INCOSE
International Council on Systems Engineering

Massachusetts Institute of Technology

SEA RI

Systems Engineering Advancement Research Initiative

Using Dynamic Multi-Attribute Tradespace Exploration to Develop Value Robust Systems

INCOSE North Texas Chapter meeting

Dr. Adam M. Ross, MIT
adamross@mit.edu
October 18, 2007

Meeting Customer Needs

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)
- Requirements capture a mapping of needs to specifications to guide design

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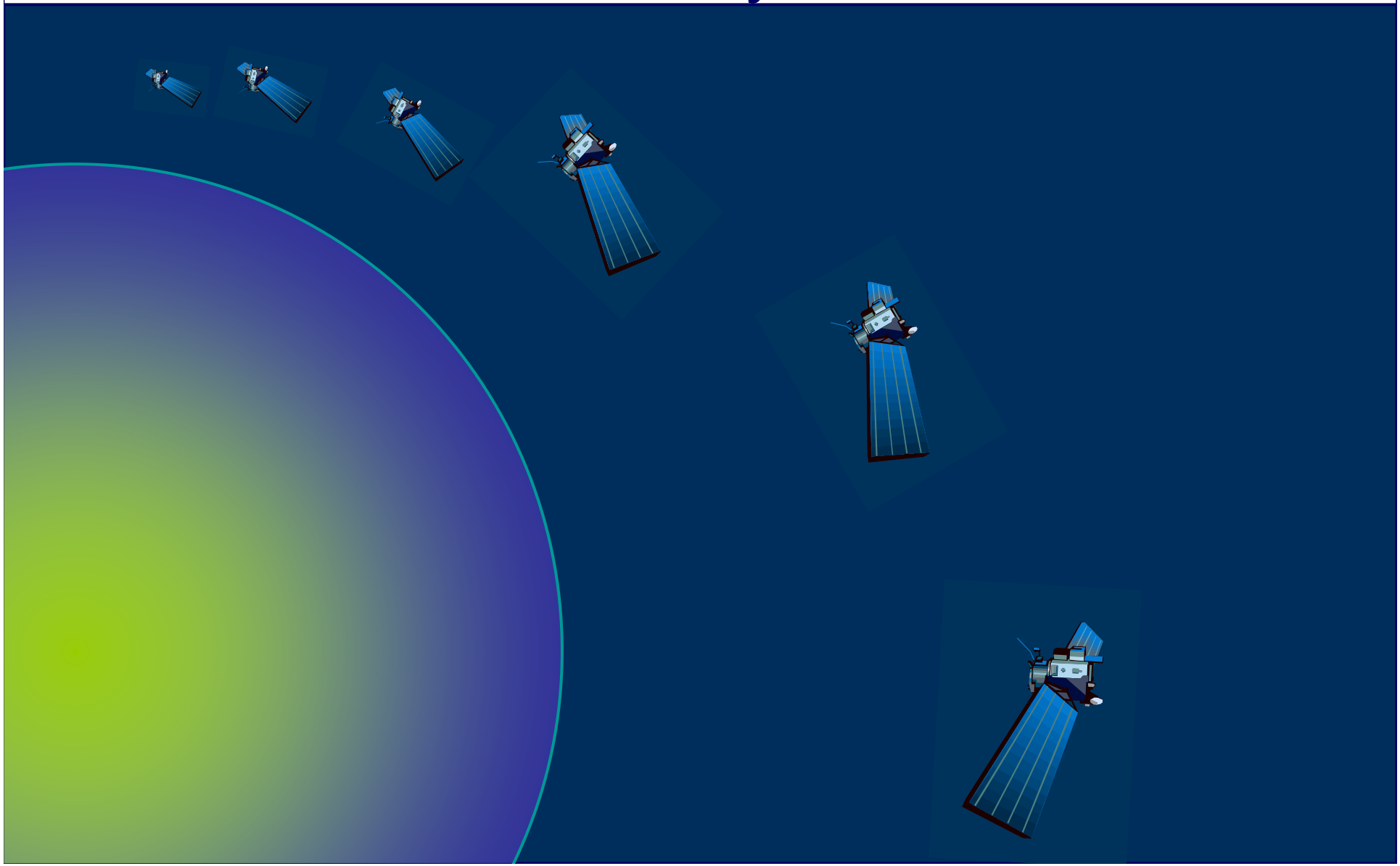
Deploying a “Valuable” System…



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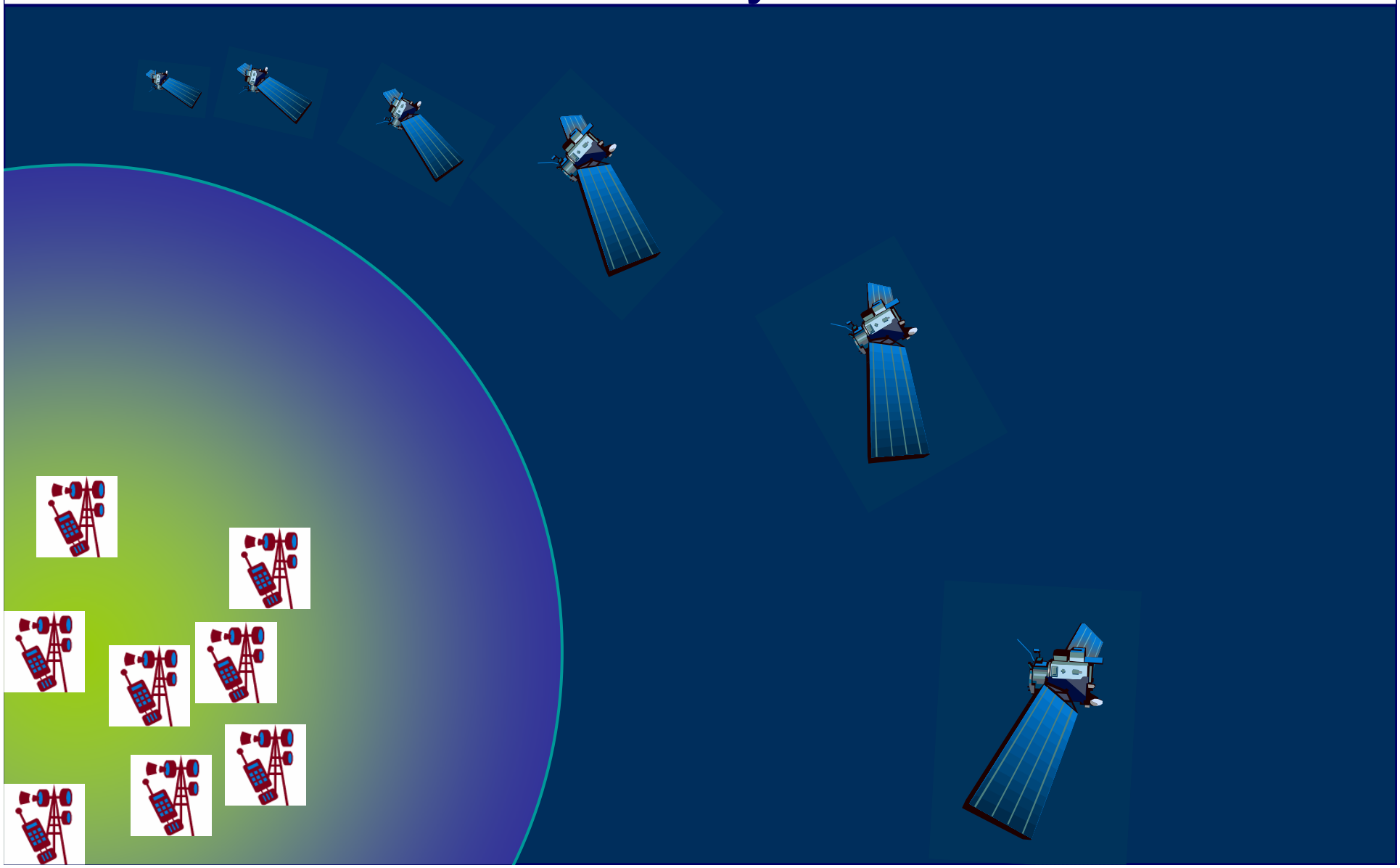

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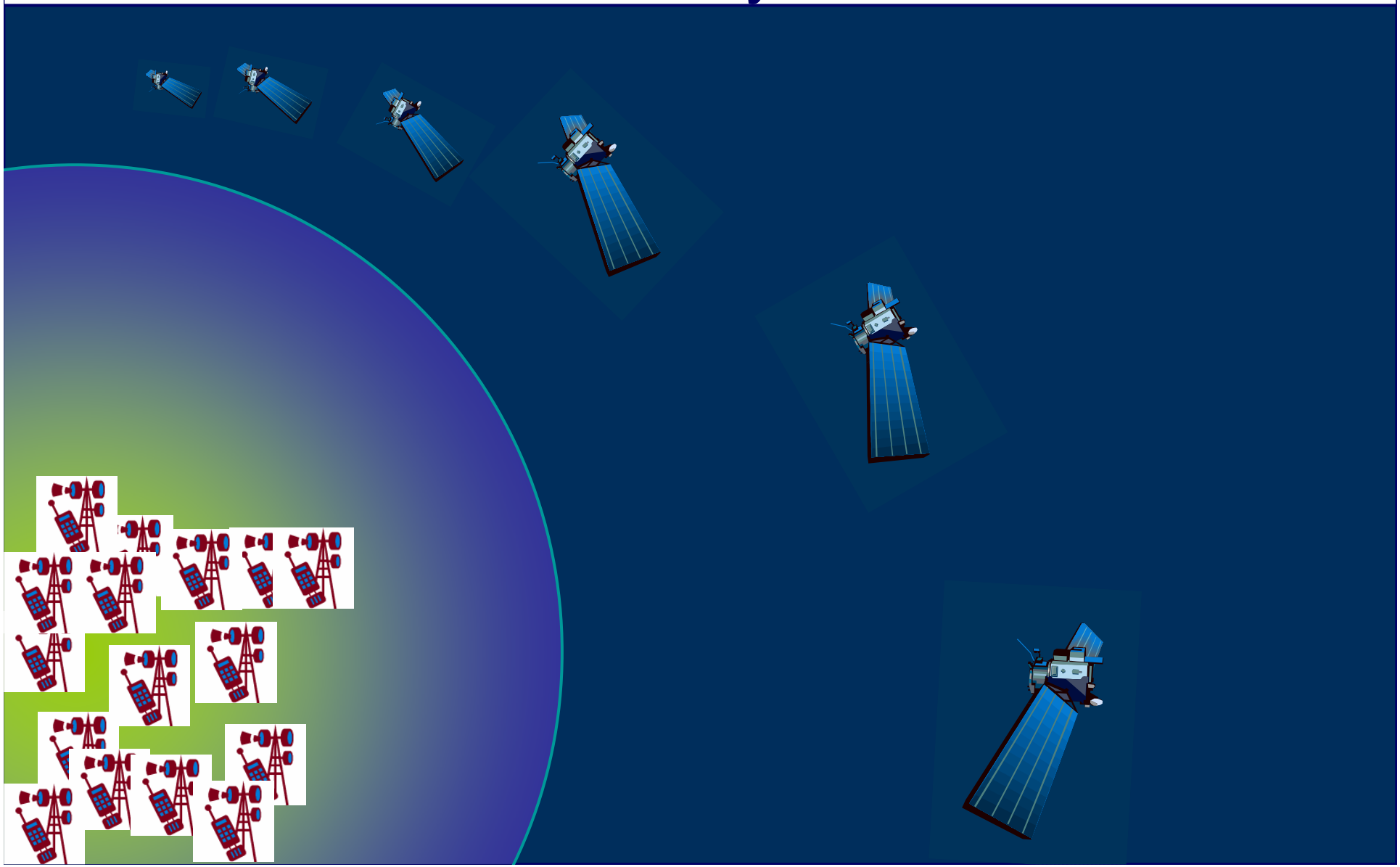

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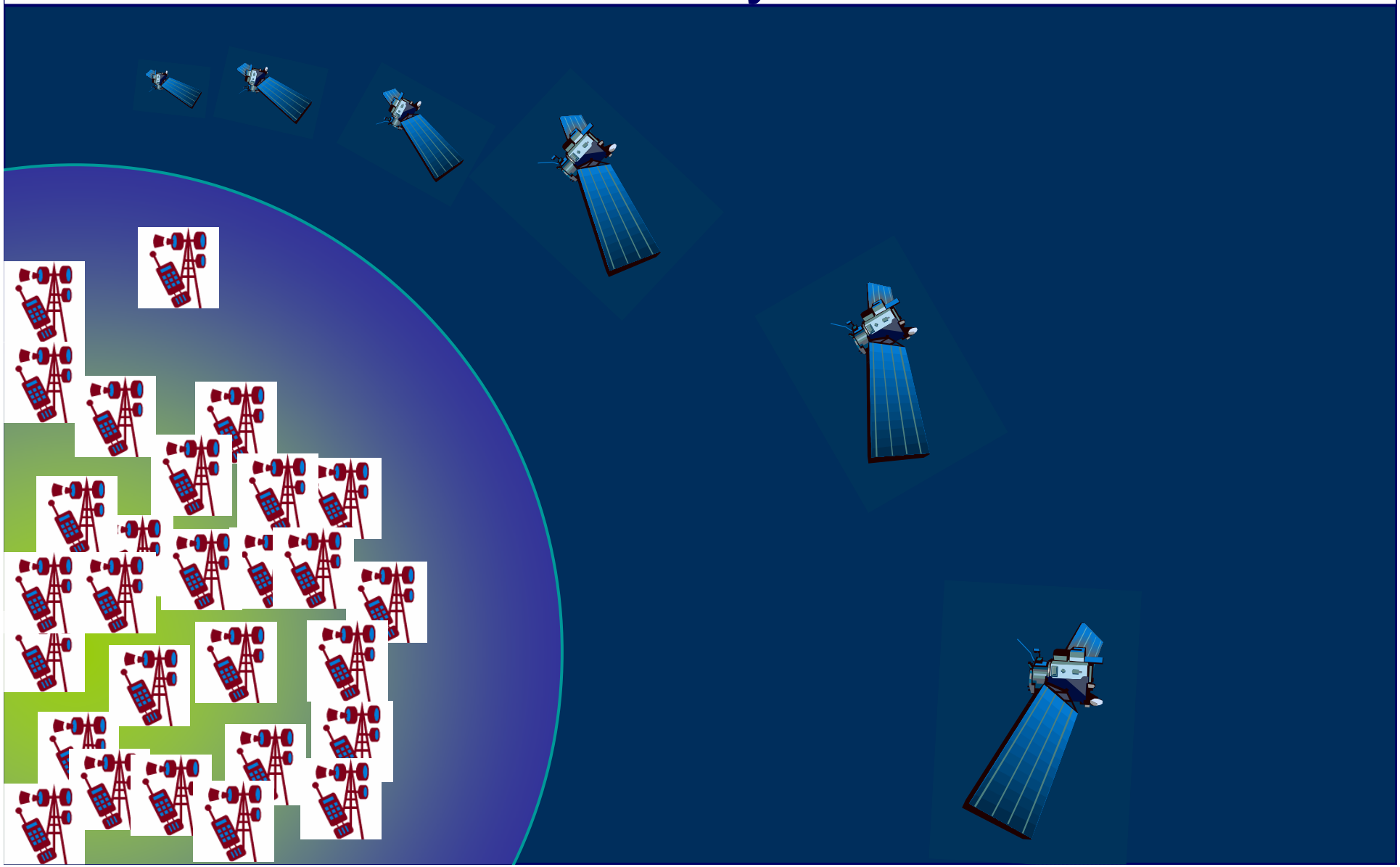

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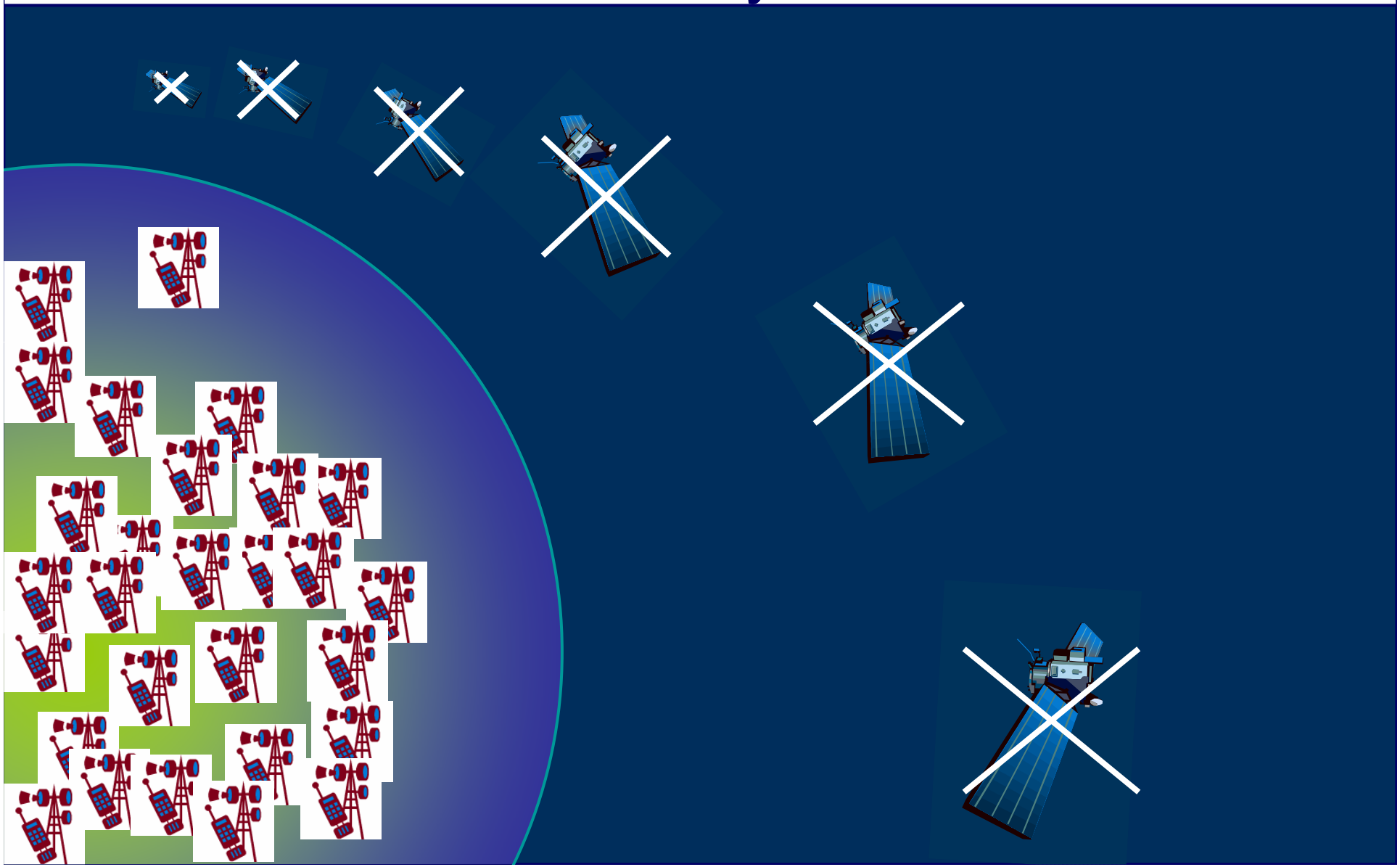

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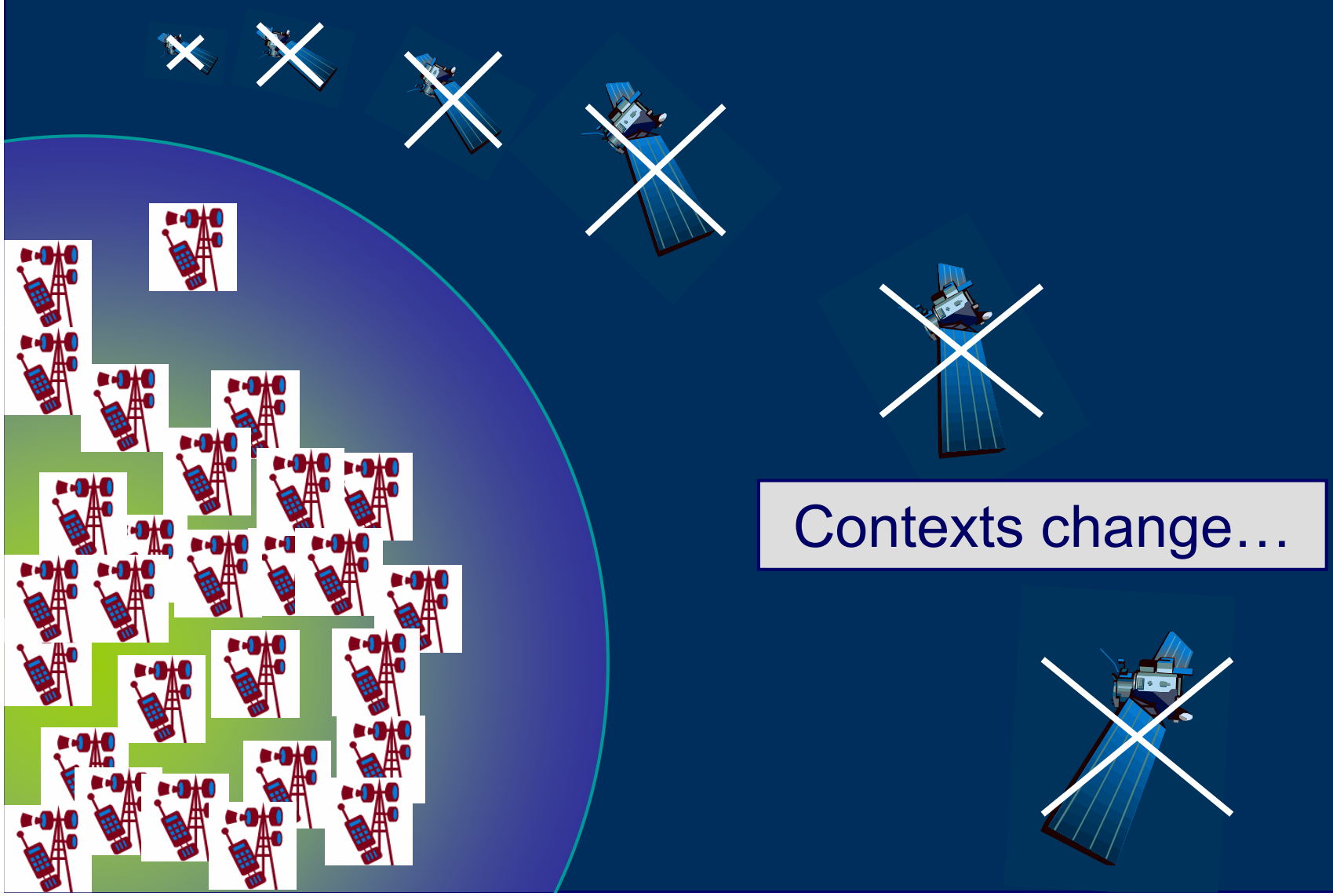
Deploying a "Valuable" System…



Contexts change…

Meeting Customer Needs (cont.)

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)
- Requirements capture a mapping of needs to specifications to guide design

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Meeting Customer Needs (cont.)

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)
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Meeting Customer Needs (cont.)

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)

- People change their minds…
- To continue to deliver value, systems may need to change as well…

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LAI/AF Systems Engineering for Robustness Workshop

Washington, DC in June 2004

- According to Dr. Marvin Sambur, "Systems Engineering for Robustness" means developing systems that are…

  - Capable of *adapting* to changes in mission and requirements
  - *Expandable/scalable*, and designed to accommodate growth in capability
  - Able to *reliably* function given changes in threats and environment
  - Effectively/affordably *sustainable* over their lifecycle
  - Developed using products designed for use in various *platforms* and systems
  - Easily *modified* to leverage new technologies

- "Robustness" scope expanded beyond classical robustness …
- Experts questioned…
  - What does it mean?
  - How can it be measured/analyzed?
  - Who is going to pay for it?

How can designers account for this new "robustness"?

*Adapted from Ross, A., Rhodes, D., and Hastings, D., "*Defining System Changeability: Reconciling Flexibility, Adaptability, Scalability, and Robustness for Maintaining System Lifecycle Value*," INCOSE Int'l Symposium 2007, San Diego, CA, June 2007

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What is System Success?

Success is defined across multiple perspectives and multiple time periods

System success, Ψ, across N decision makers at time t

Net "experience" — Net "expectations"

$$\Psi(t) = \sum_{i=1}^{N} \left[X_{DMi}(t) + \varepsilon_C^{X_{DMi}}(t) \geq Y_{DMi}(t) + \varepsilon_C^{Y_{DMi}}(t) \right]$$

$$0 \leq \Psi(t) \leq N$$

$X_{DMi}(t)$	Decision maker i unaffected system "experience" at time t	$\varepsilon_C^{X_{DMi}}(t)$	Context effect on decision maker i "experience" at time t
$Y_{DMi}(t)$	Decision maker i unaffected system "expectation" at time t	$\varepsilon_C^{Y_{DMi}}(t)$	Context effect on decision maker i "expectation" at time t

System Success: Net "experience" must meet or exceed net "expectations"

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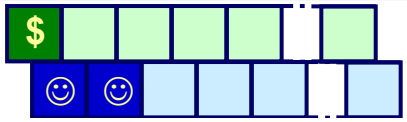
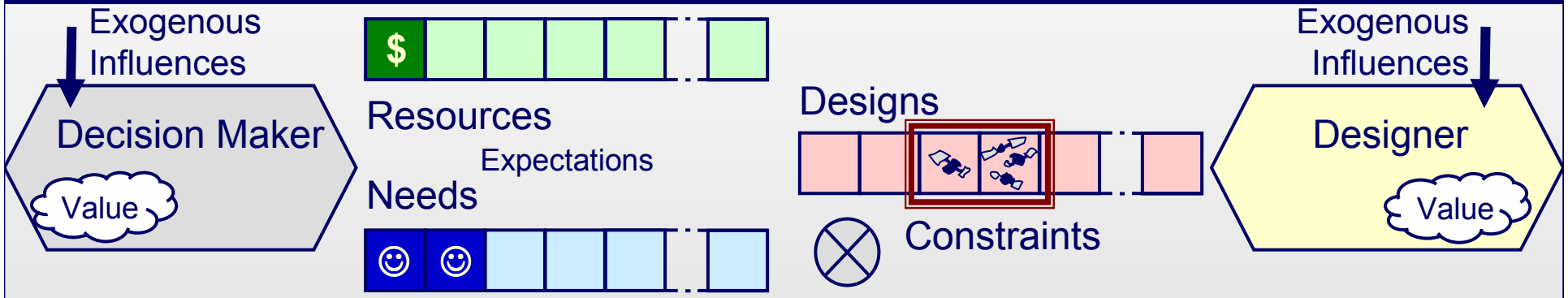
Characterizing the System Design Opportunity

Expectations



Success?



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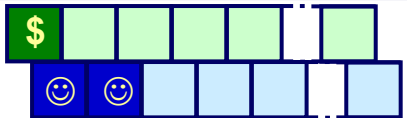
Characterizing the System Design Opportunity

Expectations

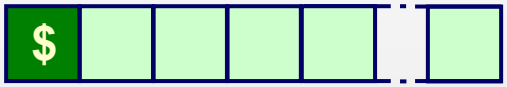


Success?

Exogenous Influences

Decision Maker

Value

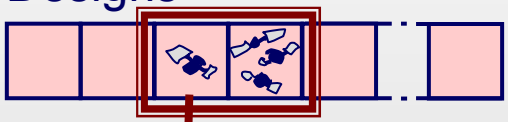


Resources

Expectations

Needs

Designs



Constraints

Exogenous Influences

Designer

Value

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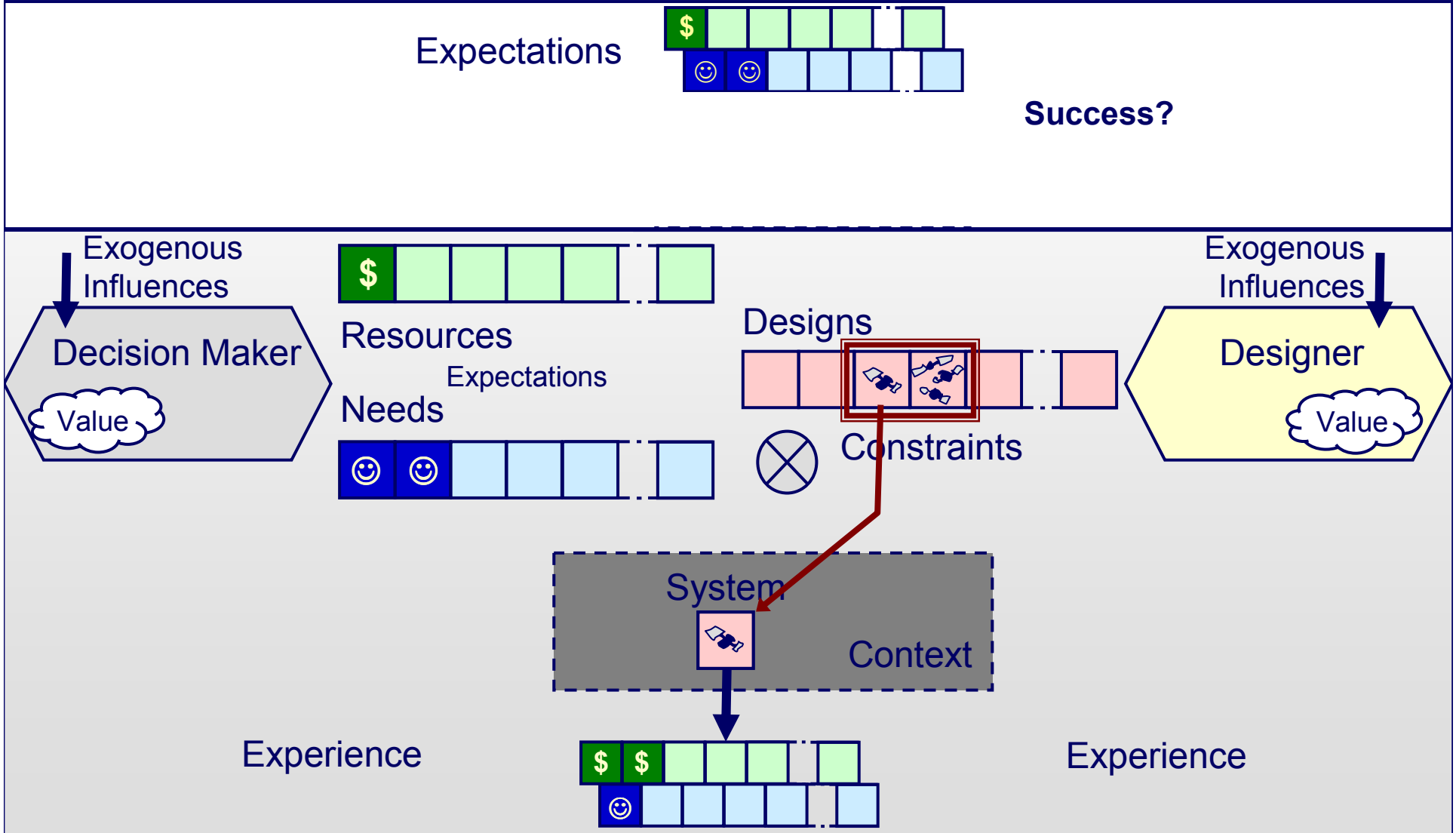
Characterizing the System Design Opportunity



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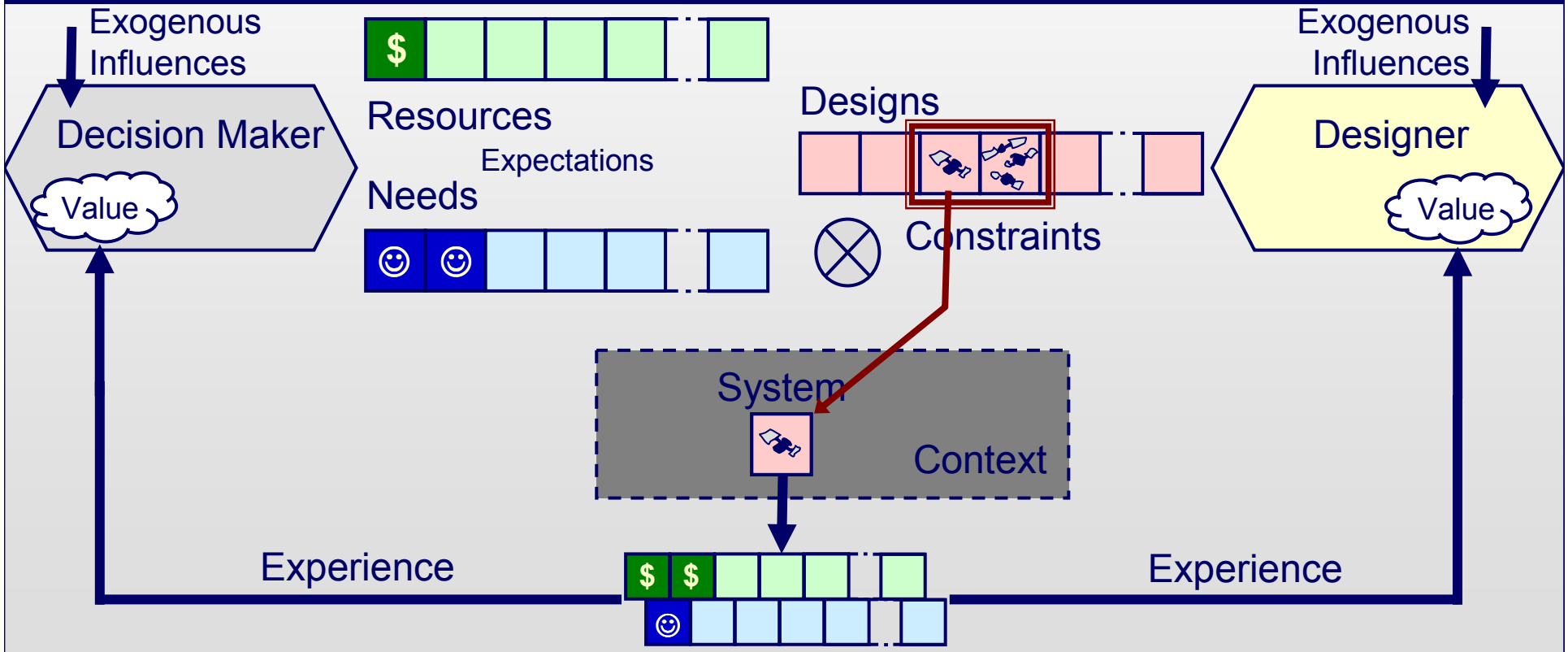
Characterizing the System Design Opportunity



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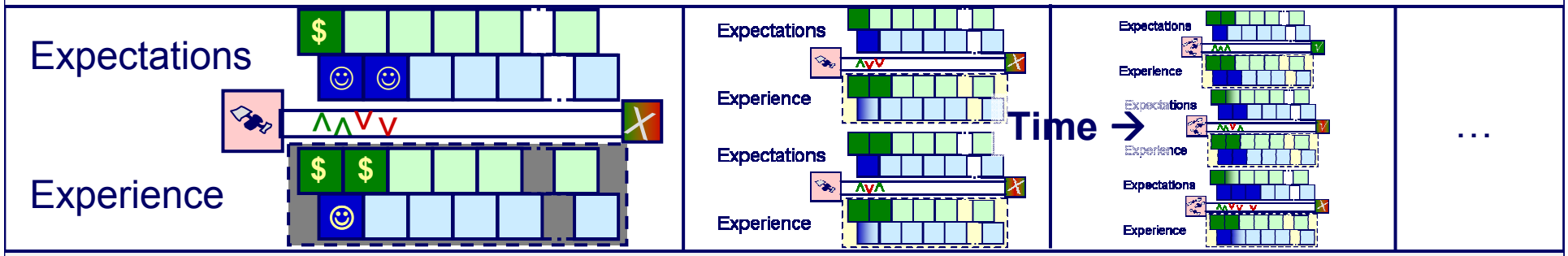
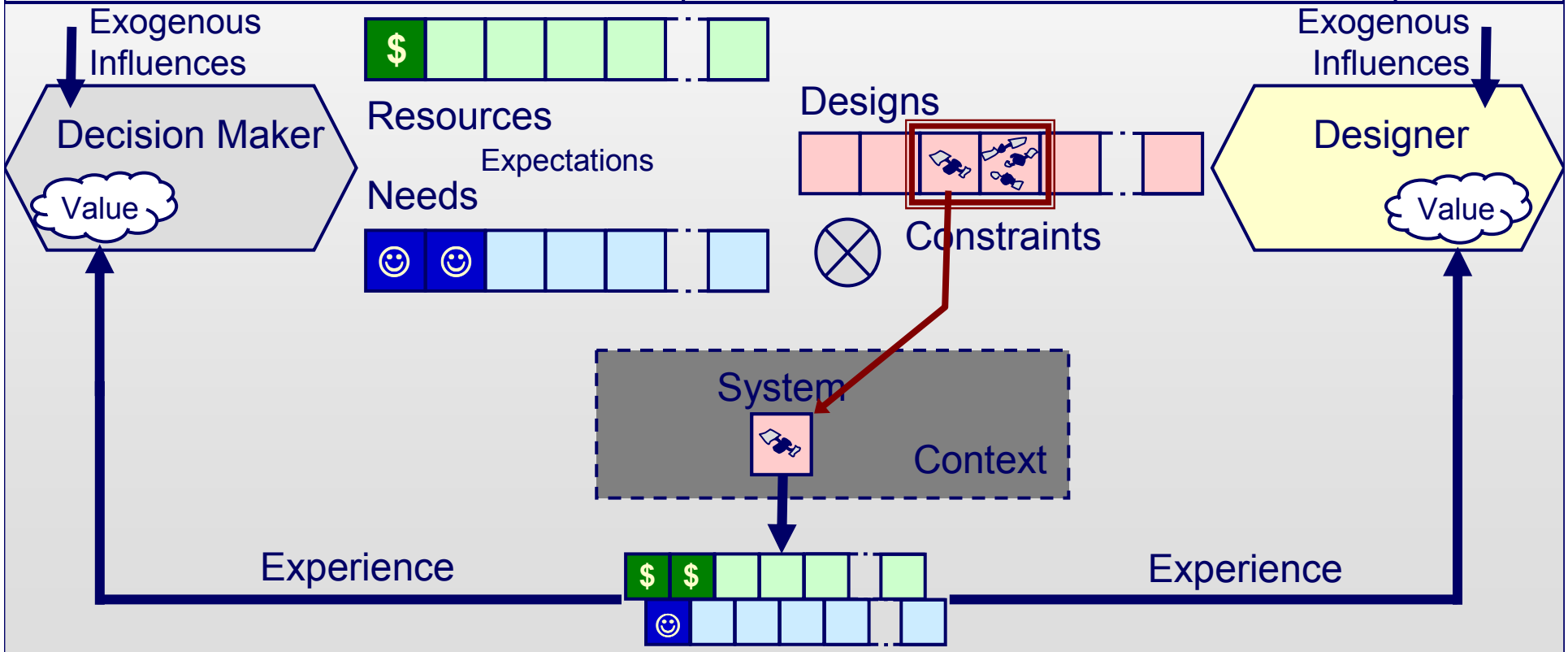
Characterizing the System Design Opportunity





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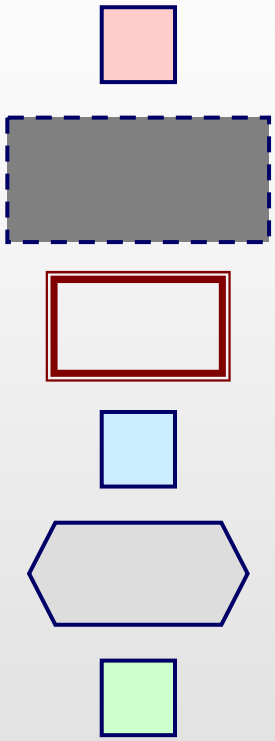
Types of Changes



- Δ Designs (including technology)
- Δ Context (including operating environment, competition)
- Δ Constraints (including “laws”)
  - Physical (e.g. nature)
  - Human-made (e.g. policy, schedule)
  - Resources (e.g. capital)
  - Scoping (e.g. self-imposed)
- Δ Needs (including attributes)
- Δ DMs (including individuals and groups)
- Δ Resources (including dollars and time)

How can System Designers cope with these types of changes during design?

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Aspects of Dynamic MATE*

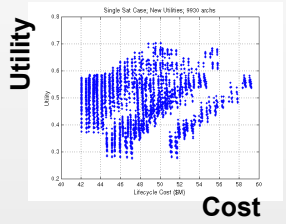
How can System Designers cope with these types of changes during design?

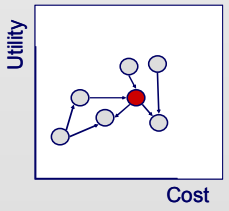
- System Success criteria
  - Expanding scope of system "value"
- Tradespace exploration
  - Understanding success possibilities across a large number of designs
- Change taxonomy
  - Specifying and identifying change types
- Tradespace networks
  - Analyzing changeability of designs
- System Epoch/Era analysis
  - Quantifying effects of changing contexts on system success

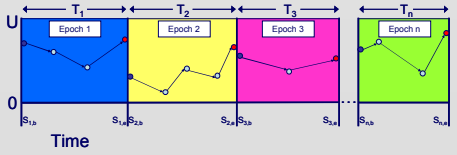
Experience(t) Expectation(t)

Exceeding

$$\Psi(t) = \sum_{i=1}^{N} \left[X_{DMi}(t) + \varepsilon_C^{X_{DMi}}(t) \geq Y_{DMi}(t) + \varepsilon_C^{Y_{DMi}}(t) \right]$$







*MATE = *Multi-Attribute Tradespace Exploration*

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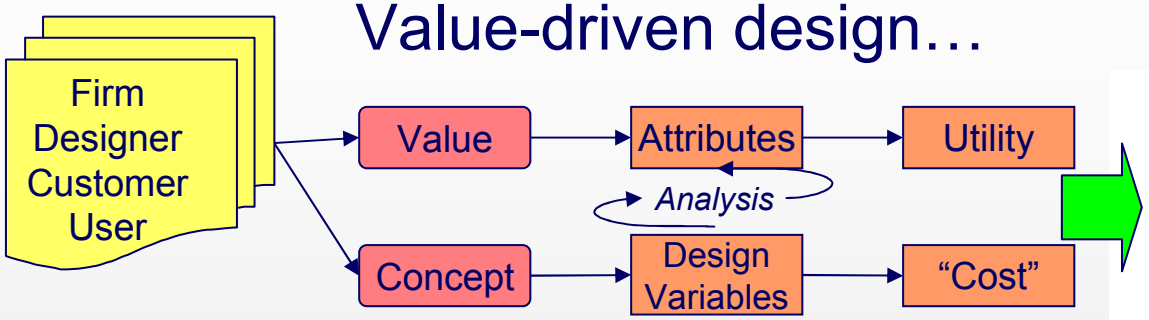
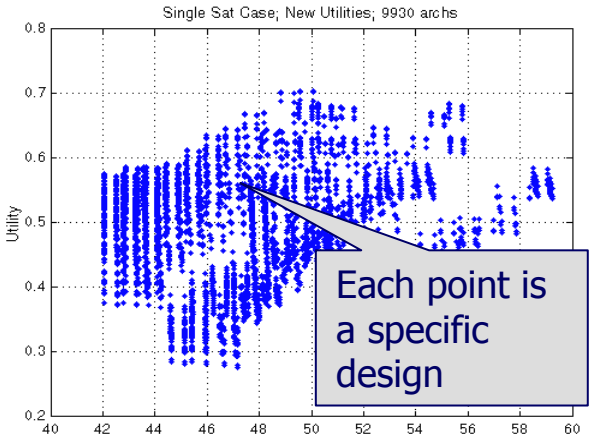
Tradespace Exploration

Value-driven design…





Tradespace: {Design,Attributes} ←→ {Cost,Utility}

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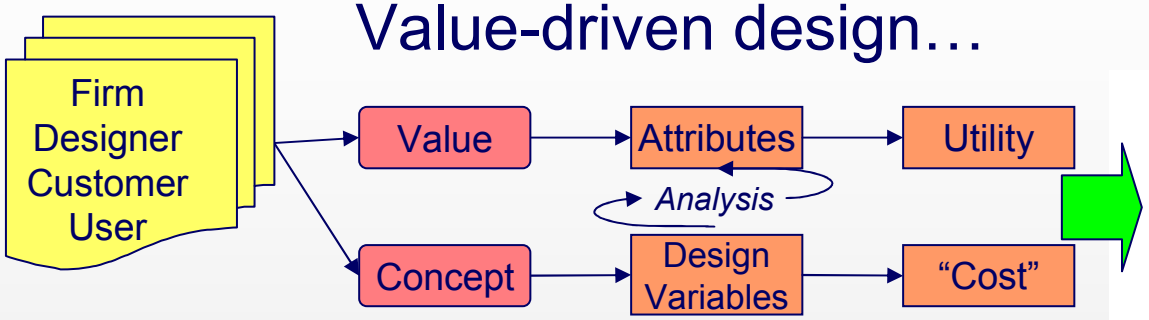
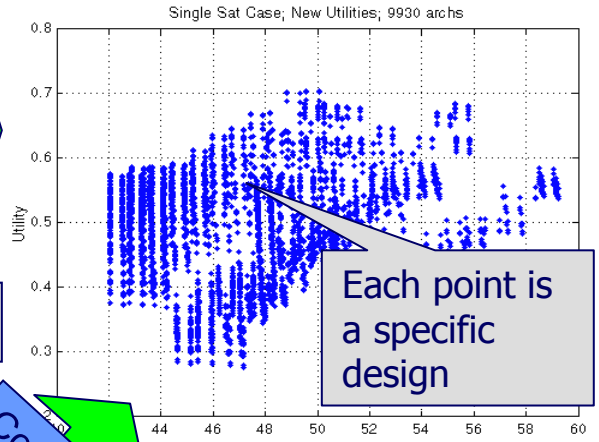
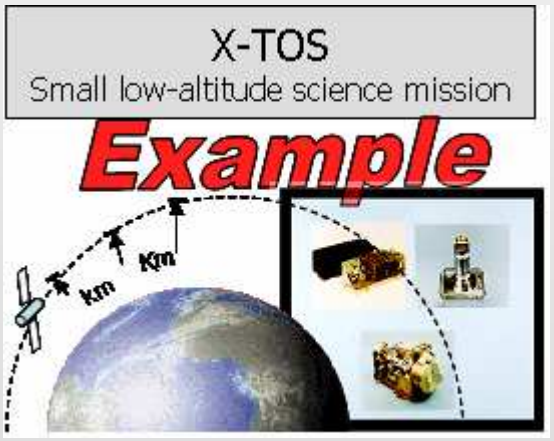
Tradespace Exploration

Value-driven design…





Tradespace: {Design,Attributes} ←→ {Cost,Utility}



DESIGN VARIABLES:
Design trade parameters

Orbital Parameters
- Apogee Altitude (km)
- Perigee Altitude (km)
- Orbit Inclination (deg)

Spacecraft Parameters
- Antenna Gain
- Communication Architecture
- Propulsion Type
- Power Type
- Total Delta V

ATTRIBUTES:
Design decision metrics
- Data Lifespan (yrs)
- Equatorial Time (hrs/day)
- Latency (hrs)
- Latitude Diversity (deg)
- Sample Altitude (km)

Assessment of cost and utility of large space of possible system designs

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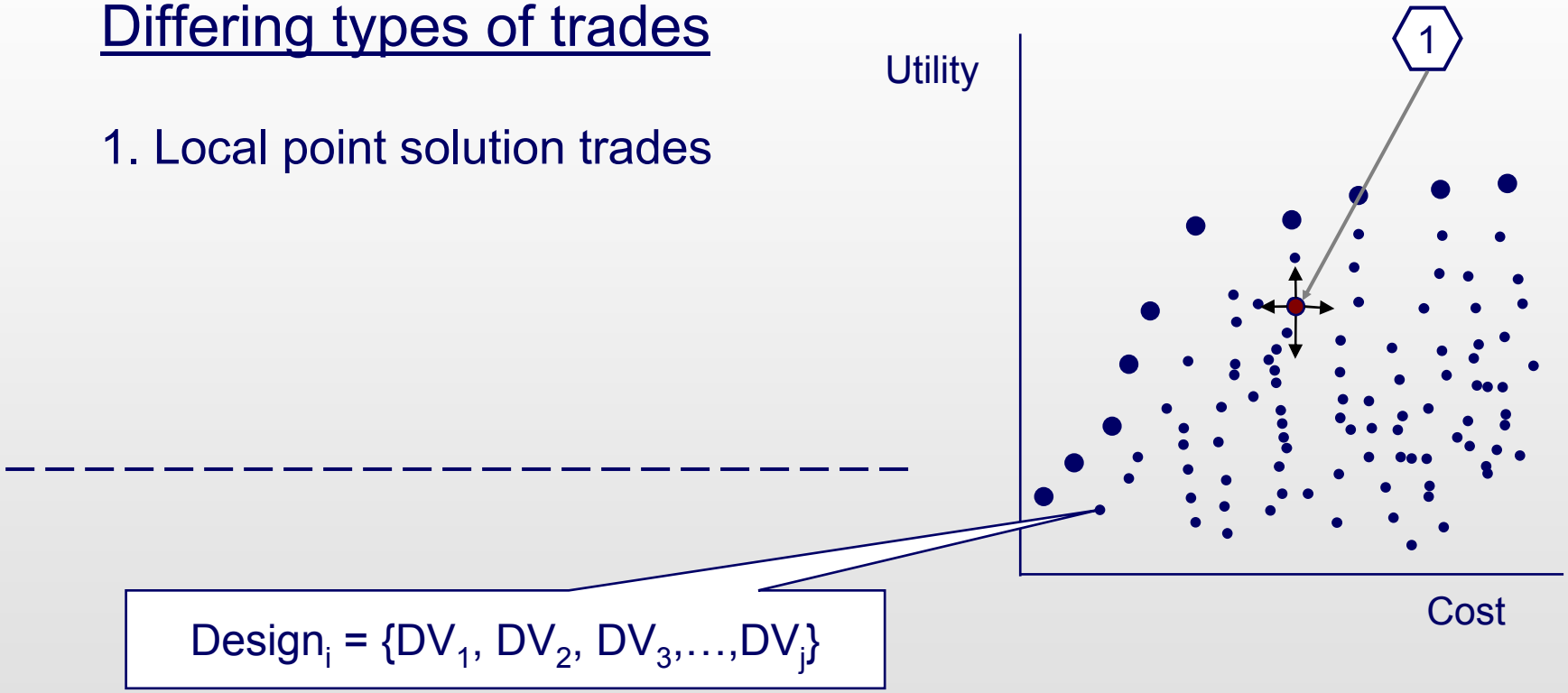
Tradespace Exploration: Avoiding Point Designs

Differing types of trades

1. Local point solution trades



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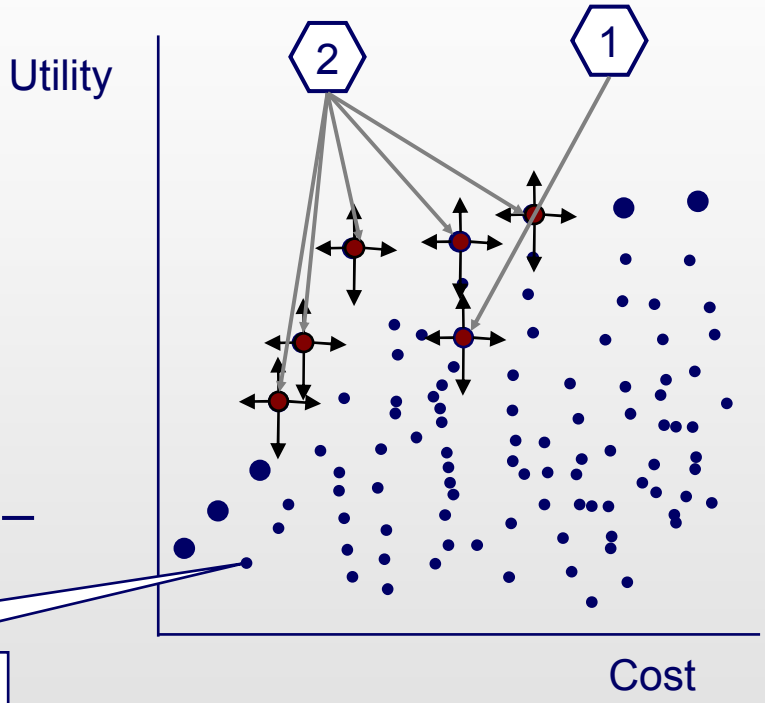
Tradespace Exploration: Avoiding Point Designs

Differing types of trades

1. Local point solution trades
2. Frontier subset solutions



$$Design_i = \{DV_1, DV_2, DV_3, \ldots, DV_j\}$$

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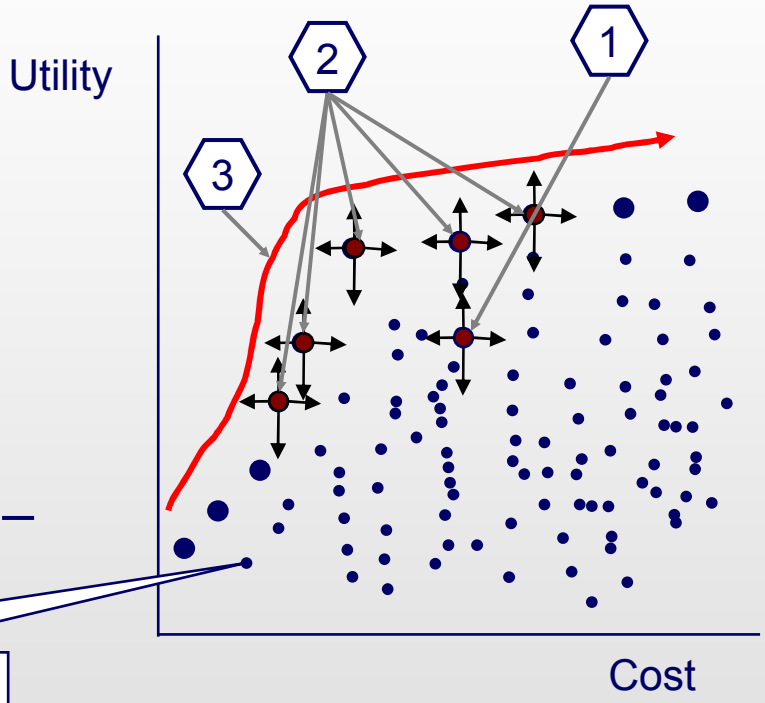
Tradespace Exploration: Avoiding Point Designs

Differing types of trades

1. Local point solution trades
2. Frontier subset solutions
3. Frontier solution set



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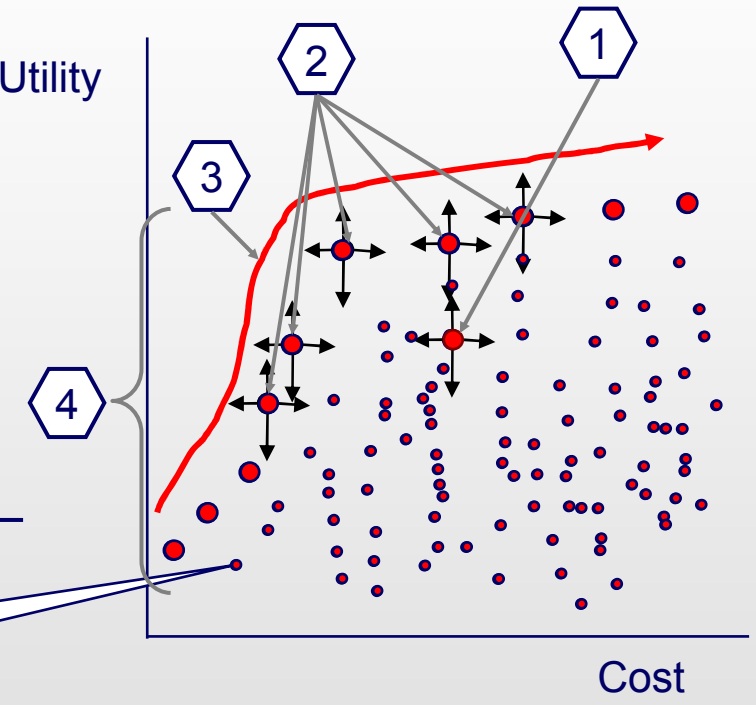
Tradespace Exploration: Avoiding Point Designs

Differing types of trades

1. Local point solution trades
2. Frontier subset solutions
3. Frontier solution set
4. Full tradespace exploration



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Tradespace Exploration: Avoiding Point Designs

Differing types of trades

1. Local point solution trades
2. Frontier subset solutions
3. Frontier solution set
4. Full tradespace exploration

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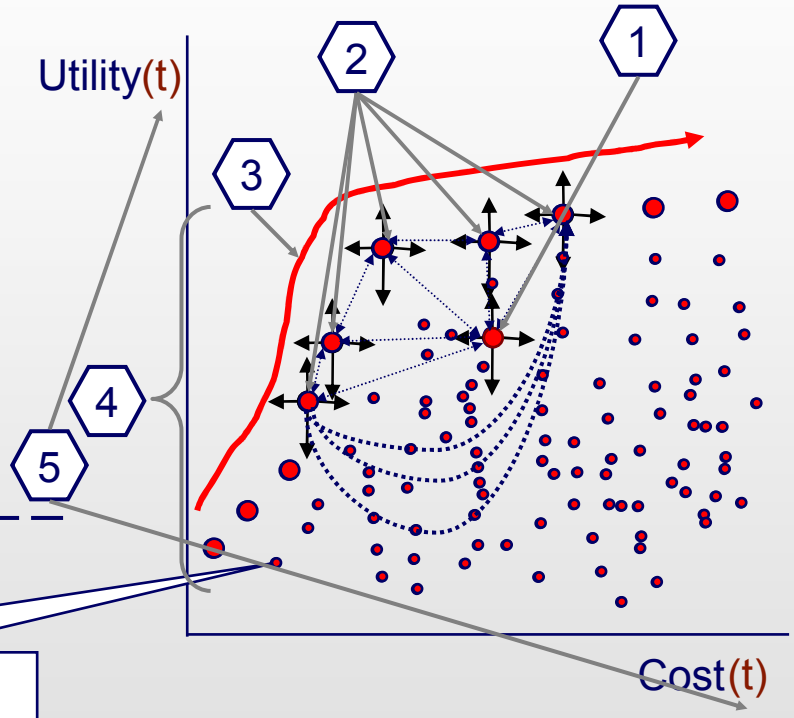
5. Dynamic tradespace relations



$$Design_i = \{DV_1, DV_2, DV_3, \ldots, DV_j\}$$

Tradespace exploration enables big picture understanding

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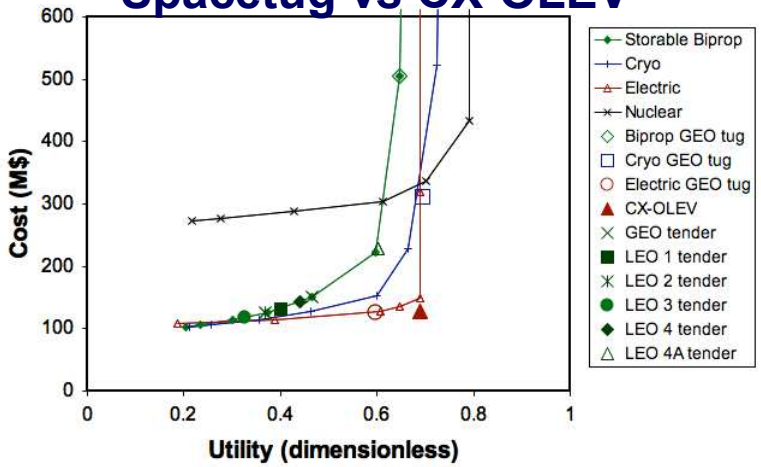
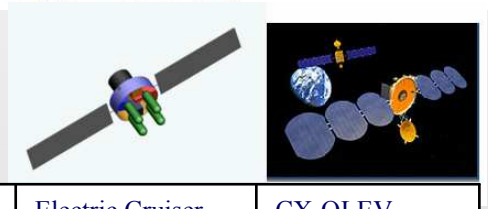
Example "Real Systems"

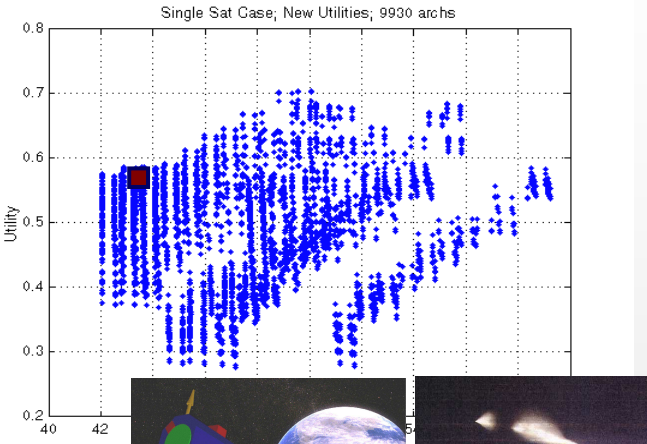
Spacetug vs CX-OLEV

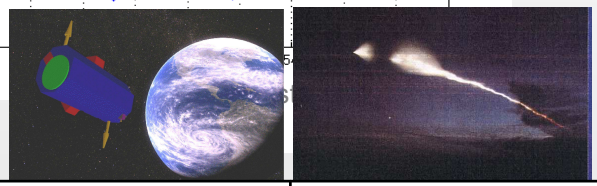




	Electric Cruiser (2002 study)	CX-OLEV (2009 launch)
Wet Mass kg	1405	1400
Dry Mass kg	805	670*
Propellant kg	600	730*
Equipment kg	300	213*
DV m/s	12000 – 16500***	15900**
Utility	0.69	0.69
Cost	148	130*

XTOS vs Streak





	XTOS (2002 study)	Streak (Oct 2005 launch)
Wet Mass kg	325 - 450	420
Lifetime (yrs)	2.3 - 0.5	1
Orbit	300 -185 km @ 20°	321a-296p -> 200 @ 96°
LV	Minotaur	Minotaur
Utility	0.61 - 0.55	0.57 - 0.54*
Modified Utility**	0.56 - 0.50	0.59
Cost $M	75 - 72	75***
Instruments	Three (?)	Ion gauge and atomic oxygen sensor

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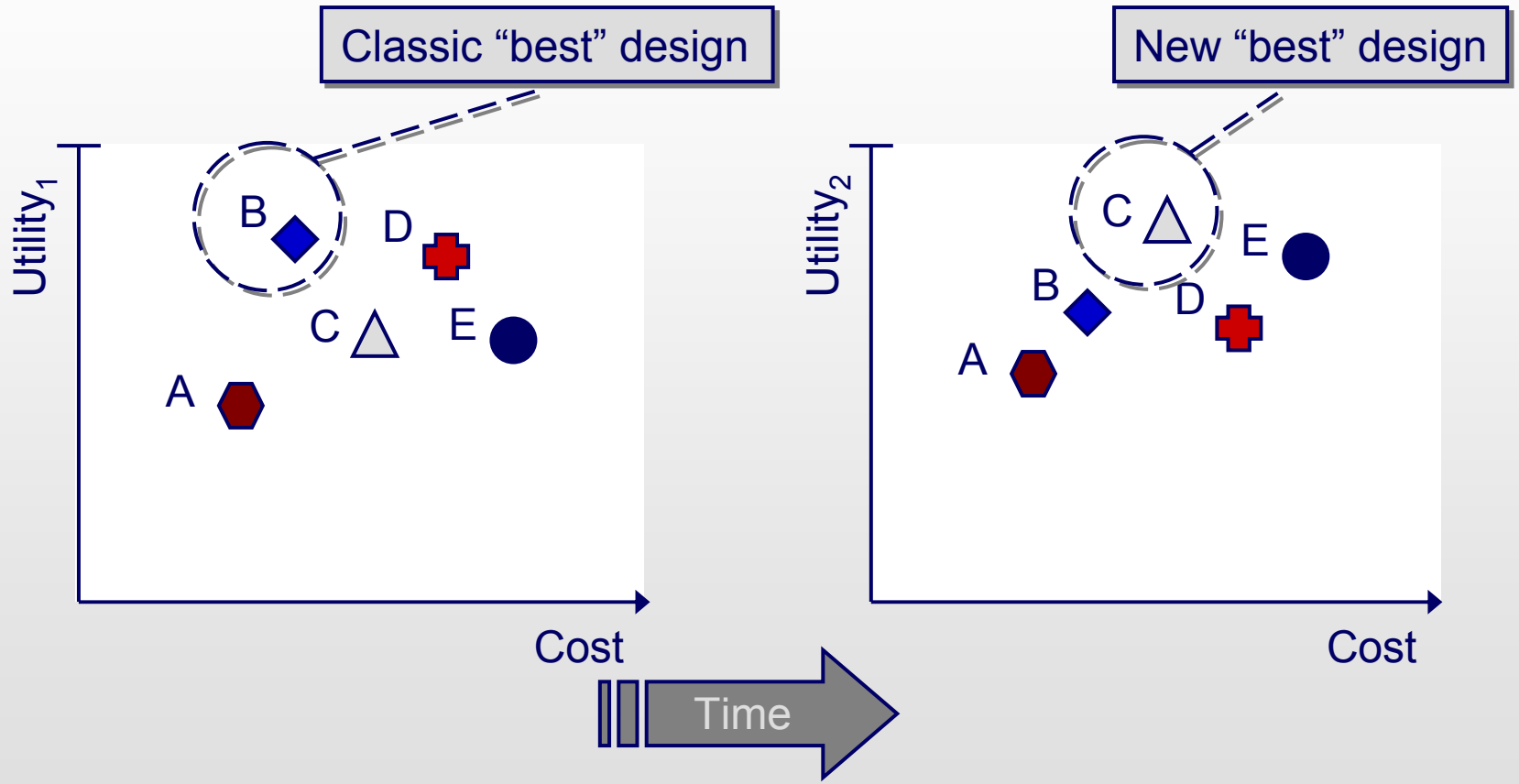
Tradespace Analysis: Selecting "best" designs



If the "best" design changes over time, how does one select the "best" design?

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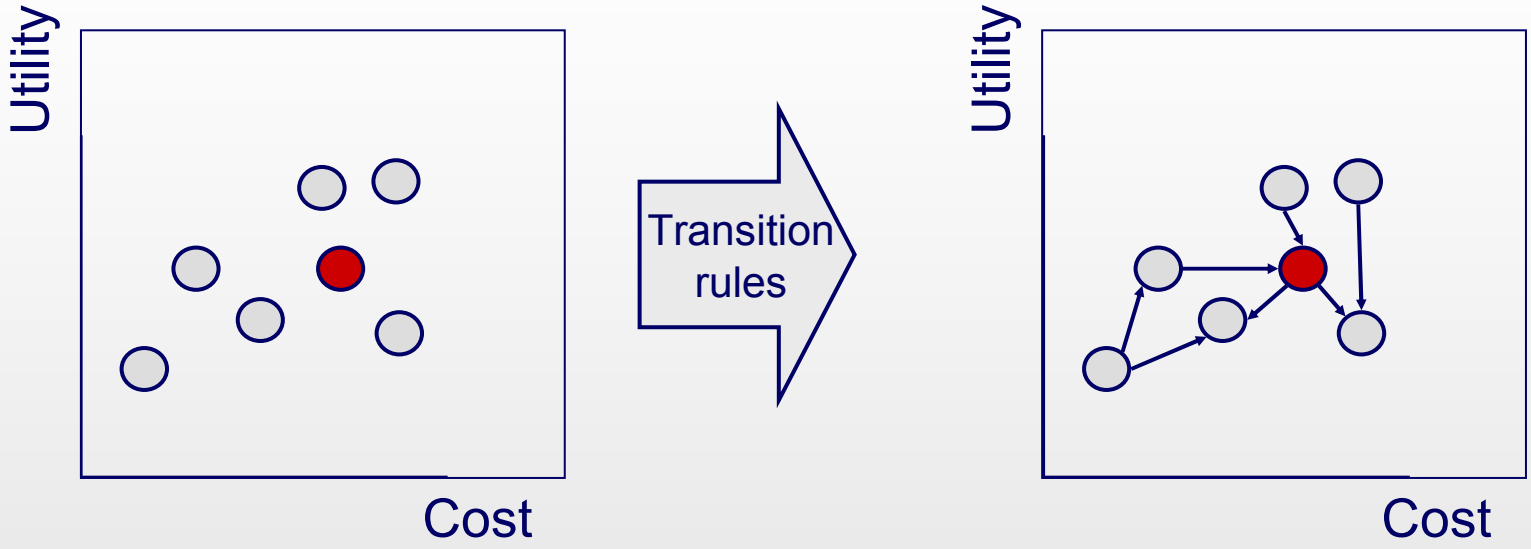
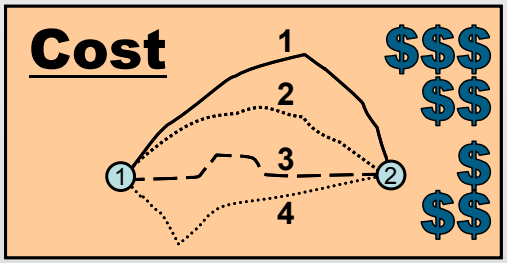
Tradespace Networks



Tradespace designs = nodes

Applied transition rules = arcs



Transition rules are mechanisms to change one design into another
The more outgoing arcs, the more potential change mechanisms

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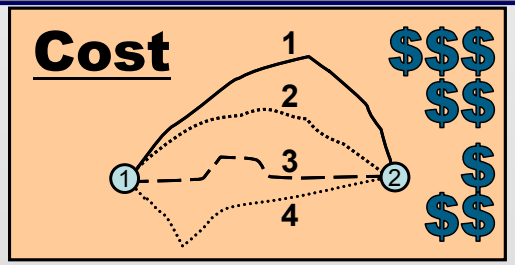
Tradespace Networks

Example: X-TOS Transition Rules

Rule	Description	Change agent origin
R1: Plane Change	Increase/decrease inclination, decrease ΔV	Internal (Adaptable)
R2: Apogee Burn	Increase/decrease apogee, decrease ΔV	Internal (Adaptable)
R3: Perigee Burn	Increase/decrease perigee, decrease ΔV	Internal (Adaptable)
R4: Plane Tug	Increase/decrease inclination, requires "tugable"	External (Flexible)
R5: Apogee Tug	Increase/decrease apogee, requires "tugable"	External (Flexible)
R6: Perigee Tug	Increase/decrease perigee, requires "tugable"	External (Flexible)
R7: Space Refuel	Increase ΔV, requires "refuelable"	External (Flexible)
R8: Add Sat	Change all orbit, ΔV	External (Flexible)

Tradespace designs = nodes

Applied transition rules = arcs



Transition rules are mechanisms to change one design into another
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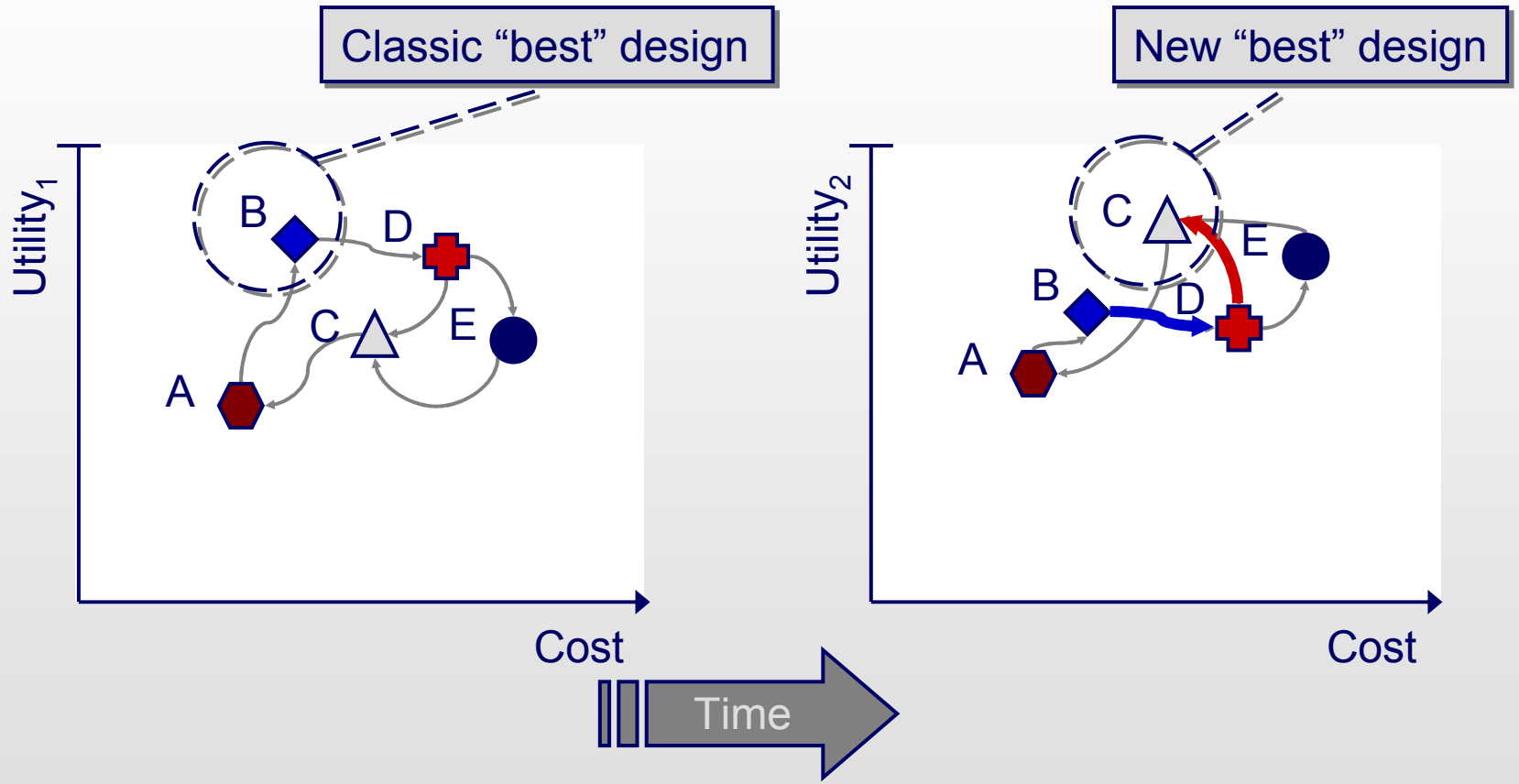
Tradespace Networks: Changing designs over time



Select changeable designs that can approximate “best” designs in new contexts

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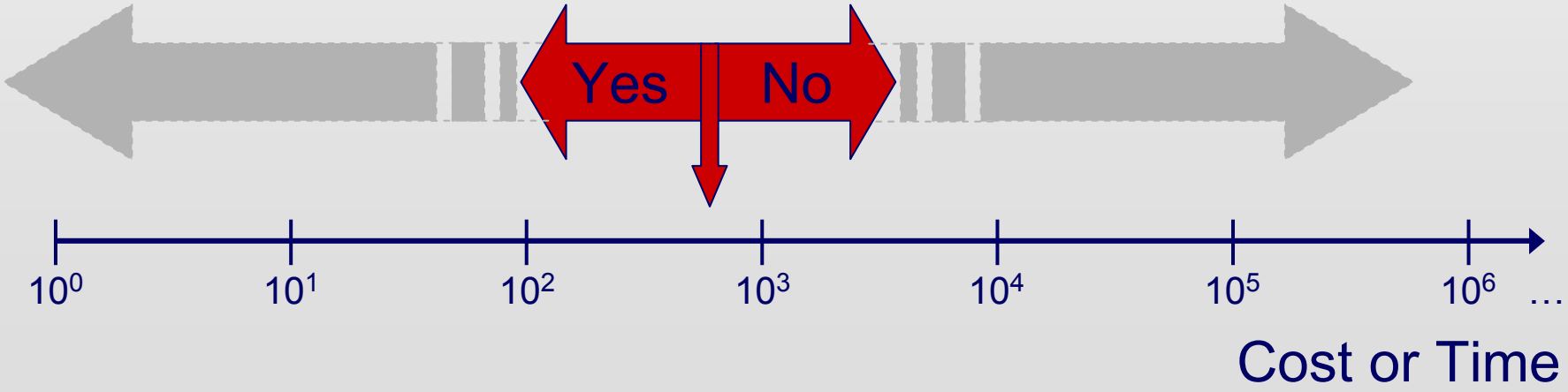
Determining Changeability

The Question: Is the system _____?

(Flexible, Adaptable, Robust, Scalable, Modifiable, Changeable, Rigid, etc…)

The Answer: It depends!

The question of changeability is partly subjective:
Is the "cost" for change acceptable?



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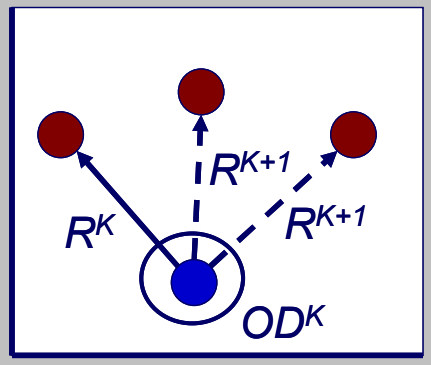
Changeability Metric: Filtered Outdegree

objective

Outdegree

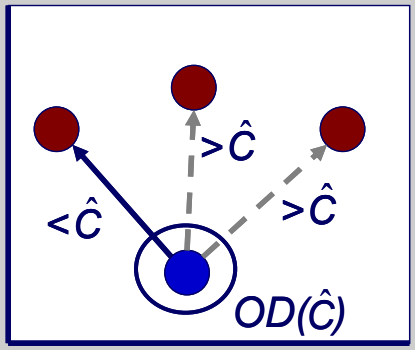
outgoing arcs from a given node



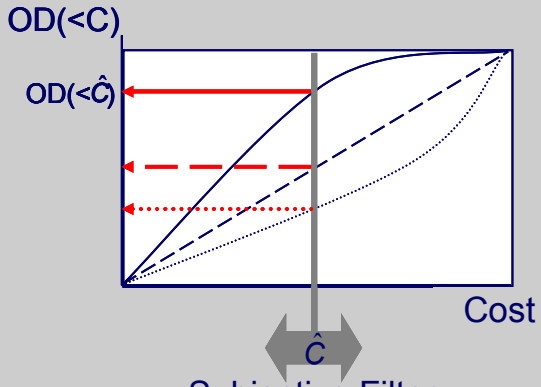
subjective

Filtered Outdegree

outgoing arcs from design at acceptable "cost" (measure of changeability)



Outdegree



Subjective Filter

Filtered outdegree is a measure of the apparent changeability of a design

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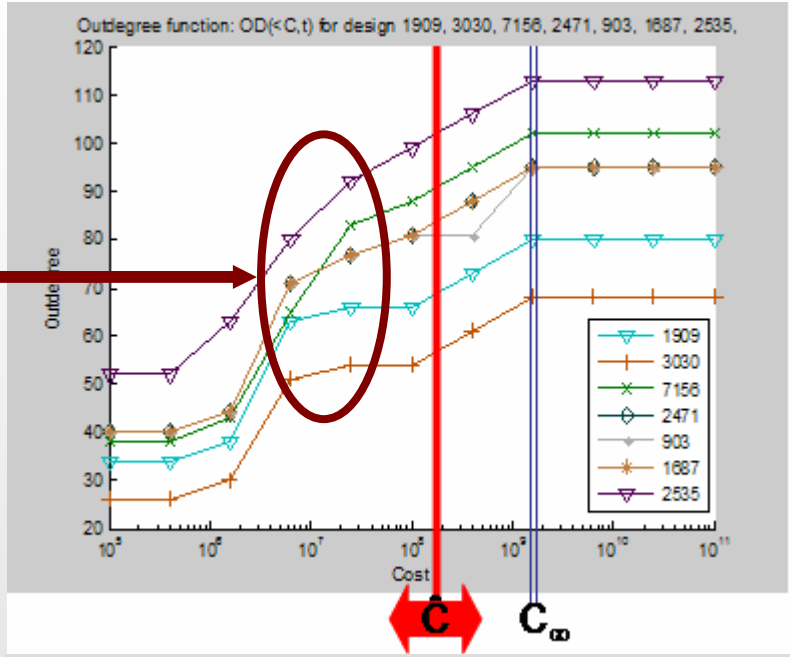
Ex: X-TOS Outdegree function



DV	2471	903	1687	2535	1909	3030	7156
Inclination	90	30	70	90	70	90	90
Apogee	460	460	460	460	1075	2000	770
Perigee	150	150	150	290	150	150	350
Com Arch	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS
Delta V	1200	1200	1200	1200	1200	1200	1000
Prop Type	Chem	Chem	Chem	Chem	Elec	Elec	Chem
Pwr Type	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Solar Array	Solar Array
Ant Gain	Low	Low	Low	Low	Low	Low	Low
Data Life	0.51	0.51	0.51	10.05	0.52	0.61	11
Lat Div	180	60	140	180	140	180	180
Eq Time	5	11	6	5	2	2	5
Latency	2.27	2.27	2.27	2.30	2.42	2.67	2.40
Sample Alt	150	150	150	290	150	150	350
Cost ($10M)	4.21	4.21	4.21	4.88	4.52	4.99	4.15

- Pareto Set designs (903, 1687, 2471) are not the most changeable
- Design 7156 becomes relatively more changeable as cost threshold increases

Outdegree functions reveal differential nature of apparent changeability

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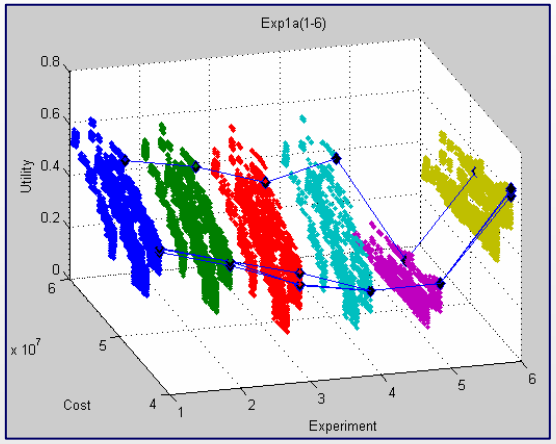
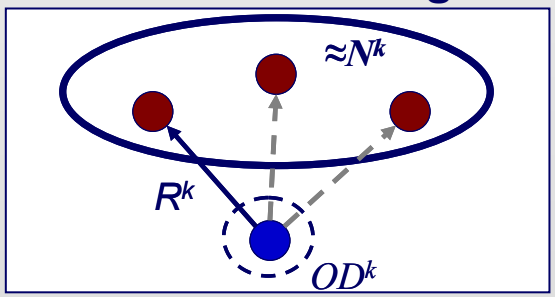
Tradespace Networks in the System Era

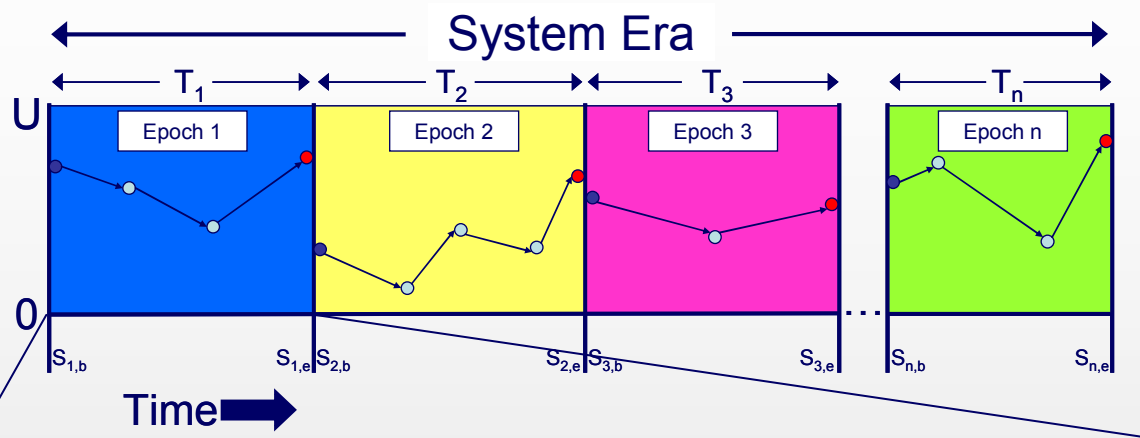
Systems Engineering Advancement Research Initiative

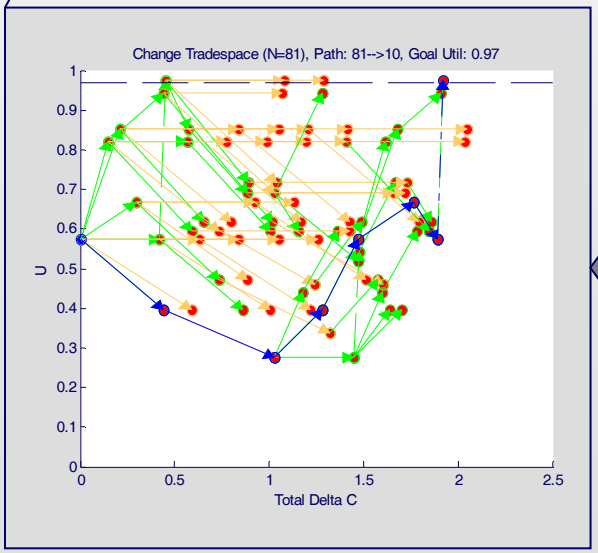
Pareto Tracing across Epochs

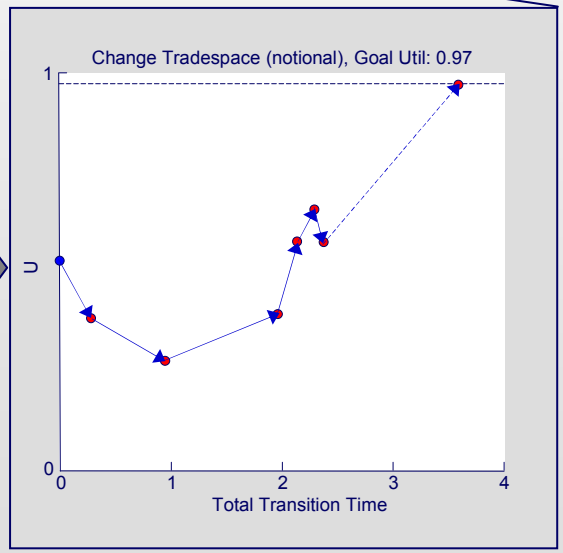


Changeability Quantified as Filtered Outdegree









Temporal strategy can be developed across networked tradespace

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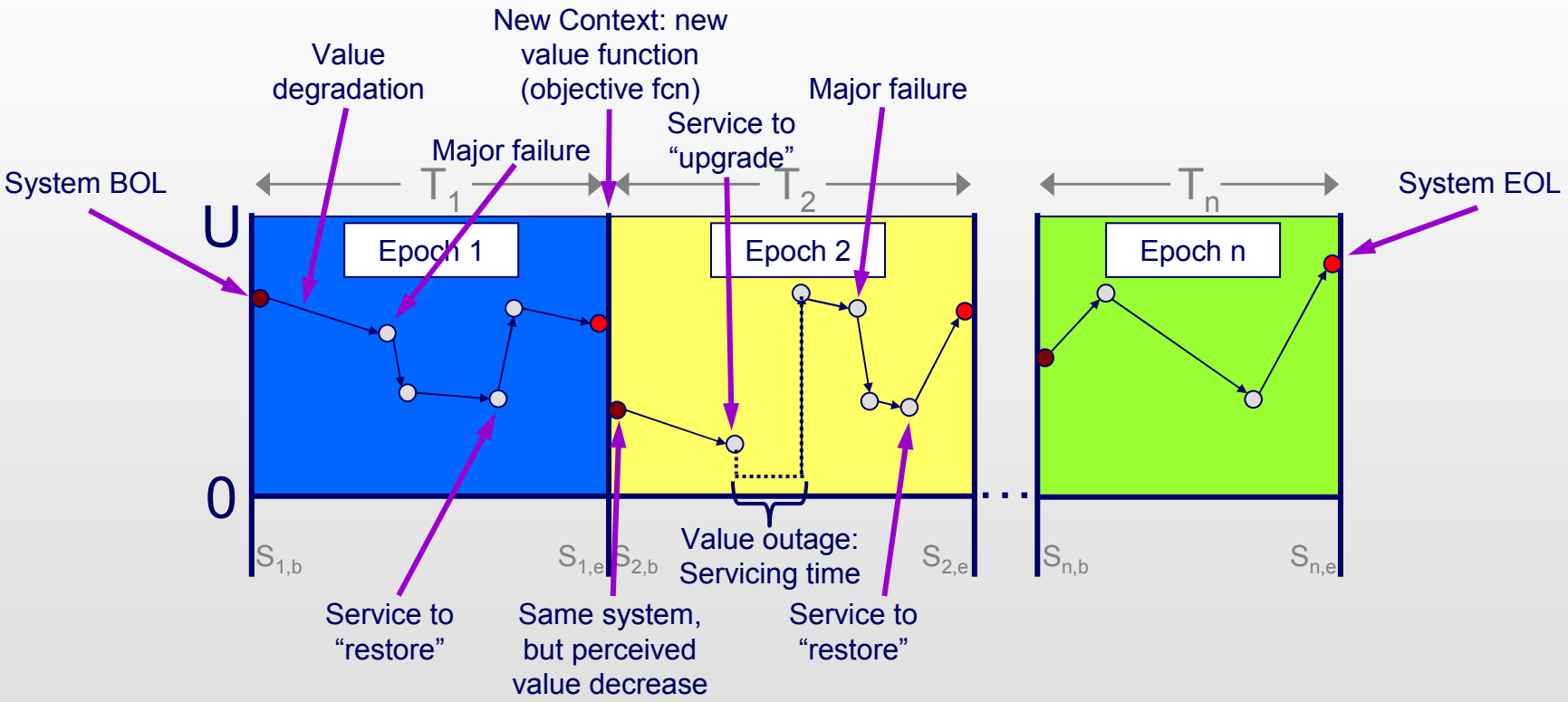
Example System Timeline

Example system: Serviceable satellite



System timeline with "serviceability"-enabled paths allow value delivery

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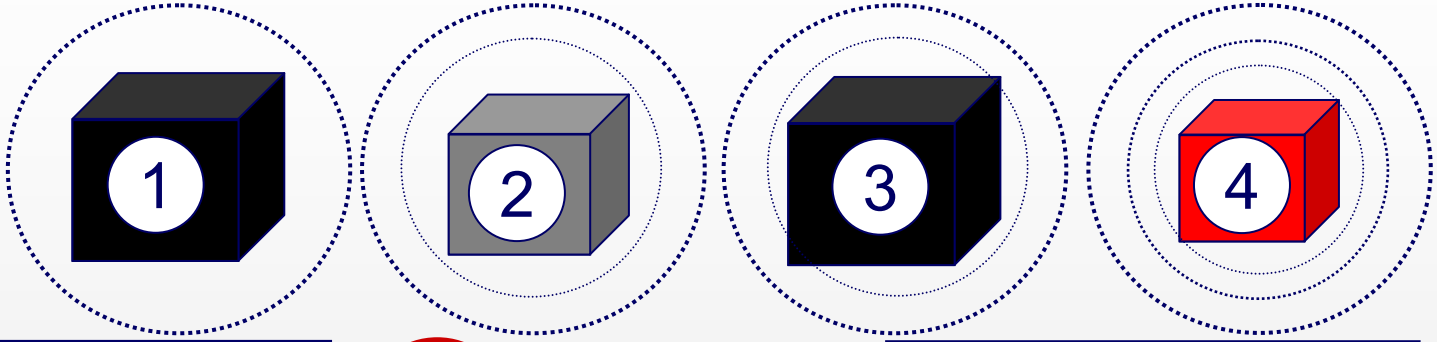
Ex: Desiring "No" Change:
Value Robustness



Preferences t=1

Attribute	k_i
Size	0.5
Loudness	0.2

Choose 3

U(3)>U(2)>U(1)>U(4)

U(4)>U(2)>U(3)>U(1)

big>small

loud>quiet

Preferences t=2

Attribute	k_i
Size	0.5
Loudness	0.2

Attribute "priority"

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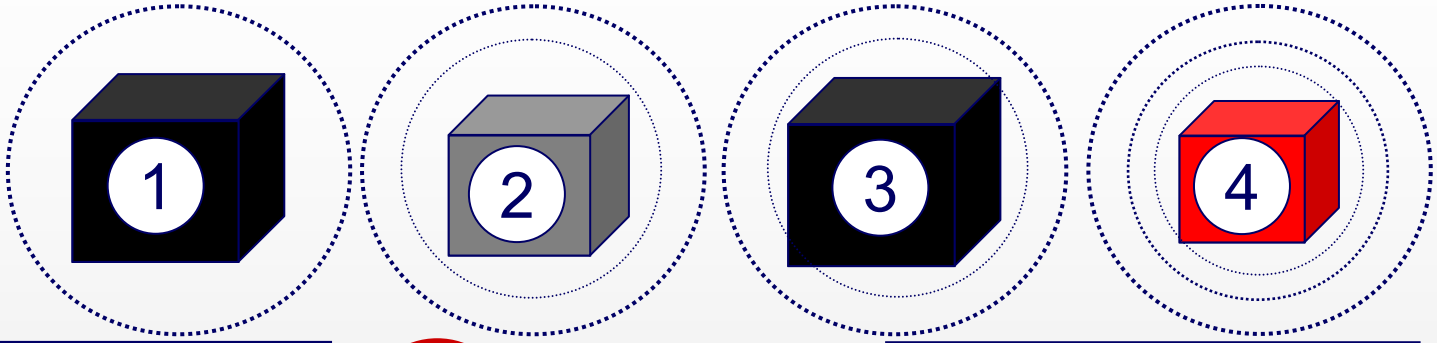
Ex: Desiring "No" Change:
Value Robustness



Preferences t=1

Attribute	k_i
Size	0.5
Loudness	0.2

Choose 3

U(3)>U(2)>U(1)>U(4)

U(4)>U(2)>U(3)>U(1)

big>small

loud>quiet

red>gray>black

Preferences t=2

Attribute	k_i
Size	0.5
Loudness	0.2
Color	0.6

Attribute "priority"

New

Choose 4

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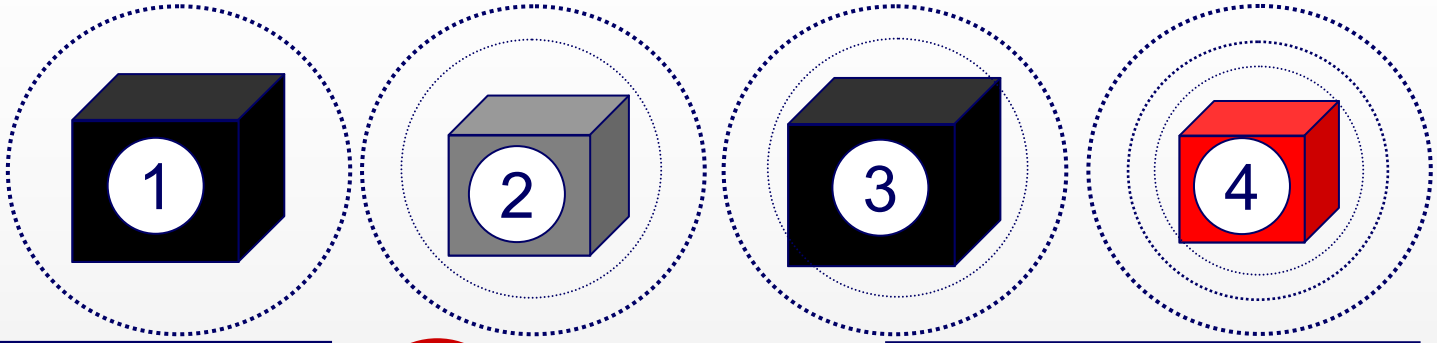
Ex: Desiring "No" Change:
Value Robustness



Preferences t=1

Attribute	k_i
Size	0.5
Loudness	0.2

Choose 3

U(3)>U(2)>U(1)>U(4)

U(4)>U(2)>U(3)>U(1)

big>small

loud>quiet

red>gray>black

Change?

Preferences t=2

Attribute	k_i
Size	0.5
Loudness	0.2
Color	0.6

Attribute "priority"

New

Choose 4

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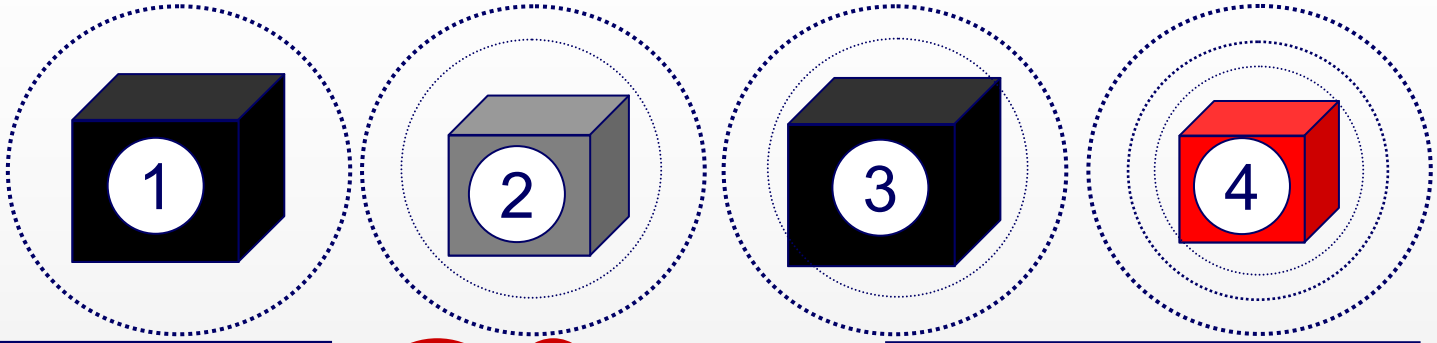
Ex: Desiring "No" Change:
Value Robustness



Preferences t=1

Attribute	k_i
Size	0.5
Loudness	0.2

Choose 3

U(3)>U(2)>U(1)>U(4)

U(4)>U(2)>U(3)>U(1)

big>small

loud>quiet

red>gray>black

Change?

Preferences t=2

Attribute	k_i
Size	0.5
Loudness	0.2
Color	0.6

Attribute "priority"

New

Choose 4

If switching costs are high, option (2) may be better choice (i.e. robust in value)

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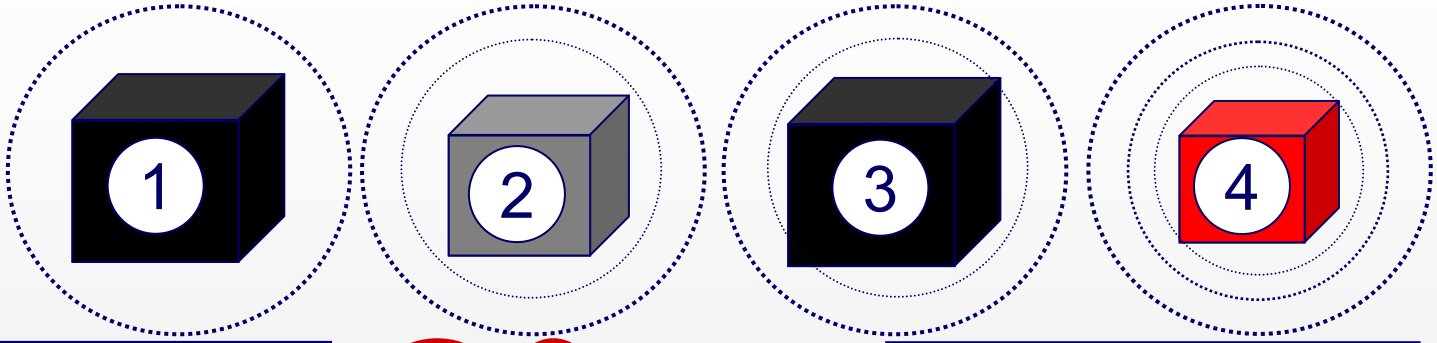
Ex: Desiring "No" Change:
Value Robustness



Preferences t=1

Attribute	k_i
Size	0.5
Loudness	0.2

Choose 3

U(3)>U(2)>U(1)>U(4)

U(4)>U(2)>U(3)>U(1)

big>small

loud>quiet

red>gray>black

Change?

Preferences t=2

Attribute	k_i
Size	0.5
Loudness	0.2
Color	0.6

Attribute "priority"

New

Choose 4

If switching costs are high, option 2 may be better choice (i.e. robust in value)

Clever designs or *changeable designs* can achieve value robustness

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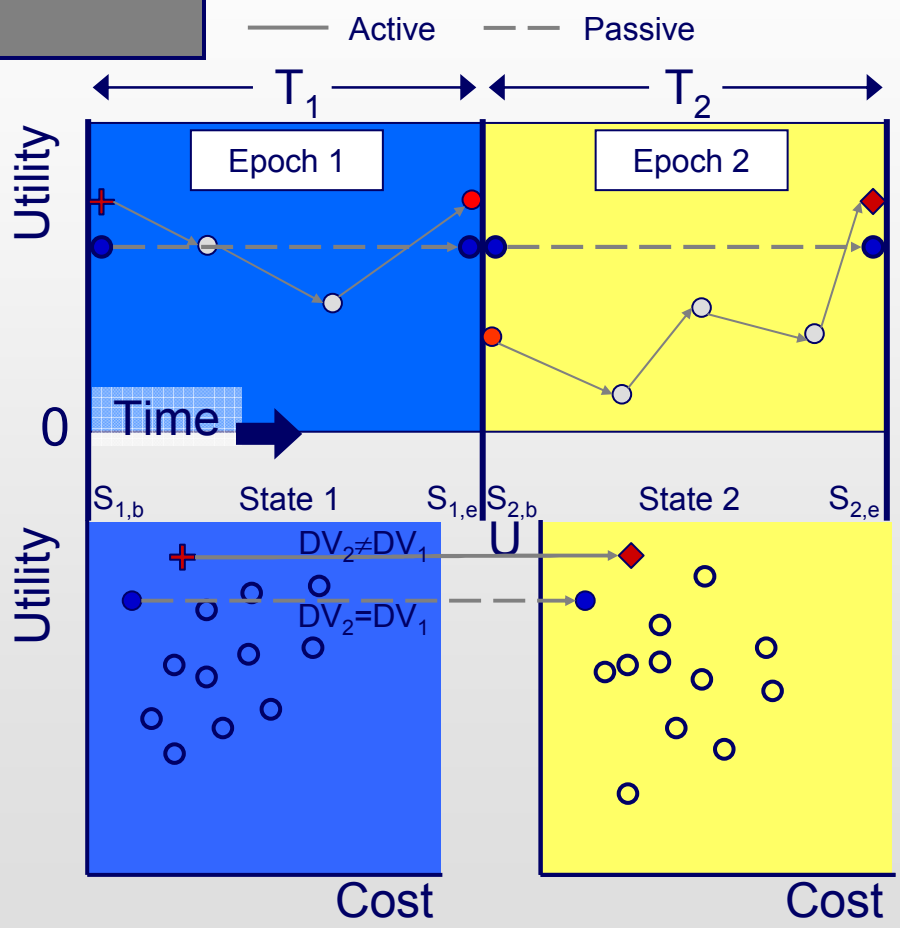
Achieving Value Robustness

Research suggests two strategies for "Value Robustness"

New Context Drivers

- External Constraints
- Design Technologies
- Value Expectations

1. Passive
   - Choose "clever" designs that remain high value
   - Quantifiable: Pareto Trace number
2. Active
   - Choose changeable designs that can deliver high value when needed
   - Quantifiable: Filtered Outdegree



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

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Dynamic MATE Summary

A Layered Approach

Perform Static MATE

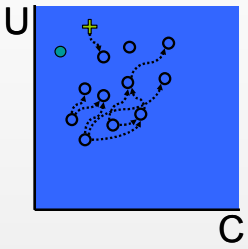
- Attributes
- Designs
- Proposed Rules

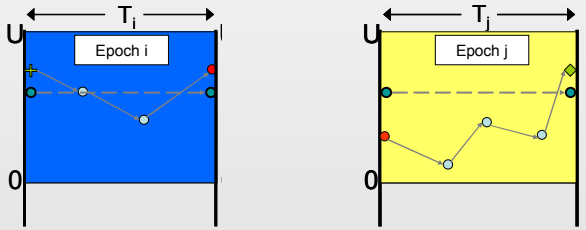
Define Epochs

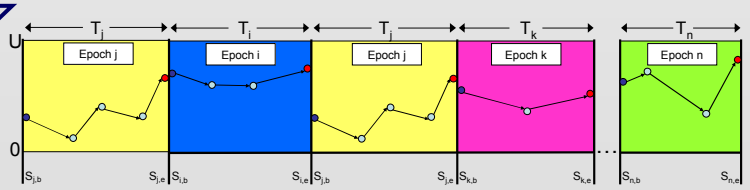
- Potential Contexts
- Δ DV, X, R

Construct Eras

- Epoch Series
- Dynamic Strategies







Changeability provides insight for achieving dynamic *value robustness*

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Designing for Value Robustness

Mindshift: recognize dynamic contexts and fallacy of static preferences; the inevitability of "change"

- Matching changing systems to changing needs leads to sustained system success
- Methods for increasing Changeability
  - Increase number of paths (change mechanisms)
  - Lower "cost" or increase acceptability threshold (apparent changeability)
- Concept-independent measure of changeability: filtered outdegree
  - Change mechanism drives filtered outdegree, as does consideration of alternative systems (future states)
  - Quantifiable filtered outdegree couples both objective and subjective measures (irreducible subjectivity → acceptability threshold)
- Changeability can be used as an explicit and consistent metric for designing systems

Designed for changeability, systems will be empowered to become value robust, delivering value in spite of context and preference changes

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Thank you for your attention!

Any questions?

adamross@mit.edu

For further details on topic please visit:
http://seari.mit.edu

Ross, Adam M., Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration. Cambridge, MA: MIT. PhD in Engineering Systems. 2006.