A Theoretical Framework for Systems Engineering and Design
Asking “Why?” rather than just “How?”

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Disclaimer

- Any opinions, findings, and conclusions or recommendations expressed in these slides are those of the author/presenter and do not necessarily reflect the views of the National Science Foundation.
Theoretical Foundations… Some Context

- Systems Engineering Vision 2025: A World in Motion
  - 2 year effort led by Sandy Friedenthal → lots of discussion…
  - Emphasized the need for theoretical foundations of SE
    (http://www.incose.org/newsevents/announcements/docs/SystemsEngineeringVision_2025_June2014.pdf)

- Inter-Agency Working Group on Complex Engineered System
  - Multiple US government agencies get together informally with the goad to transform the Government’s capability to successfully engineer large, mission-related, complex, evolving systems

- Workshop on Theory and Science of Systems Engineering
  - Paul Collopy (lead), Anna McGowan, Art Pyster, Tim Simpson
  - NSF-sponsored; co-sponsored by INCOSE and SERC
  - 50 participants from diverse communities (SE, design, computer science, architecture, system science, sociology, philosophy)
Outline

- A Theoretical Framework:
  - What?
  - Why?

- Towards a Theoretical Framework: A Start — An Example

- Research Methodology Challenges

- Key take-aways
Theoretical Framework: What and Why?
Research in SE and Design has been Mostly Descriptive

- Researchers have developed models describing current practices → Descriptive Models
  - Descriptions of work products: “what?”
  - Descriptions of processes: “how?”
- Some of these practices have been elevated to “best practices” → Prescriptive Models
Theoretical Framework: What and Why?
An Example in Systems Engineering: The V-Model

Exhibit 5—Overview of the Technical Aspect of the Project Cycle

Forsberg, Mooz, 1995.
Theoretical Framework: What and Why?
An Example in Engineering Design: Gero’s FBS Model

**Figure 2. Model of Design as a Process.**

- $B_e = \text{Set of expected behaviors}$
- $B_s = \text{Set of actual behaviors}$
- $D = \text{Design description}$
- $F = \text{Set of functions}$
- $\rightarrow = \text{Transformation}$
- $\longrightarrow = \text{Occasional transformation}$
- $\leftarrow \rightarrow = \text{Comparison}$

Gero, 1990.
Theoretical Framework: What and Why?
The Need for Explanatory Models

- The V and FBS models describe and prescribe but they **do not explain**
  Why do we engineer and design in this fashion?
  Why is this a good way of designing?

→ If we want to *improve* SE & Design, we must ask “Why?” rather than just “How?”
Theoretical Framework: What and Why?
The Need for Explanatory Models

Observe & Describe ➔ Understand & Explain ➔ Improve

SE&D Practice
Concept Definition ➔ System Architecting ➔ Functional Analysis ➔ Risk Management
Requirements Engineering ➔ Interface Definition ➔ Tradespace Analysis
Theoretical Framework for SE & Design

Explanatory Models Supported by Empirical Evidence

SE&D Practice

- Concept Definition
- System Architecting
- Functional Analysis
- Risk Management
- Requirements Engineering
- Interface Definition
- Tradespace Analysis

Theoretical Explanatory Models → Improved Methods & Tools → Empirical Charact. / Falsification

Improve Methods & Tools

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Theoretical Framework for SE & Design

Explanatory Models Supported by Empirical Evidence

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Theoretical Explanatory Models

Improved Methods & Tools

Empirical Character. / Falsification

Foundations

- Systems Theory
- Probability Theory
- Organizational Theory
- Behavioral Economics
- Decision Theory
- Economics
- Psychology
Outline

- A Theoretical Framework:
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- Towards a Theoretical Framework: A Start — An Example
- Research Methodology Challenges
- Key take-aways
Starting from the Basics…
SE & Design are Processes Aimed at Adding Value

- SE & Design are transformation processes
  - Primarily a process of information transformation
  - Transformation of materials & energy during manufacturing and maintenance phases

- What is the purpose of these processes?
  → To obtain a state of the world that is more preferred
  → To add value

- How do we add value?
  → By creating or improving artifacts
  - Value is added by using and/or selling of artifacts
Starting from the Basics…
SE & Design are Processes Aimed at Adding Value

- SE & Design are transformation processes
  - Primarily a process of information transformation
  - Transformation of materials & energy during manufacturing and maintenance phases

Why do we use process A rather than process B?
Because process A adds more value than process B

- How do we add value?
  → By creating or improving artifacts
  - Value is added by using and/or selling of artifacts
Search: A Directed Process for Adding Value
Strategy for Adding Value Effectively

- SE & Design are **Search Processes**
  - Ideation
SE & Design are **Search Processes**

- Ideation
- Analysis and Evaluation
Search: A Directed Process for Adding Value

Strategy for Adding Value Effectively

- SE & Design are **Search Processes**
  - Ideation
  - Analysis and Evaluation
  - Selection or Pruning

Why do we use this approach? *Because it Adds Value*
Theoretical Framework: Explanatory Models
Explaining SE & Design as Search

- **Model 1:** Maximizing the value $\pi$ of an artifact $a$:

  $$\mathcal{A}: \max_{a \in A} \pi(a)$$

  The value is only realized in the future and is therefore uncertain.
Model 2: Maximizing the expected value of utility:

\[
\mathcal{A}: \max_{a \in A} \pi(a) \quad \Rightarrow \quad \mathcal{A}: \max_{a \in A} E[u(\pi(a))]
\]

takes uncertainty and risk preferences into account
Theoretical Framework: Explanatory Models
Explaining SE & Design as Search

Model 2: Maximizing the expected value of utility:

\[ A: \max_{a \in A} \pi(a) \Rightarrow A: \max_{a \in A} \mathbb{E}[u(\pi(a))] \]
Model 2: Maximizing the expected value of utility:

\[ A: \max_{a \in A} \pi(a) \quad \Rightarrow \quad A: \max_{a \in A} E[u(\pi(a))] \]

Rather than caring about the value of the artifact, we care about the net present value (NPV) over the entire lifecycle.
Model 3: Maximizing the expected utility of NPV:

\[ A: \max_{a \in A} E[u(\text{NPV}(a))] \]

takes the full lifecycle into account
Theoretical Framework: Explanatory Models
Explaining SE & Design as Search

- Model 4: Maximizing the expected utility of NPV:

\[ \mathcal{A}: \max_{a \in A} E[u(NPV(a, t, C))] \]

takes into account that NPV depends on the time and cost of the development process.
Theoretical Framework: Explanatory Models
Explaining SE & Design as Search

- **Model 4:** Maximizing the expected utility of NPV:
  \[ \mathcal{A}: \max_{a \in A} E[u(NPV(a, t(\mathcal{A}), C(\mathcal{A})))] \]

- **Issue:** the search problem has become **self-referential**
  - Leads to **path dependence** \( \rightarrow \) the chosen artifact depends on the search process
  - Leads to **infinite planning recursion**
    » To achieve the optimal outcome, the problem needs to be optimally framed. But to find the optimum frame, the framing problem needs to be optimally framed…

\[ \rightarrow \text{Use heuristics… because they add value} \]
Theoretical Framework: Explanatory Models

Explaining SE & Design as Search

- **Model 4:** Maximizing the expected utility of NPV:
  \[
  \mathcal{A}: \max_{a \in A} E[u(NPV(a, t(A), C(A)))]
  \]

- **Model 5:** Maximizing from a process perspective
  \[
  \mathcal{P}: \max_{p \in P} E[u(NPV(a(p), t(p)) - C(p))]
  \]

  - No longer self-referential, but still path dependent
    \(
    \rightarrow \text{the best choice for future process steps depends on the outcomes of previous process steps}
    \)

  \(
  \rightarrow \text{Must make a tradeoff between artifact value and search time & cost}
  \)
Explaining SE&D: Why Gradual Refinement?
Gradual Refinement of System Specification

- Exhaustive Search: Cost of synthesis and analysis is too high
- Gradual refinement of system specification is advantageous because it allows for pruning → fewer specifications are considered
- But carries a risk that the most preferred alternative is also pruned
Explaining SE&D: Why Gradual Refinement?
Gradual Increase in Analysis Accuracy

- Uncertainty in prediction of artifact value, $\pi$, results from:
  - Specification uncertainty (uncertainty in $a$)
  - Analysis model uncertainty ($\varepsilon$)

$$\pi = f(a) + \varepsilon$$
Uncertainty in prediction of artifact value, $\pi$, results from:

$\pi = f(\alpha) + \epsilon$

How does gradual refinement impact value?

+ Reduces the cost of an analysis
+ Reduces the number of artifacts to be analyzed
- Increases the probability that a worse artifact will be selected

→ Overall, it is very likely that gradual refinement adds value … but not necessarily to the artifact. The added value results from reductions in process time and cost.
Explaining SE&D: Why Delegating Tasks?
Delegation of Tasks (Usually) Adds Value

- **Model 6:** Taking the organizational structure, \( o \), into account explicitly:

\[
\mathcal{O} := \max_{p \in P, o \in O} \mathbb{E}[u(NPV(a(p, o), t(p, o)) - C(p, o))]
\]

- **Pros**
  - Division of labor \( \rightarrow \) agents may be more skillful
  - Agents may be more efficient
  - Leverage \( \rightarrow \) Principal is limited in output capability

- **Cons**
  - Agents may not act as desired
  - Incentives reduces overall value
  - Cost of communication
  - Risk of miscommunication
Search: A Directed Process for Adding Value
Strategy for Adding Value Effectively

- SE & Design are **Search Processes**… but
  - Conceptualizing & parameterizing the search space is part of the search process
  - Planning the process is part of the search process
  - Task assignment and organizational resource allocation is part of the search process
  - We make decisions about the process and organization; the artifact is the outcome of the process
Theoretical Framework for SE & Design

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Theoretical Explanatory Models

Improved Methods & Tools

Empirical Characterization / Falsification

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Theoretical Framework for SE & Design
Explanatory Models Supported by Empirical Evidence

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Theoretical Explanatory Models
More Valuable Methods & Tools
Empirical Character. / Falsification

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Develop a Common Research Methodology
Crucial for Making SE&D Scientific Disciplines

- Goal of research in SE&D is to understand and improve the SE&D practice
- How can we do so in a scientifically rigorous fashion?
- Several questions arise:
  - What do we mean by “improve”?
  - What is the metric for “goodness”?
  - How do we measure “goodness” practically?
  - If this metric cannot be observed directly, which other evidence can be collected to argue improvement?
  - How do we classify and quantify the quality of the evidence?
  - What are best practices for collecting evidence?
Develop a Common Research Methodology
Crucial for Making SE&D Scientific Disciplines

- Answering these questions is beyond the scope of an effort by a single investigator
- A common research methodology requires agreement / buy-in by a large portion of the community → opportunities for discussion are needed
- A common understanding or research methodology will improve the quality of research in SE&D and will accelerate progress
Develop a Common Research Methodology
Based on the Theoretical Foundation for SE & Design

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Theoretical Explanatory Models
- Improved Methods & Tools
- Empirical Characterization / Falsification
Develop a Common Research Methodology

Some Characteristics of Rigorous Research Methods

- Based on rigorous foundation
  - Axiomatic
  - Existing theories supported by empirical evidence

- Rigorously trace to the foundations
  - Combining multiple theories – integrating, reconciling,…
  - Making advances to multiple theories
  - (Note: Work with relevant experts in other disciplines – your work should be respected by these experts, publishable in their conferences,…)

- Rigorous collection of evidence
  - Repeatable, relevant experiments
  - Falsification — not just “validation”
Key Take-Aways

- In engineering practice we ask: “How?”
- In research on engineering practices we should ask: “Why?”

- We engineer new artifacts...because it adds value

- SE & Design can be modeled as a search for value

- Normative: Good SE&D methods maximize value

- Goal: A theoretical foundation that consists of explanatory models supported by empirical evidence
ESD & SYS Program Overview

What is the Scope of Each Program?

Current State of SE&D

- Standards
- Tools
- Methods
- Theory

Advance SE&D

- Theoretical Foundation
- Enabling Technology

ESD

SYE

Future State of SE&D

- Standards
- Tools
- Methods
- Theory

Apply SE&D

Value Opportunity

New Artifact

Global Context

- Economic Context
- Environmental Context
- Socio-Political Context
- Technological Context

Enabling Technology

Theoretical Foundation

Maximize Value

http://tinyurl.com/ESD-SYS
Some References & Introductory Material