Game-Based Learning for Systems Engineering Concepts

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SEArri Research Seeks to “Change the Picture”

**ESSENTIAL ELEMENTS**

- Appropriate **competencies** in workforce
- Advanced **methods** for anticipatory analysis, decision making, and architecting
- Enabling enterprise strategies and model-based **environments**
## Building Anticipatory Capacity

<table>
<thead>
<tr>
<th>COMPETENCIES</th>
<th>METHODS</th>
<th>ENVIRONMENT</th>
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<tbody>
<tr>
<td>Ability to think deeply about ‘systems in context’</td>
<td>Perform dynamic tradespace exploration</td>
<td>Computing power/toolsets to enact methods</td>
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<td>Enhance ability to think about ‘systems in time’</td>
<td>Model-based approach to derive alternative futures</td>
<td>Support multi-stakeholder negotiations in tradespace exploration</td>
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<td>Use <em>situational leadership</em> to make decisions at multiple system levels</td>
<td>Apply methods at varying levels of fidelity</td>
<td>Enable comprehension of complex data sets</td>
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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-Driven 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

Context uncertainty
Needs uncertainty

Trade space: (Design Variables; Attributes) \rightarrow \{Cost; Utility\}

Each tradespace represents a fixed context/needs
Each point represents a feasible solution

Many epoch data sets

Era (long run) analysis
Multi-epoch (short run) analysis

Exploring Fuzzy Pareto Shale of designs of interest for a strategy

Change Mechanisms

It takes graduate students over a year to begin to really apply some of this...
SEAr's goal is to have impact, so we need to find a way to accelerate deployment of the research
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?
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
Game Design is both Art and Engineering


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
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

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

Miller’s pyramid of learning in (Schell 2008), pp 445
Designing a Purposeful Game

- 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

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

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

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

We distilled the SEArri 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”
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
“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”

Space Tug

Design Space
- Manipulator Mass
  - Low (300 kg)
  - Medium (1000 kg)
  - 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
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

Cost Space
- Dollar cost
  - Dry mass
  - Fuel cost
- Simple parametric model

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

\[ C = c_w M_w + c_d M_d \]
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

An epoch

Categories of key uncertainties → epochs
Available resources, Policy, Infrastructure, Technology, End Uses (“Markets”), Competition, etc.

Space Tug

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

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

> Technology
  - Cost of propulsion
  - Mass density

DARPA Orbital Express
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

An era

Space Tug

Eras

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

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

Related Concepts: ilities, real options, change mechanisms, changeability, adaptability, scalability, modifiability, robustness, survivability
Expanded Thinking: Core Concepts for Advanced SE

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

2. **“design” choices**
   - Includes “initial” and “delayed” alternative generation and selection

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

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

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

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”
Essential Temporal Perspective: Lifecycle Phase Impacts

SEArri 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.

- Re-conceive
- Re-design
- Re-build
- Re-integrate
- Re-deploy
- Δops
- Take offline

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.

“Race” to have system in operations to accumulate utility, prevent threats, achieve opportunities.

Experience utility

Incoming “perturbations” (threats and opportunities)
# Learning Objectives for SE Arrest Games

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

## Subset Objectives for Space Tug Skirmish

- Familiarity with SE Arrest 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
In order to develop effective learning games, the following player types were identified:

- Generic player
- Sponsor (specific application needs)
- Undergraduate student
- Graduate student researcher
- Professional (technical; e.g. “engineer”)
- Professional (social; e.g. “manager”)
- Senior decision-maker (technical)
- Senior decision-maker (social)
**Learning Objectives**

- Familiarity with SEArI constructs

**Who am I?**

- I have basic technical knowledge.
- I have basic social knowledge.
- I’m just a person who plays the game.

**Example Questions**

- What makes a good choice?
- What is the role of context?
- What are “ilities”?
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?
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:**
Space Tug Skirmish Development

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

<table>
<thead>
<tr>
<th>Card game origin</th>
<th>Computer game origin</th>
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<tbody>
<tr>
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<tr>
<td>v1.0</td>
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<td>v3.0</td>
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<tr>
<td>v3.2</td>
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<tr>
<td>Design, Ops decks</td>
<td>Play balancing</td>
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<tr>
<td>(1/2012)</td>
<td>(1/2012)</td>
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<tr>
<td>Epoch deck</td>
<td>Play balancing</td>
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<td>(3/2012)</td>
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<td>Play balancing</td>
<td>Stats, Personas</td>
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<td>Play balancing</td>
<td>Play balancing</td>
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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.
Mapping to SEArri Constructs

1. “design” choices
   - SPECs, FEATUREs
     \[ \text{design variables, attributes} \]

2. utilities
   - Satisfied contracts, income (earned $)
     \[ \text{missions (needed stats)} \]

3. costs
   - Budget (spent $)
     \[ \text{dollars} \]

4. epochs
   - Epoch cards (CONTEXT+CONTRACT and DISTURBANCE)
     \[ \text{epoch} = \text{context} + \text{need} \]

5. eras
   - Epoch mat, epoch shift token
     \[ \text{era} = \text{sequence of epochs} \]

6. “ilities”
   - ILITY
     \[ \text{all SEArri ilities plus more!} \]

Other important constructs
   - Role of time and phase-dependent choices
     \[ \text{design phase, operations phase} \]
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.
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** - abilities, 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
Evaluation of STS

The evolution of STS has lead to strong cohesiveness according to the Mitgutsch purposeful game assessment framework.
Interactive Games as a Research Medium to Improve Engineering Systems Thinking

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!

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

These goals were presented at the kick off meeting to guide priorities
End Result: Working Demo

Demo Capabilities

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

So far results are promising from a student engagement perspective...

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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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, inter-disciplinary systems engineering problems that currently confront both experts with years of experience. It also describes the development of an educational game, Space Tag: Starship, designed to be used as a training and research tool for systems engineering core concepts.

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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 systems engineers is that it takes years of engineering experience before a person is qualified to begin functioning in a systems role. This challenge is largely due to the integrative role of the systems engineer.