Systems Engineering Advancement Research Initiative

2010 SEAri Annual Research Summit

Research Topic

"Multi-Epoch Thinking and Considerations for Dynamic Strategies"

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Cambridge, MA

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Engineering Systems Division

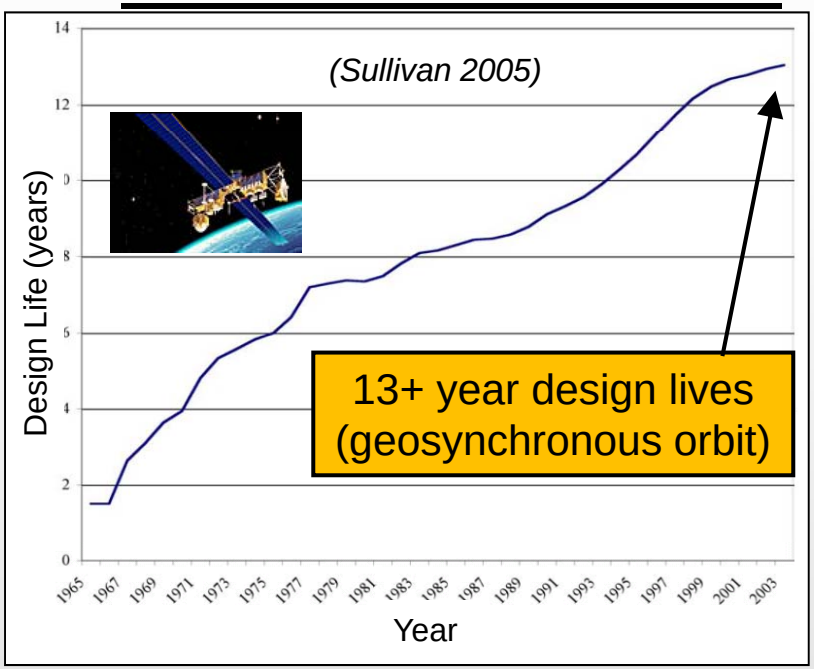
Mismatch of Design with Context

1960's Paradigm

- CORONA: 30-45 day missions
- 144 spacecraft launched between 1959-1972

(Wheelon 1997)

Evolution to Current State

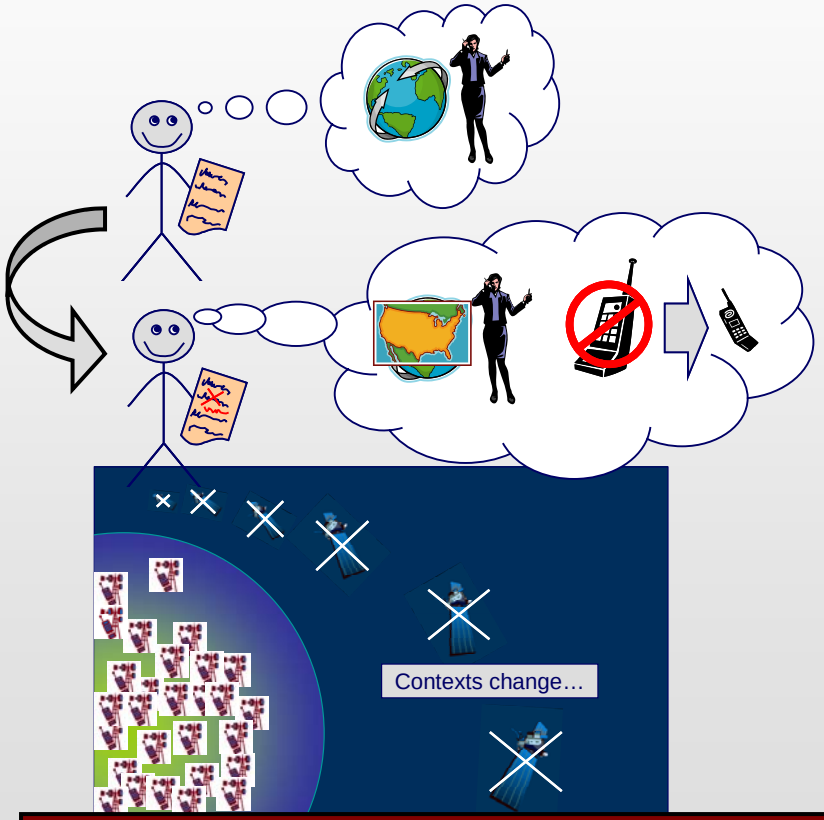


- Inability to adapt to uncertain future environments, including disturbances

"Our spacecraft, which take 5 to 10 years to build, and then last up to 20 in a static hardware condition, will be configured to solve tomorrow's problems using yesterday's technologies." *(Dr. Owen Brown, DARPA Program Manager, 2007)*

More than Missed Opportunities: Failures from Context Changes

New competitor/technology changes needs before system completed



Changing contexts can lead a technically sound system to fail

More than Missed Opportunities: Failures from Context Changes

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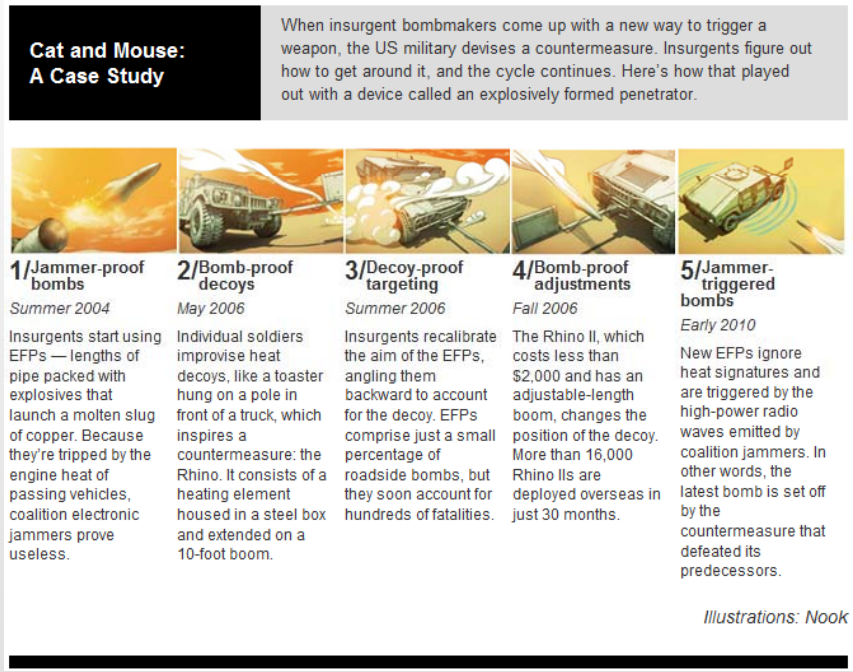
Adversary timescale shorter than "system" lifecycle



Cat and Mouse: A Case Study

When insurgent bombmakers come up with a new way to trigger a weapon, the US military devises a countermeasure. Insurgents figure out how to get around it, and the cycle continues. Here's how that played out with a device called an explosively formed penetrator.

1/Jammer-proof bombs
Summer 2004
Insurgents start using EFPs — lengths of pipe packed with explosives that launch a molten slug of copper. Because they're tripped by the engine heat of passing vehicles, coalition electronic jammers prove useless.

2/Bomb-proof decoys
May 2006
Individual soldiers improvise heat decoys, like a toaster hung on a pole in front of a truck, which inspires a countermeasure: the Rhino. It consists of a heating element housed in a steel box and extended on a 10-foot boom.

3/Decoy-proof targeting
Summer 2006
Insurgents recalibrate the aim of the EFPs, angling them backward to account for the decoy. EFPs comprise just a small percentage of roadside bombs, but they soon account for hundreds of fatalities.

4/Bomb-proof adjustments
Fall 2006
The Rhino II, which costs less than $2,000 and has an adjustable-length boom, changes the position of the decoy. More than 16,000 Rhino IIs are deployed overseas in just 30 months.

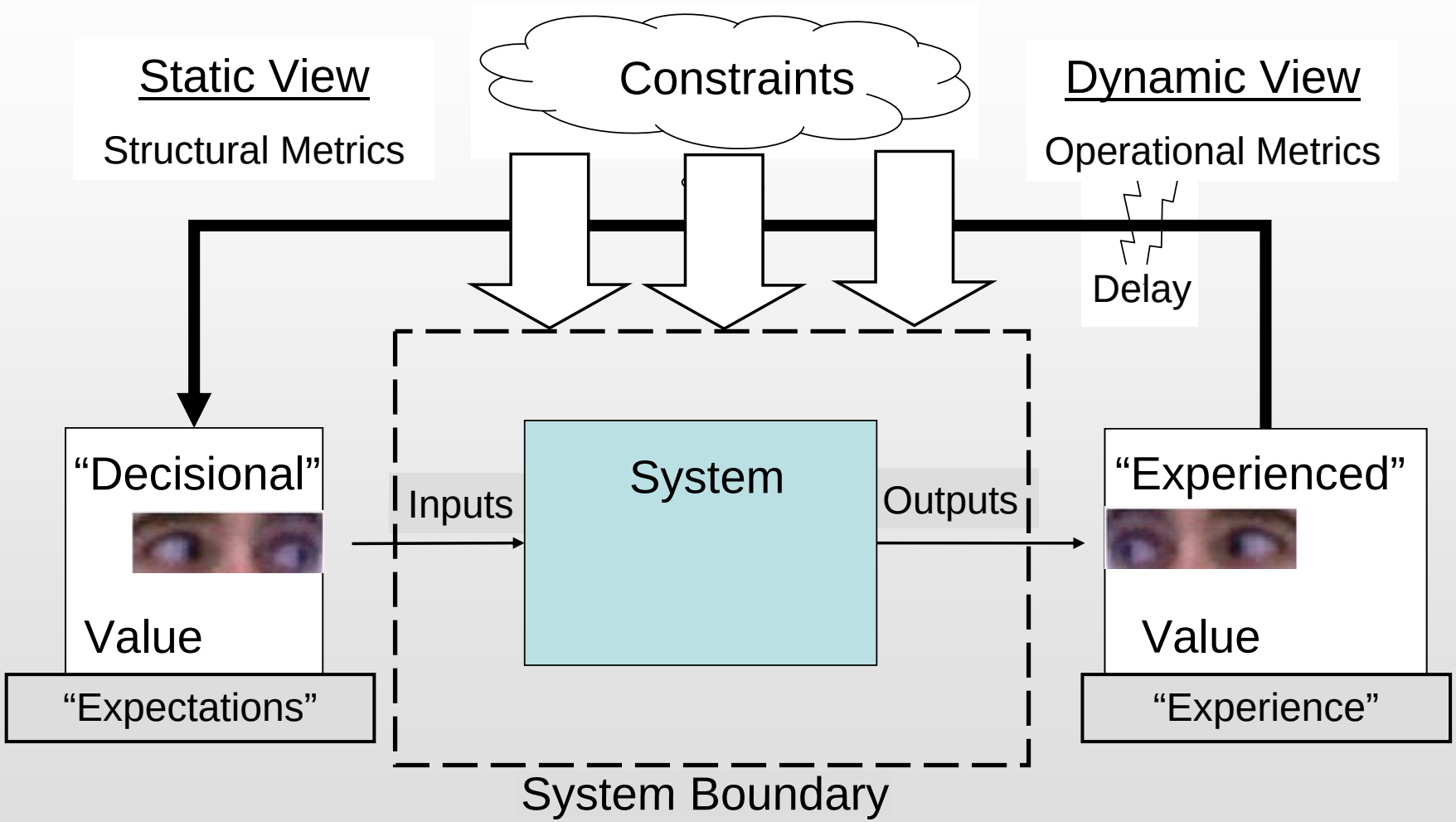
5/Jammer-triggered bombs
Early 2010
New EFPs ignore heat signatures and are triggered by the high-power radio waves emitted by coalition jammers. In other words, the latest bomb is set off by the countermeasure that defeated its predecessors.

Illustrations: Nook

Source: Wired Magazine, August 2010

Changing contexts can have high consequences if systems fail…

Dynamic System Context



*"Decision", "Experienced", and "Remembered" Utility from (Kahneman and Tversky 2000)

**Discussion of "structural" versus "operational" metrics in (Giachetti et al. 2003)

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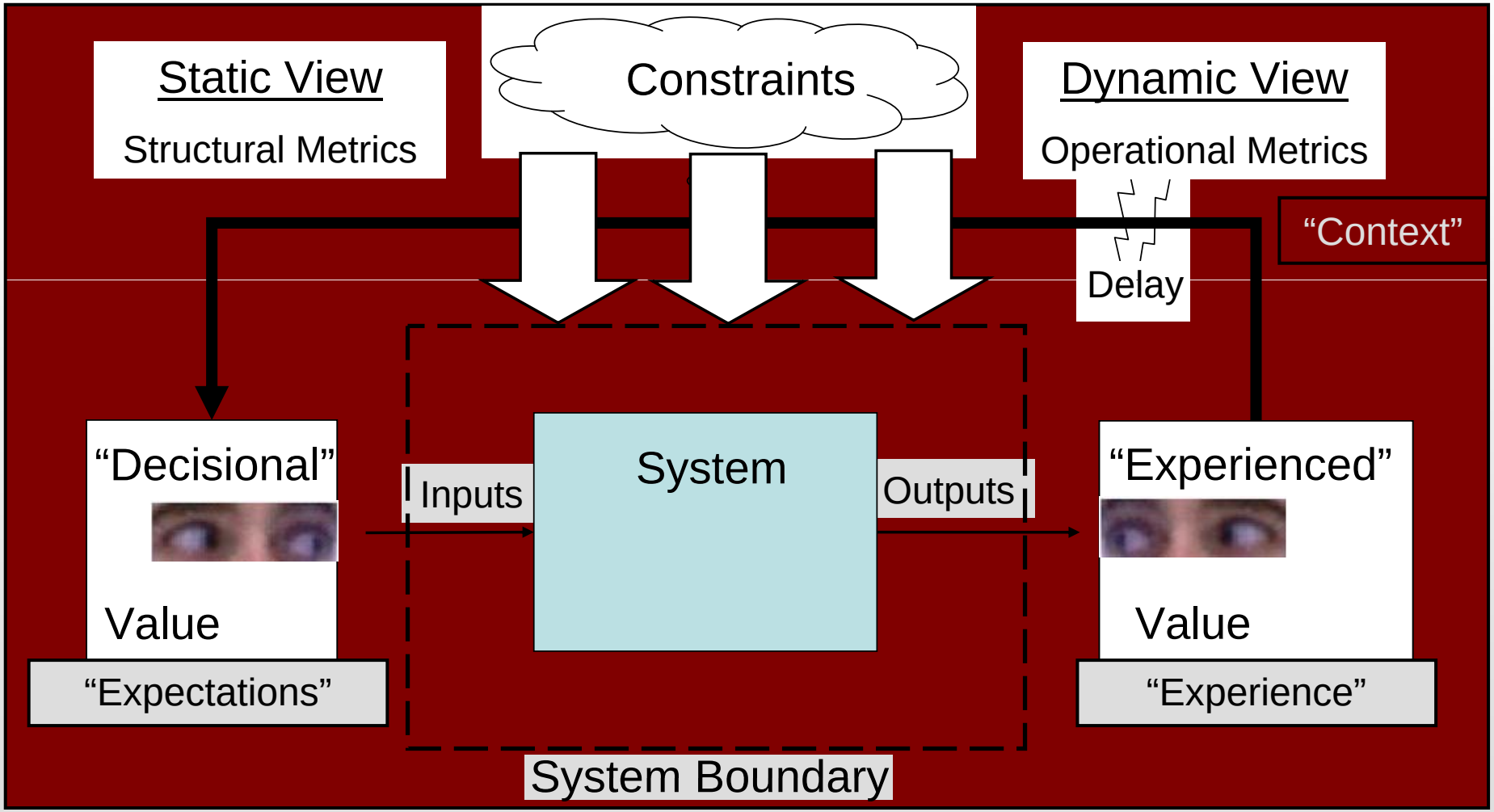

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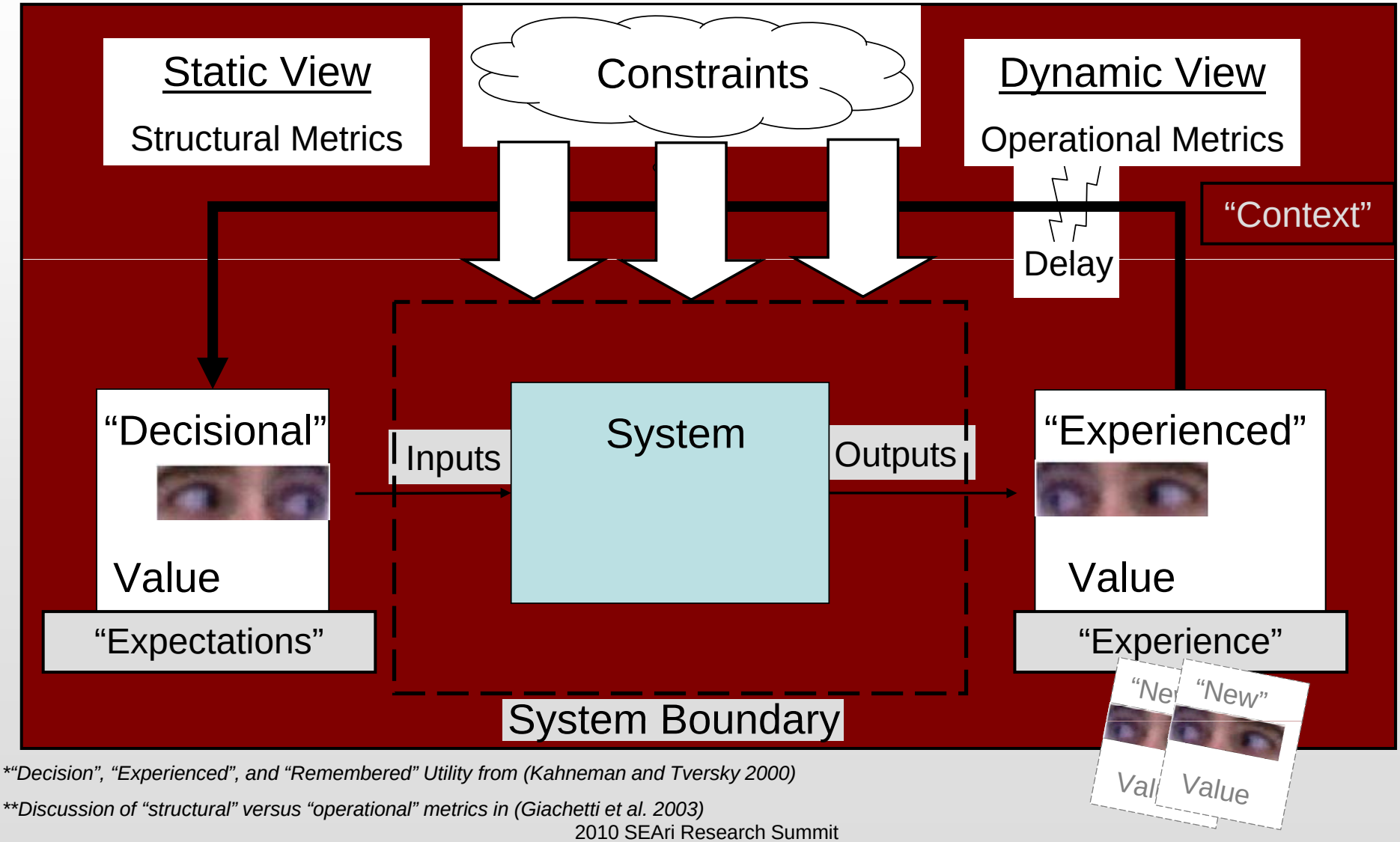

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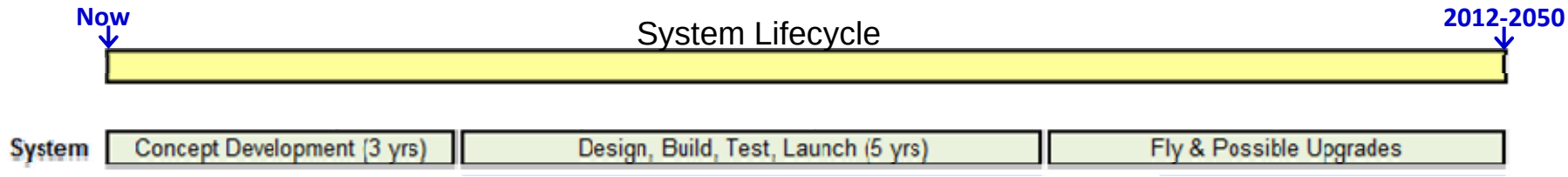
Natural Value-Centric Time Scales



- Shift in contexts occur more frequently than typical system development timelines (e.g., budgets, leadership changes, new stakeholder needs)
- Often "***time scales***" are dictated by programmatic guidelines or arbitrary dates
- Context-derived "***natural***" ***time scales*** may compete with the "artificial" program time scales imposed on a system
  - Alignment of planets (e.g. Mars every 780 days)
  - New administration (e.g. presidential every 4 years)
  - New technology (e.g. Moore's law: 24 months)
- "***Value-centric***" ***time scales*** focus on dynamic factors that impact the ***value proposition*** for the system (e.g. the metrics that define "success")

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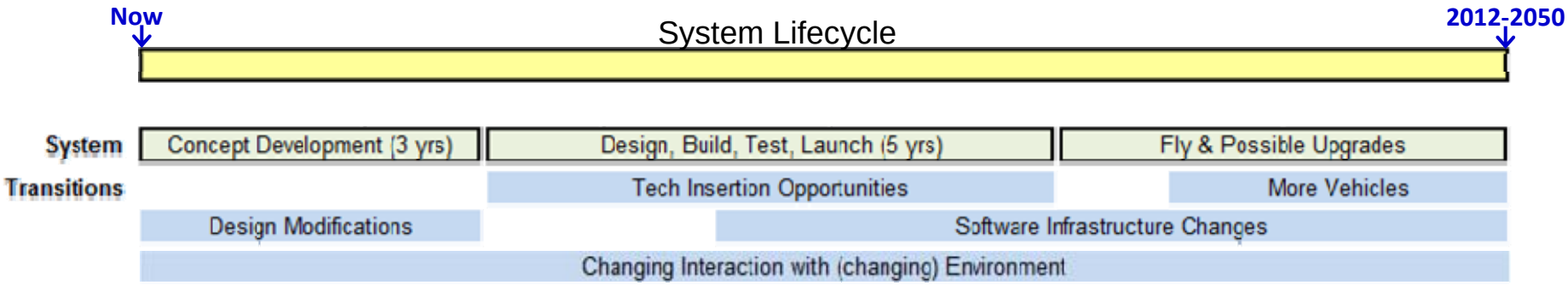

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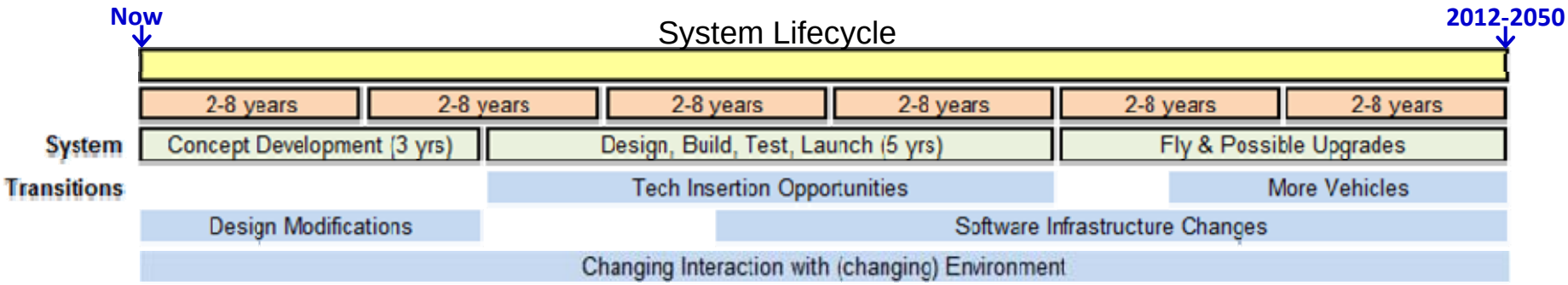

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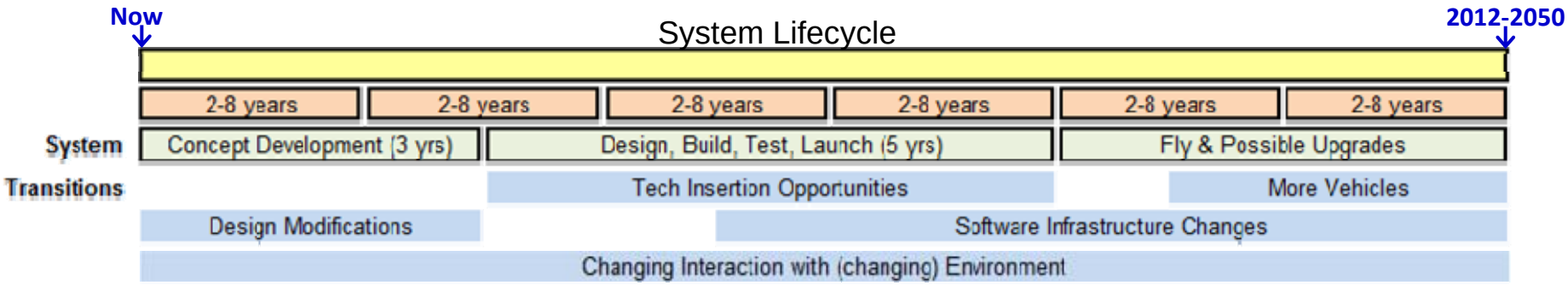

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By considering natural value-centric time scales and how systems could respond across the lifecycle, one can begin to <u>anticipate</u> value robust systems that maintain value delivery over time

An “Epoch” as a Snippet of Time

Definition of Epoch

Time period with a fixed context and needs; characterized by static constraints, concepts, available technologies, and articulated expectations

System success depends on the system meeting *expectations* within a given *context*

can change! can change!

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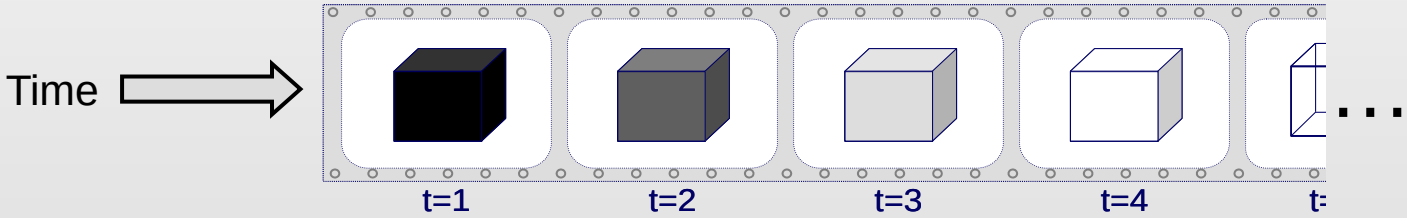

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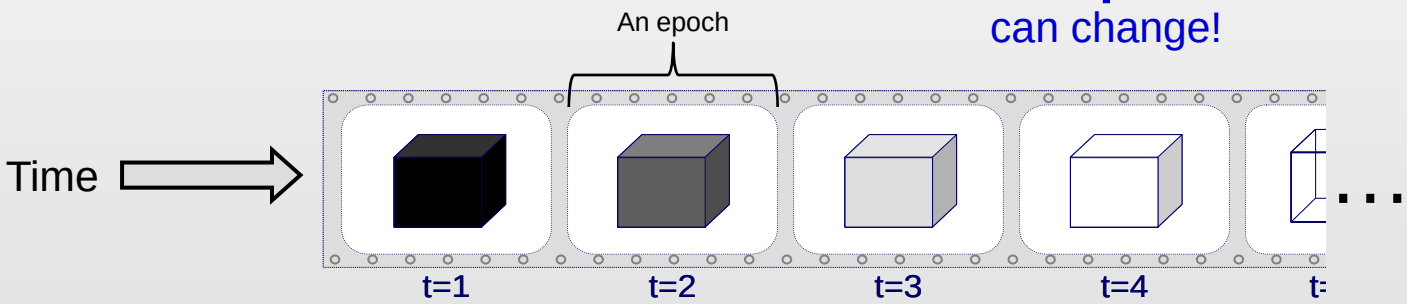

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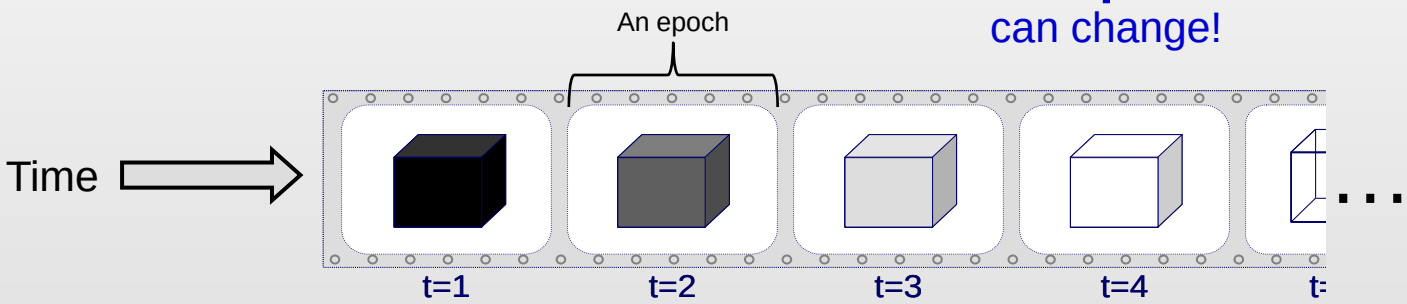


Epoch-based Thinking

Using the concept of “epoch” to generate and consider a large number of possible future contexts and needs facing a system, along with short term and long term strategies for maintaining a successful system across epochs

What Can Change: Short Run and Long Run Analysis

In economics, the ***short run*** is the decision-making period during which at least one input factor is considered fixed

Example: lease on facility (commitment can vary 6 mos to 10 yrs or more)

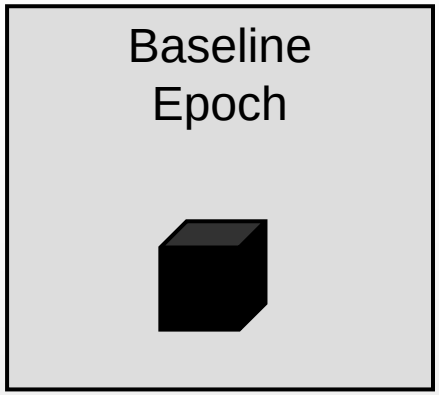
The ***long run*** is the decision-making period considered when all inputs are variable

Implication: in short run, optimize subject to fixed constraints; in long run, make strategic decisions to shift possibilities

	Short run		Long run	
	Fixed factors	**Variable factors**	**Fixed factors**	**Variable factors**
Economic Analysis	Input factors such as labor, capital equipment, regulations, knowledge	Quantity demanded, quantity supplied, dollars and time spent	none	all
Engineering Analysis	Objectives, constraints, stakeholder set, technology, concepts	Design chosen, dollars and time spent, perceived value	none	all

Natural analogy from economics to engineering leverages years of methodological validation

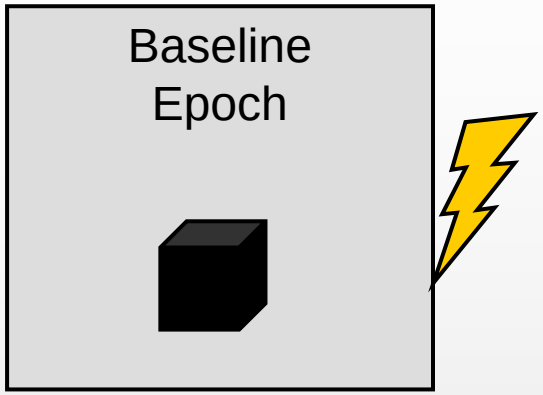
Basic Epoch Shift: System Impact-Response



System Definition

Baseline Epoch

Basic Epoch Shift: System Impact-Response



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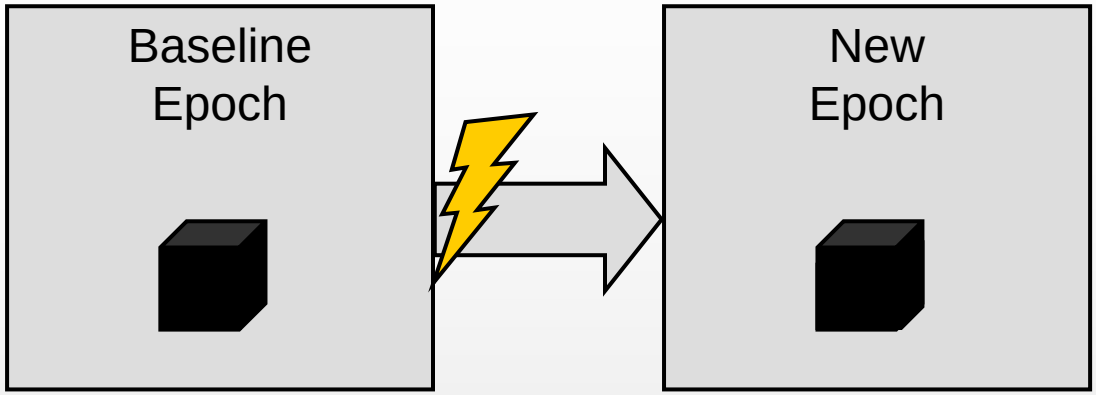
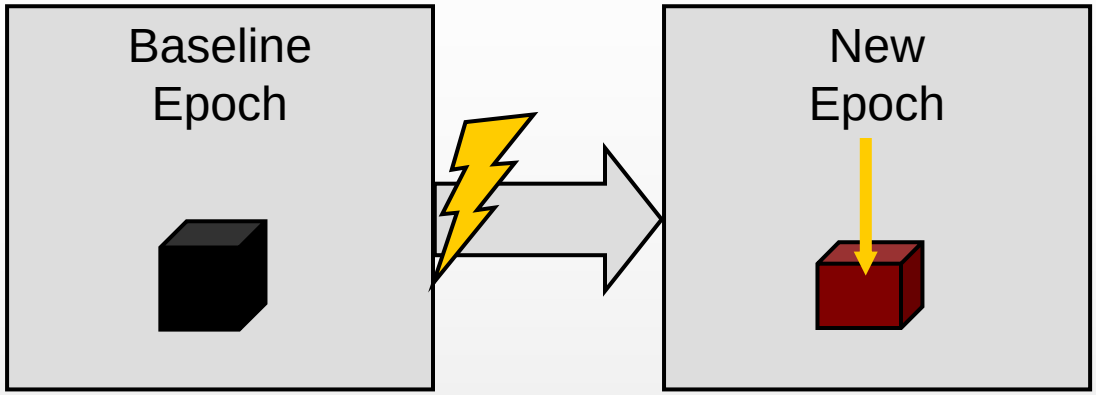


System Definition

Baseline Epoch → **New Epoch**

Basic Epoch Shift: System Impact-Response



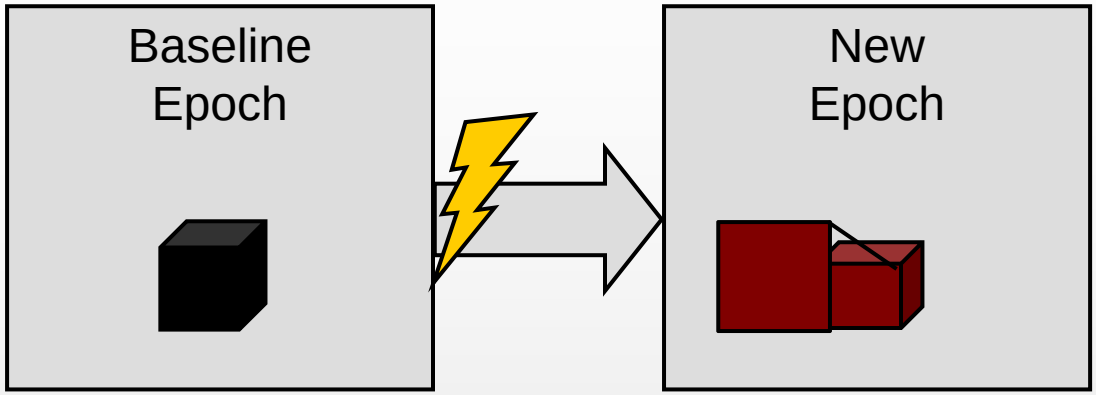
System Definition

Baseline Epoch → **New Epoch**

↓

Effect

Basic Epoch Shift: System Impact-Response



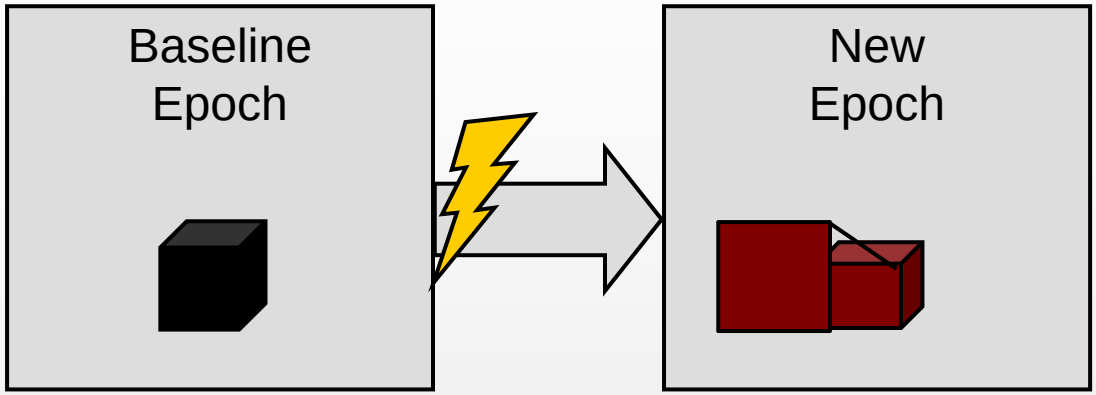
System Definition

Baseline Epoch → **New Epoch**

↓

Response(?) ← **Effect**

Basic Epoch Shift: System Impact-Response



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Response(?) ← **Effect**

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Success?

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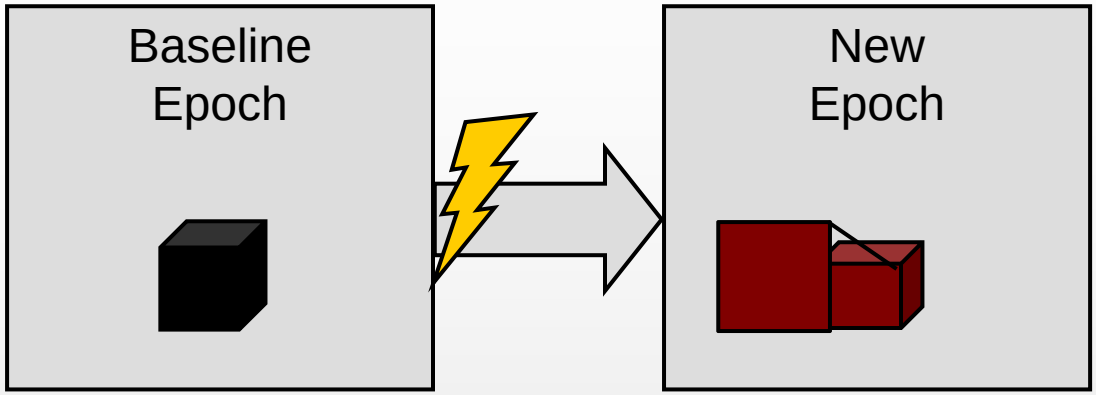


System Definition

Baseline Epoch → **New Epoch**

↓

Response(?) ← **Effect**

↓

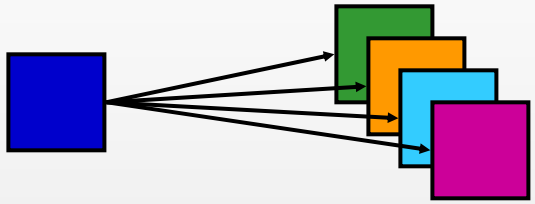
Success?

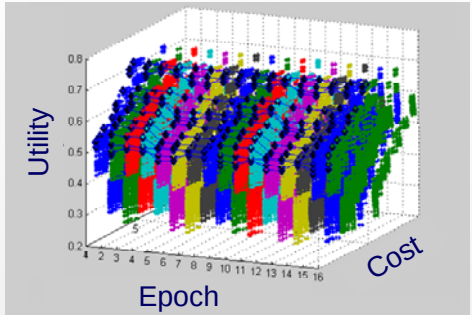
- What about analyzing across more than just pair-wise epoch shifts?
- How can the technique become generalized or even automated?

Generating Epochs

Many possible contexts and needs may unfold in the future, impacting actual and perceived system utility and cost

"Epoch-based thinking" can be used to structure anticipatory scenario analysis





Example triggers for epoch shifts impacting a system

- Change in political environment
- Entrance of new competitor in market
- Emergence of significant new or changed stakeholder need(s)
- Policy mandate impacting product line, services or operations

Categories of epoch variables can aid in thinking about key changing factors

E.g., Resources, Policy, Infrastructure, Technology, End Uses ("Markets"), Competition, etc.

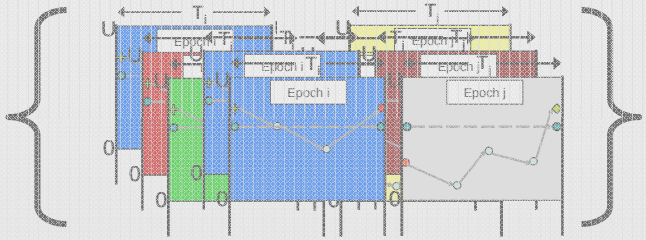
Multi-Epoch Analysis

RSC Processes

Process 3

Epoch Characterization

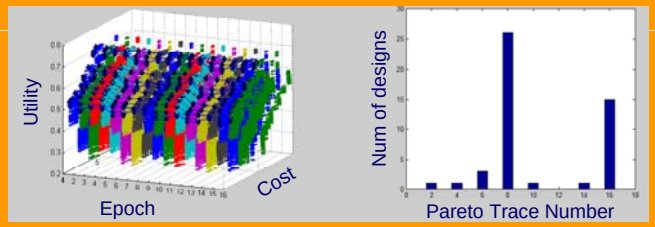
Epoch set represents potential fixed contexts and needs



Process 5

Multi-Epoch Analysis

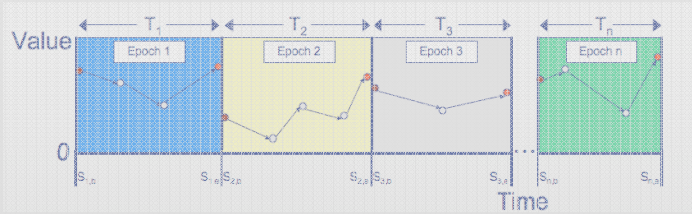
Analysis across large number of epochs reveals "good" designs



Process 6

Era Construction

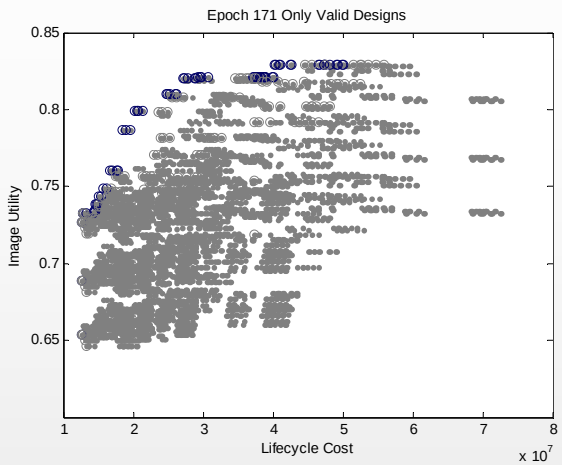
Eras represent ordered epoch series for analyzing system evolution strategies



- Cross-epoch analysis
- Within-epoch analysis
- Identification of versatile and changeable designs

For large numbers of designs and epochs, this requires an automated ability to assess epoch shift impacts

Example Metric from Multi-Epoch Analysis: Pareto Trace



Find non-dominated solutions within a given epoch (Pareto Set)

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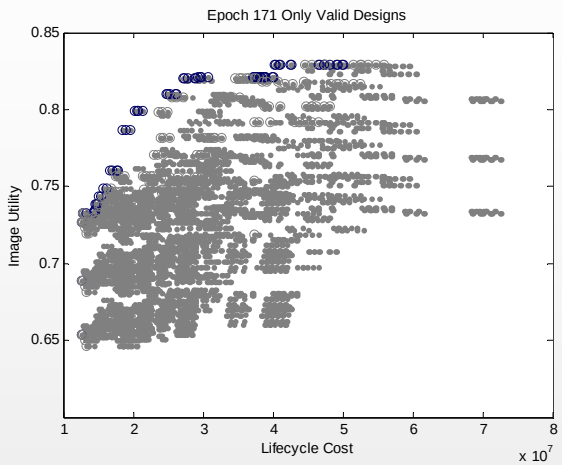

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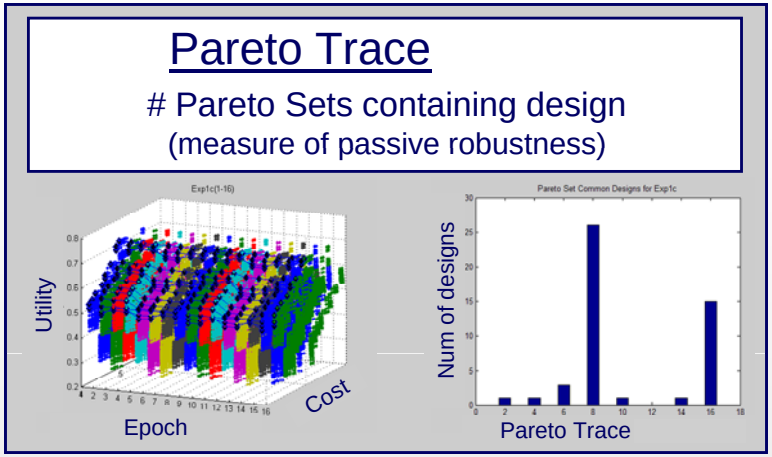

Across many epochs, track number of times solution appears in Pareto Set

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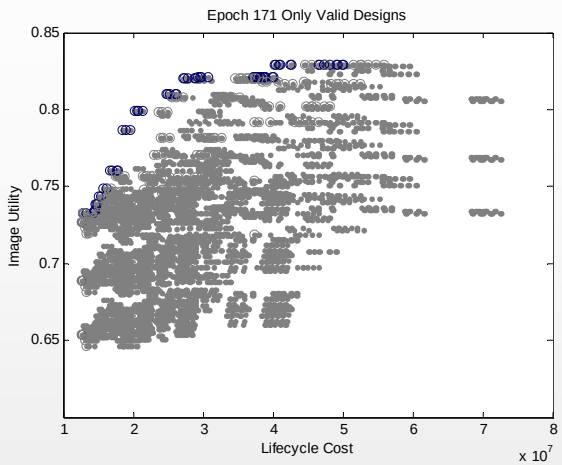
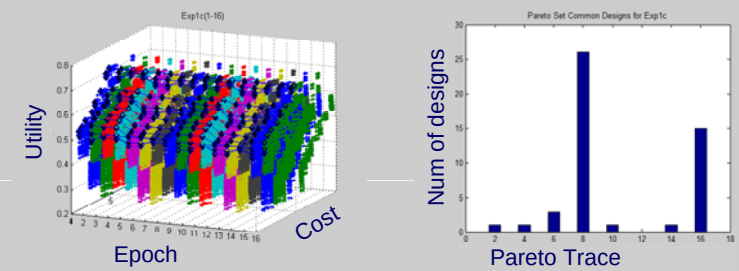


Pareto Trace

Pareto Sets containing design
(measure of passive robustness)



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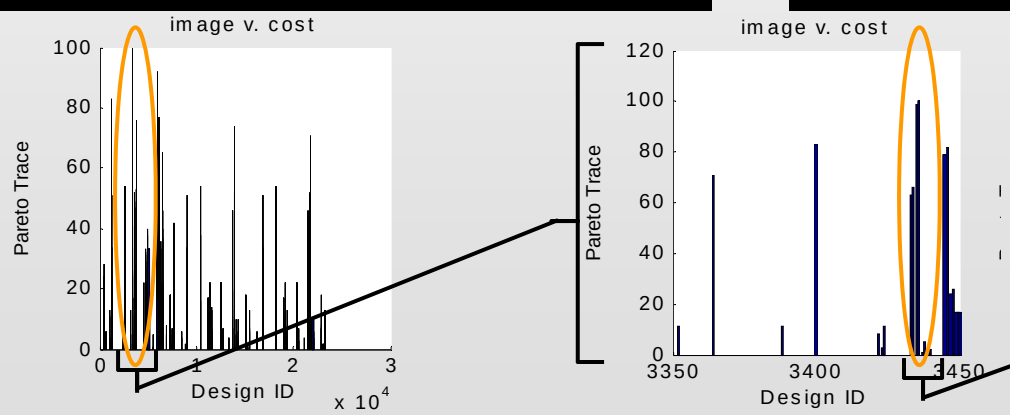


Identify designs with high Pareto Trace for further investigation

e.g. "design 3435" is in 67% of Pareto Sets

Higher Pareto Trace designs are more passively value robust

Performing Pareto Tracing to Find Epoch Shift Robust Solutions

Using multi-epoch analysis, one can perform anticipatory exploration of possible preferences for a system

- Answering "what if" questions on needs…
  - What if you don't elicit the "right" attribute priorities?
  - What if you don't elicit all of the "right" attributes?
  - What if you don't elicit the "right" utility curve shape?
  - What if you don't use the "right" utility aggregating function?
  - What if a second decision maker enters the mix?
  - …
- Finding designs in common across varying stakeholder sets and needs over time

Pareto Trace is a metric of passive value robustness across epoch variations

While Pareto Trace is a useful screening metric for "passive" strategies, what about changing systems over time to achieve value?

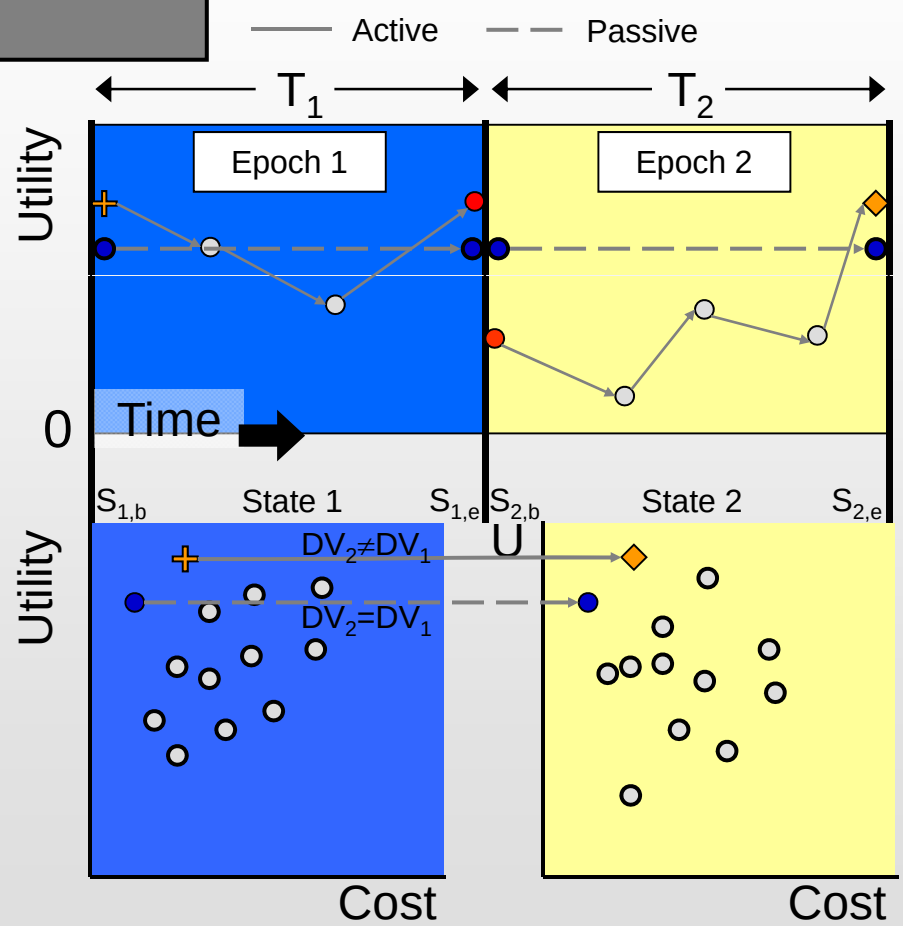
Achieving Value Robustness

Research suggests two main strategies for "Value Robustness"

New Context Drivers

- External Constraints
- Design Technologies
- Value Expectations

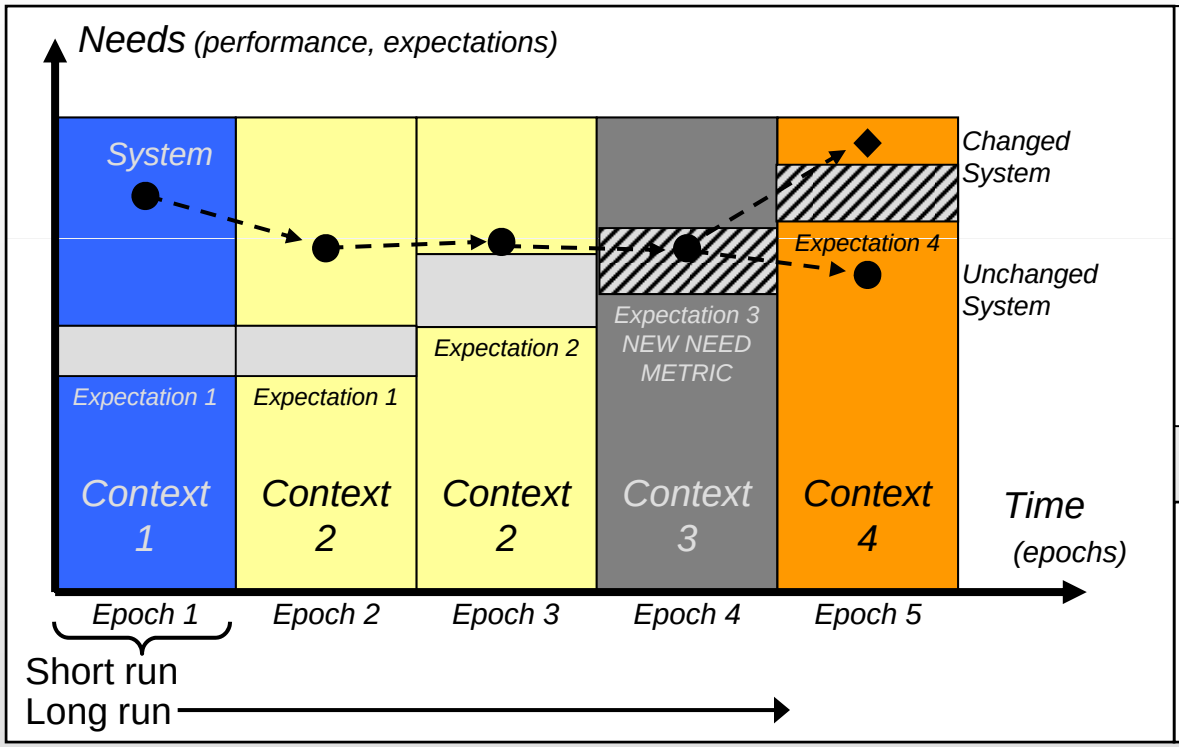
1. Passive
   - Choose "versatile" or "robust" designs that remain high value
   - Ex. Metric: Pareto Trace number
2. Active
   - Choose "changeable" designs that can deliver high value when needed
   - Ex. Metric: Filtered Outdegree



Value robust designs can deliver value in spite of inevitable context change

Using Epochs for Proposing Time-Based Strategies

Discretization of change timeline into short run and long run enables analysis



Epoch:

Time period with a fixed context; characterized by static constraints, design concepts, available technologies, and articulated needs

Era:

Time-ordered sequence of epochs

Legend

- System
- System Trajectory
- Expectations

(Ross and Rhodes 2008)

In order to pursue dynamic strategies, a system must have temporal properties, i.e., "-ilities" such as flexibility, evolvability, or survivability

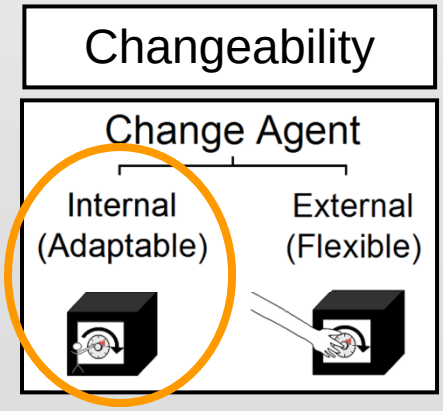
Defining Some “ilities”

robustness	ability of a system to maintain its level and set of specification parameters in the context of changing system external and internal forces
versatility	ability of a system to satisfy diverse needs for the system without having to change form (measure of latent value)
changeability	ability of a system to alter its form—and consequently possibly its function—at an acceptable level of resource expenditure
flexibility	ability of a system to be changed by a system-external change agent
adaptability	ability of a system to be changed by a system-internal change agent
scalability	ability of a system to change the current level of a system specification parameter
modifiability	ability of a system to change the current set of system specification parameters
survivability	ability of a system to minimize the impact of a finite duration disturbance on value delivery
value robustness	maintaining value delivery in spite of changes in needs or context

Defining, characterizing, and quantifying “ilities” is an active area of research, necessary in order to specify and validate such system properties in practice

Example: Defining Adaptability

changeability		ability of a system to be altered, by intention, in form—and consequently possibly in function—at an acceptable level of resource expenditure
	flexibility	ability of a system to be altered by a system-external change agent
	adaptability	ability of a system to be altered by a system-internal change agent

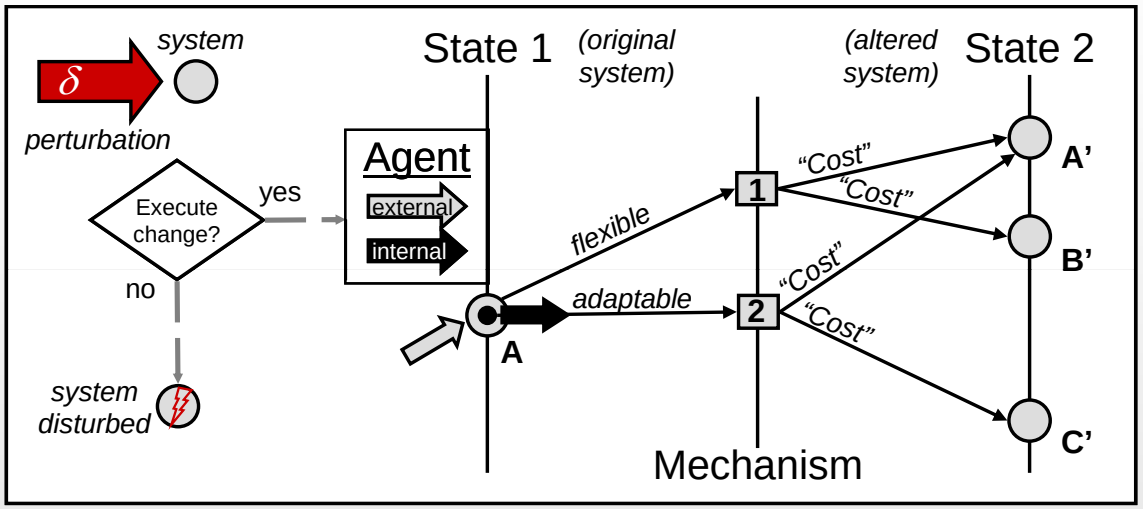


An adaptable system is one that can intentionally alter itself, typically in response to a perturbation (such as a change in context), in order to improve its value

In order to develop rigorous techniques to assess and design for adaptability, this definition must be deconstructed into a useful framework

Framework for Assessing and Designing for Changeability

Change pathway: Perturbation-Agent-Mechanism-Effect

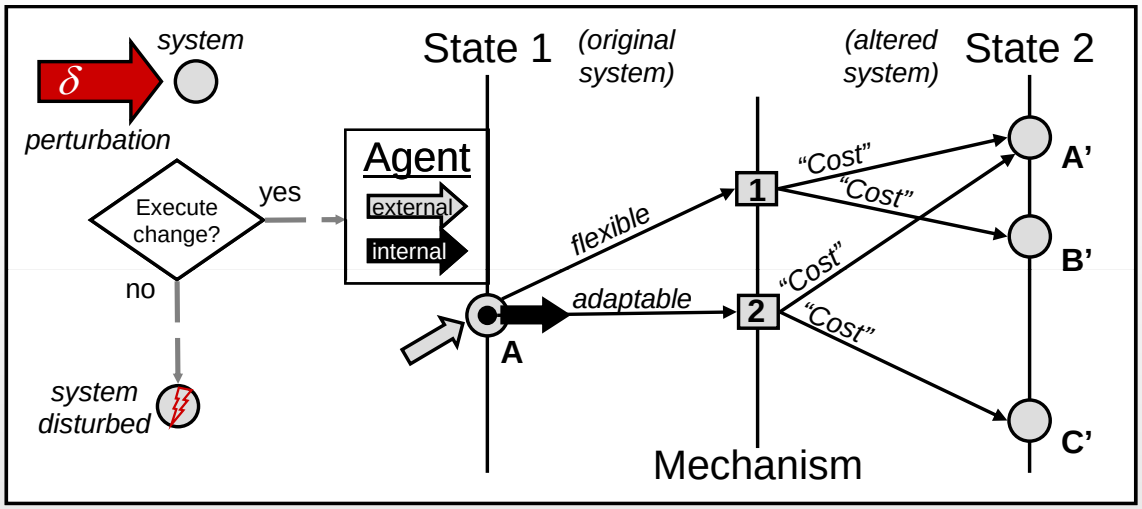


At least two questions can be asked regarding degree of changeability

1. Can a system be changed or change itself?
   - Capability question; pursue structural and operational strategies
   - Key metrics: number of destination end states, time/cost to achieve change
2. Does the change result in a "better" system?
   - Value question; analyze ***context-dependent*** performance and perceptions
   - Key metrics: utility loss/gain over time, aggregate value delivery/availability

Framework Example

Change pathway: Perturbation-Agent-Mechanism-Effect



Perturbation	*System*	Agent	Mechanism	Effect
δ	○	internal → external	1 2	○ A' ○ B' ○ C'
Δ technology	Sat. constellation	Program manager	Swap payloads	New capability
Δ business model	Aircraft fleet	Autonomous software	Redefine operations	Enhanced survivability
Δ enemy	Training system	Warfighter	Combine assets	Cost-efficiency gains

Framework helps to structure thinking about changeability, including creative generation of strategies, as well as quantification

"Dynamicism"
Matching Change with Change

- Contexts and needs for systems will inevitably shift, especially over long-lived systems
- Timescales for change are often out of a designer's control
- Multi-epoch thinking is a structured means for considering an array of possible short-run futures
- Eras can be used to characterize path-dependence of the context in the long run

Determining the best strategy, both short run and long run, is a difficult temporal problem, fraught with uncertainty.

Considerations for Dynamic Strategies

- Developing dynamic system strategies requires consideration of both the future context and needs, as well as matching system dynamic capabilities (i.e., “ilities”)
- The value of having an “ility” such as adaptability is ***context-dependent***, however analysis can be used to generate insights
- Oftentimes decisions for incorporating an “ility” into a system occurs prior to the recognition of need for such a capability
  - Costs: design, carrying, “utility-loss,” and execution
  - Benefits: at later point in time can alter system to higher value state
- Development of rigorous strategies an on-going area of research

Determining the best strategy, both short run and long run, is a difficult temporal problem, fraught with uncertainty.

Recent research seeks to better characterize the problem and suggest design principles for increasing the likelihood of realizing **value robus**t systems