Systems-Theoretic Concept Design: An Intent Model for Early Concept Generation

Alex Hillman

3 July 2024

Disclaimer

The views expressed in this presentation are those of the author and do not reflect the official policy or position of the United States Air Force, United States Space Force, Department of Defense, or the United States Government.

The views expressed in this presentation belong to the speaker and do not reflect the official policy or position of the Massachusetts Institute of Technology.

Bottom Line Up Front

- **Regardless of your lifecycle model or requirements engineering process, design tradeoffs and systems engineering decisions must be traceable to some higher level goals and guidance**

- **Primary Contribution: Systems-Theoretic Concept Design introduces an *intent model* comprised of four dimensions to more adequately capture system context & system intent for a novel, complex system**

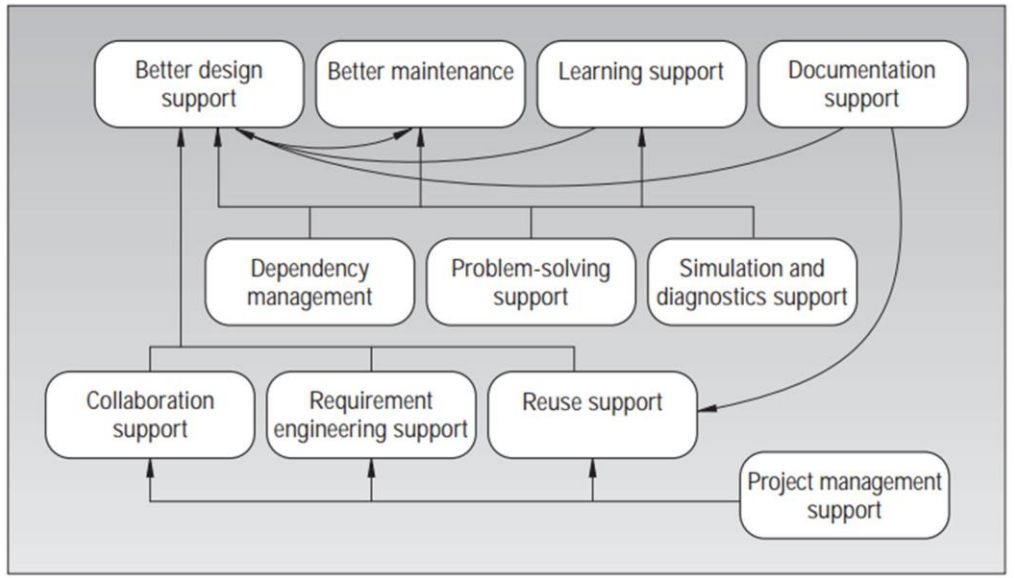
- **Next Steps:**
  - **Papers at 31st International Symposium on Transdisciplinary Engineering, AIAA Aviation & AIAA SciTech**
  - **Thesis Publication/PhD Complete Fall 2024**

***Research Goal:* Enable development programs to deliver capabilities, not platforms**

***Methodology Goal:* Thoroughly develop & propose viable Early Design Concepts**

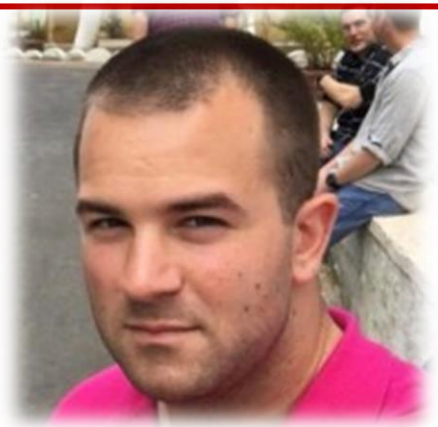
Today's Agenda

- **Speaker & Author Intro**
- **The Problem**
- **Existing Approaches & Relevant Literature**
- **STCD & the Intent Model**
- **Next Steps, Future Work**



[Lee, 1997]

Speaker & Author Intro



Alex Hillman

- Major, US Air Force
- PhD Candidate, Engineering Systems Lab, MIT
- Data Scientist, Experimental Flight Test Engineer (USAF TPS 17A)
- Recovering Statistician

Prof Nancy Leveson

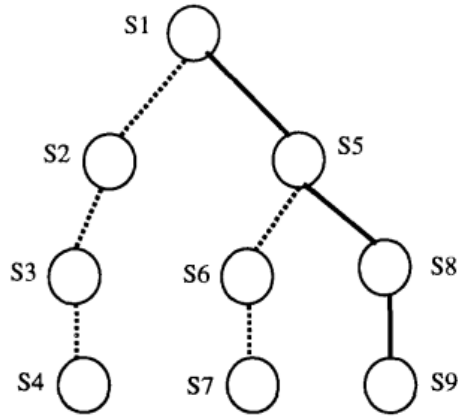
- Thesis Advisor for this work
- Interests: Software Engineering, System and Software Safety, Human-Computer Interaction
- Jerome C. Hunsaker Professor of Aeronautics, MIT Aero/Astro
- MIT Faculty 1999-Present

William “$” Young

- Committee Member
- PhD, Engineering Systems from MIT
- Retired USAF Senior Leader, former O-6 & Wing Commander
- Career Systems Thinker & Engineer with interest across lifecycle problems

Today's Agenda

- Speaker & Author Intro
- The Problem
- Existing Approaches & Relevant Literature
- STCD & the Intent Model
- Next Steps, Future Work



[Ganeshan, Garrett, & Finger, 1994]

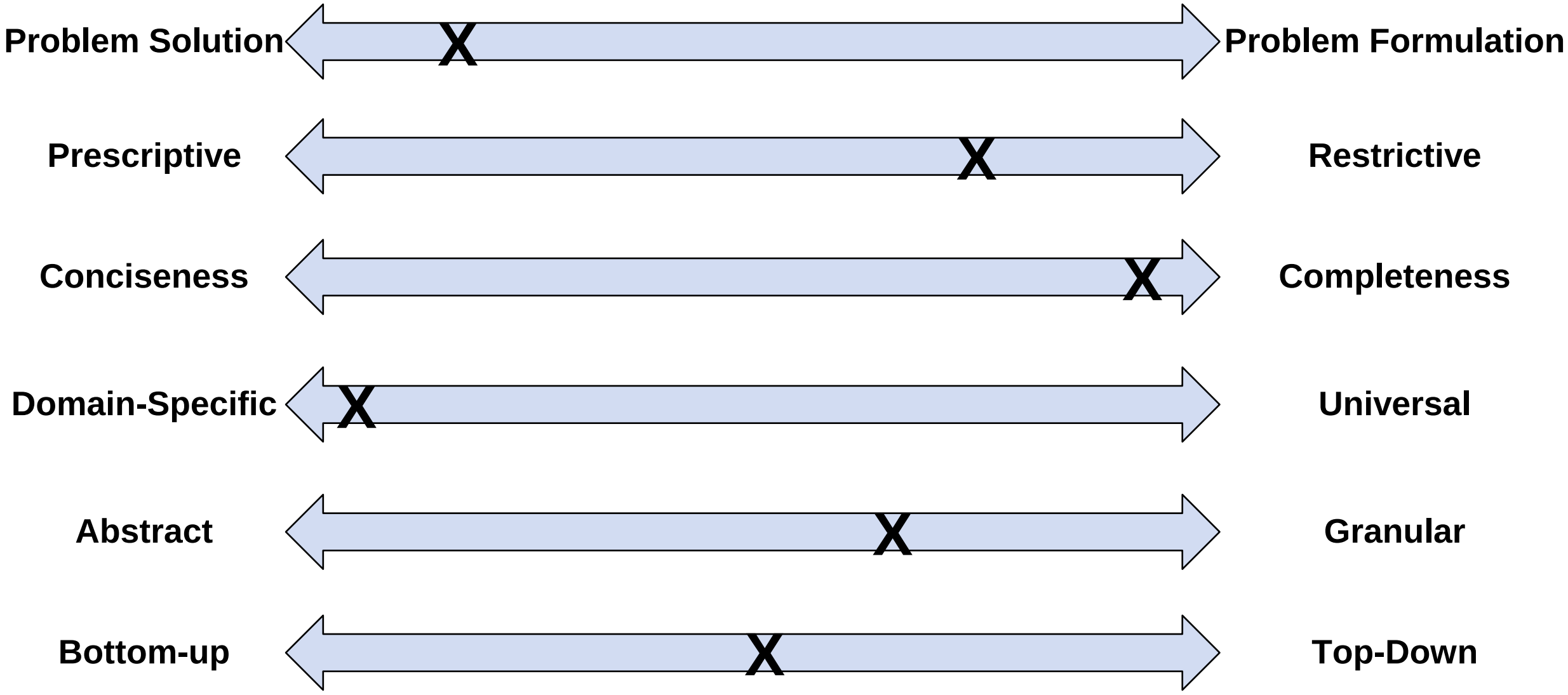
Complex Systems are Hard

- **Context Matters:**
  - **Designers love to focus on *How* a system will solve the problem at hand**
  - ***Architecture/Requirements Mismatch:* when the low-level, highly granular design specification doesn't align with high-level system goals or objectives**

- **The Cart before the Horse:**
  - **Engineers are trained and educated to apply expert precision in designing components, widgets, software, etc.**
  - **We're all guilty – decomposition guides us to solving the technical challenges we have been trained to solve**

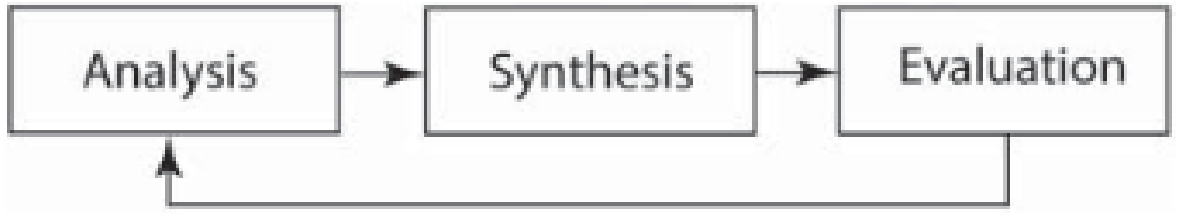
How can I create an early concept for a system that captures the appropriate context, addresses capability gaps, and does not marry a program to a particular architecture or technology?

What makes a good early concept?



Wicked Problems for Defense Systems

- **Traditional Design Thinking poses the *design problem* as a construct that has a solution**
- **Developing a *solution* during the early concept generation phase is infeasible, so why attempt to green field a solution?**
- **The design of a complex system is inherently a *wicked problem*: the design is inevitably the formulation of how the designer sees the problem space**



[Asimow, 1962]

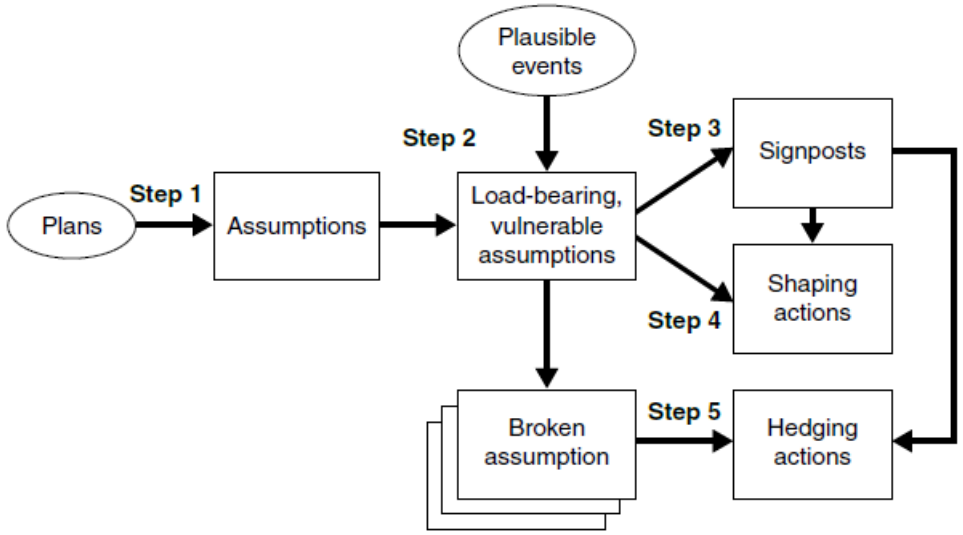
- **Defense Systems are employed as a portfolio-of-systems**
- **Capturing context across the portfolio is hard, particularly with existing design & security stovepipes**
- ***Intent* for an early design concept plays a major role in a system's success, but previous attempts to capture *design intent* or *design rationale* have not been successful**

Research Question:

How can a design team capture and document context for a novel, complex system to support future lifecycle activities?

Today's Agenda

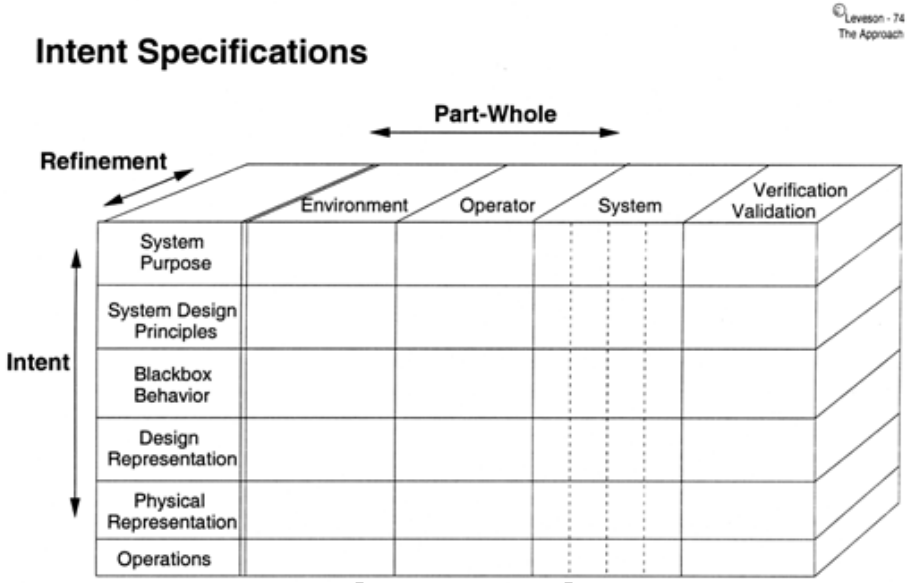
- Speaker & Author Intro
- The Problem
- Existing Approaches & Relevant Literature
- STCD & the Intent Model
- Next Steps, Future Work



[Dewar, 2002]

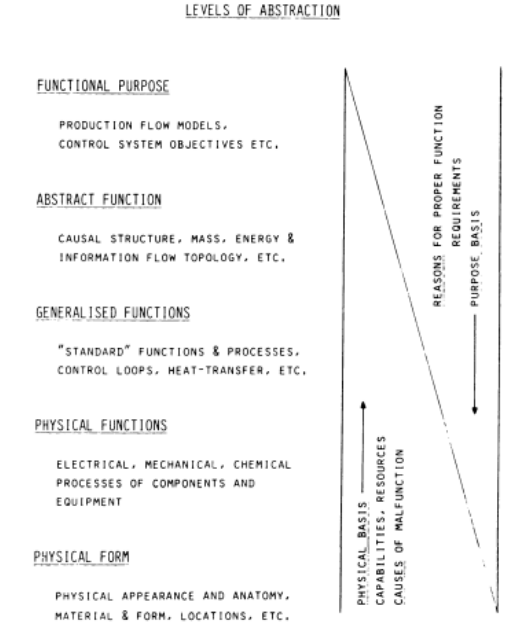
Abstraction is a Tool to Manage Complexity

- "Specifications are constructed to help us solve problems"
- An intent specification is a tool for system design
- Provides a prescribed format for writing specifications
  - Minimize semantic distance when possible, capture assumptions, use abstraction



[Leveson, 2000]

- Abstraction can be used as a means to vary resolution of a model to solve pertinent problems or ask relevant questions
- " Knowledge Representation"
- Models can be manipulated to answer only appropriate questions

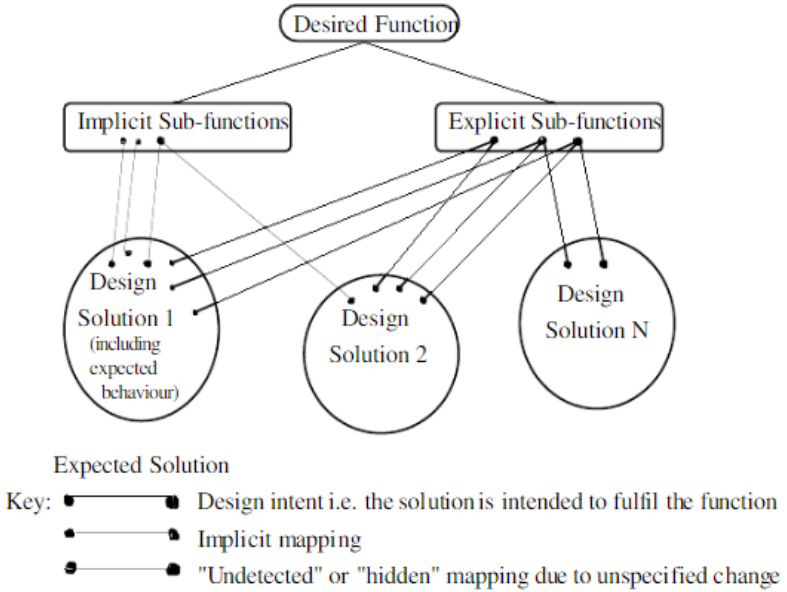


[Rasmussen, 1985]

Failure to Launch: Issues with Scale

Design Intent Mapping

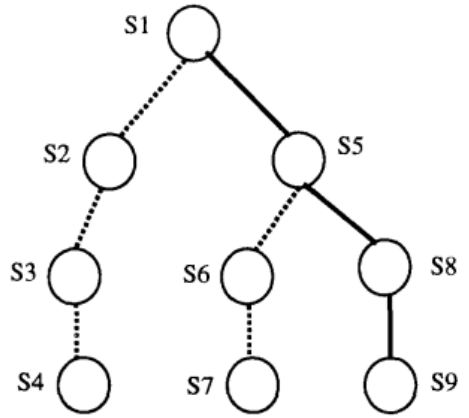
- Map high-level desired functions & decompose to subfunctions followed by technical solutions
- Reductionist, employs decomposition instead of holism, fails to scale



[Sim & Duffy]

State Tree Representation for Intent

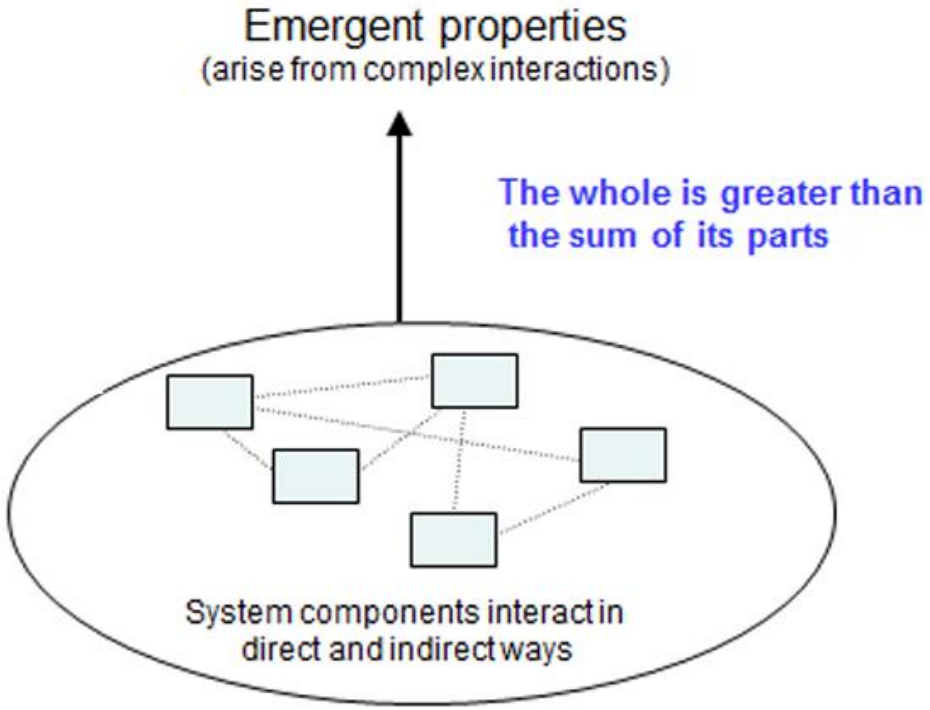
- Applied formal methods to intent
- Capture design objectives & intermediate design states
- Misses the complex interactions amongst competing design interests



[Ganeshan et al]

Systems Theory as a Guide

- **Systems Theory provides a lens through which we can study complex systems**
- **Emergent behavior is only present at the System-level**
- **Defense systems are *open systems* – they interact with their environments**
- **The *system* is just an abstraction in our minds – each stakeholder sees it differently**



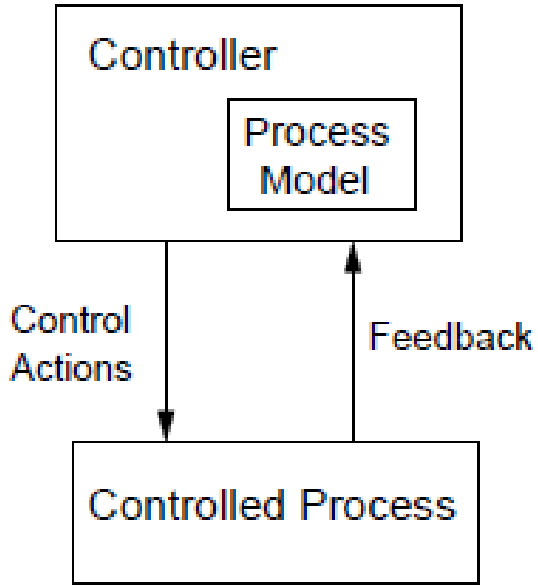
[Leveson, 2020]

STAMP as a Foundation

- **STAMP: Systems-Theoretic Accident Model & Processes**

- **3 Main Concepts to model a system:**
  - **Safety Constraints, i.e. constraints on behavior**
  - **The Hierarchical Safety Control Structure (Right)**
  - **Process Models**

- **STAMP makes crucial contributions:**
  - **Modelers can use abstraction to model complex systems and their interactions applying Systems Theory to real, applied problems**
  - **Complex interactions can be analyzed through the lens of a control-theoretic approach**
  - **Emergent properties can be analyzed using this approach**

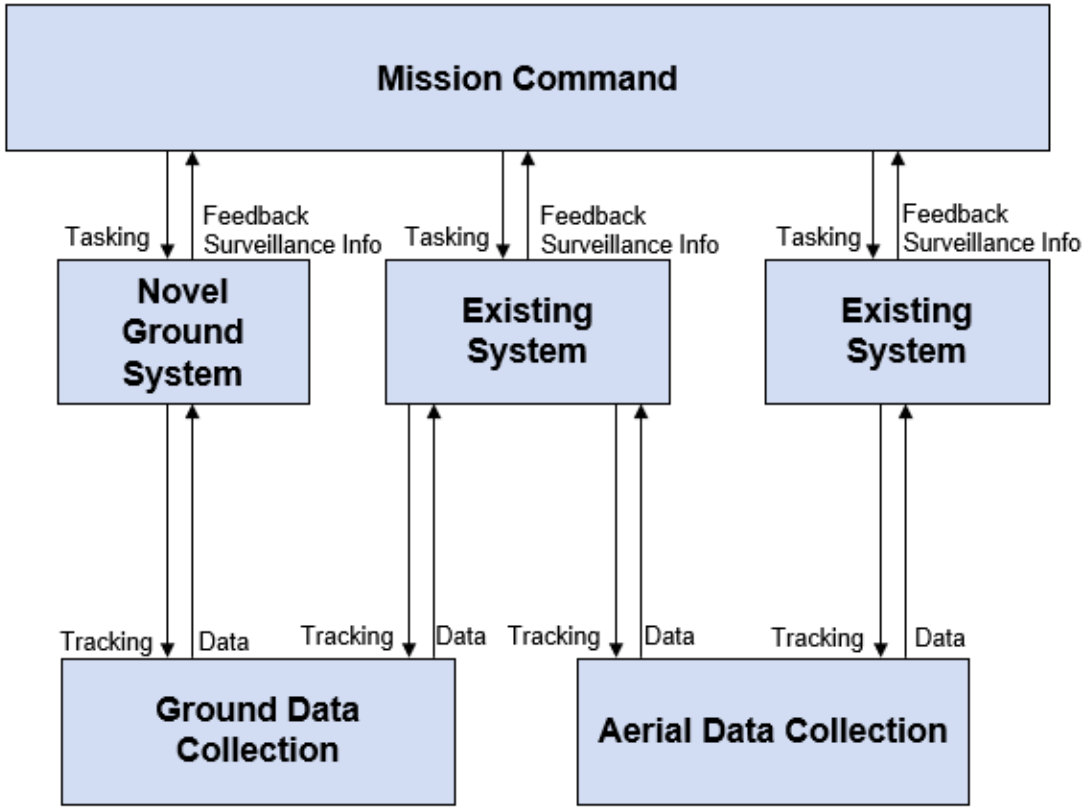


[Leveson, 2011]

Applied Systems Theory: The Portfolio-of-Systems Model

- **STCD introduced at IEEE SysCon in April 2024**
- **Leveraging the principles of STAMP, we can represent a design using a control structure, representing the existing portfolio and the new system at the Portfolio-level**
- **Capable of capturing complex interactions amongst portfolio's systems and cross-boundary control actions**

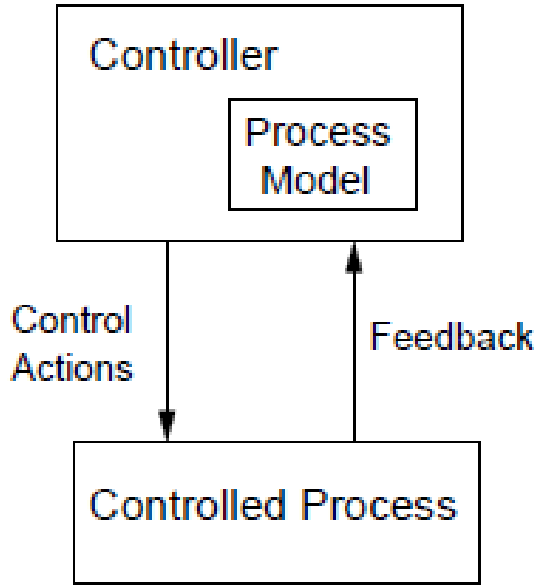
But how do we arrive at this initial design artifact while capturing portfolio context & system-level intent?



[Hillman & Leveson, 2024]

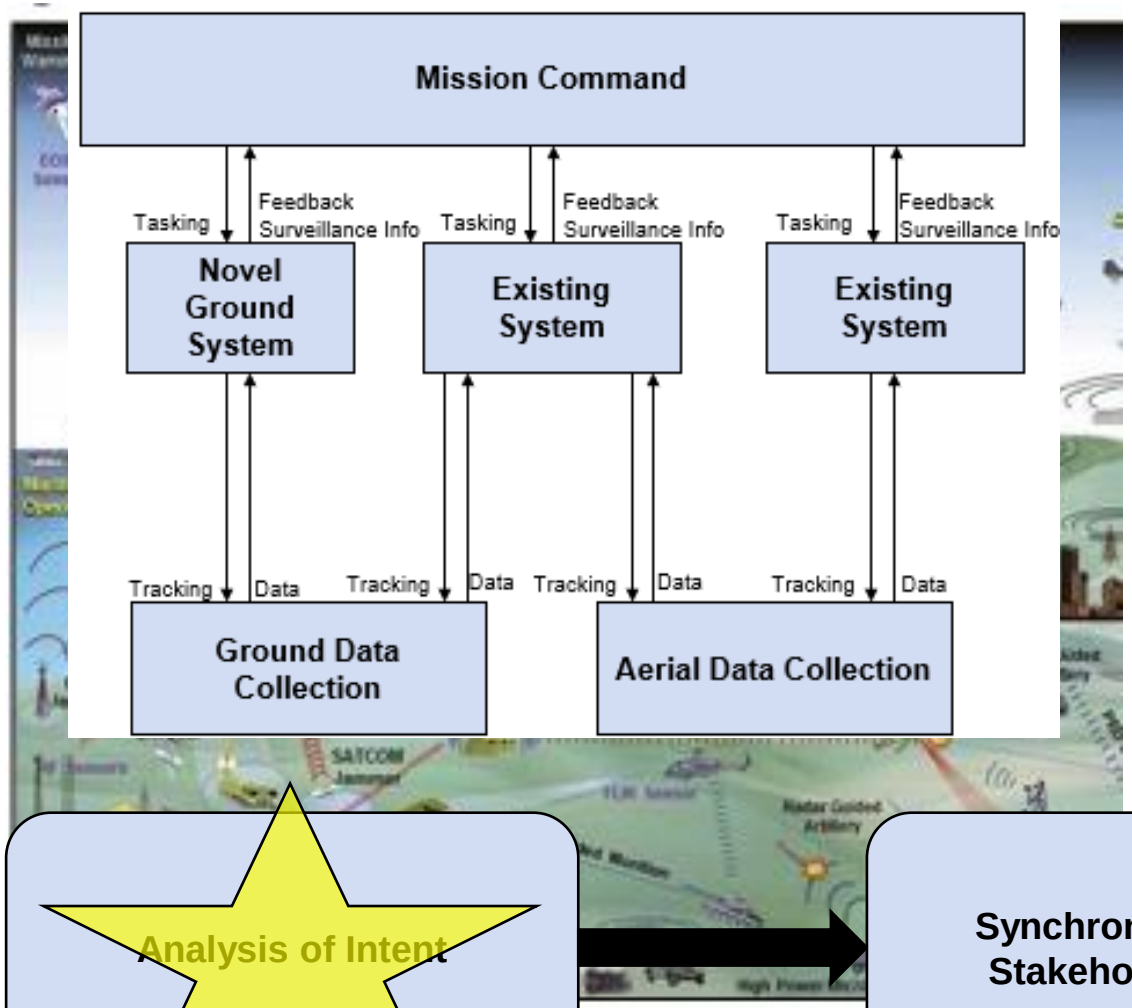
Today's Agenda

- Speaker & Author Intro
- The Problem
- Existing Approaches & Relevant Literature
- STCD & the Intent Model
- Next Steps, Future Work



[Leveson, 2011]

Brief Synopsis: Systems-Theoretic Concept Design



→ ~~Where we've been~~

→What we're trying to do!

- →Architecture Agnostic
- →Not Technology Dependent
- →Top-Down, synthetic, analytical approach
- →Foundation for System Success

Analysis of Intent → Synchronize Across Stakeholder Views → Propose Early Concept

The Portfolio-of-Systems View

- **Defense Systems are developed & deployed to support a high-level policy or portfolio-level capability**

[Hillman, Leveson, & Young, 2024]

- **The operating environment & existing elements of the battlespace are inputs into an existing process**

- **This process is a transformation of the current battlespace into some set of properties that this research calls *The End State***

A New Context for Mission Analysis

- **Capability gaps are portfolio-level shortfalls, or failures to achieve a desired *End State* or the portfolio-level policy**
  - **Policy examples: air dominance, surveillance**
- **A new system alters the existing portfolio-of-systems transformation – and the *End State* attributes will definitively change**
- **In this context, *intent* is not about a single design decision**
- **An Intent Model for a new system is built across four dimensions**

Four general dimensions to System Intent

1. **"Why"**
   - High-level goals and objectives within a portfolio-of-systems
2. **"What"**
   - High-level functions, abstract function of the new system
3. **Assumptions**
   - Any fact, statement, or opinion that captures logic or rationale behind our early development decisions
4. **Constraints**
   - Limitations or restrictions, particularly on system scope; a bounding condition that would limit system behavior or development aims

[Hillman, Leveson, & Young, 2024]

The Intent Model

- **Complexity is in our minds (Norman, 2011)… and our SE Tools are employed to manage complexity**
- **Failures to meet portfolio-level goals & objectives inform the intent model**
- **The Intent Model is a mechanism to understand the need for a new system**
  - **Capability gaps**
  - **High-level Goals & Objectives**
  - **Abstract Function**
- **Enables us to focus on *Why/What,* not *How***

The Assumptions Taxonomy

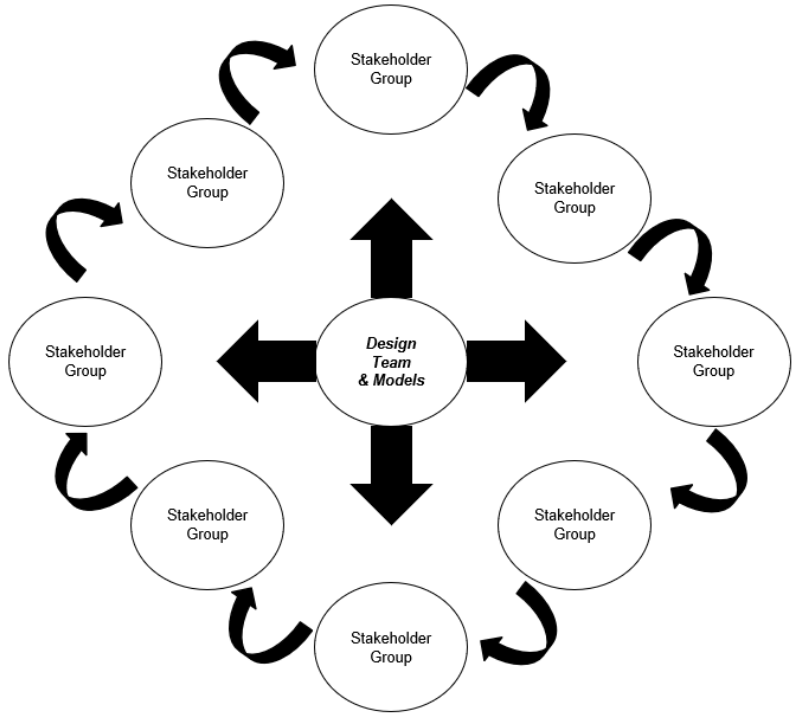
- **Assumptions matter… but as SE pros we fail to capture them & leverage them for use in future lifecycle management processes**
- **STCD proposes an assumptions Taxonomy to capture & classify these assumptions**
- **Repurposes Dewar's ABP guidance**
- **Categories are not exhaustive**
- **Authors posit they're at least useful**

Severity / *Classification*	Critical	Vulnerable	Neither
Stakeholder Assumptions			
Technical Assumptions			
Operating Environment Assumptions			
Programmatic Assumptions			
Detailed Design Assumptions			

[Hillman, Leveson, & Young, 2024]

Today's Agenda

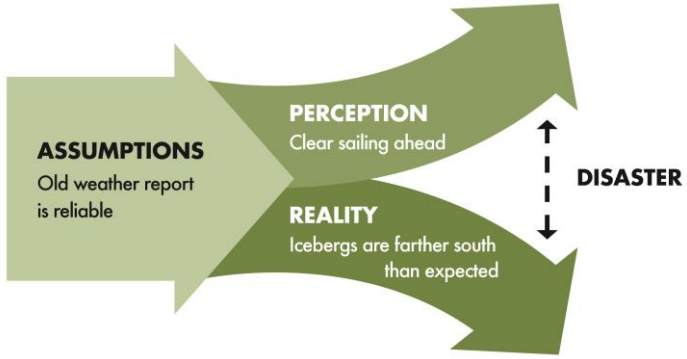
- Speaker & Author Intro
- The Problem
- Existing Approaches & Relevant Literature
- STCD & the Intent Model
- Next Steps, Future Work



[Hillman & Leveson, 2024]

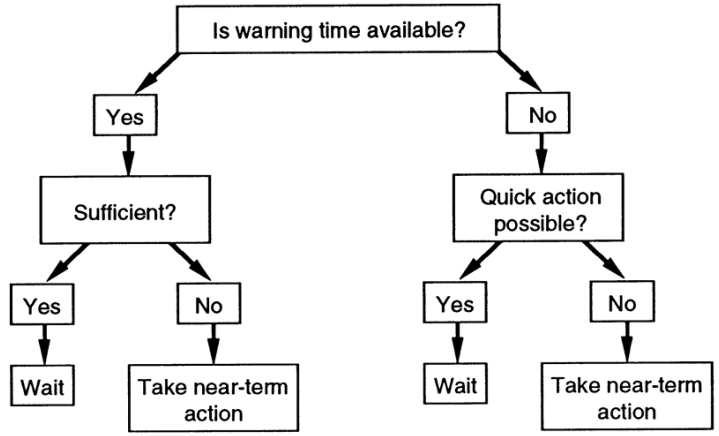
Limitations, Future Work

- **Limitations:**
  - **Context here is for systems within a portfolio**
  - **Assumptions Taxonomy hasn't been proven to be exhaustive, but the authors contend that it is at least useful**
  - **This approach is limited to the design of control-oriented systems, mainly applied to aerospace & defense/national security systems**



[The Circle of Assumptions, 2022]

- **Future Work:**
  - **Expand applicability of intent model-focused mission analysis outside of portfolios-of-systems & defense systems**
  - **Leverage intent model to use systems-theoretic principles to synchronize stakeholder mental models**



[Dewar et al, 1993]

Conclusions & Way Forward

- **Regardless of your lifecycle model or requirements engineering process, design tradeoffs and systems engineering decisions must be traceable to some higher level goals and guidance**

- **Primary Contribution: Systems-Theoretic Concept Design introduces an *intent model* comprised of four dimensions to more adequately capture system context & system intent for a novel, complex system**

- **Next Steps:**
  - **Several other pending papers in support of Systems-Theoretic Concept Design work**
  - **Thesis Publication/PhD Complete Fall 2024**

***Research Goal:* Enable development programs to deliver capabilities, not platforms**

***Methodology Goal:* Thoroughly develop & propose viable Early Design Concepts**

Questions?