A Perspective on Decision-Making Research in System of Systems Context

System of Systems Engineering Collaborators Information Exchange (SoSECIE)

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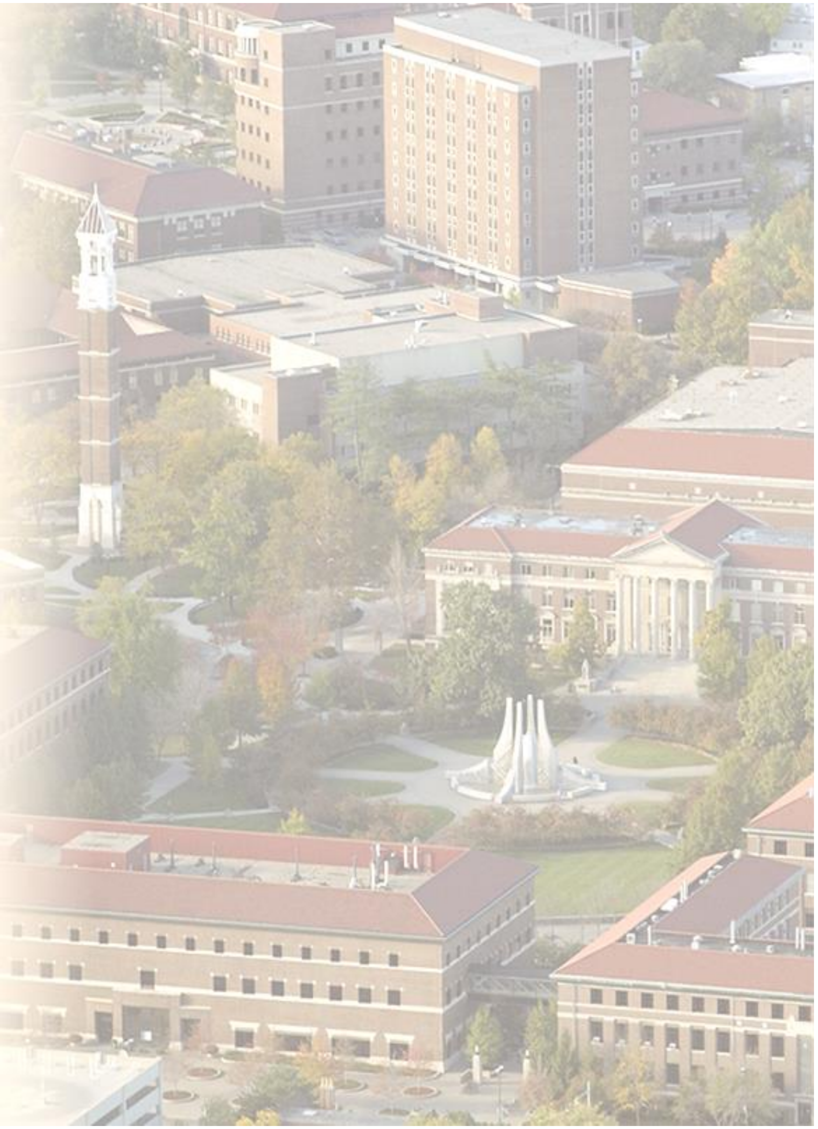
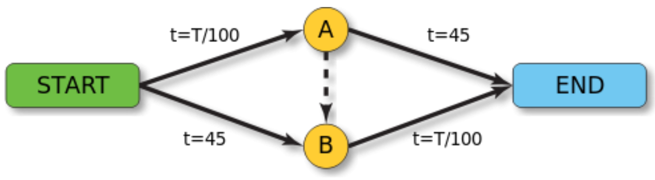


Motivations/observations

- We all make decisions – some good, some bad:

  - Braess Paradox - individual vs. social incentive equilibriums
  - Centralized vs. decentralized – overloaded information – cannot make rational decisions
  - “Mumbai cobras and mismatched incentives”
  - Defense acquisitions – jet fuel trails in the sky
  - My airline experience – the “irrational” traveller
    - Revenue management



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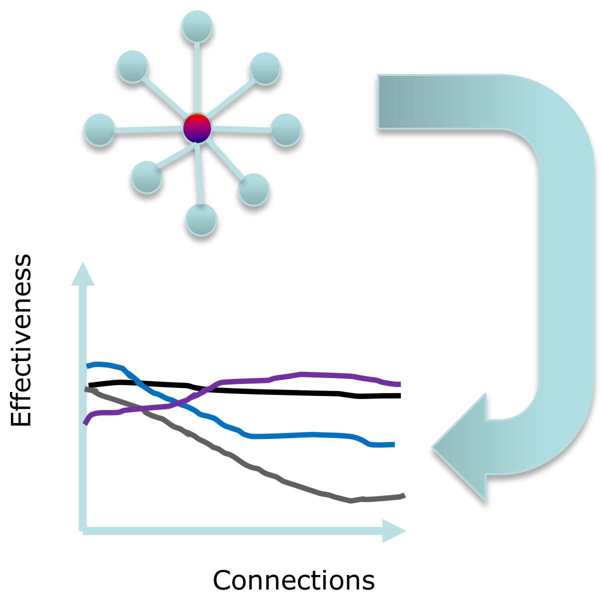


SoS – the KEY Questions

- US DoD SE/SoSE guidelines
- Transportation, Healthcare, Defense, Software Engineering etc.
- An international endeavor (beyond U.S. DoD, NSF), e.g. European Commission FP7 Efforts in SoS
- Several Major SoS Research Projects
- IBM 4 trillion dollar challenge to deal with SoS level problems

Pain Points	Question
SoS Authority	*What are effective collaboration patterns in systems of systems?*
Leadership	*What are the roles and characteristics of effective SoS leadership?*
Constituent Systems	*What are effective approaches to integrating constituent systems into a SoS?*
Autonomy, Interdependencies & Emergence	*How can SE provide methods and tools for addressing the complexities of SoS interdependencies and emergent behaviors?*
Capabilities & Requirements	*How can SE address SoS capabilities and requirements?*
Testing, Validation & Learning	*How can SE approach the challenges of SoS testing, including incremental validation and continuous learning in SoS?*
SoS Principles	*What are the key SoS thinking principles, skills and supporting examples?*

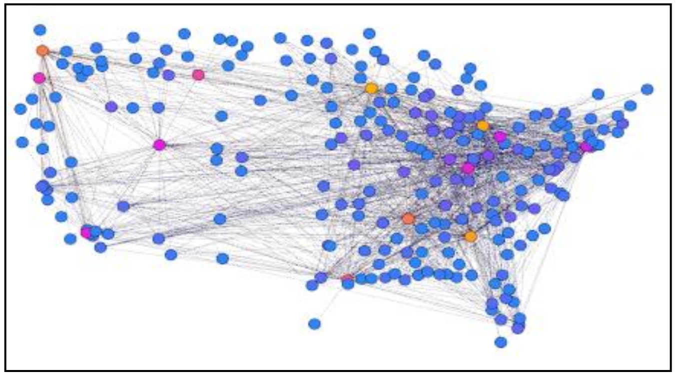
Survey identified seven 'pain points' raising a set of SoS SE questions

From: "Systems of Systems Pain Points", Dr. Judith Dahmann, INCOSE Webinar Series on Systems of Systems, 22-FEB, 2013

Operational Independence
Managerial Independence

Modeling and simulation

- **Air Transportation**
  - Crossley, Mane – Simultaneous design of aircraft and operations in SoS context
  - DeLaurentis, Kotegawa – Improved predictive modeling of terminal area forecasts due to SoS interaction
  - NASA ACES, FACET - Simulators



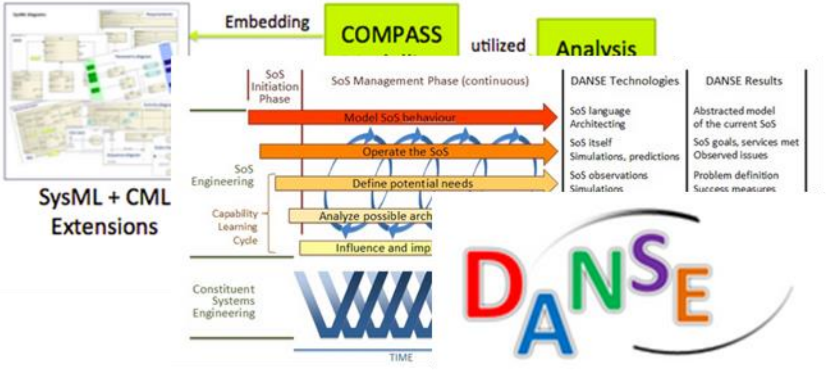
- **Defense Acquisition, SE/SoSE**
  - Defense Acquisition Guide (DAG) , Wave Model,
  - Garett et al - Interstitials of BMDS as a SoS
  - SERC – Acheson cooperative, non-cooperative dynamics of SoS meta-architecture
  - DARPA –SoS maritime application for networks

Image Sources from main websites of each effort : available on request

Decision Analysis and control

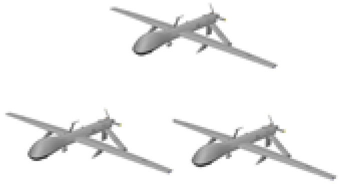
Software /Systems Engineering/Decision Support

- DANSE – technical approaches for SoS Engineering
- COMPASS – MBSE techniques for developing and maintaining SoS
- Various works from: JPL, CMU-SEI, USC, MIT, Purdue



Control Systems as a System of Systems

- Distributed/Decentralized/Consensus Control
- Smart grid systems, UAV/drone application (military, agriculture)
- VoIP, Communication Network Protocols and Routing.



Book Publications:

Jamshidi, M., System of Systems Engineering: Principles and Application, 1st Ed., Taylor & Francis Group, Boca Raton, FL. 2009

Luzeaux D, Ruault, J.R., Wippler, J., Complex Systems and Systems of Systems Engineering, October 2011, Wiley-ISTE

Rainey, L, Tolk, A., Modeling and Simulation Support for System of Systems Engineering Applications, John Wiley & Sons, Hoboken, New Jersey 2015.

A Decision Theoretic perspective

SoS stakeholders may be cooperative or non-cooperative decision-makers
Maximization of individual utility affected by:

- **Data to Information**
  - Too much data to determine value of choices
  - Too many options to quantify value of choices
  - Data privacy/segmentation
- **Rules of Autonomic Engagement**
  - Constraints on how to talk to another stakeholder
  - Information flow based on constraints
- **Perceived Fairness**
  - Good allocation for whole is not fair to individual (price of fairness)
  - Changes individual behavior/participation (gaming behavior)
- **Network structure**
  - Structure of information flow across network
  - Game/Incentive based on structure of network for resource flow

Modeling for decision making

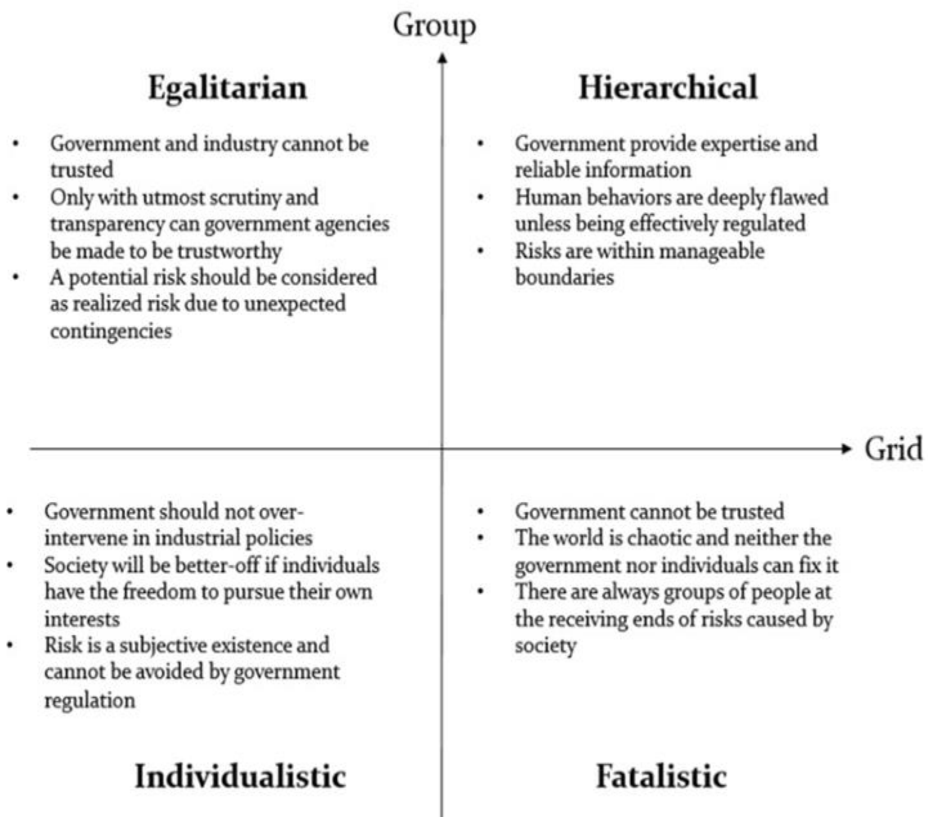
Agent Interactions and Theories

- Adaptive Markets Hypothesis (Lo)
- Reconcile modern financial economics with behavioral models to explain market dynamics (e.g.) -
- Rationality/Irrationality
- Loss Aversion
- Overconfidence
- Overreaction

- Cultural Theory
- Risk regulation driven theory – explain how certain stakeholder groups make alliance and shift equilibrium.

Modeling Framework(s)

- Agent Based Model (ABM)
- System Dynamics
- Various Stochastic Processes



Mechanism design & learning preferences

- **Mechanism Design:** involves the design of institutions and how these affect the outcomes of (stakeholder) interactions. Also known as "reverse game theory". (e.g – Auctions using Vickery Clarke-Groves Mechanisms)
- **Game Theory**: the study of mathematical models of conflict and cooperation between intelligent rational decision-makers
- **Network Science** – nature of connections between stakeholders/systems
- **Learning Preferences** – statistical/data mining to find stakeholder preferences
- We often apply these to the **product/service** not to **organization**

SoS Type	Brief Description	Potential Decision/Game Theoretic Framework
Virtual	No central management authority, no central purpose (e.g. Internet)	Preferential learning of observed utilities through stakeholder interactions
Collaborative	Voluntary participation of systems towards central objectives w/out central authority	Preferential learning of observed utilities through stakeholder interactions
Acknowledged	Core system of system objectives, manager, resources, but independent ownership. Collaborative participation between SoS and system	Auction Mechanisms where independent entities 'bid' for resources and provide a value to the overall SoS
Directed	Integrated SoS for specific purpose - central management, independent operation, but subordinate to main	Cooperative Games where shared resources and interactions between stakeholders are towards common goal.

Different ways of learning the preferences and apply the right incentive structure

* Research presented at IEEE SoSE 2015, San Antonio, TX - Davendralingam, N., DeLaurentis, D., "A Perspective on Decision-Making Research in System of Systems Context"

Prior Research (Mechanism Design)

The Idea: Can we treat policy selection as a 'game' and design game accordingly?

Our Work : Early *mechanism design* framework for policy selection in acquisitions-use of empirical data in policy generation work

Prior Efforts:

- Dagli et.al – Agent simulation of iterations: planning, implementation, analysis phases in wave model, in preparation for sequential tasks for each epoch.

- Sheard survey driven analysis on complexity, cognitive overload, difficulty of system development.

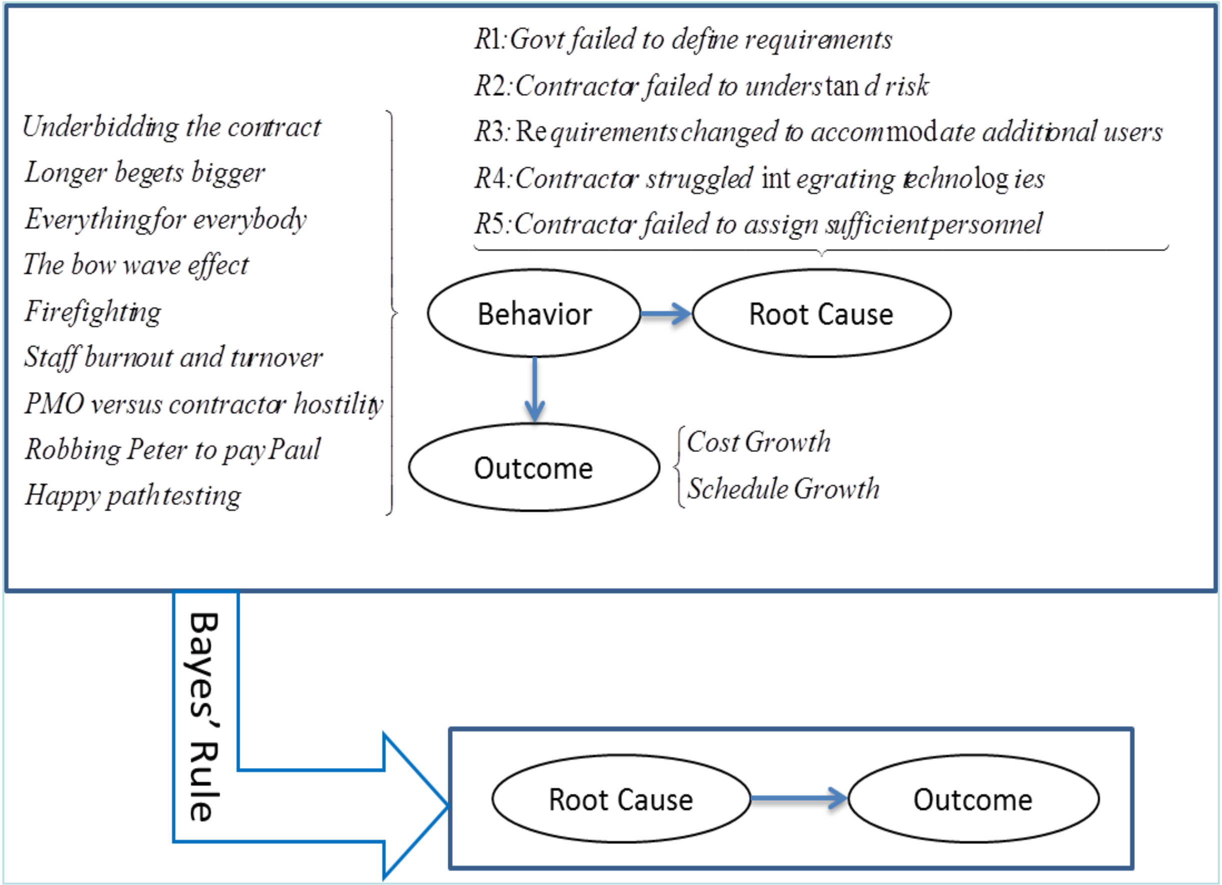
- Wirthlin – Empirical data model of US defense acquisitions as 3 processes (Budget, Requirement development, Acquisition)

  Defined : **cost, schedule**, quality, transparency and flexibility.

* Research presented at IEEE SoSE 2013, Maui, HI – Davendralingam, N., Kenley, C.R, "A Mechanism Design Framework for the Acquisition of Independently Managed System of Systems"

A Bayesian Perspective to McNew Survey

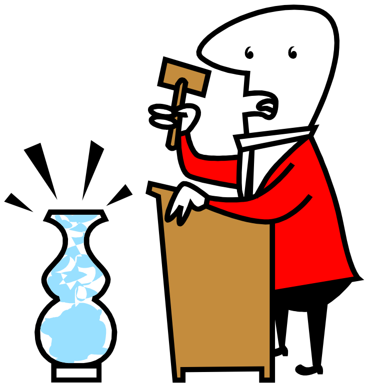
- McNew uses behavior archetypes to structure survey
- 65 program managers surveyed to confirm these ‘behaviors’ on program
- If present, confirm cost, schedule growth, root cause
- Use Bayes to determine→



P(outcomes | root cause) & P (root cause)

Mechanism Design

- Also known as ‘reverse game theory’ – invent the game,. Applied in auctions, communications networks.
- Frequently applied in auction theory (how does auctioneer maximize revenue) though mostly in single item auctions.
- *Individual Rationality:* Buyers do not achieve negative utility with truthful bids,
- *Budget Feasibility:* Buyers are constrained by resource budgets in bidding, and,
- *Incentive Compatibility:* Bidders fare best (optimal utility) when truthfully disclosing information.



A Simple Application to McNew Data

Policy generation scenario

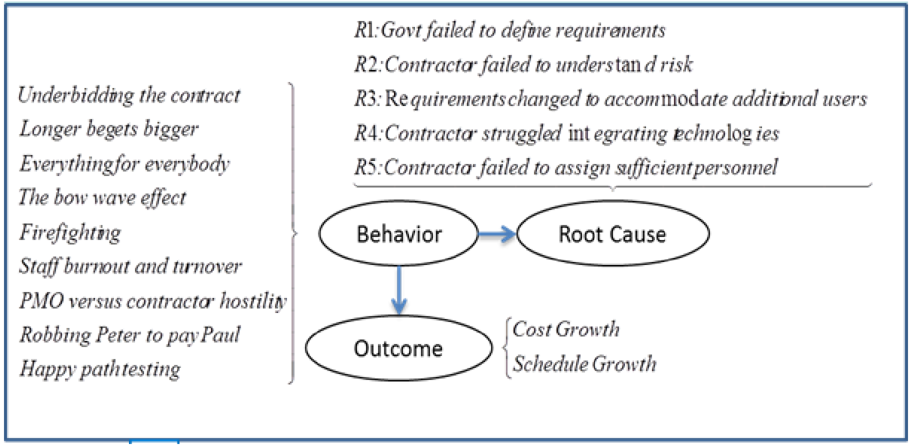
Given:

- Bayesian Analysis of McNew data
- Cost implications
- Potential gain by using policy (x_i)
- Uncertainty in correlated gains for policies (x_i)

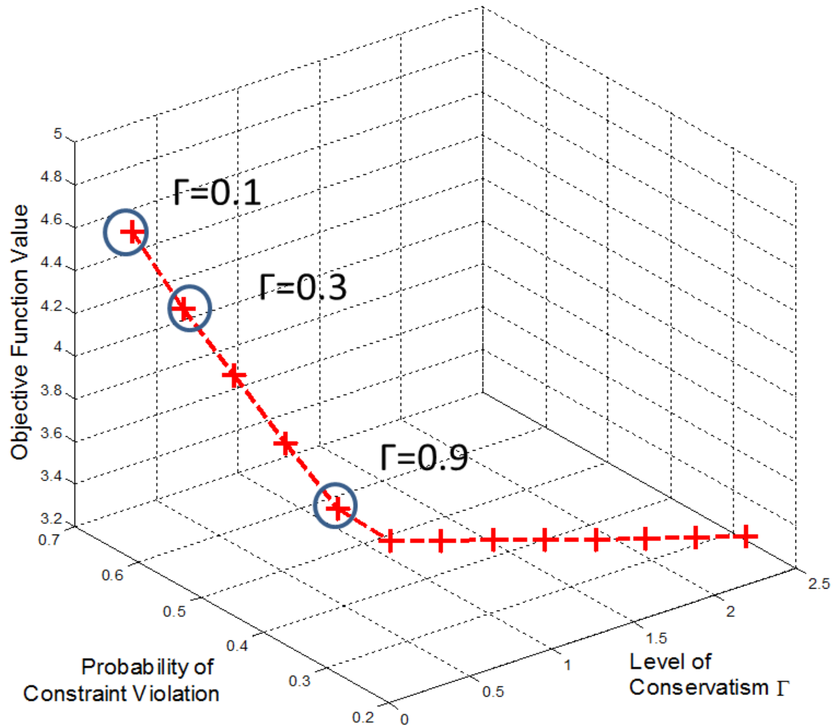
	Correlation							
	R1	R2	R3	R4	R5	SG	CG	P
R1	1.0	0.3	0.4	0.2	0.1	0.5	0.5	0.4
R2		1.0	0.4	0.4	0.2	0.4	0.5	0.3
R3			1.0	0.1	0.1	0.4	0.5	0.3
R4				1.0	0.3	0.4	0.3	0.3
R5					1.0	0.3	0.3	0.3
SG						1.0	0.8	0.6
CG							1.0	0.6

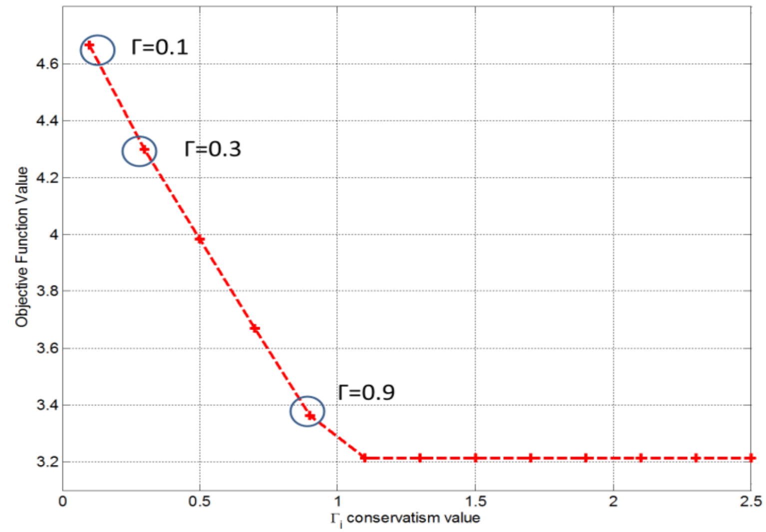
Question:

What policies should I effect at various levels of policy robustness, satisfying some mechanism conditions?



A Simple Example Application





Policy 1	1	-	-
Policy 2	1	1	-
Policy 3	1	1	1
Policy 4	1	-	-
Policy 5	-	1	1
Policy 6	-	-	1
Policy 7	1	1	1
Policy 8	1	1	1
Conservatism (Γ)	0.1	0.3	0.9
P(Constraint Viol)	0.64	0.61	0.52

- Tradespace analysis, policy control
- Objective view of policy effects given current available state

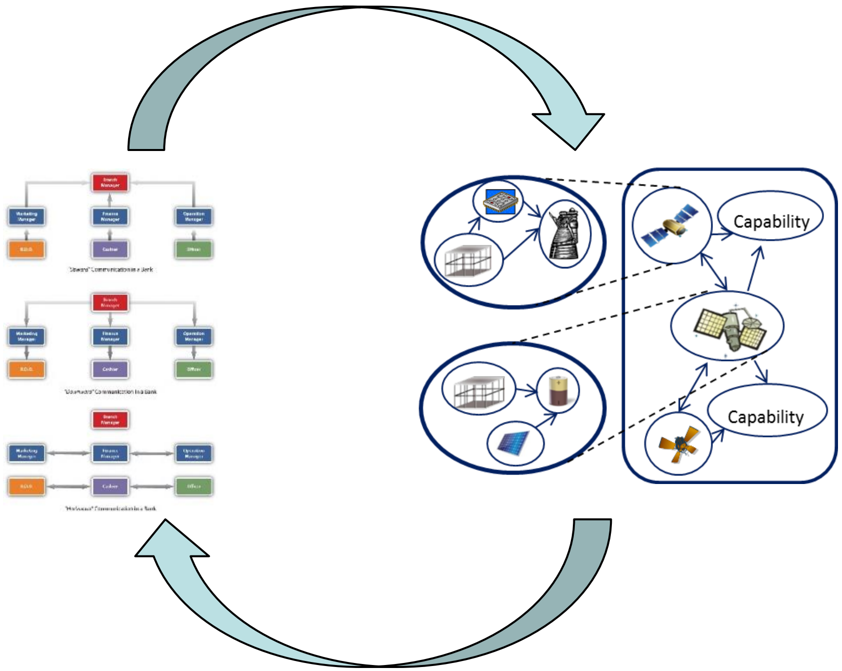
Optimal Selection of Organizational Structuring for Complex System Development and Acquisition*

- **Conway's Law**

  "..product designs tend to reflect the structure of an organization in which they are conceived.." **

- Organizational Structure
  - Connections between groups
  - Volume, type, function, form of information
  - Incentives between groups, individuals

- Complex Product Structure
  - Physical, Functional boundaries
  - Multidisciplinary Boundaries



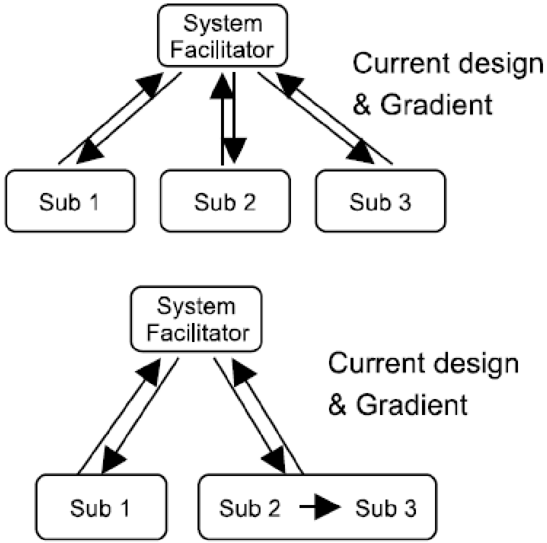
Can we reconcile them to better organize a team **AND** the end product?

* Research current funded under Naval Postgraduate School Acquisitions Research Program Grant N00244-16-1-0005

** Conway, M., "How do Committees Invent", Datamation, Vol.14, No.5, 1968, pp.28-31.

Some prior research

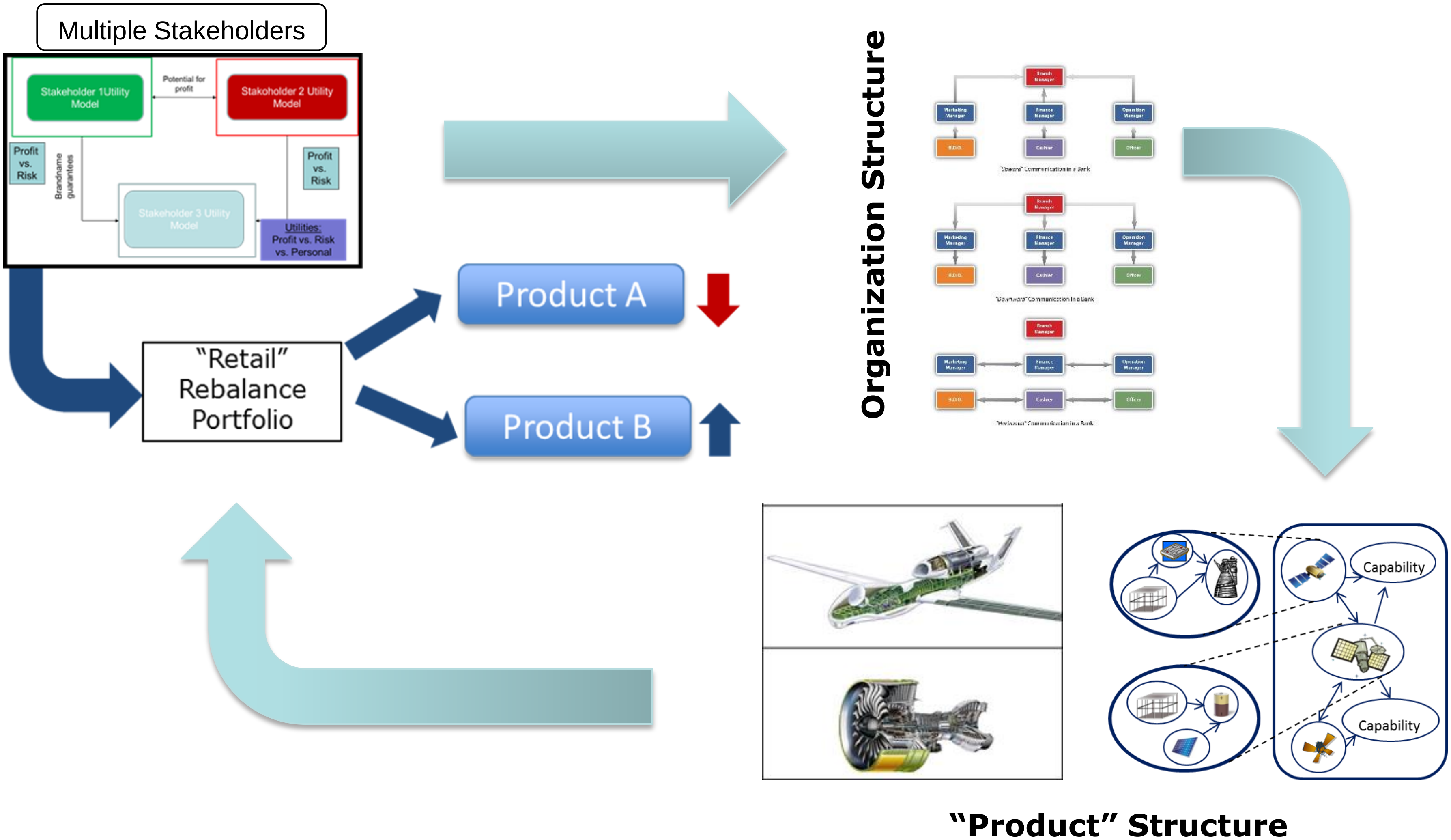
- MacCormack et al – Conway's law is a notable effect – examined software system layout and showed degree of coupling and propagation costs
- Honda et al – comparison of information passing strategies in system-level modeling
- Ulrich - how degree of product's novelty affects 5 areas of managerial importance
    - Product change, variety, component standardization, performance, development management
- Sinha & de Weck – explore how the degree of a new product's novelty affects the structure of an organization.



Different structures of information flow for concept orbital system [**Honda]

* MacCormack, A., Ruznak, J., Baldwin, C., "Exploring the Duality between Product and Organizational Architectures: A Test of the 'Mirroring Hypothesis", Harvard Business School Working Paper, 2008.
** Honda, T., Ciucci, F., Lewis, K., Yang, M., "Comparison of Information Passing Strategies in System-Level Modeling", *AIAA Journal*, Vol.53, No.5, 2015, pp.1121-1133.
*** Ulrich, K., "The Role of Product Architecture in the Manufacturing Firm", *Research Policy*, Vol.24, No.3, 1995, pp.419-440.
**** Sinha, K., James, D., de Weck, O., "Interplay between Product Architecture and Organizational Structure", 14th International Dependency and Structure Modeling Conference, Japan, 2012.

Concept Application



Summary and forward thoughts

Current SoS research mostly focus on:

- Implicit value to stakeholder(s)
- Modeling complex interdependencies/dynamics of SoS
- Acknowledges a coupled effect between organization and product structure

For **operational** and **managerial** independence questions, need to address:

- Developments in MPTs to improve the collaborative/competitive decision-making elements across stakeholders in a SoS.
- The SoS level impact of changing preferences and behaviors
- Policy generation through quantitative, decision-theoretic approach.

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