Challenges in Early-Phase Complex System Design

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Agenda

- Conceptual Design and JPL's Team X
  - *How increasing complexity and other factors are affecting early-phase design*
- Collaborative Design
  - *Benefits of concurrency*
  - *What happens when we distribute the design process?*
- Model-Based Design
  - *Is this really any different?*
  - *Effect on design process*
- Decision-Based Design Structures
  - *Benefits and challenges compared to traditional design products*

JPL missions under development for launch 2006–2010

- *Dawn:* ***May 06***
- *Kepler:* ***Jun 07***
- *Phoenix:* ***Aug 07***
- *Nuclear Spectroscopic Telescope Array (NuSTAR):* ***Aug 07***
- *Ocean Surface Topography Mission:* ***Apr 08***
- *Wide-Field Infrared Survey Explorer (WISE):* ***Jun 08***
- *Orbiting Carbon Observatory:* ***Oct 08***
- *Mars Telecommunication Orbiter:* ***Sep 09***
- *Aquarius:* ***09***
- *Mars Science Laboratory (2):* ***09 and 11***
- *Hydros:* ***Jan 10***
- *Space Interferometer Mission (SIM):* ***10/11***
- *Juno or Moonrise:* ***10***
- *Major instruments (Herschel, Planck, MIRI)*

Plus:

- *TBD Scout, Discovery, Explorer, ESSP, New Frontier, Einstein probes*
- *InSAR*
- *Project Prometheus*
- *Lunar Lander*

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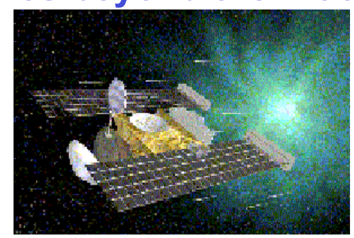
Our vision:

JPL's legacy by 2020

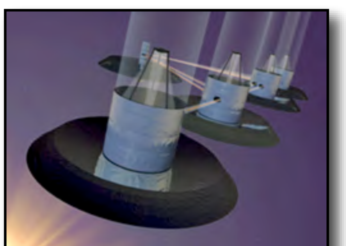
Established a continuous presence *around* and *on the surface* of Mars

Explored the Jovian and Saturnian satellites in detail and probed their surfaces and interiors for possible pre-biotic and life-favorable environments.

Returned first samples from other solar system bodies beyond the moon.

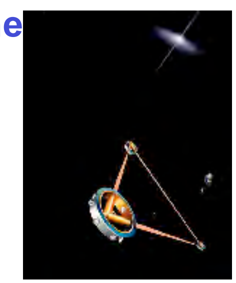


Began exploring neighboring solar systems.

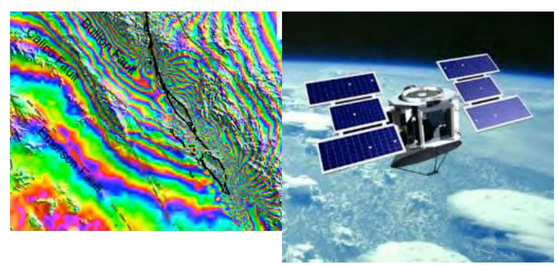


Enabled efficient access to all the bodies of the solar system

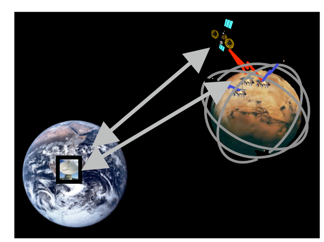
Explored the boundaries of physics to understand the forces that powered the Big Bang



Established operational capability to monitor dynamics of solid Earth and its oceans and atmosphere.

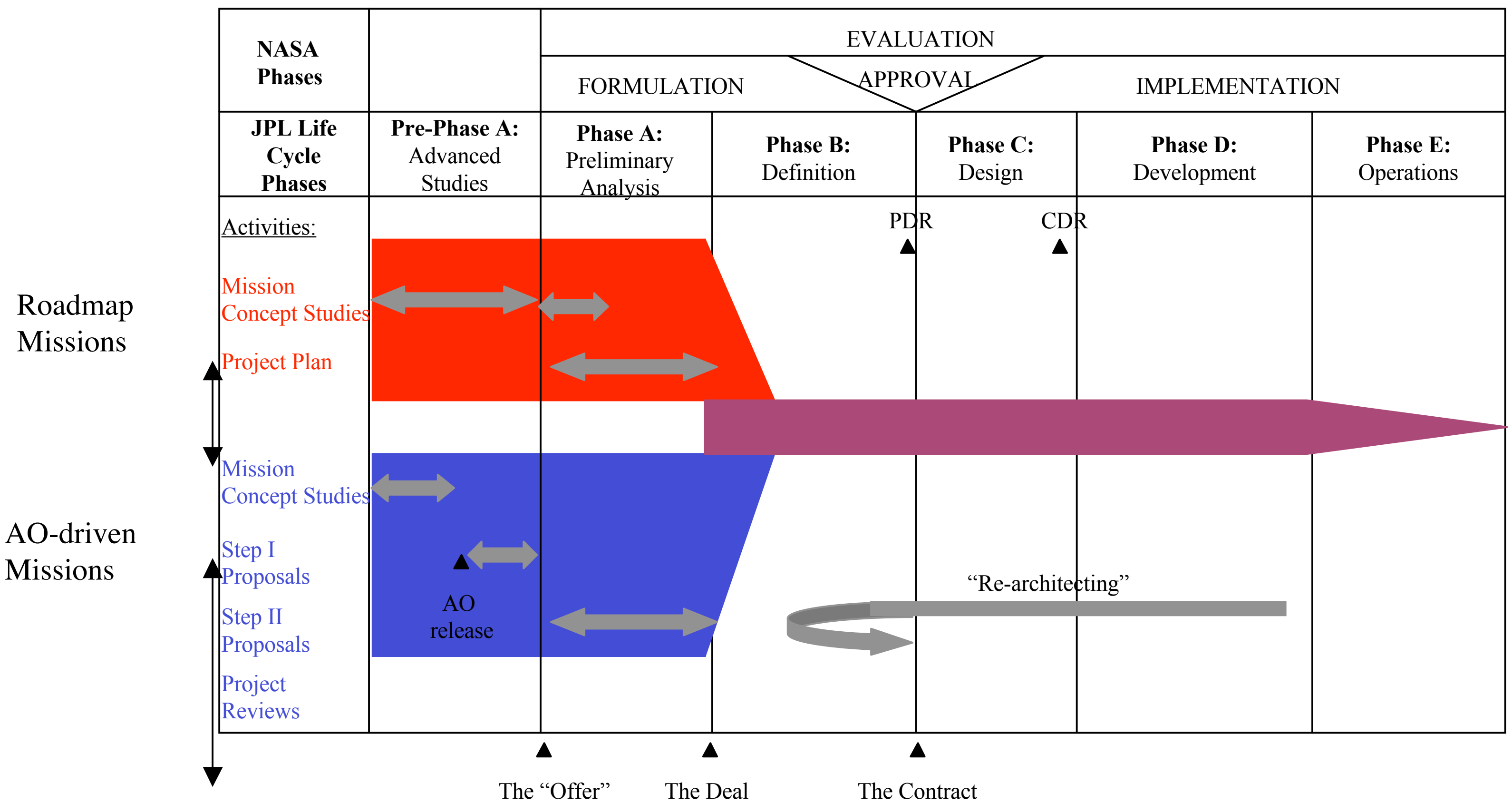


Established the Interplanetary Network, which is being commonly used by students.

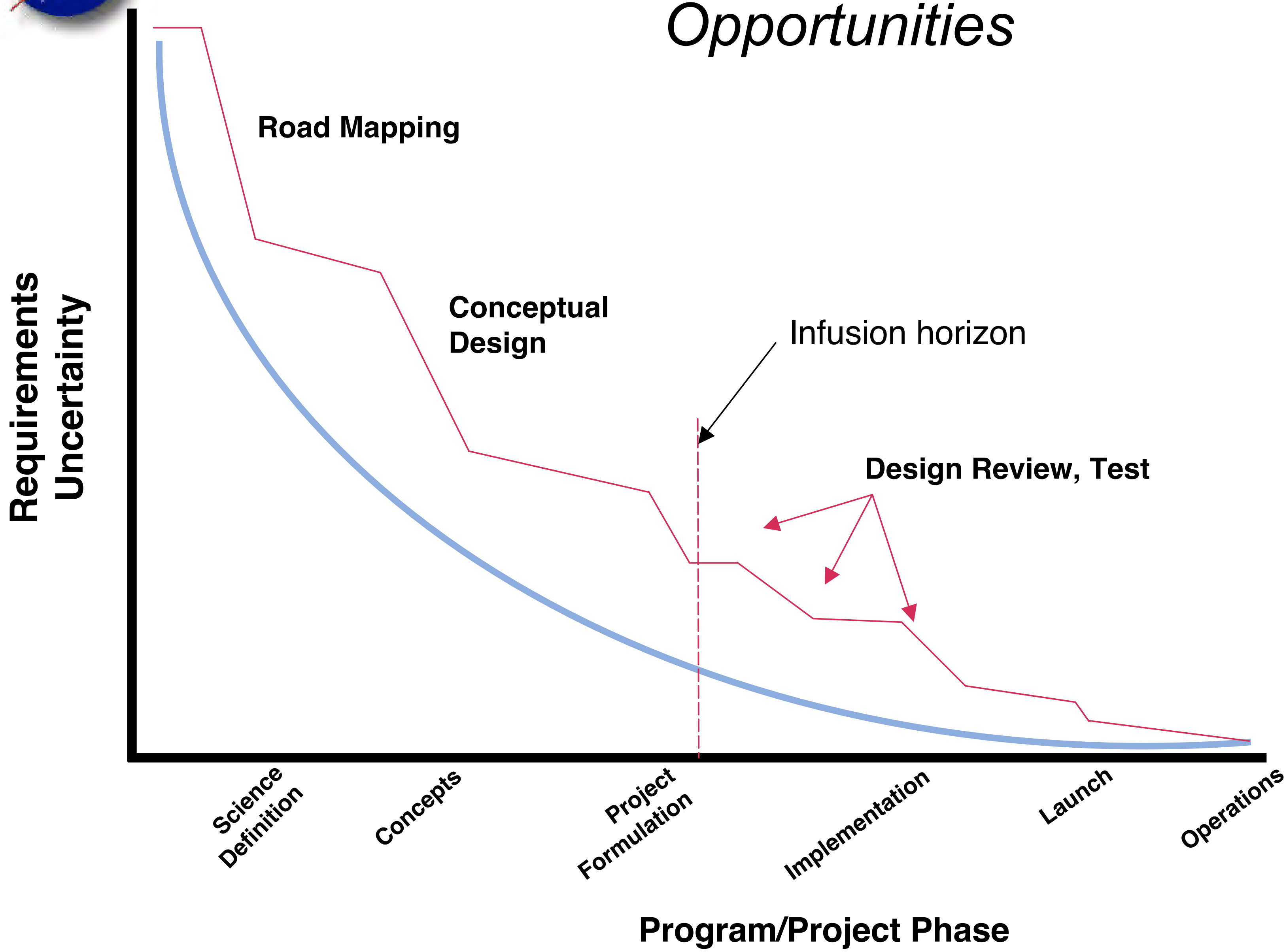


Future Desired State

The JPL Project Life Cycle: Project Architecture

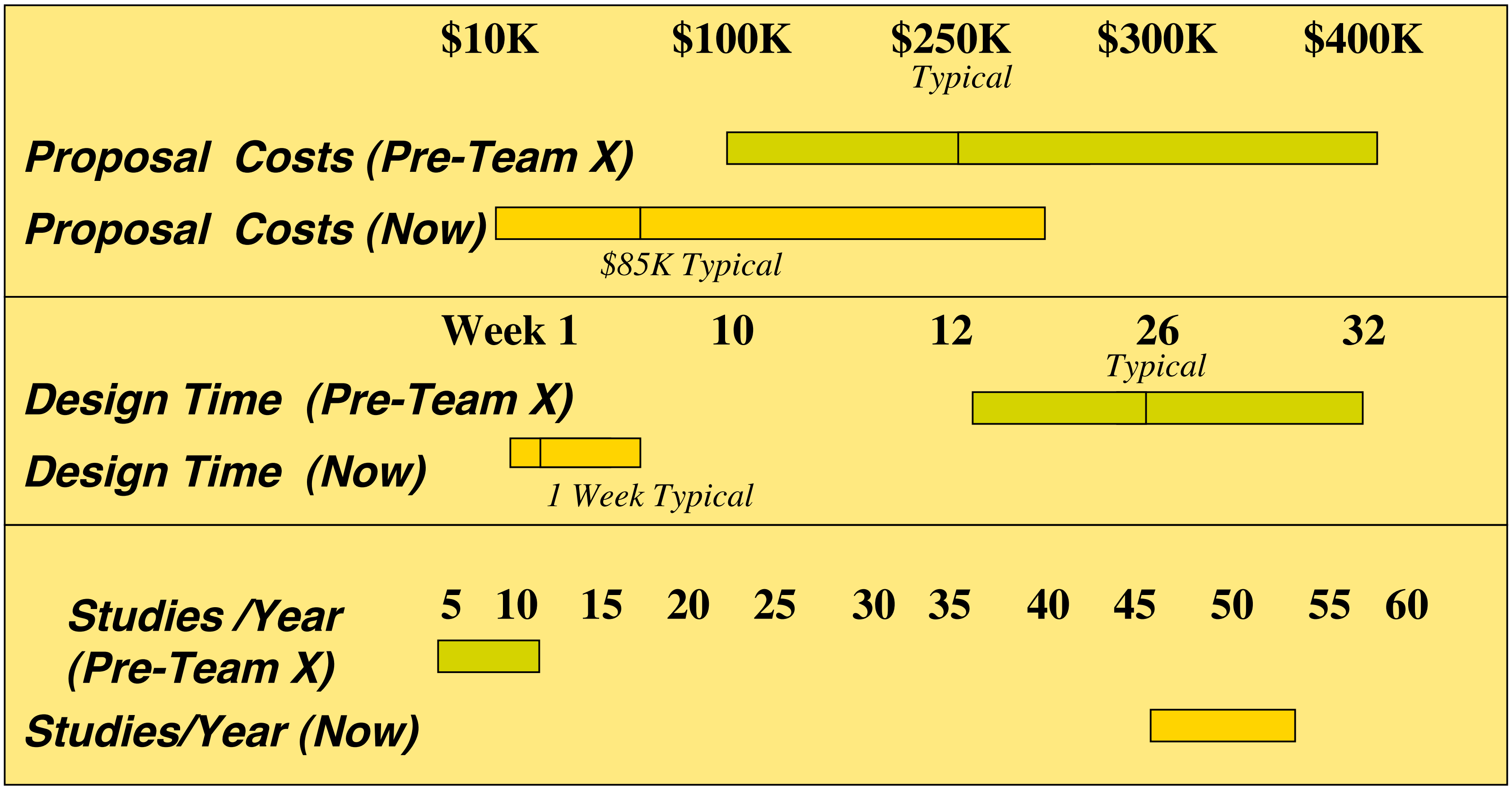


Technology Infusion Opportunities



Benefits of Team X Design Approach

Mission Studies*



* Phase-A Conceptual Mission/Spacecraft Designs

Elements of Early Formulation Design Product

- **Mission Overview**
- **Science Objectives**
- **Quad Chart**
- **Technology Needs and Assessment**
- **Project's Relation to Program**
- **Mission Requirements**
- **Project System Description**
  - *Key Drivers (hardware & software)*
  - *Redundancy*
  - *Fault Protection Concept (hardware & software)*
  - *Architecture*
  - *Software Architecture*
  - *System Trades*
  - *Flight System Mass Breakdown (w. margins)*
  - *Flight System Power Breakdown (w. margins)*
  - *End-to-End Information System Concept*
  - *Data Return Budget and Margins*
  - *Design Principles Exceptions*
  - *System Margin Summary: mass, power, cost, performance*
- **Mission Description**
  - *Environmental Conditions*
  - *Key Drivers*
  - *Mission Trades*
  - *Orbit and Trajectory (w. margins)*
  - *Navigation Concept*
  - *Launch Vehicle: Packaging, Mass and Margin; Stowed Configuration; Launch Strategy*
- **Payload Conceptual Design**
  - *Payload Configuration Diagram (s), Stowed and Deployed*
  - *Block Diagram*
  - *Heritage (hardware & software)*
  - *Mass (w. contingency)*
  - *Power (w. contingency)*
  - *Size (w. contingency)*
  - *Data Rates*
  - *Pointing Characteristics*
  - *Thermal Characteristics*
  - *Software Description*
  - *Technology Maturity Matrix*
- **Flight System Descriptions (bus, lander, etc.)**
  - *Configuration Diagram (s), Stowed and Deployed*
  - *Subsystem Concepts & Block Diagrams*
  - *Heritage (hardware & software)*
  - *Mass (w. contingency)*
  - *Power (w. contingency)*
  - *Size*
  - *Downlink/Uplink Rates*
  - *Pointing Capability*
  - *Thermal Capability*
  - *Software Description*
  - *Technology Maturity Matrix*
- **Mission Operations Concept**
  - *Concept Description*
  - *Key Drivers*
  - *Operations Scenario*
  - *Flight/Ground Interface*
  - *Overview of Mission-Critical Scenarios*
  - *Ground Data System*
  - *DSN Support or Other Ground Stations*
  - *Software Description*
  - *Data Archive Concept*
  - *Technology Maturity Matrix*
- **Project implementation Approach**
  - *WBS, WBS Dictionary*
  - *Implementation Approach (who does what)*
  - *Project Organization Chart*
  - *JPL Workforce Estimates*
  - *Project Schedule*
  - *Planetary Protection Strategy*
  - *Launch Approval Strategy*
  - *Outreach & Commercialization Plan*
- **Constraints**
- **Requirements Flowdown/Mission Traceability Matrix**
  - *Science -> Mission -> System*
  - *Requirements and Constraints Compliance Matrix (L1 requirements, HQ, programmatic, institutional)*
- **Verification/Validation Description**
  - *ATLO*
  - *Environmental Qualification*
  - *Mission V&V*
  - *Software*
  - *Fault Protection*
- **Technology Development Approach**
  - *Technology List*
  - *Technology Readiness Levels (TRL's)*
  - *Key Technology Descriptions*
  - *Technology Development Milestones*
- **Risk Management Approach**
  - *Risk Assessment and Mitigation Strategy and Risk Rating*
  - *Risk List*
- **Costs and Risk Summary**
  - *Cost-Risk Estimates by Phase and WBS (w. reserves)*
  - *Schedule Risk (w. reserves and critical path identified)*
  - *Design-to-Cost-Risk Trades*
- **Institutional Impact Assessment**
  - *Workforce Needs*
  - *Facilities*
  - *DSN Usage*
  - *Budget*
  - *% Probability of Proceeding to Implementation*

Science Traceability Matrix

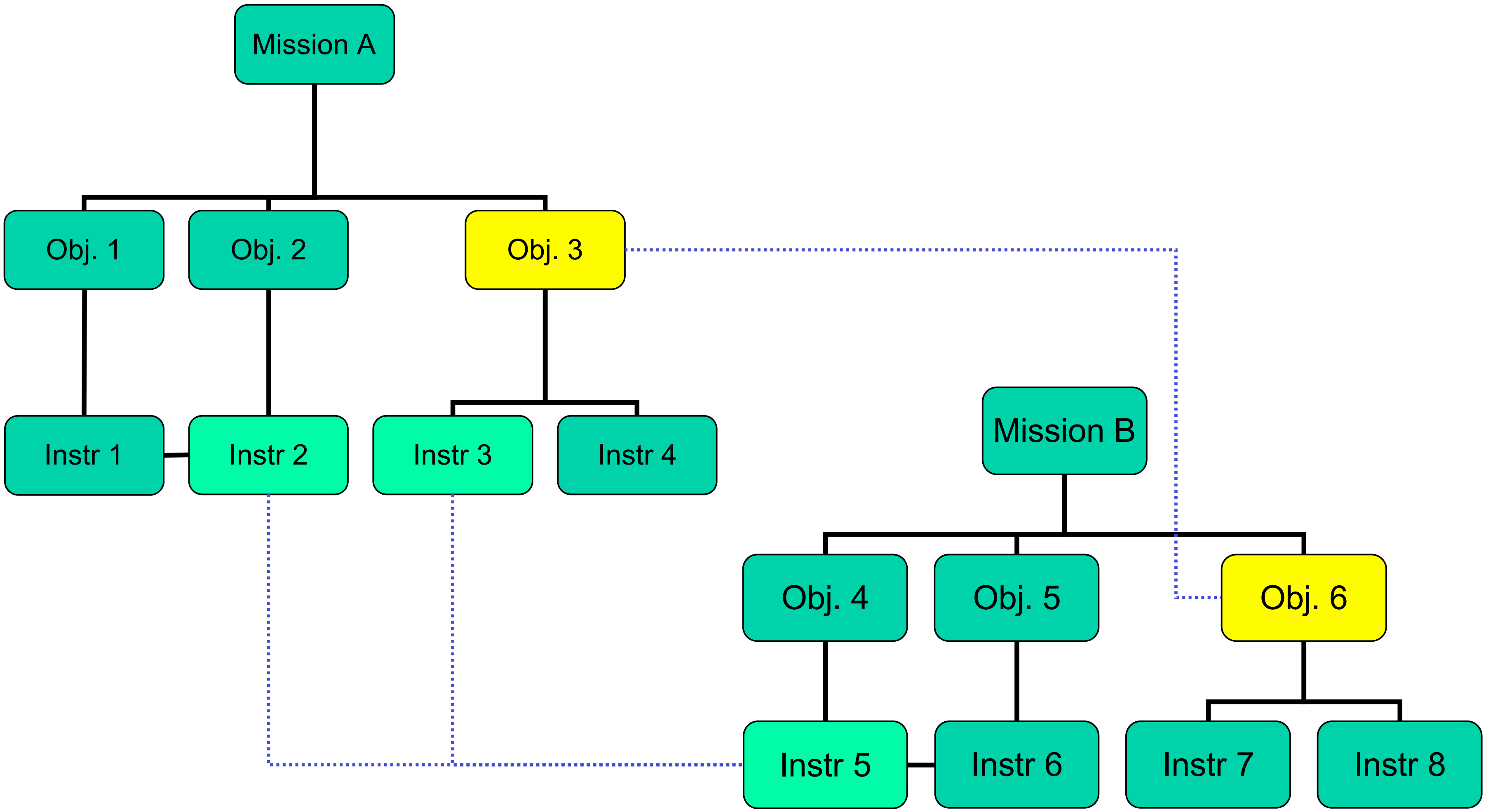
Mission A

Science Objectives Surface Station	Measurement Objectives	Measurement Requirement
Associate internal properties of PLD with mass accumulation at the surface	Determine rates of accumulation/ablation of CO_2, H_2O and Dust	5 micron continuous layer of H_2O, and Dust (<1/2 atmospheric column's worth of material), 1 mm CO_2 depth/mass equivalent.
	Estimate annual net CO_2, H_2O and Dust accumulation/ablatio[…]	<1 micron continuous layer equivalent of CO_2, H_2O and Dust.
	Determine fine-scale structure and morpho[…] seasonal frost layer	
	Relate fine-scale mor[…] and structure to curre[…] climate	

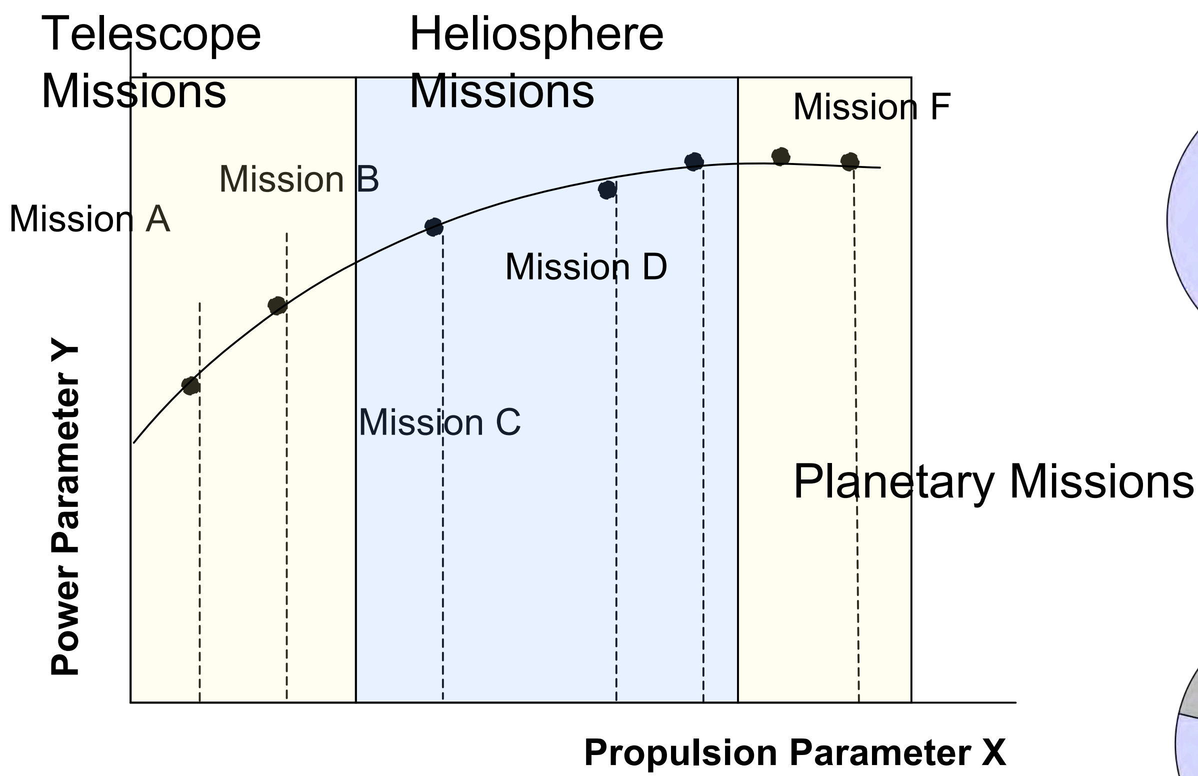
Mission B

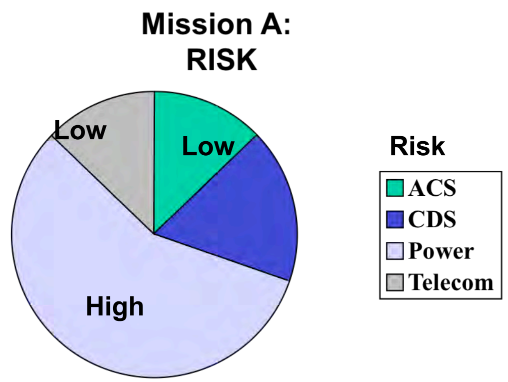
Science Objectives	Measurement Objectives	Instruments	Mission Requirements	Measurement Requirements	Data Products
Explore the nature of the interstellar medium and its implication for the origin and evolution of matter in the galaxy and the universe	1) Measure dynamic properties, elemental and isotopic composition of the interstellar gas.	ISN, PIC	Must reach the ISM to detect low-FIP ions.	PIC:100 eV-50 keV ISN:50 eV/amu 0.5 keV/amu	Velocity distributions of all neutral components. Detailed composition for neutrals in the ISM.
	2) Measure dynamic properties, elemental and isotopic compsotion of interstellar plasma	ISP	Must reach the ISM beyond the heliopause (>150AU).	ISP:50 eV/amu-0.5 keV/amu	Velocity distributions of all ionized components. Detailed composition for the ISM plasma.
	3) Maesure dynamic properties, elemental and isotopic composition of interstellar dust.	DCE, DUS	Must reach beyond heliopause to detect low-mass dust grains.	DUS: 0.5 micron -10 micron DCE:0.5 micron -10 micron	Mass distributions, dynamic properties of dust grains. Detailed elemental and isotopic composition.
	3) Measure the magentic field in the local ISM.	MAG	Must reach the ISM beyond the heliopause (>150AU).	MAG:0.1 nT-10000 nT	Magnetic field magnetude, direction and variability.
	4) Measure composition of low-energy GCR.	CR, APT	Must reach far enough away from the heliopause to detectlow-energy cosmic rays (>150AU).	CR:10 Mev/amu-5 GeV APT:10 MeV- 200 MeV	Energy distributions, detailed composititon of GCR.
Explore the influence of the interstellar medium on the solar system, its dynamics and its evolution	1) Determine the spatial scale of the heliosphere and its boundaries.	SWI, SWE, EPD, MAG, WAV, ENA, CR, UV	Must cross all relevant boundaries up to the heliopause (>150 AU).	SWI:100 eV-10 keV SWE:100 eV-50 keV EPD:10 keV/amu-10 Mev MAG:0.1 nT-10000 nT WAV:Frequency range < 5 kHz. ENA:5 keV-1 MeV CR:10 Mev/amu 5 GeV	Solar wind, plasma, field and energeticv particle distributions.
	2) Measure the dynamic evolution of the solar wind and energetic particles as a function of heliosheric distance.	SWI, SWE, EPD, MAG, WAV, ENA, CR, UV	Must have 80% coverage in the range of 80-150 AU.	SWI:100 eV-10 keV SWE:100 eV-50 keV EPD:10 keV/amu-10 Mev MAG:0.1 nT-10000 nT WAV:Frequency range < 5 kHz. ENA:5 keV-1 MeV CR:10 Mev/amu 5 GeV	Solar wind, plasma, field and energeticv particle distributions.
	3) Measure the solar wind and energetic particle distribution at a miimum of two locations.	SWI, SWE, EPD, MAG, WAV, ENA,	Must have multi-point observations, with dropped probe.	time-resolution < 5 minutes, contemporary	Contemporary, two-point solar wind, plasma, field and energeticv particle distributions.
	4) Measure the spatial and temporal evolution of pickup ions in the solar wind.	PIC, MAG, SWI, ENA, CR	Must enable pickup ion measurements from 10 AU to heliospheric boundaries.	PIC:100 eV-50 keV SWI:100 eV-10 keV MAG:0.1 nT-10000 nT ENA:5 keV-1 MeV CR:10 Mev/amu-5 GeV	Pickup ion distribution functions, composition information.

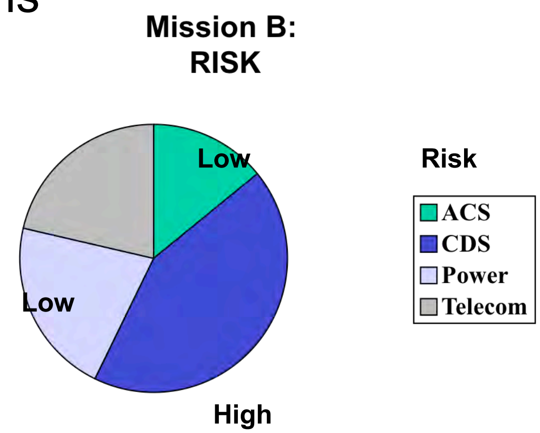
Science Traceability Tree



Parametric Performance Trends





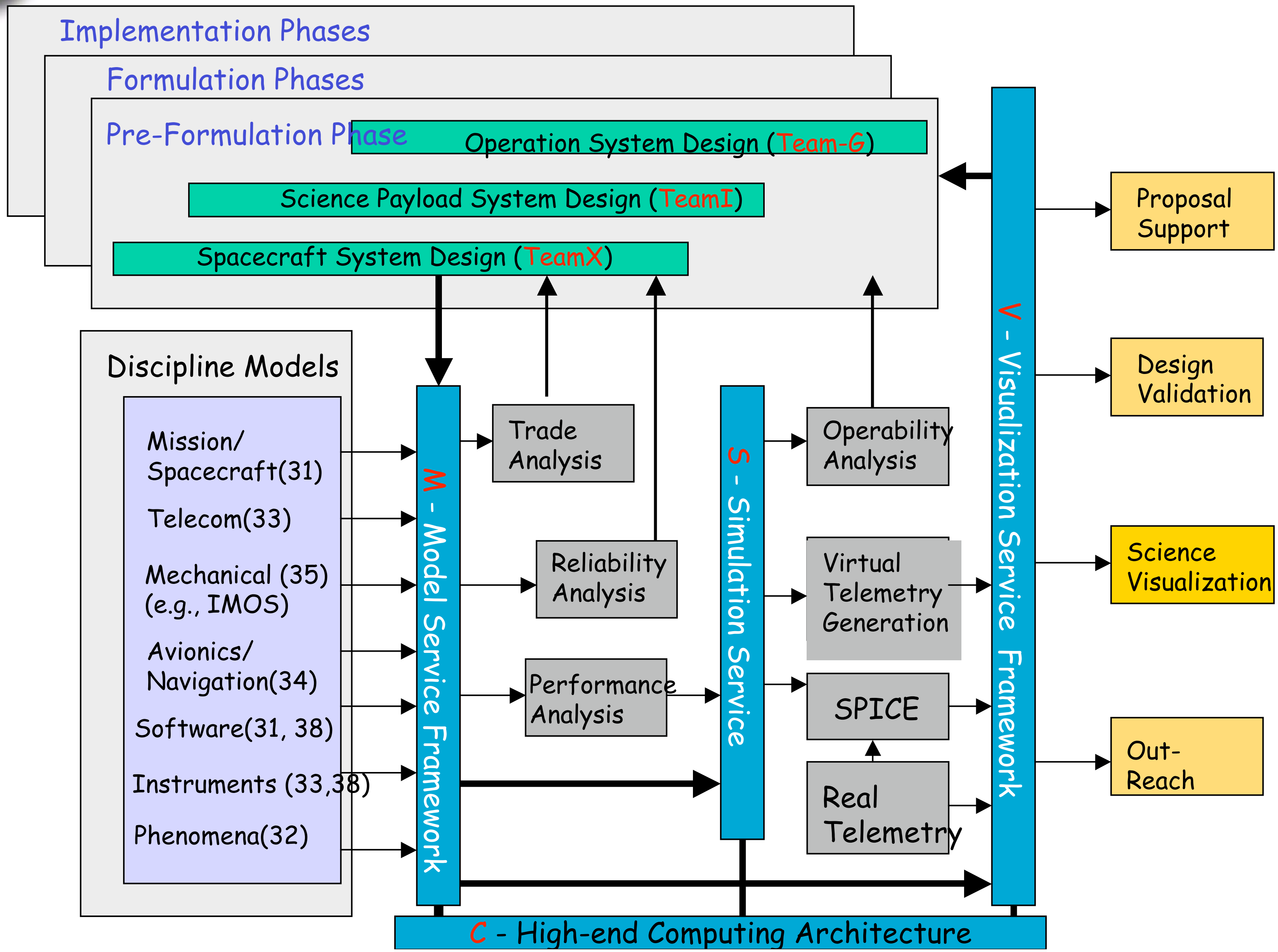


Future Desired State

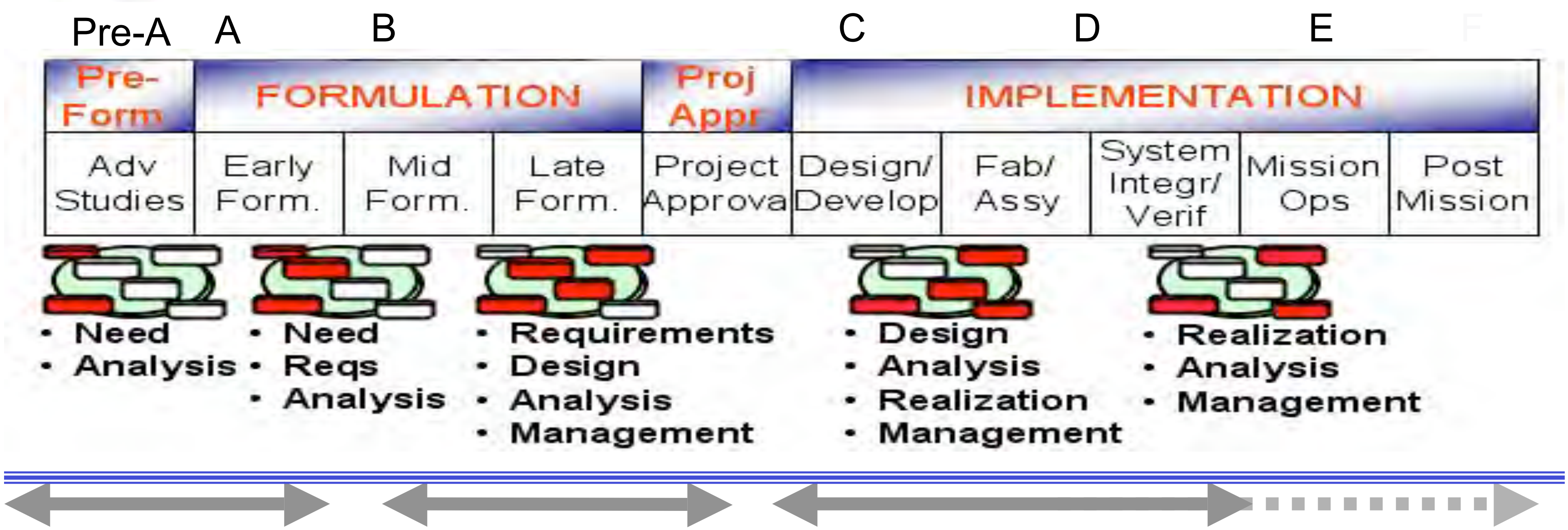
Team X and Design Collaboration

- Key issues and challenges
  - *Rapid design process occurs mostly in sidebars and between subsystems or at system/subsystem interface*
    - *Sidebars are spontaneous and dynamic (design as negotiation)*
    - *Decision latency is critical measure*
  - *Need for distributed design is increasing*
    - *More players, more complexity (including contractual), more regulations (e.g. ITAR), less money*
  - *Currently, distributed design is **not** concurrent*
    - *Poor infrastructure*
    - *Lack of sidebar interaction*
    - *Multipoint interactions still in star configuration (bottlenecks)*
    - *Design quality/speed/cost/consistency all suffer*
  - *Solutions require both*
    - *New design infrastructure*
      - Emphasis on reliability, resiliency
    - *New design process?*

Process and Capability Providers



The Model-based Vision:
Fidelity that varies with Mission Phase

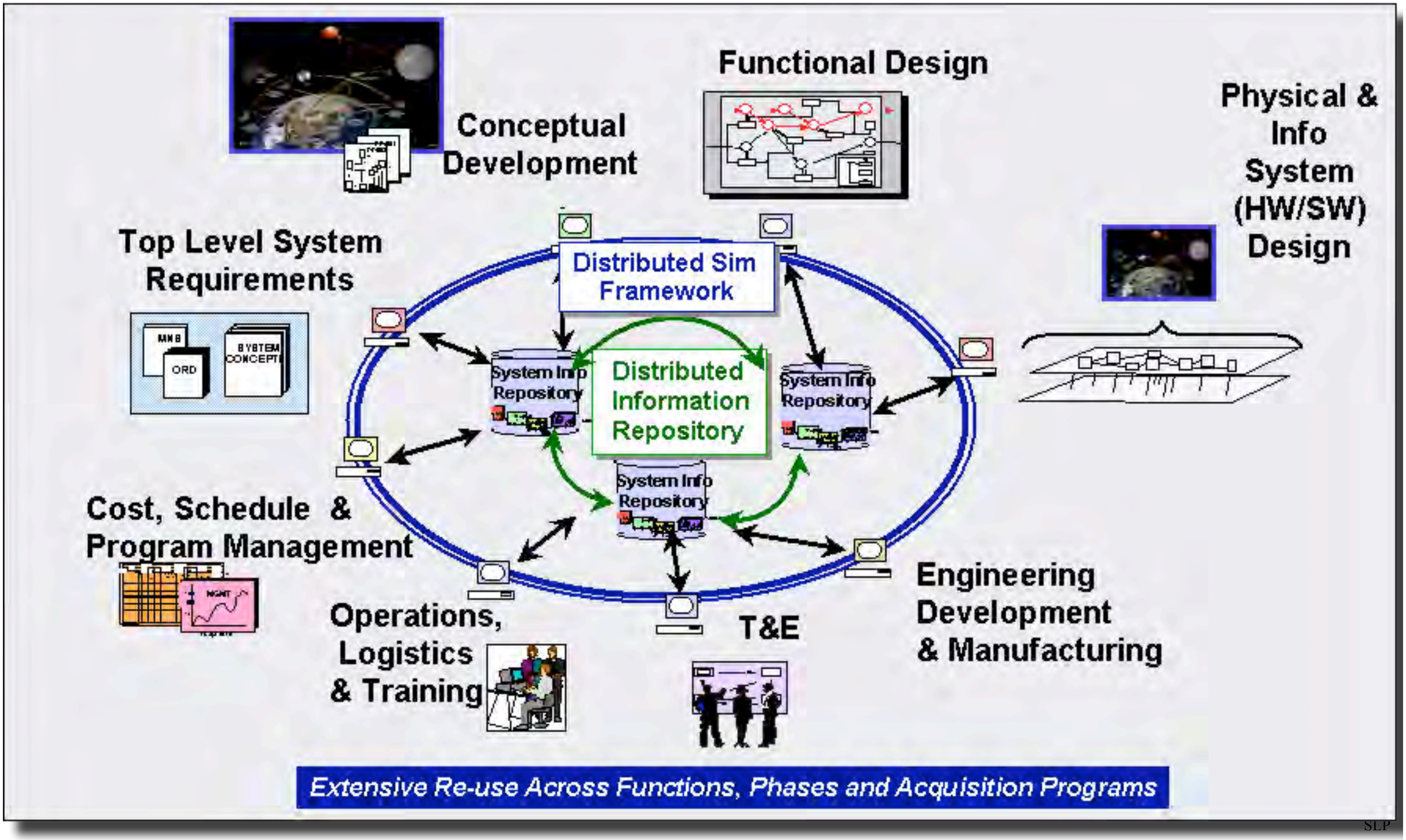


- •Broad, shallow, fast
- •Architectural Models (PDC/IDC)
- •Excel, linked functional models

- • System requirements and subsystem design models
- • Define subsystem behavior
- • Operational Analysis to validate science

- •Deep, narrow focused models
- • Integrated Models in "Foundry" tools (e.g., MCAD, ECAD, Software)
- • Define subsystem content
- • Behavior modeled in analysis tools (e.g., NASTRAN)
- •Operations-level models

Classic SBA - a Full-Lifecycle View



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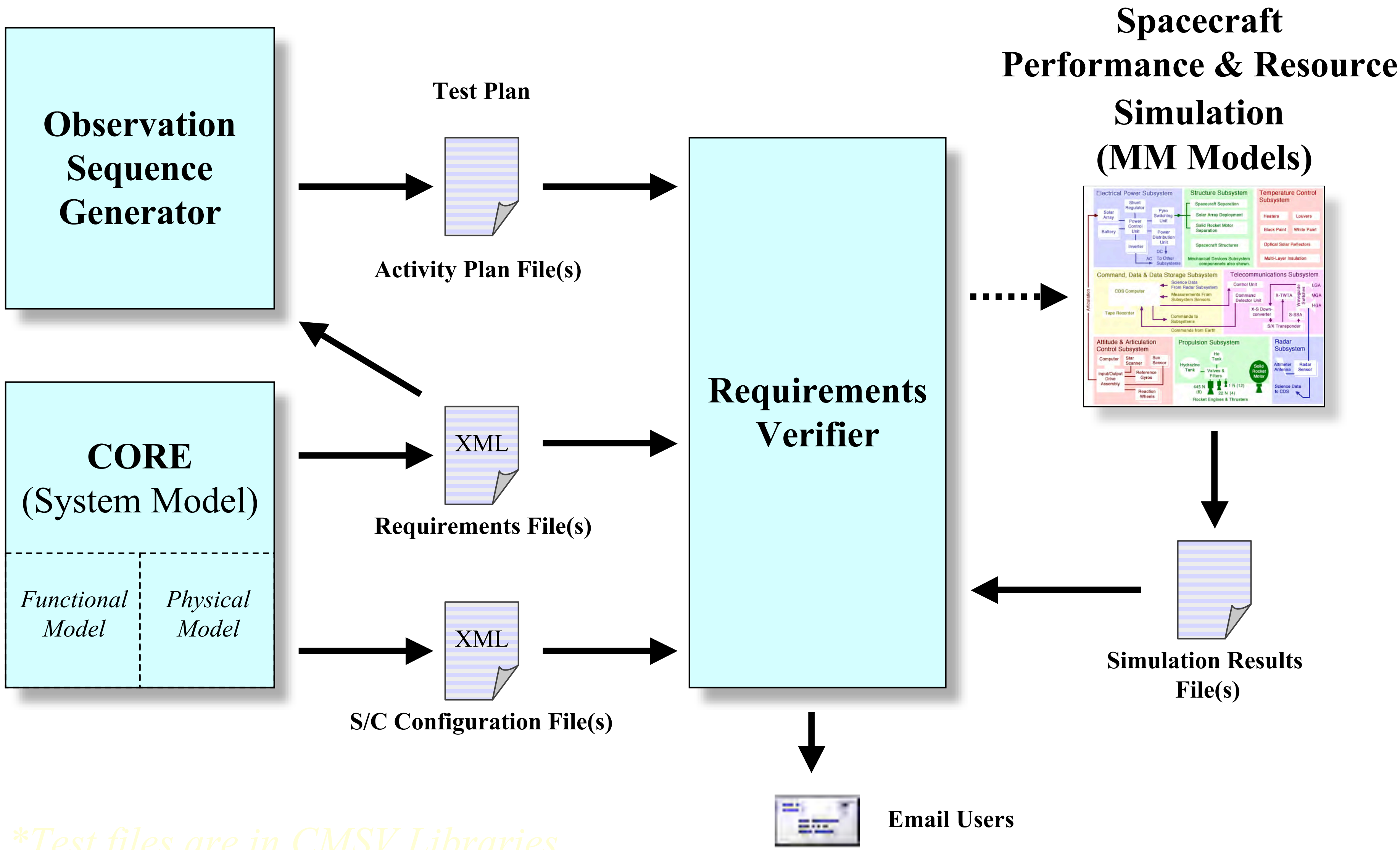
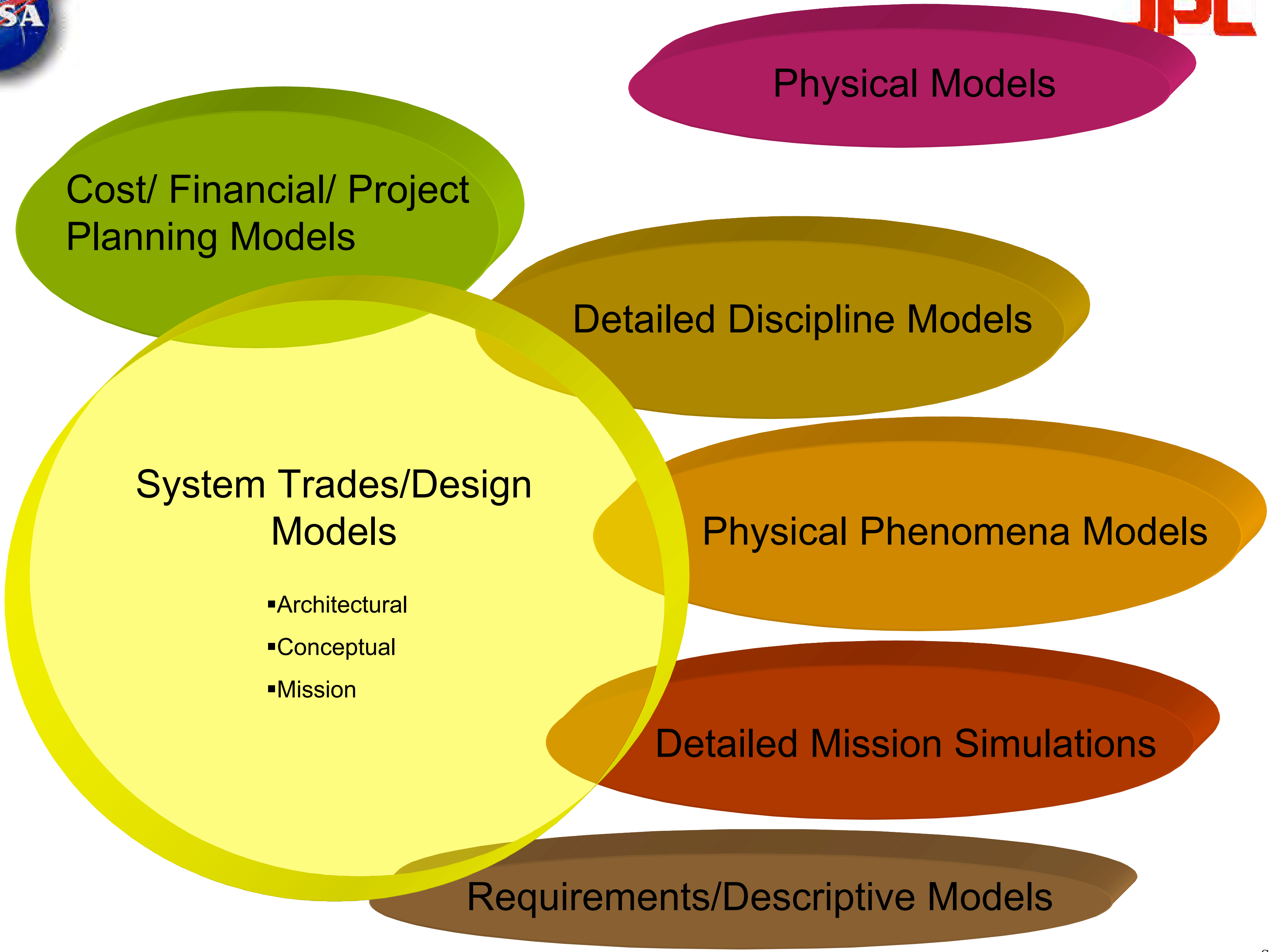
Model Based Design
Formulation Phase Concept



Context in Greater JPL Modeling Landscape

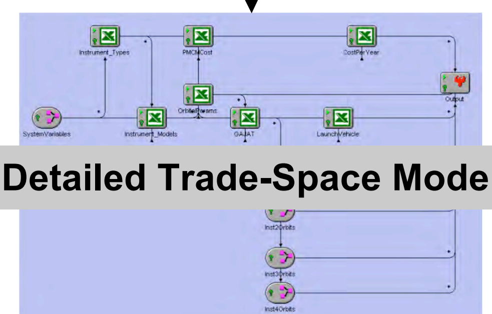


MBED Process

Define Trade-Space Variables

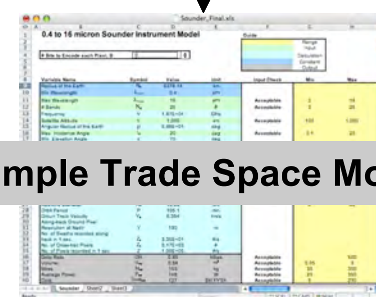
- Science Measurements
- Cost
- No. spacecraft
- Targets
- Instruments
- Trajectory
- Rover range
- Landing accuracy
- Coverage
- Launch vehicle
- **Etc.**
- **Etc.**

Detailed Subsystem Models



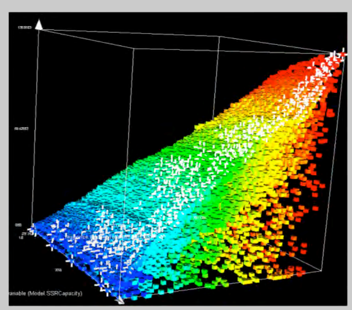
Detailed Trade-Space Model

Team X Study
Extract design sensitivities



Simple Trade Space Model

Project Trade Space
Science - Engineering - Cost
(Coming soon: Technology & Risk)



Model-Based Design

- Key issues and challenges
  - *Subsystem Model Integration and Compatibility*
    - *Added complexity = greater model disparity*
    - *Risk (and cost) hides in the interfaces*
    - *Model Credibility varies greatly - and is not necessarily tied to fidelity*
    - *IP issues may dominate*
  - *Design Process (Back-to-Front)*
    - *Models too often are a by-product of development*
    - *Model validation replaces traditional test*
    - *System Engineering no longer CM-focused*
  - *What Models?*
    - *Culture change, particularly for technology*
    - *Greatest uncertainty too often in non-physics based models*
      - Organizational
      - Software
      - Operations

Design Structures - Current Approach

(Mission/Science)
Requirements
Constraints
Priorities

SS Characteristics

Design Attributes

System
- Decomposition
- Requirements
- Allocations
  - Mass
  - Power
  - Data/Comm
- Margins

Power
- Array
- Battery
- PMAD

Propulsion

Communications

- Metrics (at various levels)
- I/F Specs
- Drawings
- Models
- Risks
- Costs

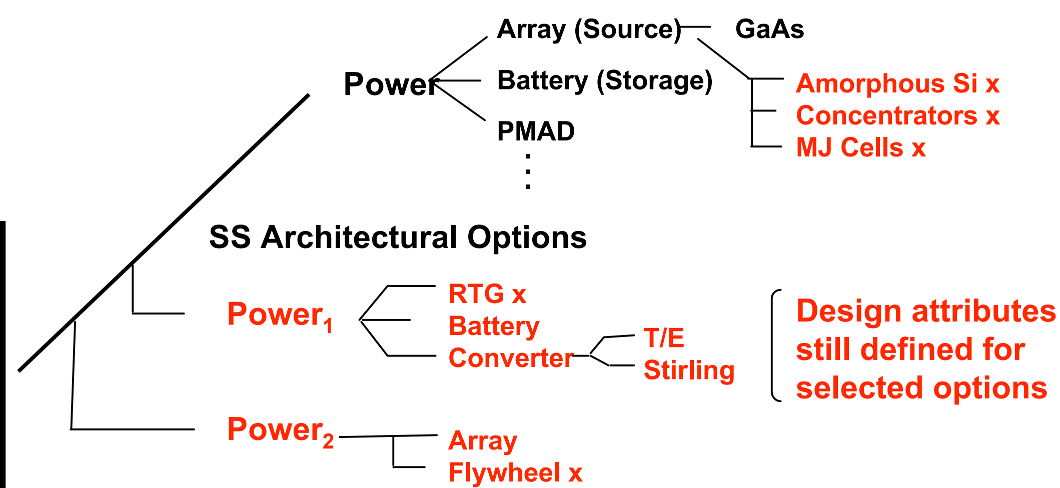
Limitations of Current Design Structures

- Static representation (point design)
- Lacks rationale (challenged only as result of exceeding resources)
- Lacks sensitivities
- Not evolvable nor easily modified
- Cannot determine design(er) performance, assumptions, biases, considerations, etc.
- Difficult to understand context in apples-to-oranges comparisons
- Not compatible with trade processes addressing significant breadth or uncertainty (e.g. long-term horizons)

Decision Content in Design Structures

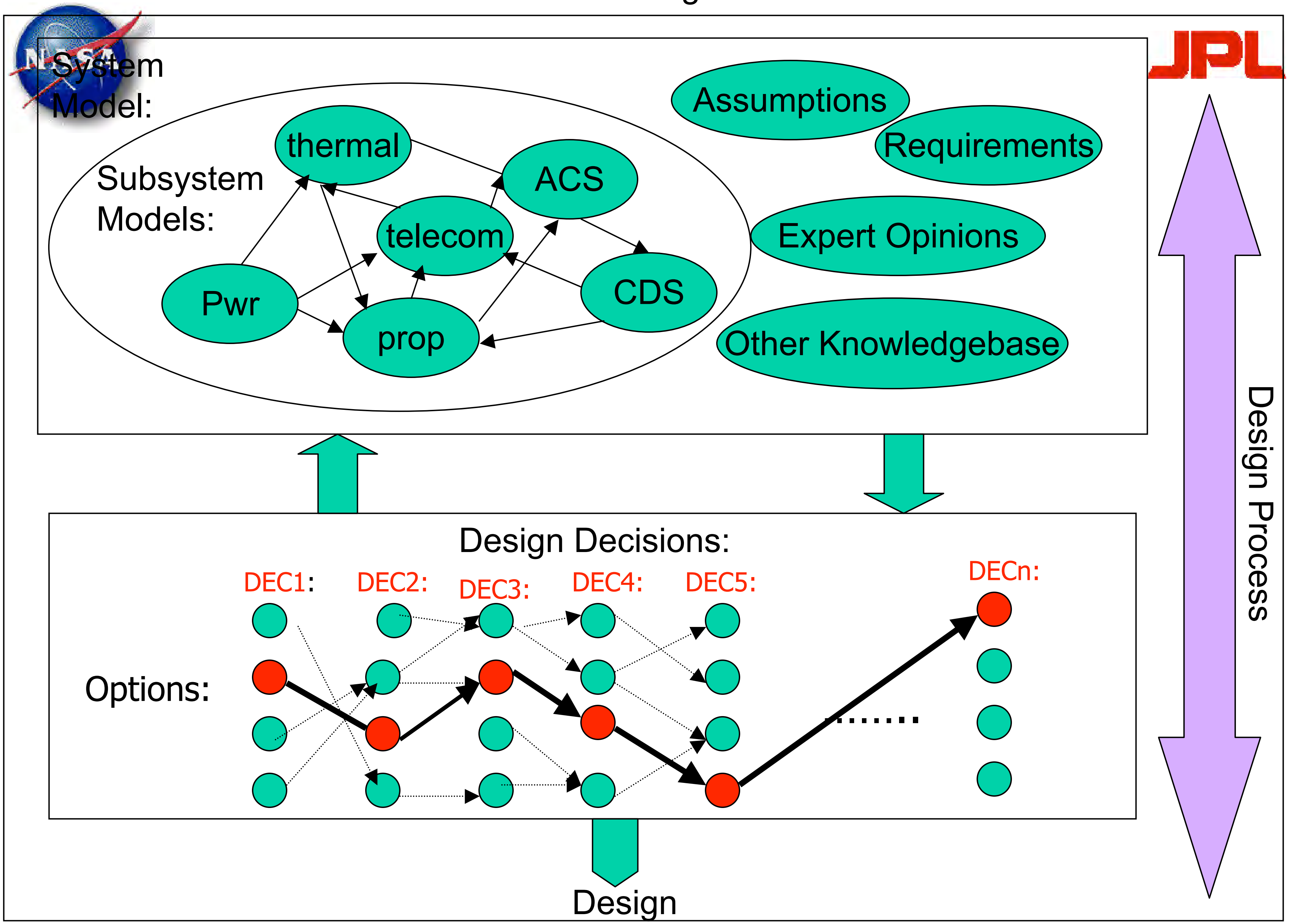
Weighted Mission/Science Requirements, Priorities, and Constraints

System
- Decomposition
- Requirements
- Allocations
- Margins



x: Options considered, rejected, and documented

Decision Based Design Structure:



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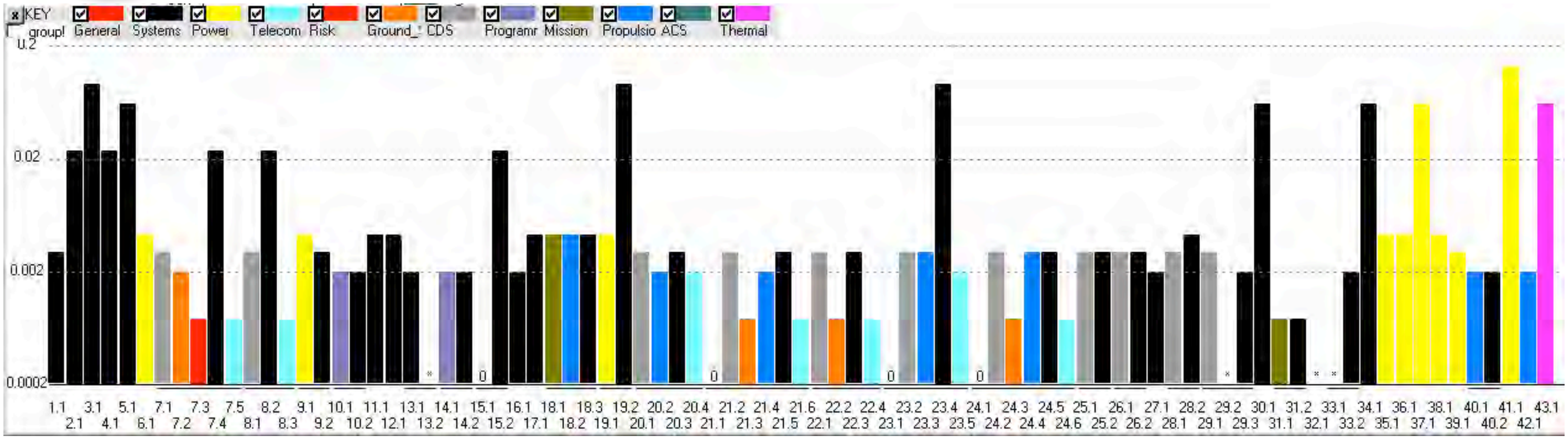
Advantages of Decision-Based Structures

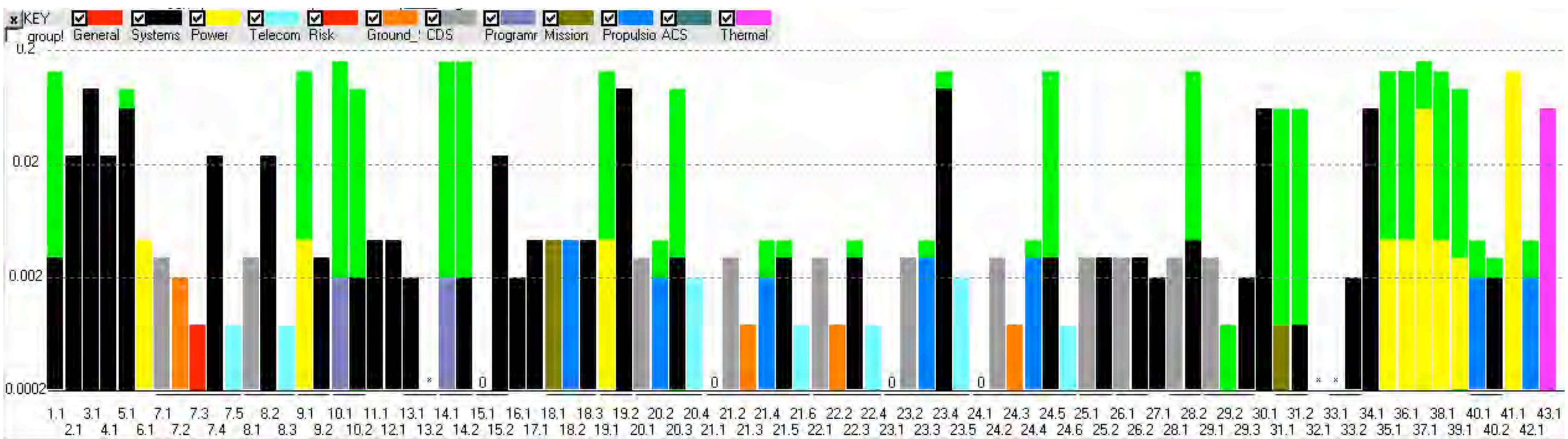
- Can be dynamic (executable?)
  - *Dependent on sufficient completion of option space*
  - *Others can add to structure (transferable)*
  - *Reusable structures (well-trod paths = libraries)*
- Design visibility (*why*)
- Design(er) performance can be considered
  - *Breadth of knowledge/number of options*
  - *Design consistency*
  - *Bias/accuracy*
- Results are fully *auditable* with reference to
  - *Options considered (any options missed?)*
  - *Design selections (rationale)*
  - *Assumptions/constraints*
    - · *Technology projections*
    - · *Constraint validity and traceability*
    - · *Market maturity and technology availability*
- Comparisons/trade capability
  - *Trade visibility*
  - *Accommodates disparate mission/system trades*
    - *emphasizes common elements of disparate designs*
- Encourages consideration of alternatives
  - *Infusion catalyst*

Backup - Risk and Design Optimization

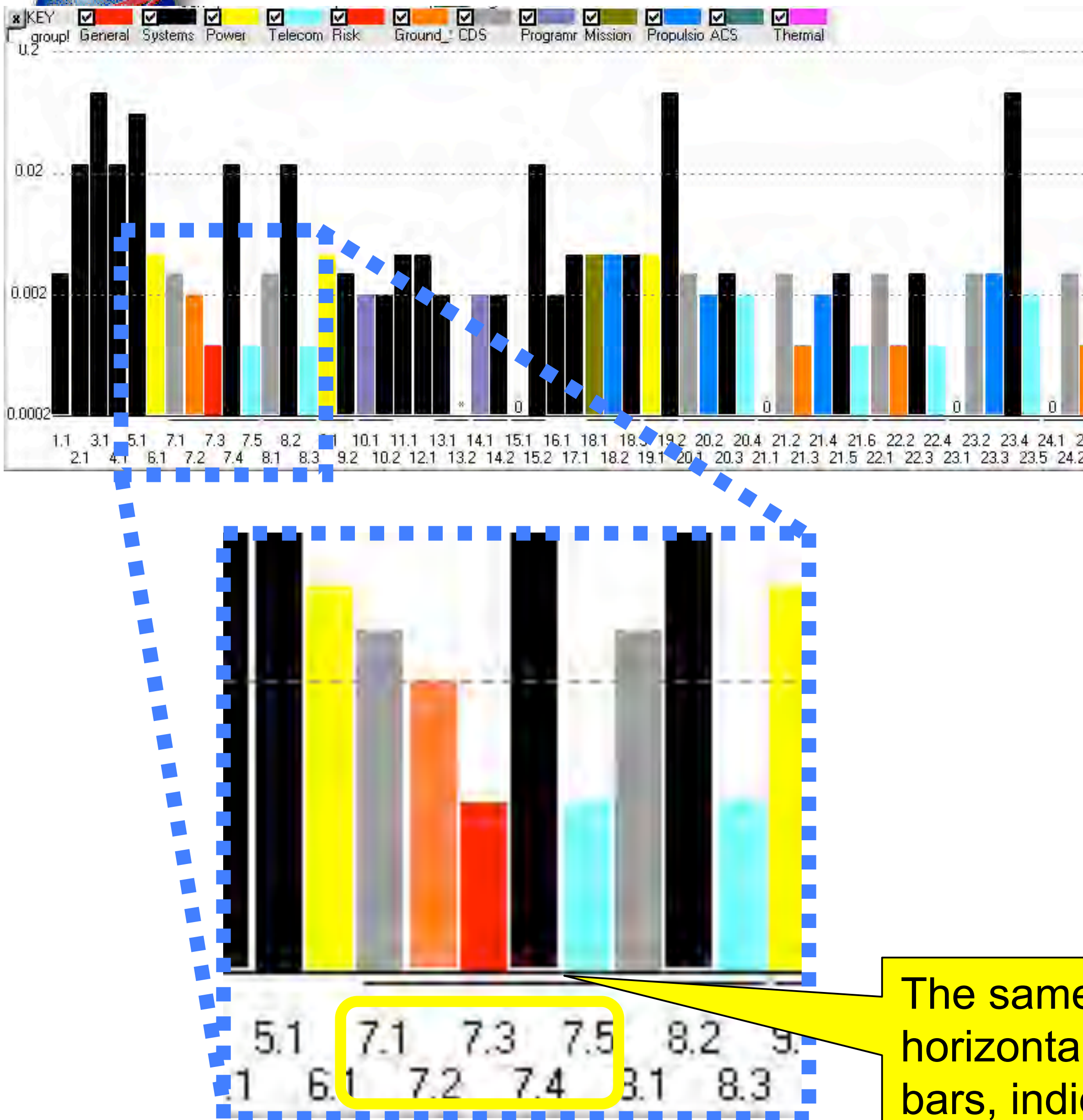
Team X risk data

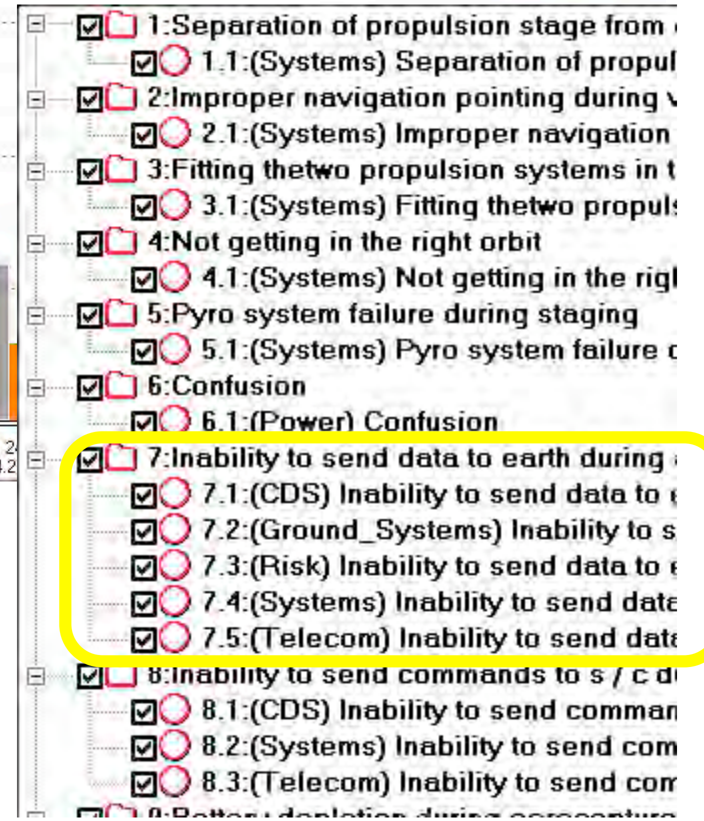


Green = amount by which risks were reduced by Mitigations



Brief explanation of what's being shown





(Textual list of risks)

The same leading digit, and the tiny horizontal line under several adjacent bars, indicates the SAME risk scored by SEVERAL TeamX chairs

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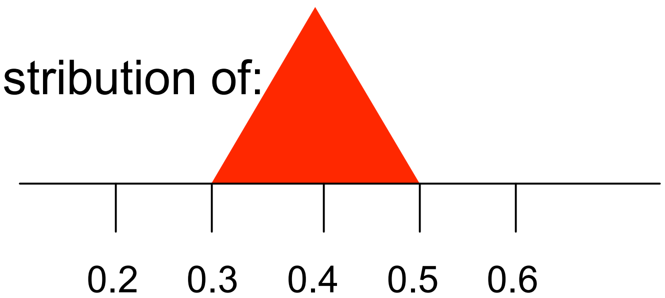
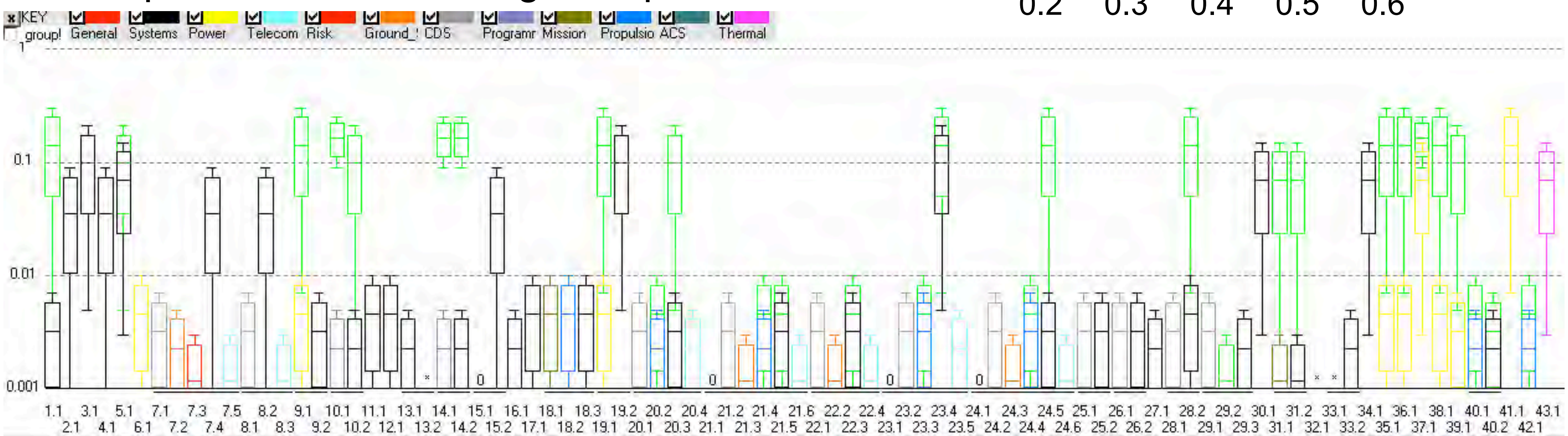
Weak form of probability distributions:

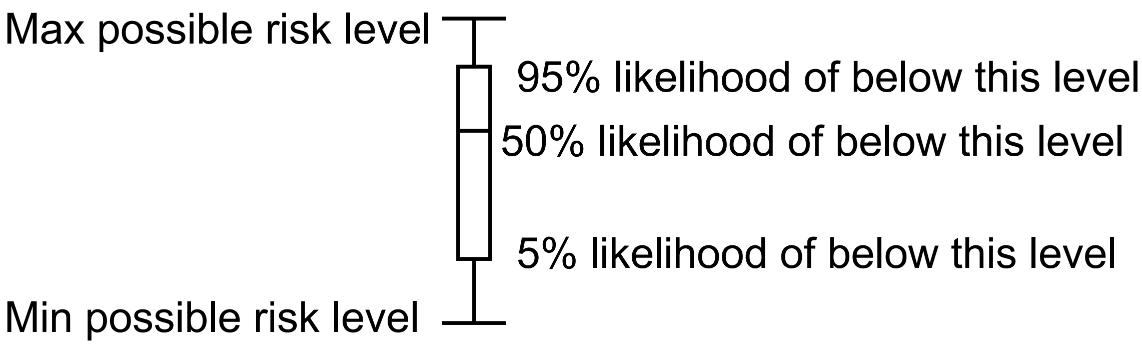
- assume a triangular distribution
(i.e., a risk in the range 0.3 – 0.5 has a likelihood distribution of:



- DDP *approximates* the calculations

- DDP plots the results using “box plots”

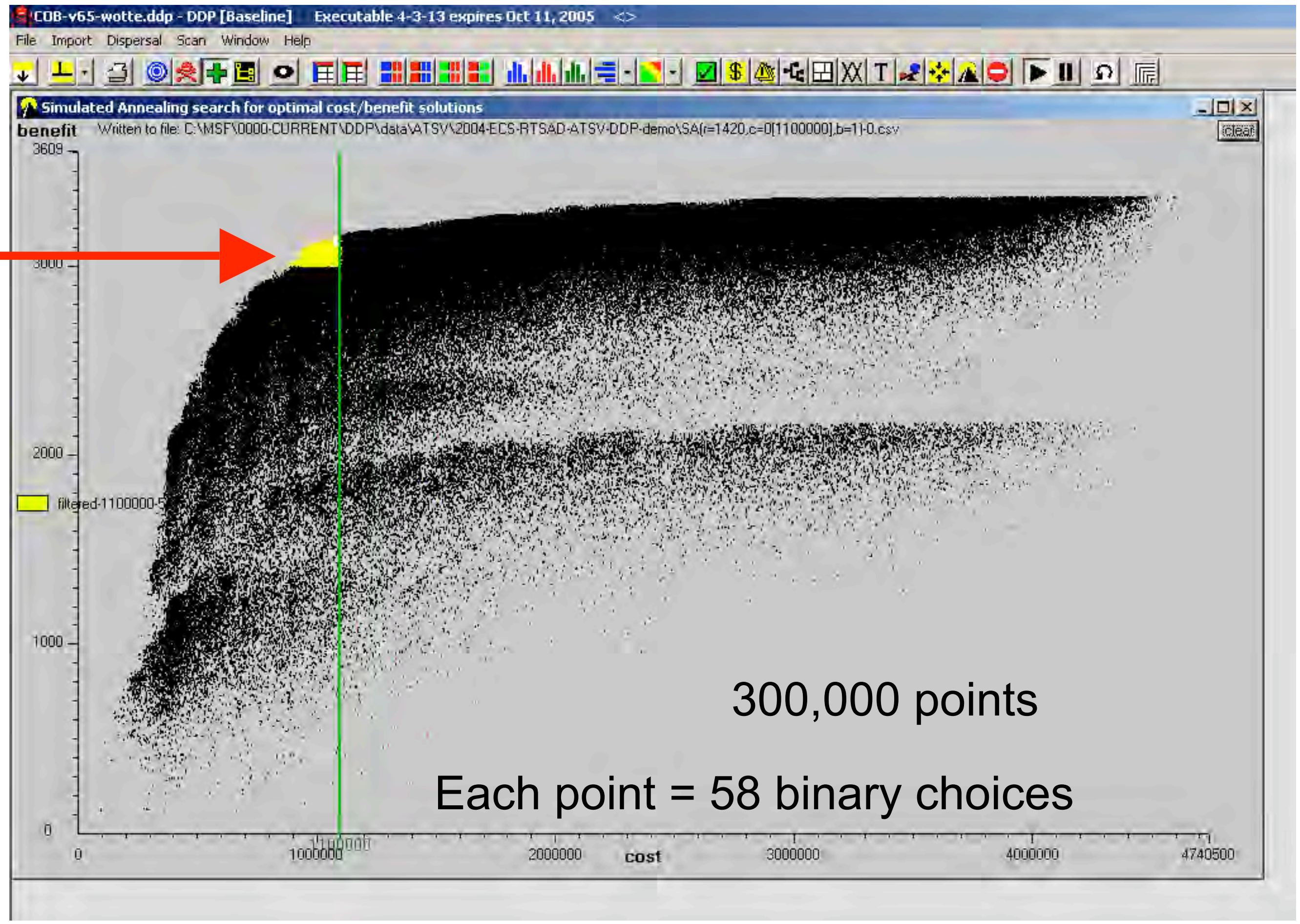




Also saved from earlier is a filtering of all those results to just the following:

Cost no more than $1,100,000, and Benefit of at least 95% of the maximum possible benefit achievable within that cost limit

Here it is!



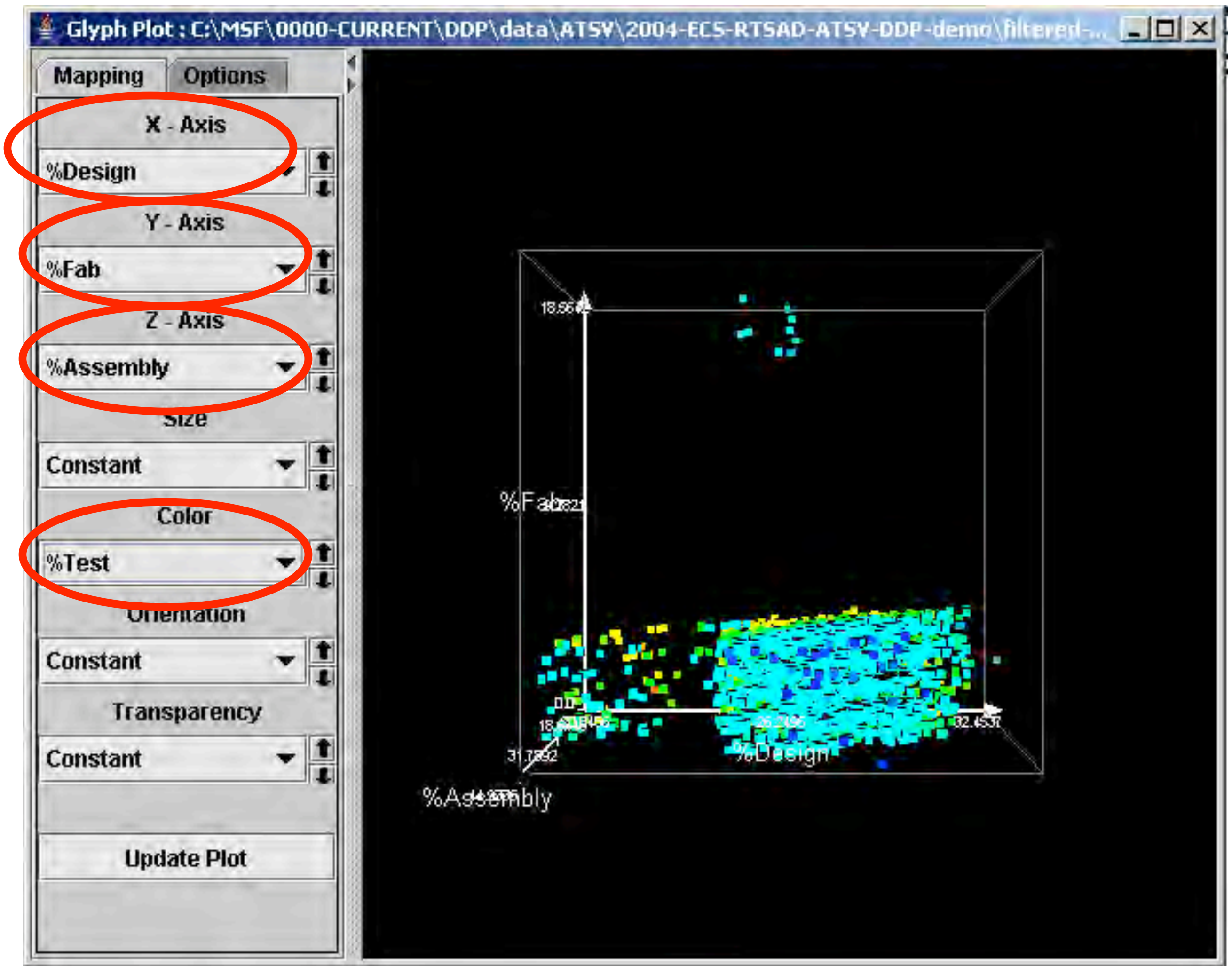
8 continued: Set ATSV to show information

8.3 For the Y-Axis, click its arrow and on the list of options select %Fab
8.4 For the Z-Axis, click its arrow and on the list of options select %Assembly
8.5 For the Color, click its arrow and on the list of options scroll up and select %Test

In the original data, mitigations (the things you can choose whether or not to do) were grouped into:

- Design
- Fab
- Assembly
- Test

Eureka: for a given solution, compute the %s of its mitigation costs in each category.



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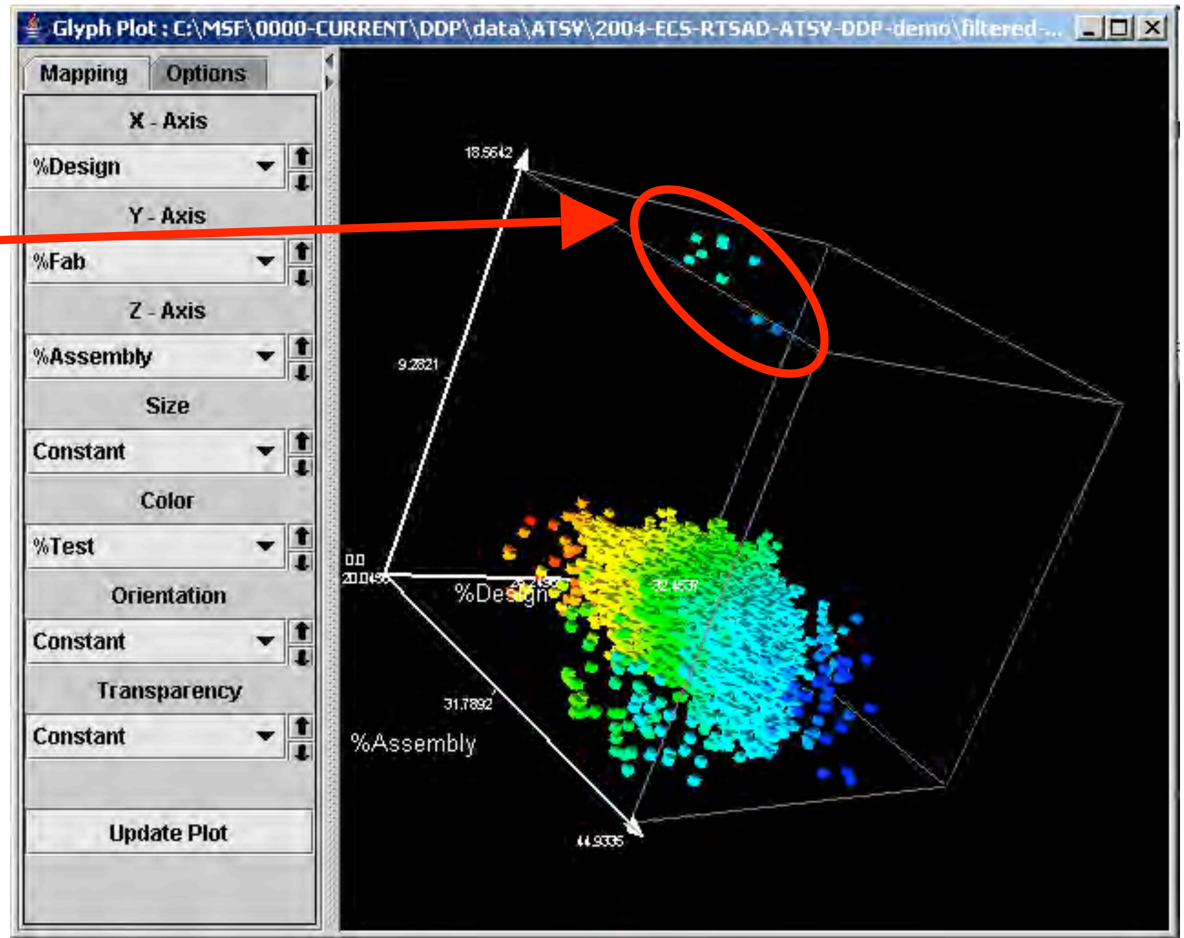
ATSV IS SHOWING YOU OVER 5,000 ALTERNATIVE SOLUTIONS

The 5000+ alternatives in this region are distinct solutions that each cost no more than $1,100,000 and each are within 5% of the maximum benefit attainable in that region.

Design, Fab, Assembly and Test are the different ways the costs can be allocated. %Design, %Fab, %Assembly and %Test, seen here as 3 axes plus color, are the percentage allocations.

Clearly, there are some distinct solution clusters, e.g.,

(Double-click on one of the tiny cubes to see the details of the solution it represents)



ATSV lets the designers understand their options, in this case options among ways to reduce risk.