Reliability Reloaded Integrated System Assessment

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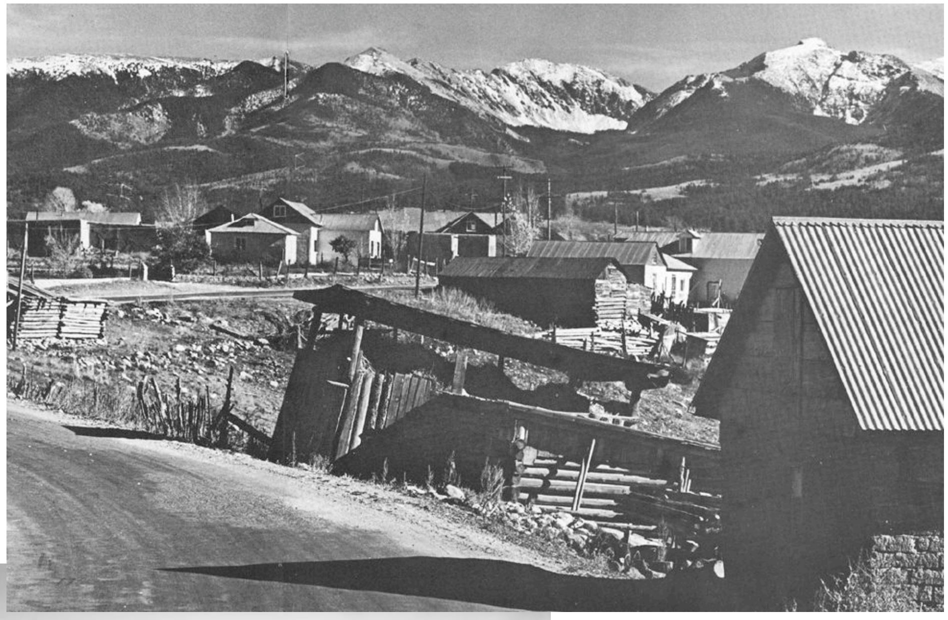
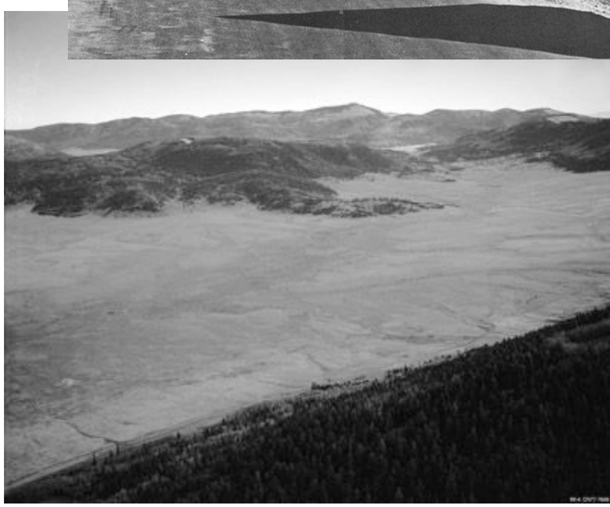
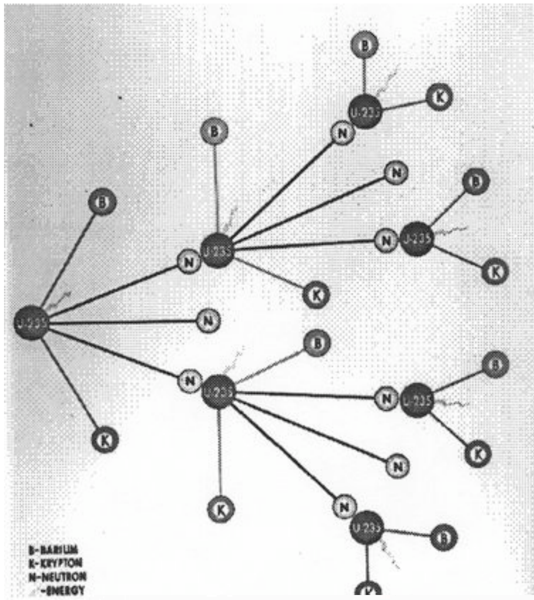


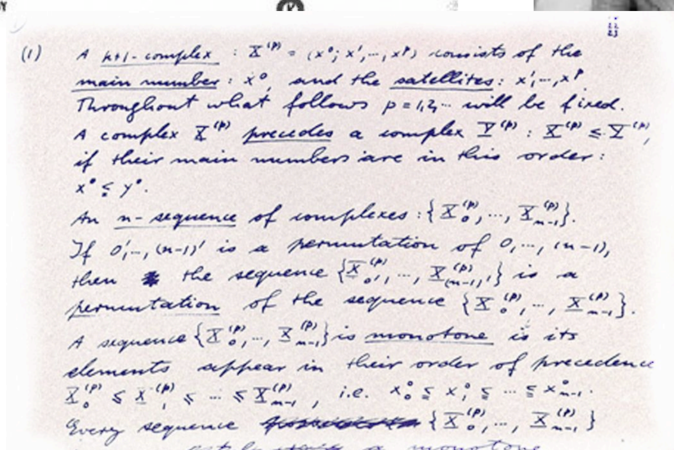


Northern New Mexico

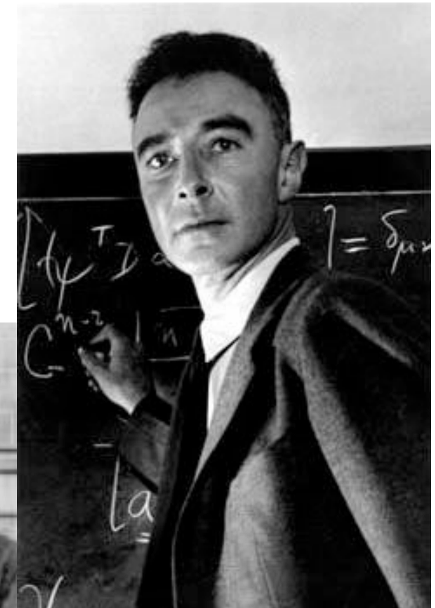
WWII Years—
the beginning

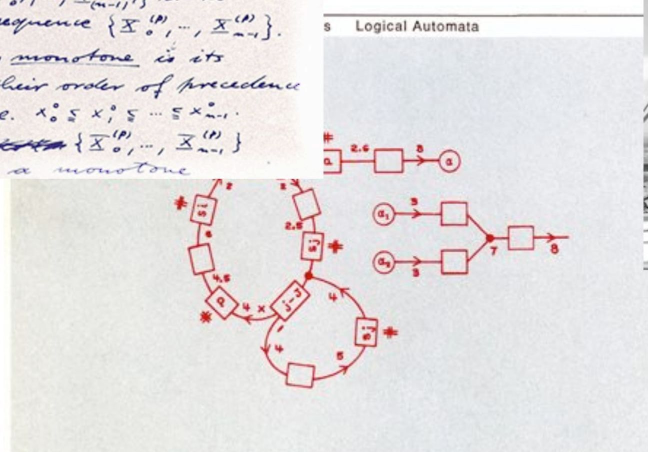
place: po box 1663

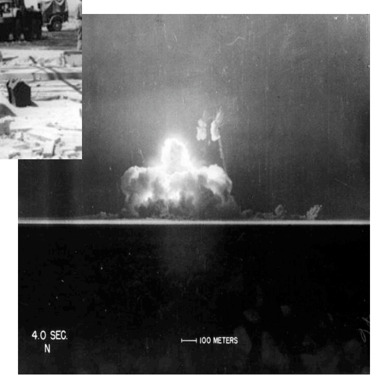




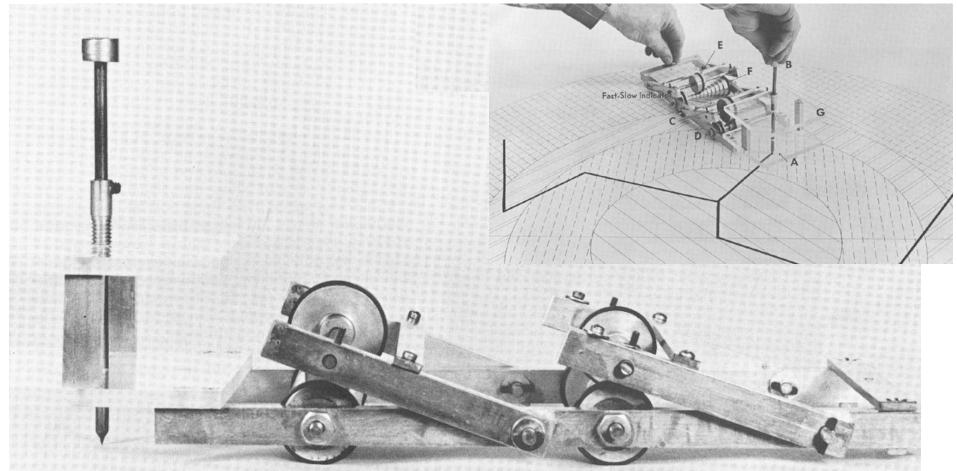
(1) A p+1-complex: $X^{(p)} = (x^0; x^1, \ldots, x^p)$ consists of the main number: x^0 and the satellites: $x^1, \ldots, x^p$.
Throughout what follows $p = 1, 2, \ldots$ will be fixed.
A complex $X^{(p)}$ precedes a complex $Y^{(p)}$: $X^{(p)} \leq Y^{(p)}$, if their main numbers are in this order: $x^0 \leq y^0$.
An n-sequence of complexes: $\{X_0^{(p)}, \ldots, X_{n-1}^{(p)}\}$.
If $0', \ldots, (n-1)'$ is a permutation of $0, \ldots, (n-1)$, then the sequence $\{X_{0'}^{(p)}, \ldots, X_{(n-1)'}^{(p)}\}$ is a permutation of the sequence $\{X_0^{(p)}, \ldots, X_{n-1}^{(p)}\}$.
A sequence $\{X_0^{(p)}, \ldots, X_{n-1}^{(p)}\}$ is monotone if its elements appear in their order of precedence $X_0^{(p)} \leq X_1^{(p)} \leq \cdots \leq X_{n-1}^{(p)}$, i.e. $x_0^0 \leq x_1^0 \leq \cdots \leq x_{n-1}^0$.
Every sequence $\{X_0^{(p)}, \ldots, X_{n-1}^{(p)}\}$ ... a monotone

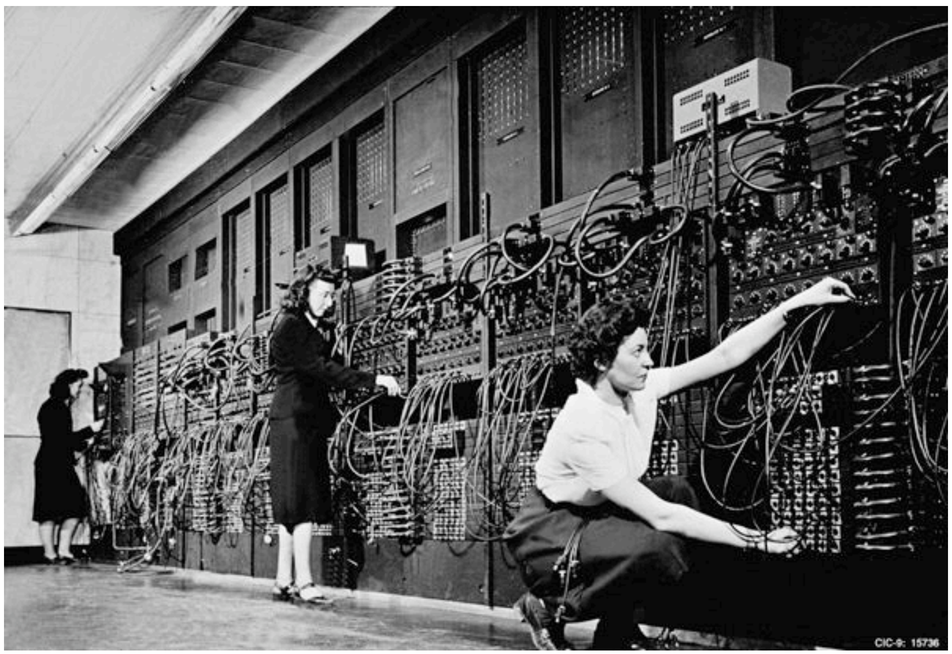


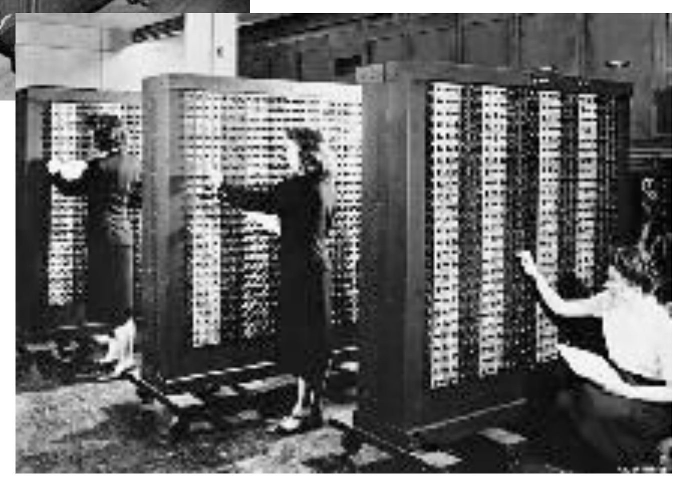




Science



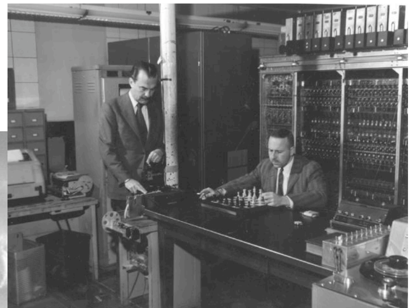


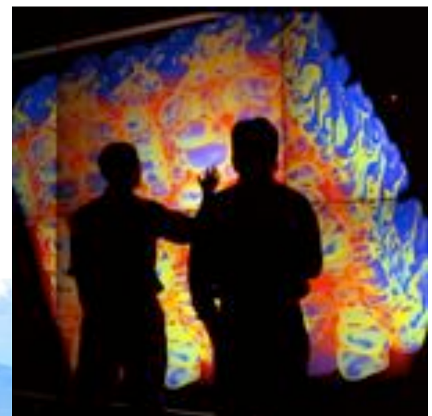


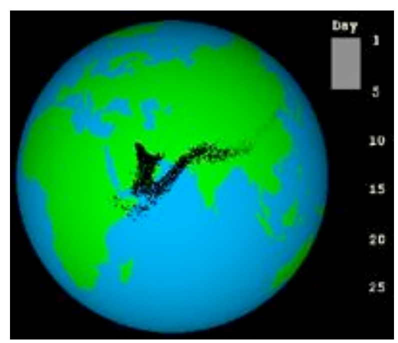
Technology

Community

Building An Institution—





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Outline

- Reliability and Role of Statistical Sciences
- Science/Application Drivers
- Examples
  - End-to-end assessment
  - System Ethnography and Design
  - Design of Experiments
- Conclusions

Cast of Collaborators

- Alyson Wilson
- Deborah Leishman
- Ron Smith
- Jane Booker
- Bill Meeker
- Nozer Singpurwalla
- Shane Reese
- Greg Wilson
- Mary Meyer
- Todd Graves
- Richard Klamman
- Laura McNamara
- Lisa Moore
- Kathy Campbell
- Christine Anderson-Cook
- Ben Sims
- David Scott
- Art Dempster
- Harry Martz
- Mike Hamada
- Andrew Koehler
- Val Johnson
- Dave Higdon
- Tom Bement
- Nick Hengartner
- Joanne Wendelberger
- Mike McKay
- Jerry Morzinski
- Max Morris
- Steve Vardeman
- Brian Williams
- Elizabeth Kelly

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What is Reliability?

- Reliability: Probability a system will perform as intended for at least a given time period when operated under specific conditions
  - Probability – measure of the likelihood of success
  - System – specify the boundaries of what will be considered the system
  - As Intended – need to specify success/failure of the system
  - Time period – assuming system will degrade over time
  - Under specific conditions – boundaries on model use
- Definition has been simplified to the study of

$$R(t) = P(T > t) = \int_t^{\infty} f(x)\,dx = 1 - F(t)$$

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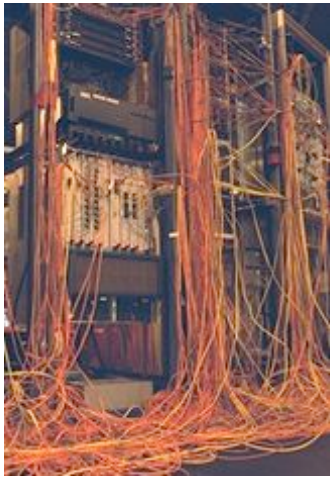
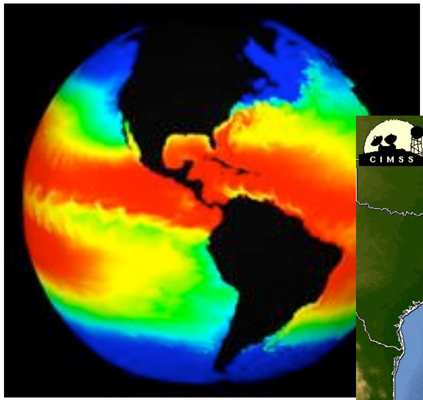
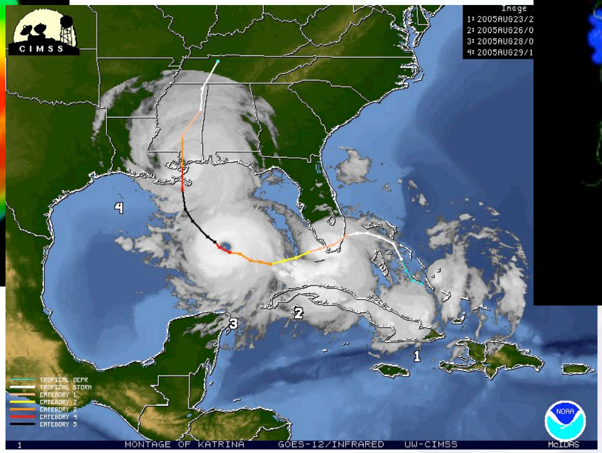
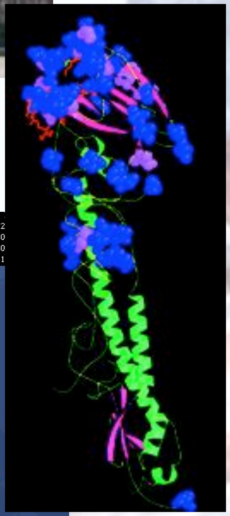
21st Century Problems









Reliability Today

- Must address future technology challenges and current business practices
- Must address decision processes – performance, safety, surety, cost, schedule, production, aging, design change, maintenance, quality, maintainability, policy, …

↕ Bridge the Gap

- Reliability ala earlier definition

The Hard Lesson

- Problem is **not** Modeling, it is Decision Making
- Optimal decision-making requires diversity of information:
  - Sources of information - theoretical models, test data, computer simulations, expertise and expert judgment (from scientists, field personnel, decision-makers…)
  - Content of the information - information about system structure and behavior, decision-maker constraints, options, and preferences…
  - Multiple communities that are stakeholders in the decision process

Reliability Today

|||

Integrated System Assessment

Challenges for Integrated System Assessments

- No full system tests
- Aging system (subsystem, components)
- Need to integrate science/engineering knowledge, models, and simulations
- Integrate information/data at various levels: system, subsystem, components, similar systems
- Choose best data to collect based on information per unit cost
- Integrate a variety of reliability representations
- Varied data types and collection schemes
- Model and measurement bias/uncertainty

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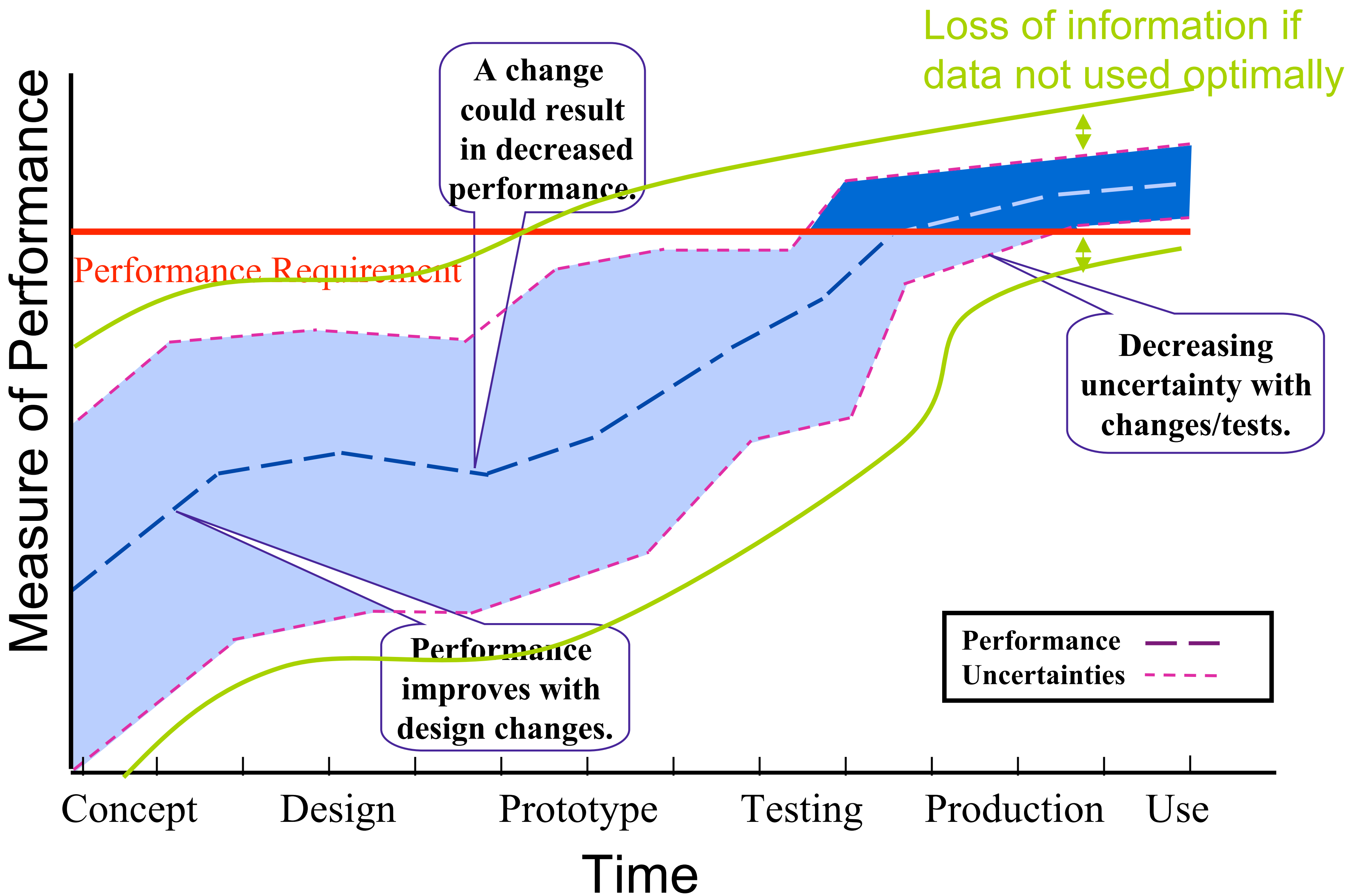
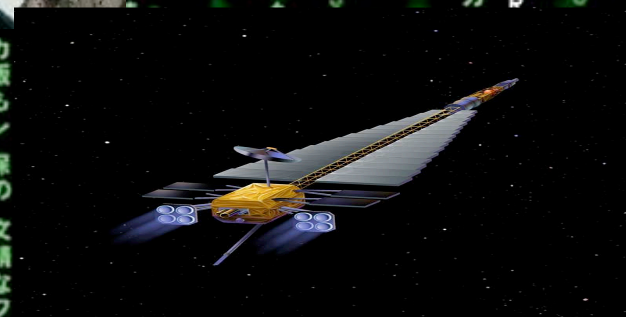
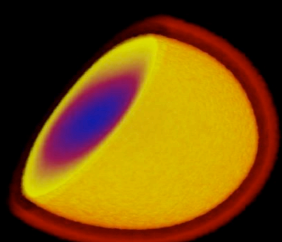
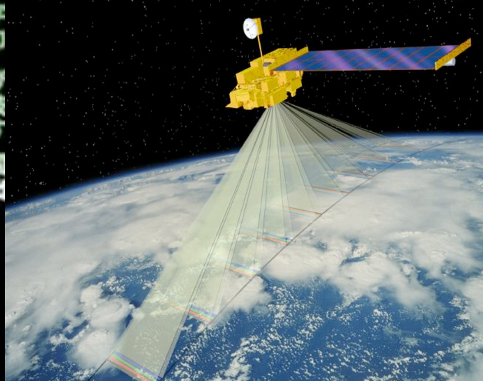
Goal: Continuous Evaluation

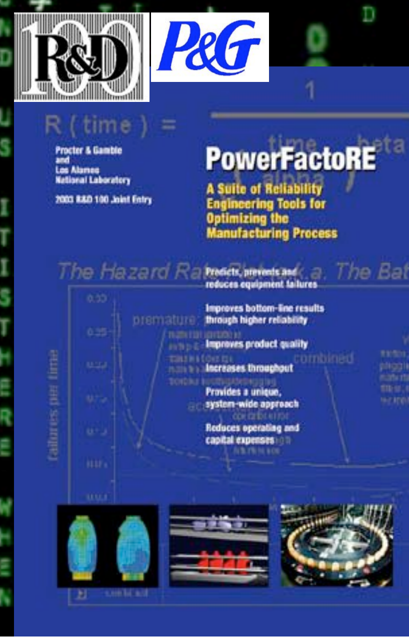


Application Drivers









Statistical Sciences is Key!

Core Questions:

- What are methods for collecting information relevant to system performance from a variety of sources not traditionally used?
- What are methods for integrating and analyzing the information with quantifiable confidence in the resulting system performance?
- What are methods for quantifying and evaluating the quality of these non-traditional sources of information?
- What are methods for evaluating resource allocation in the presence of incomplete and heterogeneous information?

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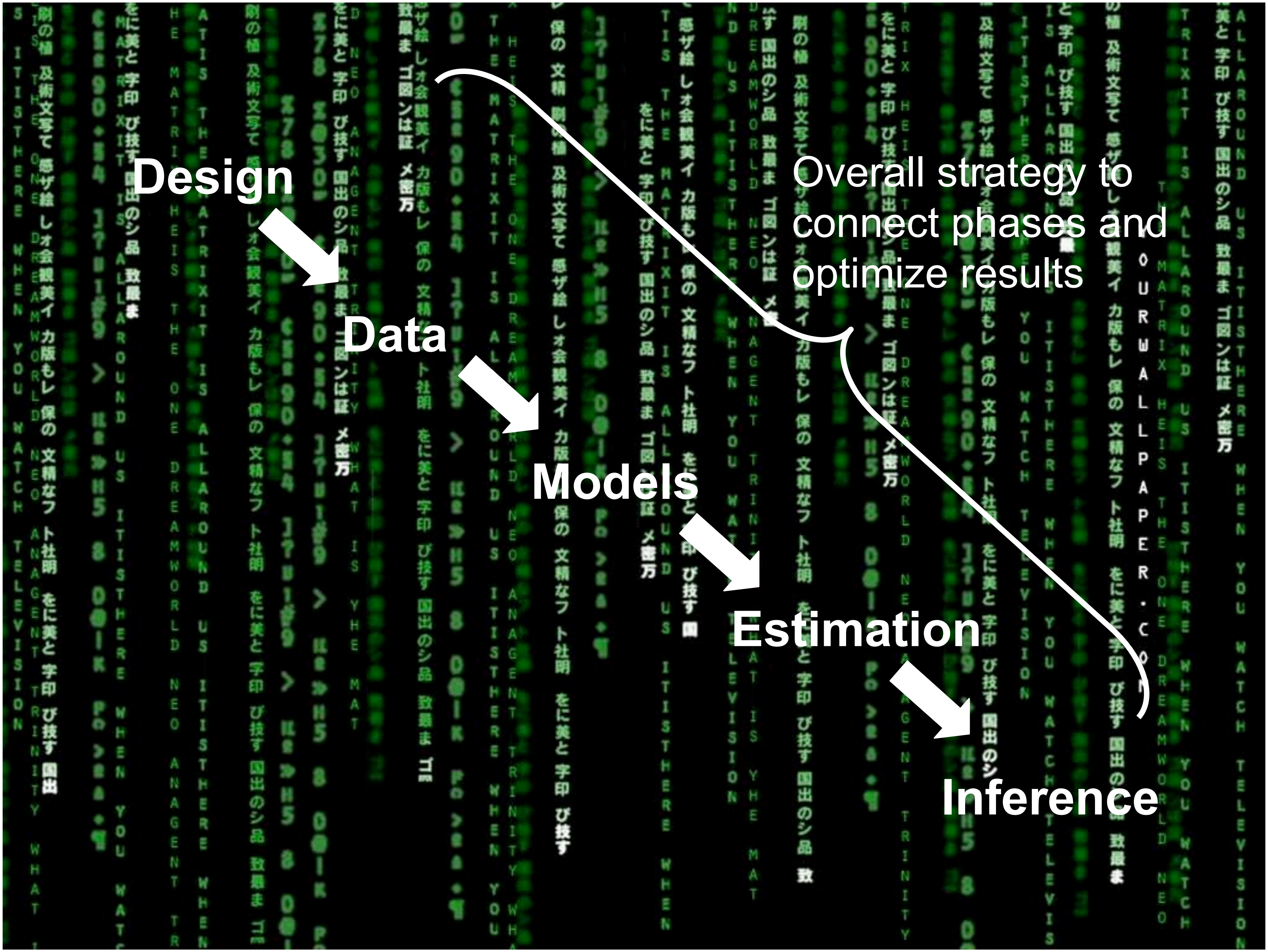

Design
Data
Models
Estimation
Inference
Overall strategy to connect phases and optimize results

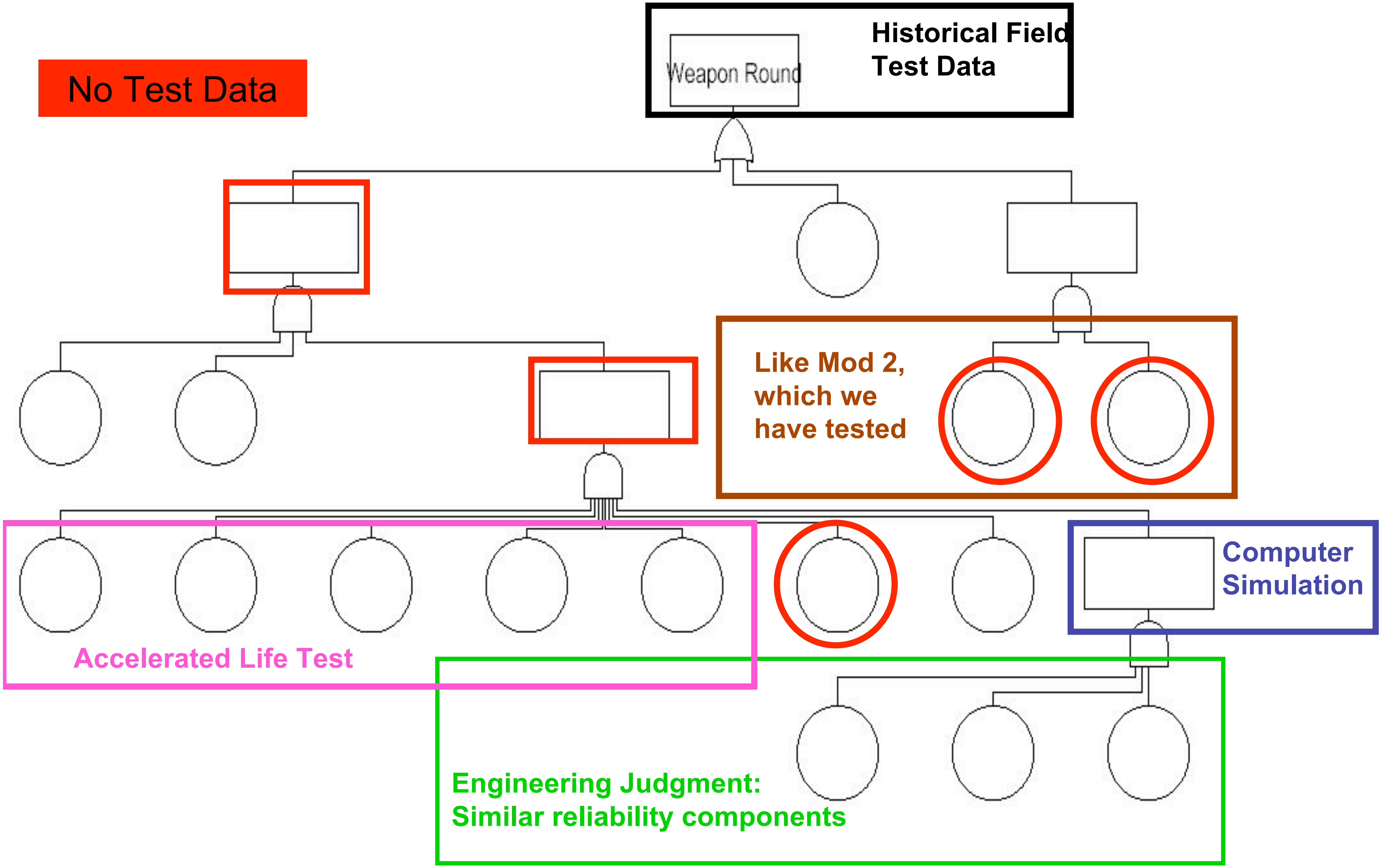
Army/Navy/Marines: Munitions Systems

- Goal: Ascertain the current reliability, and life extension of weapons stockpile.

Want a precise answer to a broad question

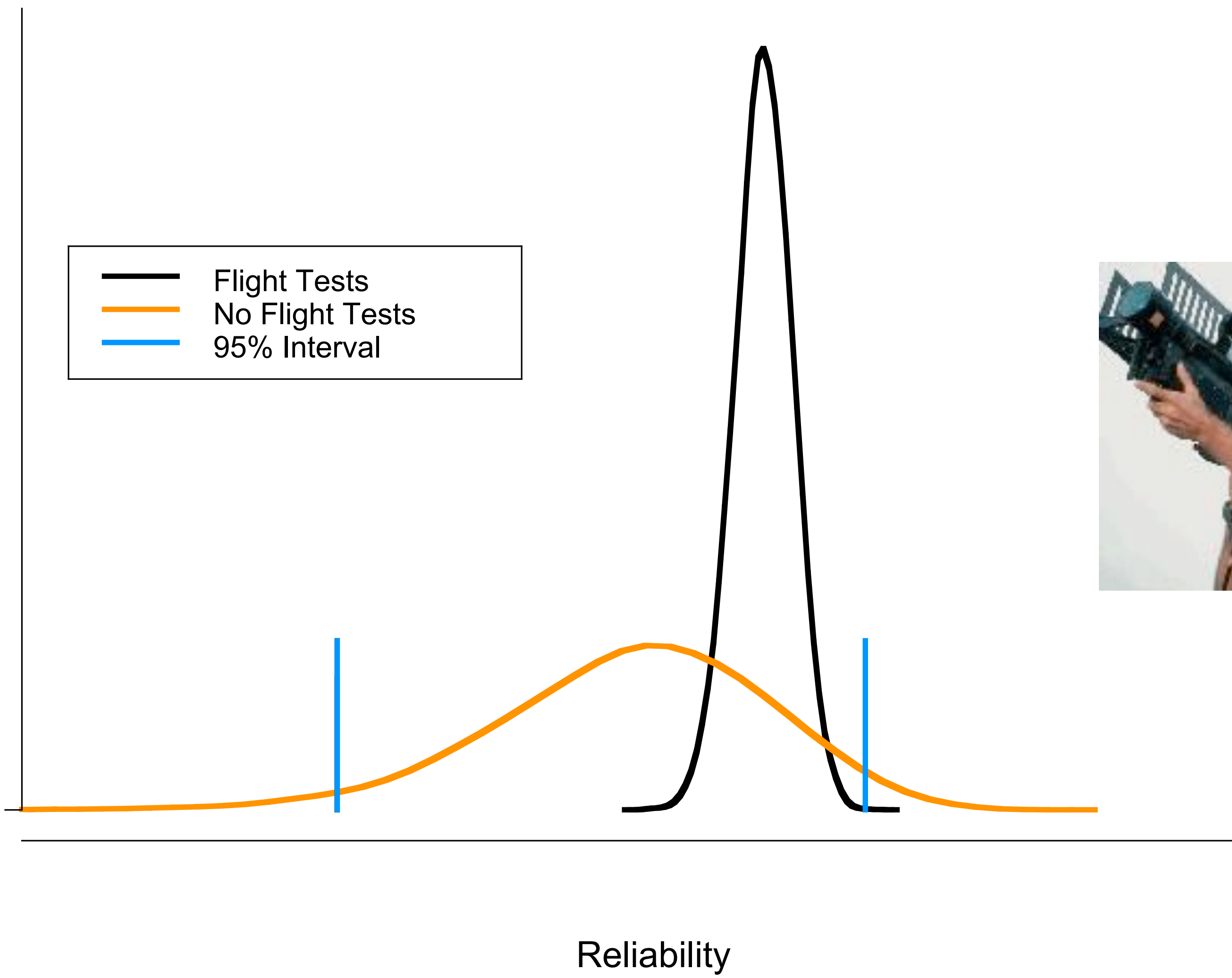
- Information: Heterogeneous sources
  - Historical field data
  - Subsystem/component tests
  - Accelerated life tests
  - Computer simulations
  - Engineering experience
  - Expert judgment

Notional System and Data Inventory

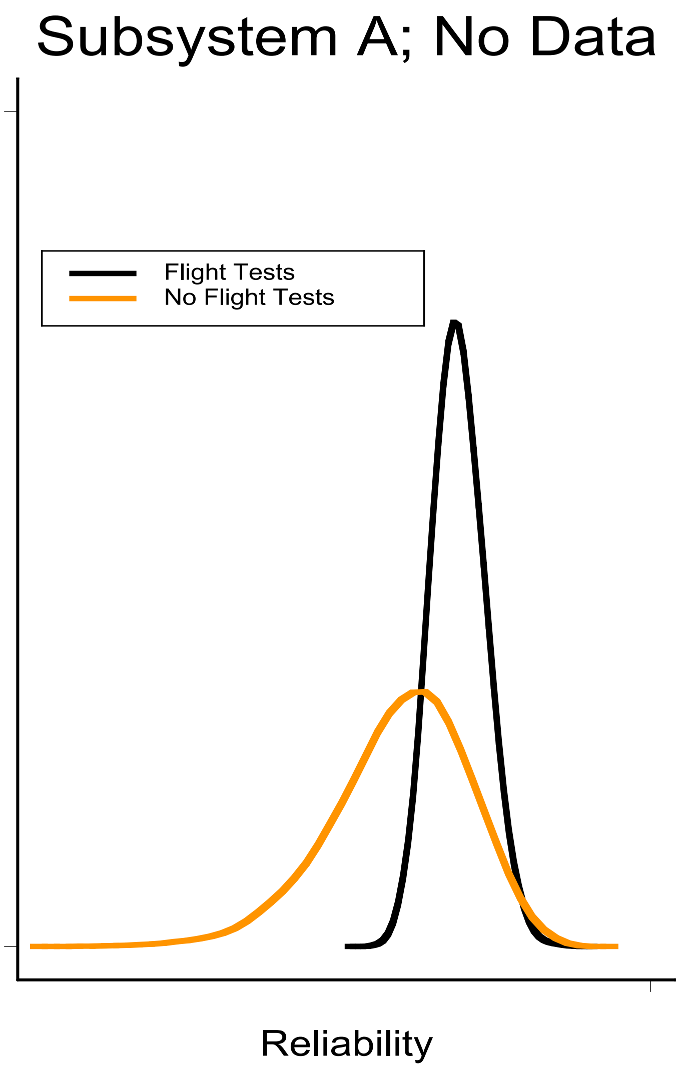


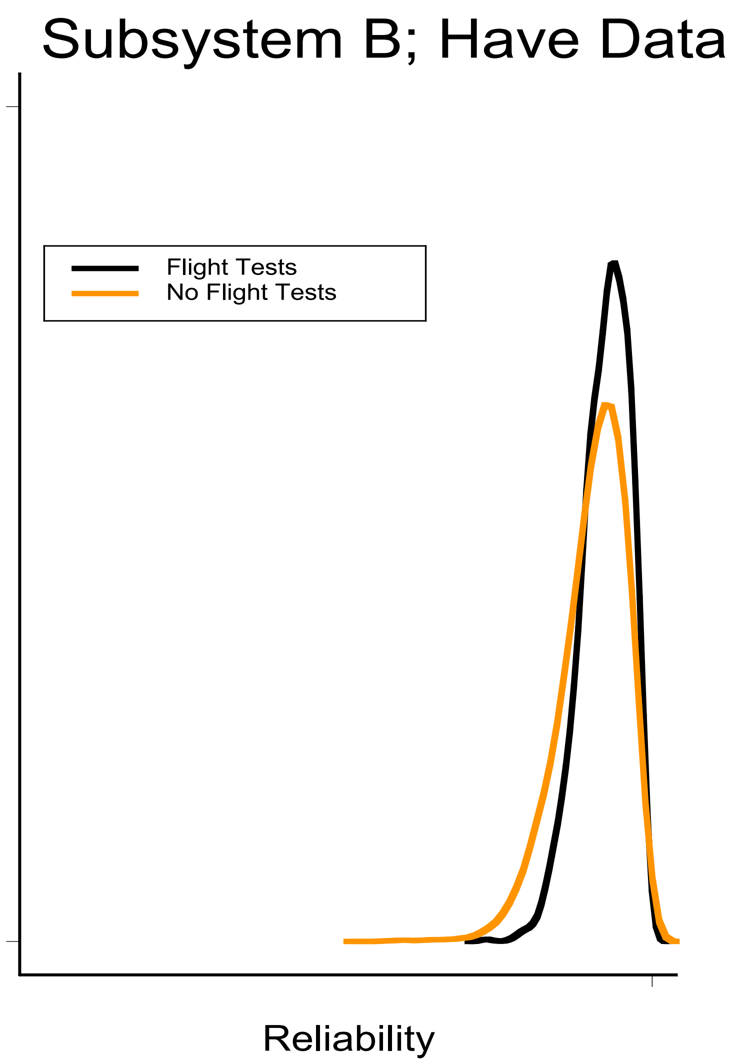
System and Component Reliability

Weapon Round

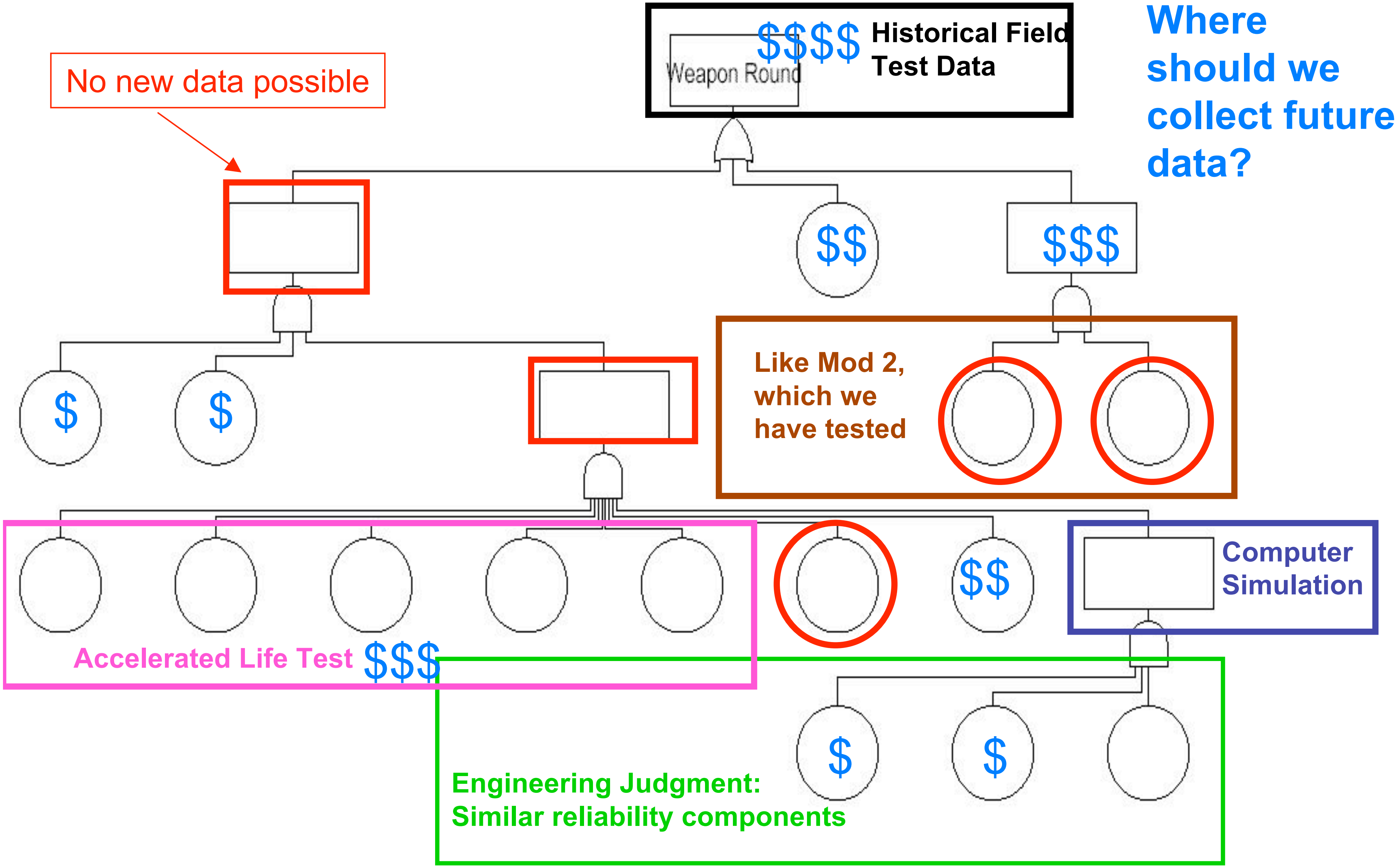


Inference


Subsystem A; No Data
Flight Tests
No Flight Tests
Reliability


Subsystem B; Have Data
Flight Tests
No Flight Tests
Reliability

Design Issues and Future Data Collection



Choice of New Data to collect related to:

- How important is that component/subsystem to the reliability of the system?
  - Less need to sample from a highly reliable component
- How well is reliability for that component already understood?
  - Diminishing returns on increases sample size
- Relative improvement to precision relative to cost of collecting data?
  - For a fixed budget, getting more “less informative pieces of data” may improve overall precision

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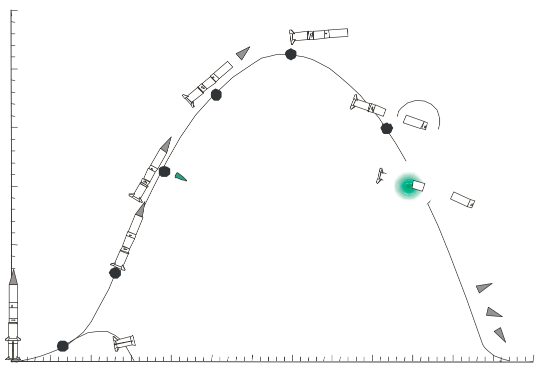
Design and Prototype Example: Missile Defense Agency (MDA)

- **PROGRAM:** Fly a high-fidelity, threat-representative missile system for Theater Missile Defense data collection and interoperability exercise
- **GOAL: "**Quantify the probability of mission success" and identify "areas of unacceptable risk" to the program
- **ISSUES**
  - Multiple partners and contractors
  - High *reliability* demanded
  - Full system testing not an option
  - System requirements dynamic
  - Diverse data sources



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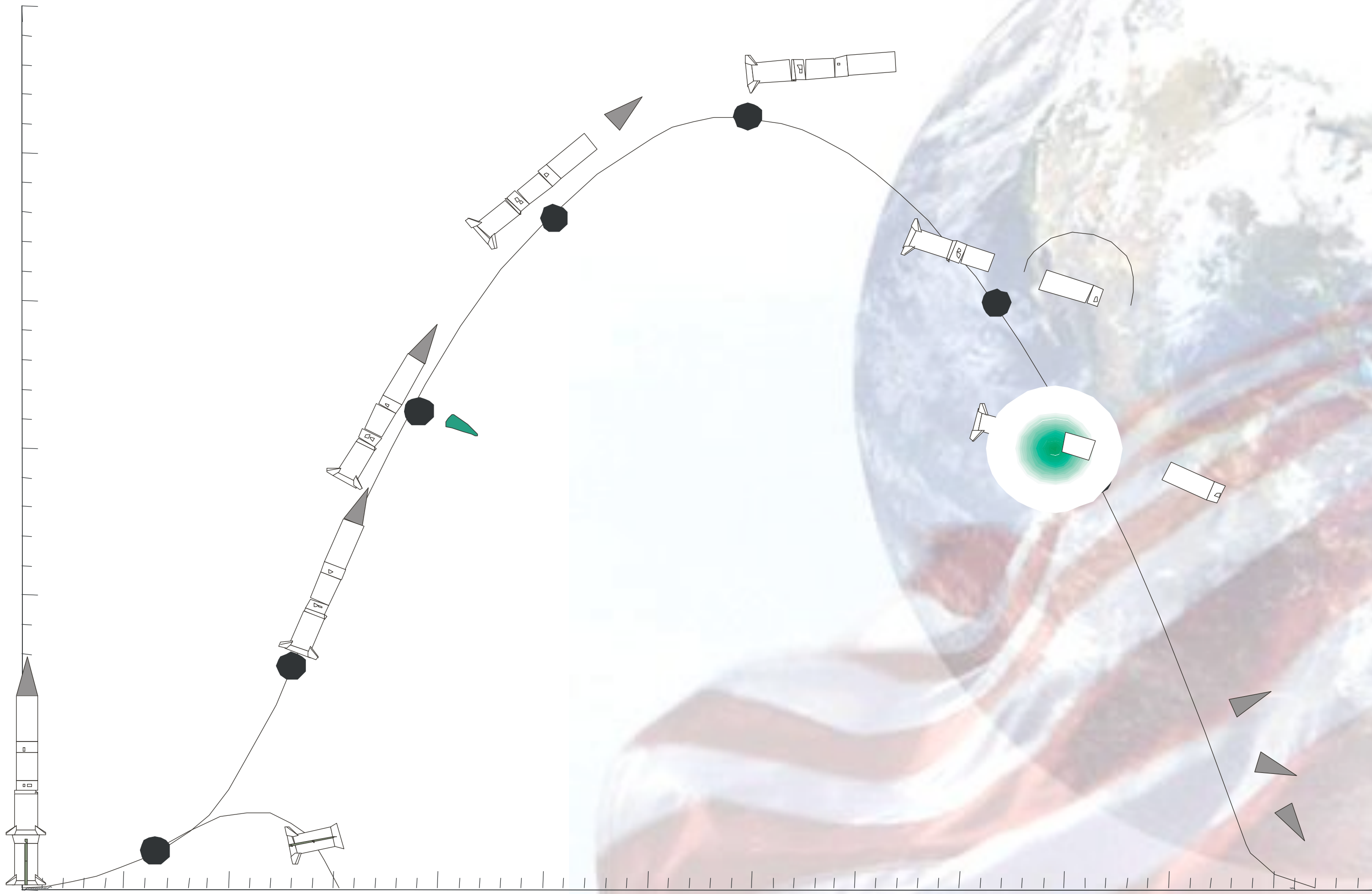
Notional Trajectory



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System Ethnography and Qualitative Modeling

- Capture social, cultural, physical aspects system
  - All “aspects” could constrain the system from functioning
- Map the decision Domain
  - Need a compact and dynamic graphical language for describing complex system structure
  - Must require consistent integration of information on component composition with behaviors
  - Representation must be able to be used to infer system-wide behaviors from observed and/or elicited information

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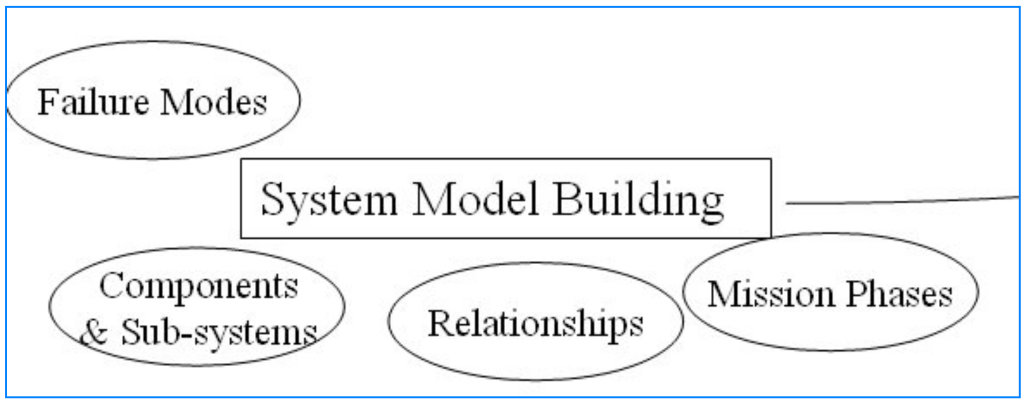
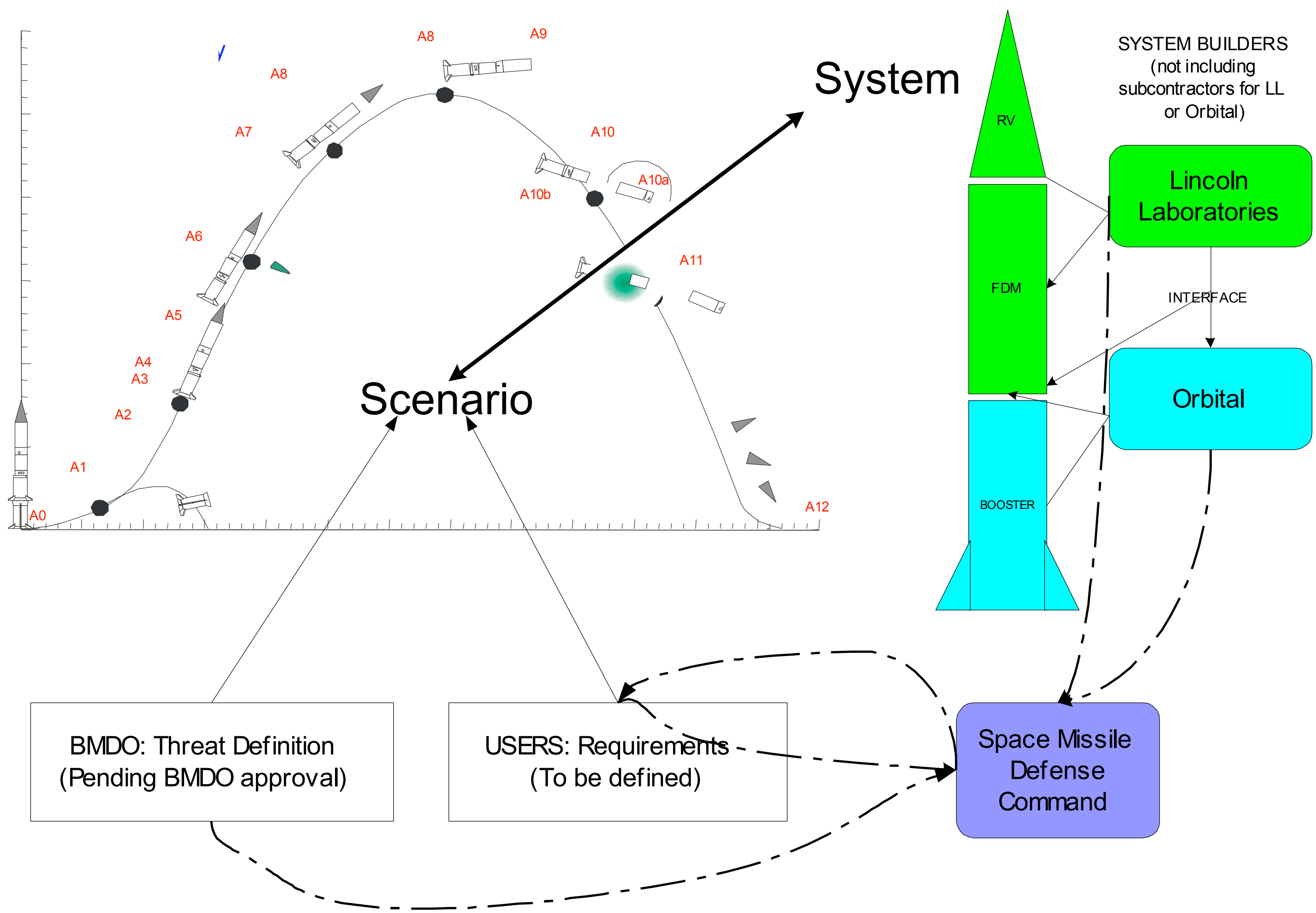
Elements of System Ethnography

- Meta model that describes the information observed or inferred from the system
- Deductive and Inductive structure

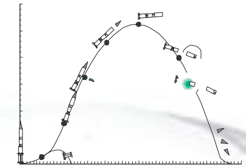


  - Entities – basic concepts of model
  - Channels – descriptions of entity relationships (social and/or technical causal structures)
  - Activities – phases of the mission and outcomes
  - Variants – distinct but related versions of the system

Notional Preliminary Representation

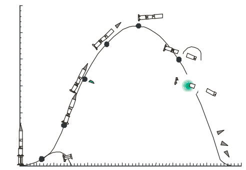


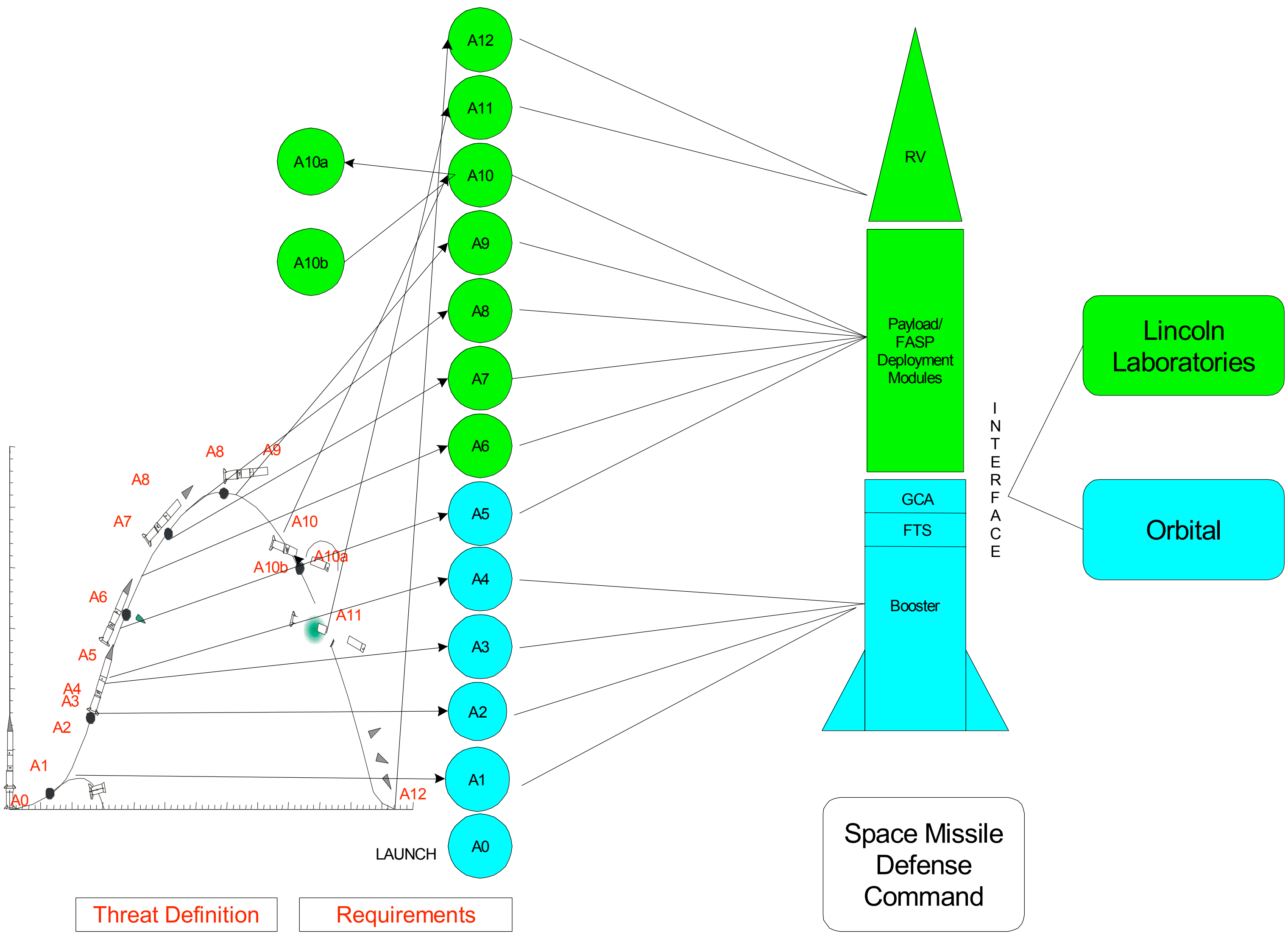
Classes of Decision Elements

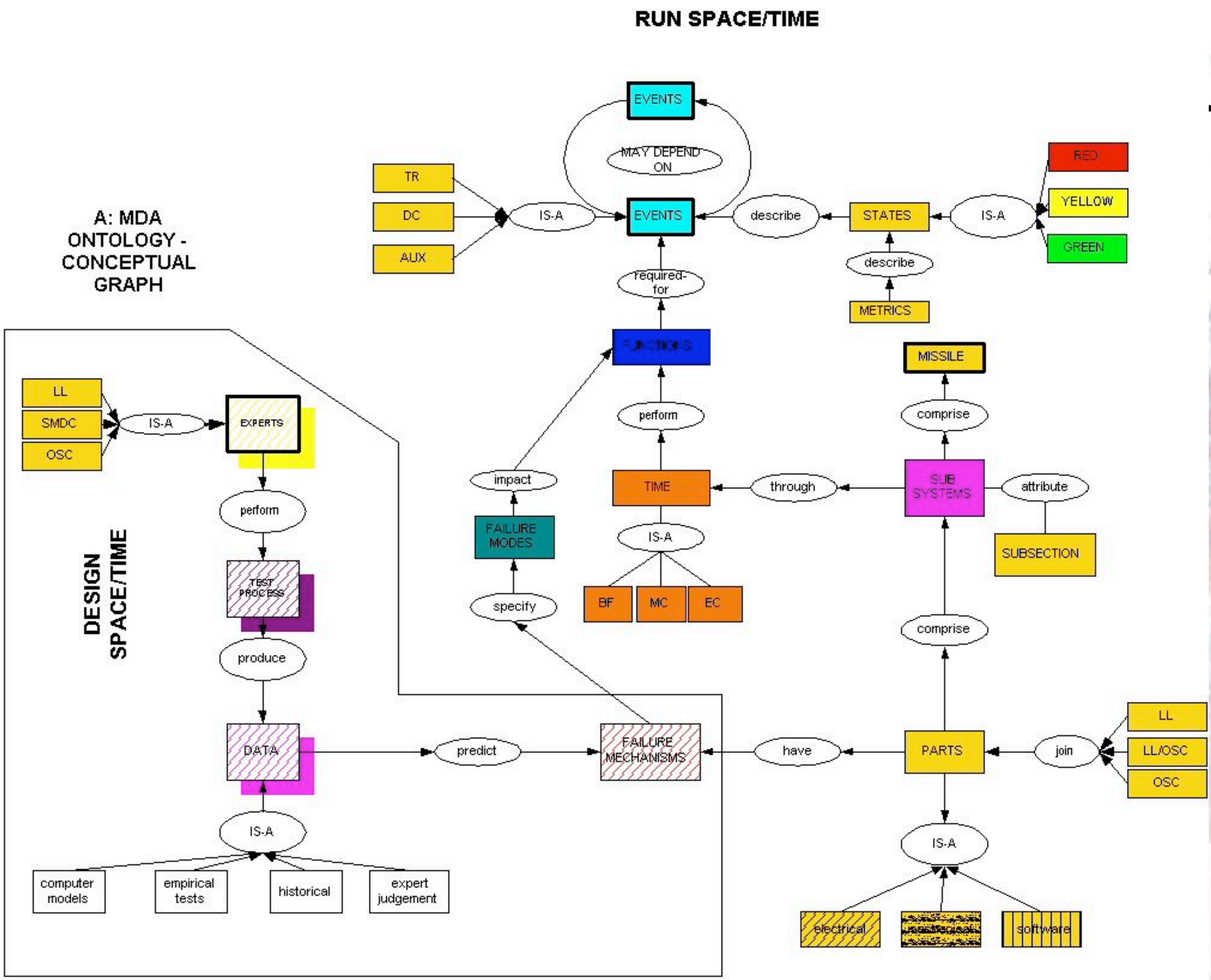


- Mechanical Elements
  - Booster and payload
  - Launch site and launch equipment
  - Data collection
- Social Elements
  - System Builders: SMDC, Lincoln Laboratory, Orbital
  - User Community: MDA, Patriot, THAAD, Navy, ….
- Threat Definition: The Scenario
  - Primary experiments, Secondary Experiments, Events, Metrics, Dependencies
  - Requirements from User Community
  - What is success? What is failure?

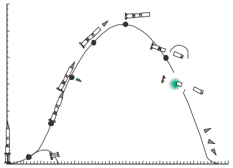
Notional Events to System

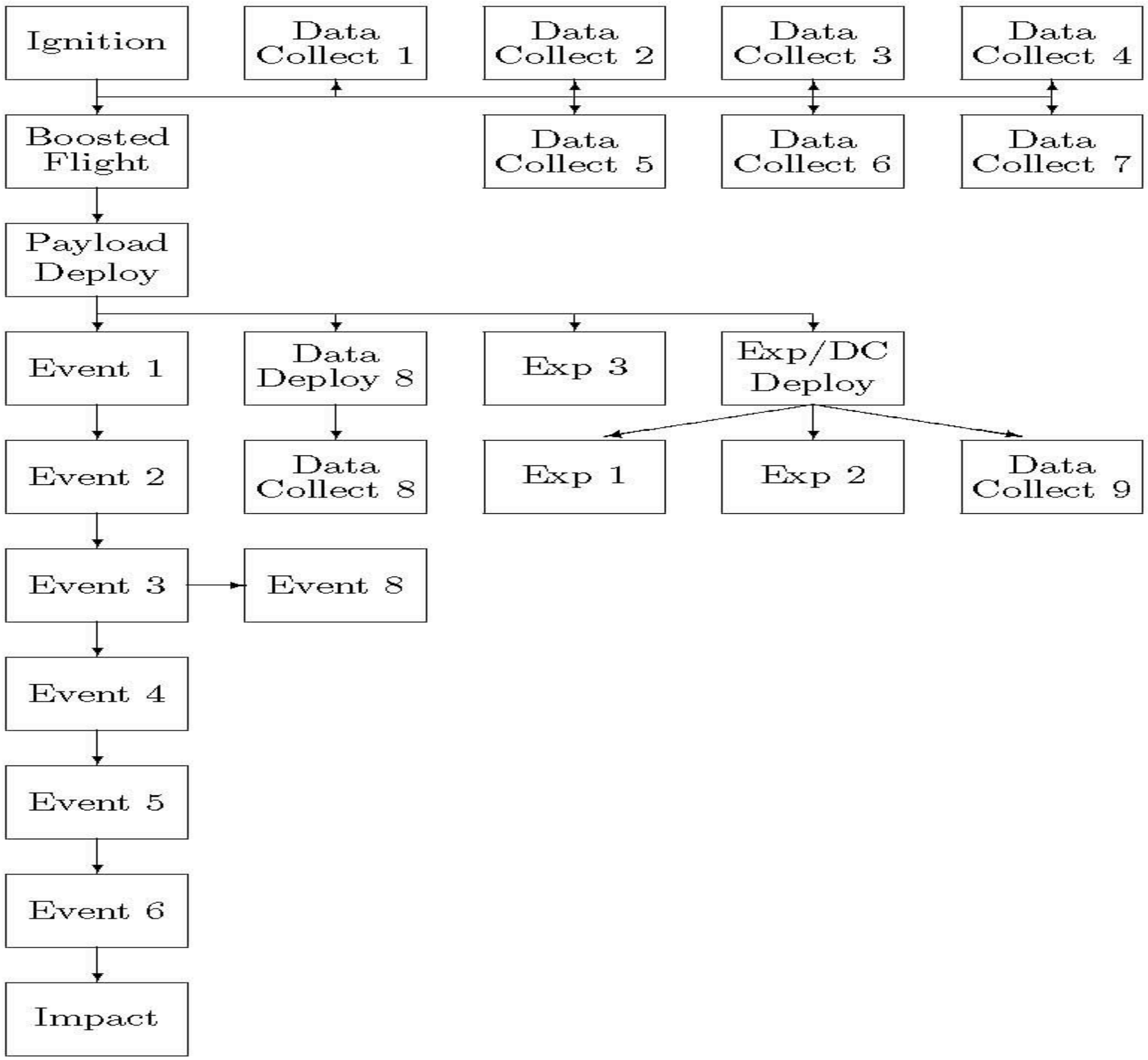




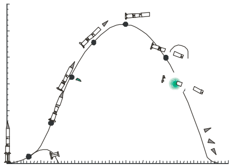

RUN SPACE/TIME
A: MDA ONTOLOGY - CONCEPTUAL GRAPH
EVENTS
MAY DEPEND ON
TR
DC
AUX
IS-A
EVENTS
describe
STATES
IS-A
RED
YELLOW
GREEN
describe
METRICS
required-for
MISSILE
comprise
perform
impact
TIME
through
SUB SYSTEMS
attribute
SUBSECTION
FAILURE MODES
IS-A
BF
MC
EC
specify
comprise
LL
SMDC
OSC
IS-A
EXPERTS
perform
TEST PROCESS
produce
DATA
predict
FAILURE MECHANISMS
have
PARTS
join
LL
LL/OSC
OSC
IS-A
electrical
software
IS-A
computer models
empirical tests
historical
expert judgement
DESIGN SPACE/TIME

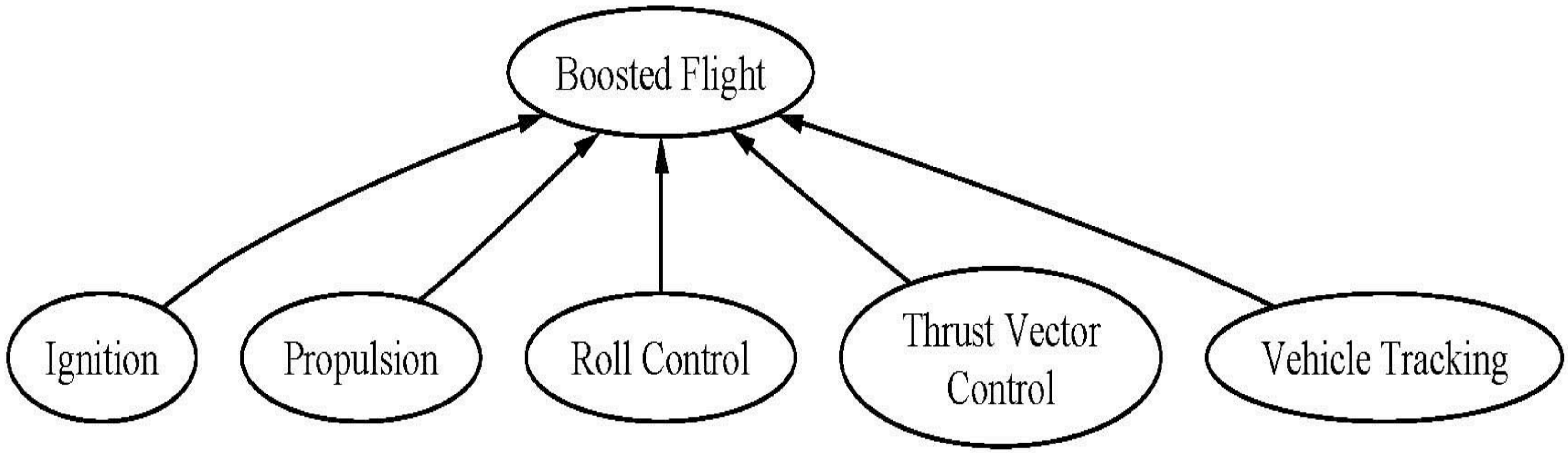
CMP Model: Event Diagram



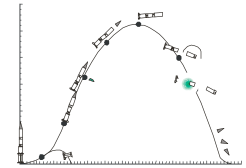


Functional Decomposition

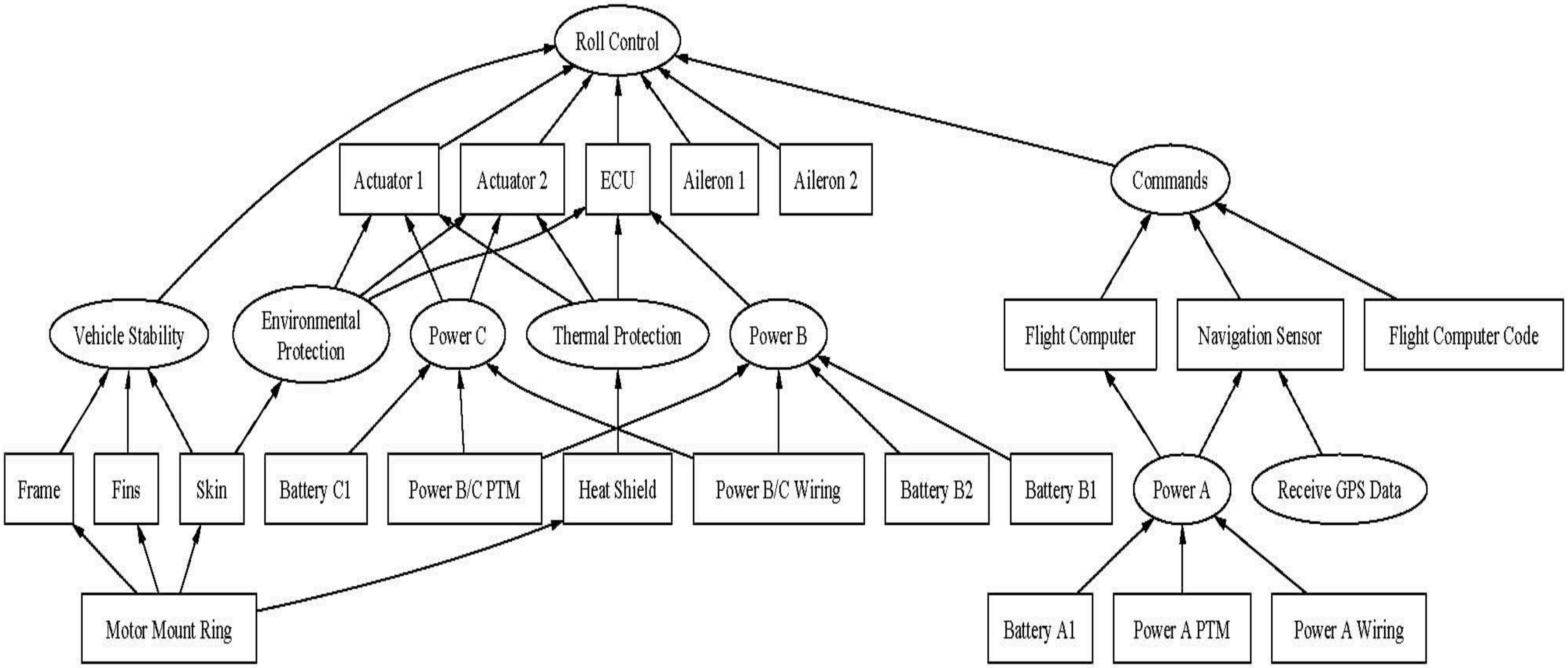




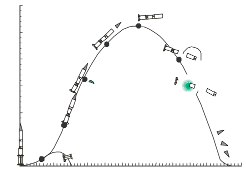
Functional and Component Decomposition



Able to derive statistical models from dependency structure



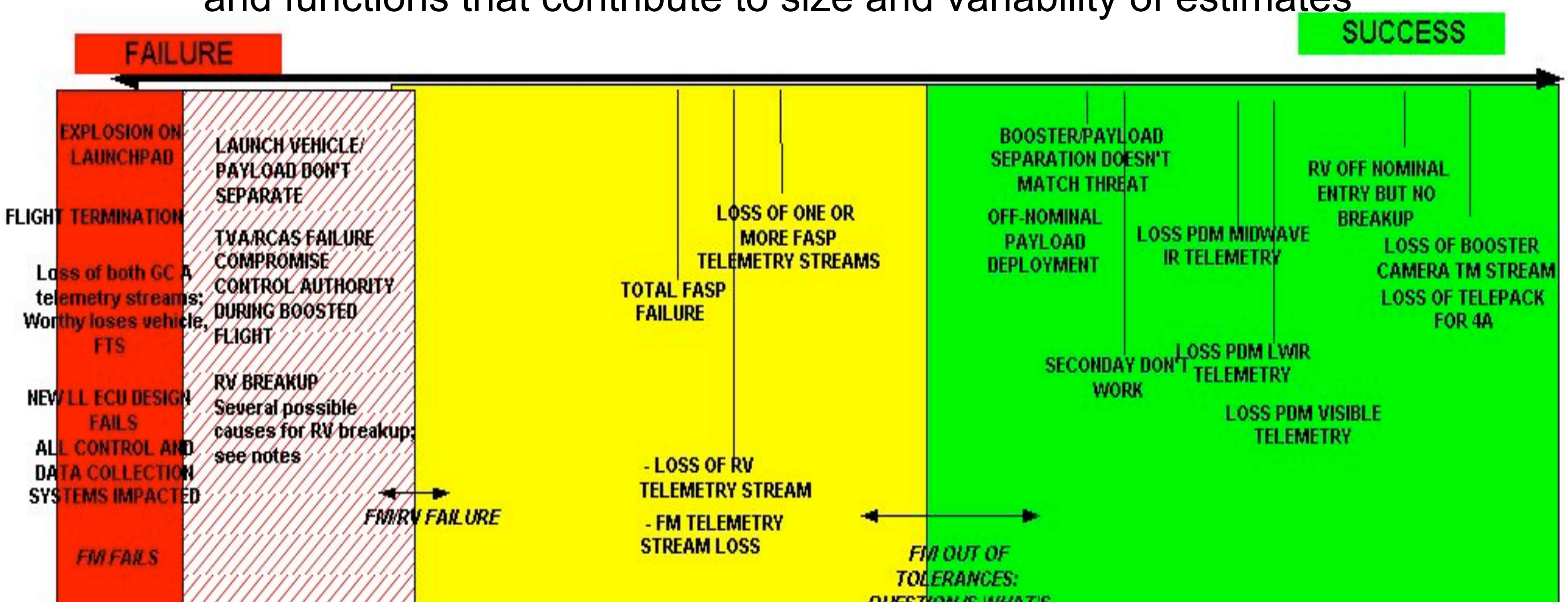
Notional Mission Success



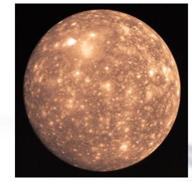
Estimates of mission success (full distributions available)

- Mission yellow is most likely (60% ± 10%)
- Mission red is second (25% ± 5%)
- Mission green is third (15% ± 5%)

- Backward chaining through system conditioned on state outcomes
  - Decompose estimates into parts, subsystems, and functions that contribute to size and variability of estimates



Example: JIMO



- Jupiter Icy Moons Orbiter Project (JIMO) is a conceptual phase project to build and deploy an unmanned spacecraft to explore the moons of Jupiter as part of a 10-15 year mission
- Exploring alternative designs for on-board nuclear reactor to supply electrical power by removing heat from the reactor
  - 2 variants using heat pipes
  - 2 variants using liquid metal

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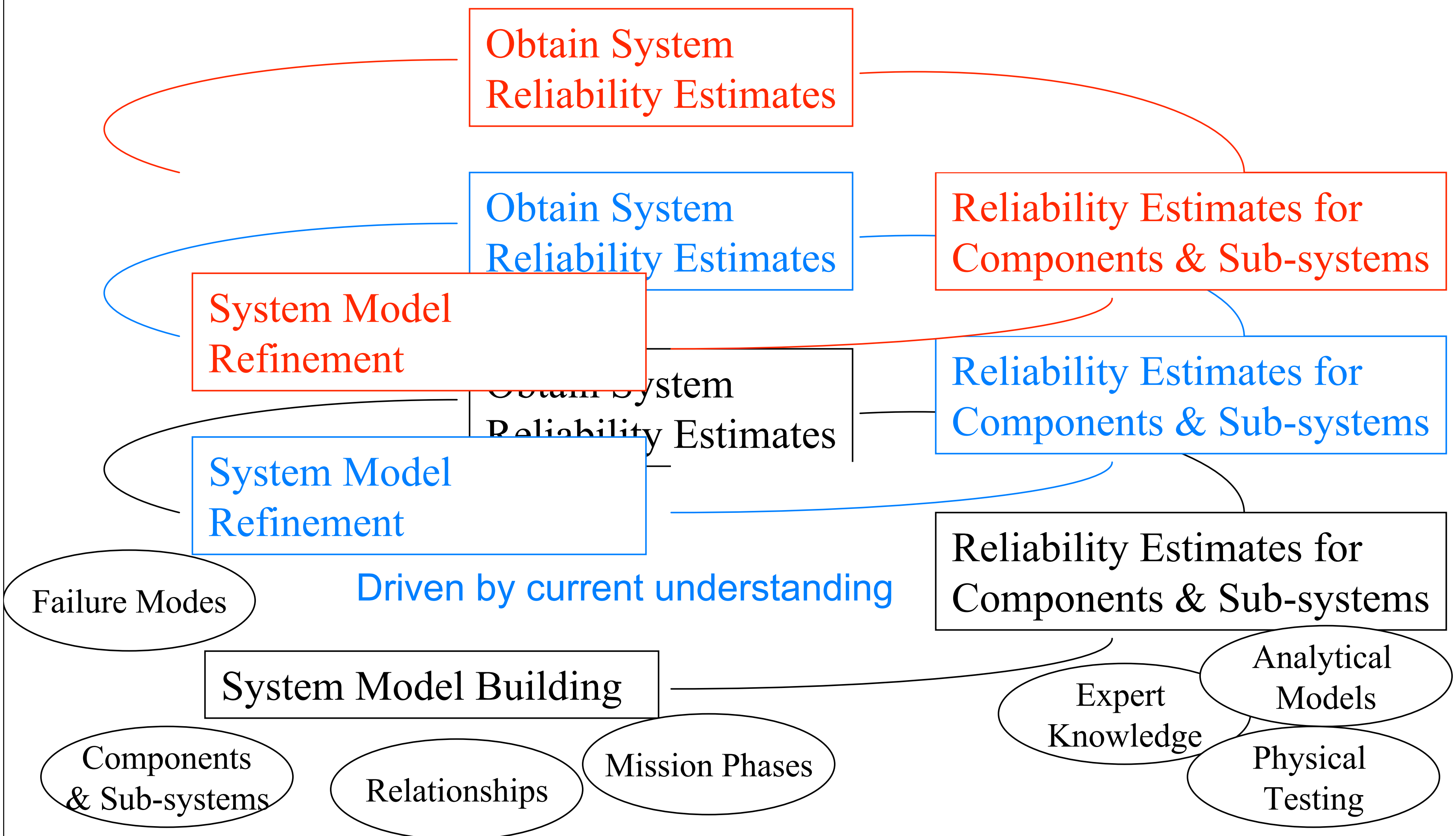
JIMO: Integrated Reliability Assessment

- Provides an ability to do on-going reliability trade-off studies as design changes
- Provides a quick way to explore implications of component behavior on system through forward propagation
- Provides a means to explore unexpected system outcomes, to design telemetry, or design system experiments through backward chaining

Integrated Reliability Assessment Spiral



New Era of Statistical Design of Experiments

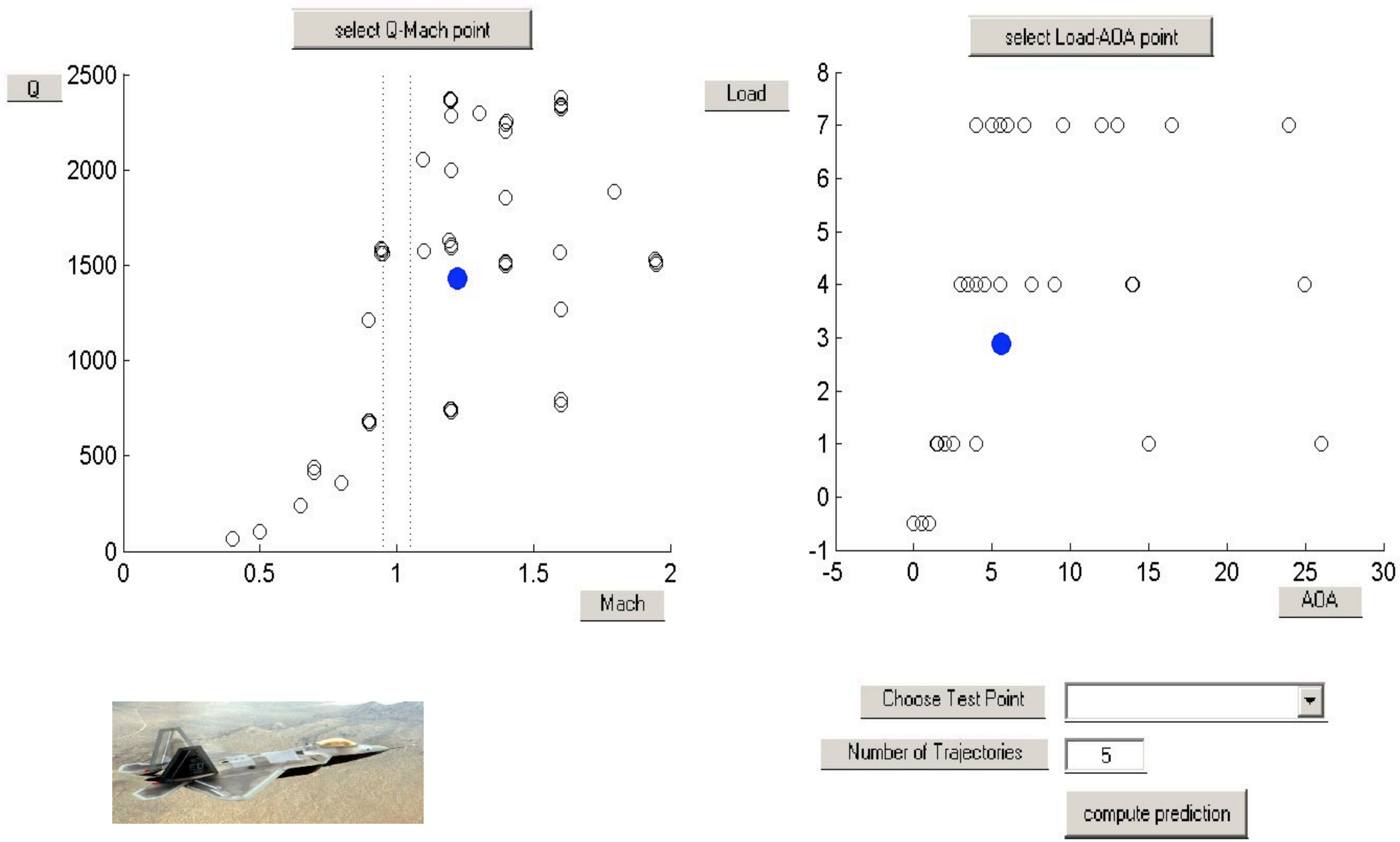
- Statistical Design of Experiments provides efficient techniques for allocating resources to different sets of experimental conditions
- Designs have traditionally dealt with single information sources (e.g., physical experiment), albeit multivariate in the response
- Designs need to account for cost limitations, heterogeneous sources of information, statistical methodology available for building response functions and predictions
- Analysis needs to evolve to accommodate non-normal and functional inputs and responses

RICE

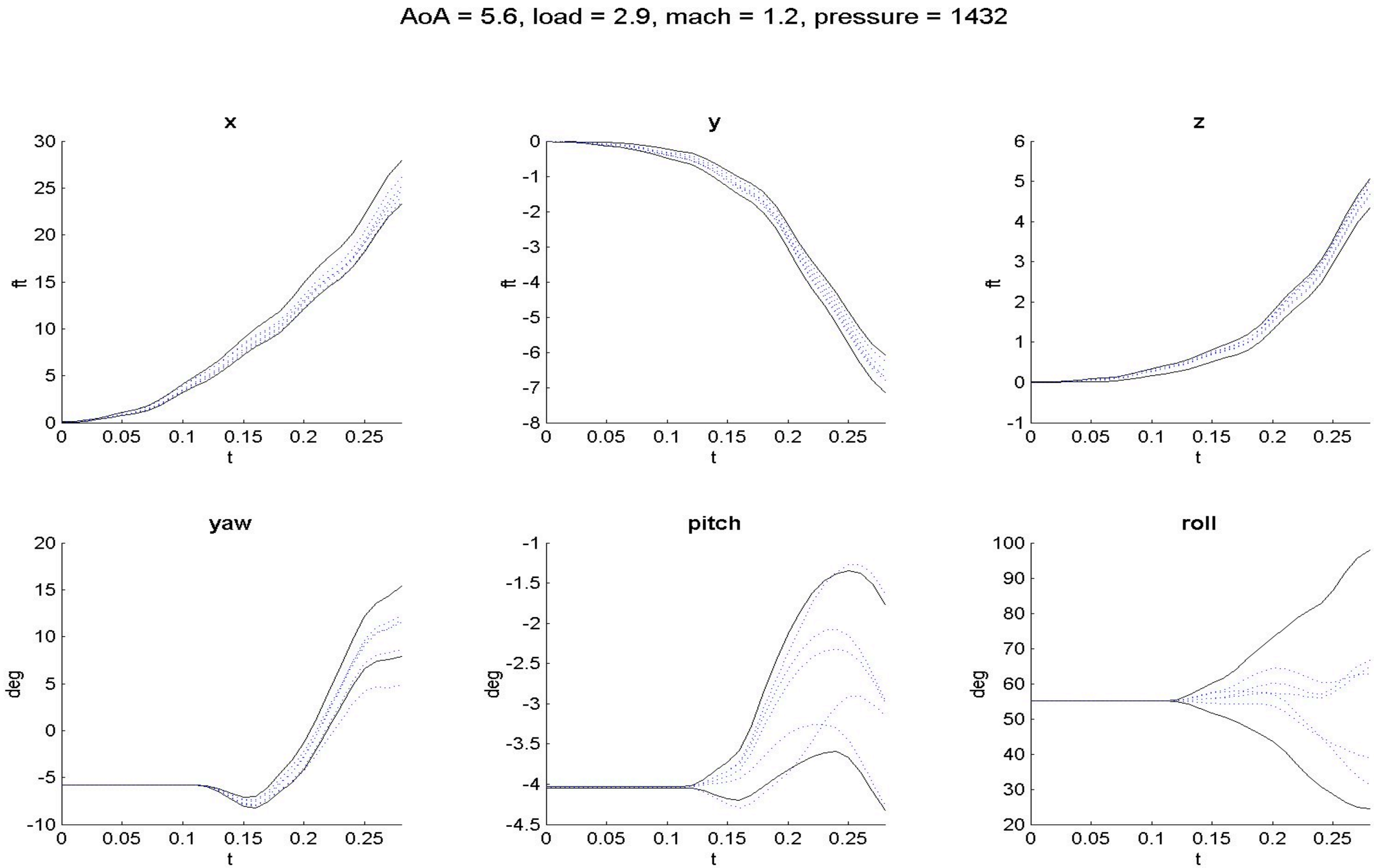
F-22 Launch Risk

- **Goal**: Optimize flight test matrix – reduce cost!
  - Describe uncertainty about missile trajectories at design points
- Multiple information sources -- use previous flight tests, wind tunnel tests, CFD, and expert judgment to describe trajectories of new flight tests
- Spatial/Temporal domain -- must model flight tests, wind tunnels, and CFD trajectories and their relationship to one another so that wind tunnel and CFD can inform about new flight tests.

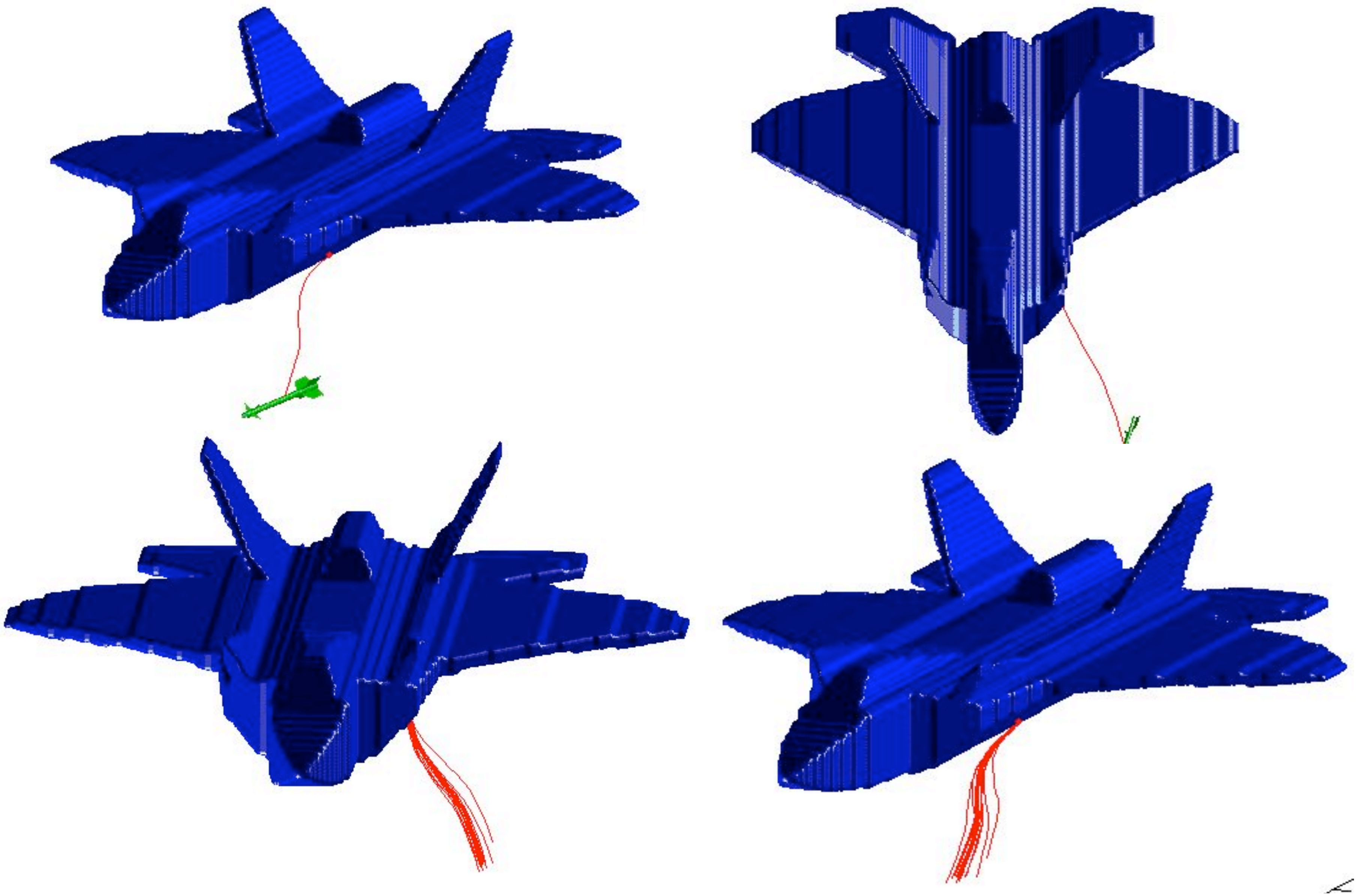
Flight Envelop Characterization



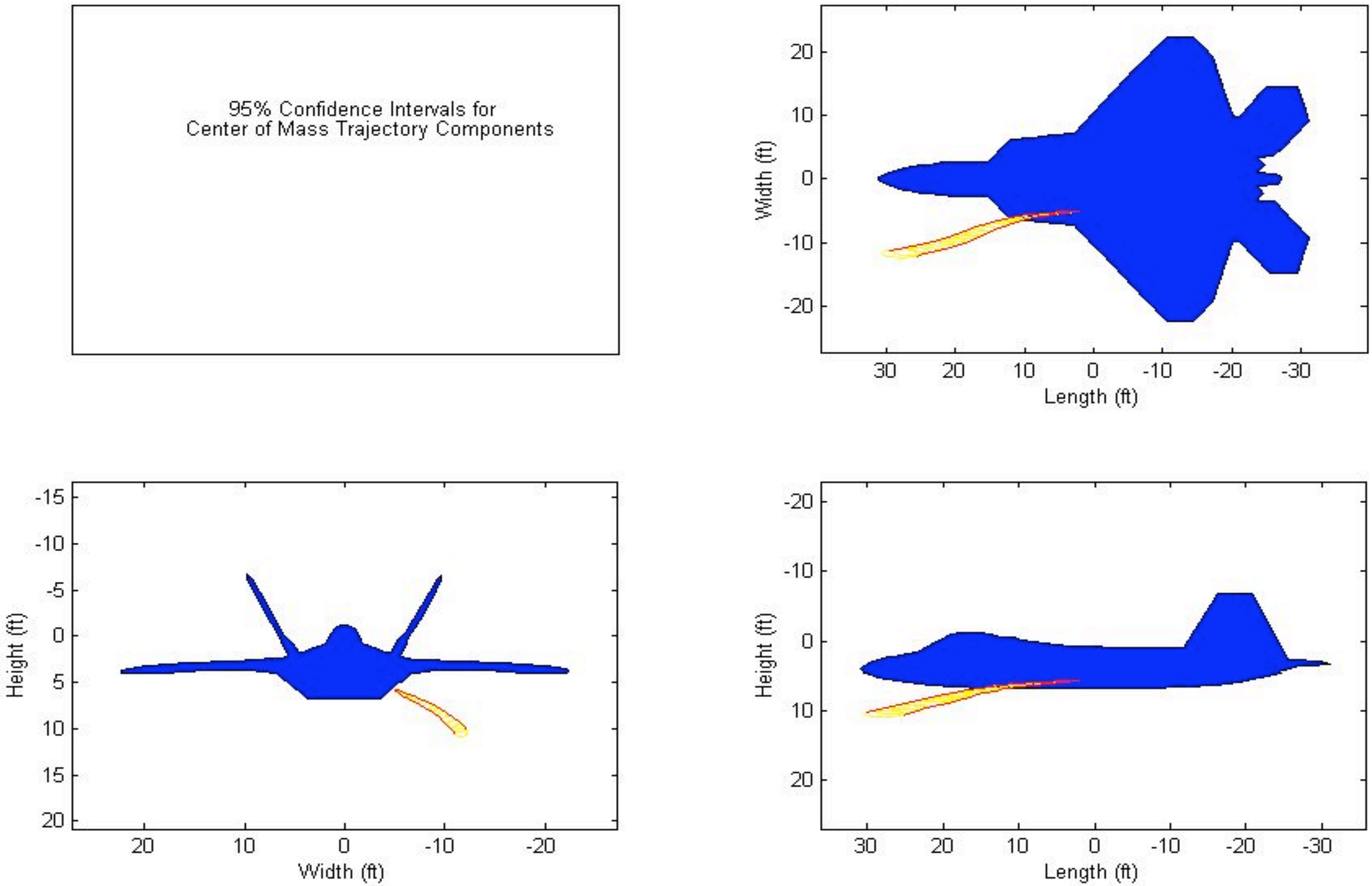
Trajectory Bounds



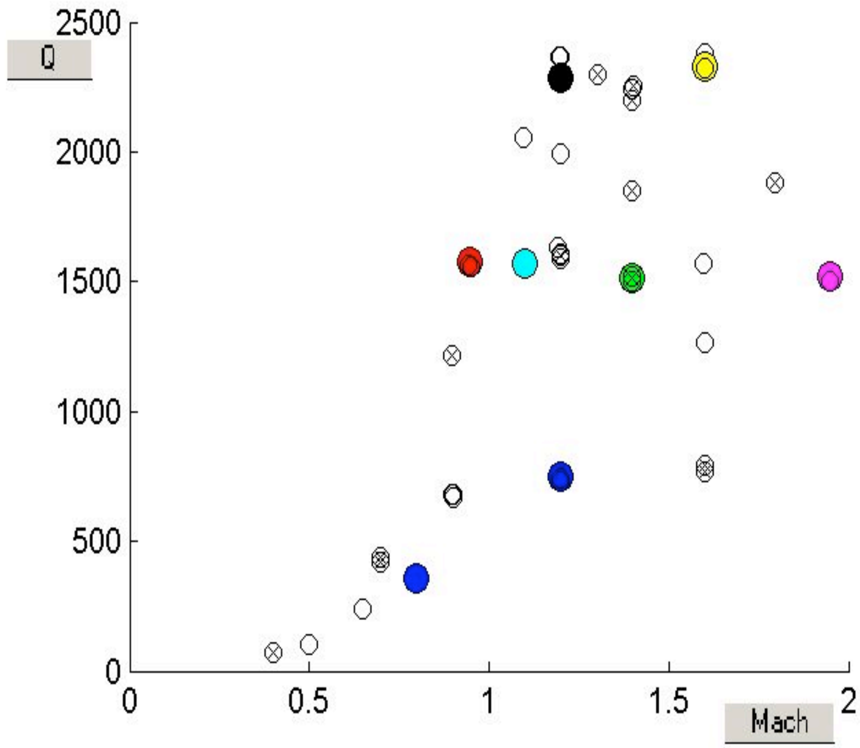
Visualization of Simulated Trajectories

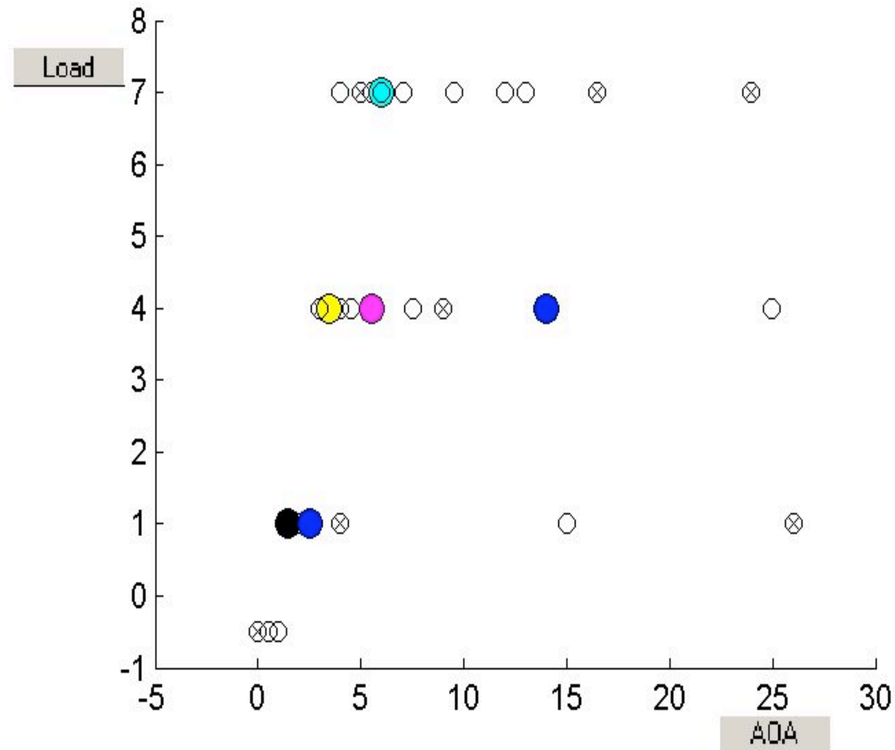


2-D Confidence Intervals



Assessing Risk: Optimizing Data Collection



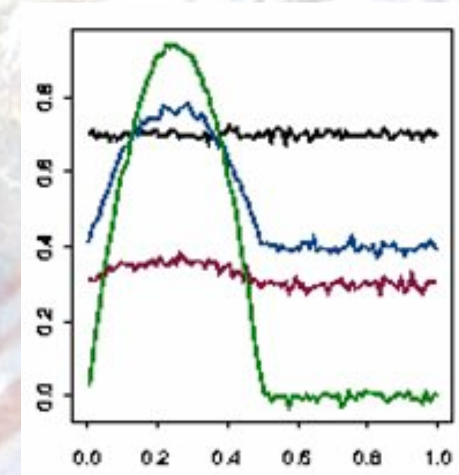


Number of Test Points: 8

Minimum Average % Error: 4.3882

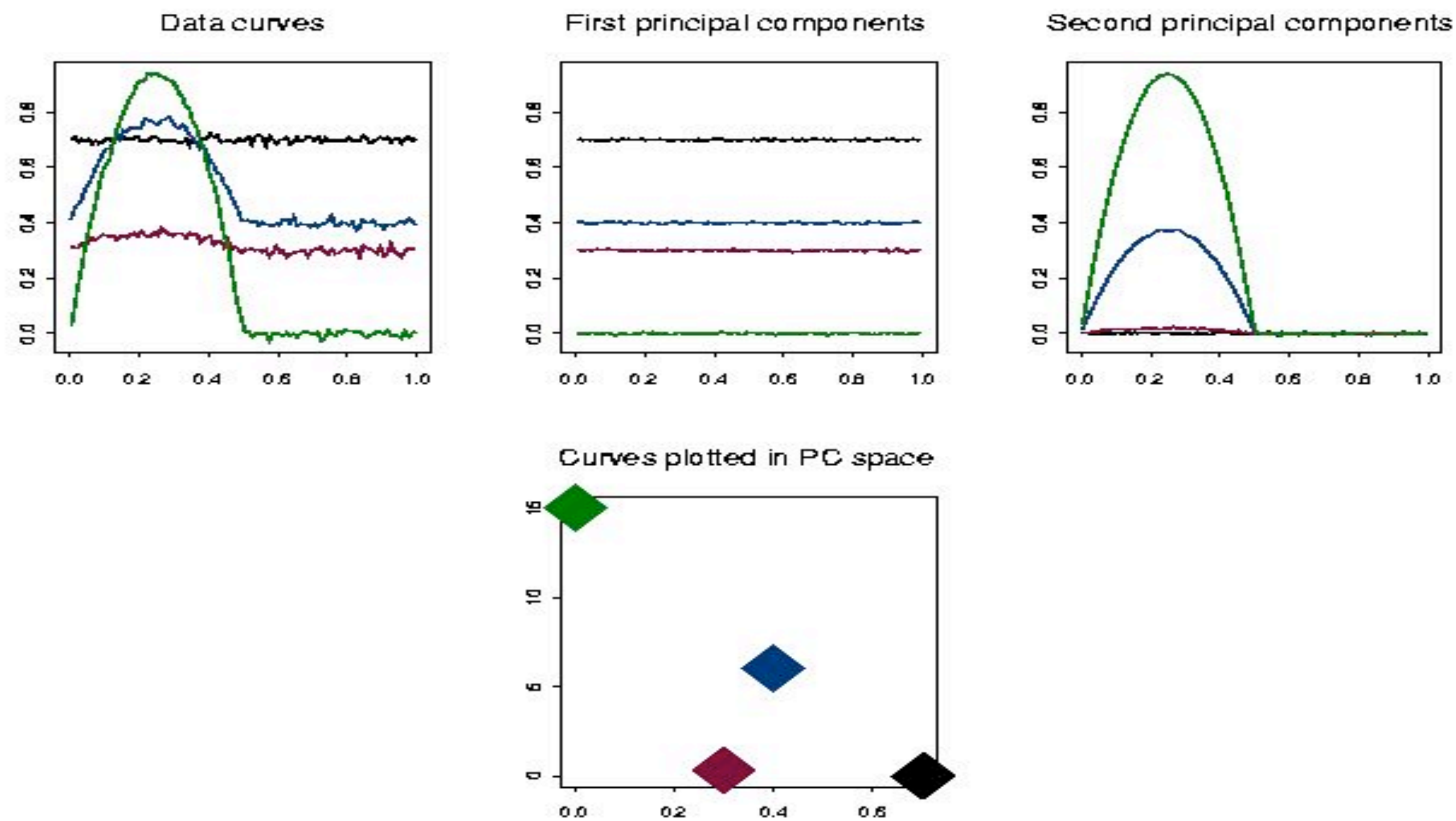
New Data Types – Functional Responses

- Collecting large amounts of data on each item may be possible
  - measurements over time, spectra, digital imaging, …
- Coping with the full richness of the data may be overwhelming
  - capturing the critical features of the data is desirable
- Key issues:
  - Reduce dimensionality, but capture important features
  - Parametrics / non-parametric



Example – Functional Component Data

Functional Data + Optimal Design



]

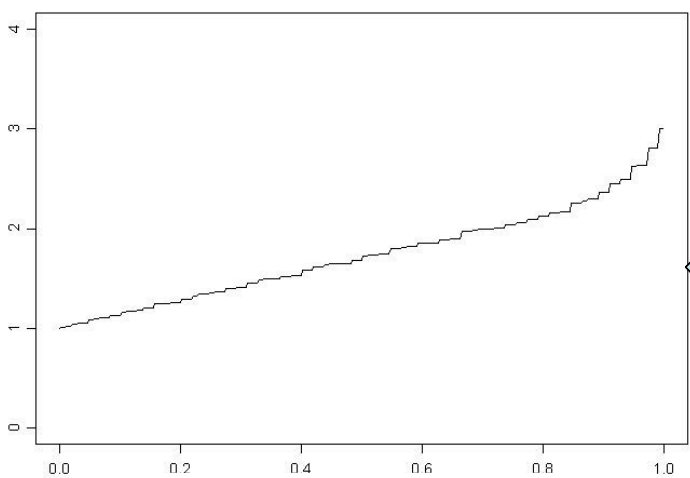
Assessing Designs: Many facets to consider

- Quality of estimation of model parameters
- Quality of prediction in design space
- Cost
- “Pure error estimate” available
- Ability to test adequacy of model assumptions (additional terms, variance assumptions, etc.)
- Flexibility for collecting data
- Robust to missing or erroneous data

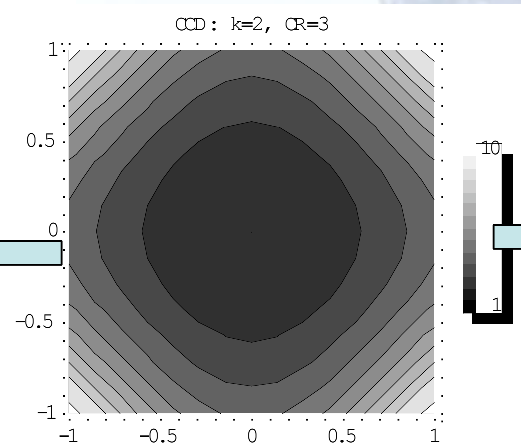
RICE

Design Assessment Tools

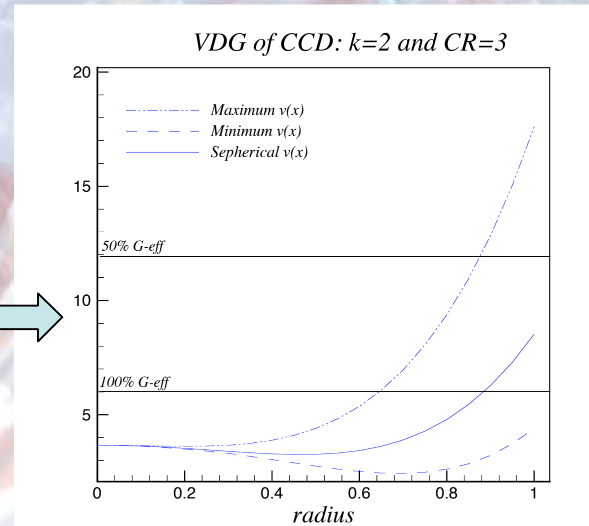
- Optimality criteria (for estimation/prediction)
  - Often too simplistic to capture all the important aspects of the design
- Graphical tools
  - Richer comparisons possible



Fraction of Design Space Plot



Prediction Variance



Variance Dispersion Graph

RICE

In General: Tools are Critically Needed

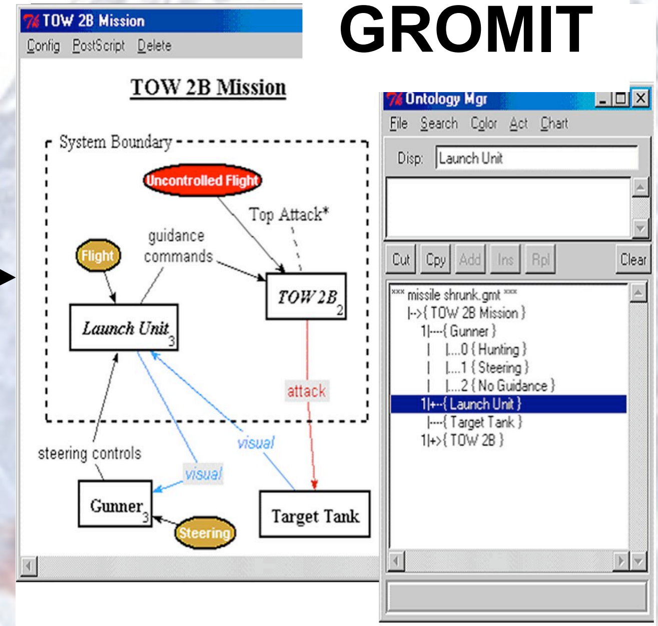
GA

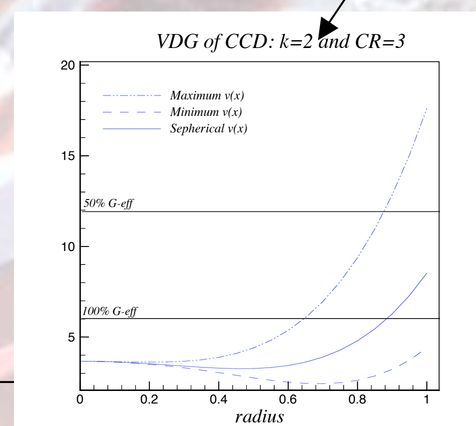
Candidates ⟺ Evaluate

$$R(t) = P(T > t)$$

$$f(y \mid \theta)\pi(\theta) / \int f(y \mid \theta)\pi(\theta)d\theta$$

GROMIT





RICE

Conclusions

- Become leaders in the science integration process!
- Understand the problem space
- Embrace consequences of the technology explosion
- Communication

Parting Thought: Our Intellectual Property Matters