Perspectives on Managing Emergent Risk due to Rising Complexity in Aerospace Systems

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Use Perspective to Manage Complexity

- Understand how complexity affects the system
- Using perspective to cast the system in a socio-technical context
- Measuring and managing complexity through addressing emergent risk
- Prevent late failures in system development with complexity management throughout the lifecycle

Systems Engineering Today

As it is taught and practiced, is fundamentally concerned with

- **identifying the separable elements** or blocks of a proposed design
- **characterizing the intended relationships** between and among those elements
- **verifying** that the actual configuration is fabricated and operated as intended in its environment

Dr. Michael D. Griffin, 2010
NASA Administrator 2005-2009
Pentagon Undersecretary of Defense for Research and Engineering

Griffin, M., "How Do We Fix System Engineering?" *61st International Astronautical Congress,* Prague, Czech Republic, Sept 2010

No Small Feat for Large Complex Systems

Think about modern transport aircraft, launch vehicles, spacecraft, submarines

"The systems engineering methods, processes, and tools which have developed over the last half-century to formalize and systematize it as an essential engineering discipline are not to be slighted."

- Griffin

Yet failures continue to occur...

- Often of the most glaring and consequential nature
- Commonly at the boundaries or interfaces between elements
- Often due to uncontrolled, unanticipated and unwanted interactions between elements
- In many cases between elements thought to be entirely separate

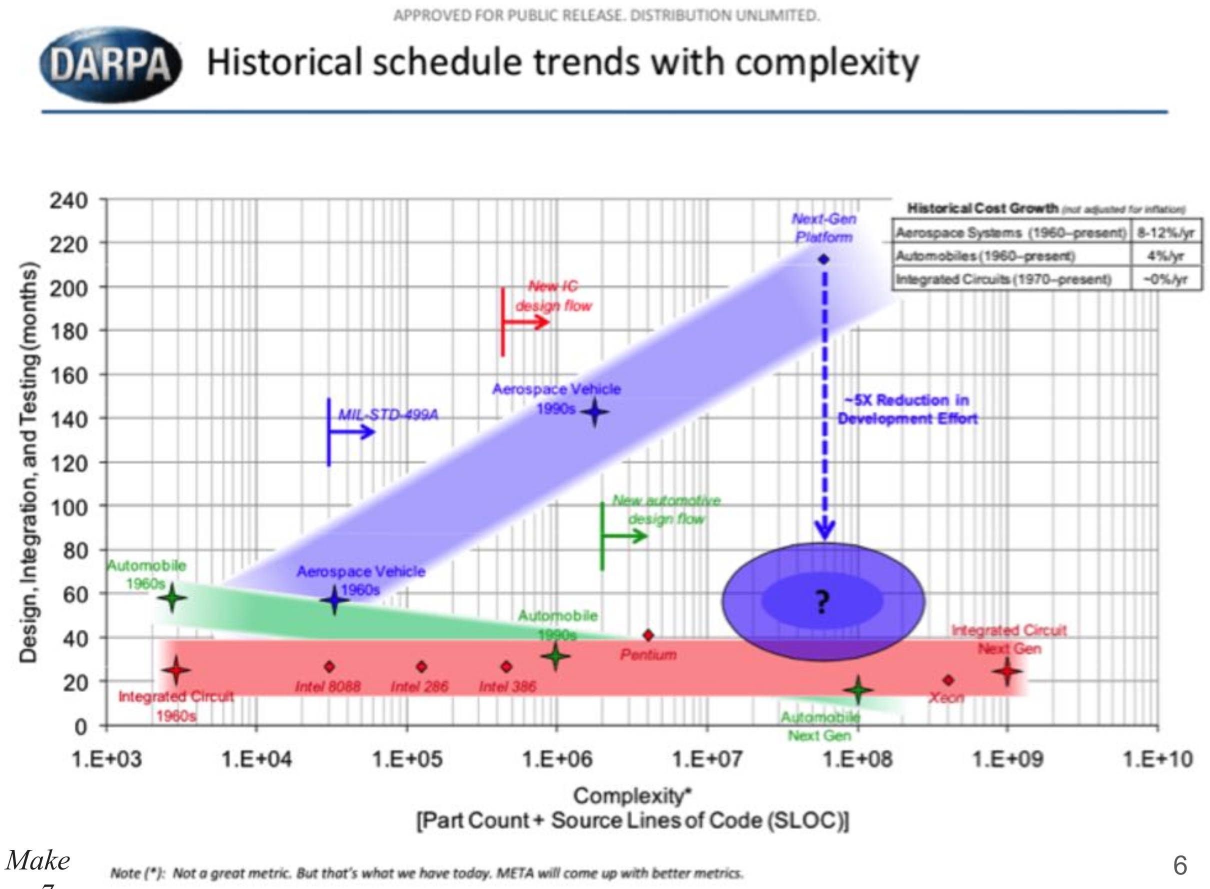
- Griffin

Complexity - A Reality of Modern Engineering

Development time vs. Complexity for

- Aerospace
- Automobiles
- Integrated Circuits

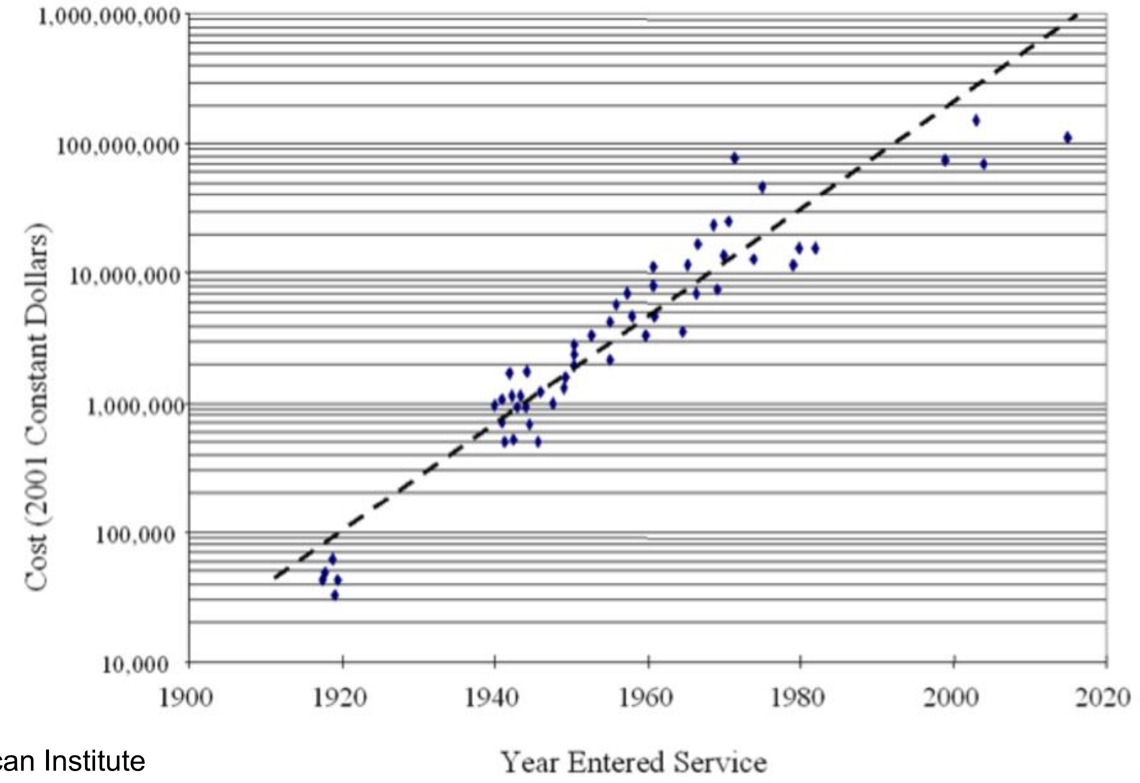
Complexity is a reality for everyone and one that has not been addressed in the aerospace community



Eremenko, P., 2010. Program Manager. *Adaptive Vehicle Make (AVM) Tactical Technology Office Proposer's Day Briefing*, 7.

Trend of Fighter Aircraft Production Cost

- From Augustine's Laws
- Adjusted for constant dollars



Augustine, N., "Augustine's Laws", 6th edition, American Institute of Aeronautics and Astronautics, 1997

Behind Schedule and Over Budget is Normal

GAO 2014

Defense Acquisitions

Cost and Schedule Changes for Programs in DOD's 2014 Portfolio

Fiscal year 2015 dollars (in billions)

	4 year comparison (2009-2014)	Since first full estimate (Baseline to 2014)
Change in total research and development cost	$17.4 billion 6.5%	$98.5 billion 52.8%
Change in total procurement cost	$57.3 billion 5.3%	$357.8 billion 45.8%
Change in total other acquisition costs	$2.2 billion 21.7%	$1.2 billion 10.4%
Change in total acquisition cost[a]	$76.9 billion 5.7%	$457.5 billion 46.8%
Average delay in delivering initial capabilities	7.0 months 8.5%	28.9 months 36.5%

Source: GAO analysis of DOD data. | GAO-15-342SP

Notes: Data were obtained from DOD's Selected Acquisition Reports and acquisition program baselines. In a few cases data were obtained directly from program offices. Some numbers may not sum due to rounding.

[a]In addition to research and development and procurement costs, total acquisition cost includes acquisition-related operation and maintenance and system-specific military construction costs.

Scope Creep and Deficiency is Common

Programs with the Largest Development Cost Percentage Increases over the Past Year

Fiscal year 2016 dollars (in millions) http://www.gao.gov/assets/680/676281.pdf

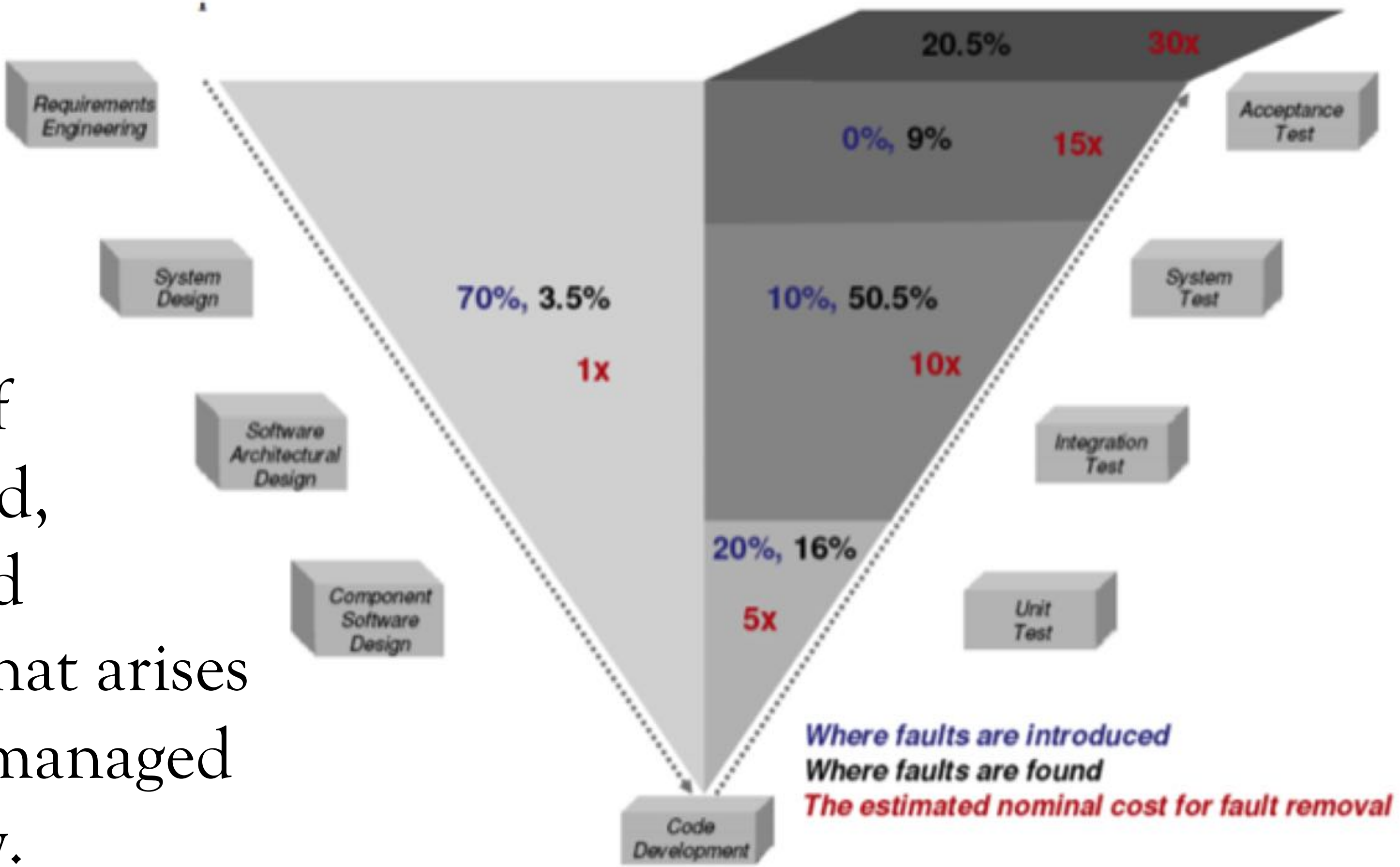
Program	Percentage increase in development cost over the past year	Amount of development cost growth over the past year	Initial capability achieved	Primary cause for development cost increase
AIM-9X Block II Air-to-Air Missile	45%	$172	No	Deficiency
MQ-8 Fire Scout	36	325	Yes	Unplanned capability
Evolved Expendable Launch Vehicle	21	528	Yes	Unplanned capability
Navy Multiband Terminal	18	135	Yes	Unplanned capability
Patriot Advanced Capability-3 Missile Segment Enhancement	9	80	No	Unplanned capability
Family of Advanced Beyond-Line-of-Sight Terminals	9	215	No	Deficiency
DDG 51Arleigh Burke Class Guided Missile Destroyer	6	364	Yes	Unplanned capability
Global Positioning System III	6	180	NA	Deficiency
Next Generation Operational Control System	5	190	No	Deficiency
LHA 6 America Class Amphibious Assault Ship	4	17	No	Unplanned capability
Littoral Combat Ship Mission Packages	4	93	No	Deficiency
EA-18G Growler Aircraft	4	85	Yes	Unplanned capability

Interaction Challenges Due to Complexity

Fourth generation combat aircraft (e.g. F/A-18)	Fifth generation combat aircraft (e.g. F-35)
15 subsystems	130 subsystems
10^3 interfaces	$\sim 10^5$ interfaces
40% functions managed by software	90% of functions managed by software

*United States Government Accountability Office. Defense acquisitions: Assessments of selected weapon programs. Report to Congressional Committees, 2009.

Emergent Risk in Complex Systems



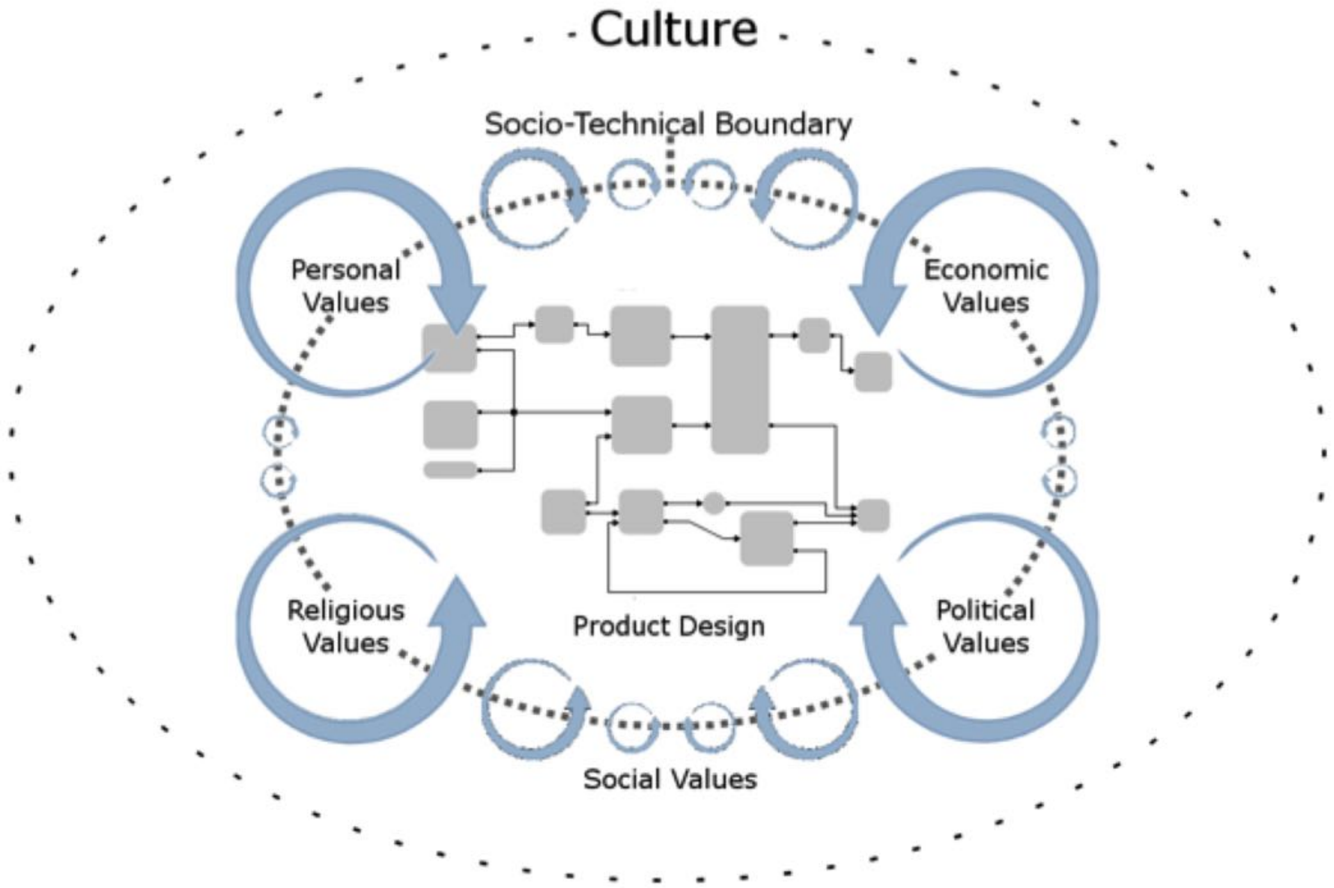
The risk of unintended, unexpected behavior that arises due to unmanaged complexity.

Sandor Becz, "Design System for Managing Complexity in Aerospace Systems"

Socio-Technical Boundary

System ↔ People
Interacting with
System (**all**
Stakeholders)

Values
Context
Culture



Perspectives

Ways in which to view and manipulate system properties:

- Systems Thinking
- Sensemaking
- Incremental Development
- Estimating Emergent Risk
- Quantitative Measurement
- Paradigm Shift

Systems Thinking Perspective

- Zoom in, zoom out
- Pay attention to feedback
  - Especially time delayed
- Challenge assumptions
  - Attitudes and beliefs
- Pay attention to what is important, not just what is quantifiable

https://www.linkedin.com/pulse/zoom-out-significantly-increase-your-learning-see-others-jay-kshatri

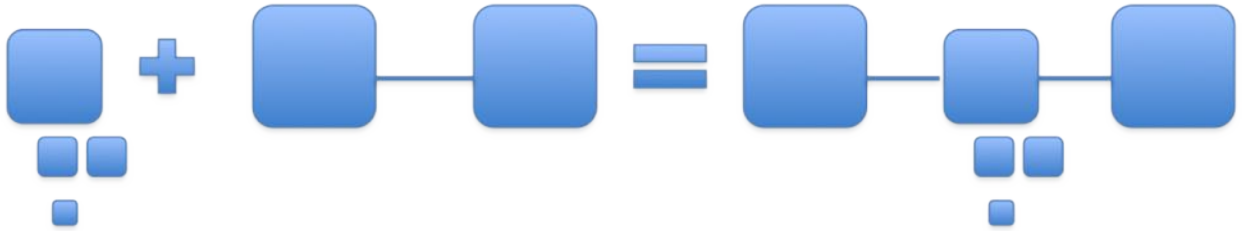
Systems Thinking: Four Simple Rules

1) Distinctions - any idea or thing can be distinguished from other ideas or things
2) Systems - any idea or thing can be split into parts or lumped into a whole
3) Relationships - any idea or thing can relate to other things or ideas
4) Perspectives - any idea or thing can be the point or the view of a perspective

Cabrera[2], "Systems Thinking Made Simple," Odyssean Press (2017)

Use Simple Rules as Visualization Tool

- Shapes for distinction
- Lines for relationships
- Point of view for perspectives



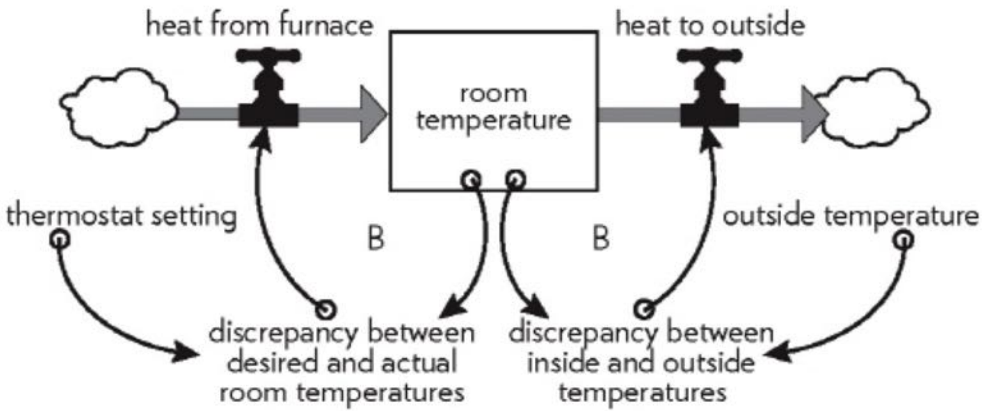
a whole with two parts, one of which has a part

a relationship between two things

a distinguished, systematized relationship between two things

- Cabrera

Example: Temperature Regulated by Thermostat and Furnace



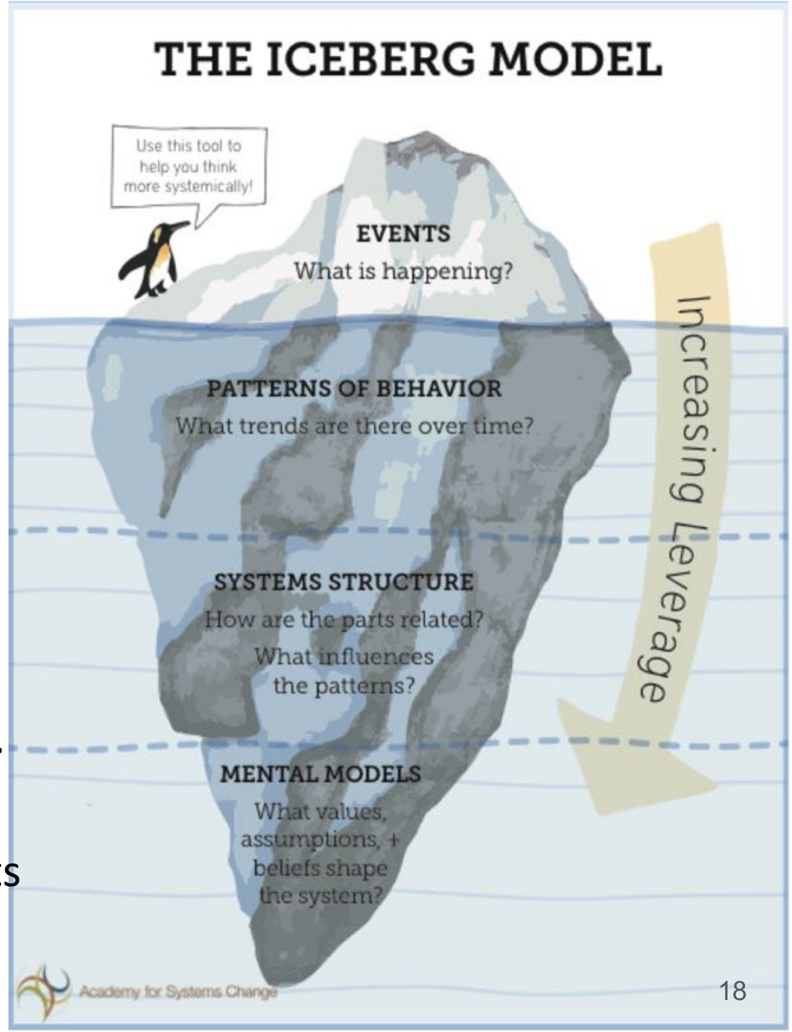
- One stock with two competing balancing loops
- Feedback is used to maintain a balance
- Time delay between setting and room temperature

Meadows, Donella H. "Thinking in systems." *Chelsea Green Publishing* (2008): 77-78.

Places to Intervene in a System

(in increasing order of effectiveness)

9. Constants, parameters, numbers (subsidies, taxes, standards)
8. Regulating negative feedback loops
7. Driving positive feedback loops
6. Material flows and nodes of material intersection.
5. Information flows
4. The rules of the system (incentives, punishments, constraints)
3. The distribution of power over the rules of the system.
2. The goals of the system
1. The mindset or paradigm out of which the system — its goals, power structure, rules, its culture — arises



What is Sensemaking?

- Making sense of an ambiguous situation
    - creating situational awareness and understanding in situations of high complexity or uncertainty in order to make decisions
    - a motivated, continuous effort to understand connections (which can be among people, places, and events) in order to anticipate their trajectories and act effectively

Cognitive edge: what is sensemaking

Cynefin Framework for Sensemaking

- Cynefin means place of belonging, habitat
- Categorize problem in terms of complexity in order to get a solution method
- Cynefin stems from complexity science
- Ferrari vs. the rainforest

Cognitive edge: what is sensemaking

Cynefin Domains

- Simple
- Complicated
- Complex
- Chaotic
- Disordered

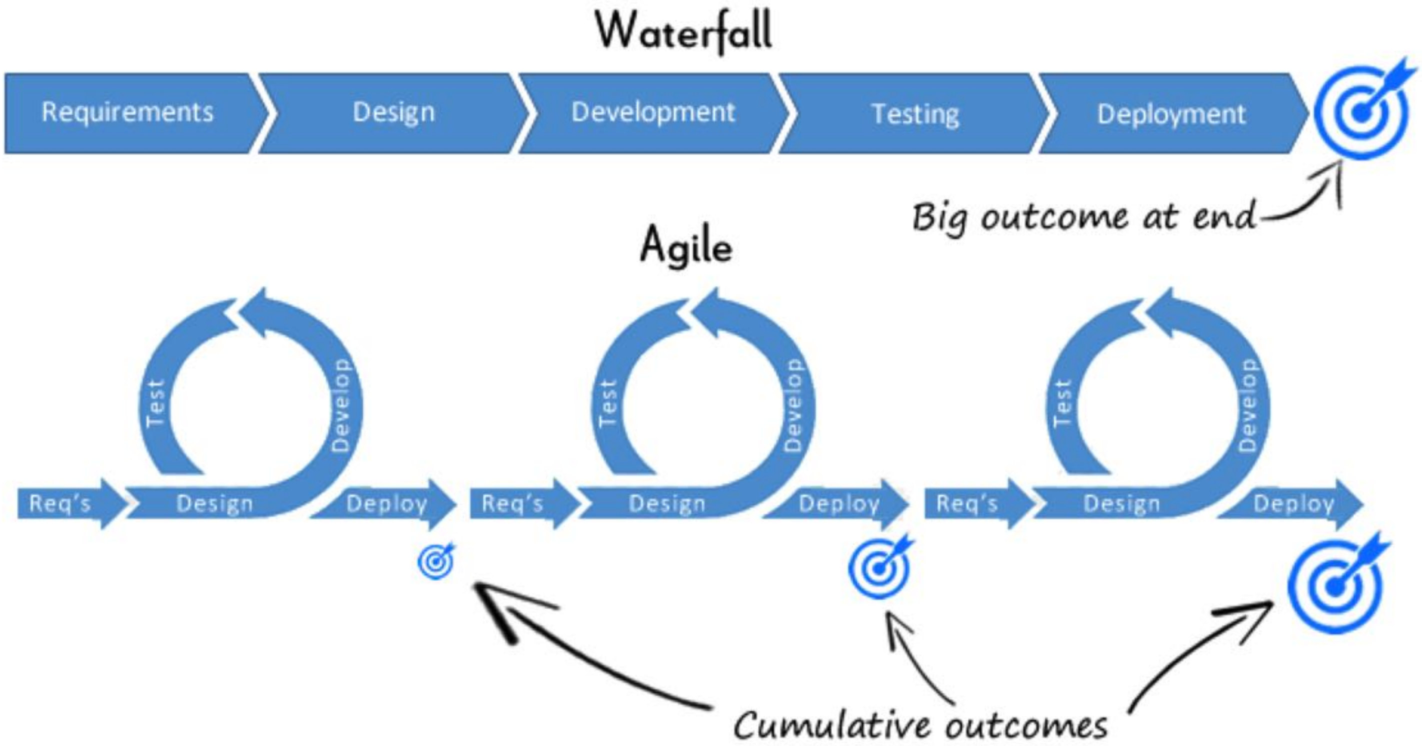
A Leadership Framework for Decision Making, Snowden and Boone, HBR, Nov 2007

Incremental Development Perspective

- Nimble, dexterous, and swift
- Adaptive and responsive to new, sometimes unexpected information that becomes available during system development
- Cross functional teams developing in short cycles

  - Agile is a good example

Traditional Waterfall and Agile



CRM Research <http://www.crmsearch.com/agile-versus-waterfall-crm.php>

Agile - Processes and People

- A good process will not save the project from failure if the team doesn't have strong players
- A bad process can make even the strongest of players ineffective
- A group of strong players can fail badly if they don't work as a team

Martin, R., Agile Software Development; Principles, Patterns and Practices, Pearson, 2002, chtpr 1

Estimating Emergent Risk Perspective

- Emergent risk is the risk of unintended, unexpected behavior that arises in a complex system during any part of a product’s lifecycle

- Complexity Breeds Fragility
    - The lower bound of complexity in aerospace is necessarily higher due to the tightly coupled nature of high risk systems and the increased need for risk mitigation, such as launch vehicles

Examples of Emergent Risk

The Study of Vulnerability

- Barings Bank in 1995 a single trader hides trades
- Boeing 777 in 2006 flies out of control due to defective software
- Comair Airline in 2004 has to stop for several days because of overloaded crew-management system
  - In August of 2016, Delta had a similar problem, overloaded reservation software

Bonabeau, Eric. "Understanding and managing complexity risk." *MIT Sloan Management Review* 48, no. 4 (2007): 62.

Emergent Risks in Industry

- Software bugs like backwards compatibility
- Tiny glitch cascades to catastrophic event
- Weakness at organizational boundaries
- Internal weakness or loophole

or

- Intentional sabotage

Bonabeau, Eric. "Understanding and managing complexity risk." *MIT Sloan Management Review* 48, no. 4 (2007): 62.

Find the Circuit Breaker

"The bad news is that complex, interconnected systems generate many, sometimes unexpected or counterintuitive vulnerabilities. But the good news is that if a small, localized, single event can trigger cascading failures, then perhaps a small, localized single intervention could act as a circuit breaker."

Bonabeau, pg 64

Search for the Circuit Breaker by:

- Having two people work on the same code
- Incentivizing feedback for problems
- Teambuilding
- Designing in robustness
- Open testing
- Disconnecting (literally)

Bonabeau, pg 68

Incentivize Feedback: US Aviation Safety Reporting System

- In the case of a regulation violation, aviators can submit reports on the incident without fear of consequences
- Self-reported incident information cannot be used by FAA enforcement authorities
- Anonymized information is available to 150,000 aviation professionals and enthusiasts
- The goal is process improvement from feedback, in this case safety

Bonabeau, pg 66

Quantitative Measurement Perspective

- Uses size, coupling, and modularity properties to quantify complexity
- Case study of three spacecraft
- Three key capabilities
  - identify complex subsystems
  - classify misrepresentations
  - trade studies of Commercial off the Shelf (COTS) and non-COTS components

Tamaskar, S., Neema, K. and DeLaurentis, D., 2014. Framework for measuring complexity of aerospace systems. *Research in Engineering Design*, *25*(2), pp.125-137.

Aspects of System Complexity

1) **Level of abstraction**-visualization at different levels of detail
2) **Type of representation**-structural or functional
3) **Size**-number of components and interactions
4) **Heterogeneity**-diversity of components and interactions
5) **Coupling**-interdependency between components
6) **Modularity**-strength of coupling, density of interconnection
7) **Uncertainty-**potential to exhibit emergent behavior
8) **Dynamics-**behavior across timescales
9) **Off-design interactions-**happen outside of design range

Coupling Complexity Metric

- Create a weighted structural network that shows the coupling
- Add feedback loops
- Assign weights
- Calculate complexity coupling value

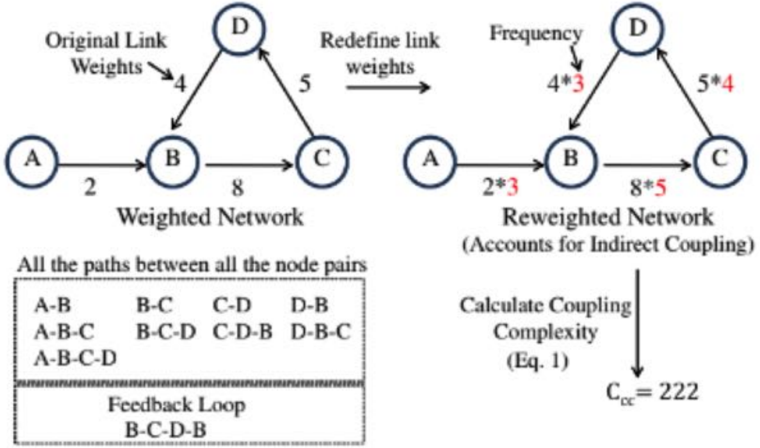


Fig. 1 Illustration of coupling complexity metric

$$C_{cc} = \sum_{s=1}^{c}\left(n_s \sum_{i=1}^{n_s} W_{is}\right) + \sum_{k=1}^{m} W_k \qquad (1)$$

- its a model...

Tamaskar, pg 130

Integration Complexity Metric

- Capture the modular decomposition process
- Quantify integration
- Assign weights
- Calculate system complexity metric

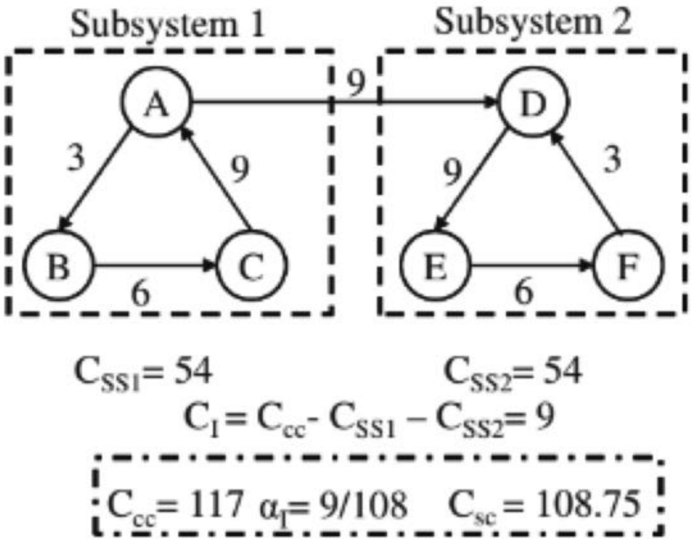


Fig. 2 Illustration of system complexity metric

Tamaskar, pg 131

Study Complexity of Spacecraft

- Apply the model to show how it works
- Sensitivity studies
- Quantitative data on spacecraft complexity

Table 1 Complexity of spacecraft

Mission	Orsted Magnetic field	HETE Gamma ray burst	Clementine Moon & 1620 geographos
Cost (FY08$K*1000)	15	23	60
Weight (Kg)	60	125	232
No. of components	47	59	68
No. of interactions	58	71	92
Complexity (C_{cc})	4,893	7,749	14,962

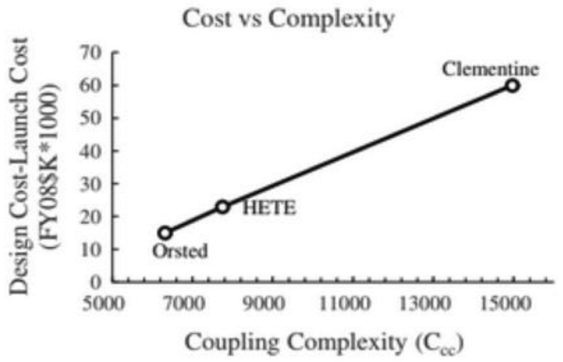


Fig. 5 Correlation of cost with complexity

Complexity Paradigm Shift Perspective

- Designing from a complexity paradigm is more competitive due to different values
  - Size vs. **Speed**
  - Control vs. **Role Flexibility**
  - Role Clarity vs. **Innovation**

- Speed and flexibility are better metrics for managing both organizational and product complexity

'Classic Science' Model	Complexity Science Model
Linear	Non-linear
Hierarchical	Non-Hierarchical
Reductionist	Holistic
Controlling	Self-Organizing
Structured	Flexible
Uniform	Diverse
Centralized	Networked

McMillan, E., "Considering Organisation Structure and Design From a Complexity Paradigm Perspective", Figure 4, 2002.

Conclusion

- Draw a socio-technical boundary around the system to see the overall system perspective
  - includes values, context and culture
- Use perspective to manage the emergent risk
  - Systems Thinking
  - Sensemaking
  - Incremental Development
  - Estimating Emergent Risk
  - Quantitative Measurement
  - Paradigm Shift