Systems Engineering Advancement Research Initiative

2011 SEAri Annual Research Summit

Research Topic

"Using Serious Gaming to Experience Dynamic Uncertainties and Ilities"

Dr. Adam M. Ross

October 21, 2011

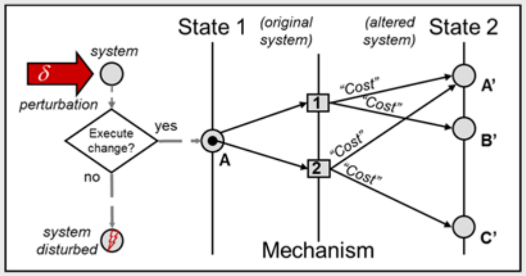
Cambridge, MA

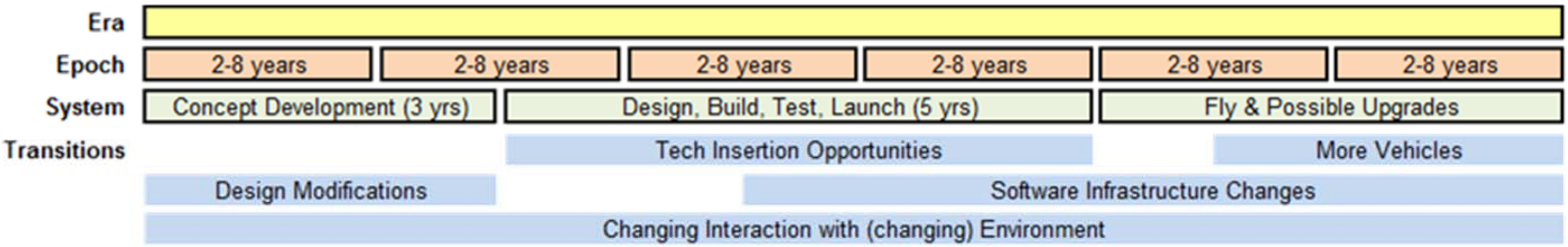
Massachusetts Institute of Technology

Engineering Systems Division

Designing for a Dynamic World

- SEAri has a decade of research on designing “value robust” systems
- Specifically targets the high leverage *early concept phase*
- Methods and metrics inform selection of promising concept designs for further analysis
- Uses exogenous uncertainties to frame the need for the ability of a system to respond to *perturbations*





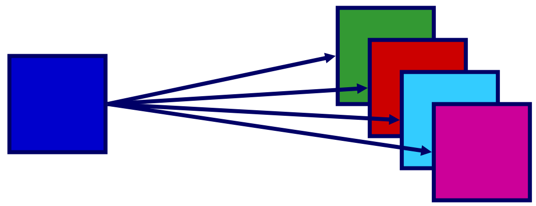
Systems developed in a dynamic world must accommodate shifts in context and needs (epoch) across their lifespan (era)

Success for modern systems is strongly determined by being able to respond to perturbations on appropriate timescales

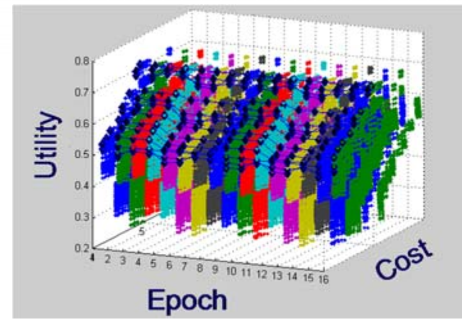
Encapsulating Uncertainties
Epochs

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

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



Today   Possible futures (epochs)



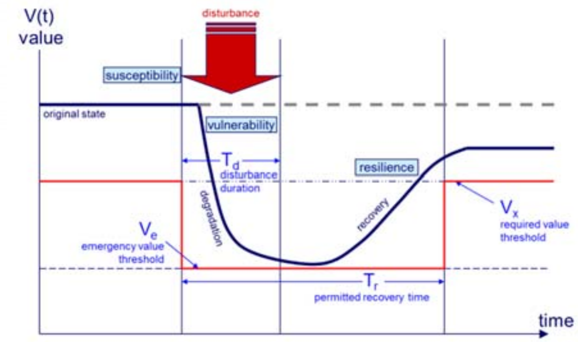
Example triggers for epoch shifts impacting a system

- Change in political environment
- Entrance of new competitor in market
- Emergence of significant new or changed stakeholder need(s)
- Policy mandate impacting product line, services or operations
- New threat environment with non-state actors using improvised attacks

<u>Categories of uncertainties can aid in thinking about key changing factors</u>

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

Related "ilities"
Changeability and Survivability



value robustness	ability of a system to maintain value delivery in spite of changes in needs or context
changeability	ability of a system to be intentionally altered in form or operations, and consequently possibly in function, at an acceptable level of "cost"
flexibility	ability of a system to be altered by a system-external change agent
adaptability	ability of a system to be altered by a system-internal change agent
survivability	ability of a system to minimize the impact of finite-duration disturbances on value delivery
susceptibility	reduction of the likelihood or magnitude of a disturbance
vulnerability	satisfaction of minimally acceptable value level during and after disturbance
resilience	timely recovery to an acceptable value level after a disturbance

A ***valuably changeable*** system is one that can be intentionally altered, typically in response to a perturbation (such as a change in context), in order to improve its value

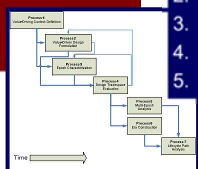
Ten Years of Research on Methods and Metrics

Methods for Value-Centric Analysis

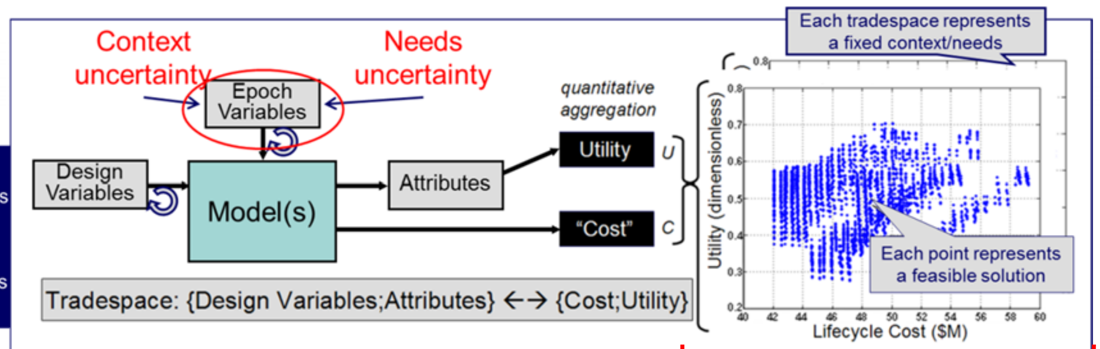
Multi-Attribute Tradespace Exploration

Epoch-Era Analysis

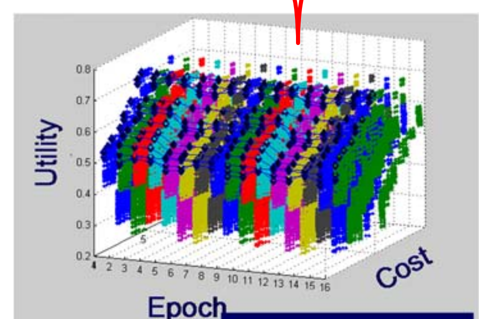
RSC consists of seven processes:
1. Value-Driving Context Definition
2. Value-Driven Design Formulation
3. Epoch Characterization
4. Design Tradespace Evaluation
5. Multi-Epoch Analysis
6. Era Construction
7. Lifecycle Path Analysis



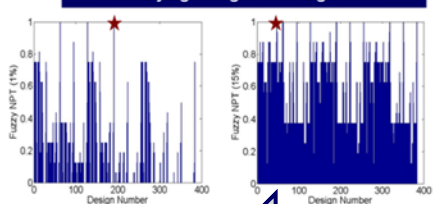
VASC
1. Set up data for epoch-era analysis
2. Identify designs of interest
3. Define rule usage strategies
4. Multi-epoch changeability analysis
5. Era simulation and analysis



Many epoch data sets

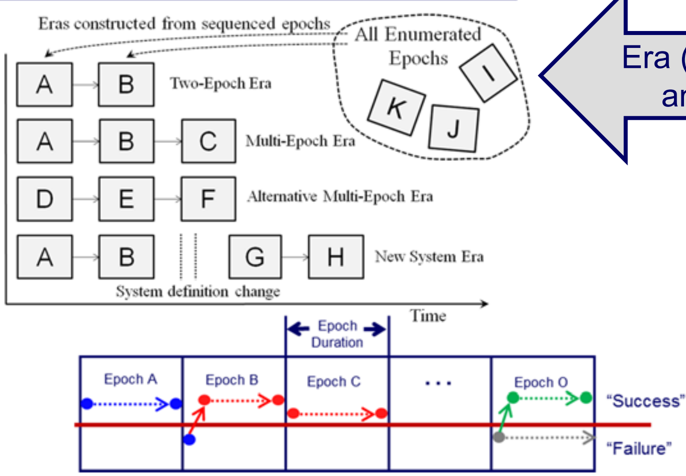


Identifying designs with high fNPT



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

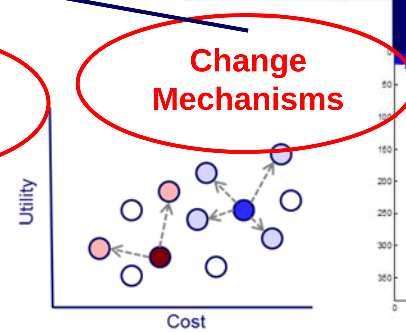
Strategy	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
MaxU	N/A	N/A	N/A	100.0%	89.2%	N/A
MaxEff	N/A	N/A	N/A	100.0%	97.1%	N/A
Survive	N/A	N/A	N/A	94.9%	0.0%	N/A
MaxP	N/A	N/A	N/A	96.8%	31.5%	N/A



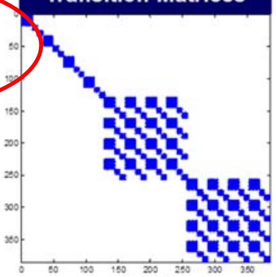
Era (long run) analysis

Multi-epoch (short run) analysis

Exploring Fuzzy Pareto Shift of designs of interest for a strategy



Collapsing Mech. Transition Matrices



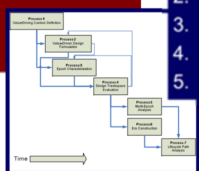
Ten Years of Research on Methods and Metrics

Methods for Value-Centric Analysis

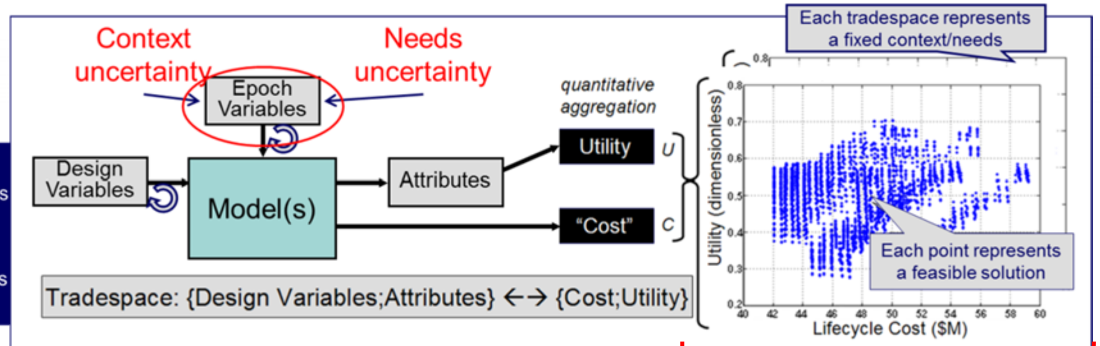
Multi-Attribute Tradespace Exploration

Epoch-Era Analysis

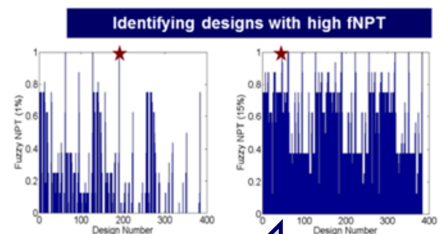
RSC consists of seven processes:
1. Value-Driving Context Definition
2. Value-Driven Design Formulation
3. Epoch Characterization
4. Design Tradespace Evaluation
5. Multi-Epoch Analysis
6. Era Construction
7. Lifecycle Path Analysis

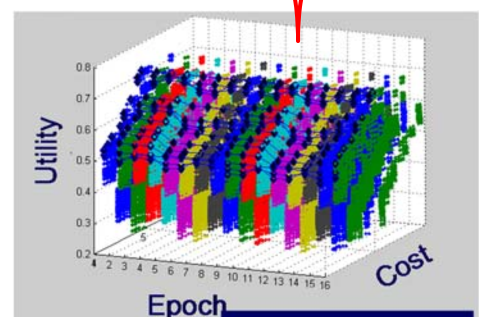


VASC
1. Set up data for epoch-era analysis
2. Identify designs of interest
3. Define rule usage strategies
4. Multi-epoch changeability analysis
5. Era simulation and analysis



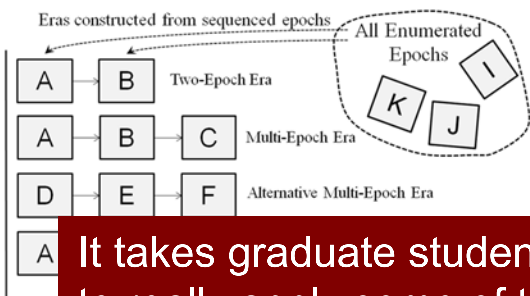
Many epoch data sets





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



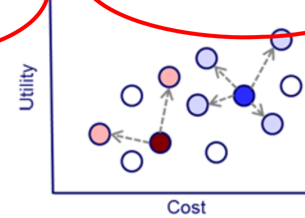
Era (long run) analysis

Multi-epoch (short run) analysis

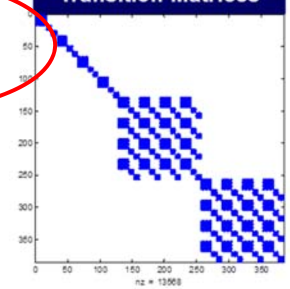
Exploring Fuzzy Pareto Shift of designs of interest for a strategy

Strategies
- Maximize Utility
- Maximize Efficiency
- Survive
- Maximize Profit

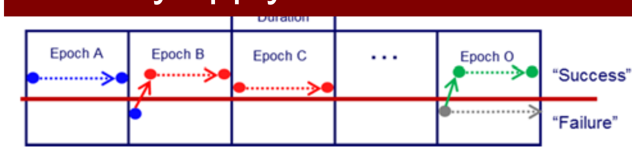
Change Mechanisms



Collapsing Mech. Transition Matrices



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



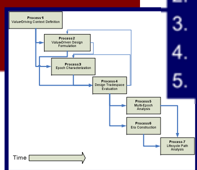
Ten Years of Research on Methods and Metrics

Methods for Value-Centric Analysis

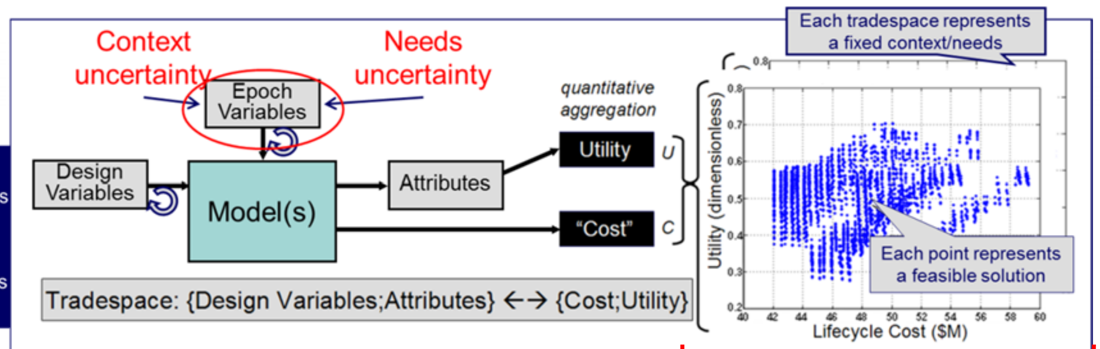
Multi-Attribute Tradespace Exploration

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

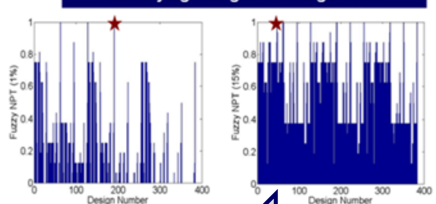


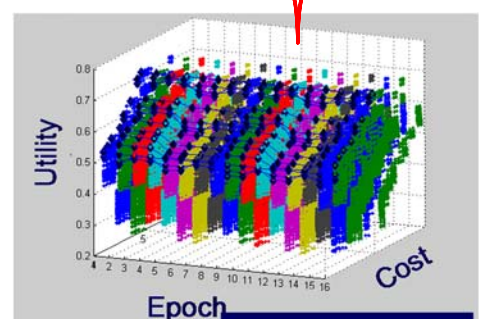
VASC
1. Set up data for epoch-era analysis
2. Identify designs of interest
3. Define rule usage strategies
4. Multi-epoch changeability analysis
5. Era simulation and analysis



Many epoch data sets

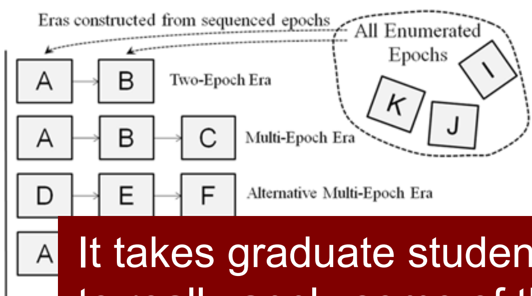
Identifying designs with high fNPT





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

Exploring Fuzzy Pareto Shift of designs of interest for a strategy

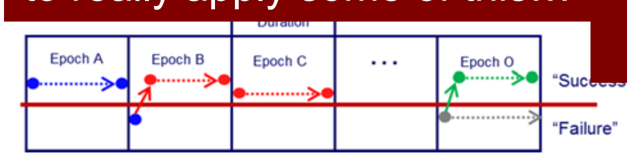
Collapsing Mech. Transition Matrices

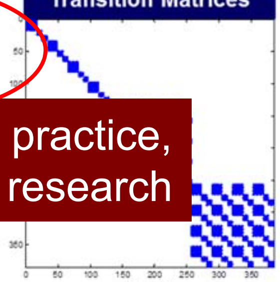
Strategies

Change Mechanisms

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

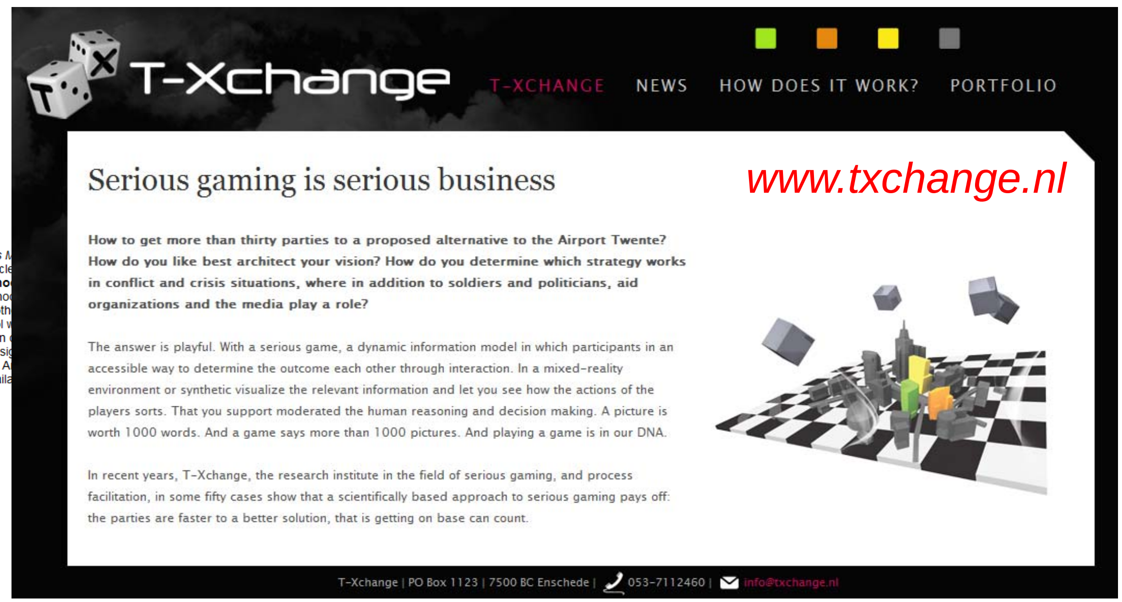
SEAri's goal is to impact practice, so we need to find a better way to teach the research





Tackling Problems using "Games"

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



Is this 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

Work

Play

Learning

Fun

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

Work

Play

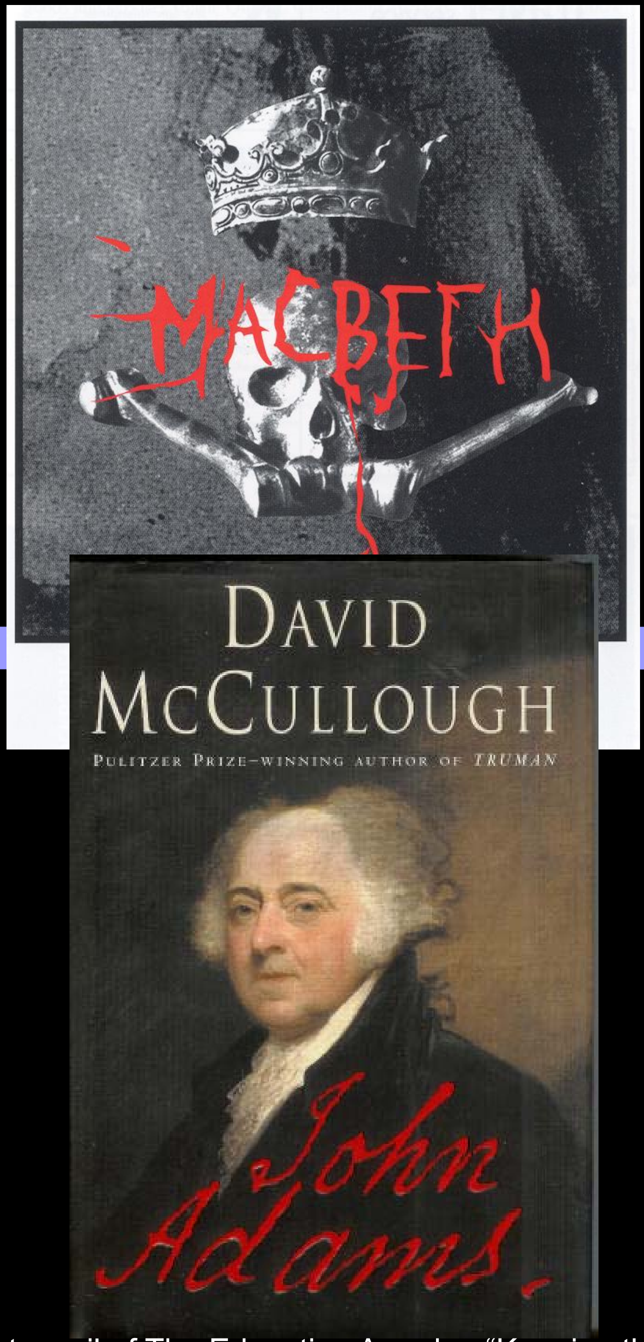
Learning

Fun

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

Work

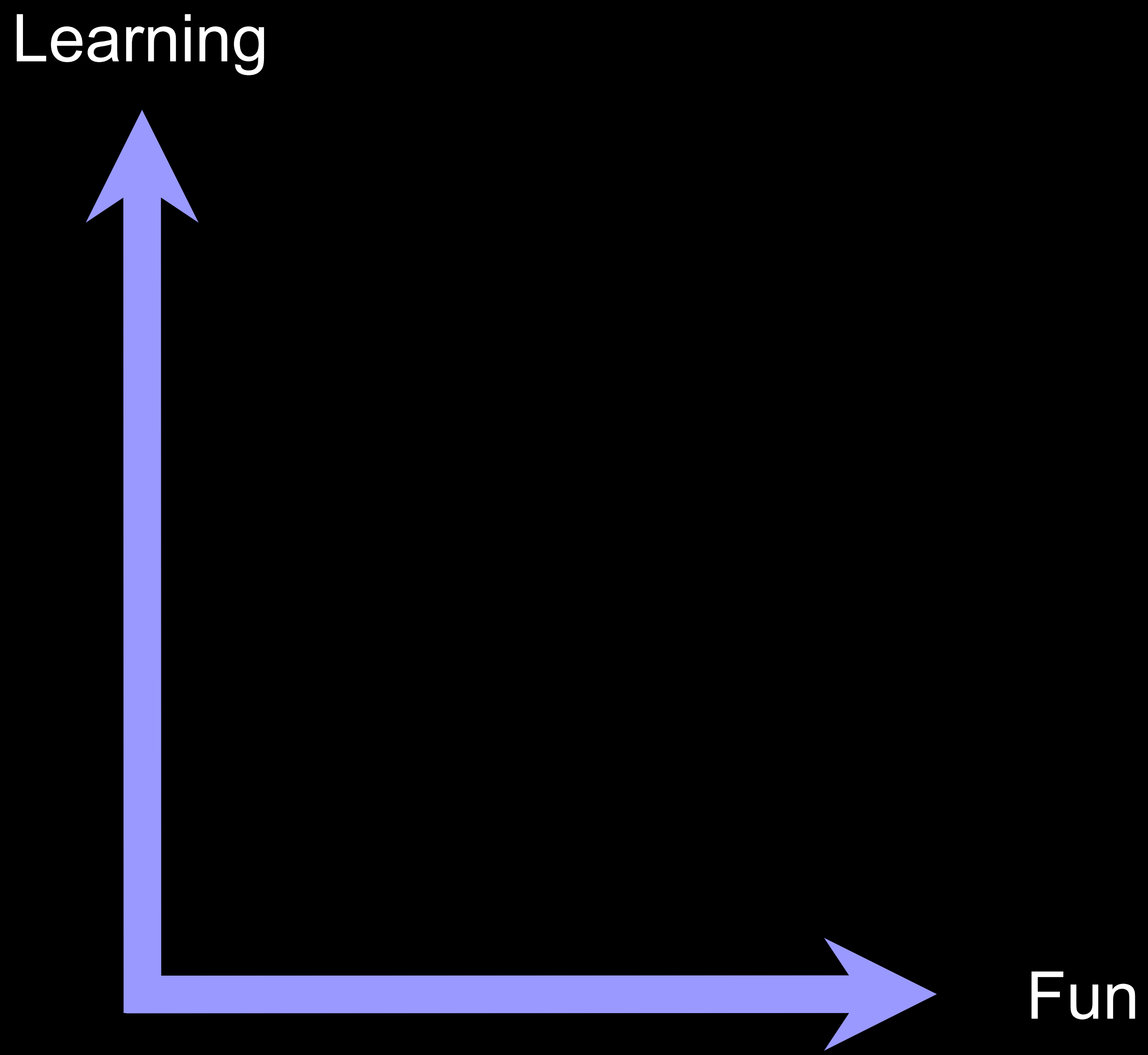
Play



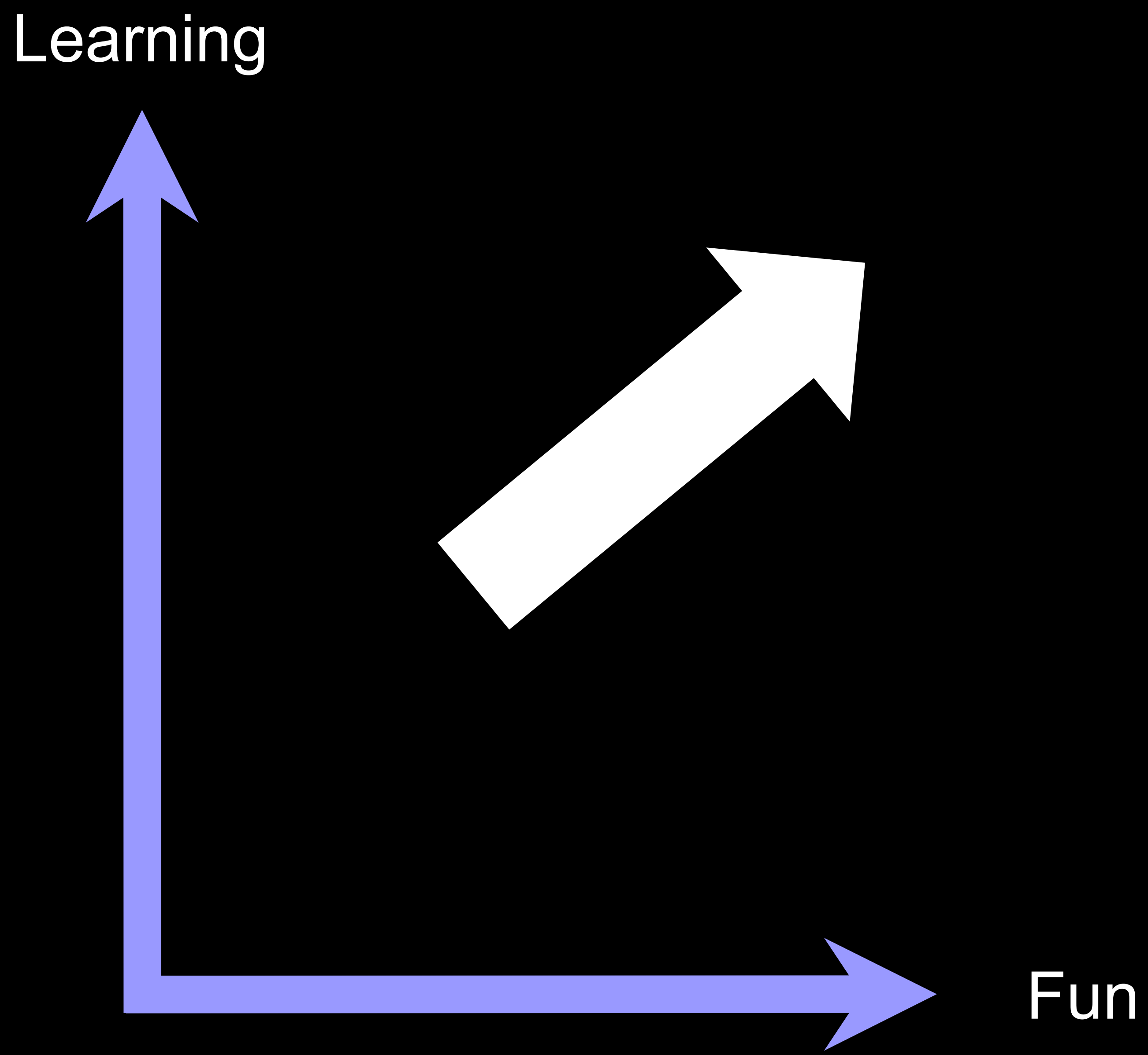
Learning

Fun

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



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



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

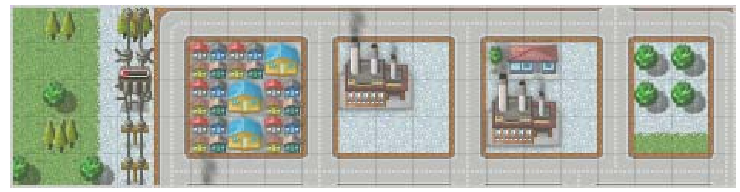
A Game is More than Monopoly

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



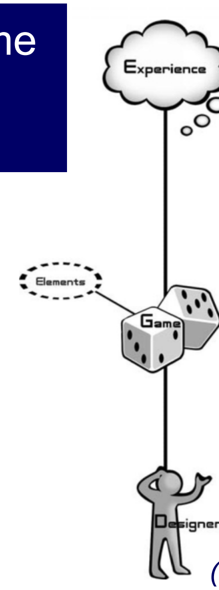
Windfall: a strategy game about building wind farms to create clean energy profitably. *Persuasive Games* (http://www.persuasivegames.com)

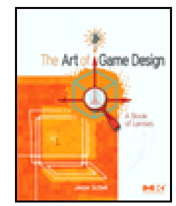
Microsoft Flight Simulator X: Gold Edition: Experience realistic flights with day/night and weather effects, multiplayer races and over 80 missions worldwide

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

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.



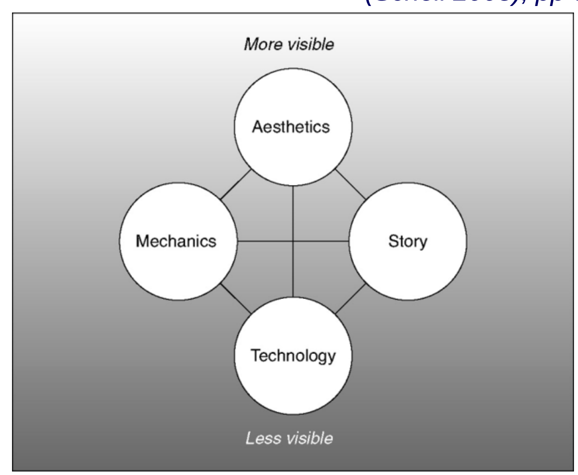


(Schell 2008), pp 39

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



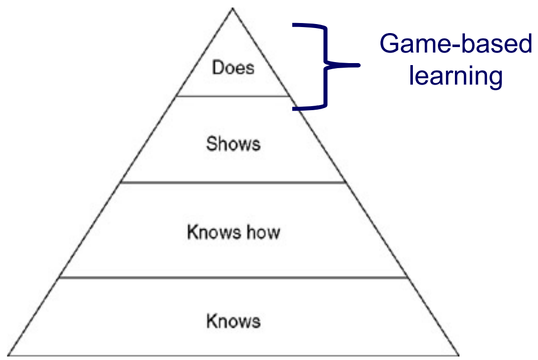
(Schell 2008), pp 42

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



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

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

Summer Project Motivation

- Summer 2009 (updated 2010)
  - VisLab created as means to “experience” the data
  - Users have fun while gaining insight and learning

Summer Project Motivation

- Summer 2009 (updated 2010)
  - VisLab created as means to “experience” the data
  - Users have $\boxed{\text{fun}}$ while gaining insight and learning

UNEXPECTED!

Summer Project Motivation

- Summer 2009 (updated 2010)
  - VisLab created as means to “experience” the data
  - Users have $\boxed{\text{fun}}$ while gaining insight and learning

    UNEXPECTED!

- Summer 2011
  - Find a way to develop a “game” to teach, clarify, simulate SEAri constructs
  - And be fun!

Summer Project Motivation

- Summer 2009 (updated 2010)
  - VisLab created as means to "experience" the data
  - Users have $\boxed{\text{fun}}$ while gaining insight and learning

UNEXPECTED!

- Summer 2011
  - Find a way to develop a "game" to teach, clarify, simulate SEAri constructs
  - And be fun!

GOAL: *Develop interactive games for accelerated insights into dynamic system strategies using six SEAri constructs*
("design" choices, utilities, costs, epochs, eras, and "ilities")

High Level Project Goals

Interactive Games for Accelerated Insights into Dynamic System Strategies

June 6 to August 16, 2011

Goals

- To develop a “game” to let players better understand the “ilities” and the effects of changing contexts & needs on valuation
- To develop useful visual and interactive constructs to communicate short run and long run scenario analysis using SEAri constructs
- To be able to gather player game data (to compare how users “optimize” and make decisions in this dynamic decision environment to strategies derived through SEAri algorithms)
- To have a software platform that enables easy modification to demonstrate the universality of the problem type across various system problem applications

These goals were presented at the summer project kickoff meeting

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

3 Methods and 6 Constructs for Summer Project

SEARI METHODS AND CONSTRUCTS

SEAri Methods

- The following **methods** were developed by SEAri:

  1. **MATE** (Multi-Attribute Tradespace Exploration) (sometimes just “TSE”)
     - Guides the exploration of many design choices (tradespace) in terms of benefits and costs to different stakeholders
  2. **EEA** (Epoch-Era Analysis)
     - Analyzes short run and long run impacts of changing contexts and needs on design(s)
  3. **RSC** (Responsive Systems Comparison)
     - Combines MATE and EEA into 7 process structured method

- The methods generate and manipulate the constructs

SEAri methods seek to improve the way engineers and decision makers generate, characterize, evaluate, and select “design” choices in a dynamic world

SEAri Constructs

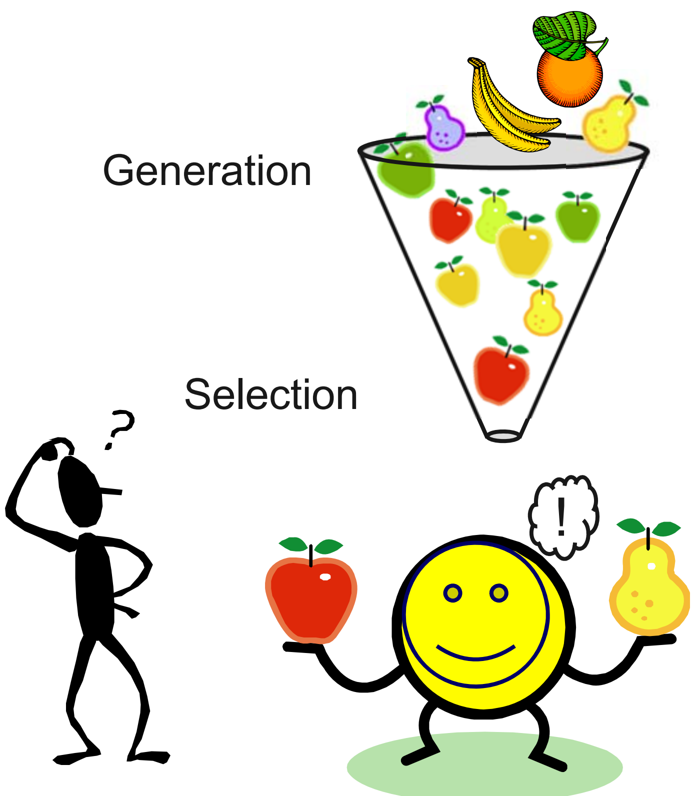
The following constructs form the core “elements” for the summer project:

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

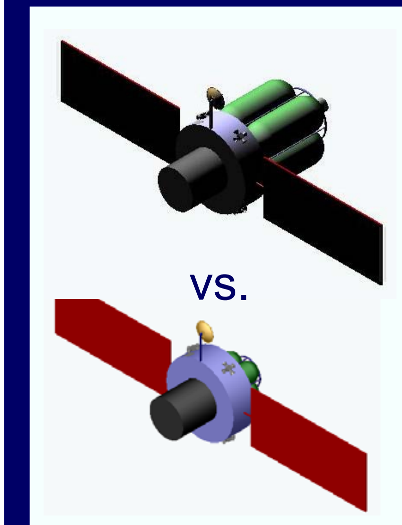
“Design” Choices

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



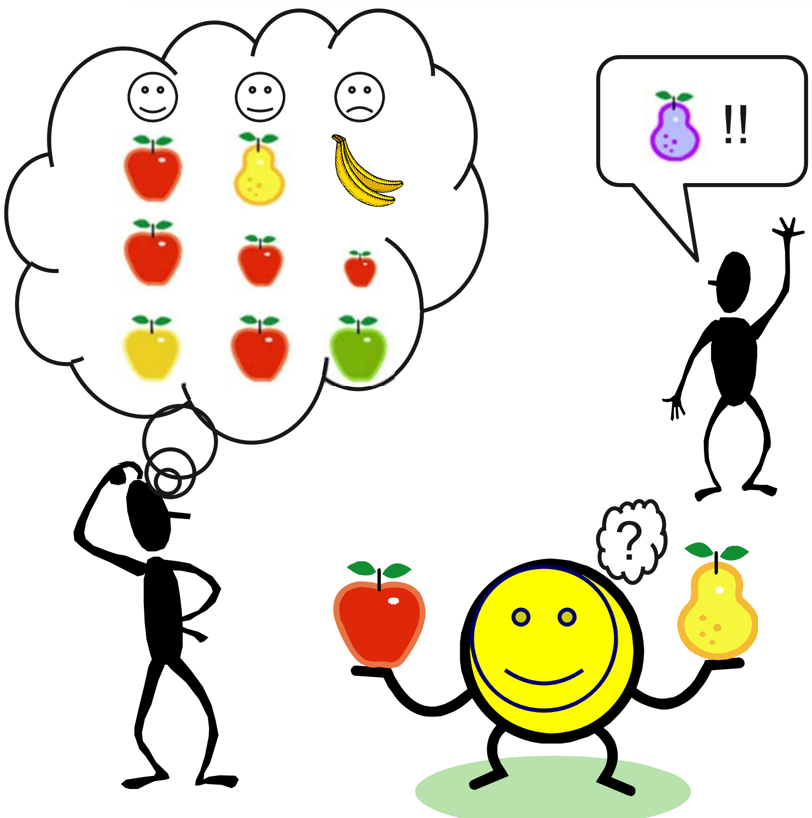
Design Space

- Manipulator Mass
  - Low (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

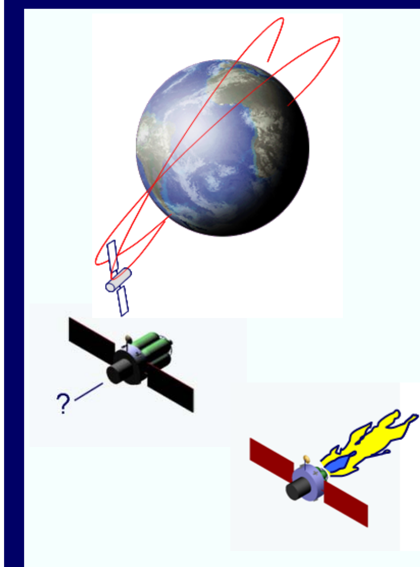
Related Concepts: designs, design vectors/variables, concepts, configurations, alternatives, choices, selections

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]

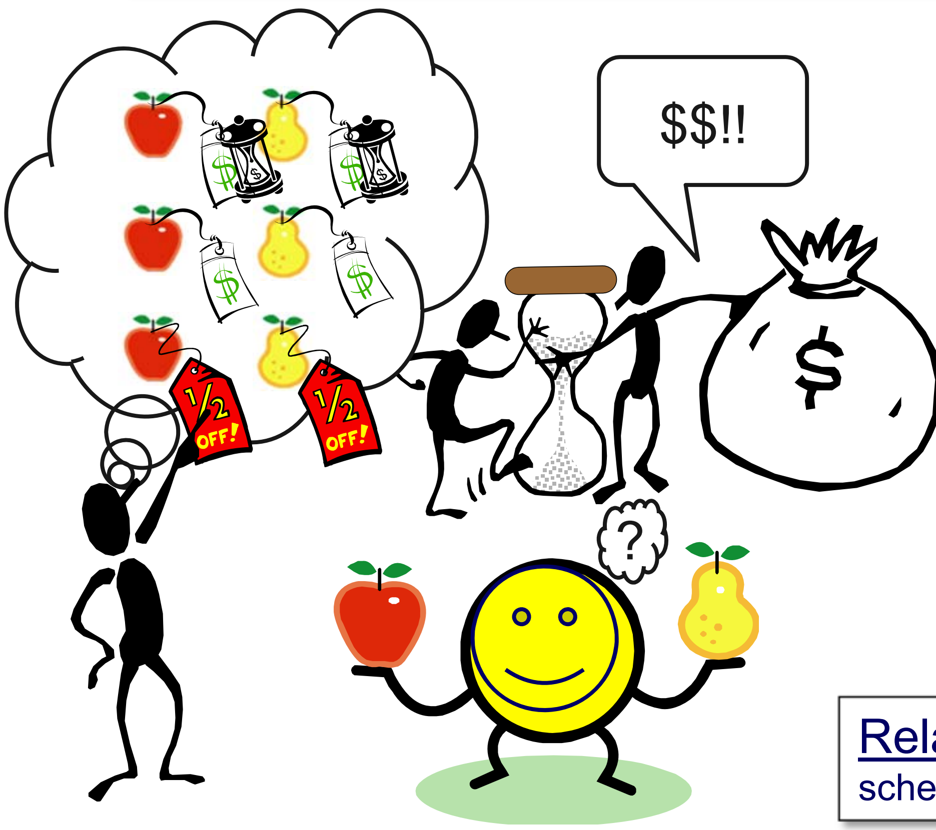
>Speed
- Can change orbits quickly (binary) [0→1]

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

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

$$

$$C = c_w \; M_w + c_d \, M_d$$

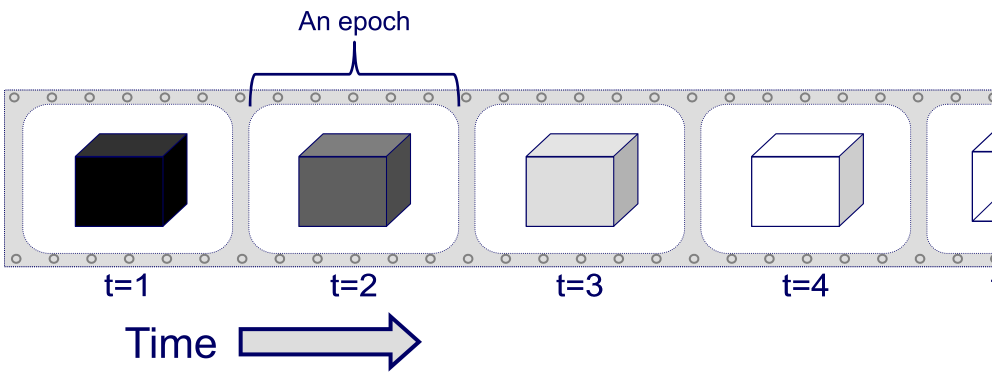
Cost Space

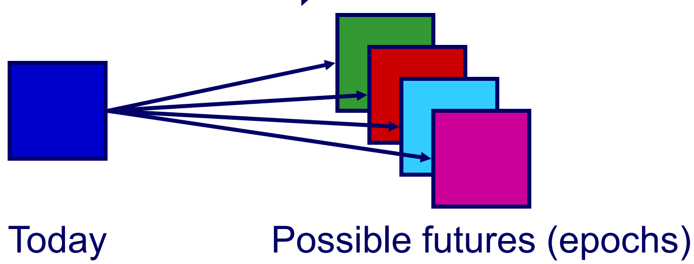
- >Dollar cost
  - – Dry mass
  - – Fuel cost
- >Simple parametric model

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

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

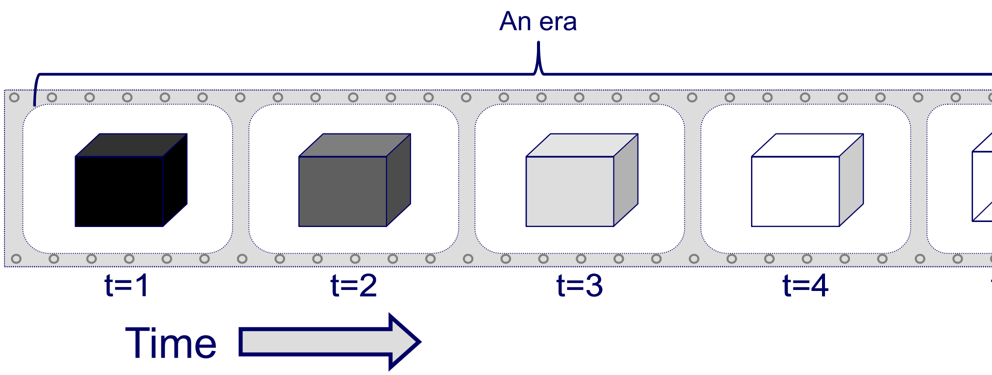
Categories of key uncertainties → epochs

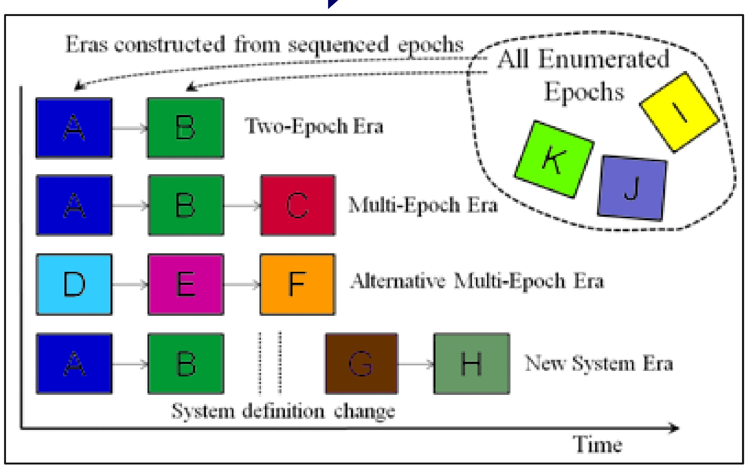
Available resources, Policy, Infrastructure, Technology, End Uses (“Markets”), Competition, etc.

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

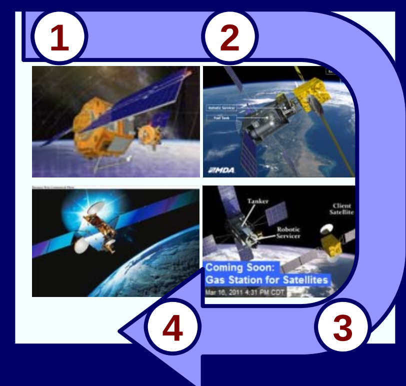
Eras

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





Space Tug



Eras

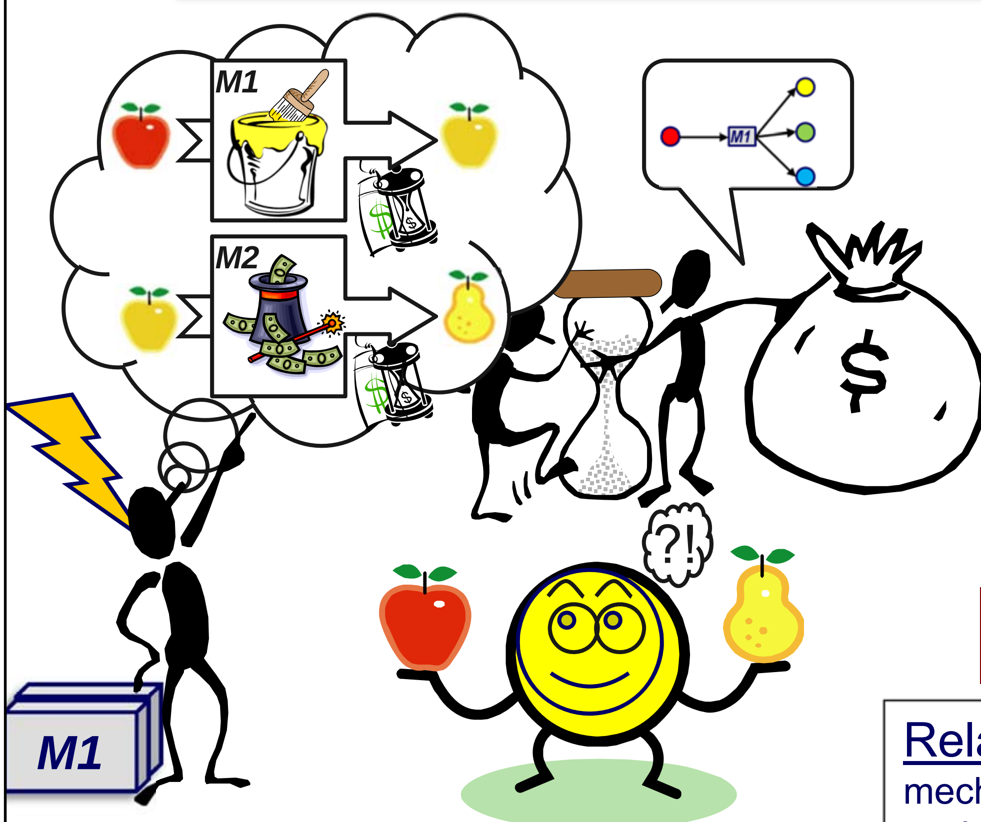
>Sequence of epochs
1. Demonstration
2. Comsat Servicer
3. Orbital Infrastructure
4. Orbital Rescue

IED attacks in Iraq:
(*Wired*)

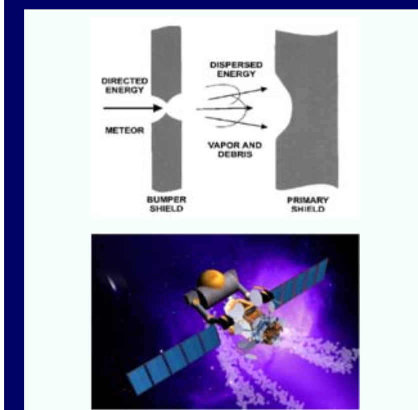
Related Concepts: eras, epoch ordering, long run, contexts, expectations, futures, uncertainties

“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



Space Tug



Ilities Space

>Survivability
- Shielding
- Avoidance
- Replacement

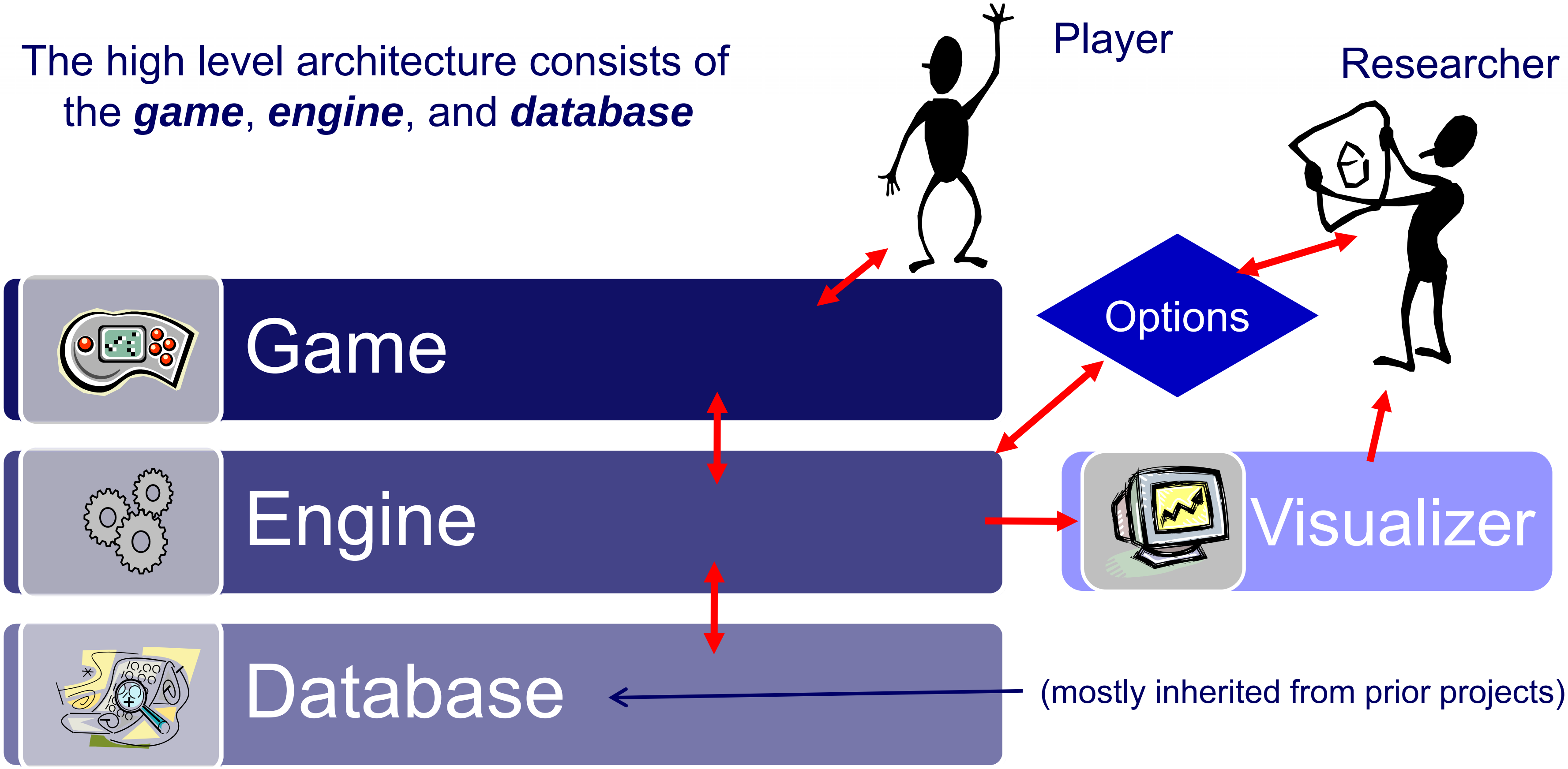
>Evolvability
- Refuelability
- Modular propulsion

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, flexibility, adaptability, scalability, modifiability, robustness, survivability

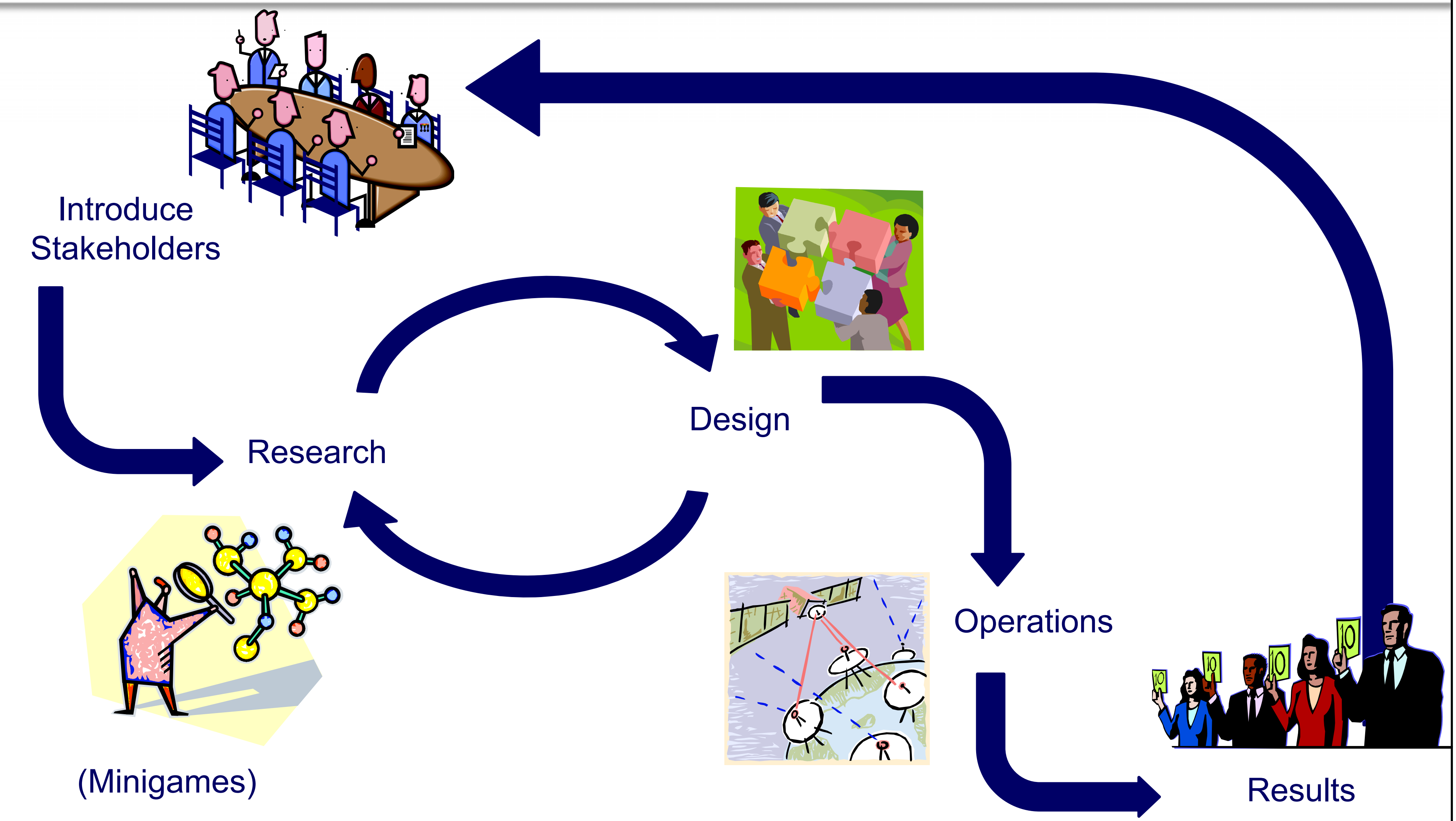
Layered Architecture

The high level architecture consists of the ***game***, ***engine***, and ***database***

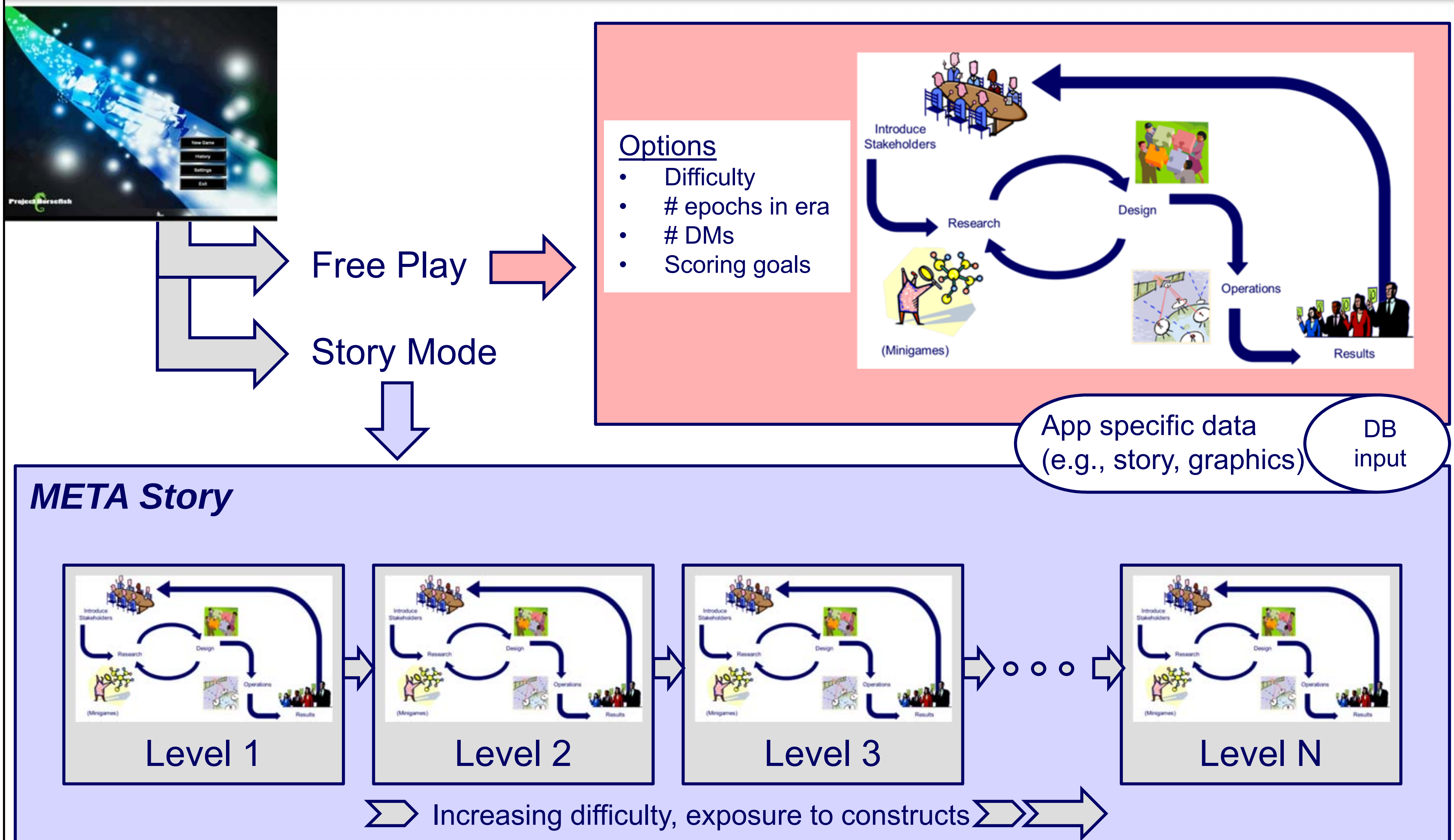


This summer's goal was to develop the engine and the game

Game Conceptual Flow

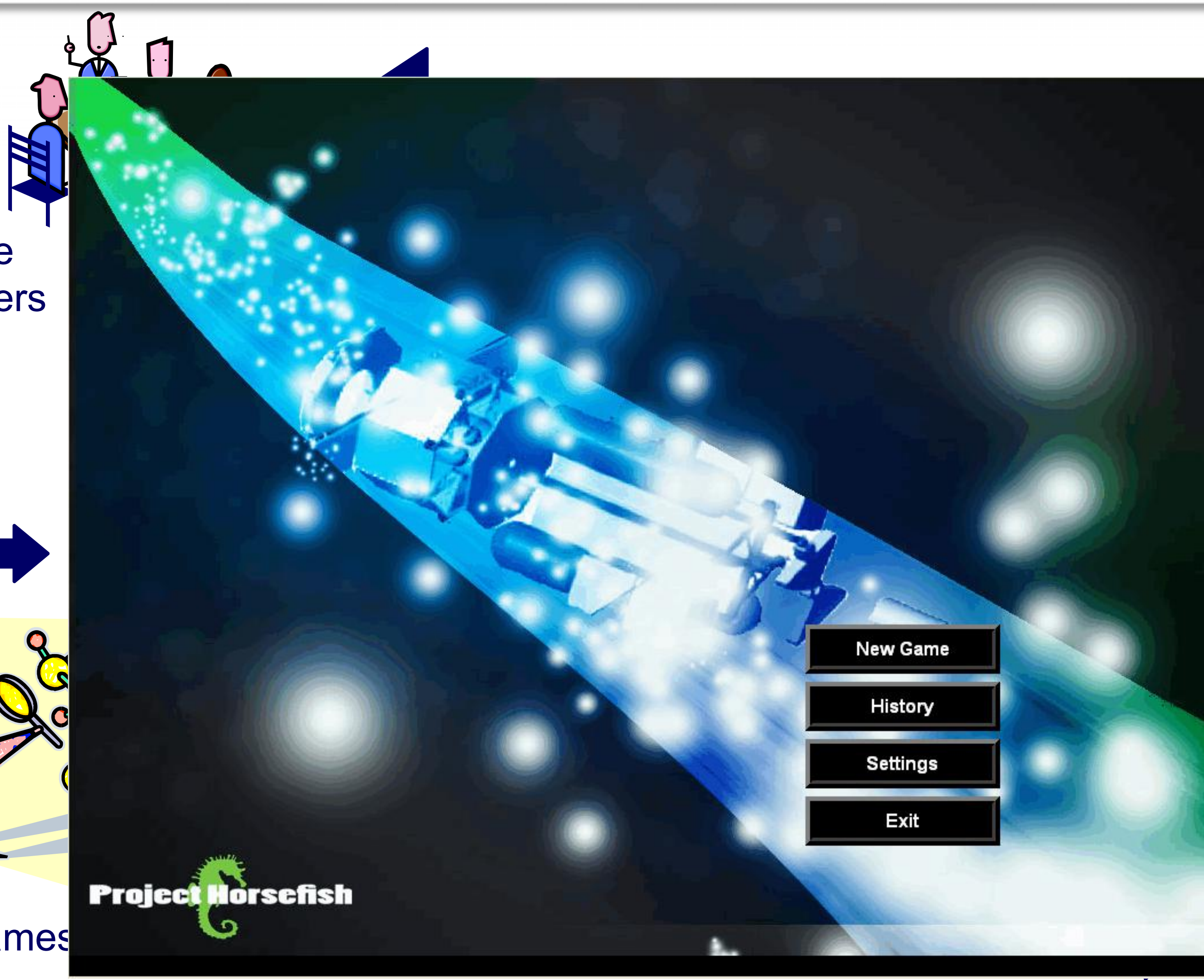


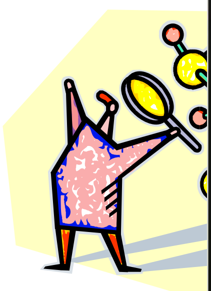
Game Architecture Outline



Brief Game Outline

Introduce Stakeholders

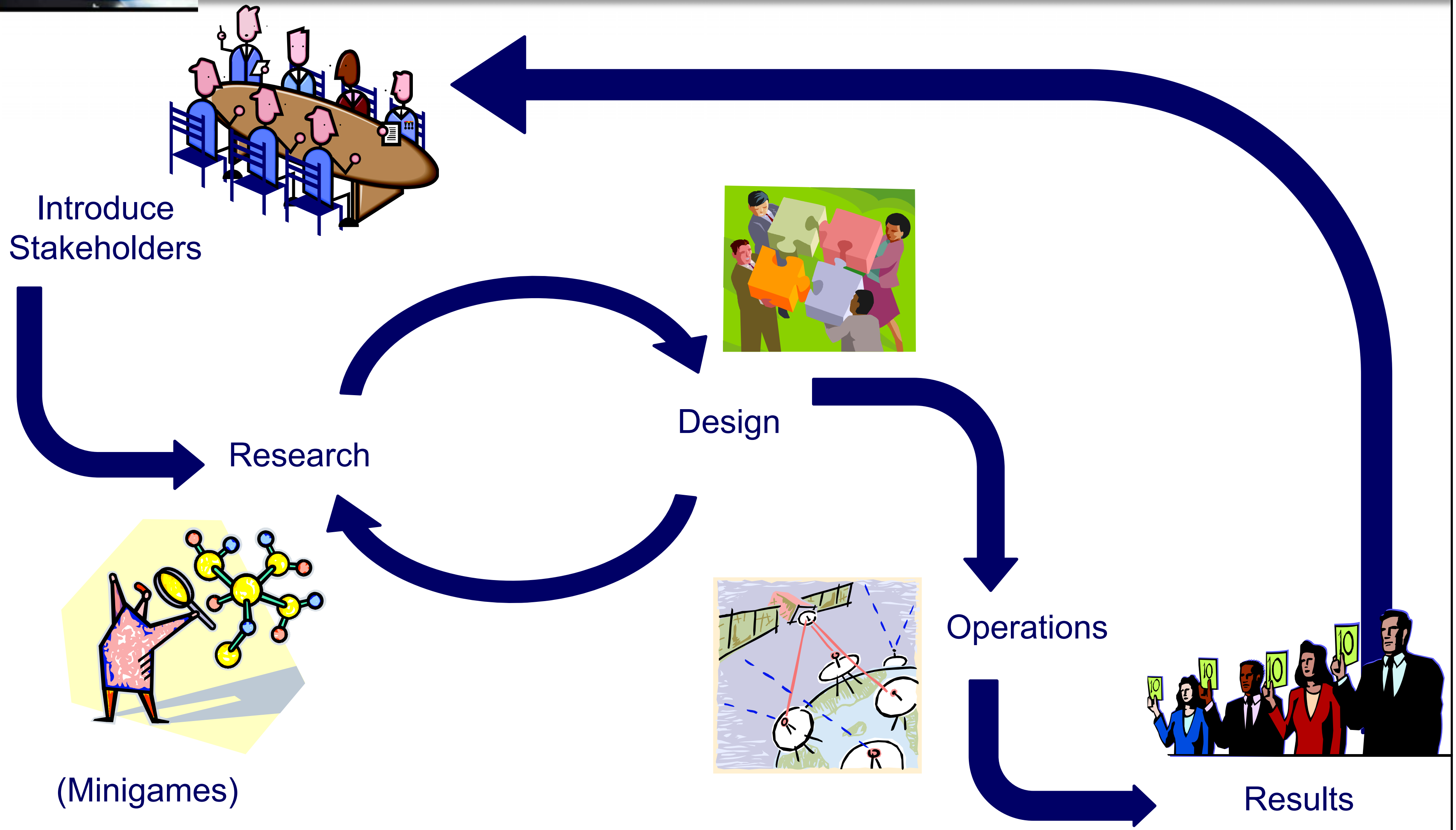




(Minigames

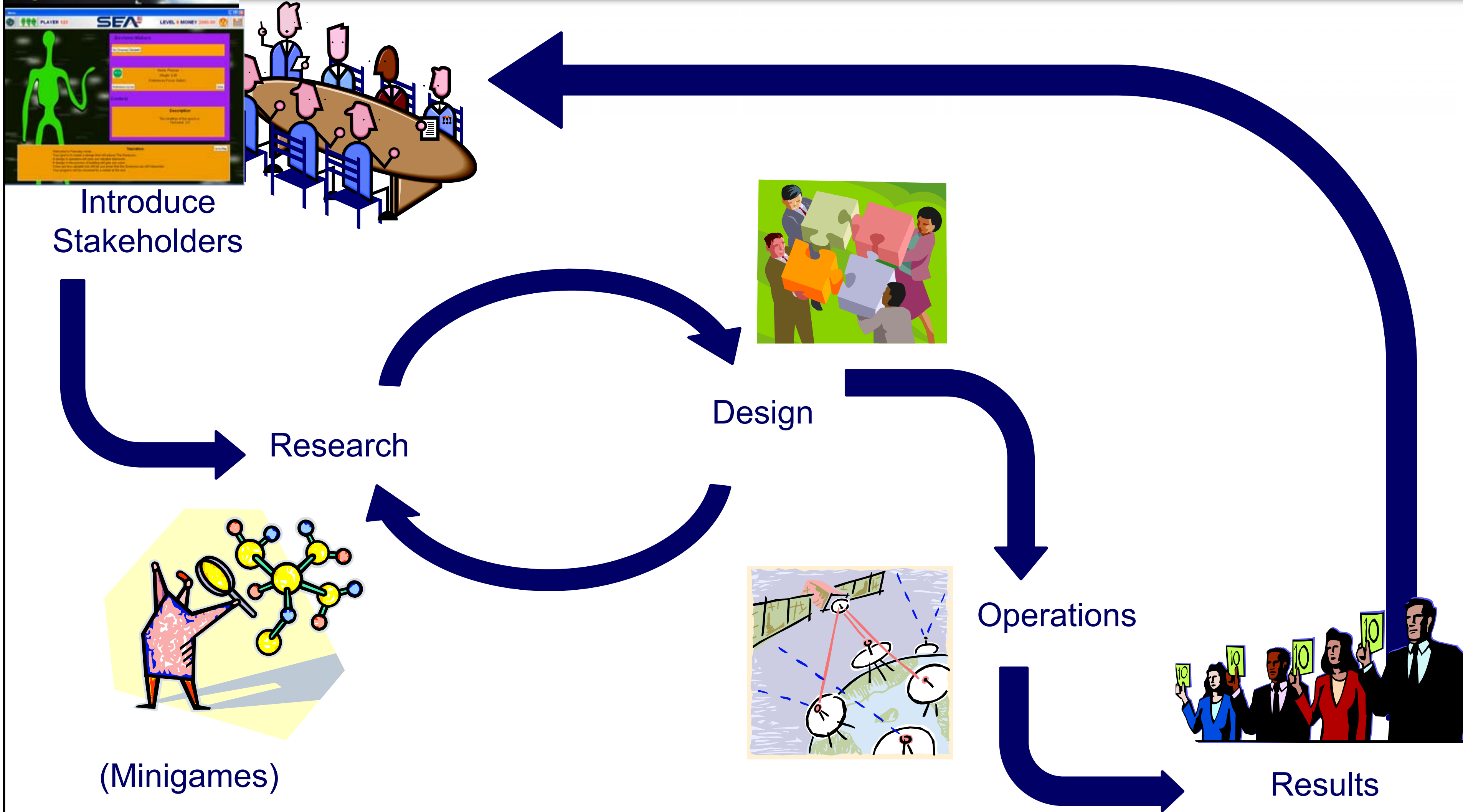
Results

Brief Game Outline



Brief Game Outline

Brief Game Outline



Brief Game Outline

Introduce Stakeholders

(Minigames)

Results

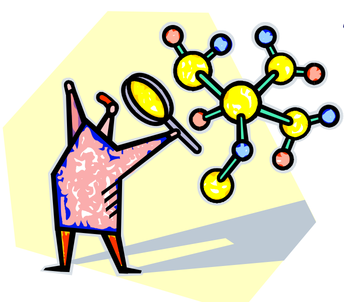
Brief Game Outline

Introduce Stakeholders

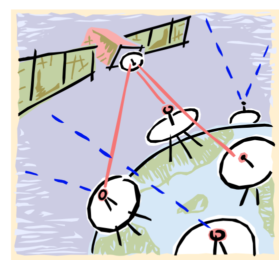
Research

Design

Operations

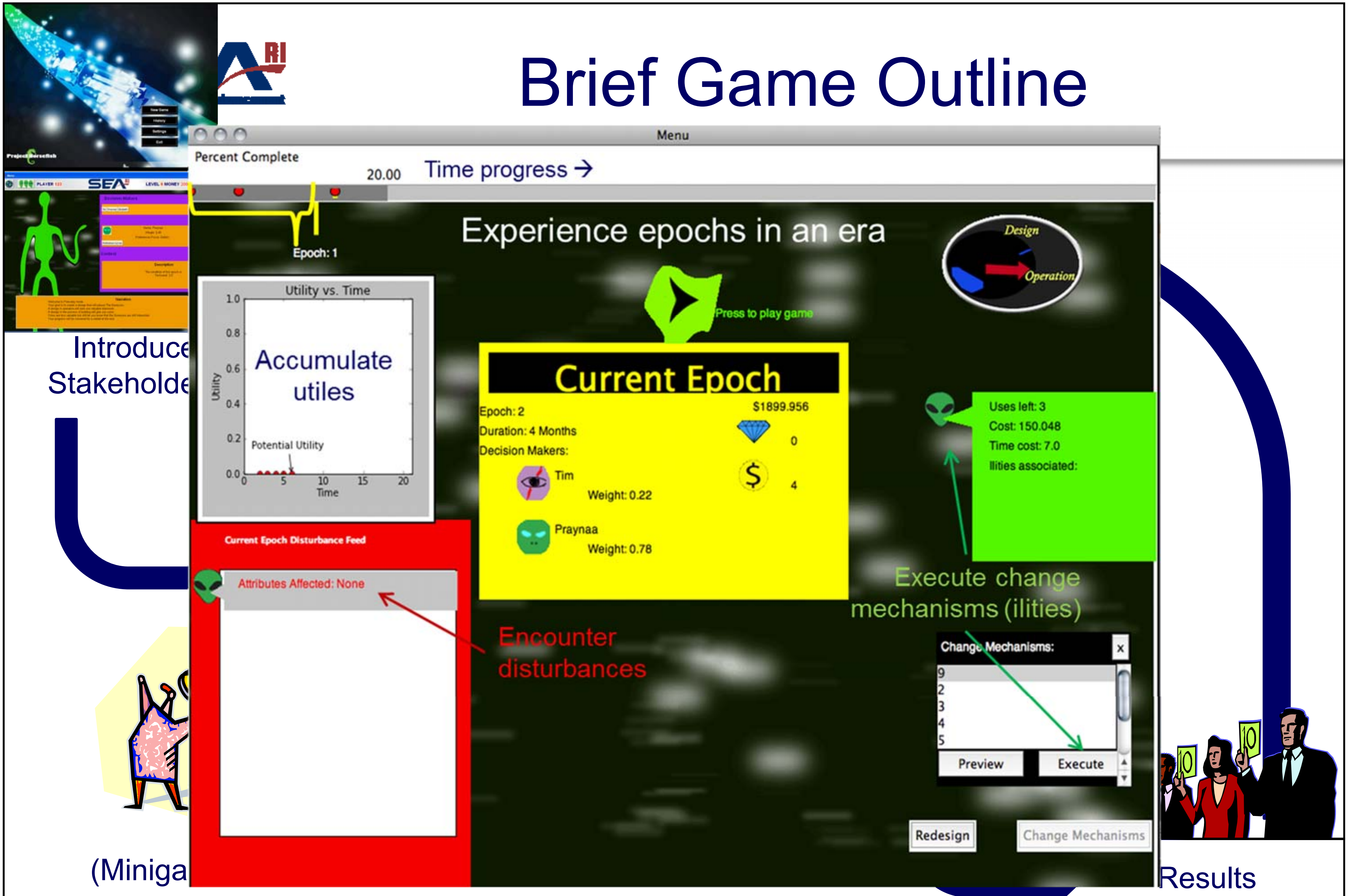


(Minigames)

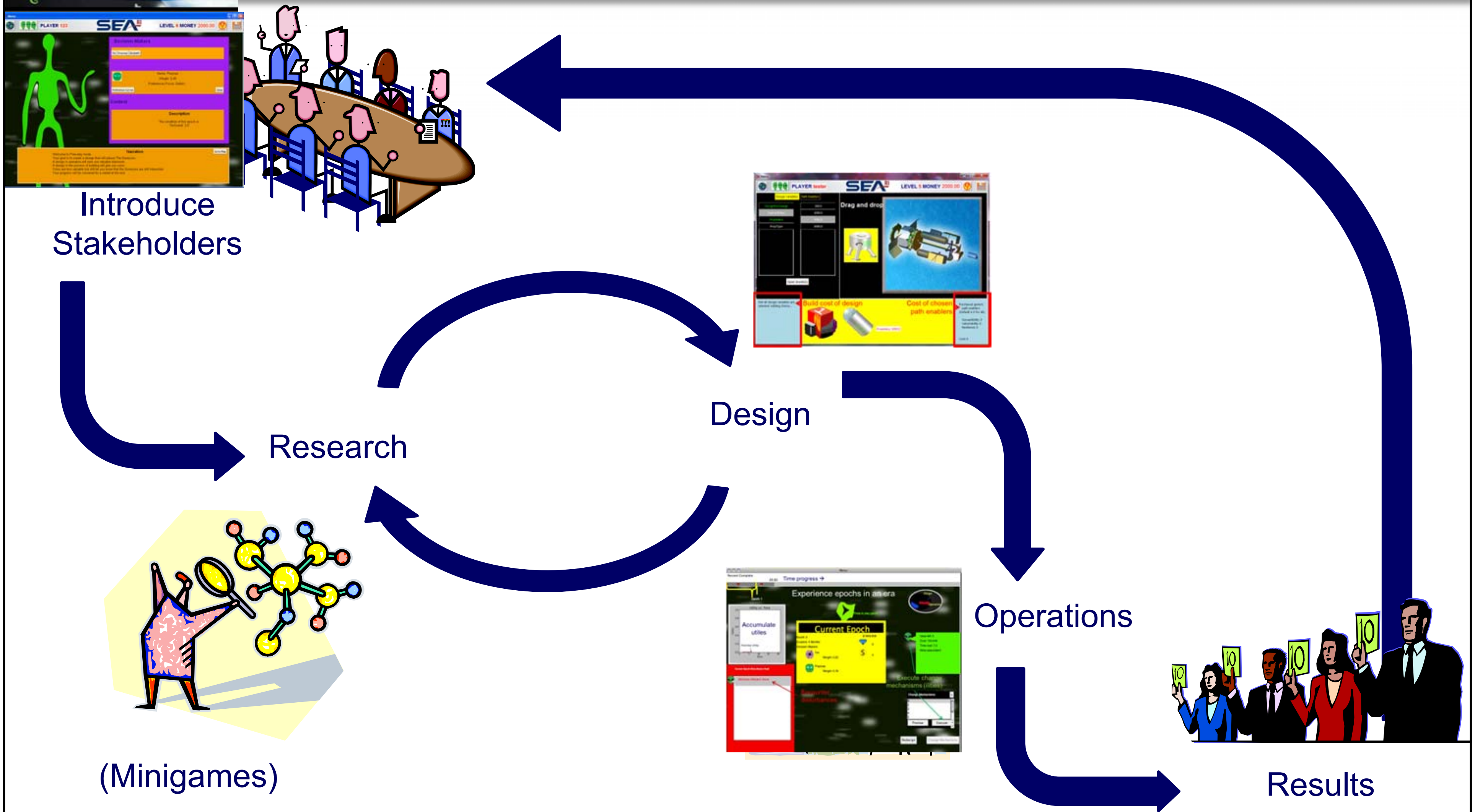


Results

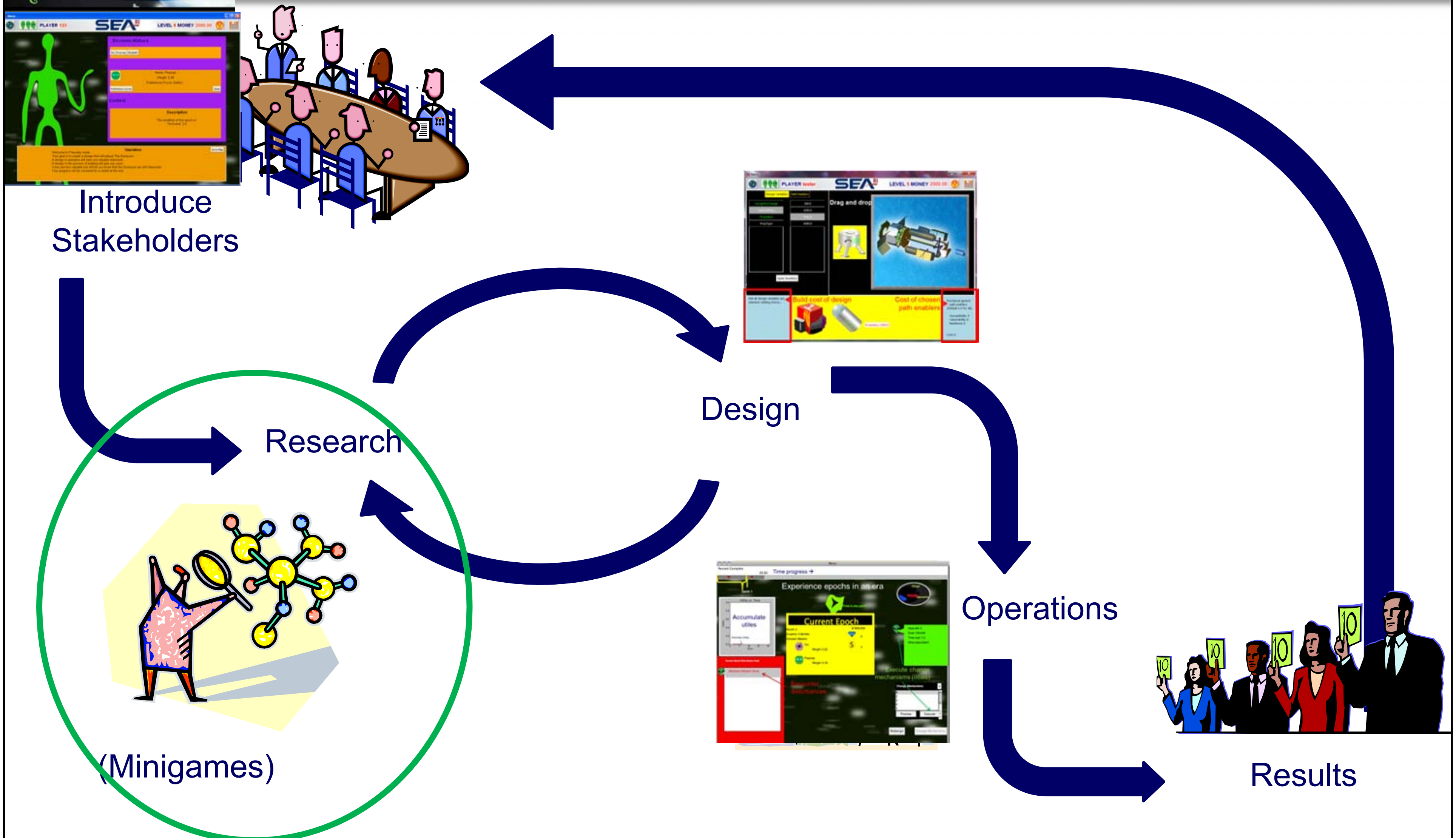
Brief Game Outline



Brief Game Outline



Brief Game Outline

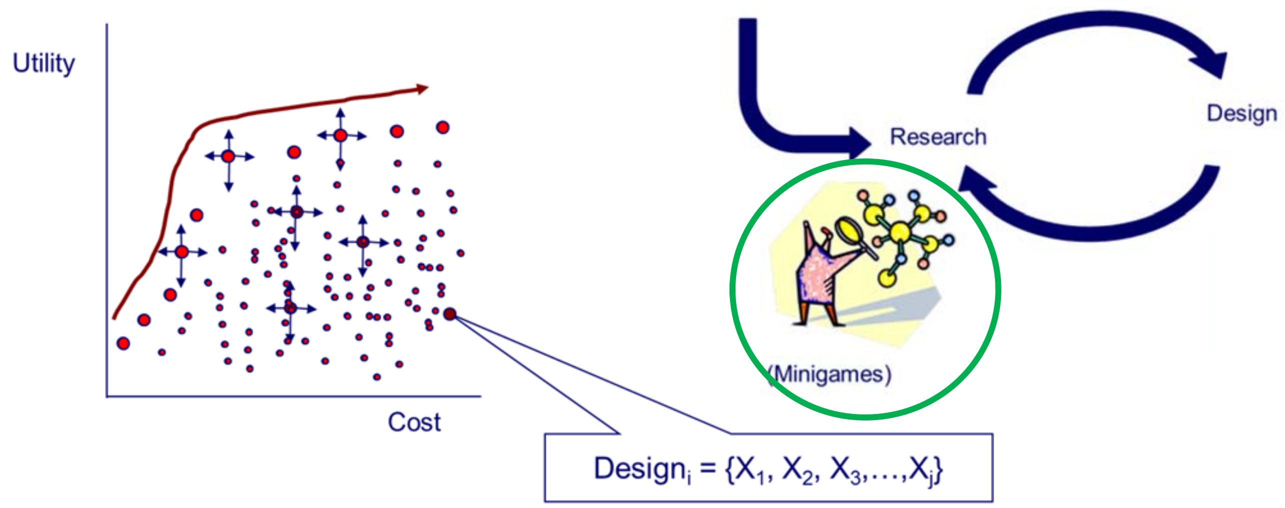


Research Minigame 1
Hit the Pareto

Goal: Propose a design as close as possible to Pareto Frontier, within constraints

Gameplay: Make a design given an epoch

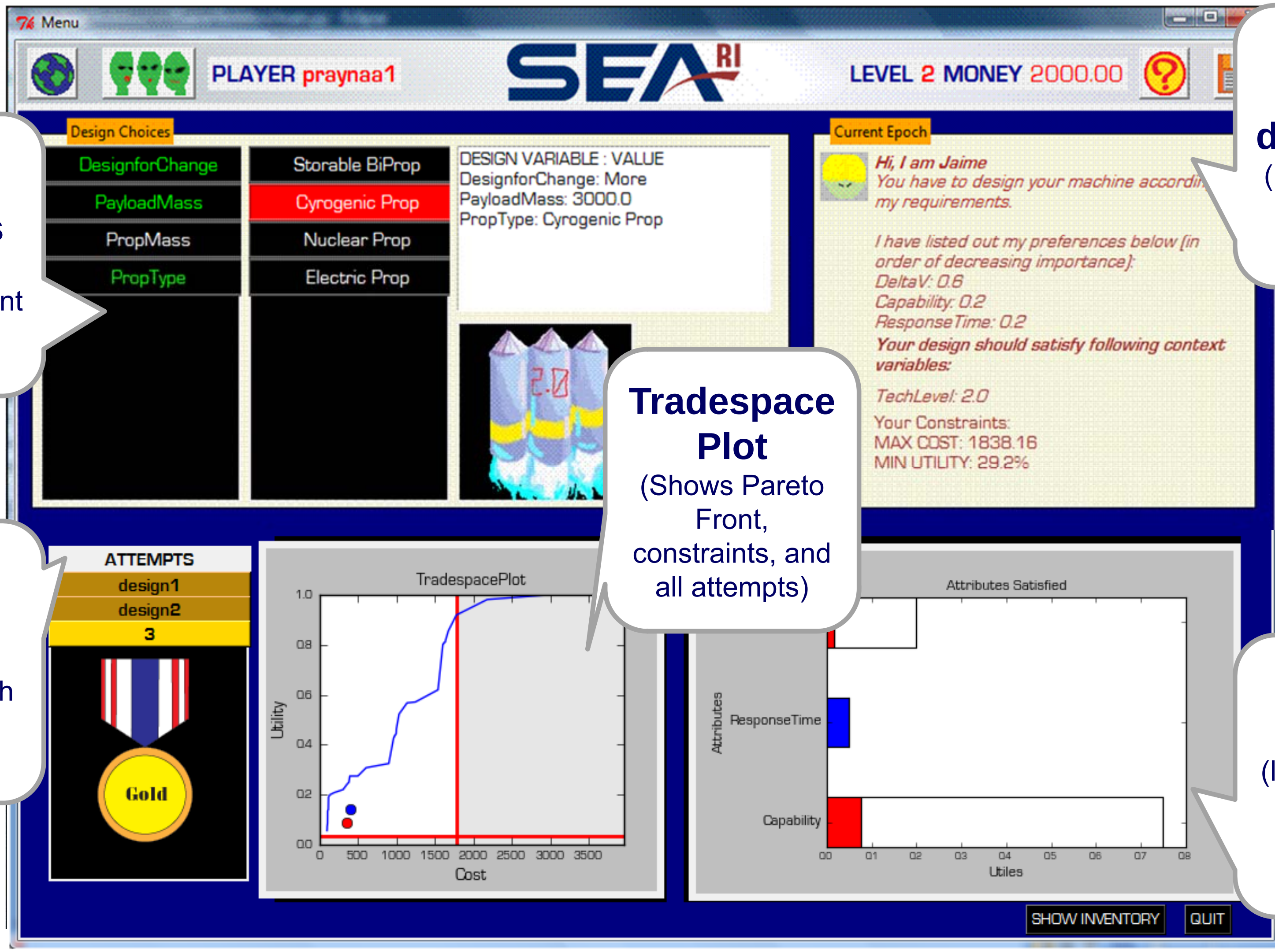
Constraints: Maximum cost and minimum utility, depends on difficulty level



Hit the Pareto Interface

Design Variables
(Choose the design you want to "test")

Epoch description
(prefs, context, constraints)



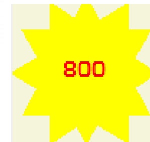
Tradespace Plot
(Shows Pareto Front, constraints, and all attempts)

Attempt Medals
(Three attempts, each scored with medals)

Attribute Levels
(length=relative importance, colored by fill %)

Hit the Pareto Scoring

- Points
  - Based on Fuzzy Pareto Number
  - Normalized to 1000



- Failures
  - *Infeasible*: Not following constraints
  - *Invalid*: Negative Utility

- Medals
  - Depends on points and difficulty level
  - E.g. for medium level:

Medal	Fuzzy Point Range	Point Range
Gold	0-3	800-1000
Silver	4-6	550-800
Bronze	6-10	200-550
Wood	>10	0-200

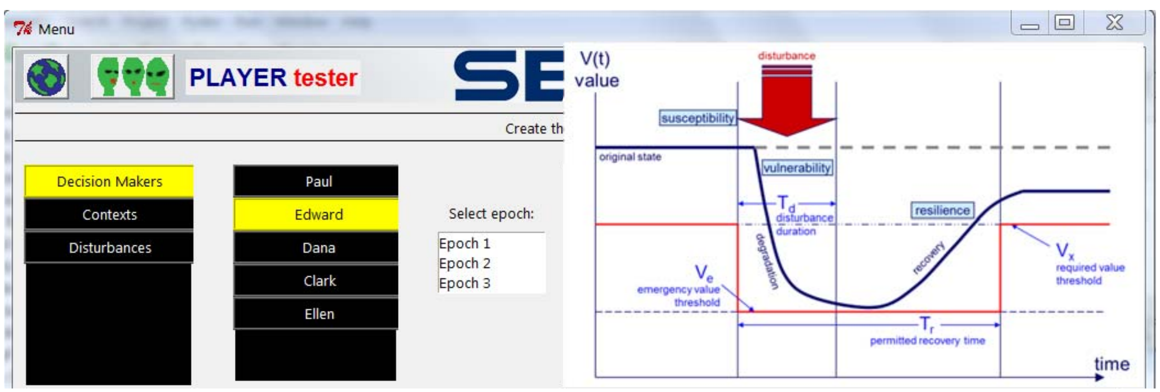
Research Minigame 2
Destroy Your Design

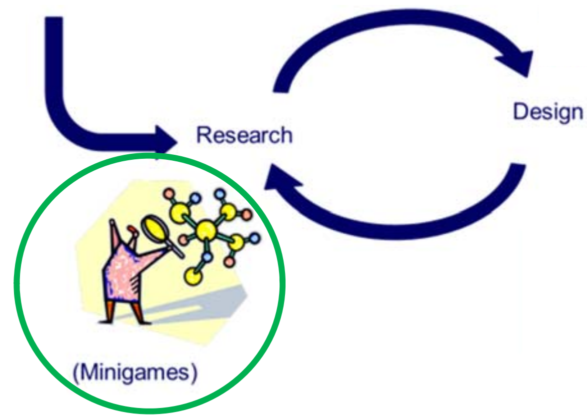
Goal: Discover a three-epoch era where your level design will achieve poorly

Gameplay: Construct a difficult to survive era

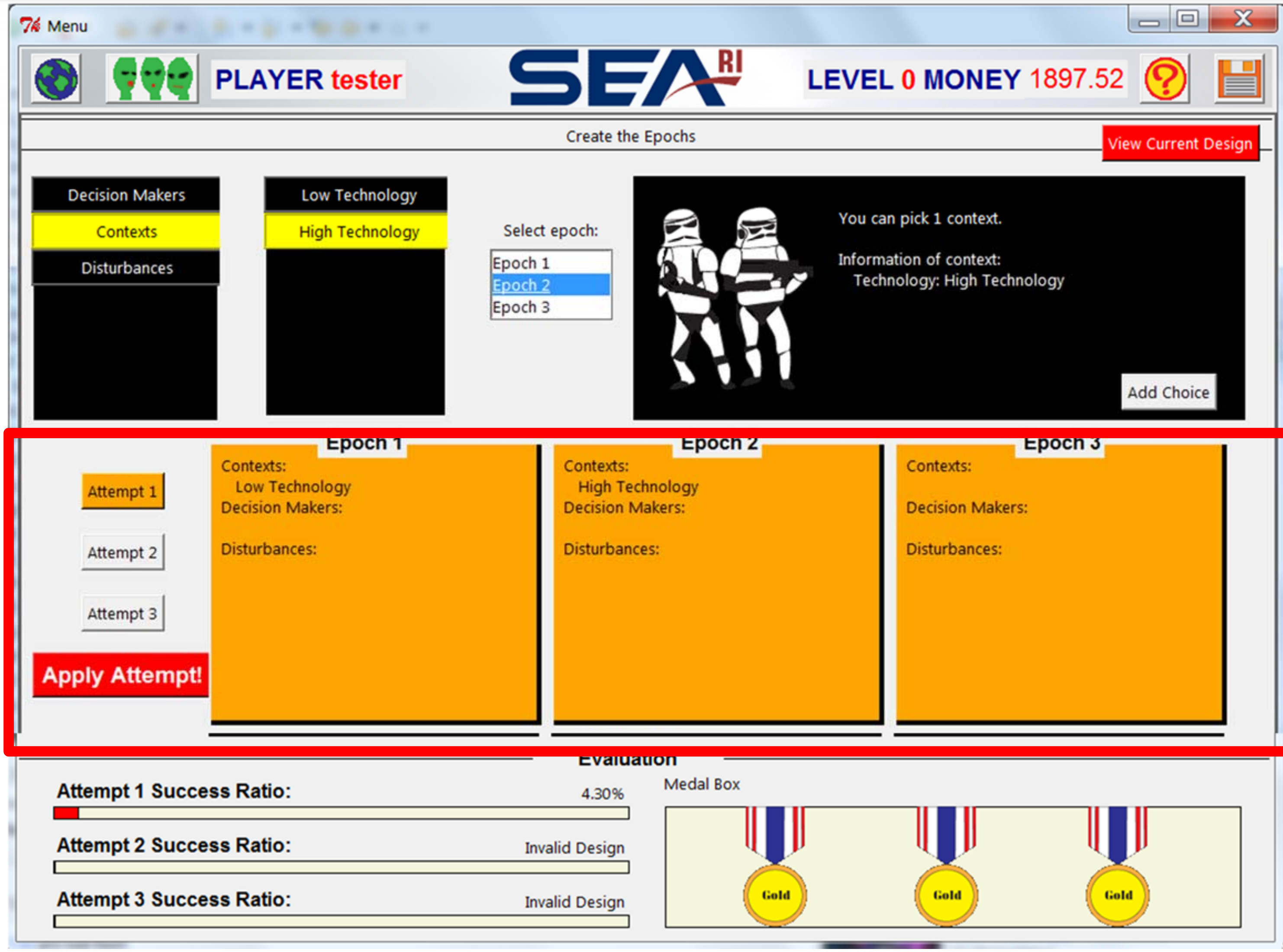
Constraints:

- Up to 3 decision makers who have a preference set in each epoch
- One context for each epoch
- Up to 2 disturbances for each epoch (order matters!)





Destroy Your Design Interface



Constructed Era Description

2011 SEAri Research Summit

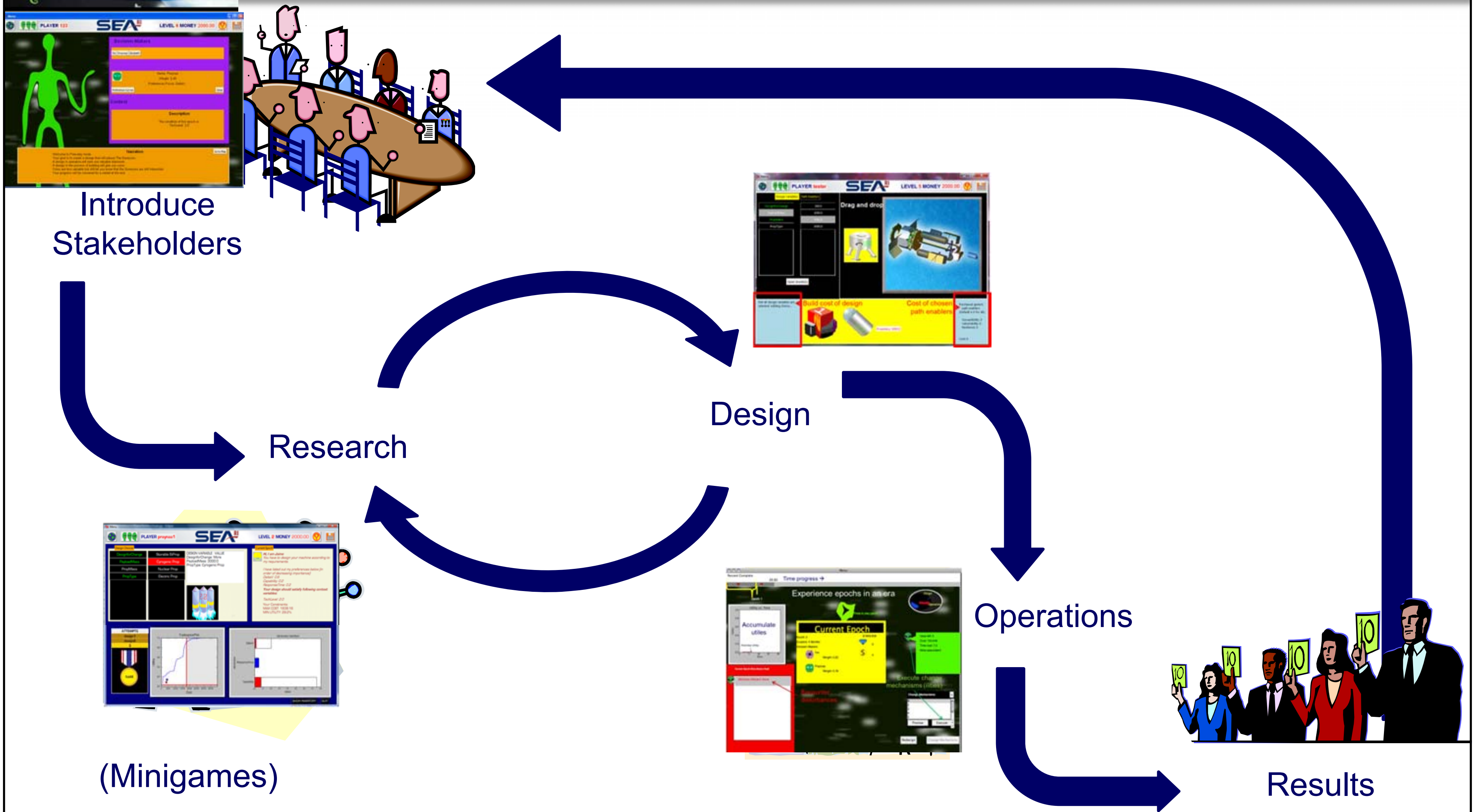
Destroy Your Design
Scoring

The goal is to achieve the ***lowest fraction remaining utility*** possible, which is determined by the ratio of the utility of current design over maximum achievable utility of the era

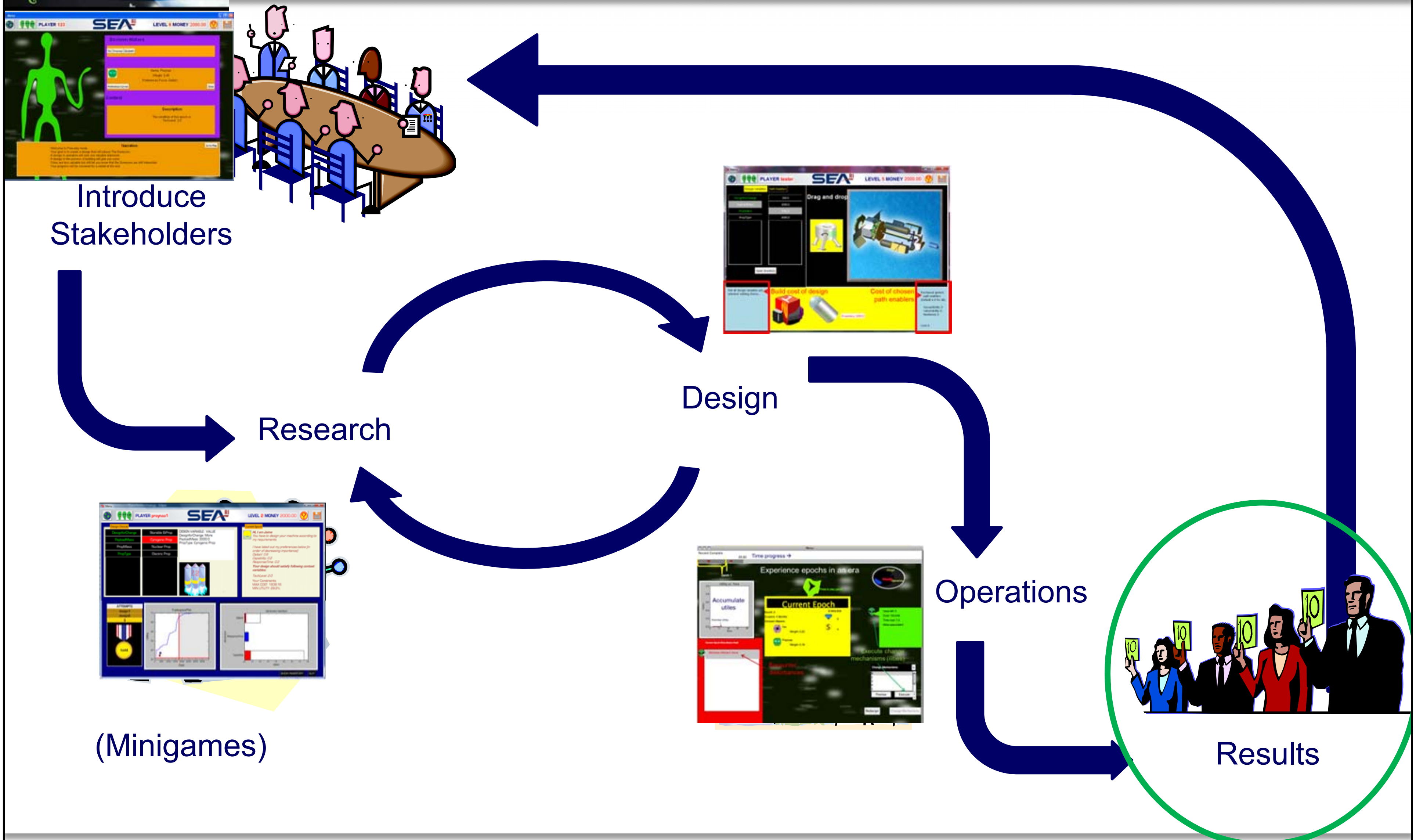
Medal	
Gold	0% ≤ remaining utility < 10%
Silver	10% ≤ remaining utility < 25%
Bronze	25% ≤ remaining utility < 50%

Success ratio = fraction of remaining utility

Brief Game Outline

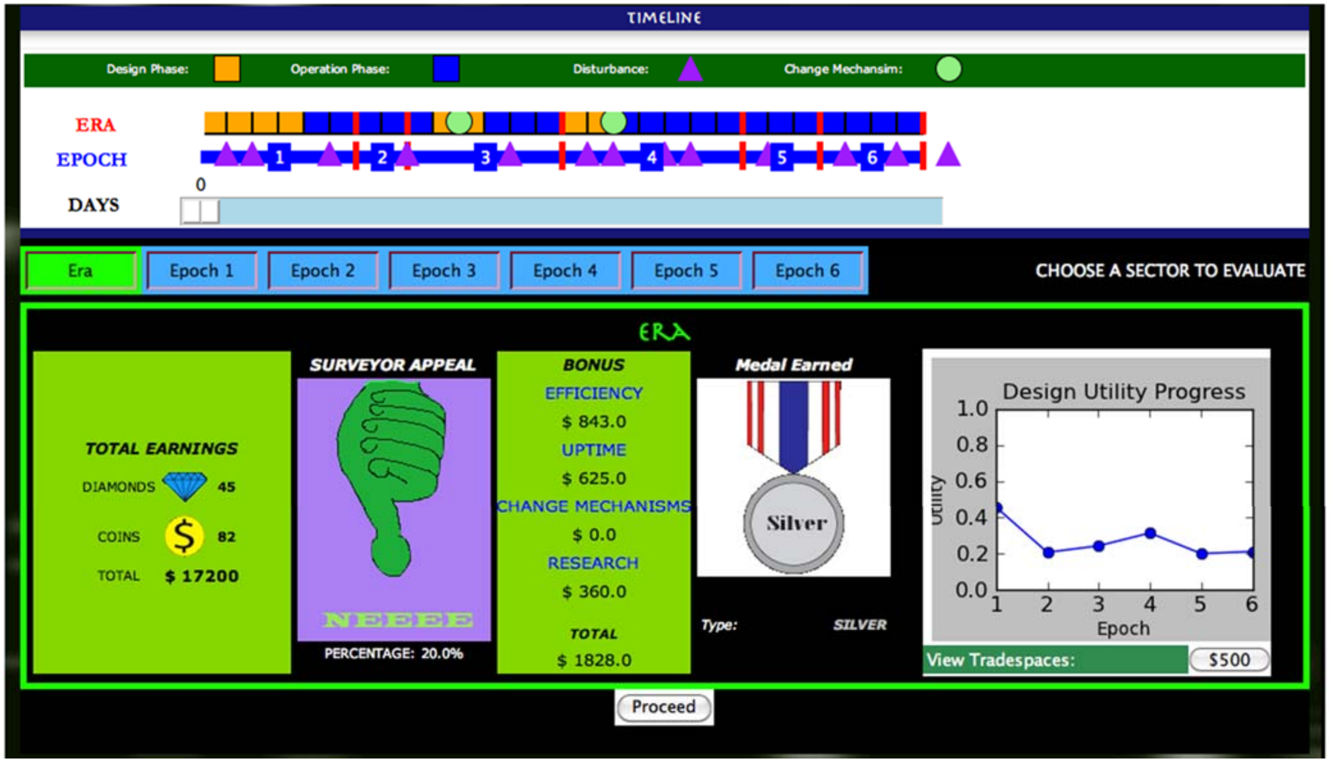


Brief Game Outline



Evaluation Screen
Era View

- Directly follows Operations (Mission)
- Layout
  - Timeline — *Visually organizes Mission by Era, Epoch, Days (Scrollable)*
  - Tabs — *Easily cipher through to see Era/Epoch specific data*

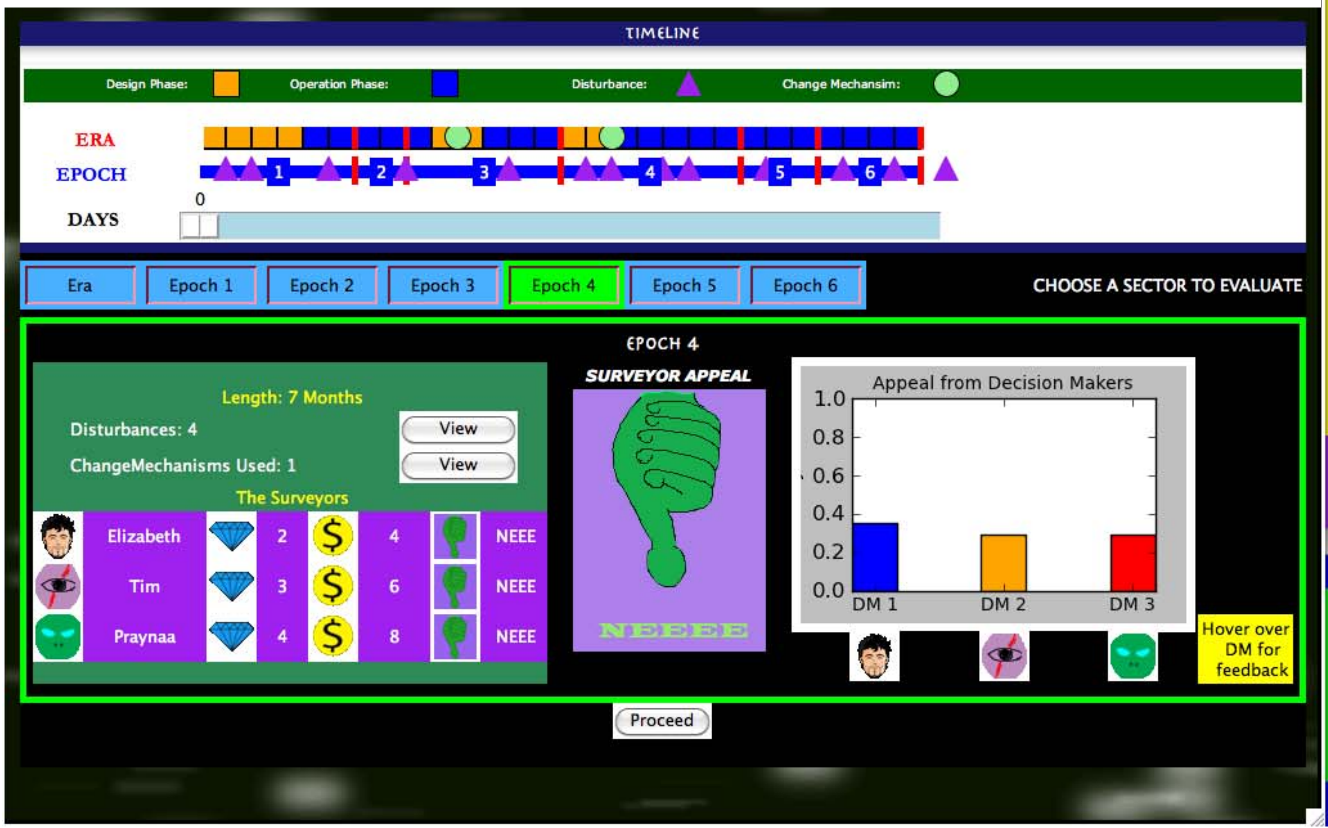


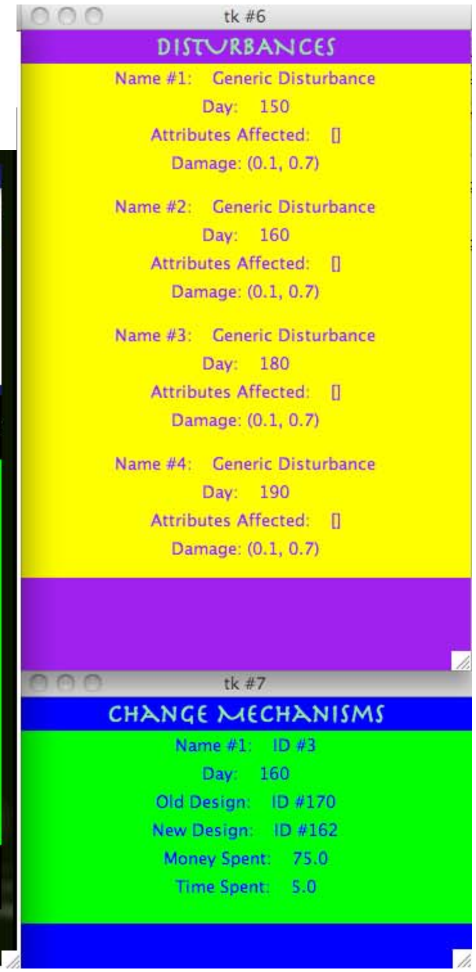
Era Tab

- Scoring
  - Total Earnings
  - Surveyor Appeal
  - Bonus
  - Medal Earned
- Graph
  - Visual diagram
  - View More option

Evaluation Screen
Epoch View

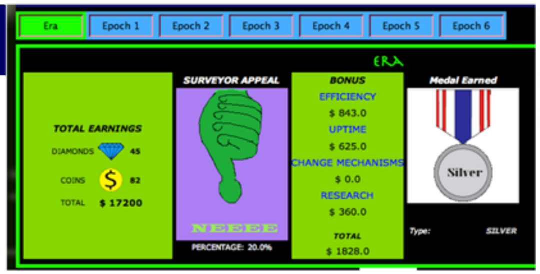
- Epoch Tab
  - Point / Utility Distribution among each decision maker
  - Options to view disturbances / executions
  - Audio of decision maker based on performance





Evaluation Screen
Overall Scoring

Four categories shown in Era tab:



Scoring

- Total Earnings
  - Diamonds:  Effective Utility in Operations
  - Coins:  Basic Utility in Design
- Surveyor Appeal
  - Percentage that player pleased all decision makers
  - Averages all DMs with "Thumbs Down" weighted more

- Bonus
  - Cost Efficiency — *Compares cost of design to that on the Pareto Line*
  - Uptime — *Percentage in era when design is valid in operations*
  - Change Mechanisms — *Compares design effective utility before and after execution*
  - Research — *Averages points and high scores achieved in minigames*
- Medal
  - Averages above three percentages with maximum possible value
  - Type: *-Gold*  *-Silver*  *-Bronze* 

Discussion

- Inheritance of VisLab software was key
- Development is just demonstration, low level of maturity
  - One spiral, little play testing
  - Still a promising product, showing potential for vision
- This game currently demonstrates only one “skin” (i.e., “SpaceTug”) that can be applied to the engine
- Designed with extensibility in mind, especially in the mini games
- Further work would vastly improve gameplay experience
- Learning occurs for both developers and players

The game and engine were developed such that students can pick up this project in future efforts

Contributions

- Experience teaching SEAri concepts to a non-SE, younger audience
- A serious game that looks at complex systems engineering from many perspectives
  - Tradespace Exploration – Hit the Pareto
  - Identifying Weaknesses – Destroy Your Design
  - Era Analysis – Operations Mode
- Pioneering the use of serious games in systems engineering
- Experience using game constructs to illustrate SEAri constructs
- Extensible architecture (engine) for future game development

The SEAri Summer Project was a successful multi-disciplinary exercise in using new methods to communicate SEAri research

Hopefully to be continued…