Assessing Changeability in Aerospace Systems Architecting and Design Using Dynamic Multi-Attribute Tradespace Exploration

(AIAA 2006-7255)

Adam Ross, MIT Postdoctoral Associate
and Daniel Hastings, MIT Professor
AIAA Space 2006, Session 52-SPS-4
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Presentation Overview

1. Introduction
2. Defining Changeability
3. Quantifying Changeability
4. Case Applications
    1. Hypothetical Low Earth Orbit Satellite
    2. Currently Deployed Weapon System
    3. Proposed Large Astronomical Observatory
5. Discussion
6. Conclusion

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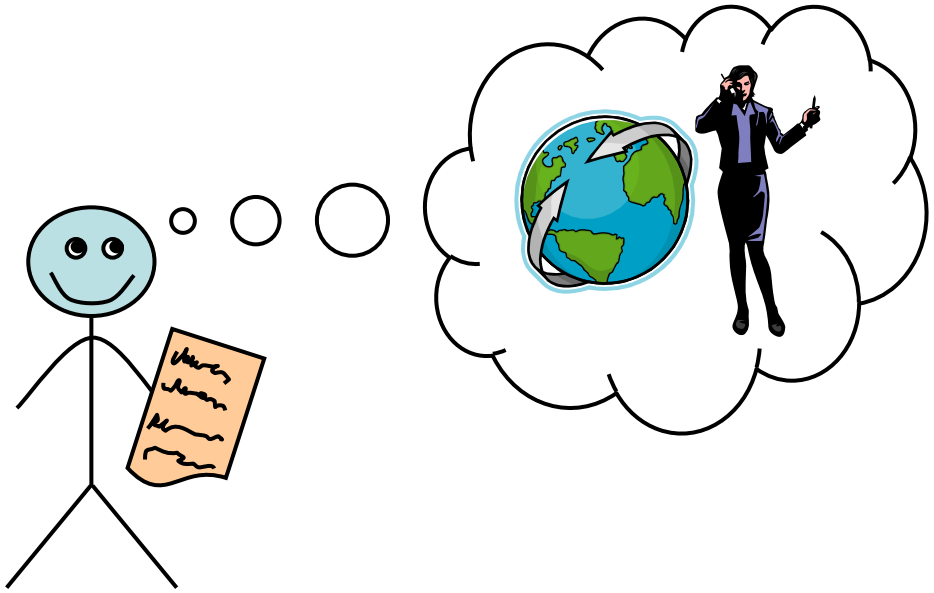
Meeting Customer Needs



- 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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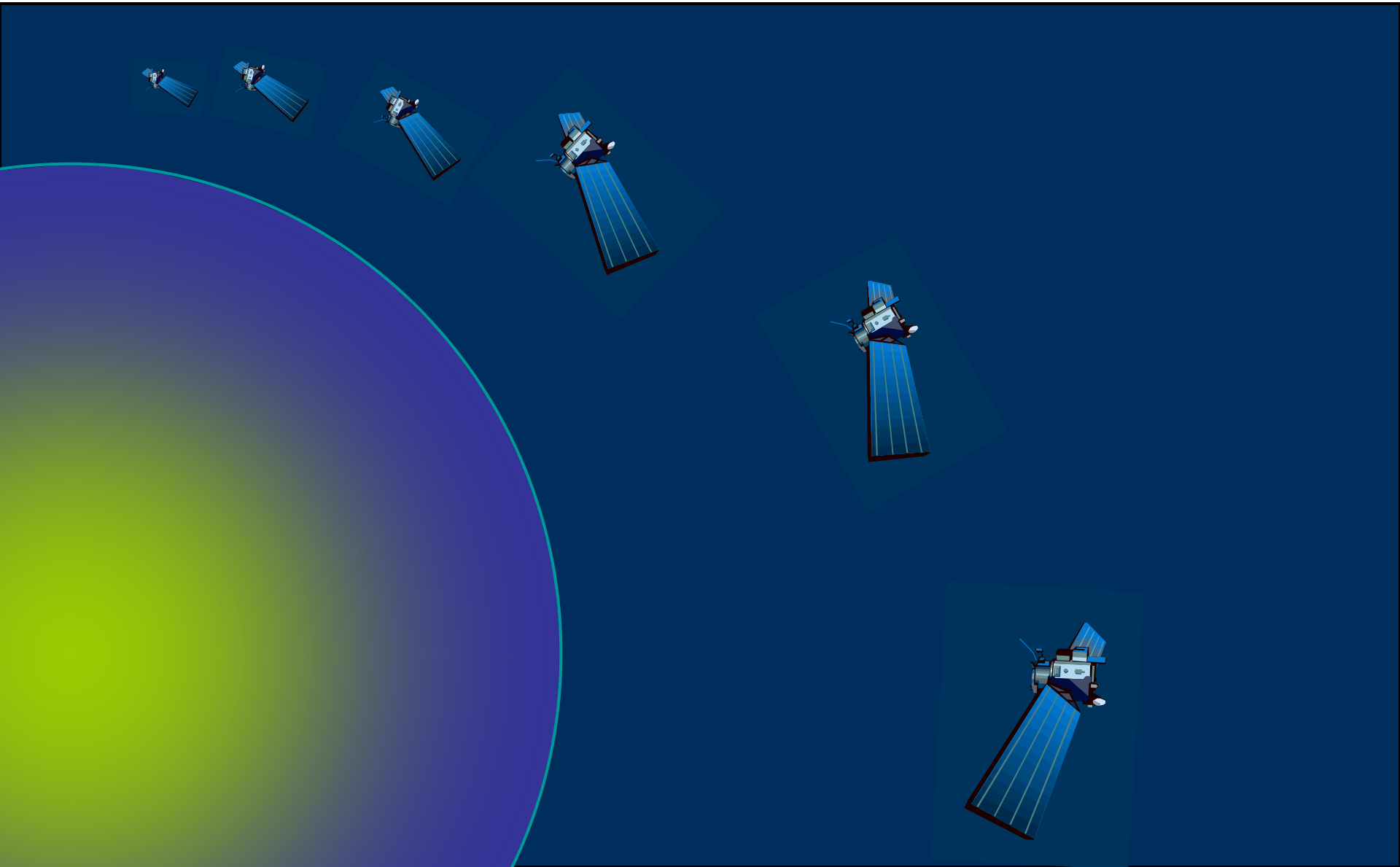
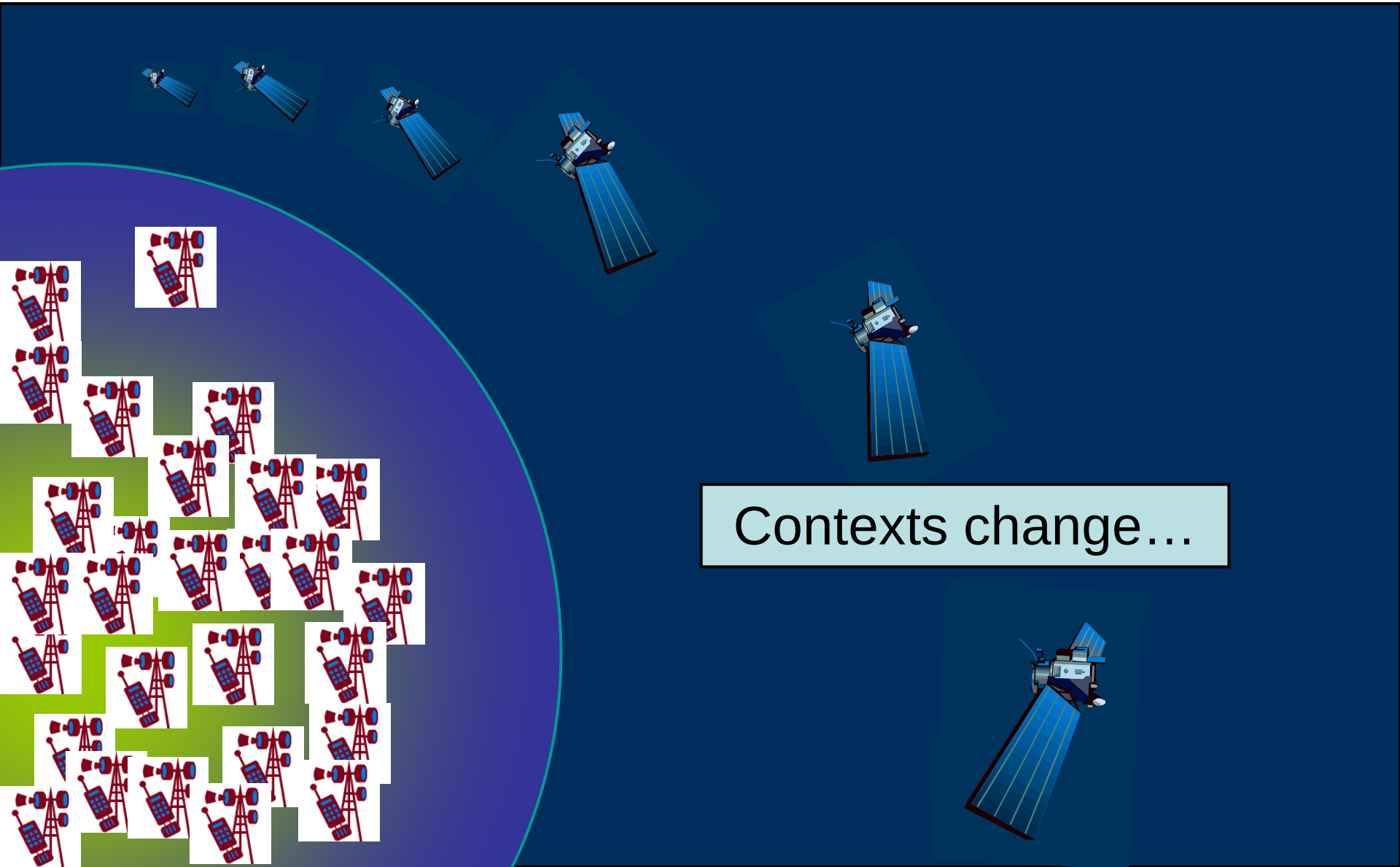
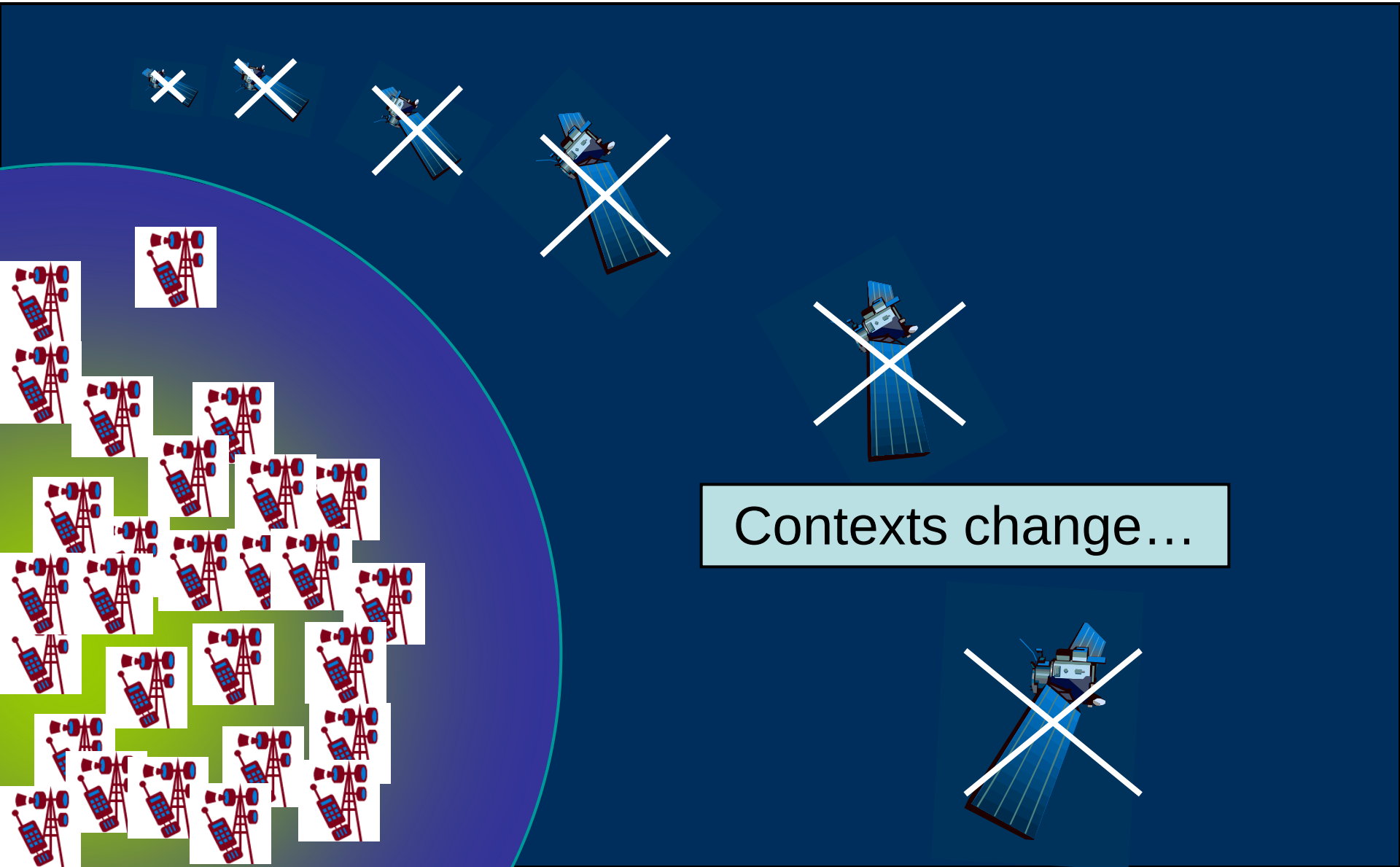
Deploying a “Valuable” System…



Deploying a “Valuable” System…



Deploying a “Valuable” System…



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…)
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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 must change as well…

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Defining Changeability

- **What is change?**
  - **Defined by differences…**
  - **Necessity of time…**
- **Three parts**
  - **Change agent ("who" caused change, force instigator)**
  - **Change mechanism (how changed, including "cost")**
  - **Change effect (what changed, "State 2 – State 1")**
- **All things change, but some things are more "changeable" than others**

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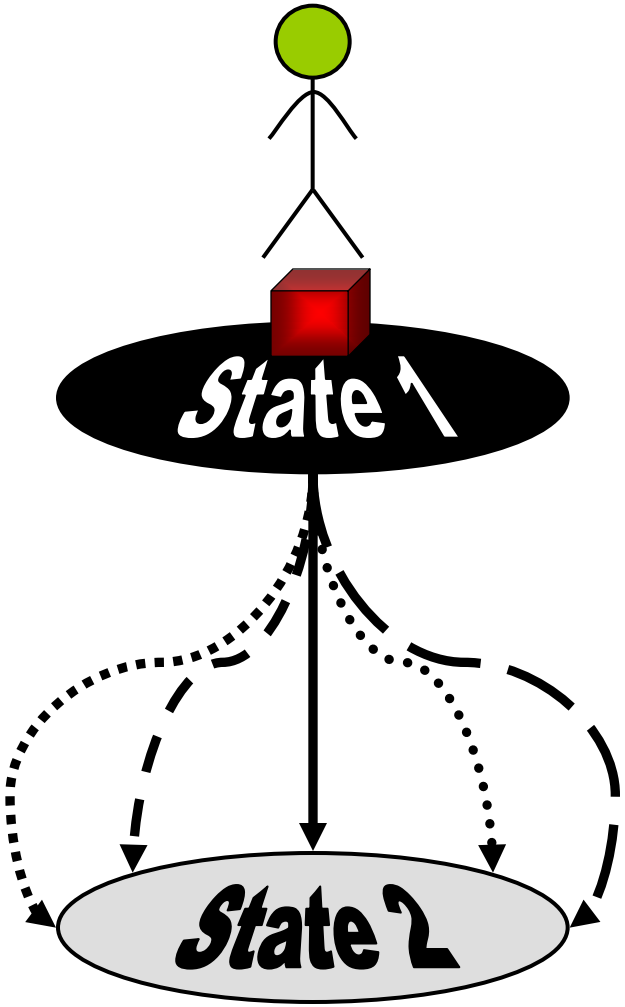
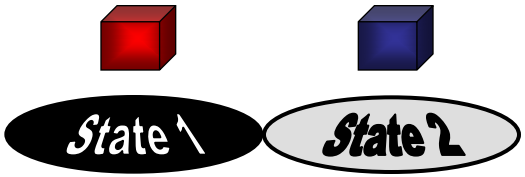
The Elements of Change



Change Agent

Change Mechanism

Change Effect



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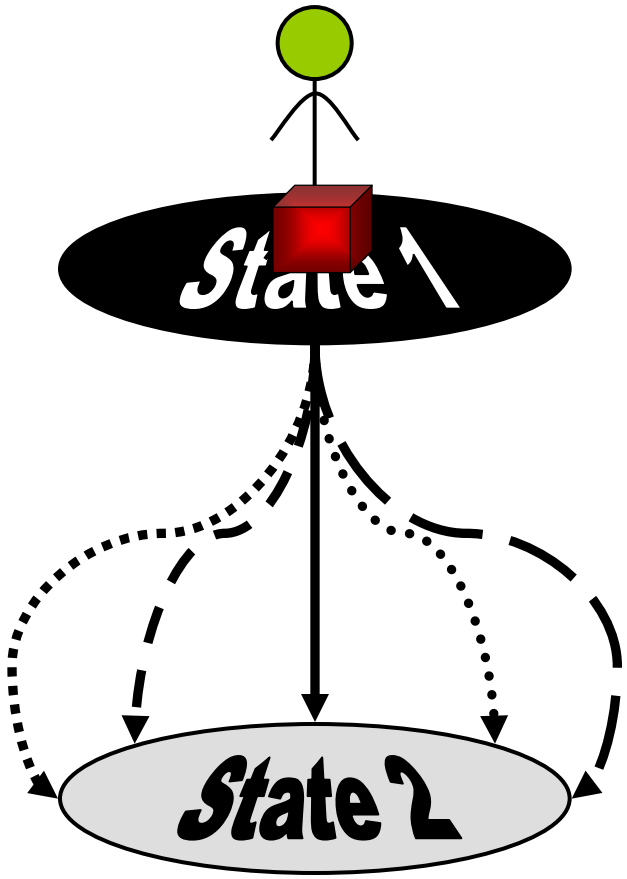
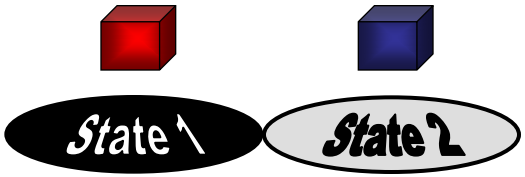
The Elements of Change



Change Agent

Change Mechanism

Change Effect



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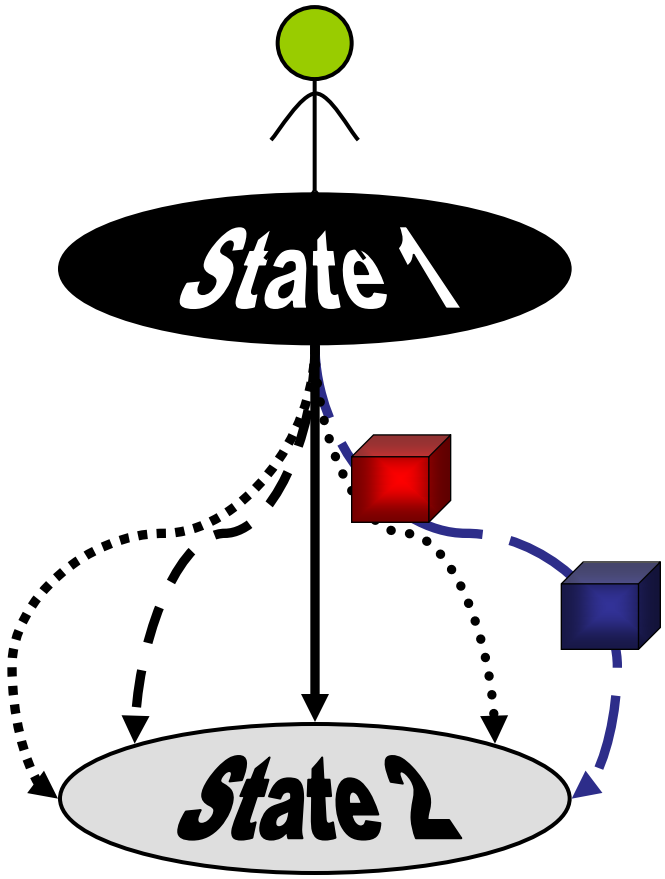
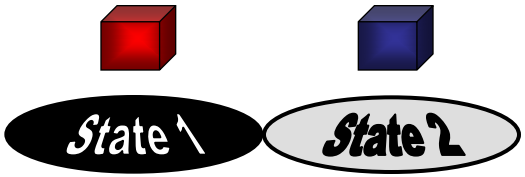
The Elements of Change



Change Agent

Change Mechanism

Change Effect



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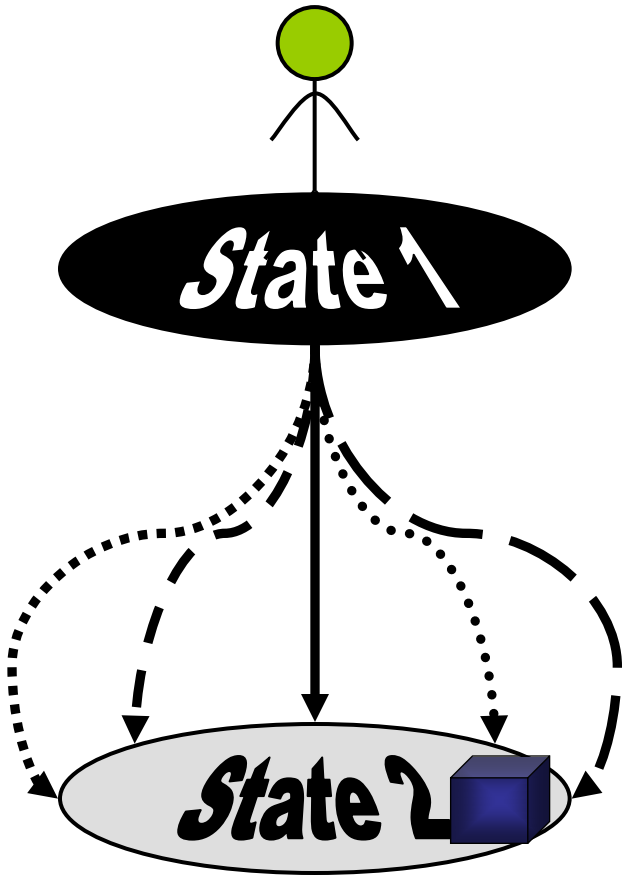
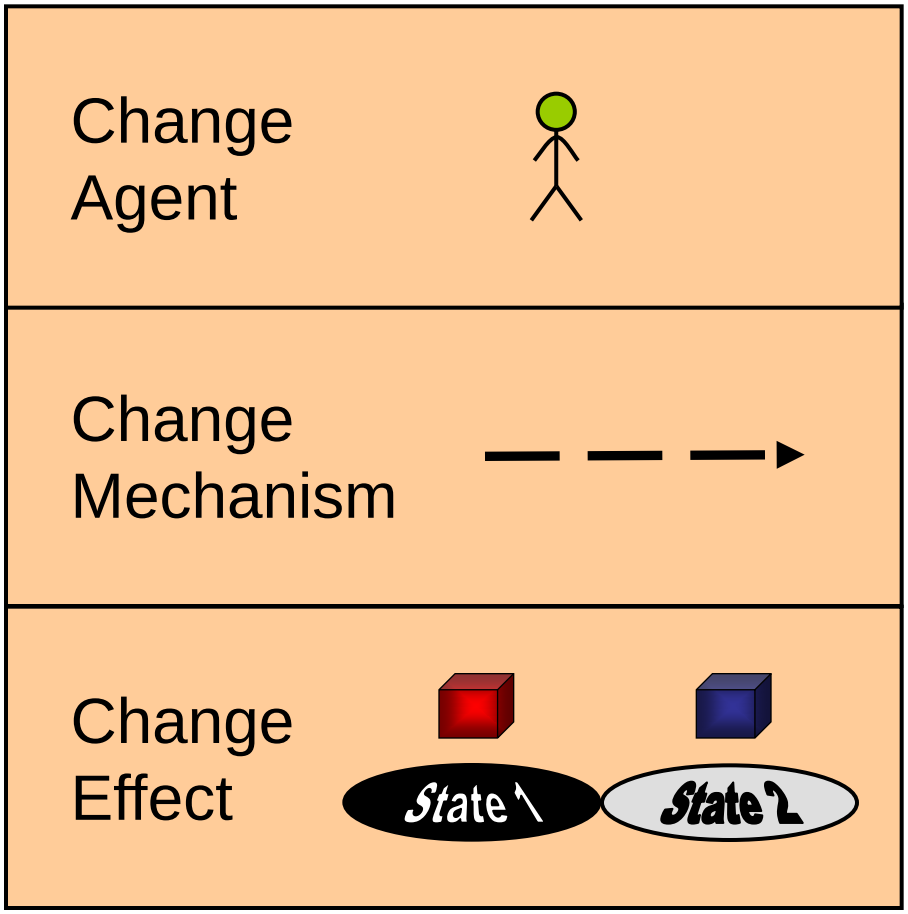
The Elements of Change





Change elements can be used to classify the change type…

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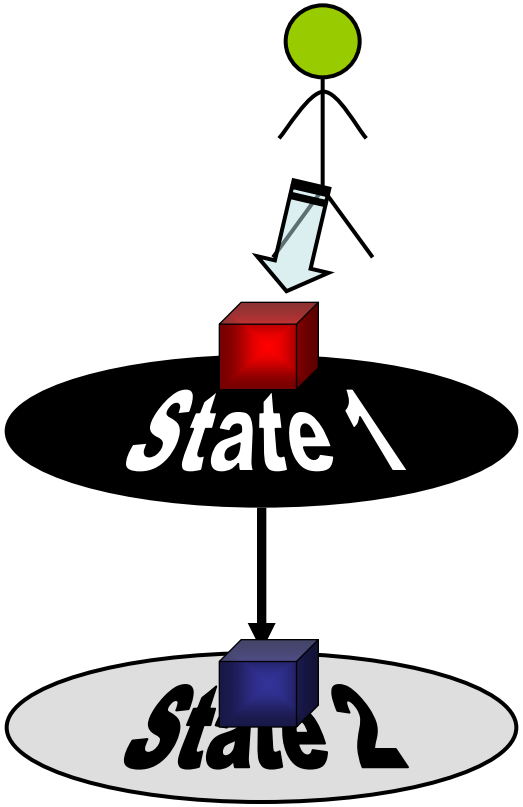
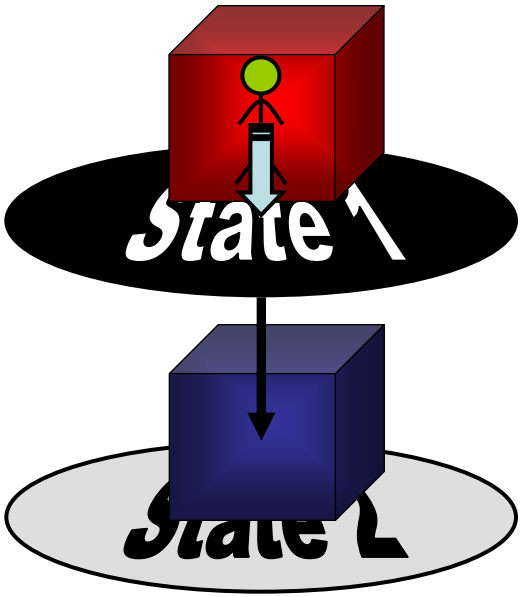
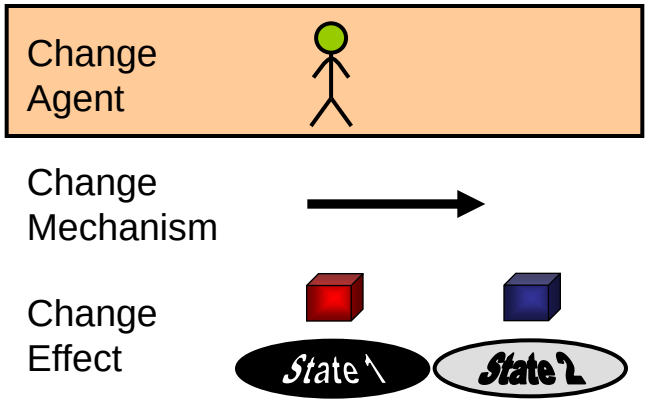
Flexibility vs. Adaptability: Change Agent Origin

Flexible
Change-type
(Outside System)



Adaptable
Change-type
(Inside System)





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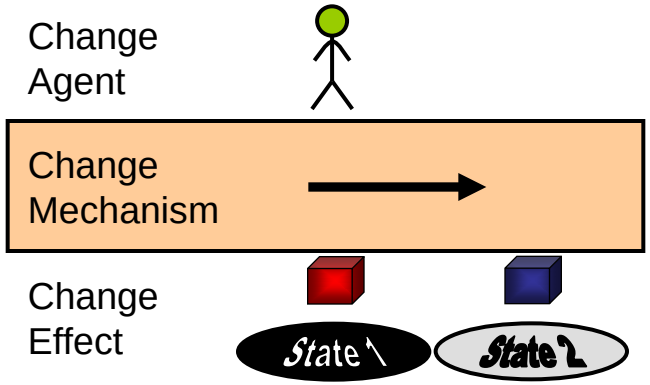
How to Change: Change Mechanism

Will revisit in a few slides



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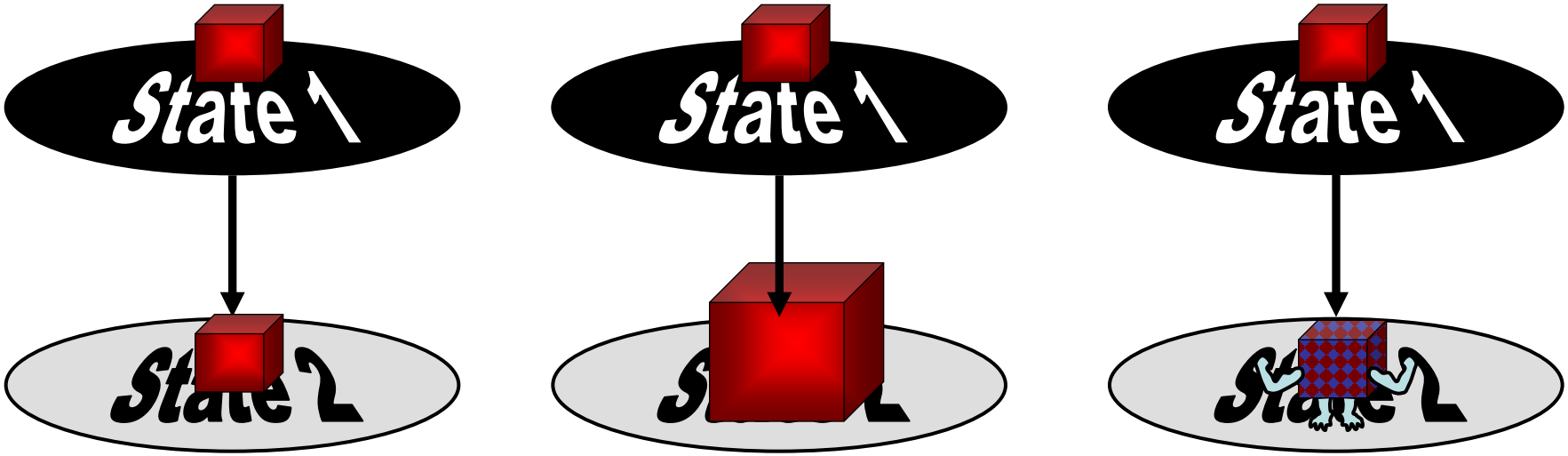
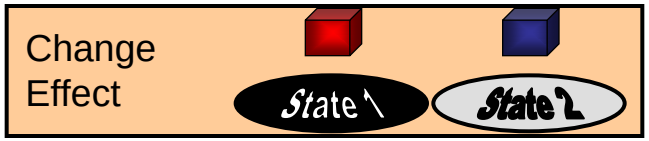
Robustness, Scalability, Modifiability: Change Effect

Robust (No change)	Scaleable (Parameter level)	Modifiable (Parameter set)



Change Agent

Change Mechanism



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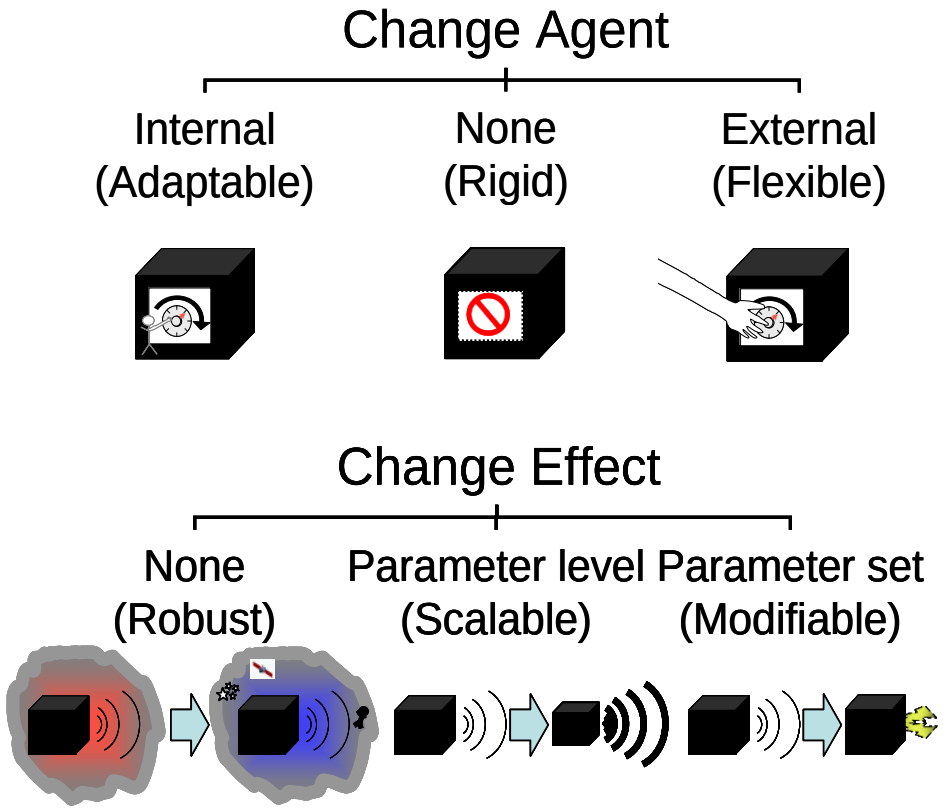
Change Agents and Effects

Changeability

Change agent origin

+

Change effect type



Change agents and effects are used to classify the change type… what about change mechanisms?

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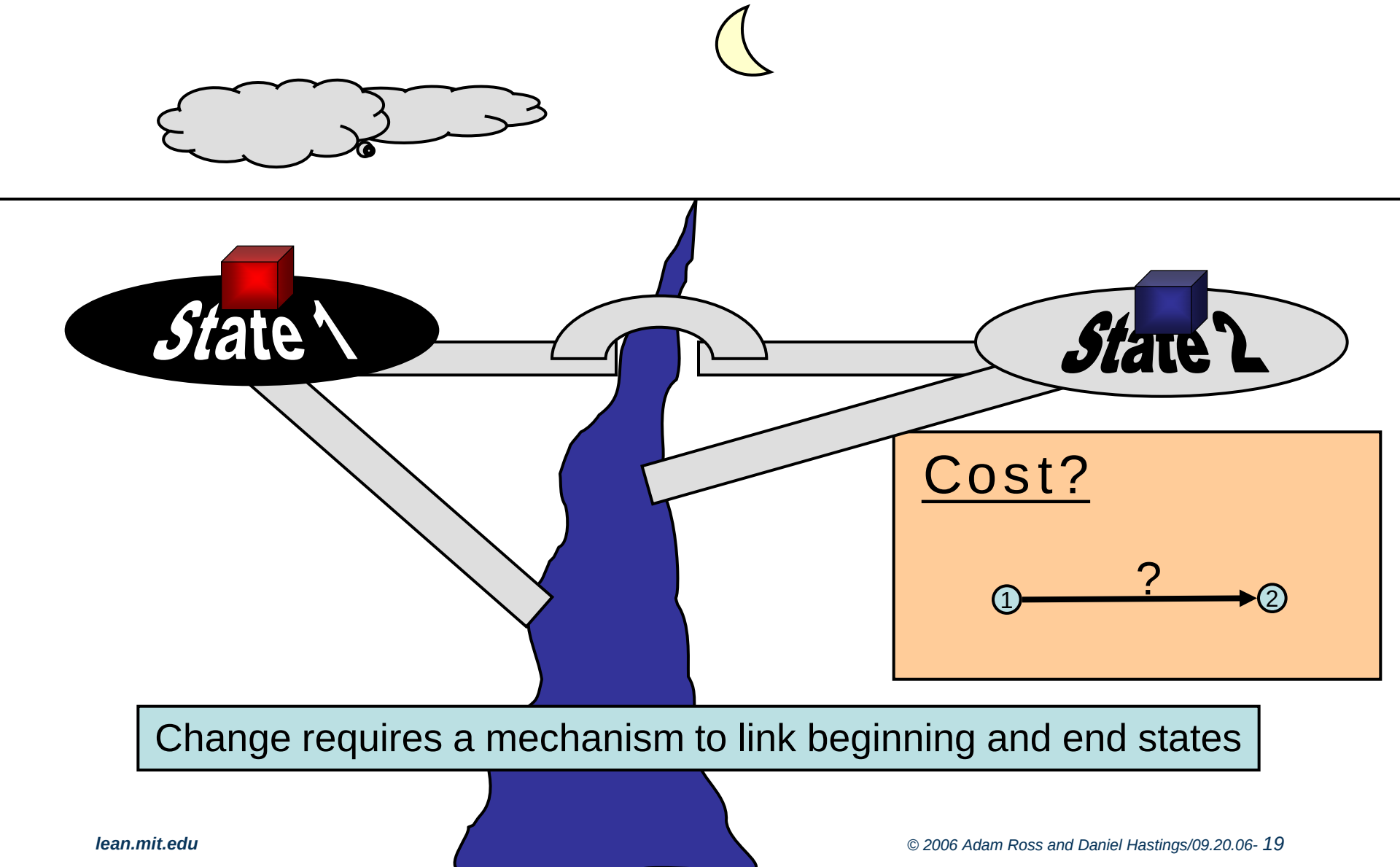
Change Mechanism



Change requires a mechanism to link beginning and end states

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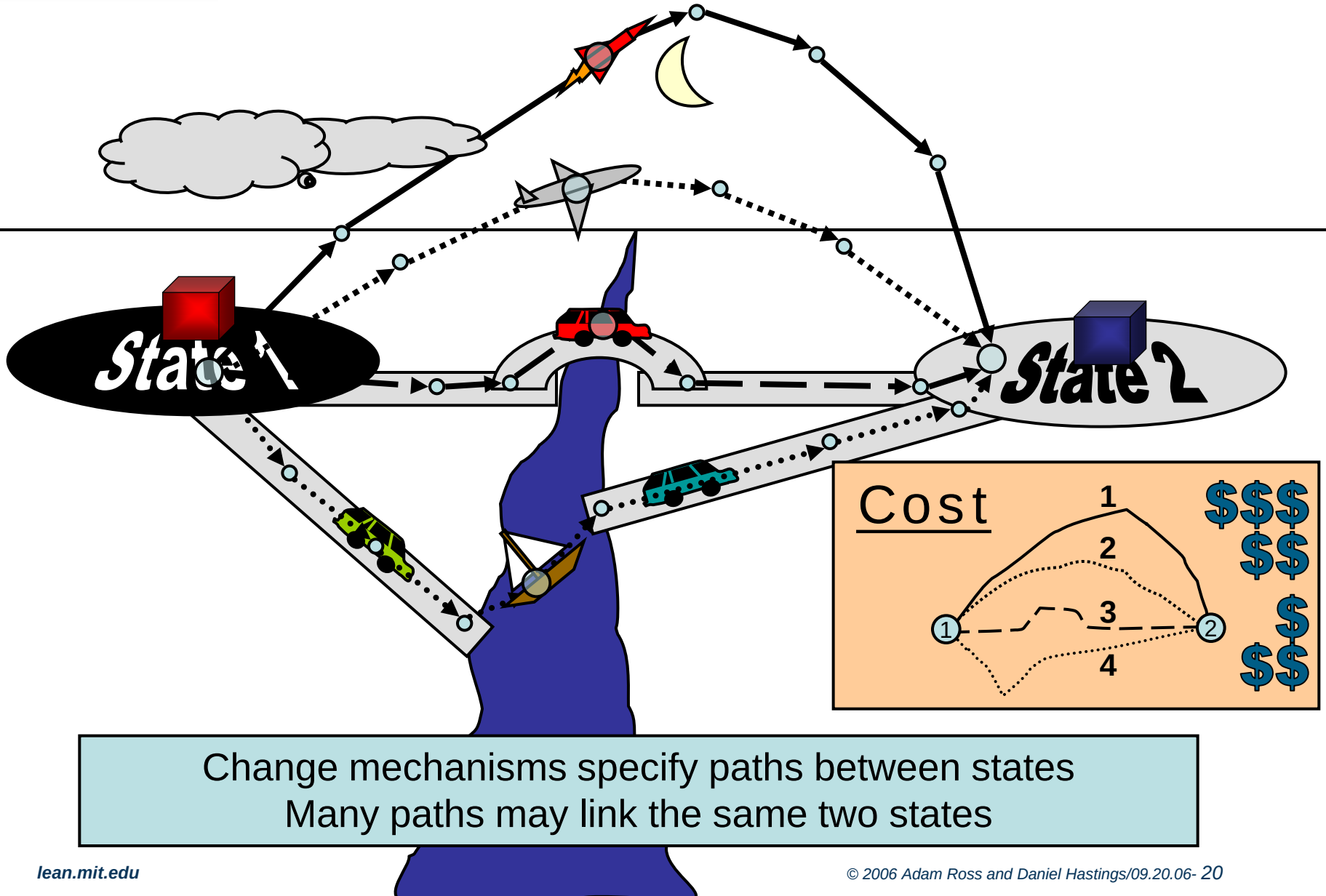
Change Mechanism



Change mechanisms specify paths between states
Many paths may link the same two states

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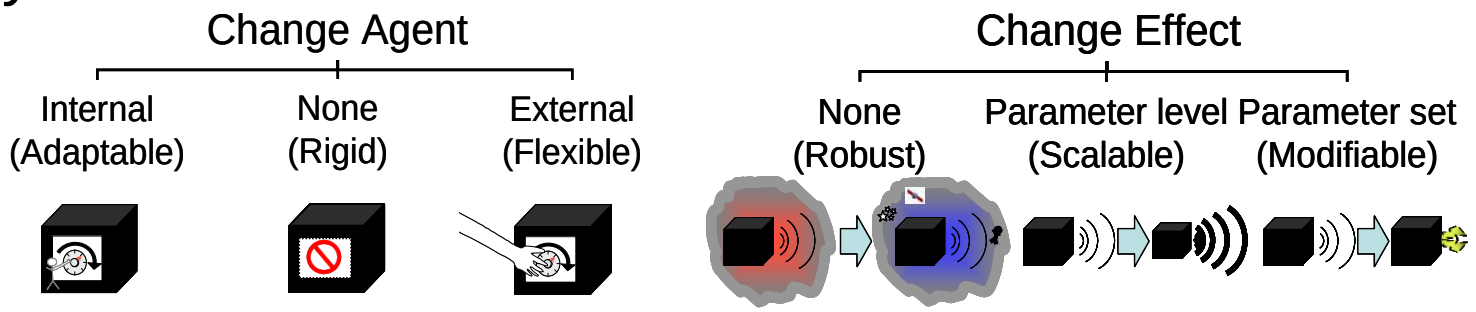
Change Summarized

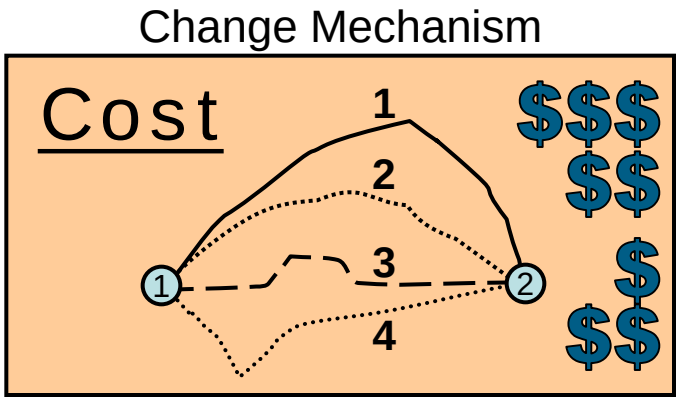
Changeability

Change type

+

Ways to change





Now that changeability is defined… how can it be used to evaluate systems?

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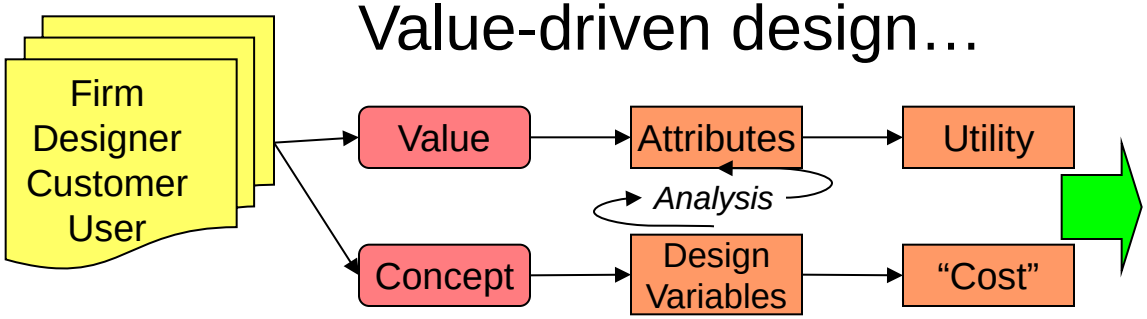
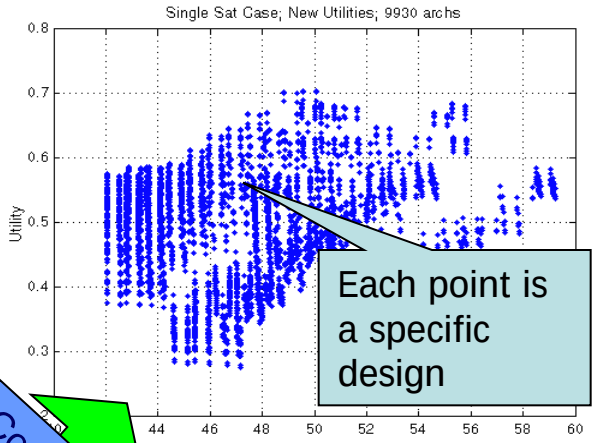
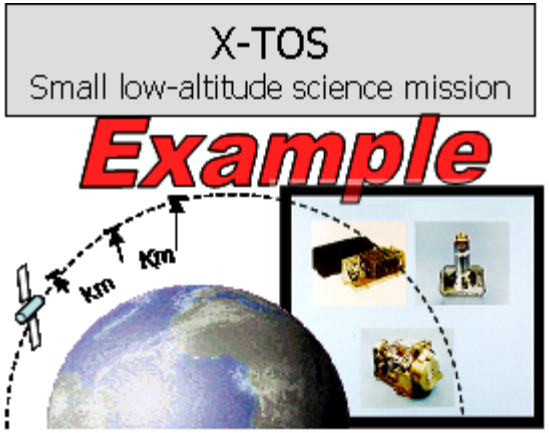
Tradespaces Defined

Value-driven design…





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



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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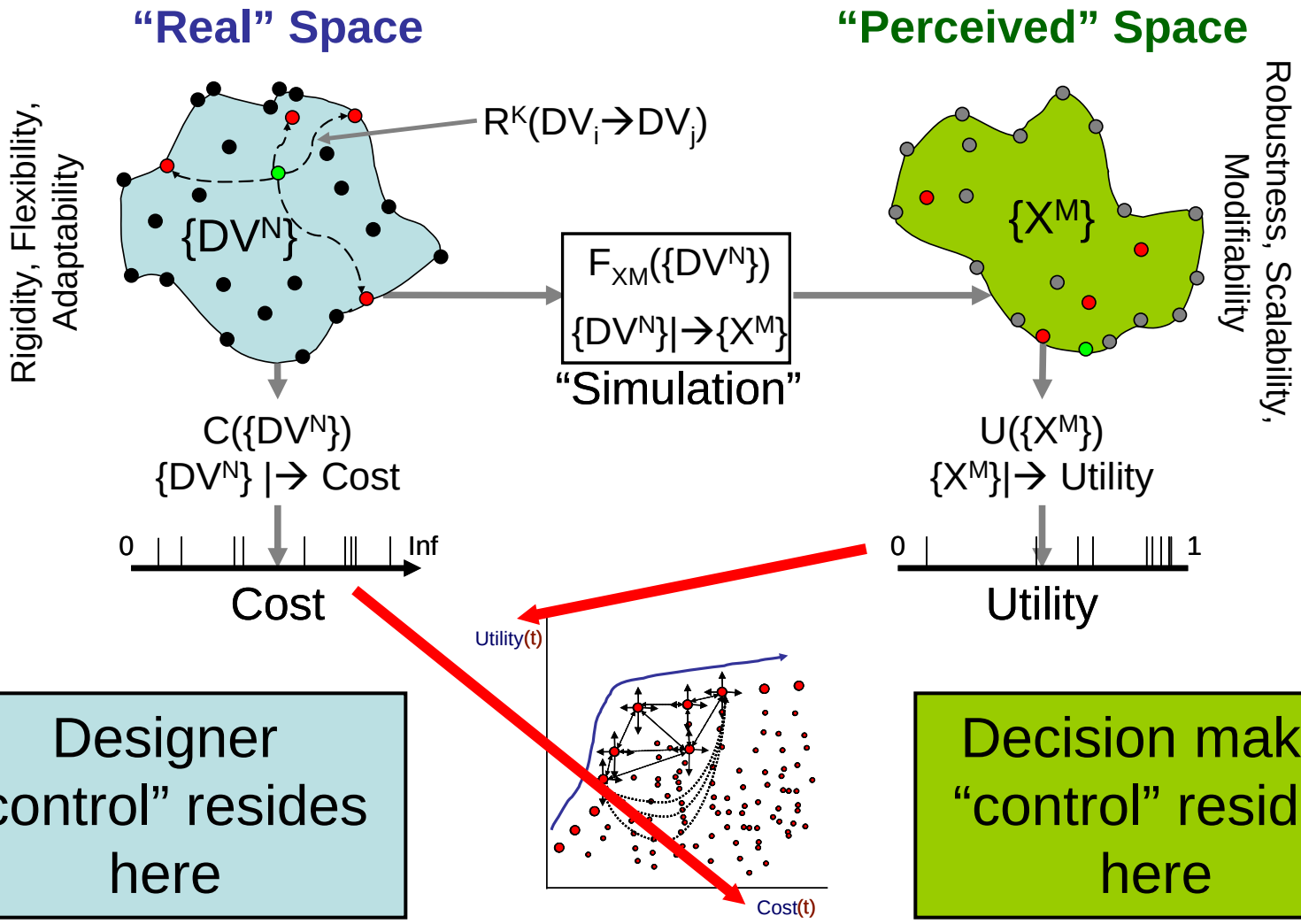
Mapping Reality to Perception



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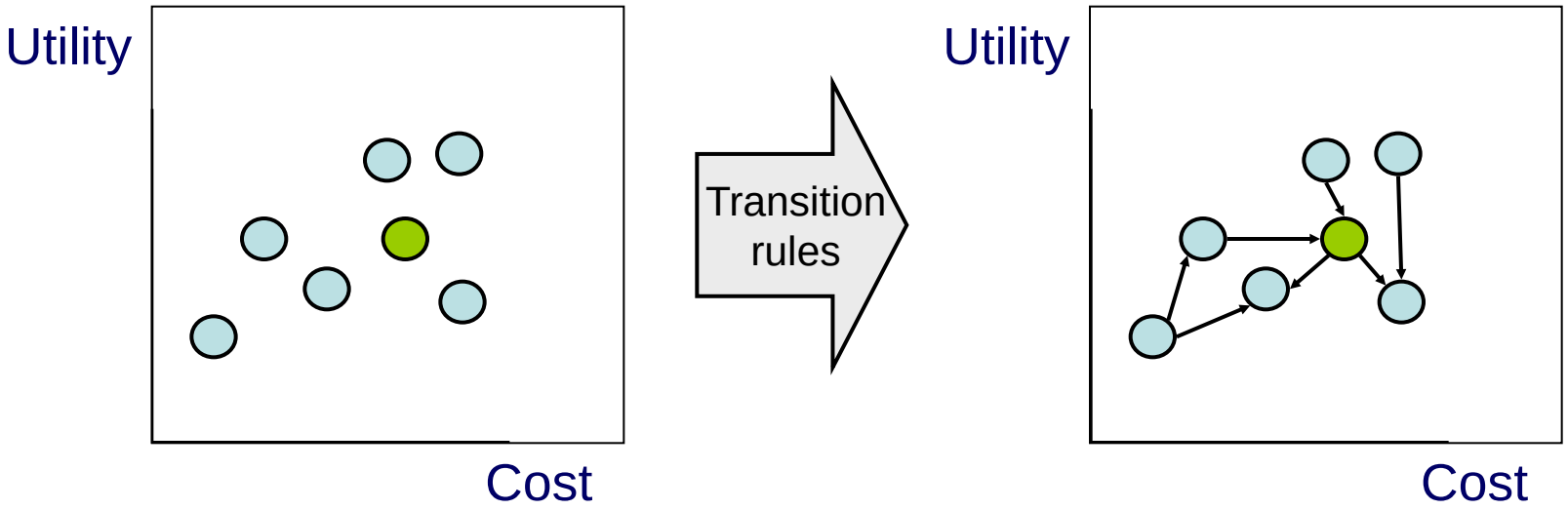
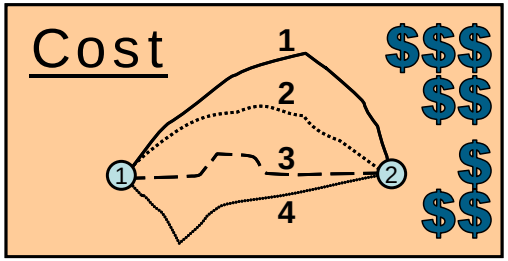
Tradespace Networks



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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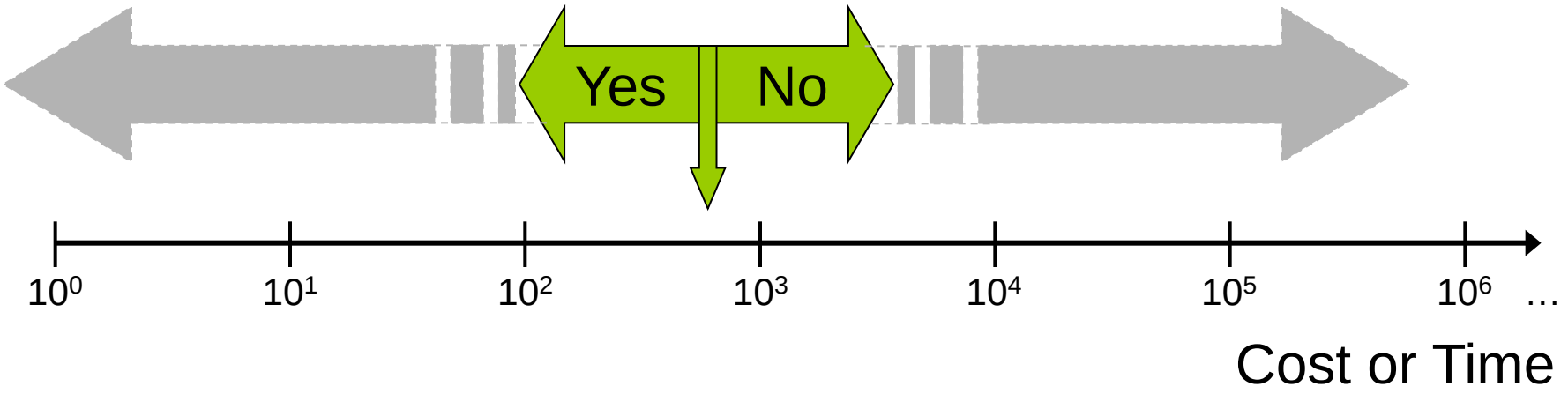
Determining Changeability

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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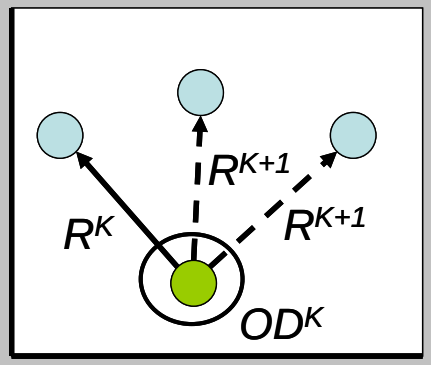
Changeability Metric: Filtered Outdegree

objective

Outdegree

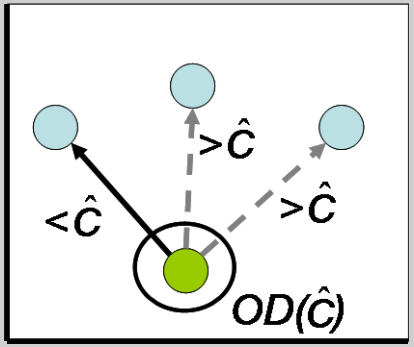
outgoing arcs from a given node



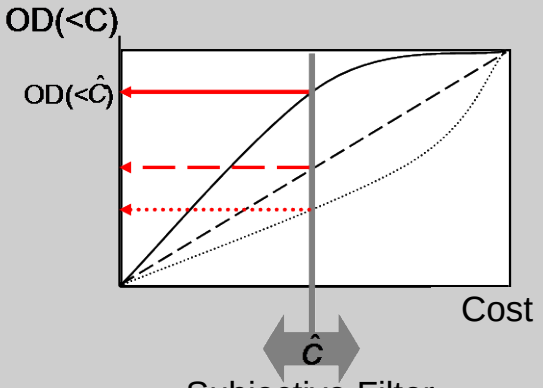
subjective

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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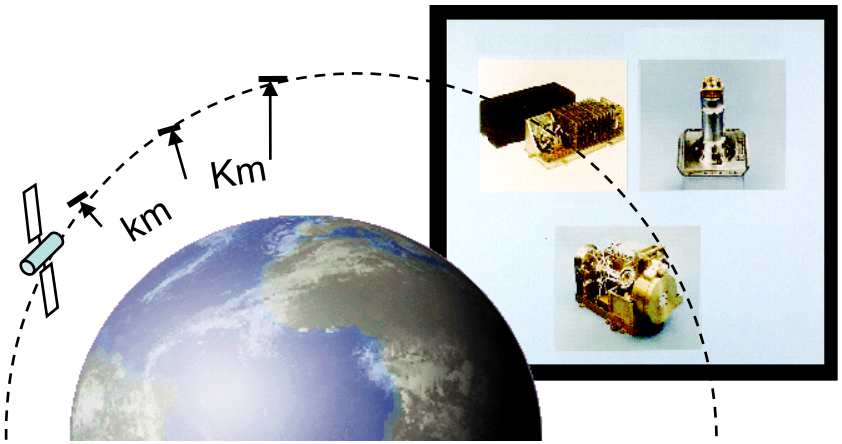
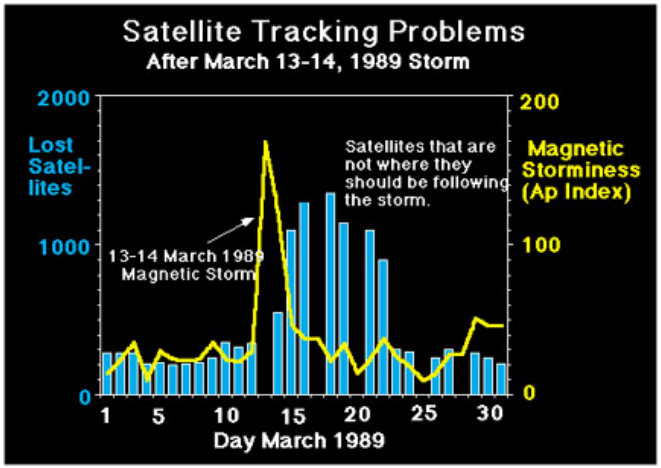
Case Application: X-TOS





- **Goal: Determine atmospheric density over range of altitudes and latitudes**
- **Low Earth orbiting satellite with in-situ sampling payload**
- **Customer: Payload scientist at AFRL/Hanscom**
- **Mission analyzed and system designed by MIT graduate space system design course in Spring 2002**

Number of Designs Explored: 50488

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X-TOS Real→Perceived

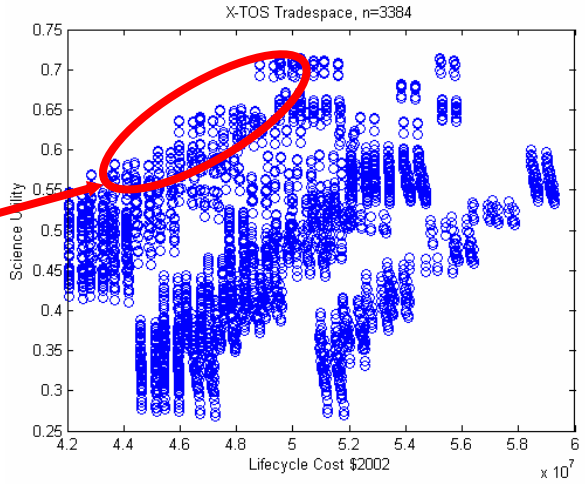
Designer defined

Decision Maker defined

Design Parameters			Attributes		
Inclination	Inc	Current	Data Lifespan	DL	Current
Apogee Altitude	Aa	Current	Latitude Diversity	LD	Current
Perigee Altitude	Ap	Current	Equator Time	ET	Current
Communication Architecture	CA	Current	Latency	L	Current
Total Delta-V	ΔV	Current	Sample Altitude	SA	Current
Propulsion Type	PpT	Current			
Power Type	PwT	Current			
Antenna Gain	AG	Current			

Model/ Simulation

Pareto Set (highest utility at given cost) = "best" designs



Static analysis reveals set of value efficient designs ("Best" designs at a given lifecycle cost)

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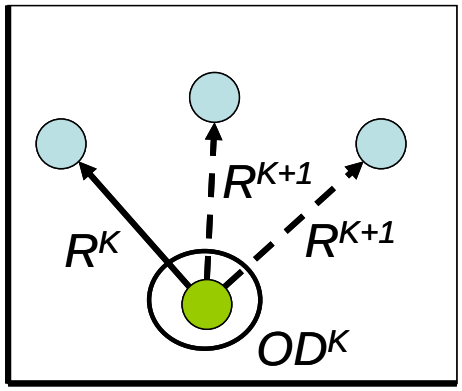
X-TOS Tradespace Network



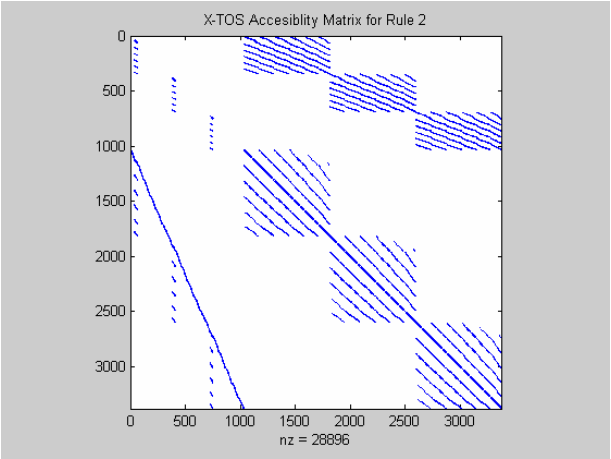
Rule-Effects Matrix X-TOS			Design Variables								Path Enablers			Change Origin	
			Inc DV1	Aa DV2	Ap DV3	CA DV4	ΔV DV5	PpT DV6	PwT DV7	AG DV8	Rf IV1	Tg IV2	Up IV3	Flx	Adp
Rule	Plane change	R1	↑↓				↓								X
	Apogee burn	R2		↑↓			↓								X
	Perigee burn	R3			↑↓		↓								X
	Plane tug	R4	↑↓									X		X	
	Apogee tug	R5		↑↓								X		X	
	Perigee tug	R6			↑↓							X		X	
	Space refuel	R7					↑				X			X	
	Add sat	R8	↑↓	↑↓	↑↓	↑↓	↑↓							X	

Rules are generated and evaluated in terms of effects on design parameters

Proposed X-TOS 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)

Rules are used to specify transition paths between any two designs using automated algorithms



Accessibility matrices specify links between design i and j

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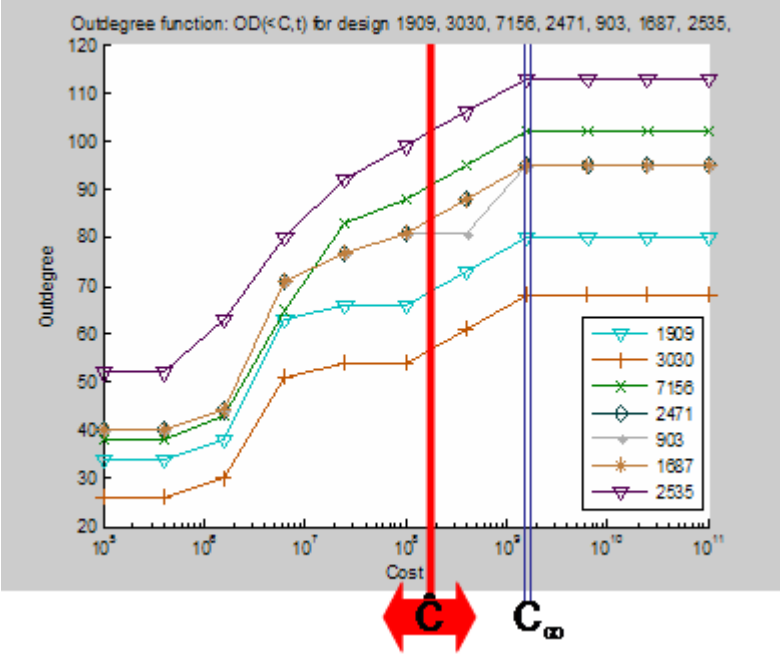
Outdegree results



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, 2535, 2471) are not the most changeable

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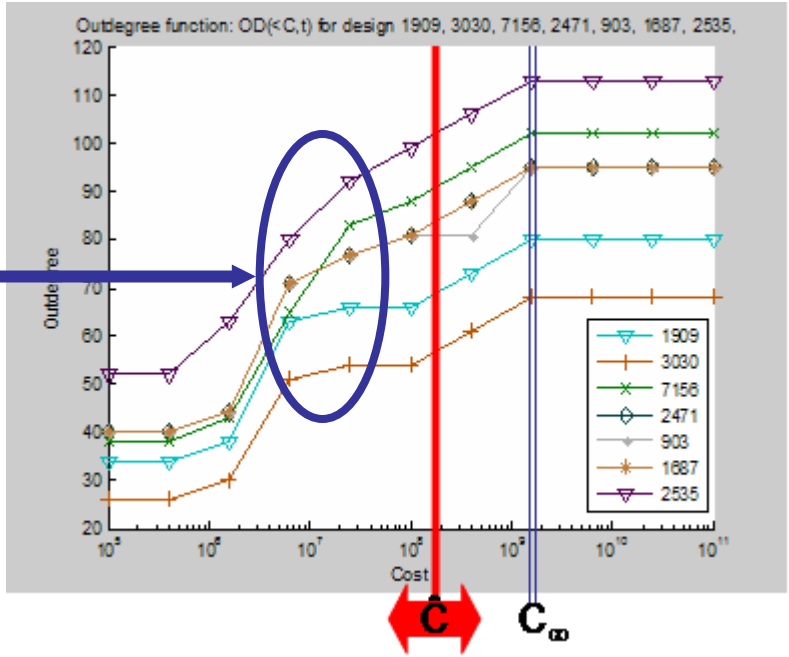
Outdegree results



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
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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, 2535, 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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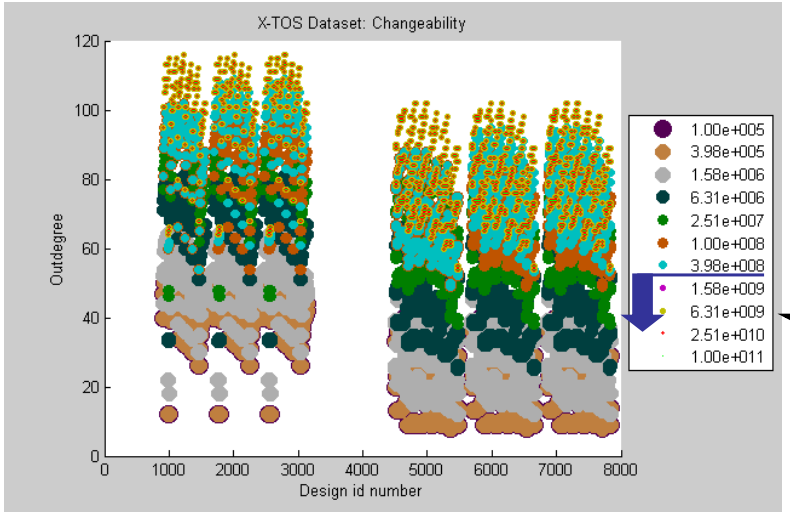
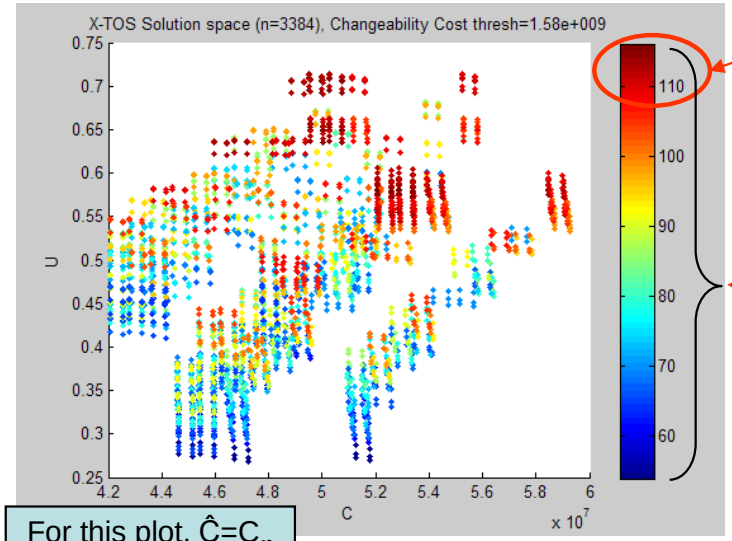
Outdegree Tradespaces



↑Ĉ

Apparent changeability increases differentially across a tradespace with increasing acceptable cost threshold



More changeable (ie including flexible, adaptable, scalable and modifiable)

Colored by outdegree

Outdegree-colored tradespace shows dominated designs with superior changeability

For this plot, $\hat{C}=C_{\infty}$

Tradespace changeability analysis allows focus on more changeable system designs

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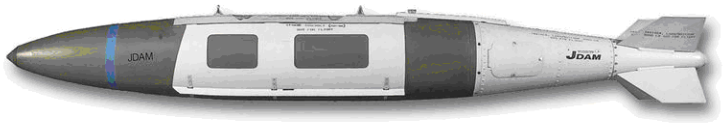
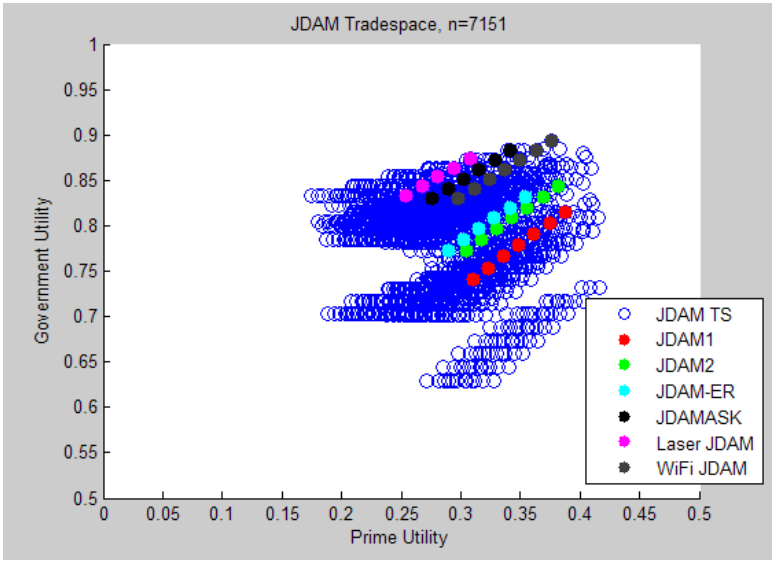
Please see paper (and thesis) for more details

Other Case Studies

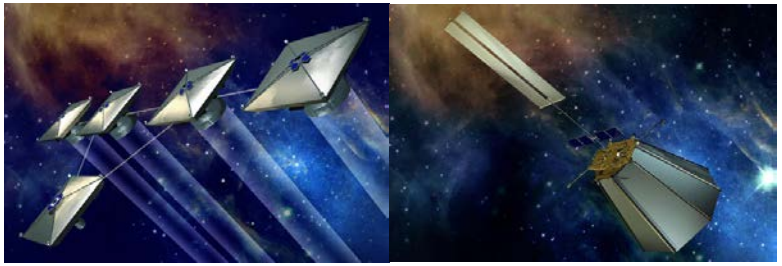
Joint Direct Attack Munition (JDAM)

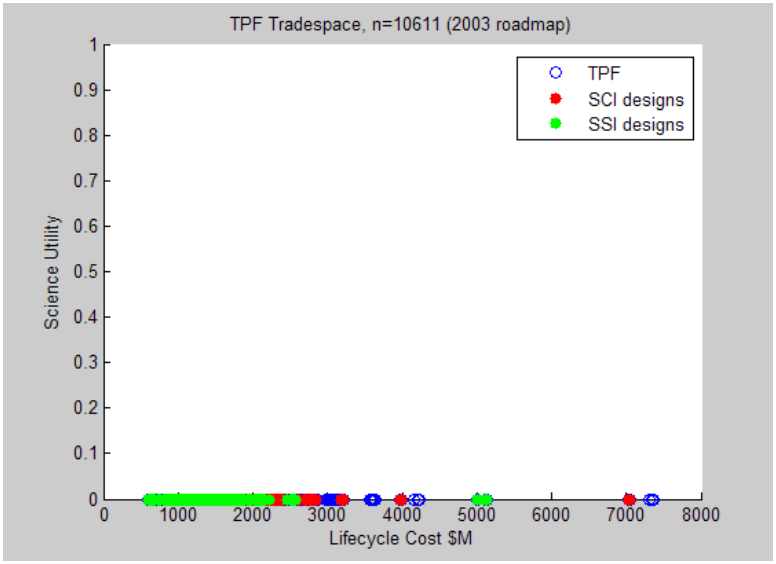




- System highly flexible
- Potential variants may readily address future needs

Terrestrial Planet Finder (TPF)





- Science expectations may be diverging with time
- Should seek reconfigurability, dynamic scheduling

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Discussion

- Computational requirements
- Effort for static and dynamic modeling
- Focus on Design for Changeability
  - Increase number of paths (change mechanism)
  - Lower “cost” or increase acceptability threshold (apparent changeability)
  - Mindshift: recognize dynamic context and fallacy of static preferences
- Concept-independent measure of changeability

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Conclusion

- **Change includes three elements**
  - **Change agent**
  - **Change mechanism**
  - **Change effect**
- **Change taxonomy links agents and effects**
- **Change mechanism drives filtered outdegree**
- **Quantifiable filtered outdegree couples both objective and subjective measures**
- **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?

For further details on topic please see:

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

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Back-up Slides…

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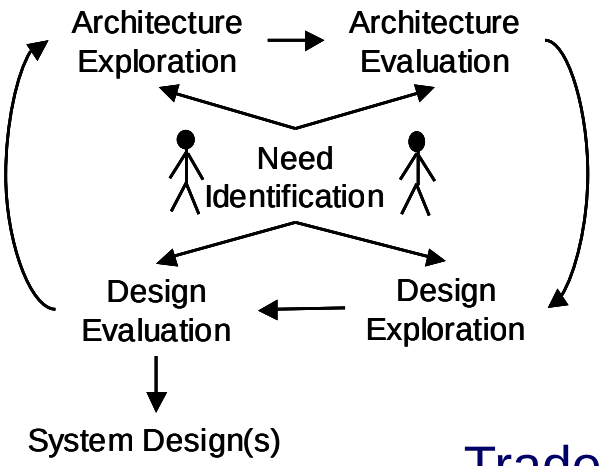
3. Static Value-centric Design: Multi-Attribute Tradespace Exploration

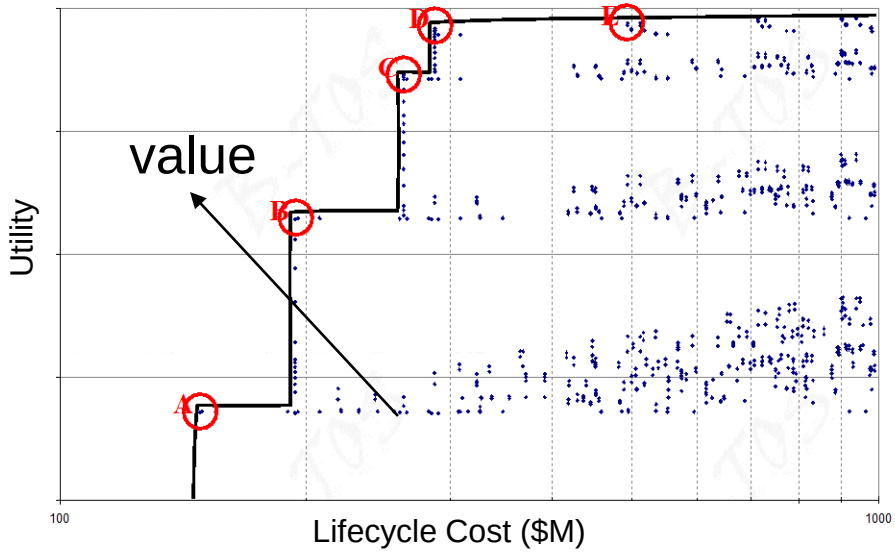
Dual-SM
Aero/Astro, TPP 2003



MATE is…

- A decision maker preference-directed tradespace exploration process
- A formalized framework and flexible philosophy
- Robust to changes and concepts
- Extended by 8 MIT theses (2002-2004)

Tradespace Solution Spaces



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3.1 Articulated Value: Attributes as Decision Metrics

Attribute: A decision maker-perceived metric that measures how well a *decision maker-defined* objective is met

In the limit ranges converge to a point, the attributes become requirements

Attribute Characteristics

- Definition
- Units
- Range (least-most acceptable)

In practice, the "Rule of 7" applies: Human mind limited to roughly 7 (7 ± 2) simultaneous concepts*

$$\text{Attribute}^i \equiv X^i$$

*Miller, G. A. "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information." *The Psychological Review* 63 (1956): 81-97.

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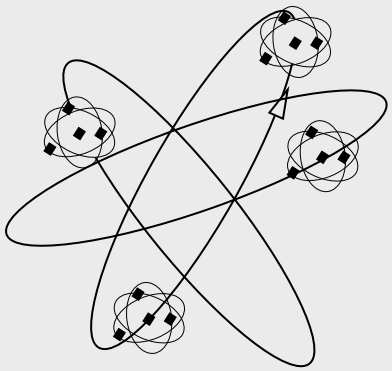
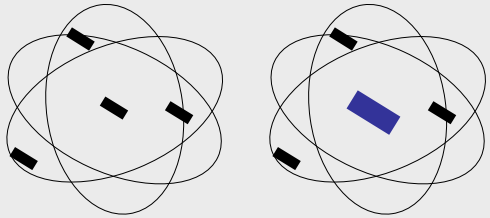
3.2 Quantified Concepts: Design Variables as Tradable Parameters

Design Variable: A designer-controlled quantitative parameter that reflects an aspect of a concept

Swarm Orbit Parameters

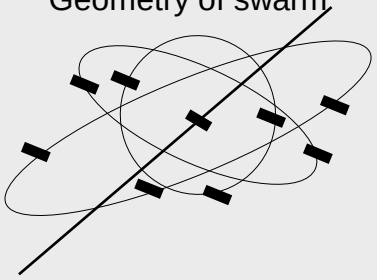


No mothership / Mothership



Number of spacecraft in swarm

Geometry of swarm

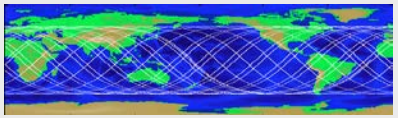


Design Vector

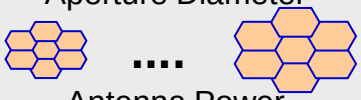
S/C per Cluster

Clusters

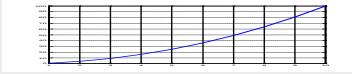
Constellation Altitude



Aperture Diameter



Antenna Power



Design Variable^i ≡ DV^i

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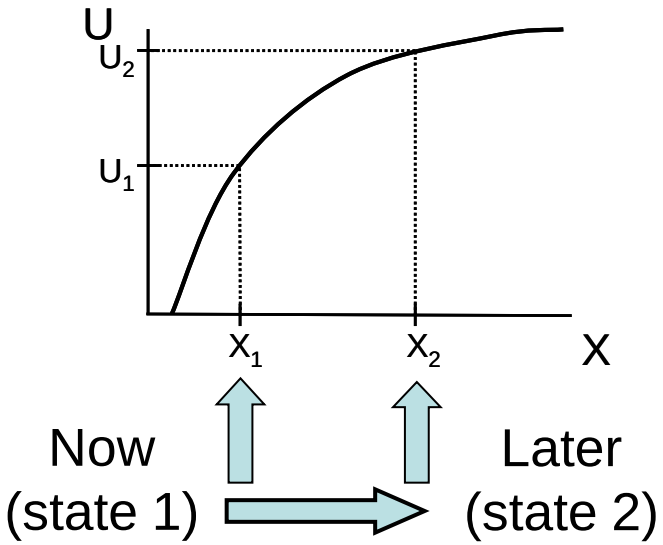
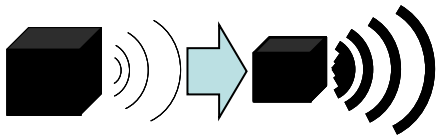
6.2 Types of Changes: Scalability





Change in attribute level

"Scalable"

A box can be quantified in terms of *scalable in* X^i

(i.e., can X^i be changed from X^i_1 to X^i_2?)

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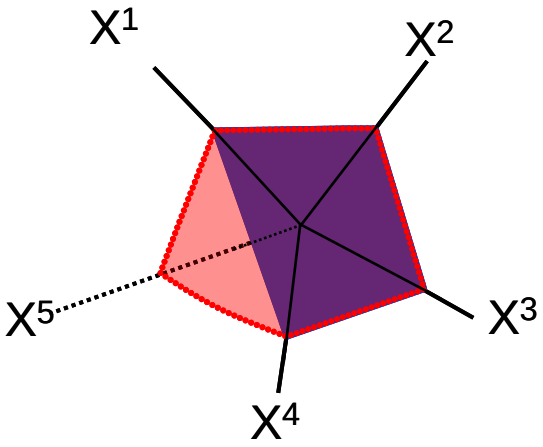
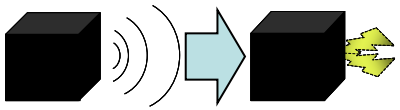
6.2 Types of Changes: Modifiability



Now (state 1) → $U=f(X^1,X^2,X^3,X^4)$

Later (state 2) → $U'=f(X^1,X^2,X^3,X^4,X^5)$



Change in attribute set

"Modifiable"

A box can be quantified in terms of *modifiable in* X^i

(i.e., can X^i be added to or deleted from the attribute set?)

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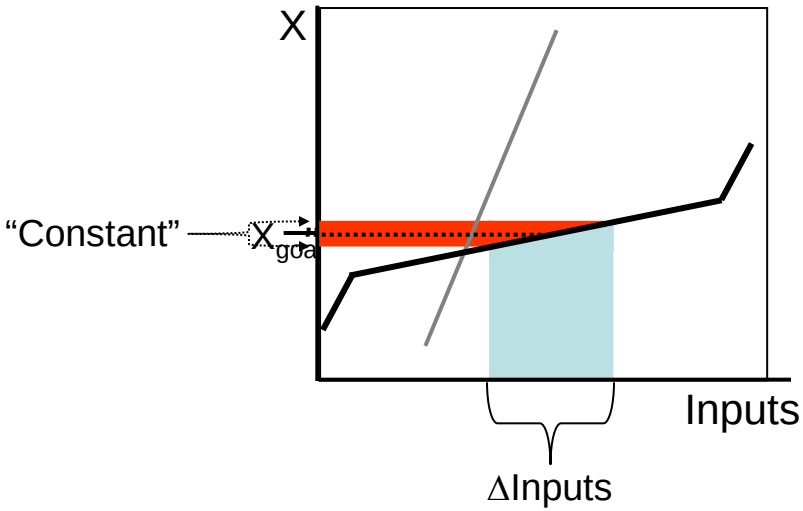
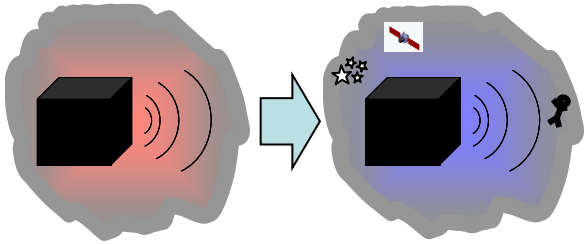
6.2 Types of Change: Robustness





No change in perceived value

"Robust"

A box can be quantified in terms of *robust in X^i to "Input" change*

(i.e., can X^i remain "constant" over range of "Input"?)

Since the level of attribute performance is a function of the inputs (and constraints including environment), robustness is an insensitivity to the inputs (and constraints)

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