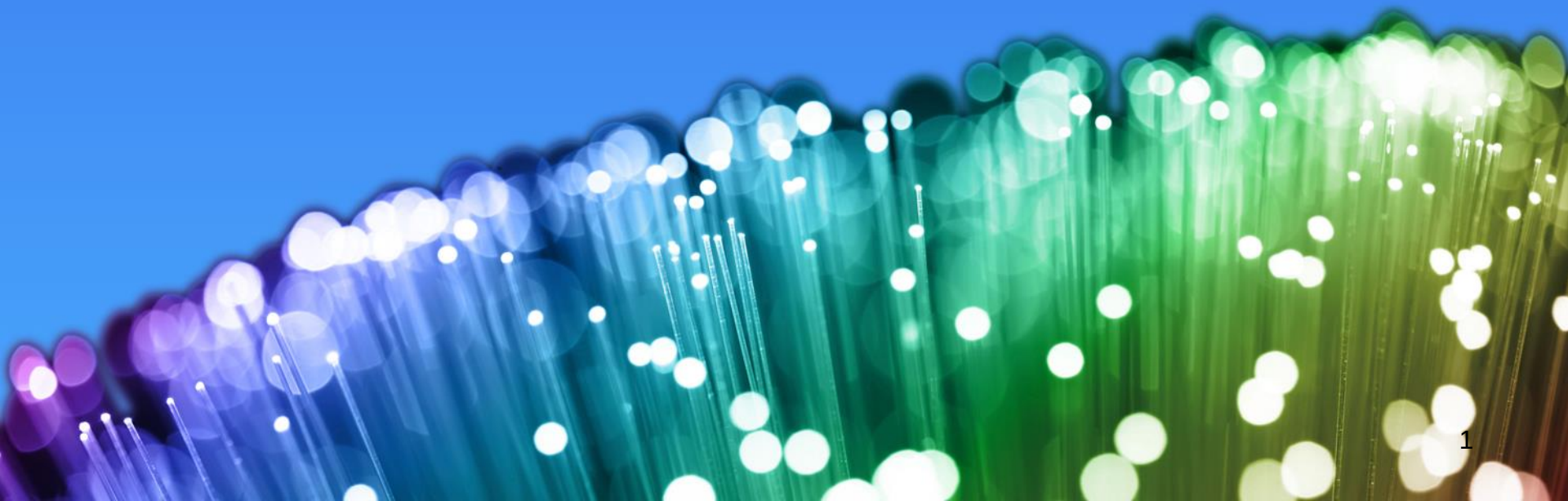
# Research Directions for Developing a Rigorous Foundation for MBSE

Chris Paredis
Program Director
NSF ENG/CMMI Engineering & Systems Design, Systems Science
cparedis@nsf.gov
(703) 292-2241

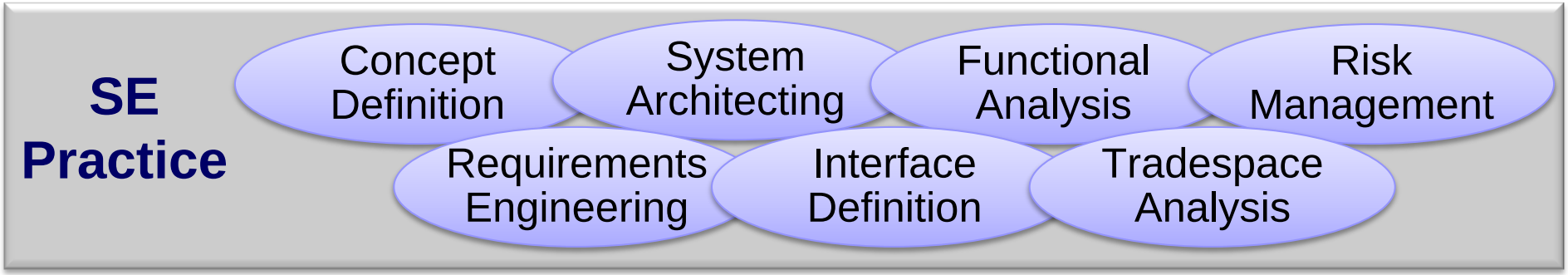


# Disclaimer

- 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 Foundation: What and Why?

## How Best to Practice SE Depends on the Context




- The context is constantly changing…
  - Increasing complexity
  - Shorter lifecycle times
  - Decentralization
  - Systems of Systems
  - Mass-customization
  - Human-centered
  - Cloud-based high-performance computing
  - Big data
  - Immersive data visualization
  - Net-enabled collaboration
- Aero/Defense → Security, Health, Transport, Mfg, …

# Theoretical Foundation: What and Why?

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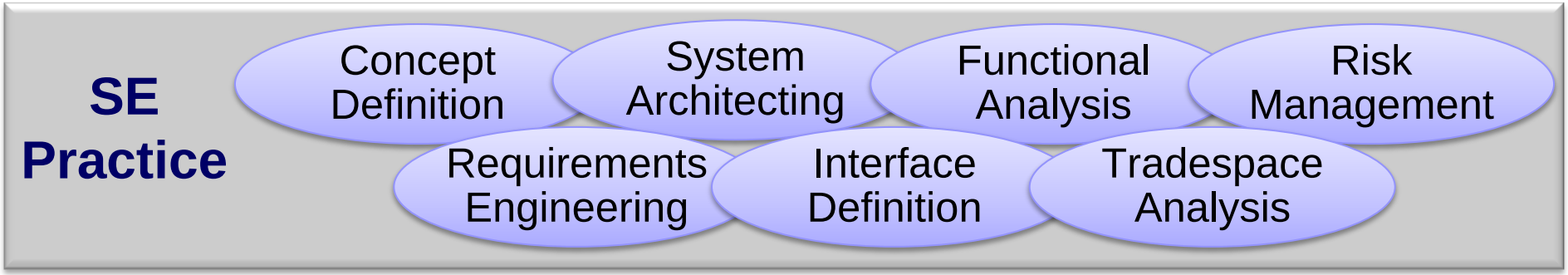


- T
  - Decentralization
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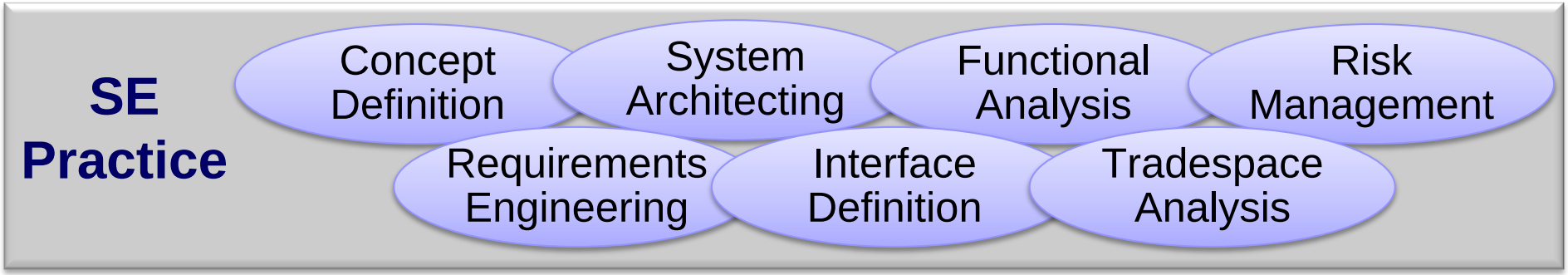
  - Net-enabled collaboration

**To adapt efficiently to a new context and to extend to new domains, we must have models that explain rather than just describe**

- Aero/Defense → Security, Health, Transport, Mfg, …

# Theoretical Foundation: What and Why?

## The Need for Explanatory Models




Observe & Describe → Understand & Explain → Extend & Improve

We need to ask not only "**How** do we do SE?"

but also "**Why** do we do it this way?"

# Theoretical Foundation for SE

## A Rigorous, Scientific Methodology

**SE Practice**

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

Observe & Describe → Understand & Explain → Extend & Improve

**Foundations**

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

# Theoretical Foundation for SE

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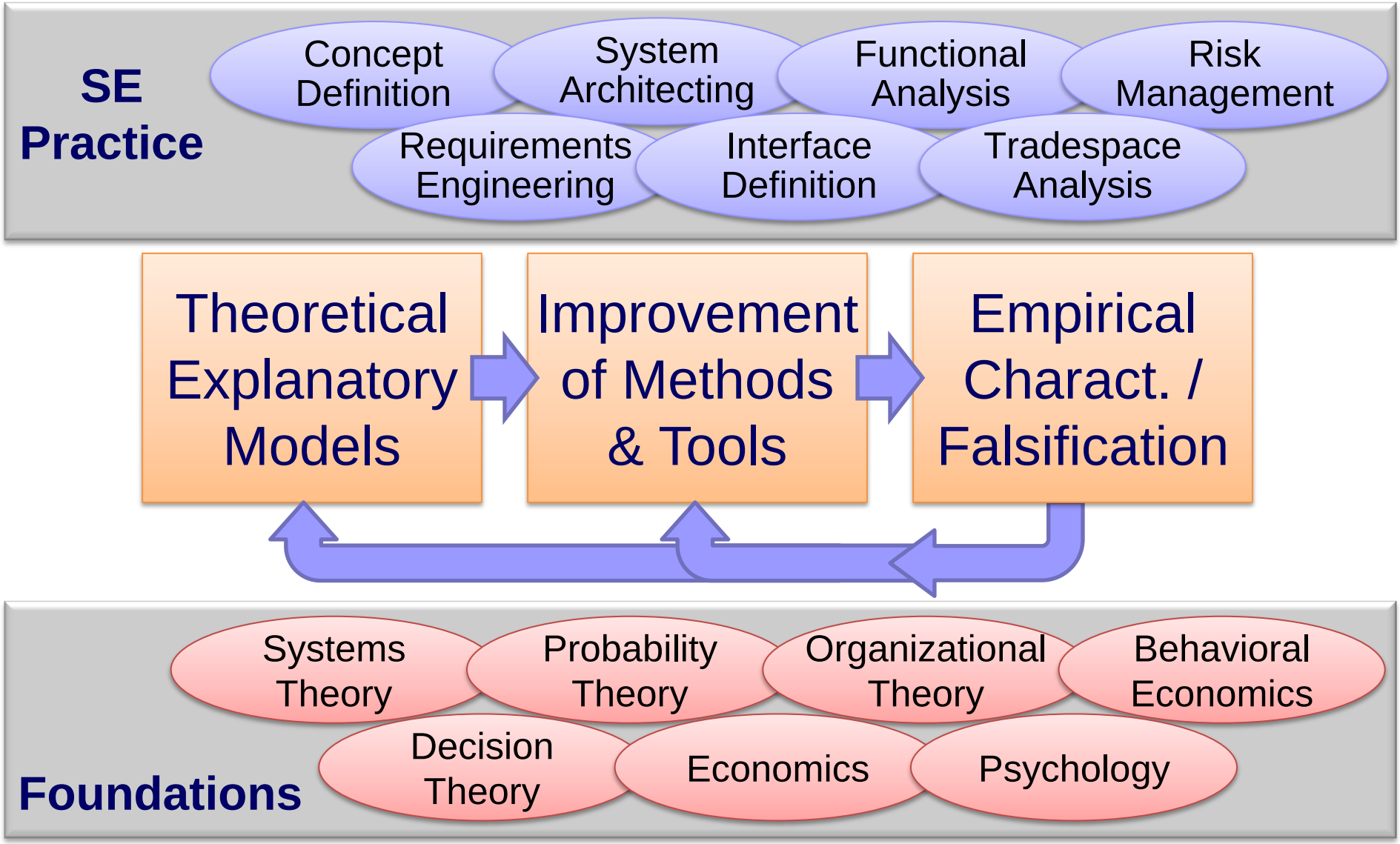


# Presentation Overview

- The need for a theoretical foundation for SE

- A common theoretical foundation?
  → start from the basics

- Some research issues in MBSE

# Starting from the Basics…

## SE is a Process with a Purpose

- What is the purpose of the SE process?

→ To obtain a state of the world that is more preferred

→ To add value

# What do we Mean by Value?

## Value is an Expression of Preference

- Value is an expression of preference — the more an outcome is preferred, the higher the value assigned to it
  - A philanthropist may assign high value to an alternative that significantly increases well-being even if it cannot be produced at a profit
  - An environmentalist may assign high value to environmentally friendly, sustainable alternatives
  - A publicly traded company may assign high value to profitable alternatives
- Value is often expressed in monetary terms
  - If a designer prefers outcome A over outcome B then he/she is willing to pay an amount of $\Delta v = v_A - v_B$ to exchange B for A
  - Applies to any preference without loss of generality

# Starting from the Basics…

## SE is a Process with a Purpose

- What is the purpose of the SE process?

→ To obtain a state of the world that is more preferred

→ To add value

- How do we add value?

→ By creating or improving artifacts

- How do models play a role?

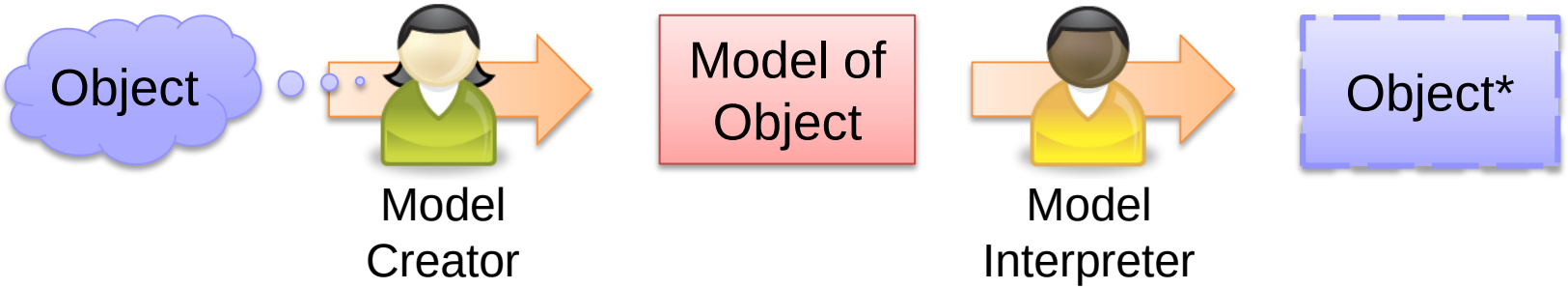
→ Specify a plan before execution

→ Predict the consequences

Creating a plan adds value

# Starting from the Basics: What is a Model?

## A model is an expression of human thought




- In SE, we model aspects of the artifact being engineered
  - Description
    - Structure of Environment
    - Measurements
  - Specification
    - Structure of artifact
    - Behavior of artifact
    - Manufacturing process
    - Operations/Maintenance plan
  - Prediction
    - Performance
    - Cost & Schedule

    → Value
- Why Model-Based Systems Engineering?

  → Modeling more formally adds value

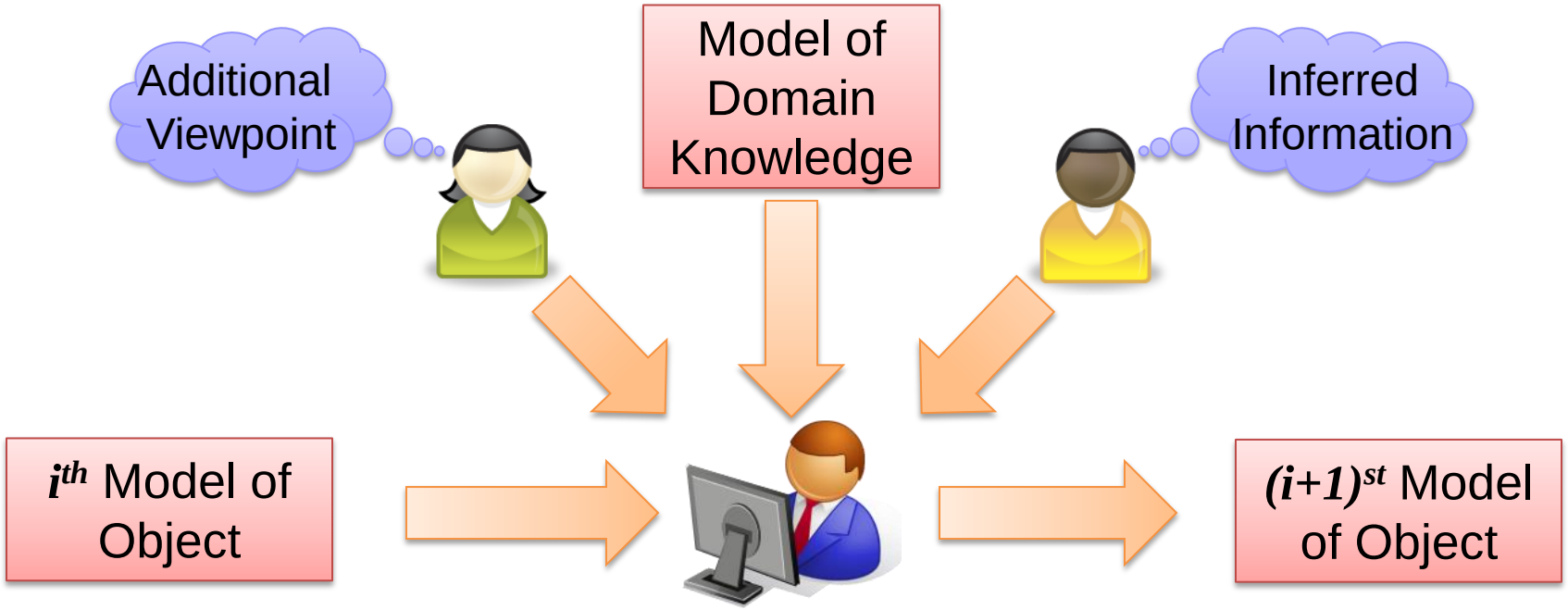
# Why Do We Model?

## Modeling adds value by enhancing…

- Communication
  - The model interpreter can extract information about the object without having first-hand knowledge of it, or without interacting with the modeler
- Memorization
  - Helps humans overcome the cognitive limitations of short-term memory
- Inference or Reasoning
  - Through the application of mathematics, we can infer new information about the modeled object.
  - Inference mechanisms include logic, algebra, differential/integral calculus, probability theory, optimization,…
- Understanding
  - We model things that are too complicated to think through in memory

# Modeling as a Transformation Process

## Incrementally and collaboratively refining thoughts




**Transform Model**

- Inference or Reasoning
- Abstraction, Refinement
- Augmentation, Integration

Add Value by Enhancing Human Cognition

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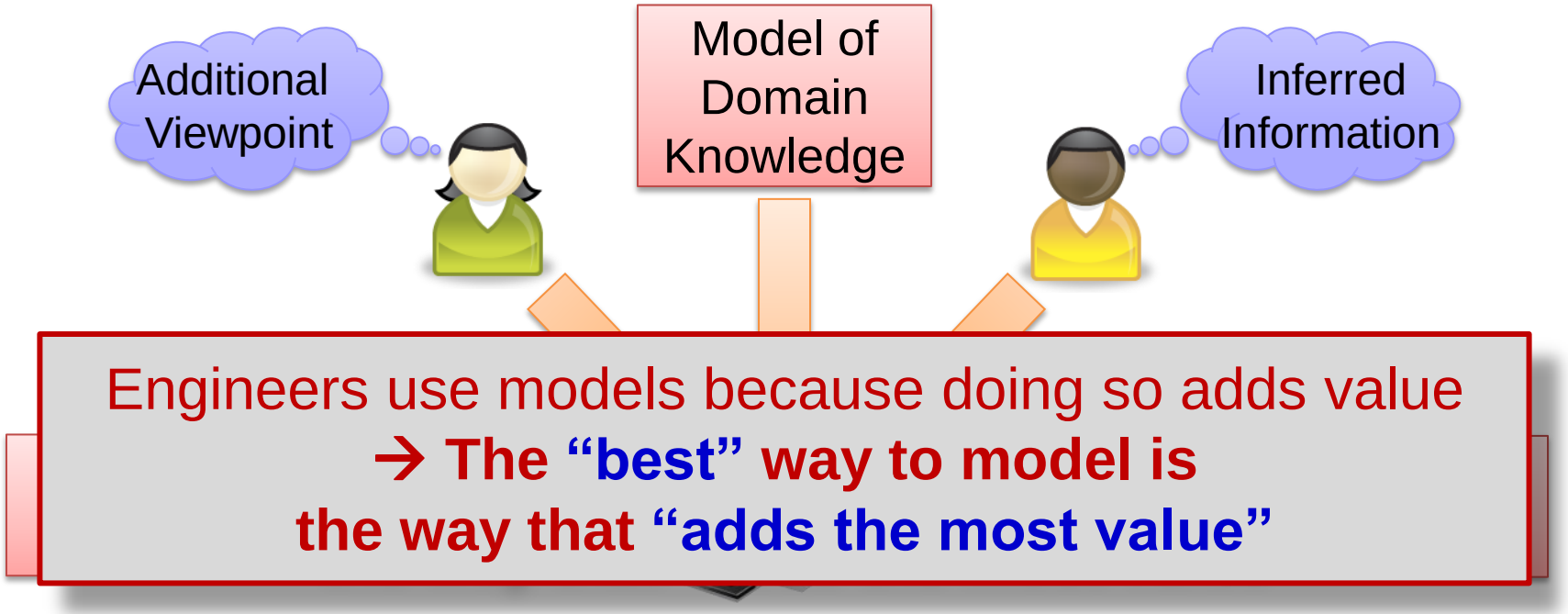


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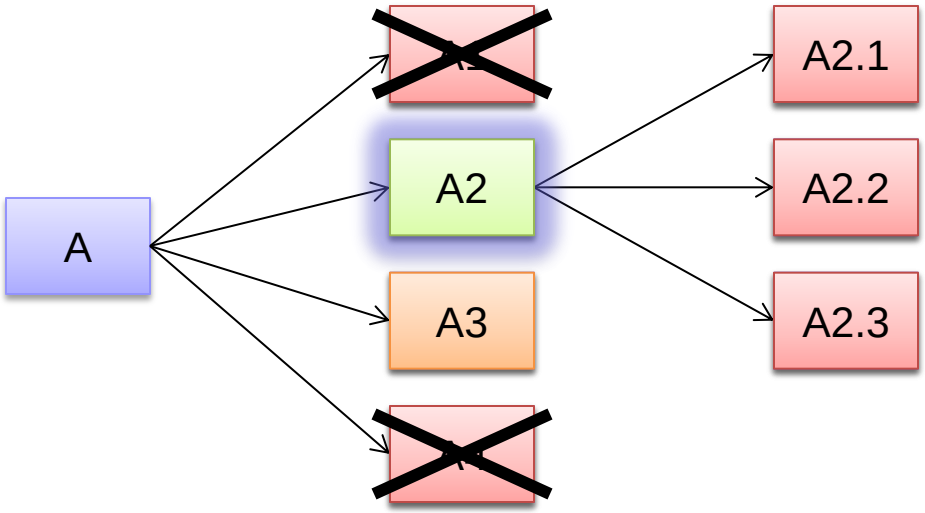
# Systems Engineering: A Search Process

## Strategy for Adding Value Effectively

- Ideation → Analysis and Evaluation → Selection or Pruning



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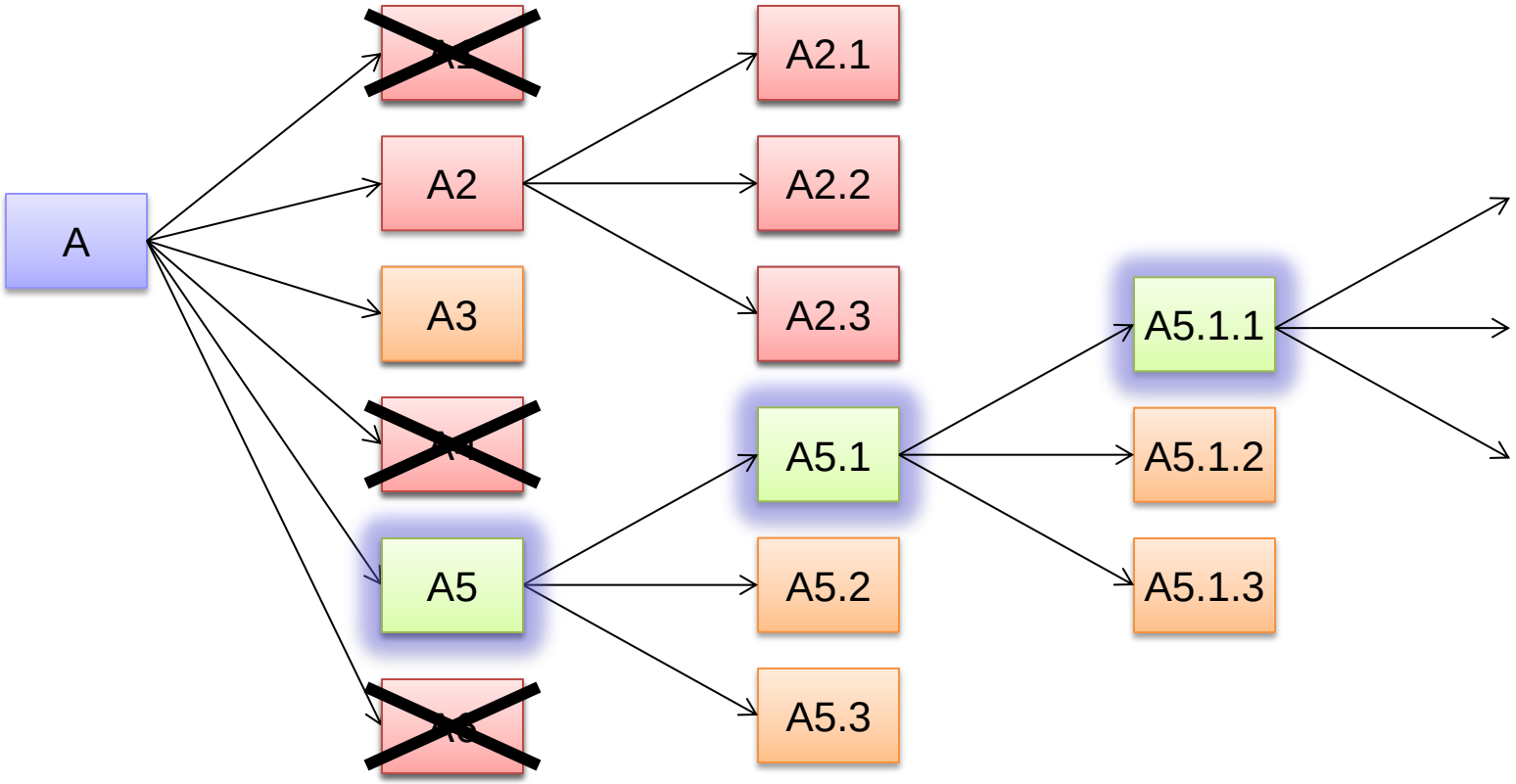
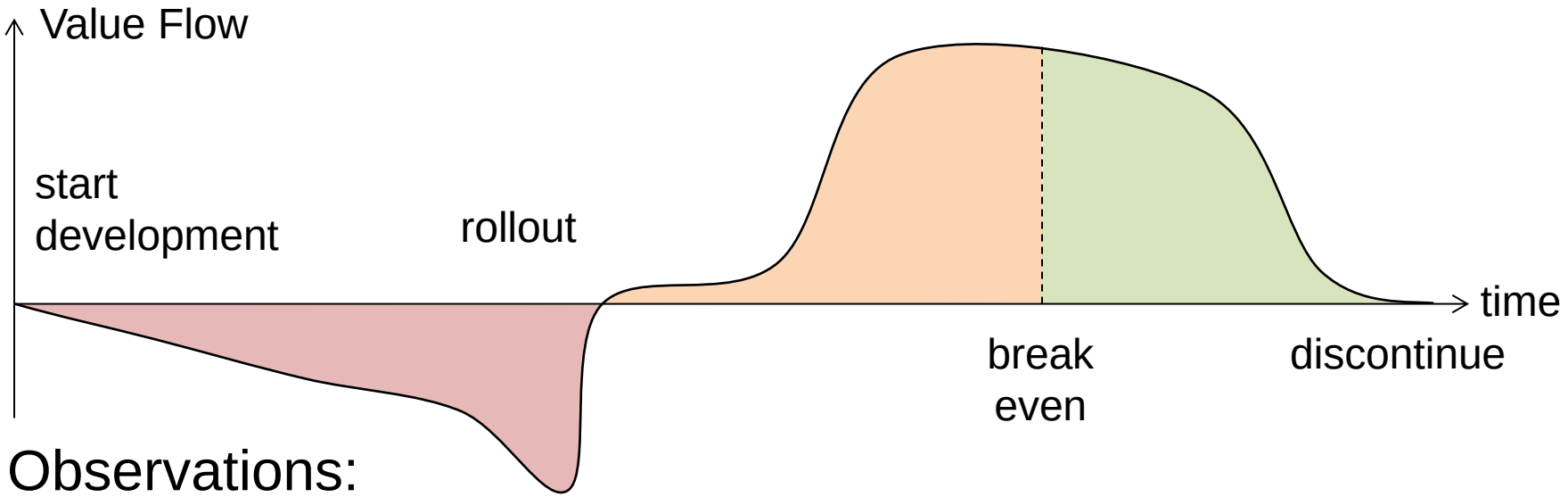


# Systems Engineering: A Search Process

## Value Flows Throughout the Lifecycle




- Observations:
  - Initially, negative value flow: We invest in developing a detailed plan to gain confidence that the realized artifact results in positive value
  - The cost of development influences the overall outcome
    → we must consider the value of the full product life
    → need to trade off cost/time of development vs quality/performance of artifact

# Systems Engineering: A Search Process

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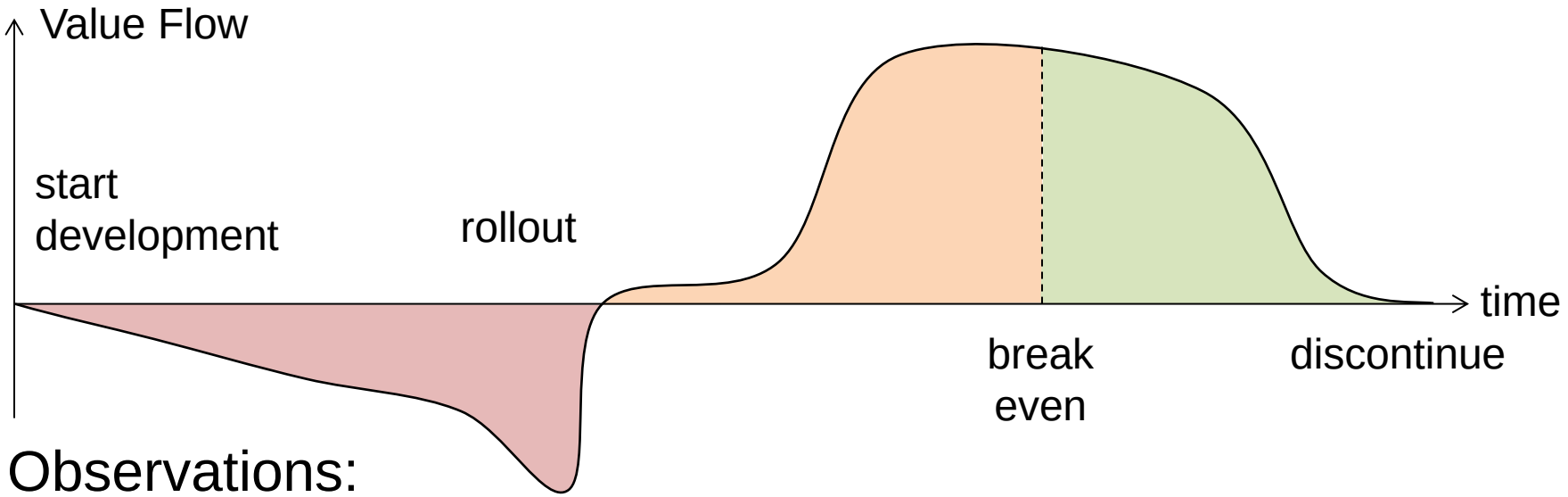


- Observations:
  - Value flows occur in the future → must account for time preferences
  - Value flows are uncertain → must account for uncertainty preferences

→ Probability theory, decision theory, microeconomics

→ Maximizing the expected utility of net-present value

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

# SE in an Organizational Context

## Many Independent Decision Makers

- Multiple decision makers as leaders
  - Group preferences are often intransitive
    → an organizational objective function does not exist
  - Must be considered as a negotiation → game theory
    → group behavior emerges from the actions of individuals
  - Win-win can often be achieved through cooperation rather than competition

- Individual decision makers at all levels
  - Incentives must be used to align individual preferences with organizational objectives → principal-agent theory
  - Decomposition of decision problems, and coordination and synchronization of decision processes is needed
    → mechanism design, distributed control theory

# SE in an Organizational Context

## Many Individual Experts

- No individual has all the knowledge about the system… instead, many individuals have deep knowledge about different, specialized aspects of the system
  - How do we integrate all the knowledge such that we develop successful, valuable systems?
    → distributed cognition — knowledge is embodied in the environment, among people, and across time
  - Inverse problem: How do we divide up the problems so that the necessary knowledge is easily identified, compiled and integrated?
  - How do we achieve common understanding and avoid miscommunication? → modeling and ontology engineering
  - How do we discover which knowledge is relevant and needed in the first place? → sensemaking and situational awareness

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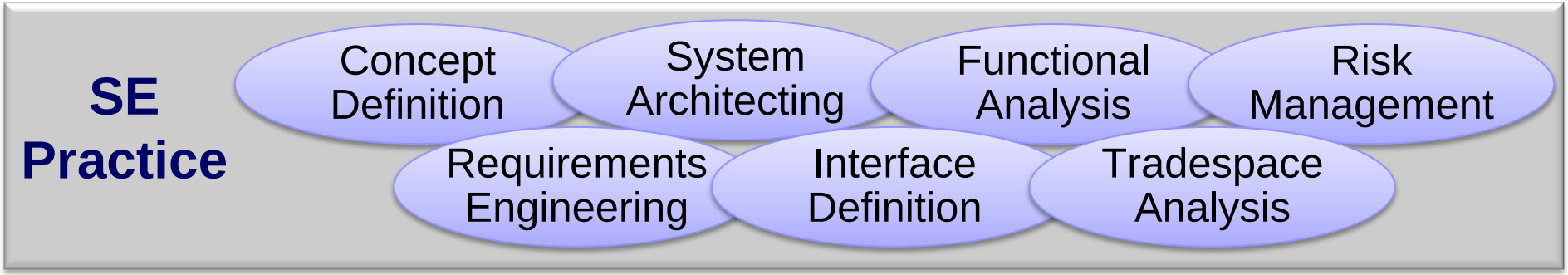


We need to ask not only "**How** do we do SE?"

but also "**Why** do we do it this way?"

Answer should be:

Because this way is most valuable

# Key Takeaways

Not only ask “How?” but also “Why?”

- Purpose of systems engineering:  to add value
- Adopting practices that rigorously build on a sound integrative theoretical foundation adds value
- Relevant underlying bodies of knowledge encompass mathematical sciences as well as human sciences
- Significant improvement is possible by adapting existing, known theoretical foundations for use in MBSE