Value-Based System of System Development

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Background

- Constellation Systems Study
  - Explore the overall architecture and near-term implications for returning to Moon and going on to Mars
    - CEV requirements
    - Transportation system architecture
    - Organization for systems engineering and integration (SE&I)
  - Multiple industry study teams funded by NASA
  - Our team: Draper Laboratory and MIT
- Components of the architecture we studied
  - Launch/transportation, Information system, surface operations, campaigns, software/avionics, safety and risk, enterprise, policy
- 6 month renewable study (12 months total—Sept 04 to Aug 05)

Evolution of Thought About the Challenge

- MIT 16.89 Graduate Design Class *Space Systems Engineering* semester study (report May 2004)
- Proposal summer 2004
- Project first phase September 2004
  - Technical trades and architecting
  - Stakeholder value analysis
  - Mid-term review December 2004
- Extension phase February 2005
  - Refine technical architecture concepts (focused)
  - Response to pop-up issues
  - Continue stakeholder value analysis
  - Begin enterprise architecture study
- Change of NASA Administrator April 2005
- Project complete August 2005

Starting Points

- Sustainability: "primary organizing principle of the architecture concept"
- Elements of sustainability:
  - Well-understood and minimized risks communicated to all stakeholders
  - An affordable system
  - Prolonged and recognized delivery of value to all stakeholders
  - A steady cadence of successes (addressing policy robustness)
- High-level design principles:
  - Design for sustainability (which includes affordability)
  - A holistic view of the SoS with a focus on value delivery
  - A highly modular and accretive design to allow for evolvability and extensibility
  - Mars as the reference goal to validate the Lunar exploration concept

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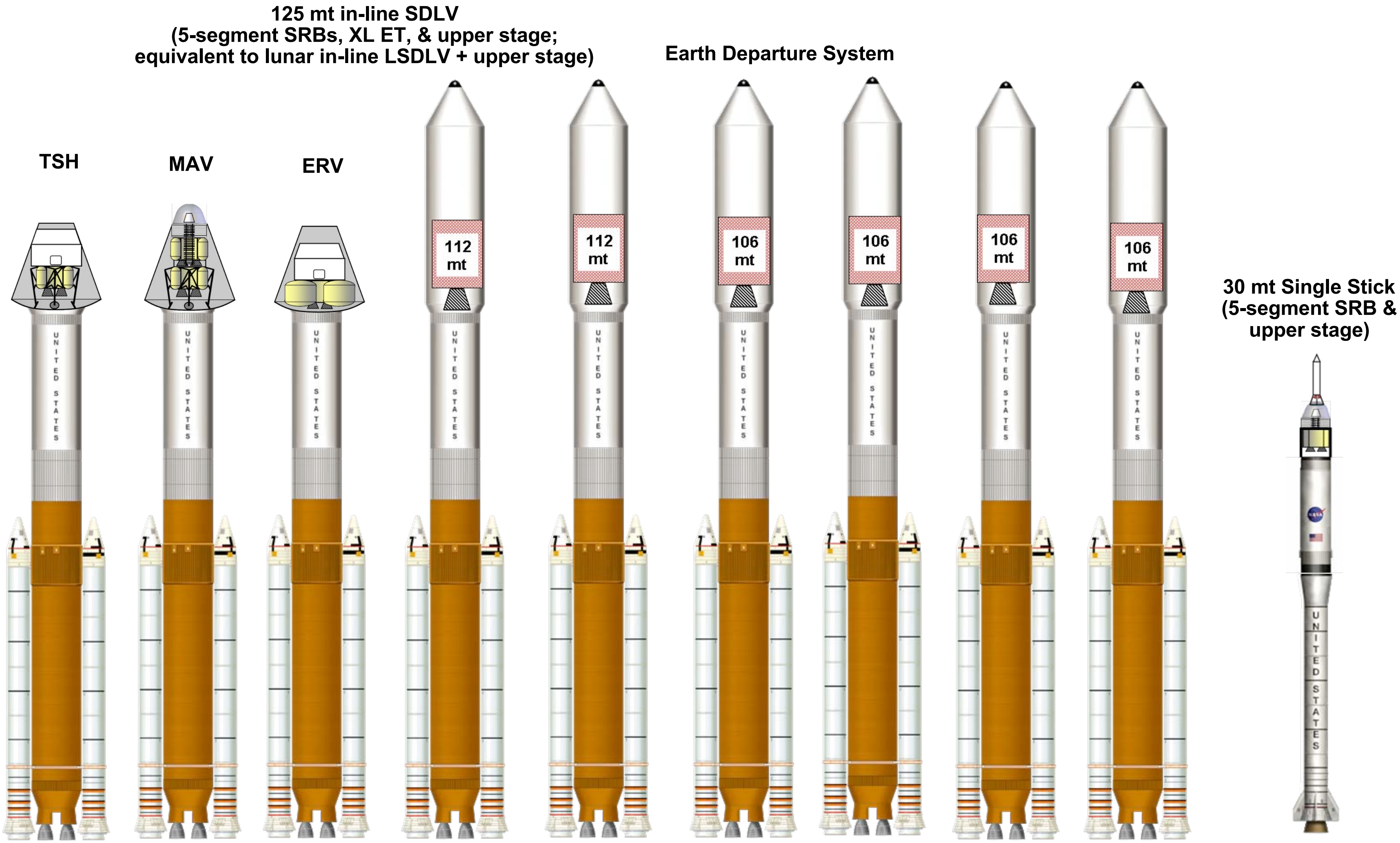
Initial Structure for the Study

- **Sustainability Team:**
  - **Enterprise architecture**
  - **Policy**
  - **Value delivery to stakeholders**
- **Architecture Team:**
  - **CER System architecture**
- **Vehicle Team:**
  - **CEV System design**
  - **CEV subsystems**
- **Organization structure changed multiple times to reflect evolving study needs, understanding of the problem**

Initial study structure reflects declared sponsor interests, existing architecture concepts, ideas about important departures from historical approaches

Baseline Mars Transportation Architecture



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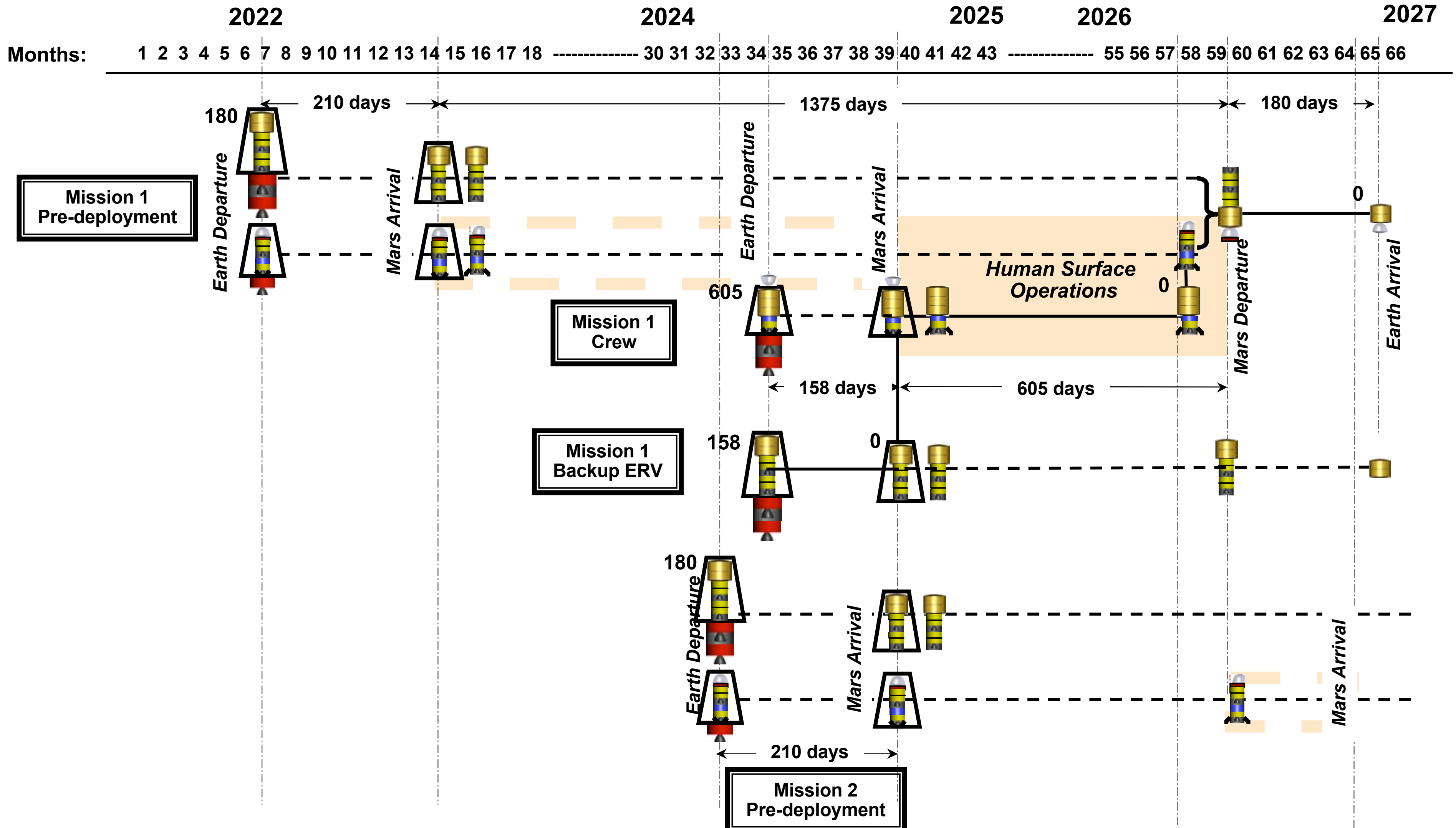
Mars Mission Campaign TImeline (Arch 969 w/ ERV)



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Baseline Commonality
Hardware Development Roadmap

LEO / ISS Mission Hardware

LES for CEV capsule:

CEV + IPU (27 m^3):

Rendezvous & Deorbit stage:

CEV power pack:

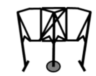
CEV launch vehicle:

Design Philosophy: Maximize hardware commonality to minimize gap between lunar and Mars missions and overall development and production costs

Short Lunar Mission Hardware

Common in-space propulsion stage (LCH$_4$ / LOX):
Core propulsion stage
Regular strap-on tanks
XL strap-on tanks

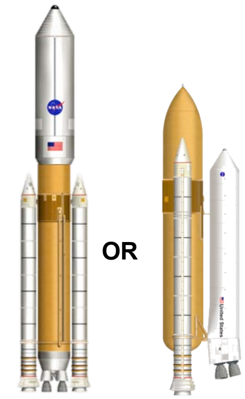
Lunar landing gear & exosceleton:



Engine 1 (LCH$_4$ / LOX)
Restartable, non-throttleable:

Engine 2 (LCH$_4$ / LOX)
Throttleable:

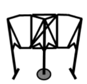
Common Earth departure stage (LH$_2$ / LOX)

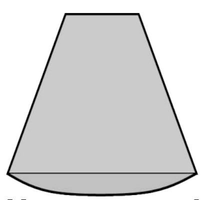


Heavy Lift Launch Vehicle:
("2 stages", 100 mt to LEO)

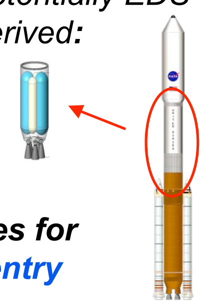
Mars Mission Hardware

Mars landing gear & exosceleton:





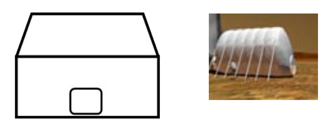
SDLV upper stage (125 mt to LEO)
Potentially EDS-derived:



Heat protection and parachutes for Mars Aerocapture and Aeroentry

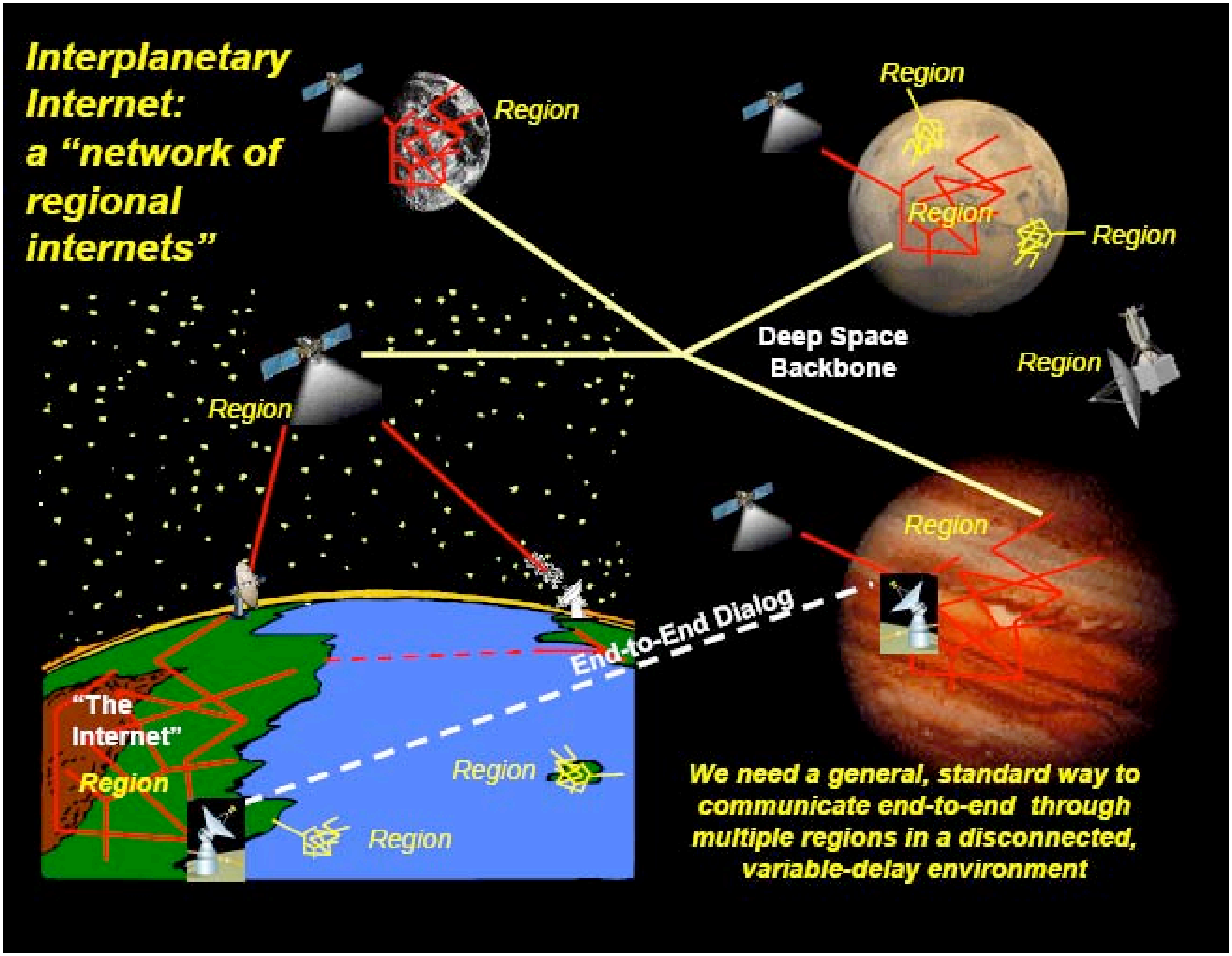
Long Lunar Mission Hardware

Habitat core and inflatable pressurized tent for planetary surfaces:



Note: Block upgrades across phases are not depicted

Future Space Communications: Interplanetary Internet (IPN)



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Exploration System Stakeholders

- Direct and indirect beneficiaries of space exploration activities
- Categorized into stakeholder super groups that correspond with general areas of societal impact

Stakeholders Addressed				
Exploration	Science	Economic	Security	Public
Explorers, Engineers and Technologists, NASA	Scientists, NASA, Other US agencies	Commercial enterprises, Other US agencies, Engineers and Technologists	DoD, Intelligence, International Partners	US Public, Media, Educators, Executive Branch, Congress, NASA

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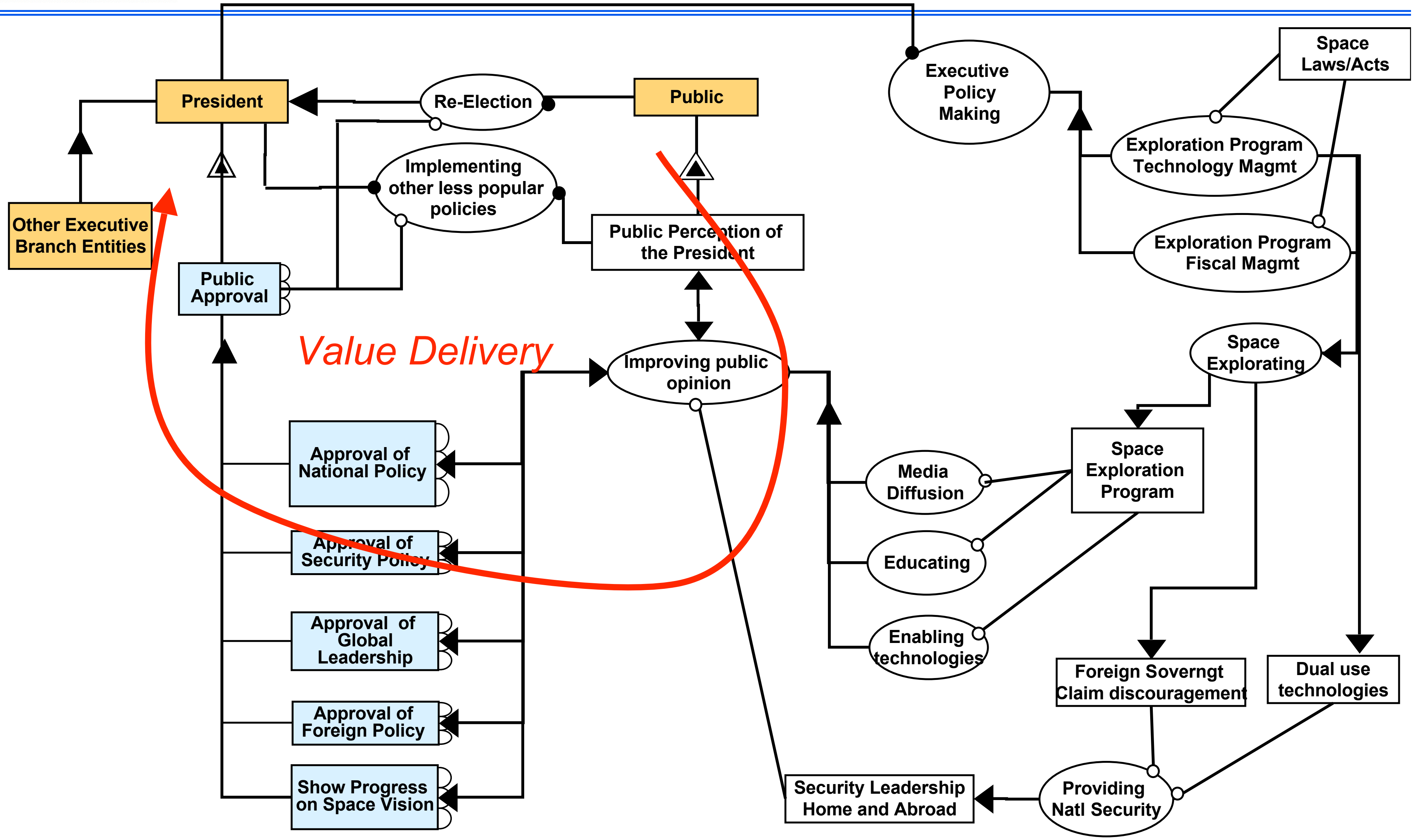
Formal Modeling of Stakeholder Interests: Executive Branch



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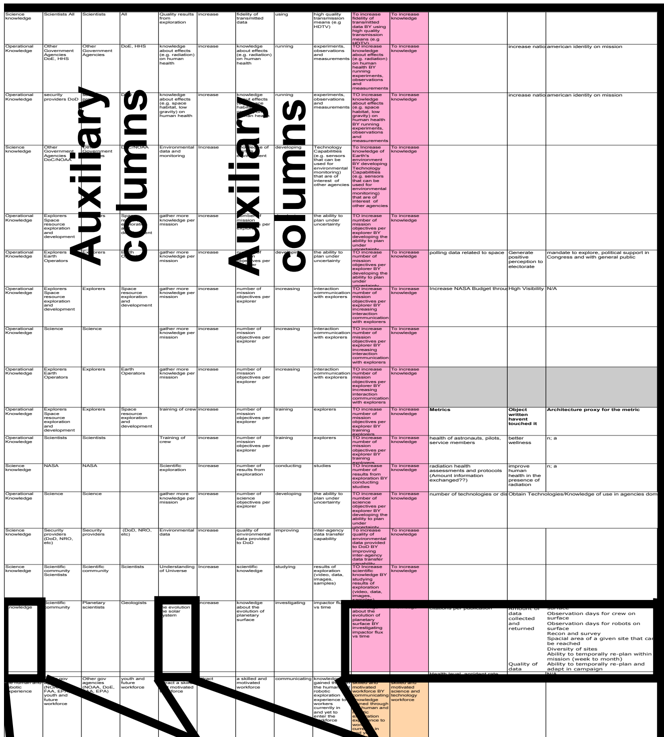
From Stakeholder Interests to Technical Measures

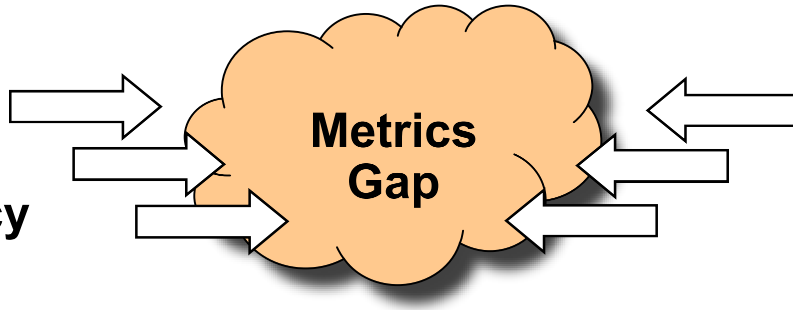


- Identify stakeholder, their needs and derived objectives (14)
- Stakeholder needs (171)
  - Use object process modeling (OPM) to define value flow system and descriptive language
- Overarching Exploration objectives (39)
  - Clustered through objectives hierarchy tree
- Translate objectives into metrics, proximate measure and indicators
- Proximate indicators drive system of systems architecture

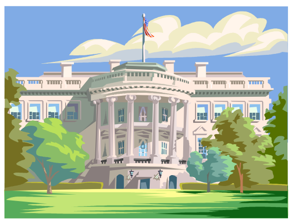
Stakeholder	Need	Objective	Overarching objective	Metric	Proximate Measure	Indicator
Scientists	Scientific knowledge	TO understand origin, evolution and fate of the solar system BY interpreting geologic environments	To increase knowledge	# of publications, # of citations	Amount of data collected and returned	Science payload delivered to M surface
						Observation days for crew on surface
						Observation days for robots on surface
					Quality of data	Recon and survey
						Spacial area of a given site that can be reached
						Diversity of sites
						Ability to temporally re-plan within mission (week to month
						Ability to temporally re-plan and adapt in campaign

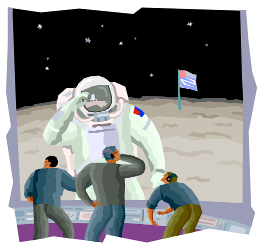
The Gap Between Value and Engineering Metrics

- Stakeholder Values
  - Pride, inspiration, economic development, policy support, etc.



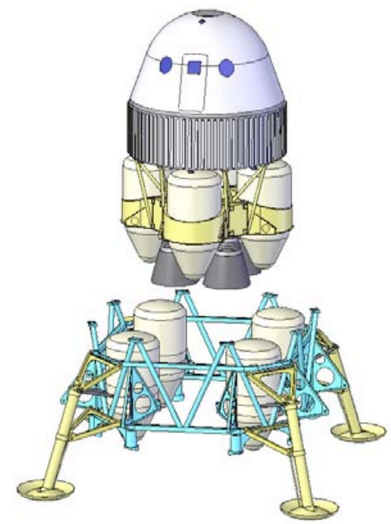
- Technical Architecture
  - Kg, N, M, K°, bits/sec, etc.





The gap is caused (in part) by:

- Stakeholder diversity/ dispersion
- Different levels of stakeholders definition/ aggregation
- Multiple pathways for flows of benefits
- Multiple interaction modes (e.g., markets, hierarchies, clans, etc.)
- Temporal separation between cause and effect



The *architect* is the arbitrator in interpreting/ bridging the gap

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Exploration Functions

	A	B	C	D	E
66	Continuously increasing safety and reliability				
67		Inspecting and overseeing technical systems safety			
68			Architecture review and analysis		
69			Manufacturing oversight		
70			Increasing safety/minimizing risk		
71				Mitigating hazards	
72				Having contingency plans	
73				Validating systems	
74				Testing systems	
75				Ensuring crew skill diversity	
76		Inspecting and overseeing operations safety			
77			Assessing Risk		
78			Instilling safety culture		
79			Capturing tacit operations knowledge		
80		Ensuring explorer health			
81			Explorer health monitoring and evaluating		
82				Mitigating radiation exposure	
83					Radiation Health assessing
84				Managing thermal environment	
85				Assuring crew diversity	

Background

- Based on inputs from all effort areas in the study
  - 550 functions defined
- Addresses both social and technical exploration systems
- Organized into hierarchical tree structure
  - 7 levels of hierarchy
  - 6 main branches in the hierarchical structure

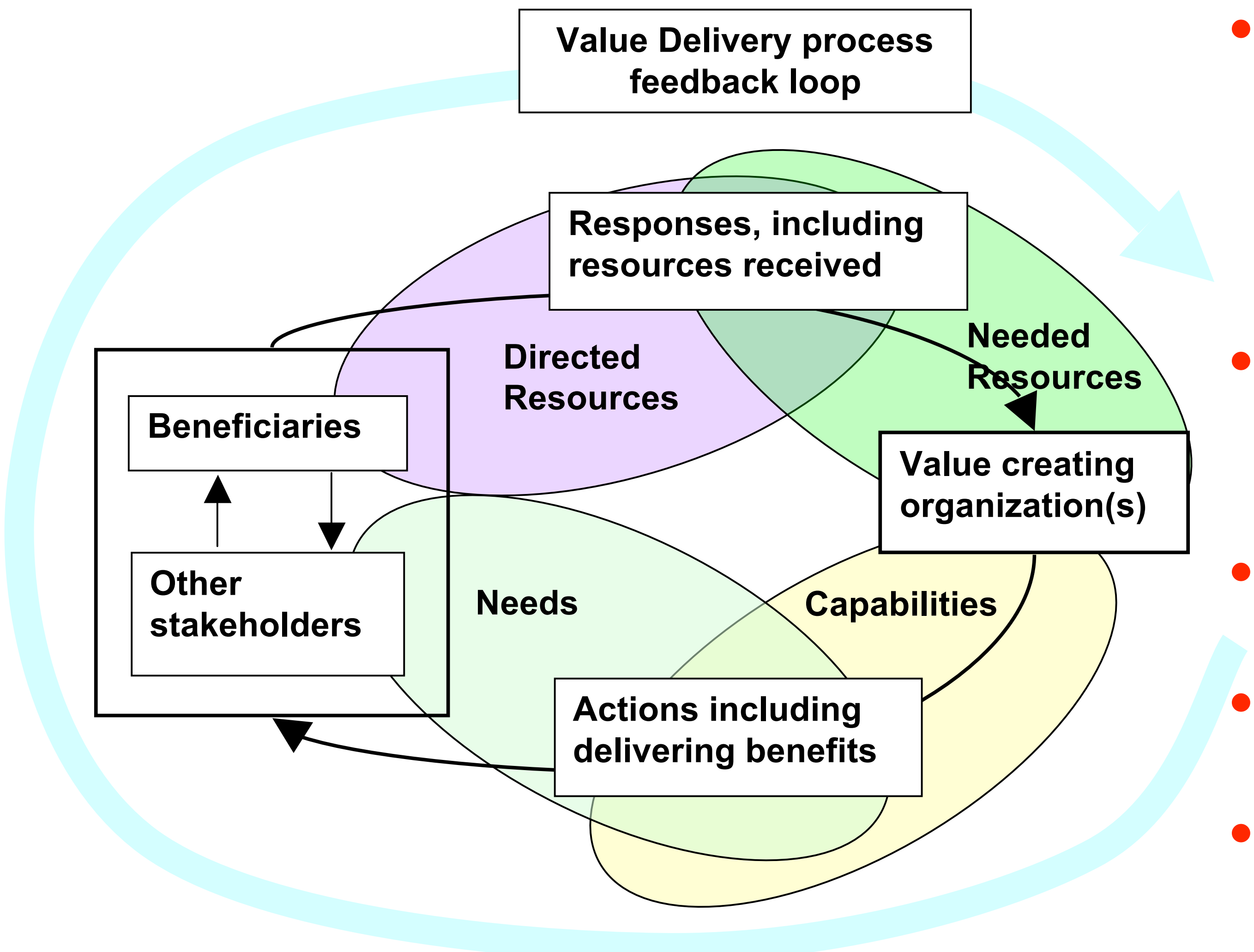
Function Population

- L0—6 functions
- L1—26 functions
- L2—68 functions
- L3—150 functions
- L4—205 functions
- L5—91 functions
- L6—4 functions
- Total: 550

Implications

- Defining the architecture in a useful way involves mapping functions to forms
- Comprehensive list provides holistic perspective
  - Enterprise functions based on surrogate enterprises
- Disparity in progress between technical and enterprise system definition highlights differing analytical maturity levels
  - What is driving the architecture? Stakeholder values or modeling capability?

Value Defines, is Delivered by Architecture



- The Value Delivery System (i.e., the architecture) must be designed to deliver value to the stakeholders, and actually deliver that value
- Actual value delivery process depends on nature of relationships/ exchanges among stakeholders
- Proximate measures feed the technical architecture process
- Enterprise architecture governs value flows among stakeholders
- This architecting process was found to be highly Iterative

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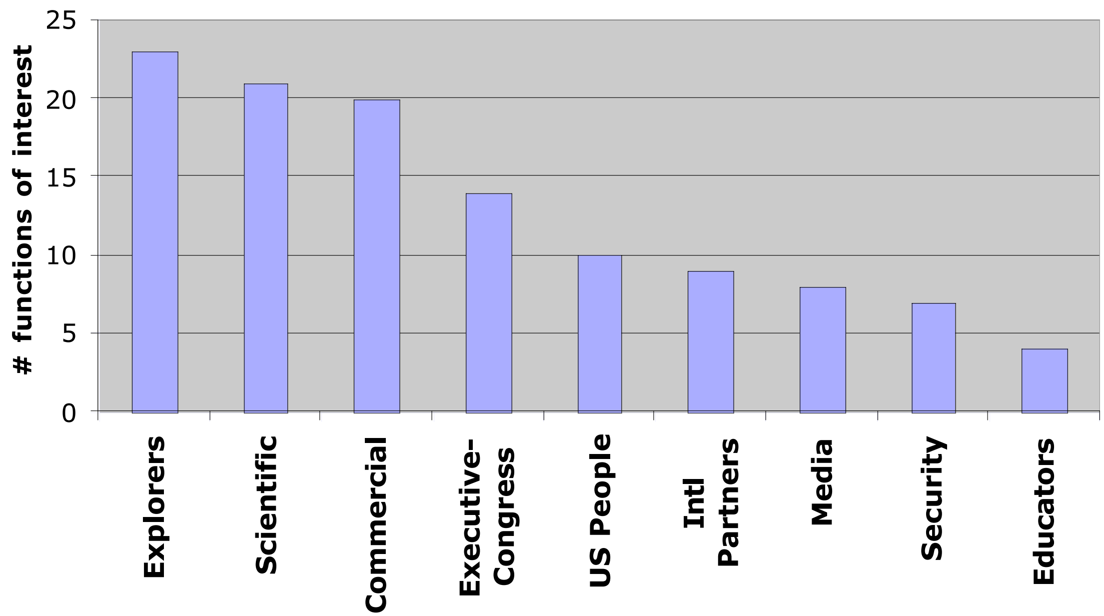
Which Stakeholders Benefit From This Architecture?



The architecture that emerged (based on fairly narrowly-defined technical merit) most looked like previous architectures, and not surprisingly most addressed the needs of legacy stakeholders

- **Benefits valued by stakeholders are linked to the functions that produce those benefits**
- **Sum of exploration functions that produce stakeholder-valued benefits are displayed by stakeholder in graph**
  - **Not weighted (e.g., by $, intrinsic value, etc)**
- **Top beneficiaries are**
  - **Explorers/Scientists (traditional NASA constituency; technology and jobs)**
  - **Commercial (providing launch services and exploration systems, jobs)**
  - **Executive and Congress (fiduciary concerns, political capital)**

Comments on Enterprise Architecting

- Creating and adapting structures in response to needs
  - Create structures that enable value creation (e.g., new products are created by innovative product development *systems*)
  - More efficient enterprises are created through an on-going transformation process that relies on feedback, analysis and correction
  - High-performance supplier and logistics networks are created in the service of providing customers with fast, inexpensive, high-quality products in a way that beats competitors and makes money
- There is evidence that a few exceptional enterprise architects with vision have created new ways of structuring enterprises
  - This process generally unfolds over many years (decades), with accounts suggesting it was largely through the types of processes outlined above:
    - Solving problems a few at a time, relentlessly, with deliberate and focused alteration of decision rules
  - We haven't systematically investigated whether there have been other enterprise architects that have been equally visionary and have led their enterprises to ruin—Is EA unequivocally good?

Lessons Learned

- Large gap between stakeholder analysis and technical system architecting
  - Stakeholder analysis is immature in theory, tools, concepts, empirical evidence, (i.e., which apply: economics, political science, physics, decision theory, etc?)
  - Phasing of work: don't start the stakeholder analysis at the same time you start hardware architecting
- No formal theory-supported methods to derive technical measures from societal stakeholder values independent of architecture concepts
- Formalized analytical processes can yield any number of solutions depending on the assumptions made along the way
  - Formality is not a (very good) substitute for architecting judgment
- The *architect* is ultimately the arbitrator to bridge the gap between stakeholders and technical system, whether intentional, systematic, transparent, acknowledged, or not
  - In our study, the technical architecture concept was fairly defined at the outset; in reality the architecture is even more defined by existing constraints
- Enterprise and system of system architecting challenges introduce social and temporal dynamics that are not well characterized/modeled in existing system architecting methods