A Value-Driven Perspective of Modeling and Optimization in Systems Engineering

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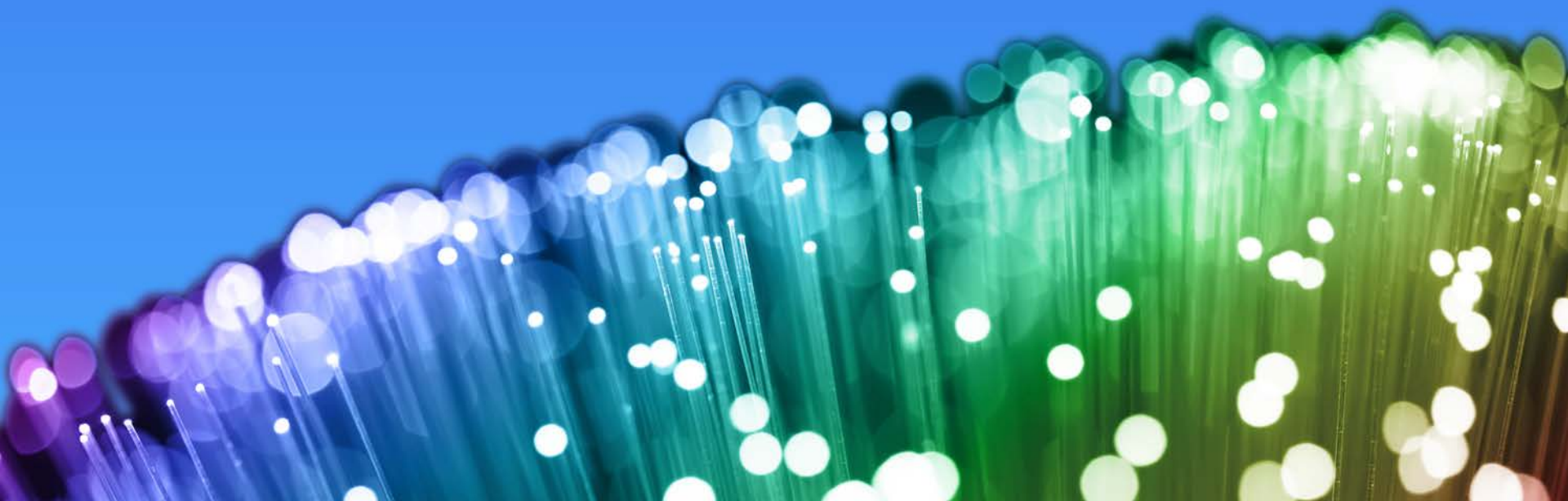


Disclaimer & Acknowledgment

- 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.

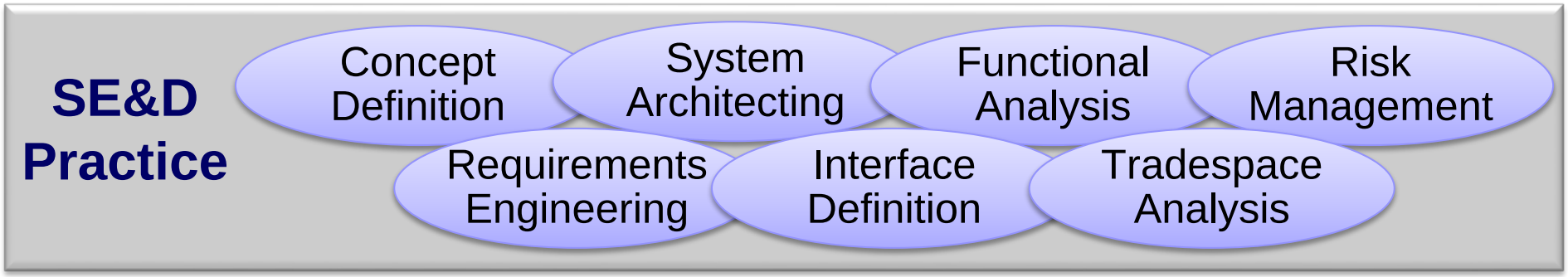
- Acknowledgment:
  - SE Vision 2025 Working Group

    (http://www.incose.org/newsevents/announcements/docs/SystemsEngineeringVision_2025_June2014.pdf)
  - Interagency Working Group on Engineering of Complex Systems
  - My students, in particular, Ben Lee

    (B.D. Lee & C.J.J. Paredis, "A Conceptual Framework for Value-Driven Design and Systems Engineering," *24th CIRP Design Conference*, Milan, Italy, April 14-16, 2014.)

Need for a Stronger Theoretical Foundation

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

Need for a Stronger Theoretical Foundation

An Example: The V-Model

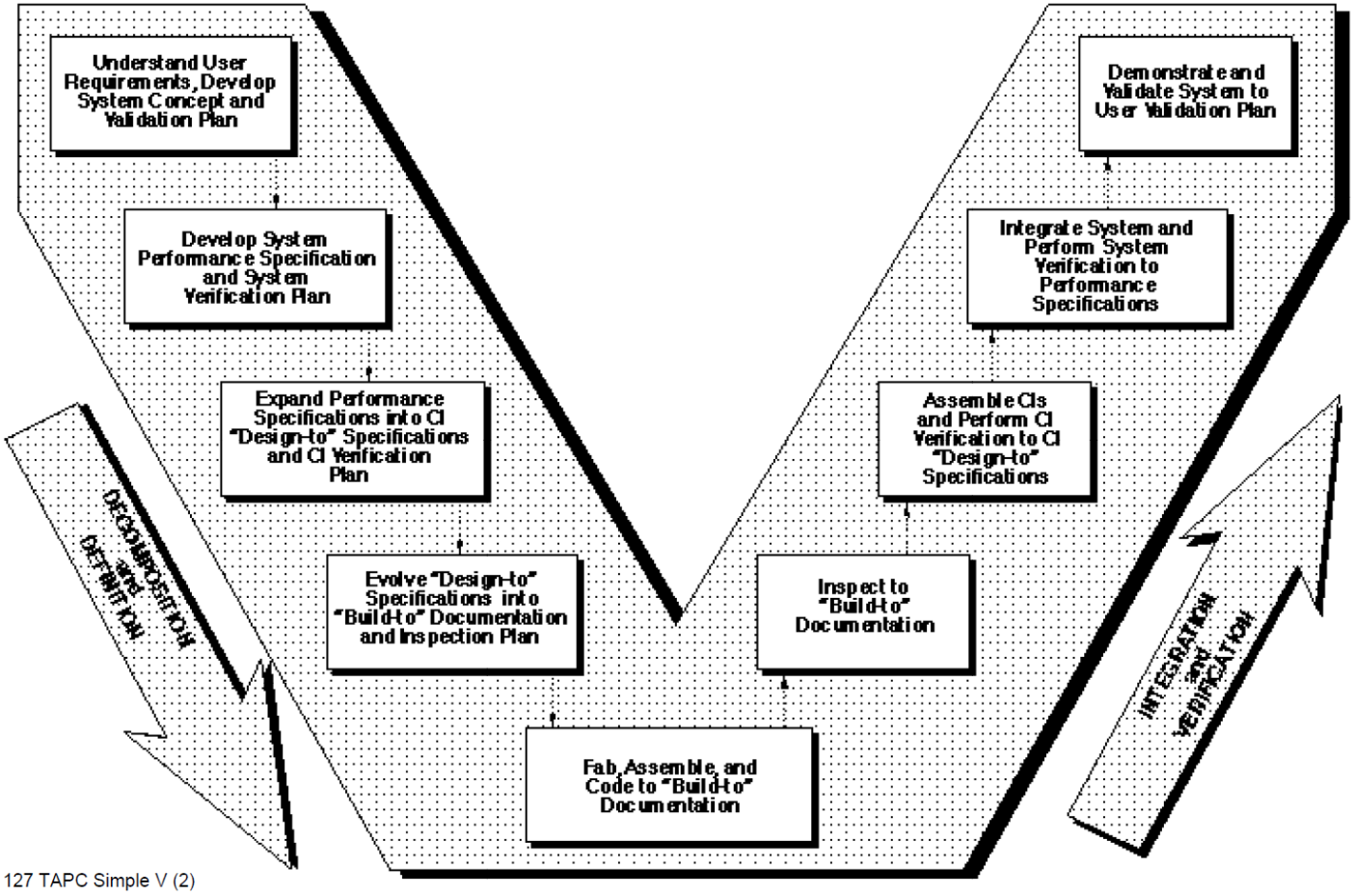
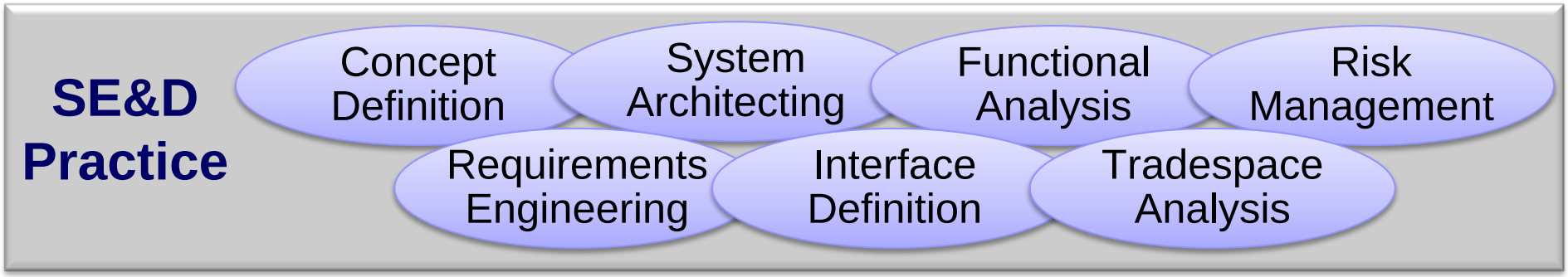


Exhibit 5—Overview of the Technical Aspect of the Project Cycle

Forsberg, Mooz, 1995.
http://ife2010.wikispaces.com/file/view/SE+%26Project+Cycle,+Forsberg%26Mooz,+1995.pdf

Need for a Stronger Theoretical Foundation

The Need for Explanatory Models



- The V model describes and prescribes but **does not explain —** Why do we design in this fashion?

Why do we use **modeling, simulation** and **optimization** in the way we do?

Is this a good way?

Presentation Outline

- Need for a Stronger Theoretical Foundation:
  - Asking “Why?” rather than just “How?”
- To Explain Why… Start from the Basics
  - Value-driven perspective of systems engineering & design
  - The role of modeling and simulation in SE&D
- Explaining & Questioning Current Practices
  - Gradual refinement
  - Optimization framing
- Key Take-Aways

Starting from the Basics…

SE & Design are Processes with a Purpose

- 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?

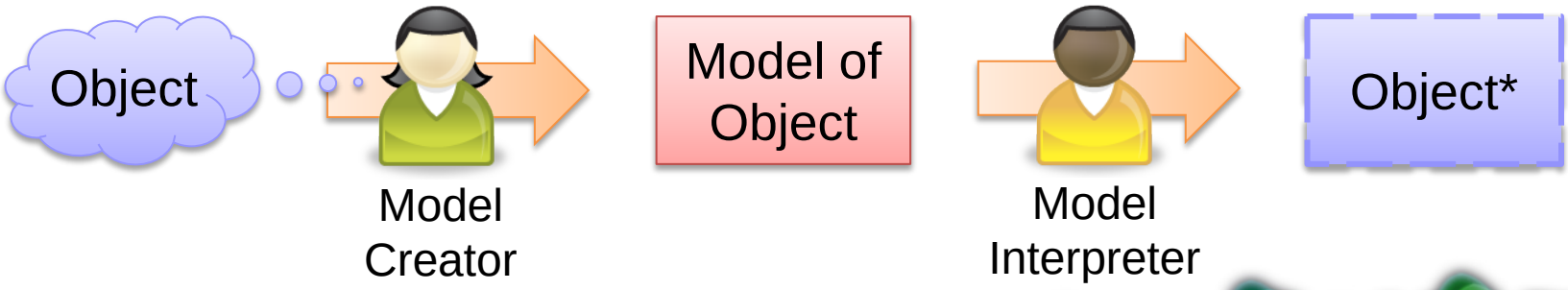
→ By creating or improving artifacts

- SE & Design are transformation processes
  - Primarily a process of information transformation — we compile information specifying a plan for how to create or improve artifacts

Starting from the Basics…

A model is an artifact that represents a (real or imagined) object

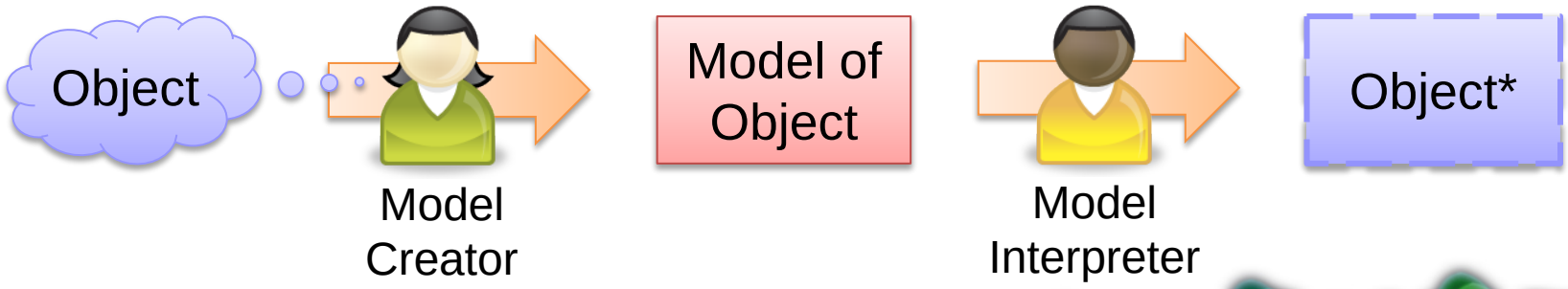
- A model is an artifact
  - An expression of human thought — created by one or more humans
- A model is a representation of an object
  - Object = anything a human can think of — imagined or observed
  - Representation = an externalization of the thought – a sculpture, a drawing,
    a textual description, or a more formal representation in a modeling language with (more) formal syntax and semantics
  - The model reveals something about the object to an interpreter



Why Do We Model?

Expressing and representing thoughts help us with…

- Communication
- Memorization
- 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



Why Do Engineers Use Models?

Systematically planning to improve the world

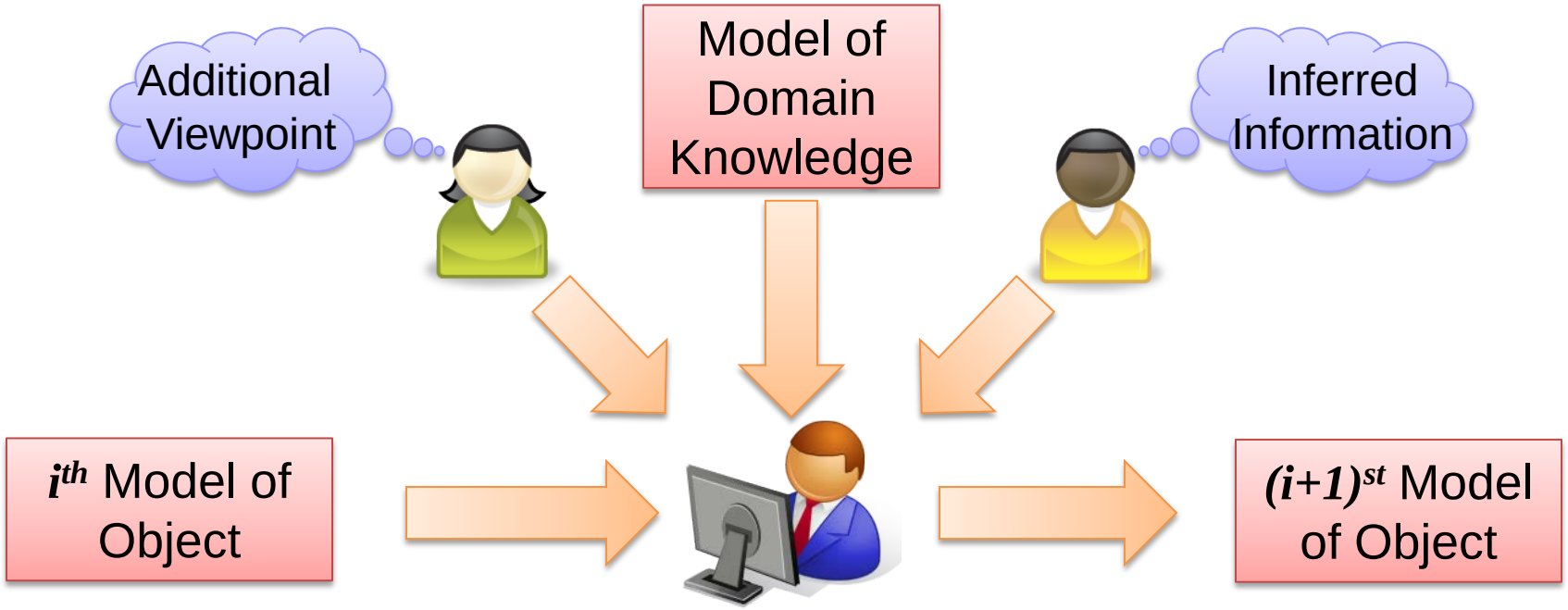
- Models are a valuable means for arriving at a desired world state
  - Models serve as a plan for how to transform the real world. The plans are often complicated — modeling them adds value
  - Models are used to anticipate consequences in the real world — we can feel confident that the consequences are valuable before executing the plan
  - Models allow us to reuse knowledge and experience — avoiding the costs of having to relearn

→Engineers use models because doing so adds value

→The “best” way to model is
“the way that adds the most value”

Modeling as a Transformation Process

Incrementally and collaboratively refining thoughts



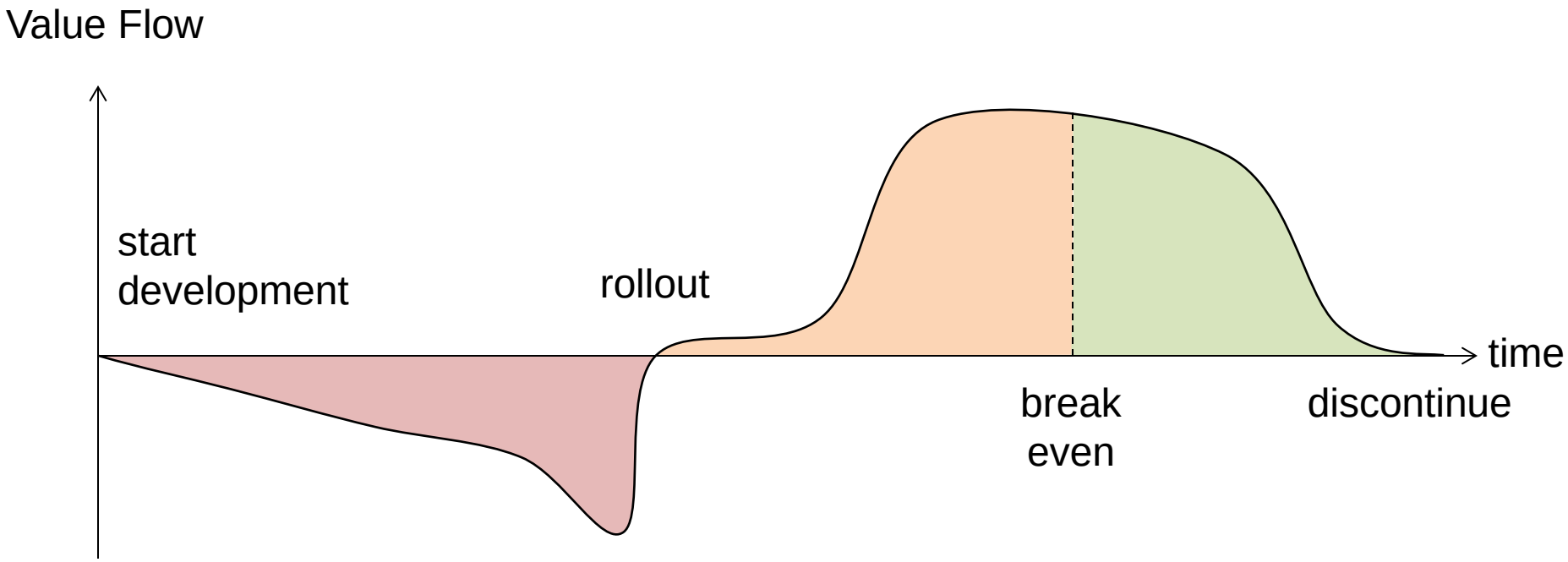
Transform Model

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

Add Value by Enabling Better Decisions

The Value of M&S Engineering

A Search Process to Maximize Value



- Maximizing the expected utility of net-present value:

$$\mathcal{A}\colon \max_{a \in A} \mathrm{E}[u(NPV(a))]$$

The Value of M&S Engineering

A Search Process to Maximize Value

- Maximizing the expected utility of NPV:

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

- Issue: the search problem has become self-referential
  - Leads to path dependence → the chosen artifact depends on the path taken through the artifact search space
  - 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…

The Value of M&S Engineering

A Search Process to Maximize Value

- Maximizing the expected utility of NPV:

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

- Maximizing from a process perspective

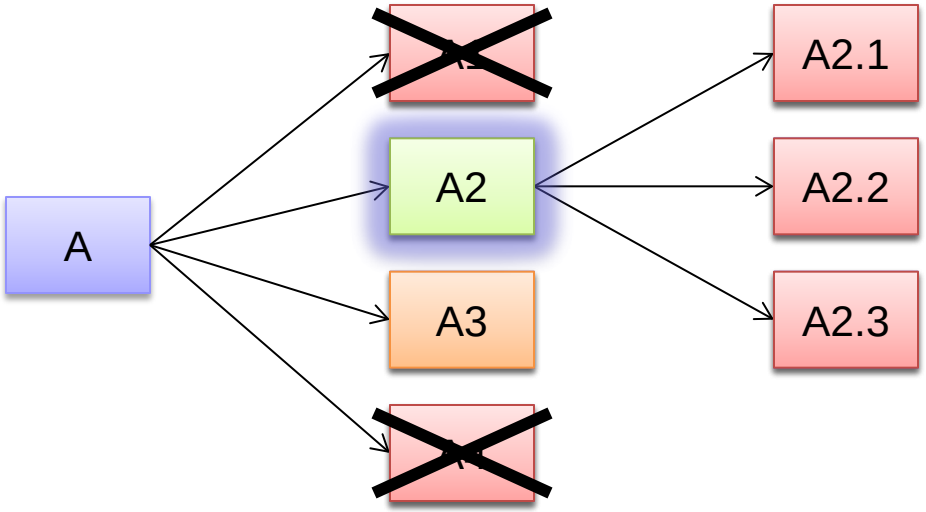
$$\mathcal{P}: \max_{p \in P} \mathrm{E}\left[u\left(NPV(a(p), t(p), C(p))\right)\right]$$

  - No longer self-referential, but still path dependent → the best choices for future process steps depend on the outcomes of previous process steps

M&S and Optimization in Search

Strategy for Adding Value Effectively

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



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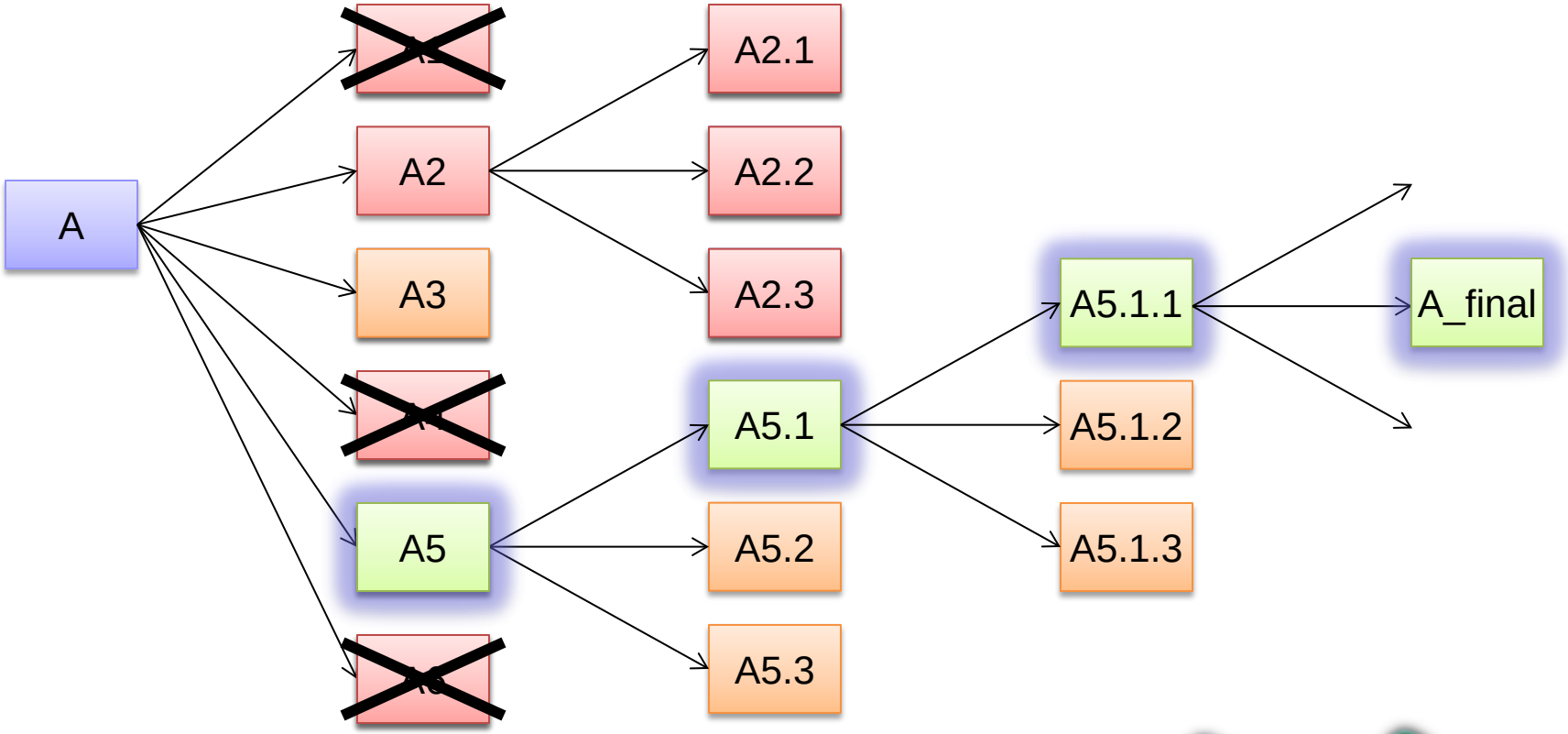
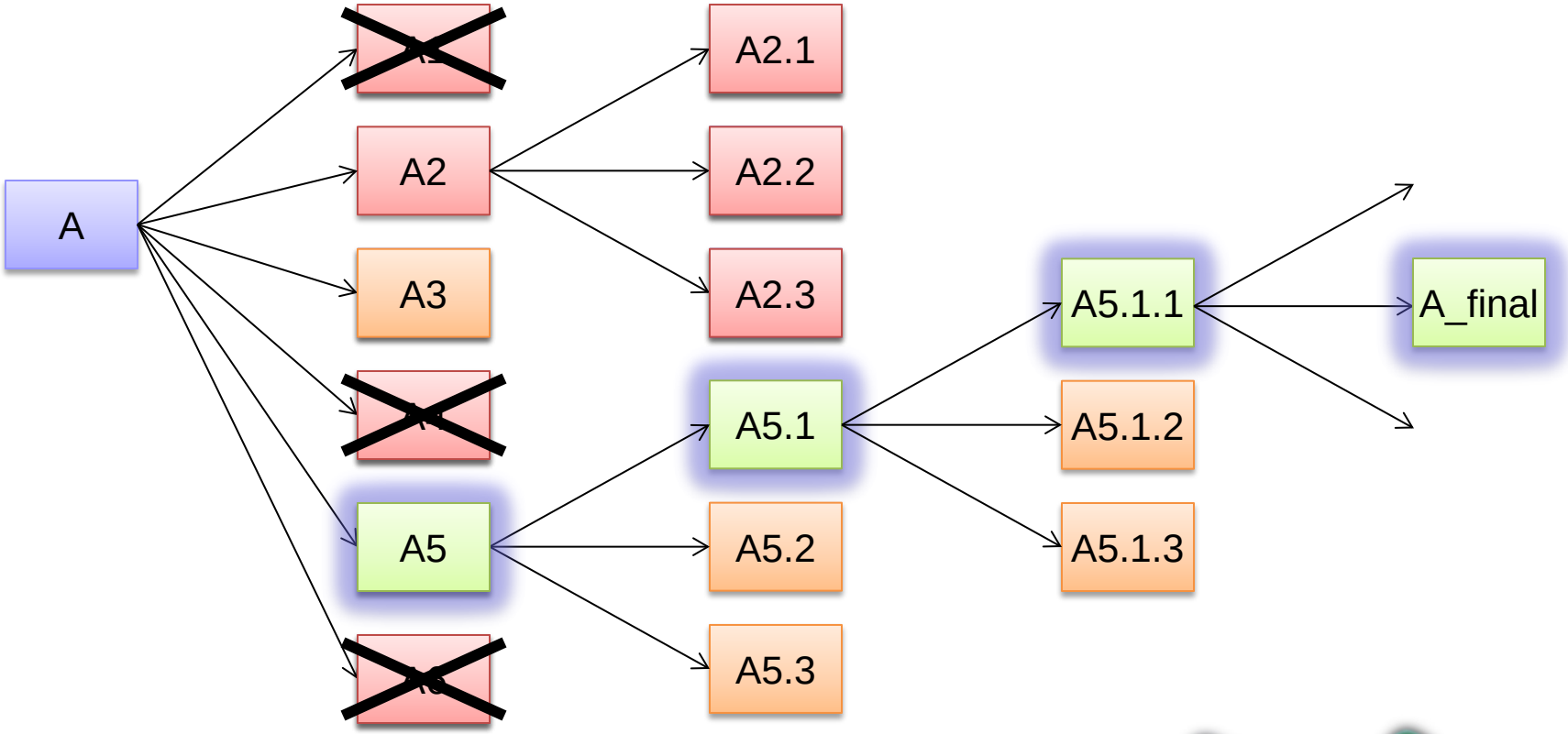


M&S and Optimization in Search

Strategy for Adding Value Effectively

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



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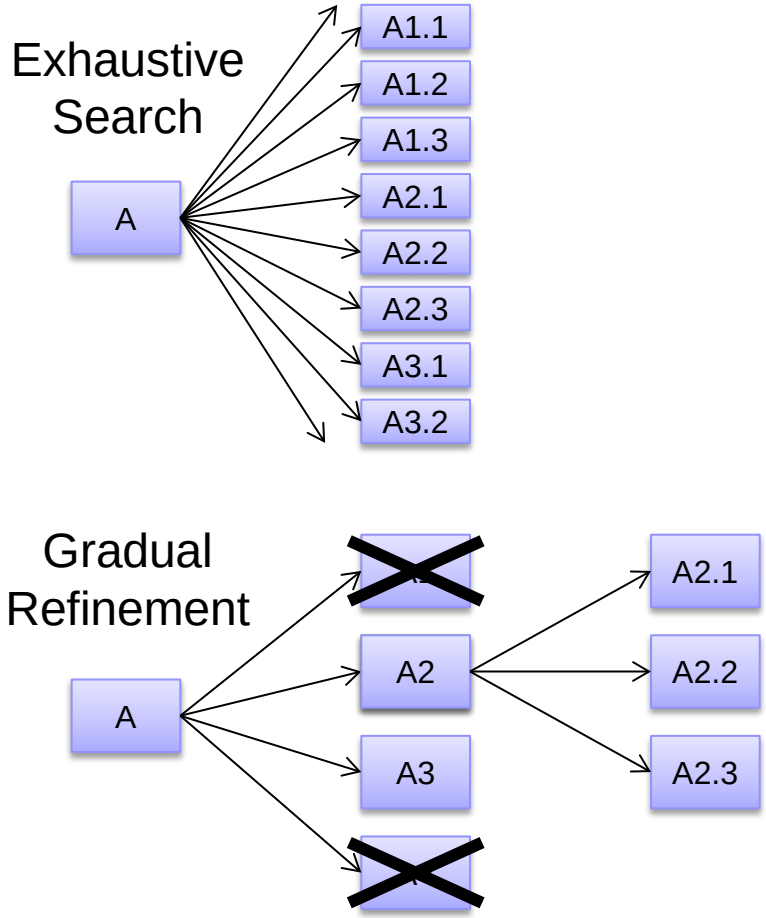
Explaining M&S: Why Gradual Refinement?

Gradual Refinement of System Specification



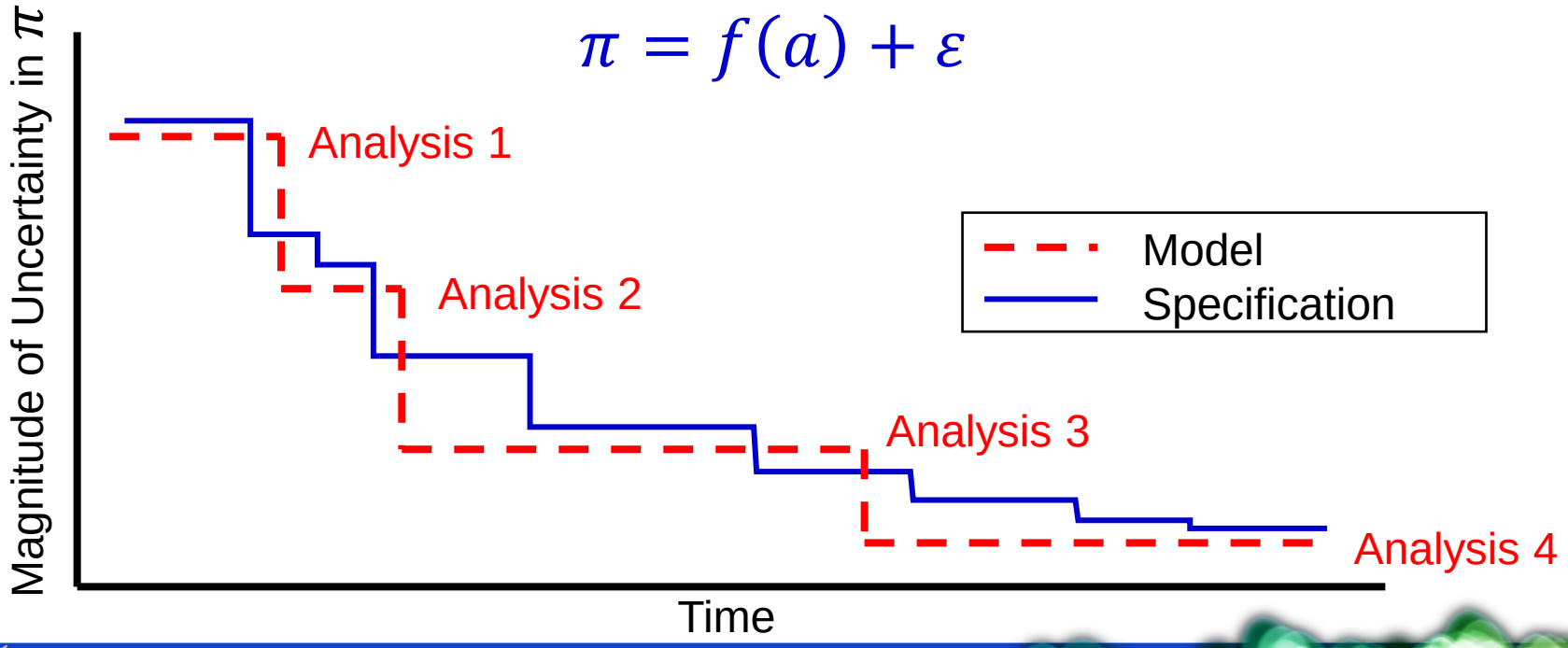
- Exhaustive Search:
  - Cost of synthesis and analysis is too high
- Gradual refinement of system specification is advantageous because
  - it allows for pruning → fewer specifications are considered
  - facilitates ideation
- But it carries a risk that the most preferred alternative is also pruned

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

Explaining M&S: Why Gradual Refinement?

Gradual Increase in Analysis Accuracy

- Uncertainty in prediction of artifact value, π, results from:
  - Specification uncertainty (uncertainty in a)
  - Analysis model uncertainty (ε)
- More accurate models (smaller ε) tend to be more expensive



Explaining M&S: Why Gradual Refinement?

Gradual Increase in Analysis Accuracy

- How does gradual refinement impact value?
  - + Reduces the cost of ideation
  - + Reduces the cost of an analysis
  - + Reduces the number of artifacts to be analyzed
  - – Increases probability that a worse artifact will be selected
- Conclusion:
  - – 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.

→ Gradual refinement is a good process heuristic

Framing of Optimization Problems

Gradual Increase in Analysis Accuracy

- Common practice:
  - Define the optimization space
  - Create a (deterministic) model for the objective
  - Optimize → to find the optimal design alternative

Why is this a good approach?

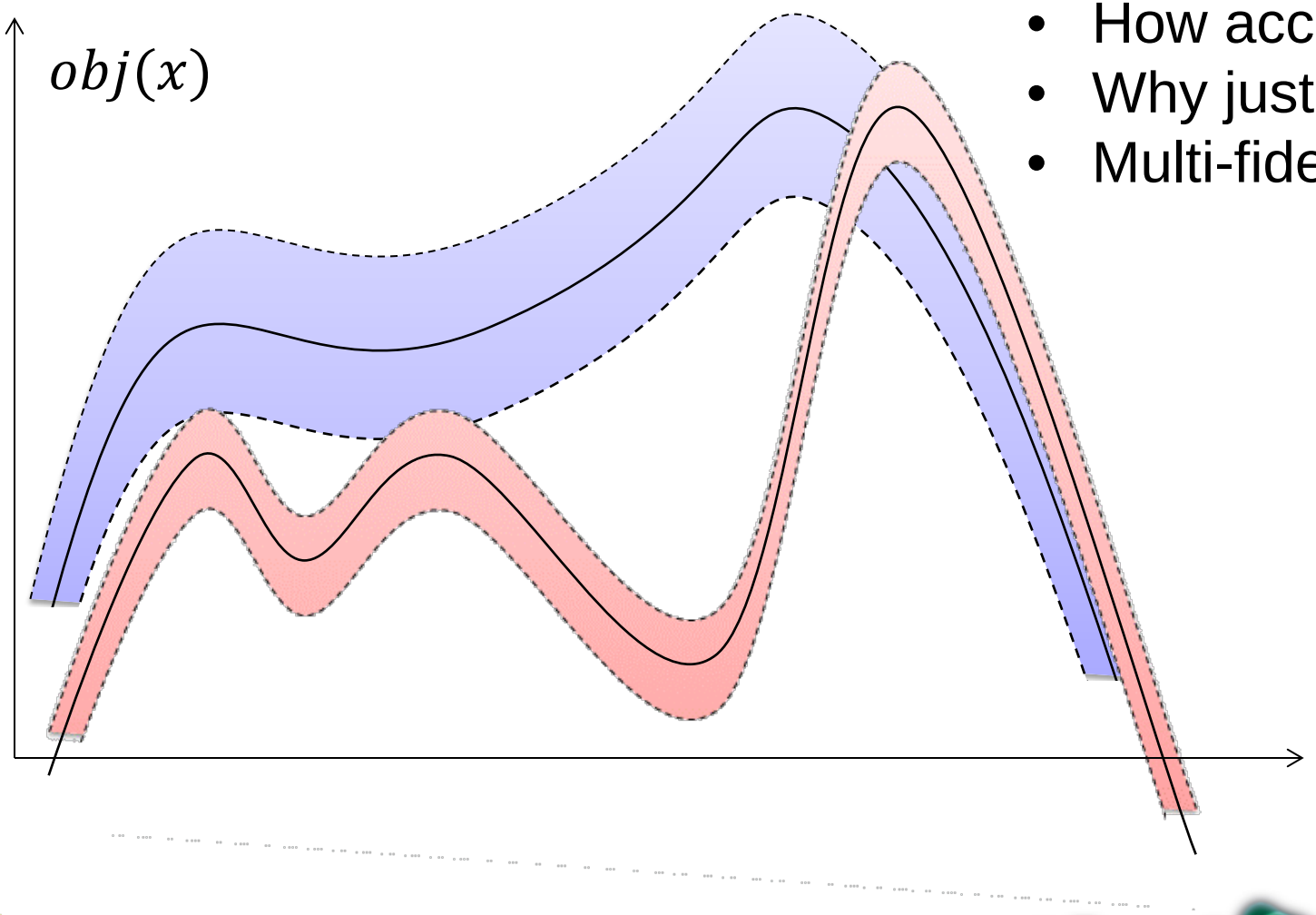
Is this really a good approach?

- Should be answered based on value maximization

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

Framing of Optimization Problems

Which Analysis Model?



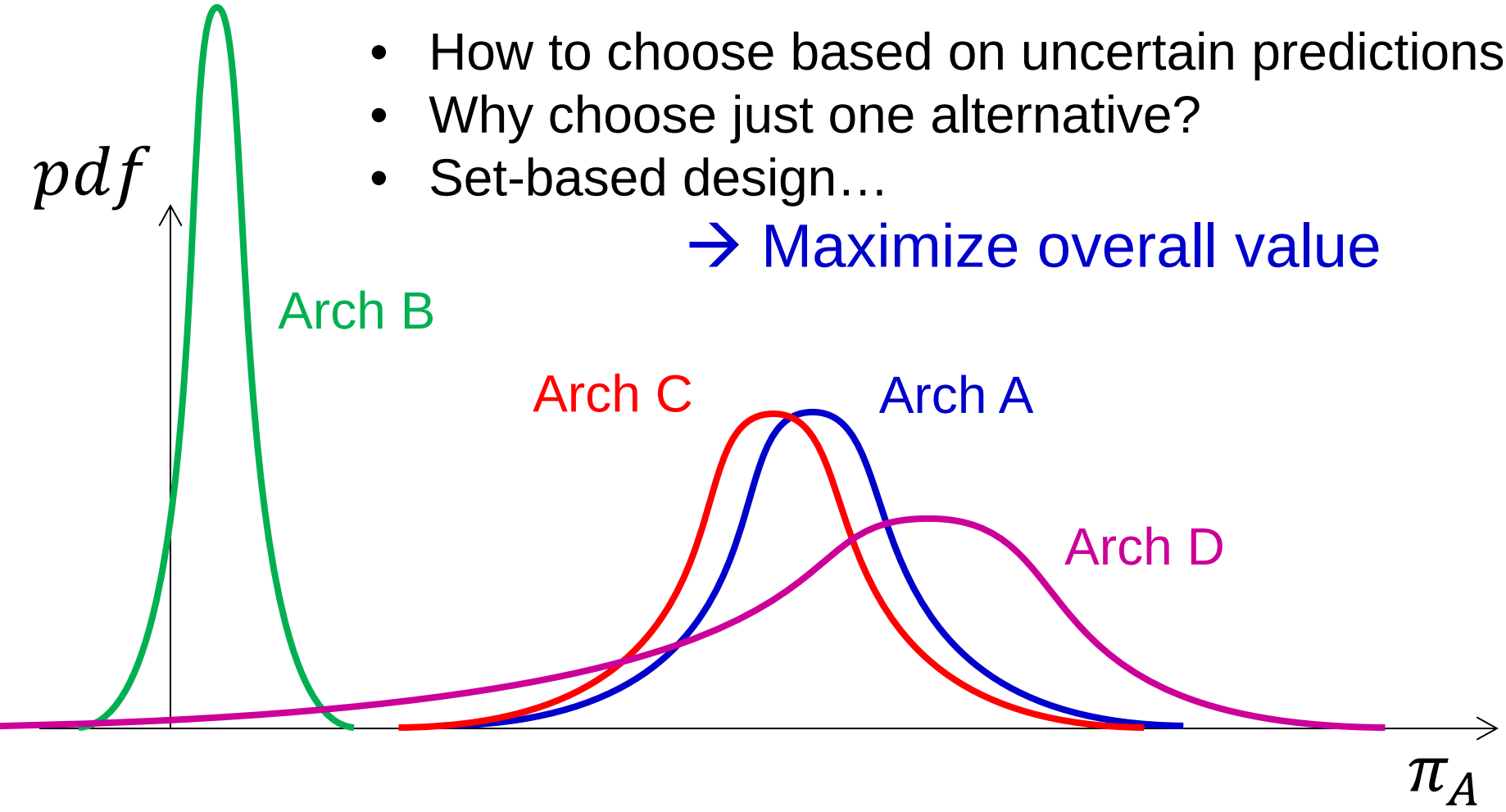
- How accurate?
- Why just one model?
- Multi-fidelity models…

Framing of Optimization Problems

"Optimal" or "Optimized" Design Alternative?

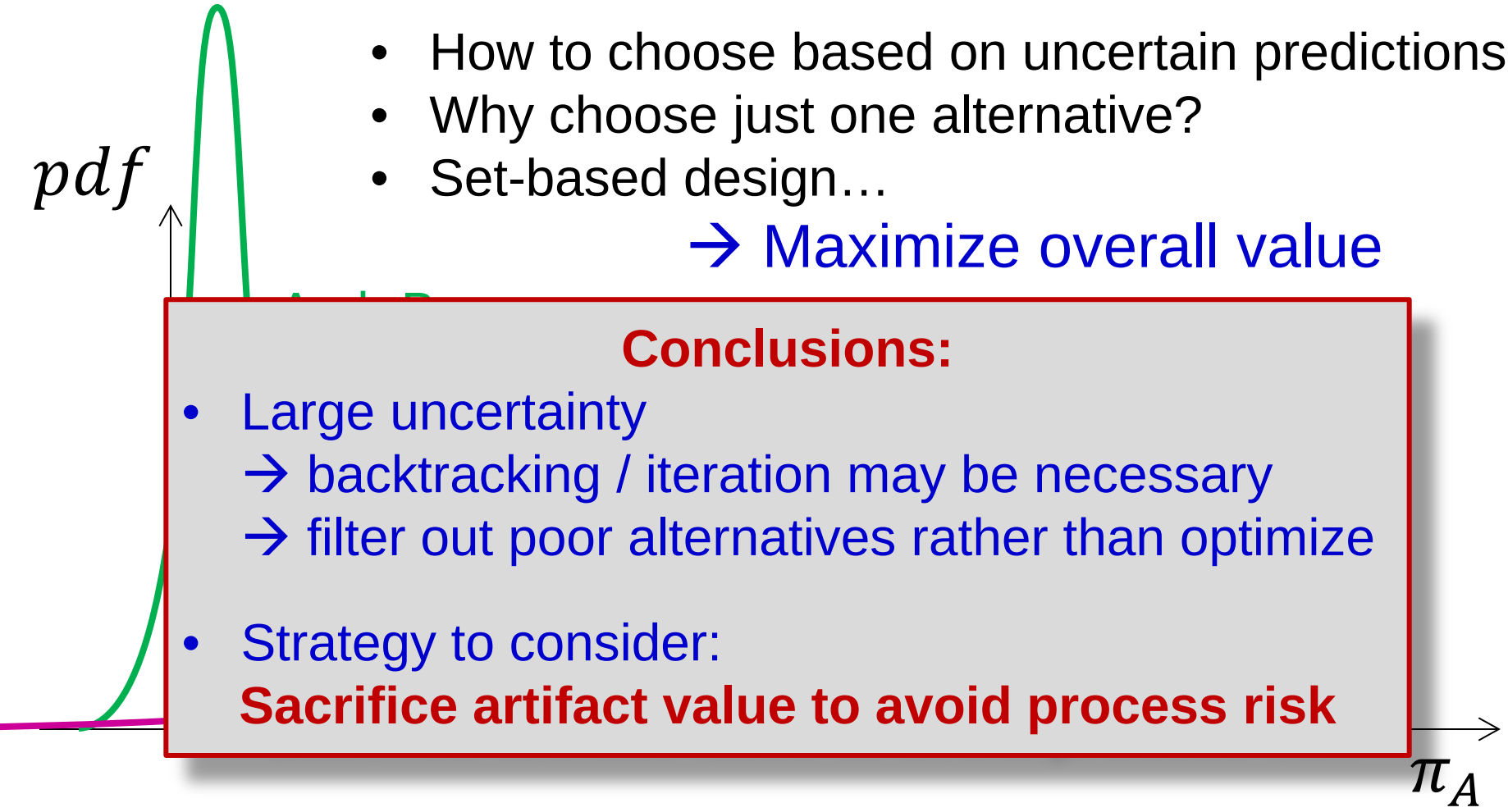
- How to choose based on uncertain predictions?
- Why choose just one alternative?
- Set-based design…

→ Maximize overall value



Framing of Optimization Problems

"Optimal" or "Optimized" Design Alternative?



- How to choose based on uncertain predictions?
- Why choose just one alternative?
- Set-based design…

→ Maximize overall value

Conclusions:

- Large uncertainty
  → backtracking / iteration may be necessary
  → filter out poor alternatives rather than optimize
- Strategy to consider:
  Sacrifice artifact value to avoid process risk

M&S and Optimization in Search

Strategy for Adding Value Effectively

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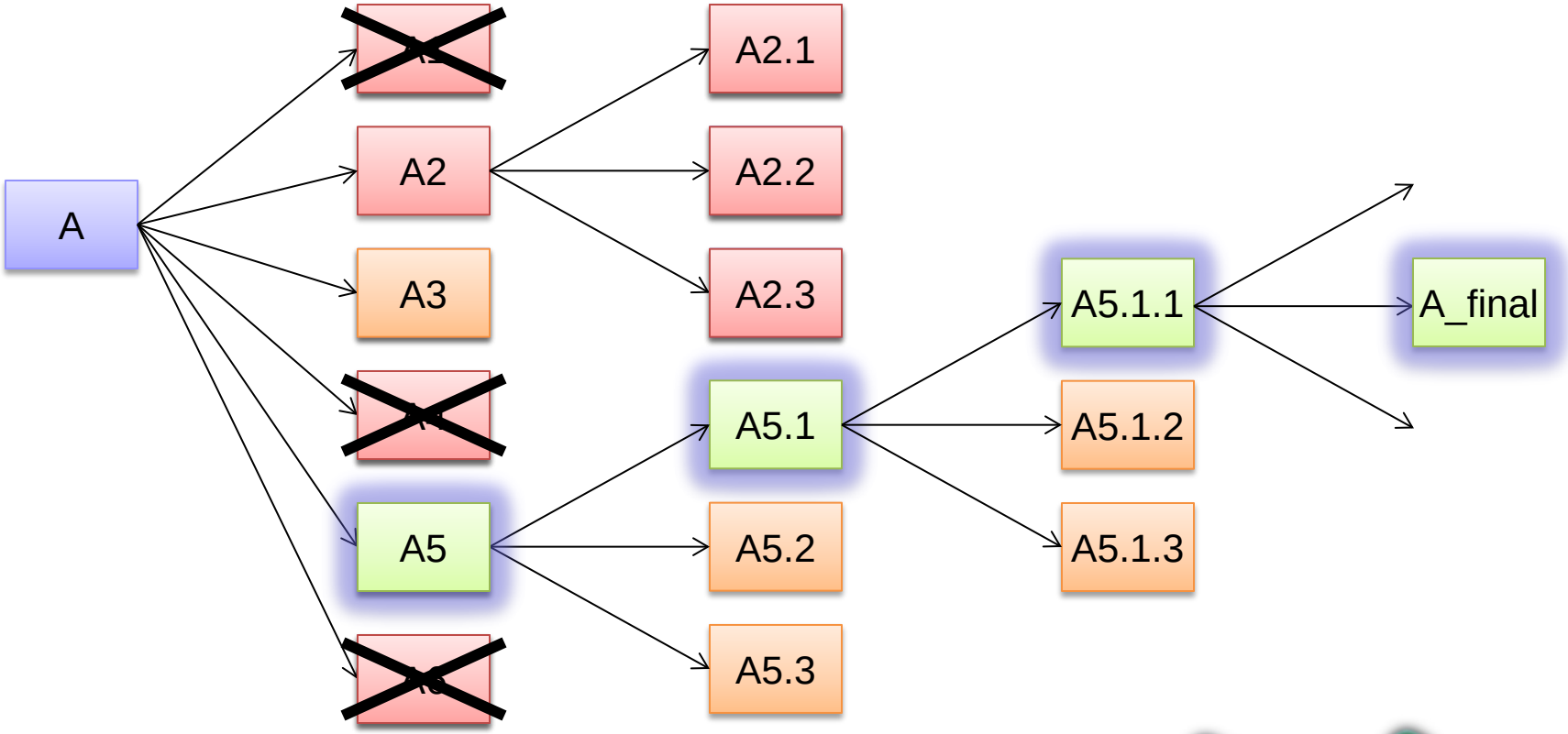
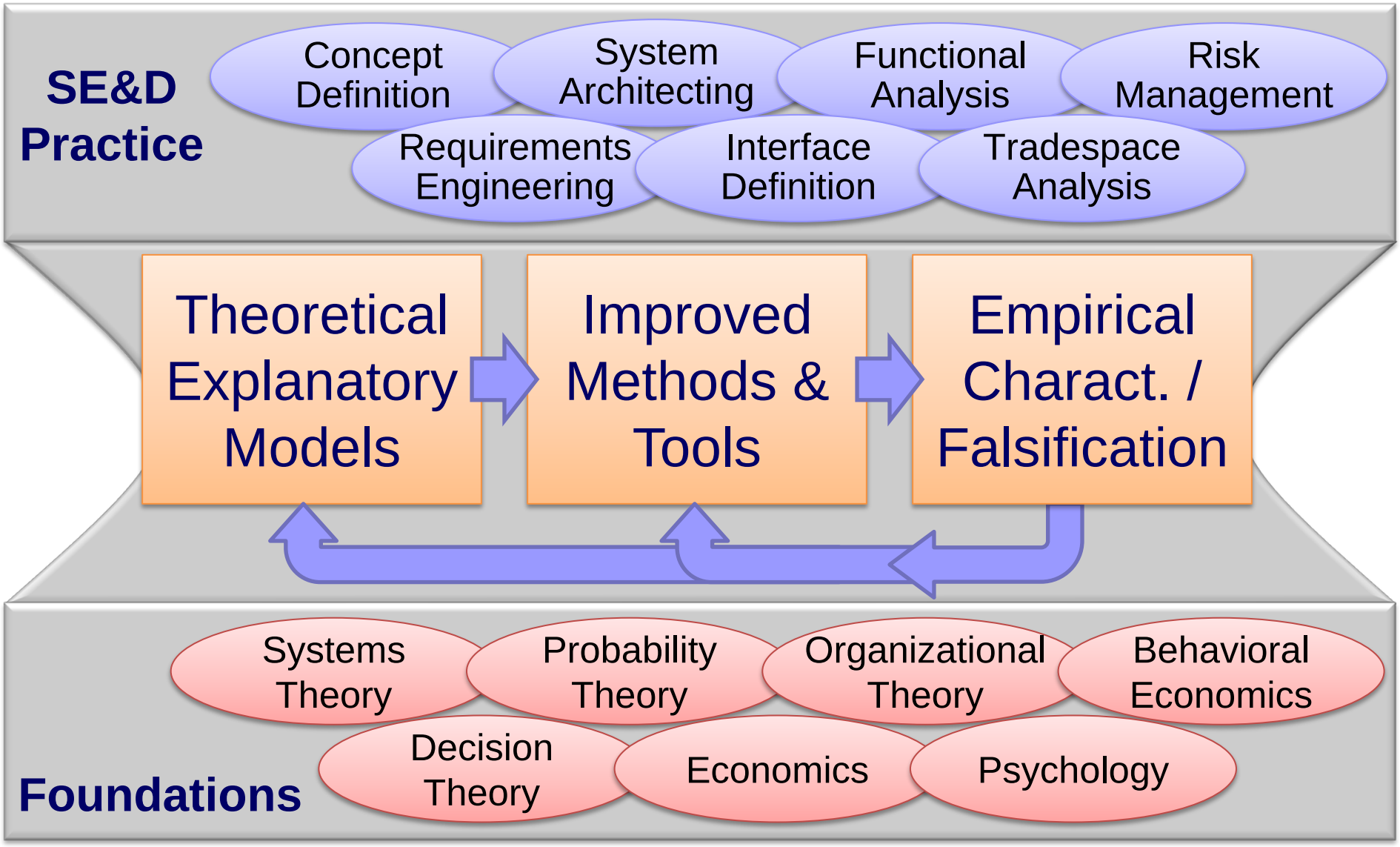


Theoretical Framework for SE & Design

Explanatory Models Supported by Empirical Evidence



Key Take-Aways

- Systems engineering and design are purpose-drive — the purpose is to add value
- Modeling and simulation add value by allowing engineers to plan ahead
- Gradual refinement of models is a good idea… because it adds value
- Optimization problems should be framed in the context of a broader search strategy

Ask “Why?” rather than just “How?”