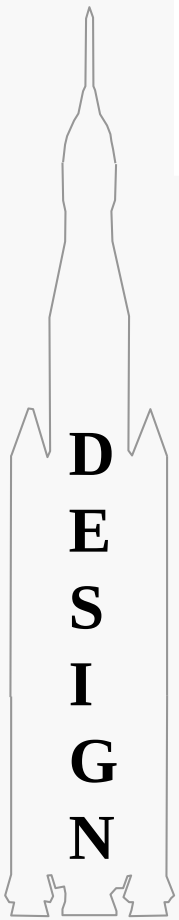


System State Models and SysML

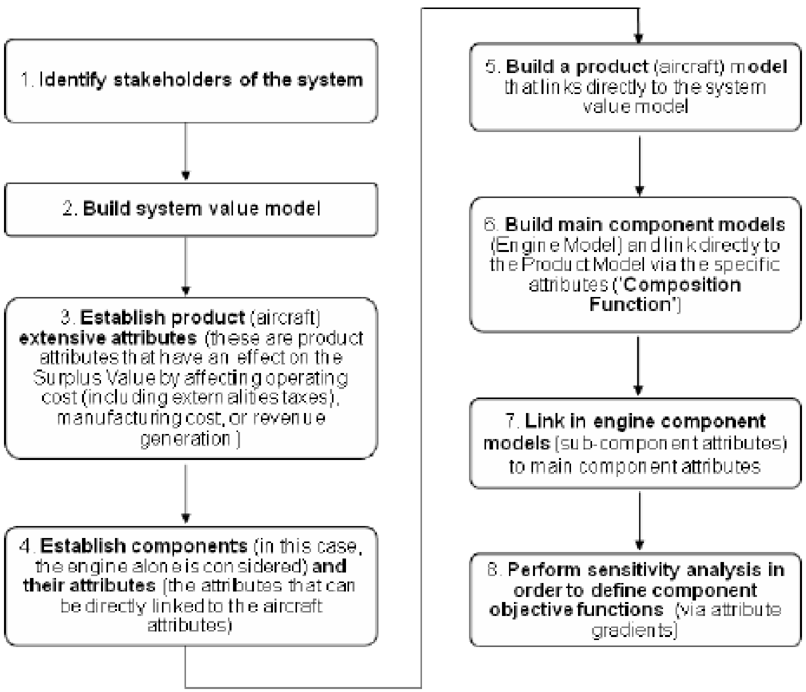
- **SysML provides an architectural model**
  - Supports functional decomposition
  - Supports traceability
- **SysML is Not Executable**
  - Does not model actual system relationships or behavioral interactions
  - State Machine Model can be viewed in SysML formats but not executed
- **SysML does not explicitly cover State Variable Modeling**
  - Goal Function Tree is in SysML
  - Not all SysML vendors support State Variable representations easily

What is a value model?

$$
\begin{aligned}
SurplusValue = {} & Disc_p \text{ x } Marketsize \text{ x} \\
& \left(\begin{aligned} & Disc_c \text{ x } Utilization \text{ x} \\ & \quad Revenue\ per\ flight - Cost\ per\ flight - Delay\ and\ cancellation\ costs - Externalities\ tax\ per\ flight \\ & - Manufacturing\ costs \end{aligned} \right) \\
& - Development\ costs
\end{aligned}
$$

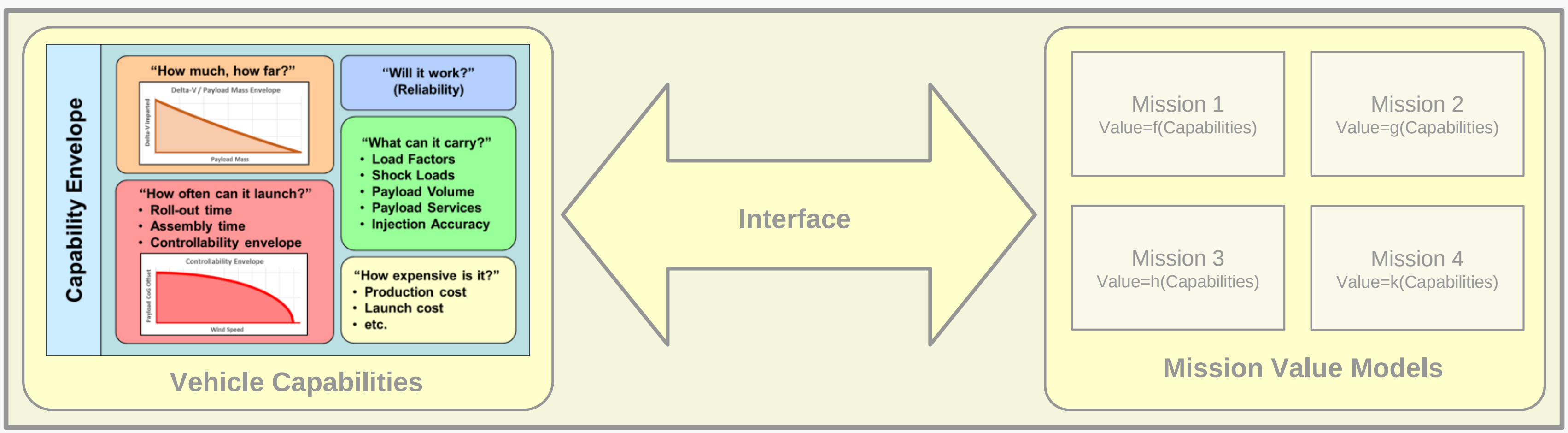


Payload
Dev Cost
Dev Time
Mfg Cost
Ops Cost
Reliability



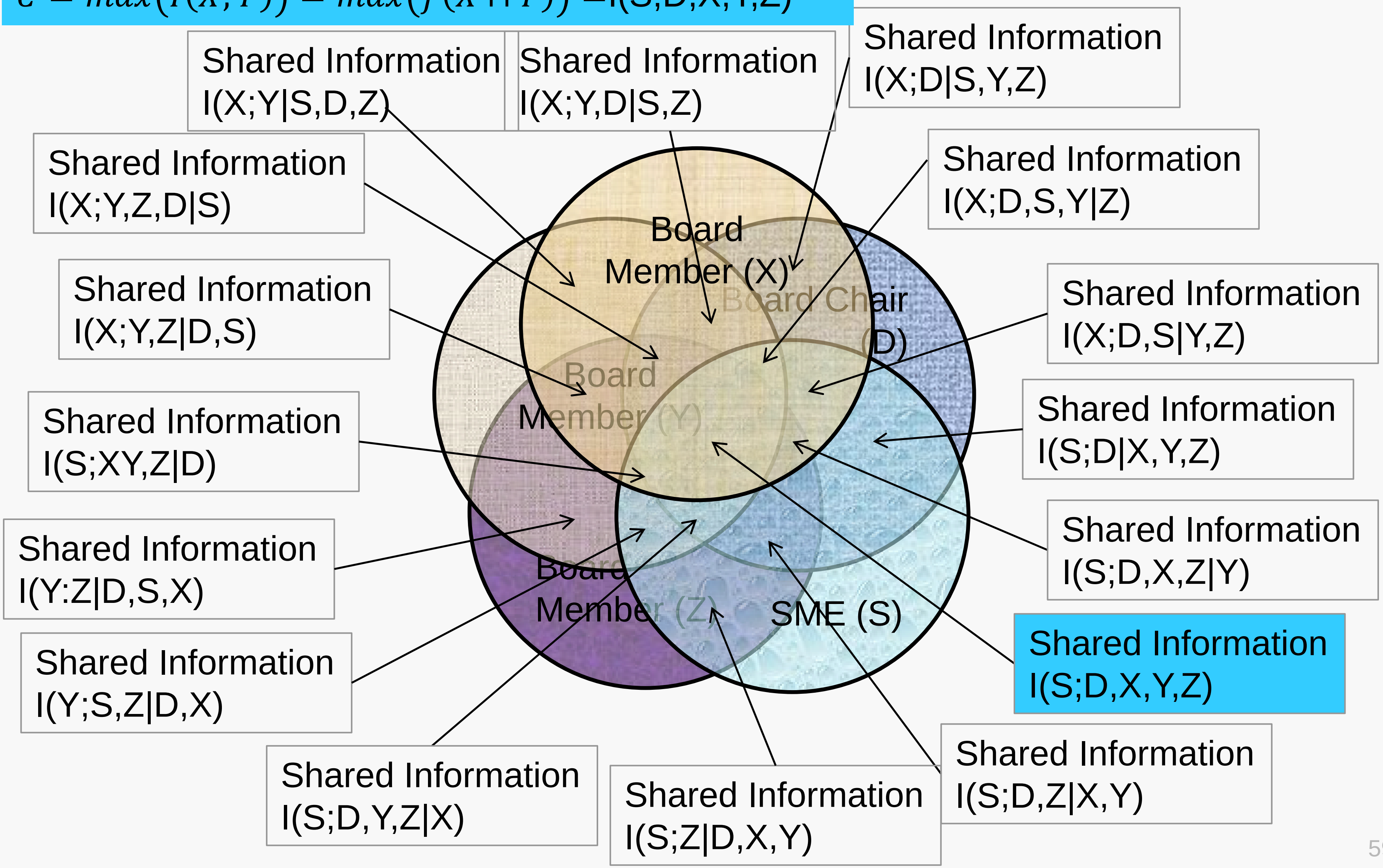
System Robustness: Capability to support Missions

- **Valuation framework based on interface between launch vehicle capabilities and individual mission value models:**
  - SLS capabilities are characterized independently of any given mission.
  - Portfolio of all desired missions (with associated mission value models) expresses NASA's overall priorities and objectives in a quantifiable and traceable way, and allows for capturing shifts in these priorities.
  - Simulation-based interface between SLS capabilities and mission value models assesses value delivered by any given vehicle design.
  - This framework can be used to evaluate launch vehicles other than SLS.



Set Theory Representation of Board Structure

$C = max(I(X;Y)) = max(f(X \cap Y))$ =I(S;D,X,Y,Z)



Cognitive Science

Mediated Learning Phases

Input Phase
Gathering Information

- Clear perception
- Systematic search
- Labeling
- Spatial orientation
- Temporal orientation
- Conservation
- Precision and accuracy
- Using 2+ sources of information at one time

Elaboration Phase
Processing/Using Information

- Defining the problem
- Relevant cues
- Comparing
- Remembering
- **Summative behavior**
- **Seeing relationships**
- **Logical evidence**
- **Interiorization**
- **Hypothetical thinking**
- **Inferential thinking**
- Systematic planning
- Categorization
- **Flexibility**
- **Reversability**

Output Phase
Expressing the Solution

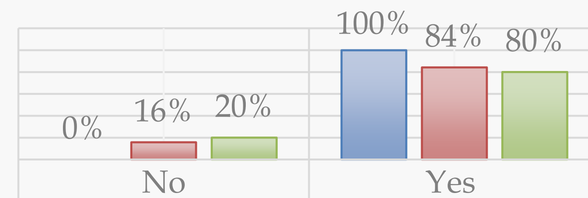
- Overcoming egocentric communication/ behavior
- Overcoming blocking
- Overcoming trial and error
- Precision and accuracy
- Visual transport
- Restraining impulsive behavior
- Motivation

Decision Making and Communication

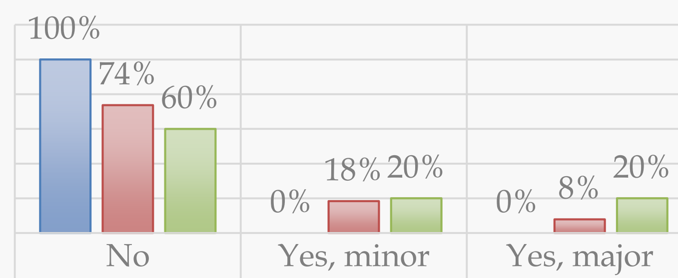
- **Track 3 Change Requests**
  - Flight Termination System (FTS) Architecture Option 10A (CR 53)
  - Data Requirements List Update (CR 70)
  - Core Stage Forward Skirt Umbilical (CR 82)

- **Sample Questions**
  - Was there adequate time and/or materials to perform an assessment
  - Were there any gaps in communication during the CR review?

- **Overall Process Assessment**
  - The decision-making process is less process dependent than expected - As long as the process matches the needs of the decision makers and an effort is made to get all needed individuals involved, different processes can be used effectively.



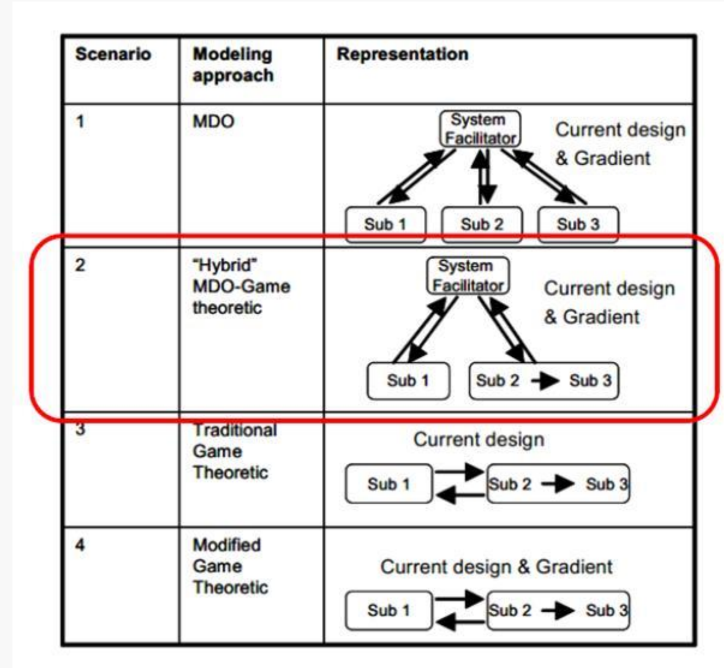
	No	Yes
CR 53	0%	100%
CR 70	16%	84%
CR 82	20%	80%

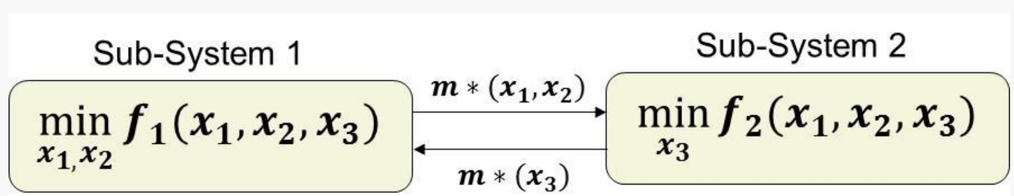


	No	Yes, minor	Yes, major
CR 53	100%	0%	0%
CR 70	74%	18%	8%
CR 82	60%	20%	20%

SLS Organizational Structure Modeling

- **Interviewed 12 Marshall engineers/designers (w/J. Shelton)**
  - Understand strategies used to integrate subsystems with each other
- **Common strategy across subsystems – margins**
  - Keep some percentage of a parameter in “back pocket” as hedge for future negotiations
  - Biased Information Sharing
  - (Here, “margins” different from “safety margin”)
- **How does maintaining a margin affect optimality of the final design?**
  - Model as simple 2 Player System with 3 design parameters
  - 15 problem test suite





System Engineering Processes

1. **Stakeholder Expectations**
2. **Technical Requirements Definition**
   a. Logical Decomposition
3. **Design Solution Definition**
4. **Product Implementation**
5. **Product Integration**
6. **Product Verification**
   a. Product Validation
7. **Product Transition**
8. **Product Operation and Sustainment**
9. **Technical Planning**
   a. Technical Risk Management
   b. Technical Assessment
   c. Decision Analysis
10. **Configuration Management**
   a. Technical Data Management
   b. Requirements Management
   c. Interface Management

Mission Context

Policy & Law

Technical Integration (Physics Basis Focus)

Organizational Structure & Information Flow

Focus on the intent of the processes not the processes themselves