Game-Based Learning for Systems Engineering Concepts

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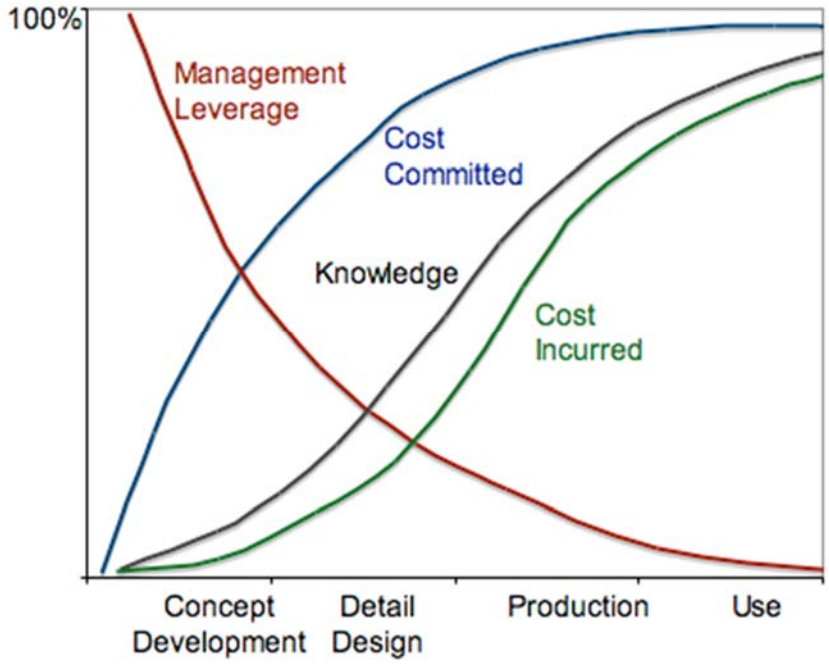
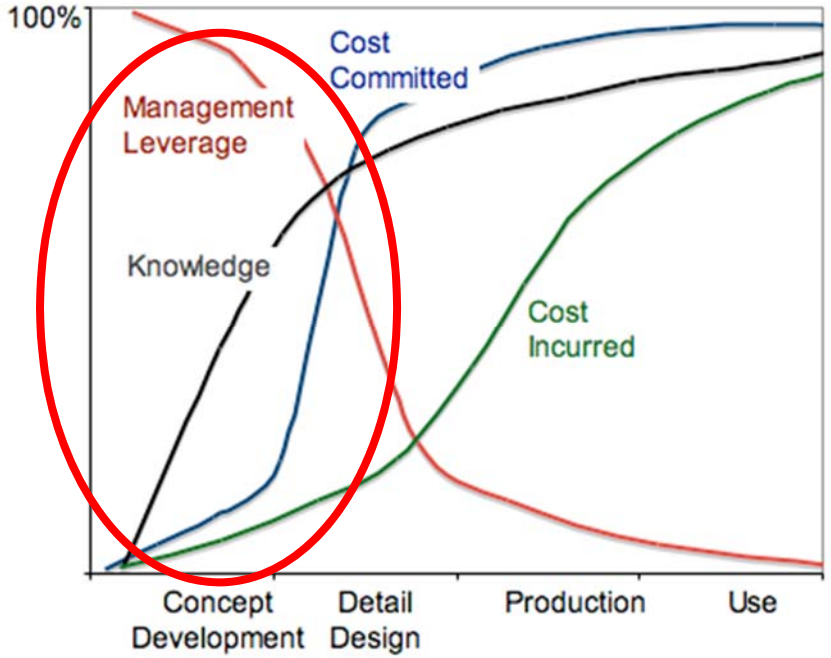
SEAri Research Seeks to "Change the Picture"



Classic paradigm



New paradigm

ESSENTIAL ELEMENTS

Appropriate **competencies** in workforce

Advanced **methods** for anticipatory analysis, decision making, and architecting

Enabling enterprise strategies and model-based **environments**

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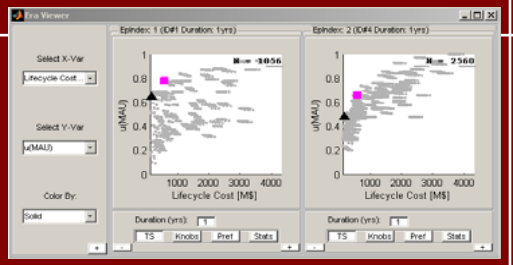
Building Anticipatory Capacity

COMPETENCIES	METHODS	ENVIRONMENT
Ability to think deeply about 'systems in context'	Perform dynamic tradespace exploration	Computing power/toolsets to enact methods
Enhance ability to think about 'systems in time'	Model-based approach to derive alternative futures	Support multi-stakeholder negotiations in tradespace exploration
Use *situational leadership* to make decisions at multiple system levels	Apply methods at varying levels of fidelity	Enable comprehension of complex data sets



Rhodes, D.H. and Ross, A.M., "Anticipatory Capacity: Leveraging Model-Based Approaches to Design Systems for Dynamic Futures," 2nd Annual Conference on Model-based Systems, Haifa, IL, March 2009.

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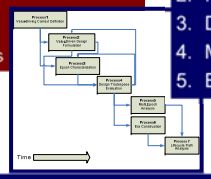
Fourteen Years of Research on Methods and Metrics

Methods for Value-Centric Analysis

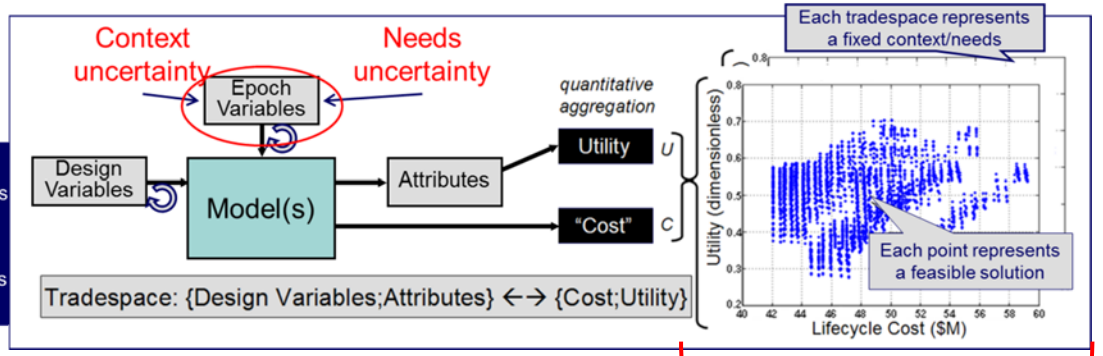
Multi-Attribute Tradespace Exploration

Epoch-Era Analysis

RSC consists of seven processes:
1. Value-Driving Context Definition
2. Value-Driven Design Formulation
3. Epoch Characterization
4. Design Tradespace Evaluation
5. Multi-Epoch Analysis
6. Era Construction
7. Lifecycle Path Analysis



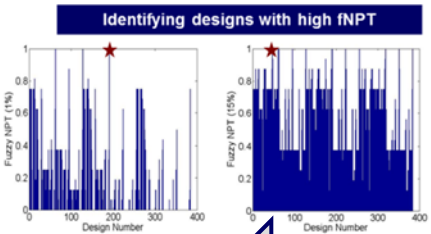
VASC
1. Set up data for epoch-era analysis
2. Identify designs of interest
3. Define rule usage strategies
4. Multi-epoch changeability analysis
5. Era simulation and analysis

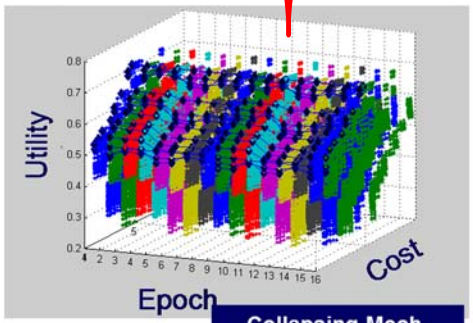


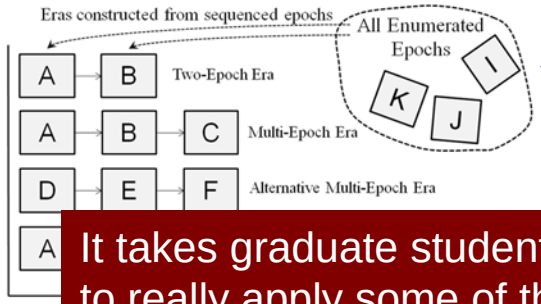
Many epoch data sets

Likelihood of Design E executing each transition rule across a 10 year era (per strategy)

Strategy	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
MaxU	N/A	N/A	N/A	✓ 100.0%	✓ 89.2%	N/A
MaxEff	N/A	N/A	N/A	✓ 100.0%	✓ 97.1%	N/A
Survive	N/A	N/A	N/A	✓ 94.9%	✗ 0.0%	N/A
MaxP	N/A	N/A	N/A	✓ 96.8%	✗ 31.5%	N/A



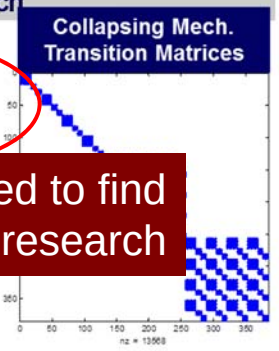




Era (long run) analysis

Multi-epoch (short run) analysis

Change Mechanisms



It takes graduate students over a year to begin to really apply some of this…

SEAri's goal is to have impact , so we need to find a way to accelerate deployment of the research

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Tackling Problems using "Games"

There is growing interest in using the medium of games for learning how to solve both complex and complicated problems

"Good educational games lend themselves to systemic understandings. Games appear to be particularly good for immersing learners within systems and enabling them to explore the emergent properties of systems." (K. Squire 2011, p. 36)

Given that it takes >1 year for ***graduate*** students to master the research, how can we use games to ***accelerate*** learning of core concepts and constructs ?

What makes games an applicable medium for SEAri research?

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The Four Freedoms of Play

- Freedom to Experiment
- Freedom to Fail
- Freedom to Try on Identities
- Freedom of Effort

From Scot Osterweil of The Education Arcade, “Keeping the Play in Learning Games”, 6/9/2011

A Game is More than Monopoly

A game is a problem-solving activity, approached with a playful attitude
Schell 2008, pg 37

- Entertainment
- "Edutainment" = "Serious" games
- Education
- Simulations
  - Management flight simulators
  - Aircraft flight simulators

(Aldrich 2009)

Monopoly: Classic family board game by Hasbro; buy and sell properties in Atlantic City

Windfall: a strategy game about building wind farms to create clean energy profitably. *Persuasive Games* (http://www.persuasivegames.com)

Microsoft Flight Simulator X: Gold Edition: Experience realistic flights with day/night and weather effects, multiplayer races and over 80 missions worldwide

Whether stated goal is to teach a lesson or to escape reality, the main purpose of games is to create an "experience" in the mind of the player

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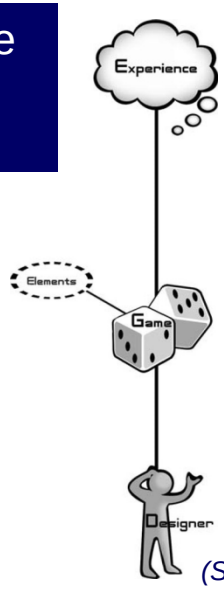
Game Design is both Art and Engineering

Material from his work as professor of entertainment technology and game design at Carnegie Mellon's Entertainment Technology Center (ETC):
Schell, Jesse, *The Art of Game Design: A book of lenses*, Elsevier, 2008.

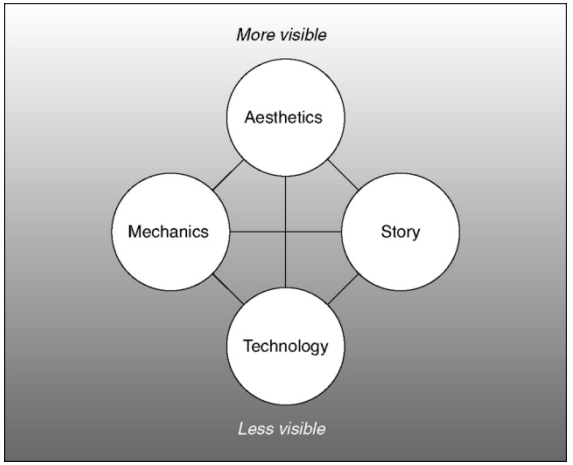
Four Basic Elements of a Game

- Mechanics
  - Procedures and rules of a game
  - Describe the goals, how players can and cannot try to achieve them, and what happens when they try
- Story
  - Sequence of events that unfolds in a game
  - Linear and pre-scripted, or branching and emergent
- Aesthetics
  - How a game looks, sounds, smells, tastes, and feels
  - Has most direct impact on game experience
- Technology
  - Any materials and interactions that make a game possible, such as paper and pencil, plastic chits, or high-powered lasers
  - Is the medium in which aesthetics take place, in which mechanics occur, and through which a story is told

(Schell 2008), pp 41-43



(Schell 2008), pp 39



(Schell 2008), pp 42

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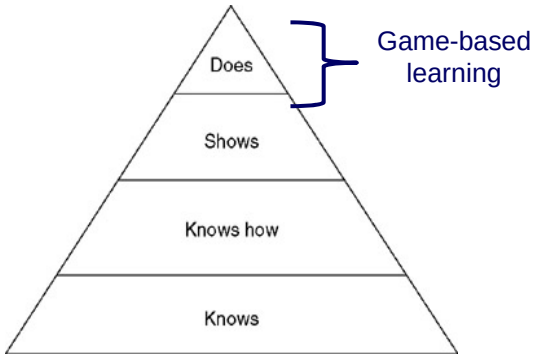
More than Just "Play"

Transformation and Responsibility

- Good for us
  - Emotional maintenance
  - Connecting
  - Exercise
  - Education
    - Facts
    - Problem Solving
    - New Insights
    - Curiosity
- Bad for us
  - Violence
  - Addiction

- Responsibility
  - Intend to do good
- Being accountable
  - Do no harm



Miller's pyramid of learning in (Schell 2008), pp 445

Games are a powerful medium that creates (potentially transforming) experiences in players

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Designing a Purposeful Game

From Mitgutsch and Alvarado 2012 (Fig 1, p. 3)

- K. Mitgutsch has worked for years on purposeful game design and assessment
- His framework synthesizes his perspective of the serious game design/assessment literature
- There is no real consensus in the community on this, so we picked this framework since it resonated with us and he convinced us to try it

Mitgutsch K and Alvarado N. "Purposeful by Design? A Serious Game Design Assessment Framework." *Proceedings of the International Conference on the Foundations of Digital Games* (FDG '12). ACM. New York, NY, 2012; 121-128.

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Challenge in using Games for Systems Education Research

- Games show promise for the field
  - Role-playing, failure, etc.
- Content for SE games may not be mature
  - Part of SEAri research is construct creation
- Games themselves are systems
  - As growing literature shows
- Key questions:
  - How to use games to teach immature system concepts?
  - How to use games to conduct research into systems constructs?
- Approach for now: exploratory

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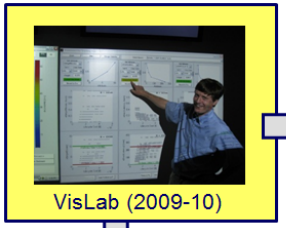
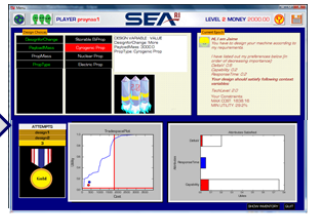
SEAri Approach for Purposeful Game Development

Goal: Develop experience with purposeful game design for education and research

- Deconstruct SEAri research
- Develop learning and research objectives
- Develop player profiles
- Conduct short projects in game development
- Playtest
- Repeat


VisLab (2009-10)


Tradespace Explorers (2011-12)

Space Tug Skirmish (2011-13)

Digital Space Tug Skirmish (2013-present)

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SEAri Core Concepts

We distilled the SEAri research into “core concepts”

The constructs form the essential concepts to be incorporated into the game projects.

Each construct has a large amount of associated research literature

1. **utilities**
2. **“design” choices**
3. **costs**
4. **epochs**
5. **eras**
6. **“ilities”**

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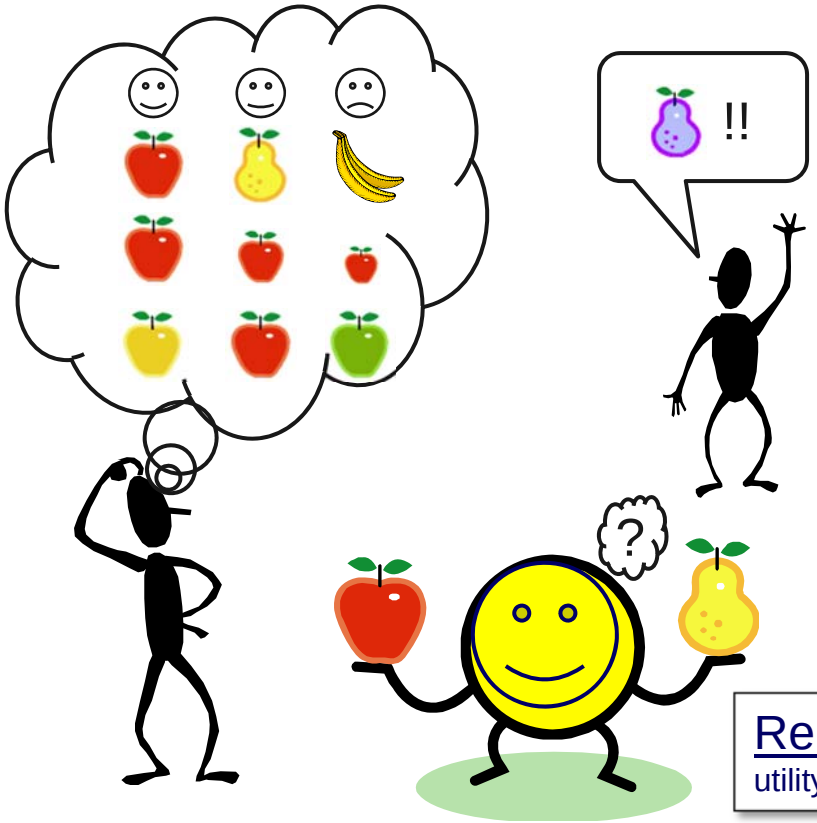
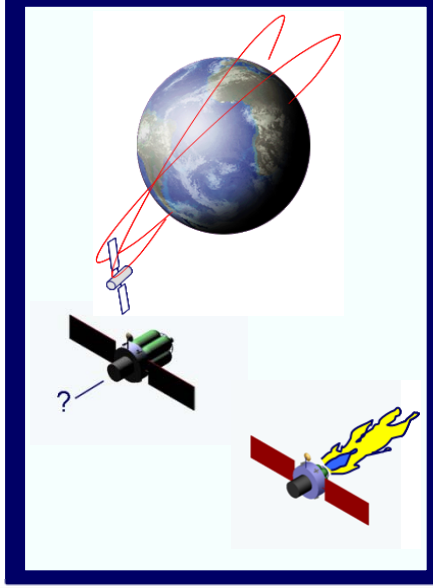
Benefits: Utilities

The benefit accrued from a "design" choice
- Is subjectively defined, varying by person
- Can be multi-criteria
- Can vary over time



Space Tug



Utility Space

>Delta-V
- Velocity the vehicle can impart (km/sec) [>0→12]

>Interaction Capability
- What the vehicle can do to target (kg) [>0→5000]

>Speed
- Can change orbits quickly (binary) [0→1]

Related Concepts: attributes, single attribute utility, multi-attribute utility, benefits, criteria, score, performance, rewards, effectiveness

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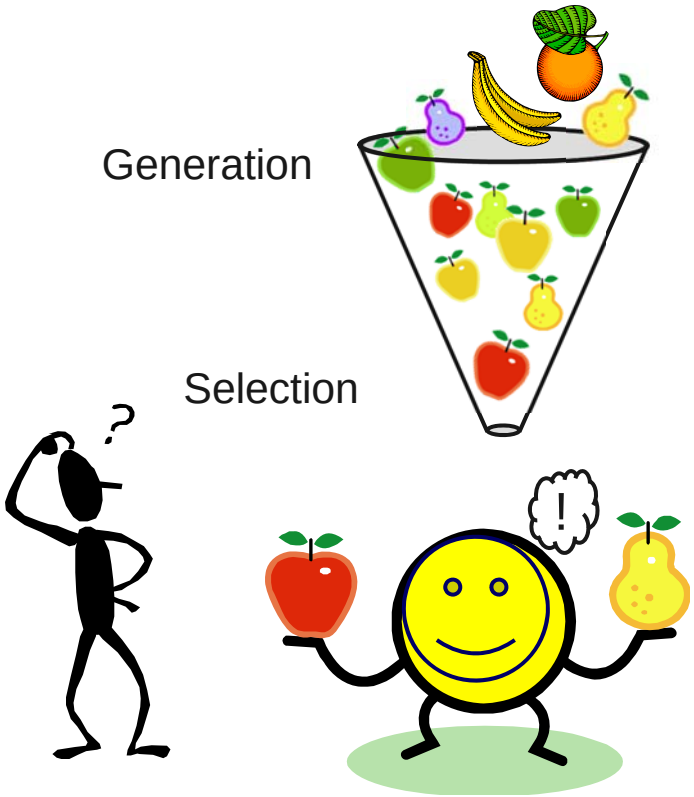
“Design” Choices

Decisions on a “design” alternative that is in the control of the “Designer”

- Can be on entire alternative or aspect(s) of an alternative
- Can be done during generation or selection of alternatives
- Can be done initially or later in the “lifecycle”



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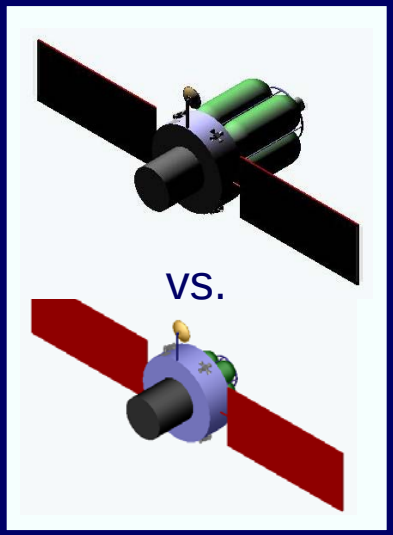

Design Space

>Manipulator Mass
- Low (300kg)
- Medium (1000kg)
- High (3000 kg)
- Extreme (5000 kg)

>Propulsion Type
- Storable bi-prop
- Cryogenic bi-prop
- Electric (NSTAR)
- Nuclear Thermal

>Fuel Load - 8 levels

Related Concepts: designs, design vectors/variables, concepts, configurations, alternatives, choices, selections

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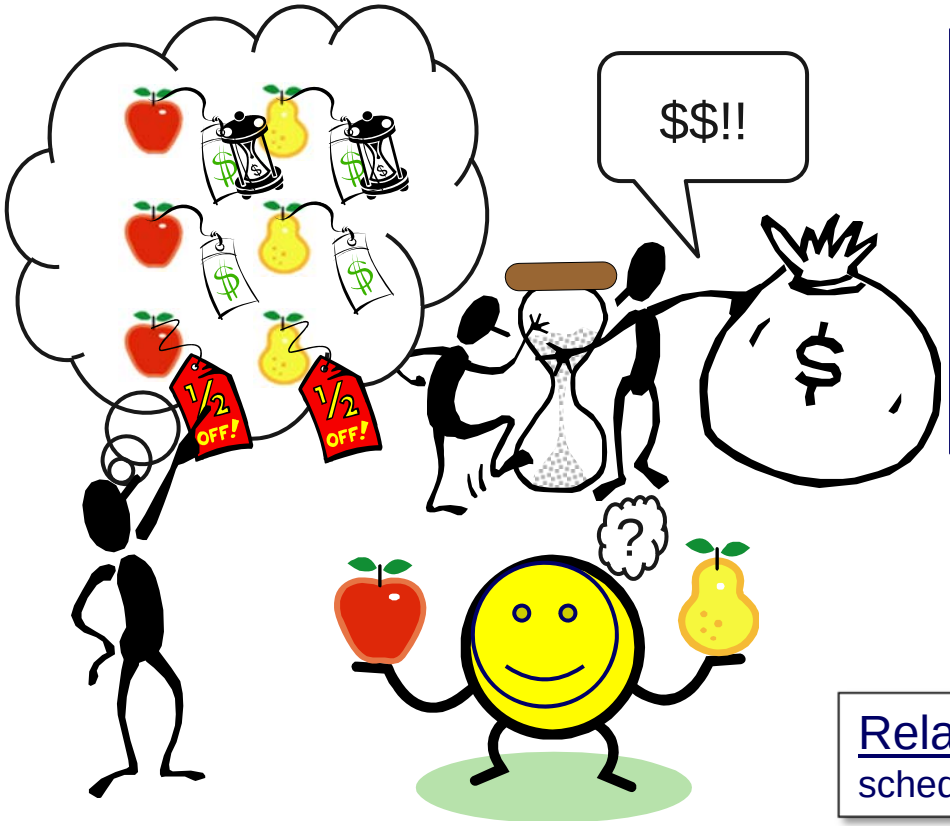
Resources: Costs

The expended resources for a design choice to achieve the utilities

- Can be incurred initially, over time, and at end of life
- Can be multi-criteria (not necessarily dollars)
- Often subject to constraints (such as budgets and schedules)



Space Tug

$$

$$C = c_w M_w + c_d M_d$$

Cost Space

> Dollar cost
  - Dry mass
  - Fuel cost
> Simple parametric model

Related Concepts: costs, dollars, budget, time, schedule, expenses, resources, effort, penalties

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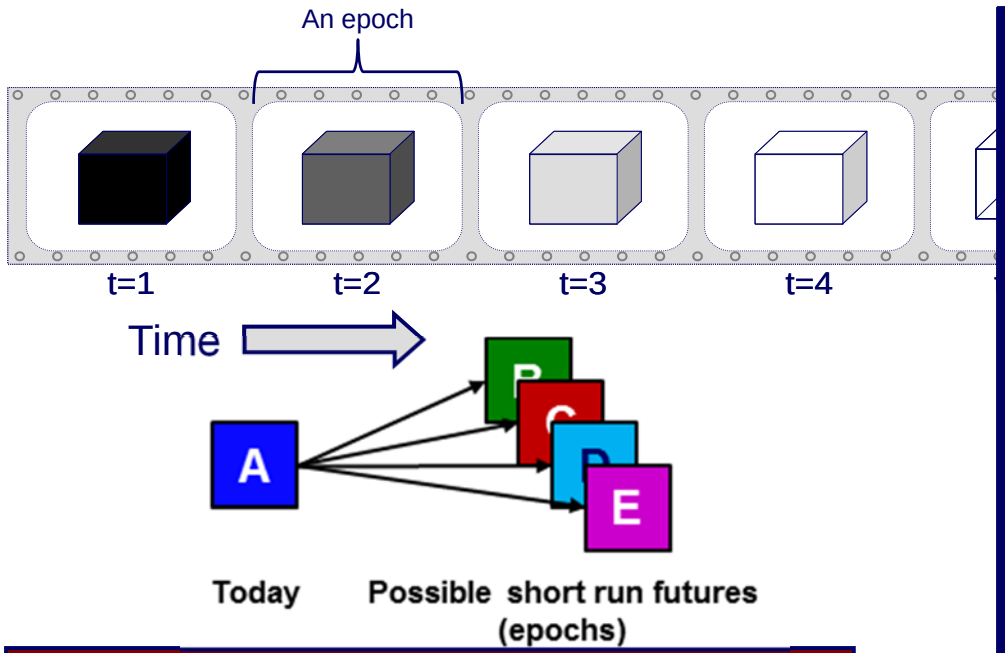
Uncertainties: Epochs

The short run period of "fixed" context and expectations for a choice

- Defined by factors outside of "Designer" control (uncertainties played out)
- Can be many possible epochs
- Concept is relative to defined "fixed" factors that may vary in the future



Space Tug

DARPA Orbital Express

Epochs

>Expectations
- Rescue mission
- Military mission
- Tender mission
- Space Debris Collector
- Tech Demo
- Refueler

>Technology
- Cost of propulsion
- Mass density

Categories of key uncertainties → epochs

Available resources, Policy, Infrastructure, Technology, End Uses ("Markets"), Competition, etc.

Related Concepts: epochs, epoch variables, short run, contexts, expectations, futures, uncertainties

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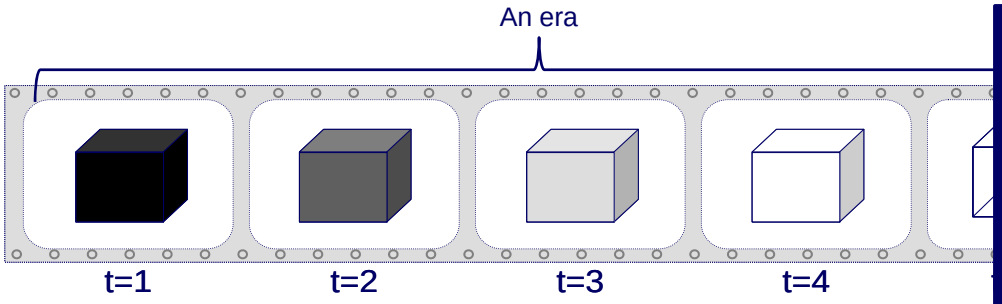
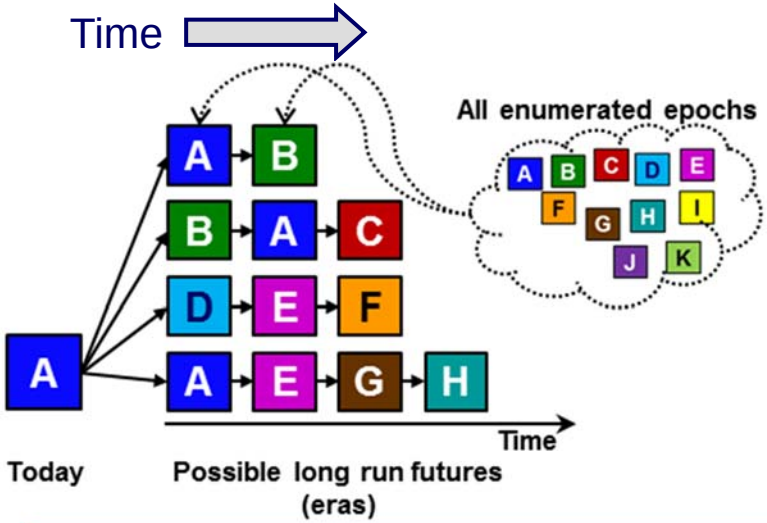
Time-dependence: Eras

The long run, time-ordered sequences of epochs

- Represents “path-dependency” of uncertain future timelines
- Allows for strategy development of choices over time
- Concept is relative to defined “fixed” factors that may vary in the future





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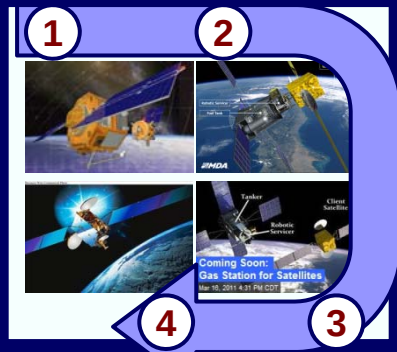

Eras

>Sequence of epochs

1. Demonstration
2. Comsat Servicer
3. Orbital Infrastructure
4. Orbital Rescue

IED attacks in Iraq: (*Wired*)

Related Concepts: eras, epoch ordering, long run, contexts, expectations, futures, uncertainties

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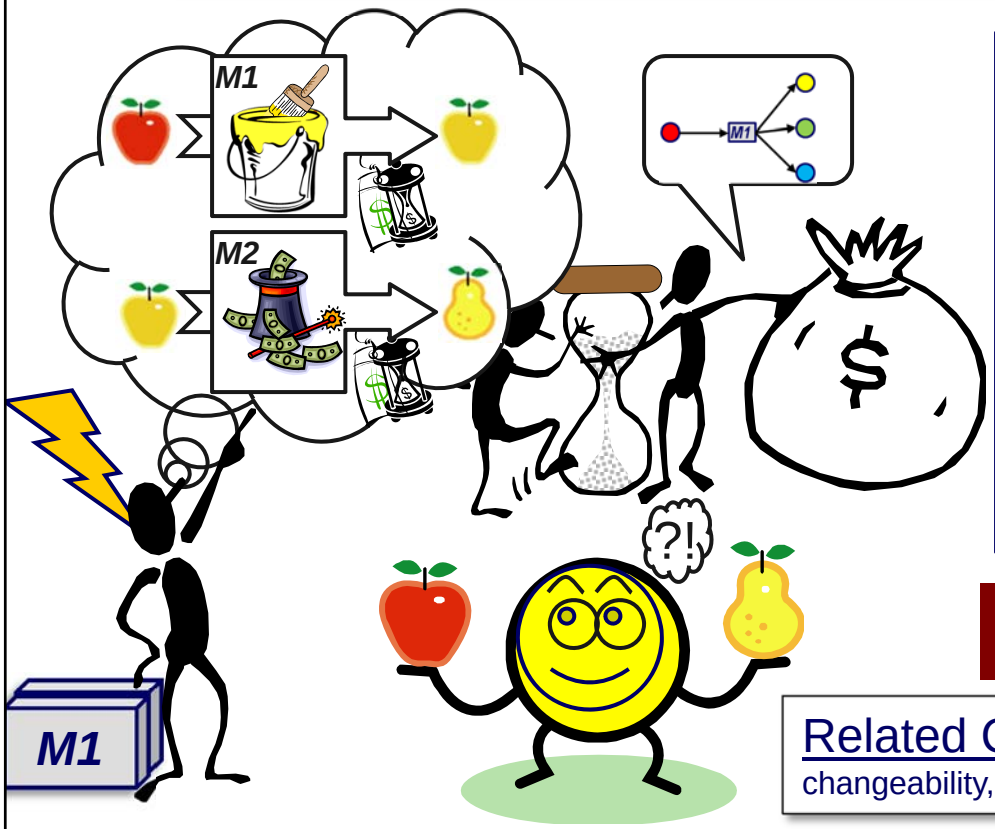
Contingent Value: "ilities"

The ability of a choice to change over time or not need to change over time

- Usually defined in reference to a perturbation (e.g. disturbance → survivability)
- Can be regarded in terms of "degree of" and "value of" each "-ility"
- Usually require an embedded "option" or "mechanism" to execute with costs



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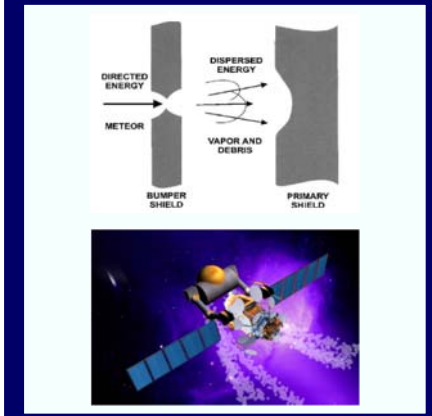

Ilities Space

- >Survivability
  - Shielding
  - Avoidance
  - Replacement
- >Evolvability
  - Refuelability
  - Modular propulsion

Each "-ility" corresponds to a particular aspect of the choice over a particular range; multiple "ilities" can co-exist or conflict

Related Concepts: ilities, real options, change mechanisms, changeability, adaptability, scalability, modifiability, robustness, survivability

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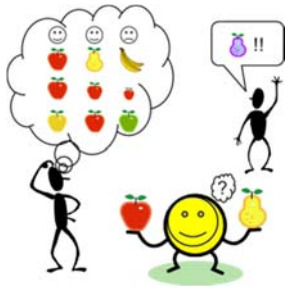
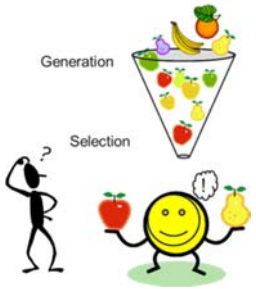
Expanded Thinking: Core Concepts for Advanced SE



1. benefits
- The benefit accrued from a design choice (subjectively defined, varies by person and across time)

utilities by DM

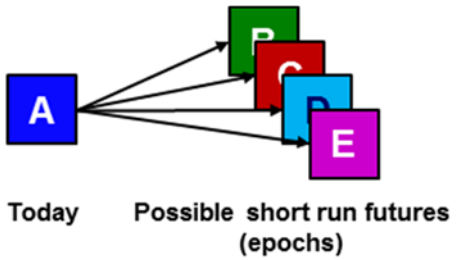


2. "design" choices
- Includes "initial" and "delayed" alternative generation and selection

design/path variables

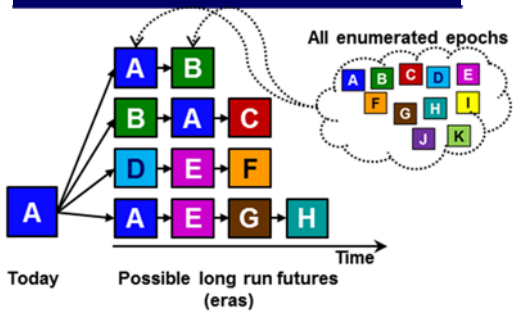
3. resources
- The expended resources required to achieve the utilities, incurred initially, over time, and at the end (may not be $$, include time)

costs



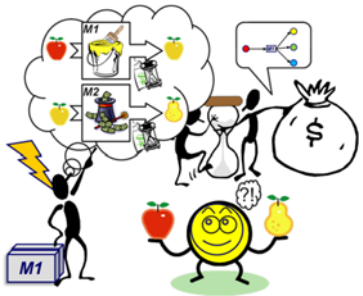
4. uncertainties
- The short run "fixed" context and cost/utility expectations for a choice; outside of a "designer's" control; looking to the future, many possible epochs exist, one for each uncertain version of reality

epochs



5. time-dependence
- The long run, time-ordered sequences of epochs; captures "path-dependency" of uncertain timelines, allowing for strategy development of "choices" over time

eras



6. contingent value
- Temporal system properties that represent the ability of a choice to change over time or not need to change over time, often in response to a revealed "disturbance"

"change-type" ilities

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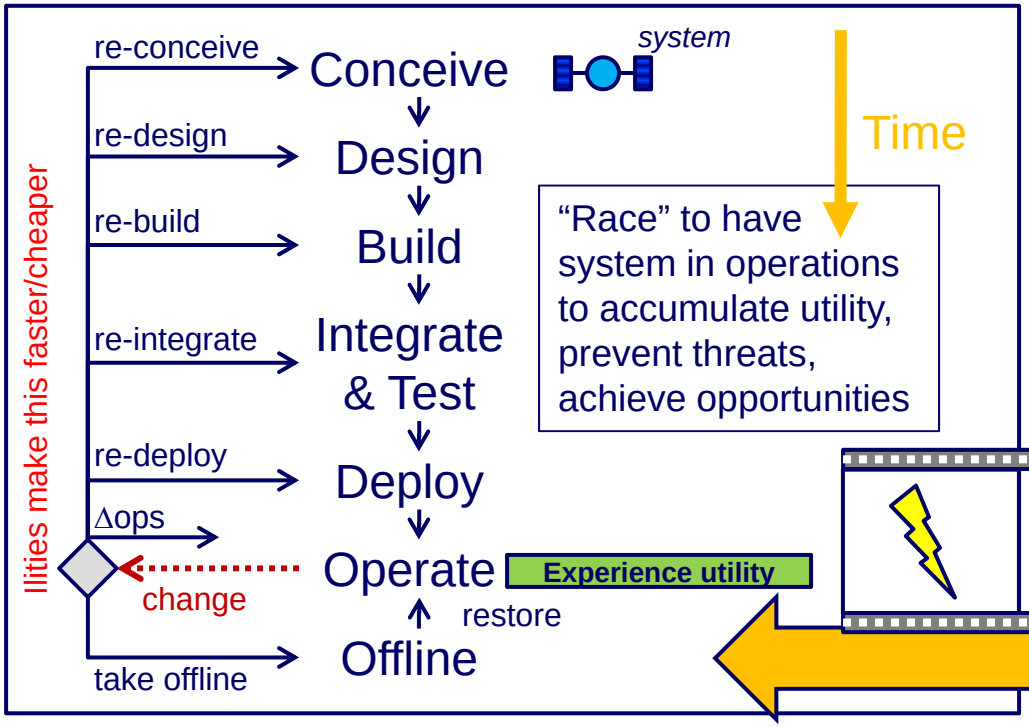
Essential Temporal Perspective: Lifecycle Phase Impacts

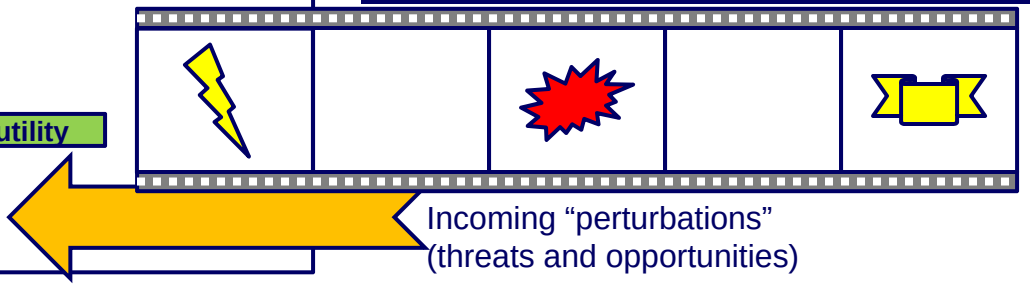
SEAri constructs combine into a dynamic tension when considered together

The time in a lifecycle when a change occurs is an important consideration for "ilities" and tradeoffs



The farther a change goes back into the lifecycle, the longer before utility is experienced again

Choices can be made to give an option to change later in lifecycle, or to reduce the time and cost for getting back to operations



"Successful" response time and cost must be matched to the perturbation

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Learning Objectives for SEAri Games

In order to develop effective learning games, the following learning objectives were identified:

Subset Objectives for Space Tug Skirmish

- Familiarity with SEAri constructs
  - Recognize epochs, eras, ilities
  - Recognize choices, utilities, costs
  - Understand difference between different ilities
- Basic understanding of dynamic relationships among the constructs
  - Each choice has costs and utilities in tension
  - Ilities only useful over time (across epoch shifts and eras)
  - Ordering of epochs in eras matter

Add'l Objectives for Tradespace Explorers

- Advanced understanding of dynamic relationships among the constructs
  - "Best" choice varies per epoch
  - Value of ilities dependent on epoch ordering and strategic goals
  - Portfolio of ilities may be desired
- Examples applied to different types of systems
- System customization and data-logging options for research data
- Examples of non-technical application of the constructs
- Examples of constructs in familiar professional technical context
- Application of constructs to strategy formulation and investment decisions
- Application of constructs to specific problem
- Demonstration of specific constructs

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Player Types for SEAri Games

In order to develop effective learning games, the following player types were identified:

Subset Players for Space Tug Skirmish

- Generic player
- Sponsor (specific application needs)

Subset Players for Tradespace Explorers

- Undergraduate student
- Graduate student researcher
- Professional (technical; e.g. “engineer”)
- Professional (social; e.g. “manager”)
- Senior decision-maker (technical)
- Senior decision-maker (social)

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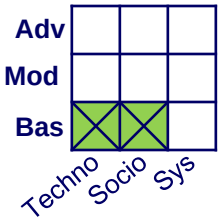
Generic Player



Who am I?

I have basic technical knowledge.

I have basic social knowledge.

I'm just a person who plays the game.

Learning Objectives

- Familiarity with SEAri constructs

Example Questions

- What makes a good choice?
- What is the role of context?
- What are "ilities"?

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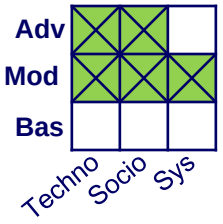
Contrast: Sponsor



Who am I?

I have moderate to advanced technical knowledge.

I have moderate to advanced social knowledge

I have moderate systems knowledge.

Learning Objectives

- Familiarity with SEAri constructs
- Basic understanding of dynamic relationships among the constructs
- Advanced understanding of dynamic relationships among the constructs
- Application of constructs to strategy formulation and investment decisions
- Application of constructs to specific problem
- Demonstration of specific constructs

Example Questions

- How can these constructs solve my specific problem?
- How do I trade-off real options?

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Game developed to support the “familiarity” and “basic understanding” learning objectives

Credits

Game Concept:

Matt Fitzgerald

Card Design:

Matt Fitzgerald and Adam Ross

Artwork:

Elaine Han, Morgan Lai, Adam Ross

Play Testers:

D. Ashpole, T. Boning, J. Kalas, M. Lao, J.C. Beesemyer, D. Fulcoly, P. Grogan, H. McManus, B. Mekdeci, N. Ricci, M. Schaffner, M. Wu

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Space Tug Skirmish Development

STS was an offshoot of Summer 2011
It has evolved through ongoing playtesting and refinement

Summer project 2011

Card game origin (7/2011)

(12/2011)	(1/2012)	(3/2012)	(5/2012)	(5/2013)	Summer project 2013 (8/2013)	(11/2013)	
v1.0	v1.1	v2.0	v2.1	v3.0	v3.1	v3.2	…
Design, Ops decks	Play balancing	Epoch deck	Play balancing	Stats, Personas	Play balancing	Play balancing	

Computer game origin

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Overview of Goal and Play

You are owner of a Space Tug business, seeking fortune in outer space…

- Goal
  - Be the first player to amass $100M by the end of your turn in operations
- Play
  - Three decks of cards: Epoch, Design, Operations
  - Play progresses through rounds, where one Epoch card is played and each player takes a turn
  - Players can be in either Design or Operations phase (and can switch)
  - Players play Design cards in Design phase and Operations cards in Operations phase
  - In Design Space Tugs can be improved, while in Operations money can be earned
- Set-up
  - Shuffle cards
  - Draw 7 cards (mix of Design/Ops)
  - Initial funds: $30M to each player
- Rules
  - Turn
    - Draw (1 card/turn),
    - Declare launch (free, design->ops) or recover ($5M, ops->design), cannot play
    - Play (2 cards in design, 1 card in ops), if did not change phases
    - Discard (down to 7)
  - Cards can be destroyed (discarded) or disabled (inactive, but repairable)
  - Contracts won by meeting stat requirements during ops; features provide income in ops

You start the game in “Design” phase, but must launch into “Operations” phase in order to earn income. Cards can only be played during their indicated phase; you may switch between phases during the game.

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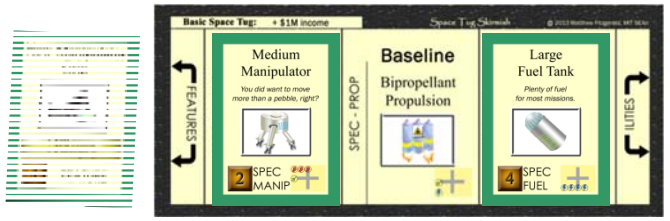
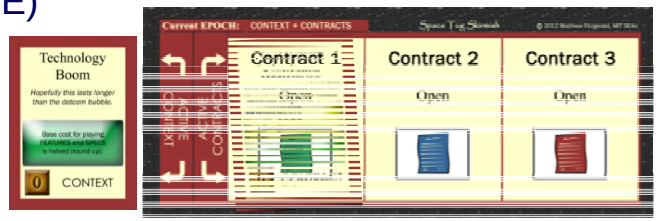
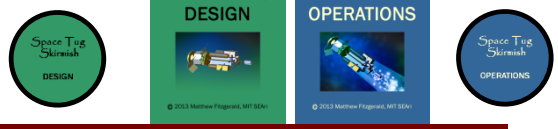
Mapping to SEAri Constructs

1. **"design" choices**
   - SPECs, FEATUREs
     design variables, attributes
2. **utilities**
   - Satisfied contracts, income (earned $)
     missions (needed stats)
3. **costs**
   - Budget (spent $)
     dollars
4. **epochs**
   - Epoch cards (CONTEXT+CONTRACT and DISTURBANCE)
     epoch = context + need
5. **eras**
   - Epoch mat, epoch shift token
     era = sequence of epochs
6. **"ilities"**
   - ILITY
     all SEAri ilities plus more!







Other important constructs

- Role of time and phase-dependent choices
  design phase, operations phase

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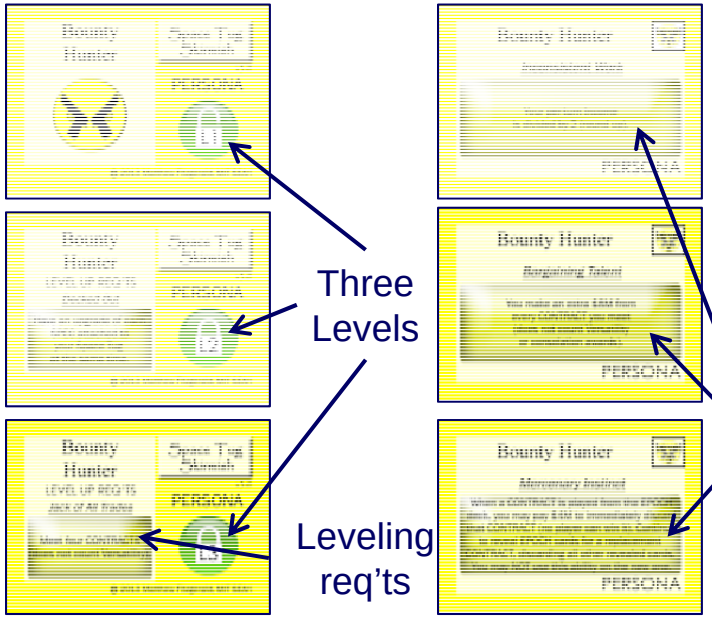
Persona Expansion Set

The persona deck puts you in the shoes of a wide cast of characters, each with a unique set of strengths and weaknesses, for even more wild multiplayer fun! Win with them all to become a true Space Tug Skirmish master!

We found people tended to stick to particular strategies after repeated play.
This interferes with meeting alternative learning objectives.
Solution: creation of "personas" for asymmetric gameplay.



Personas incentivize varied gameplay to encourage experiencing of alternative pedagogical aims

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Personas: Incentivizing Alternative Gameplay

Level 1 - a negative reinforcement.
Direct players away from certain behaviors in order to force them to reconsider habits that they may have formed
Level 2 - a positive reinforcement.
Reward completing the first objective by enhancing the value of playing in the style that completes it.
Level 3 - another positive reinforcement.
Provide the player with an additional 'power' or leverage over the game in favor of their persona's playstyle

Bounty Hunter - specs + contracts, high risk high reward

Venture Capitalist - speed play, begin with more money, cash out faster

Research Professional - card advantage, accumulation of options

Systems Engineer - ilities, combat uncertainty

Military Tactician - attacks, combat opponents

Conscientious Objector - non-interaction, individual play

Technology Startup - 'all in', protect a big investment and ride it to victory

Cutthroat Businessman - features + income play, slow and steady wins the race

Landed Elite - economies of scale, advantages of buying bulk

University Team - productivity, playing extra cards

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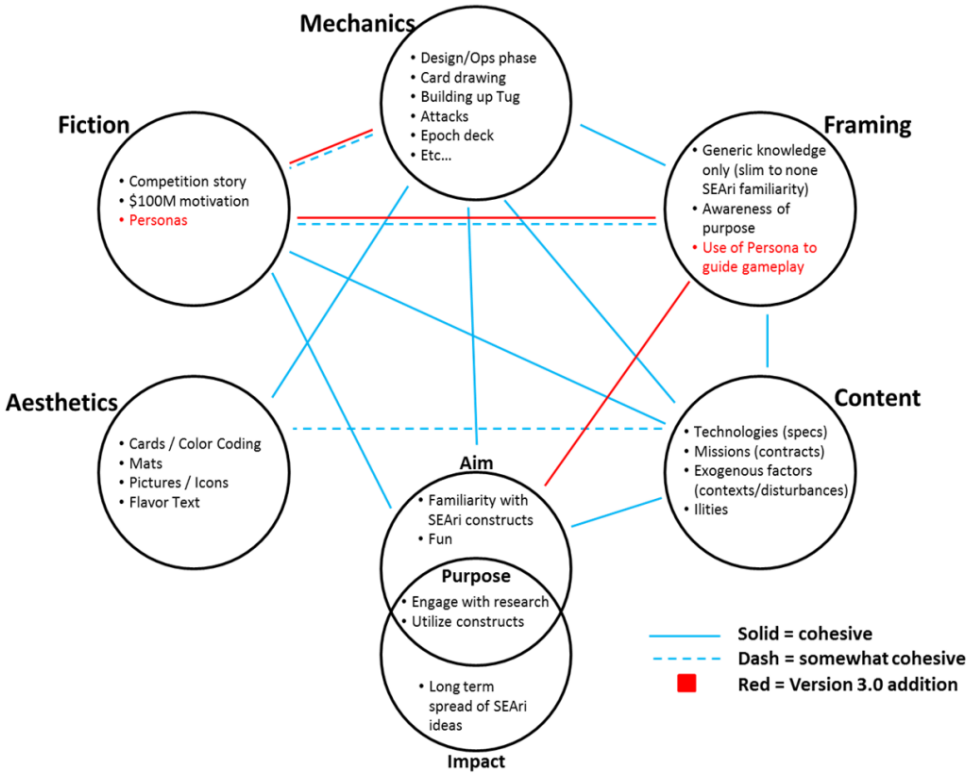
Evaluation of STS



The evolution of STS has lead to strong cohesiveness according to the Mitgutsch purposeful game assessment framework

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2013 High Level Project Goals

Interactive Games as a Research Medium to Improve Engineering Systems Thinking

June 13 to August 20, 2013

Goals

- To implement Space Tug Skirmish v3.0 as a software-based game…
  - Operationalize game mechanics
  - Compelling visual and interactive experience

- …with tracking…
  - Database to store game state and player actions with standard schema
- …and level design capabilities
  - Separate scripted (i.e. deck and possible player AI) game design functionality
- To have a software platform that enables easy modification (e.g. change card properties, modify game rules)
- **Most importantly: preserve engaging player experience with game!**

These goals were presented at the kick off meeting to guide priorities

A game is a problem-solving activity, approached with a playful attitude.
Schell 2008, pg 37

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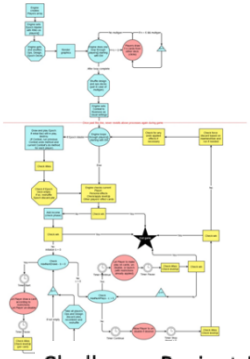
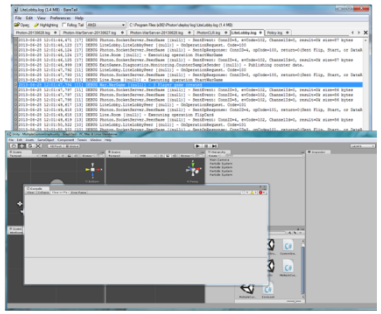
End Result: Working Demo

Challenge Project A- Operationalizing Mechanics

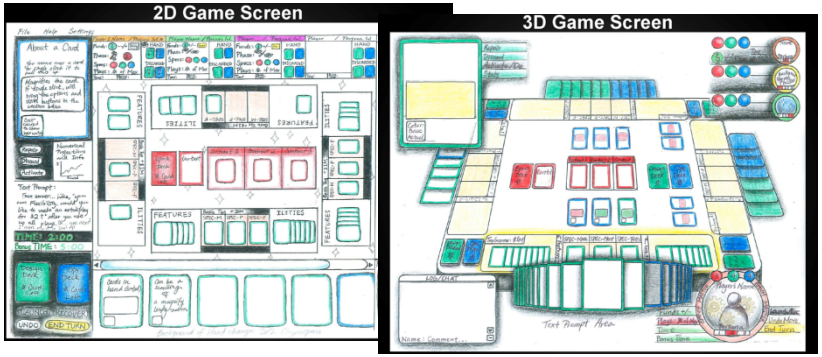


Challenge Project D- Data Logging and Feedback

- Photon
- Unity

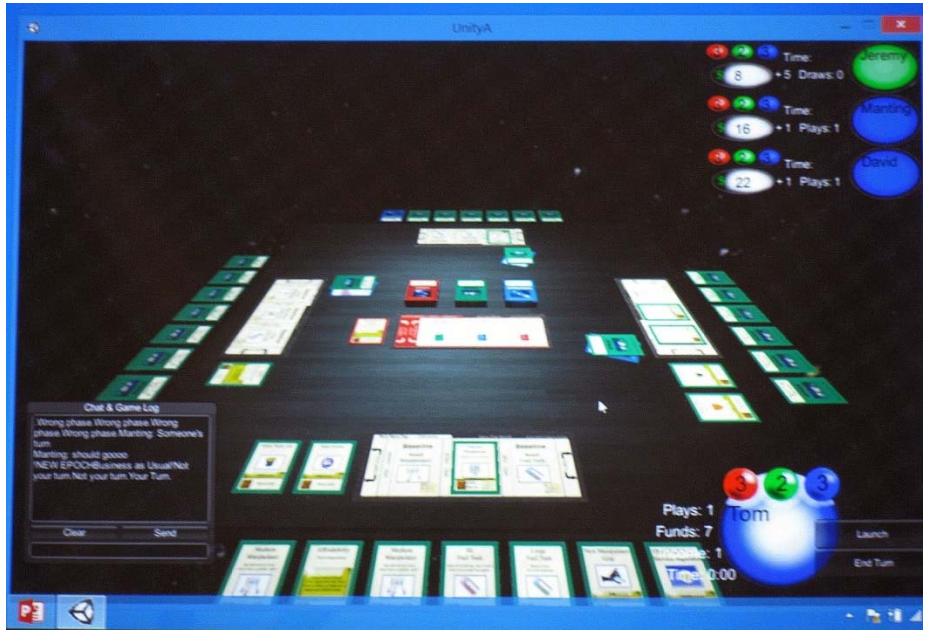


Challenge Project E – GUI Design



Demo Capabilities

- Implemented STSv3.1
- Most of cards, including 2 Personas
- Online
- 1-4 players
- Editable card decks
- Preliminary data tracking



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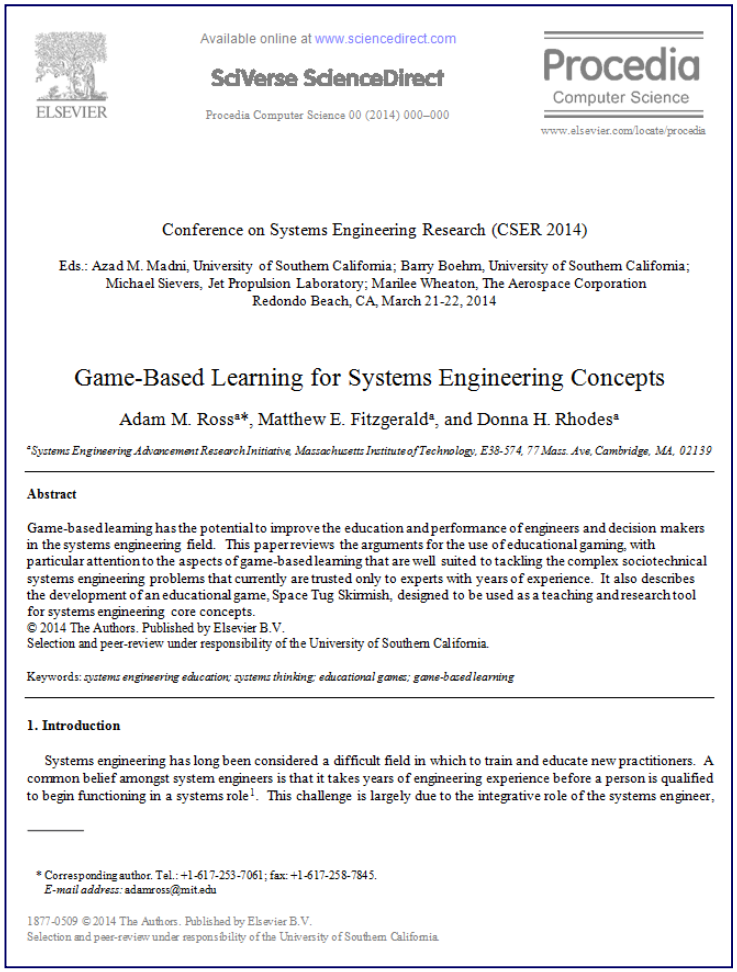
Discussion

So far results are promising from a student engagement perspective…



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Conference on Systems Engineering Research (CSER 2014)

Eds.: Azad M. Madni, University of Southern California; Barry Boehm, University of Southern California; Michael Sievers, Jet Propulsion Laboratory; Marilee Wheaton, The Aerospace Corporation
Redondo Beach, CA, March 21-22, 2014

Game-Based Learning for Systems Engineering Concepts

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Abstract

Game-based learning has the potential to improve the education and performance of engineers and decision makers in the systems engineering field. This paper reviews the arguments for the use of educational gaming, with particular attention to the aspects of game-based learning that are well suited to tackling the complex sociotechnical systems engineering problems that currently are trusted only to experts with years of experience. It also describes the development of an educational game, Space Tug Skirmish, designed to be used as a teaching and research tool for systems engineering core concepts.

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Selection and peer-review under responsibility of the University of Southern California.

Keywords: *systems engineering education; systems thinking; educational games; game-based learning*

1. Introduction

Systems engineering has long been considered a difficult field in which to train and educate new practitioners. A common belief amongst system engineers is that it takes years of engineering experience before a person is qualified to begin functioning in a systems role[1]. This challenge is largely due to the integrative role of the systems engineer,

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Selection and peer-review under responsibility of the University of Southern California.

Next Steps

- Pursue funded research
- Share results (e.g. via papers)
- Build community interest
- Continue development of STS (card and digital)
- Develop experiments
- Collect data
- …

Open Questions

- Efficacy of knowledge transfer
- Transferability of knowledge
- Game as microcosm
- …

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QUESTIONS?

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GAME-BASED LEARNING FOR SYSTEMS ENGINEERING CONCEPTS

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