Architecting Systems to Create Value

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With thanks to:

Dr. Bruce Cameron

Prof. Dov Dori

Many students!

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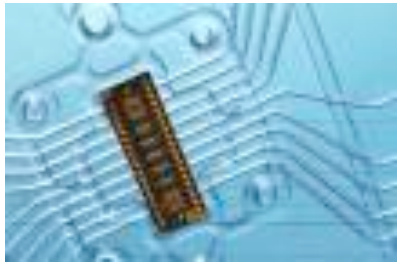
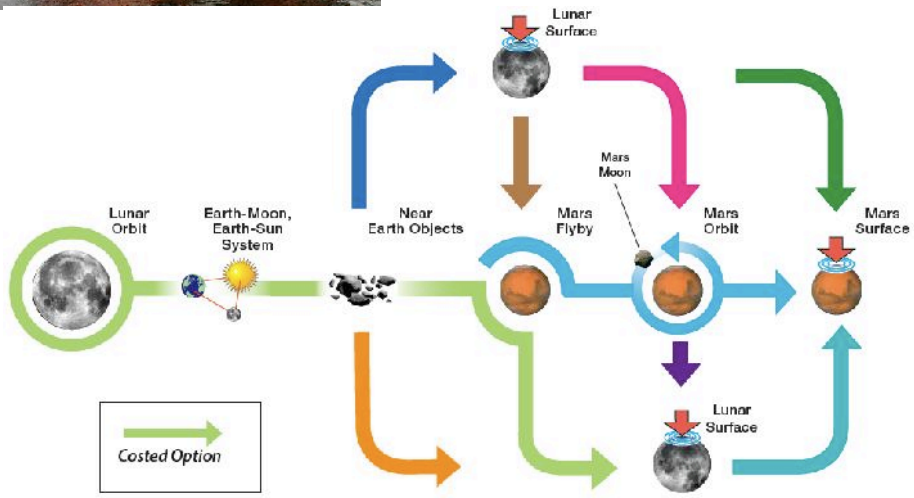
The Challenge

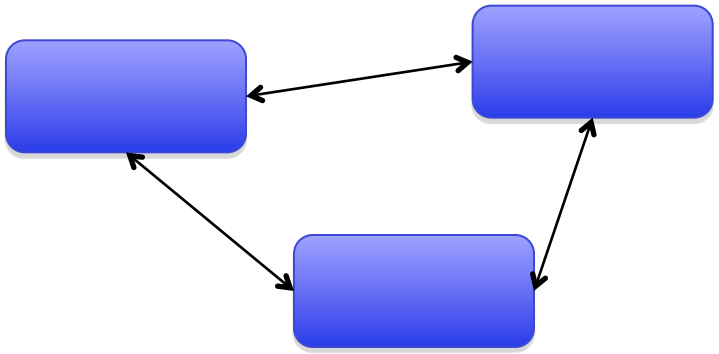
- We conceive, design, implement and operate complex and sometimes unprecedented systems
- Do they deliver sustained value?
- Are they architected well?



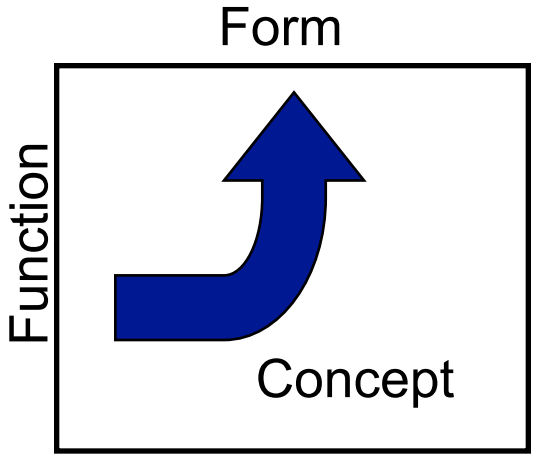


System + Architecture

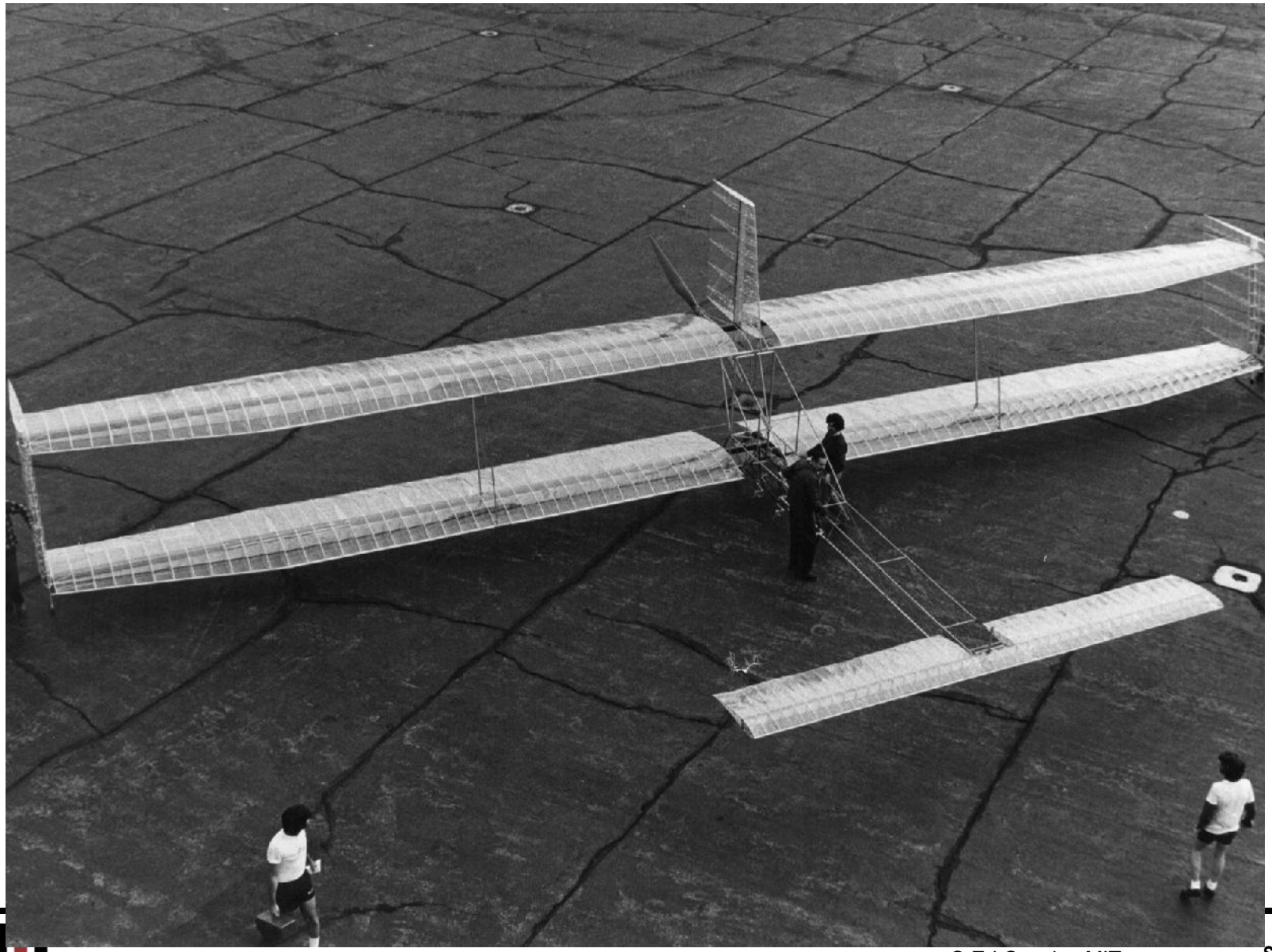
System: A set of interrelated entities which perform a function, whose functionality is greater than the sum of the parts



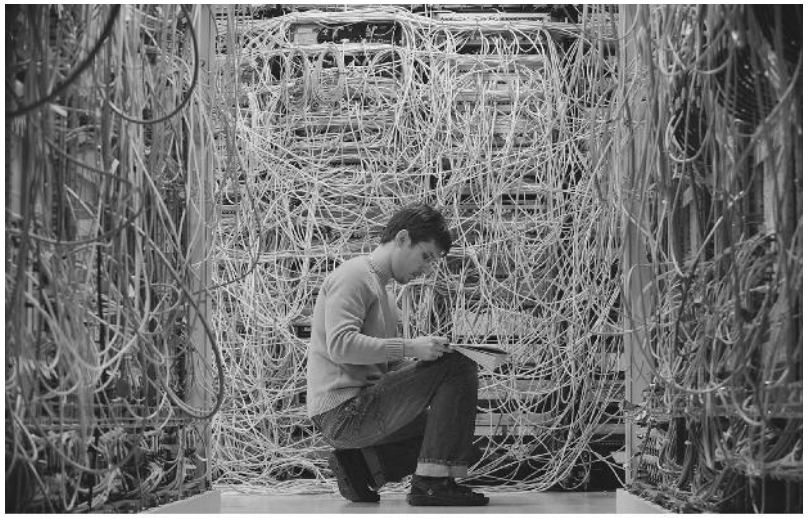
Architecture: The embodiment of concept, and the allocation of physical/informational function to elements of form, and definition of relationships among the elements and with the surrounding context.



Architecture is Form + Function

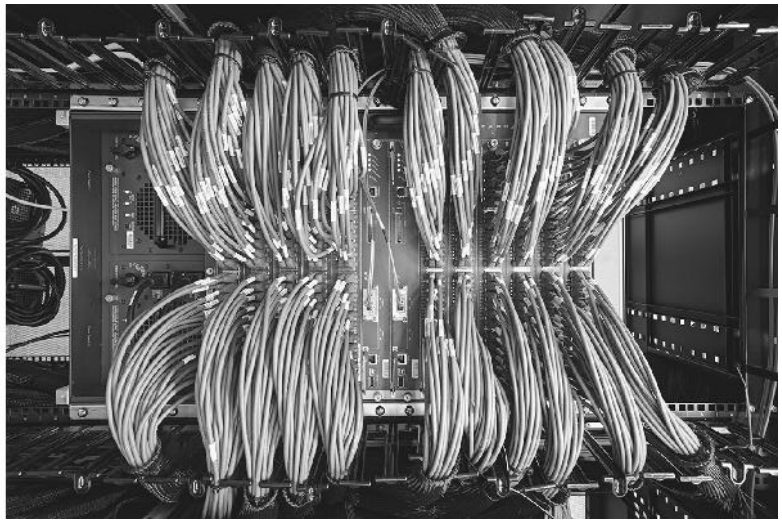


Complex Systems



Concord cockpit – www.canovair.com

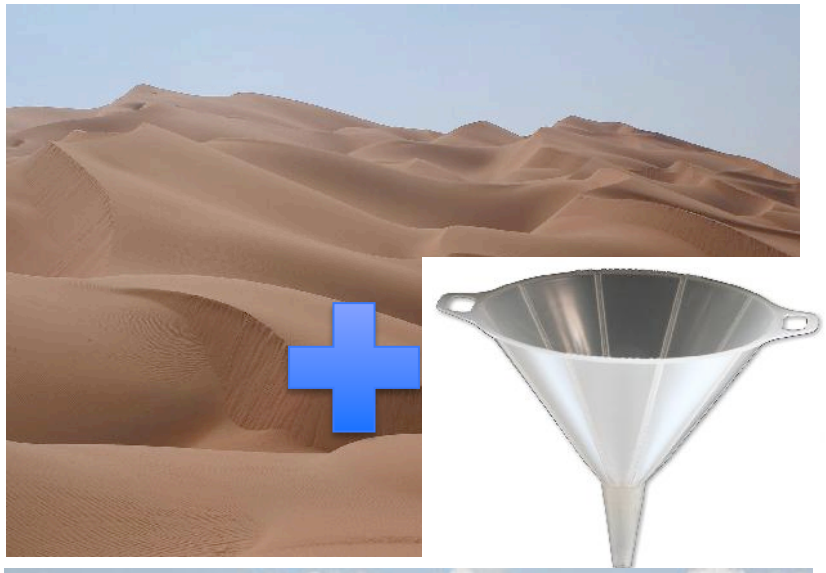
Made Less Complicated



A Principle: complexity exceeds comprehension

The Power and Magic of Systems is in Emergence

Function



Performance

Reliability

Emergencies

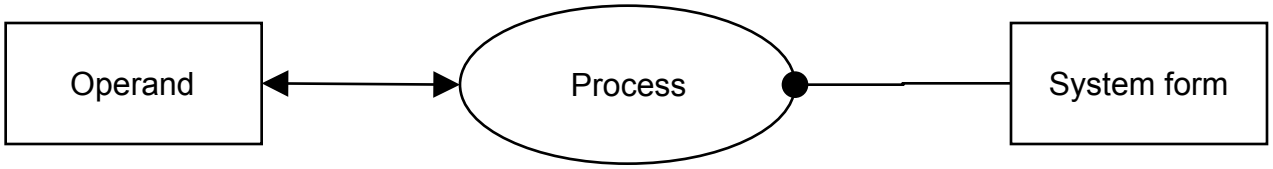
Form and Function of the System

- **How do we predict emergence?**

Benefit

Function		Form
Passengers	Transporting	Transport Aircraft
Operand	Process	Instrument

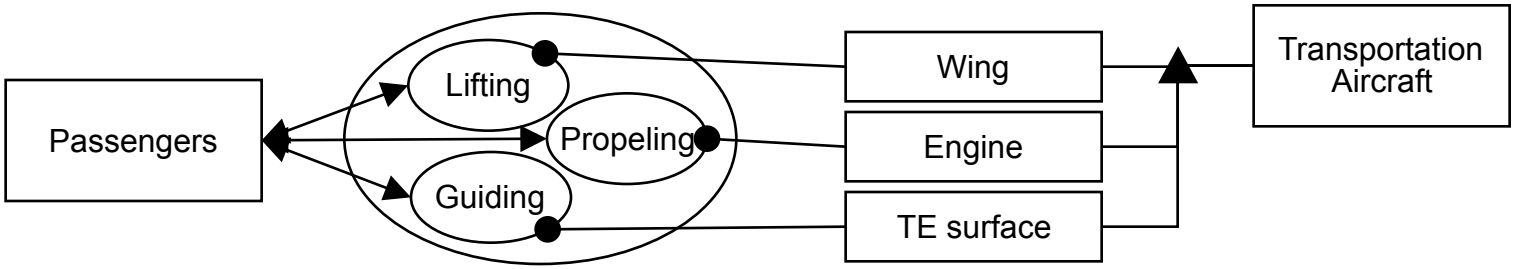
Cost



Entities of the System: Form and Function

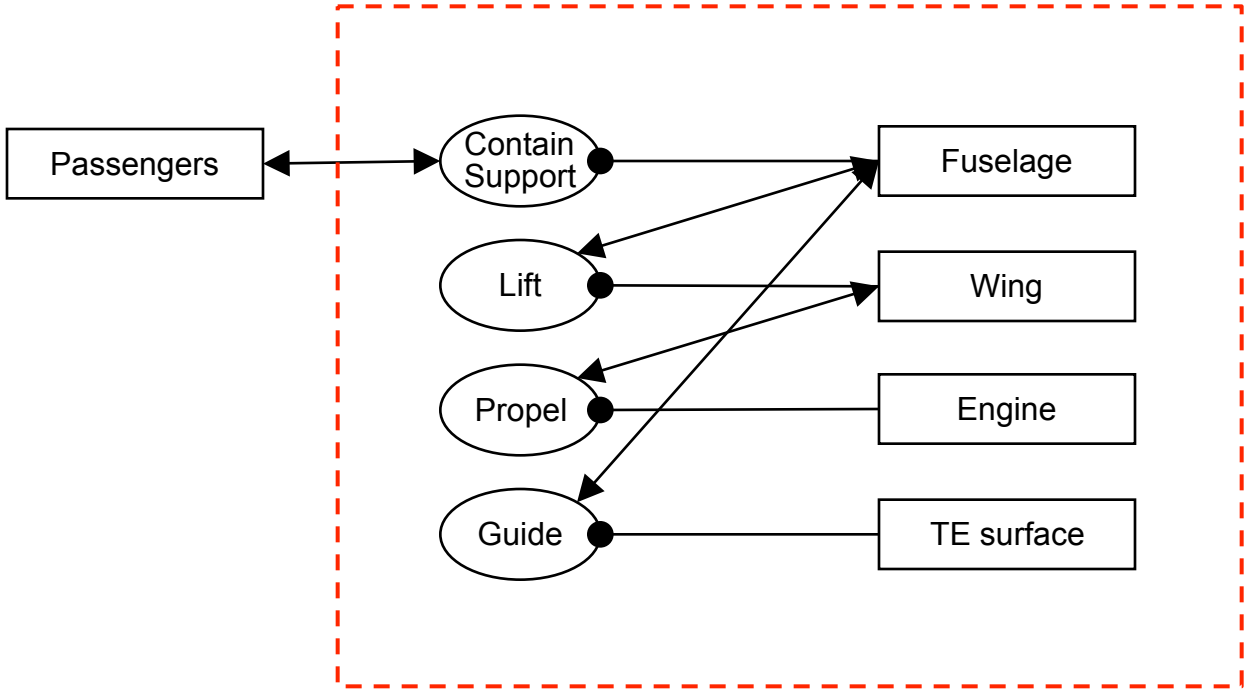
- **Holism and focus**
- **Divide and conquer**

System Function	Entity Function	Entity Form	System Form
Move Passengers	Lift payload	Wing	Transport Aircraft
	Propel vehicle	Air breathing engine	
	Stabilize/ guide vehicle	Trailing edge surfaces	



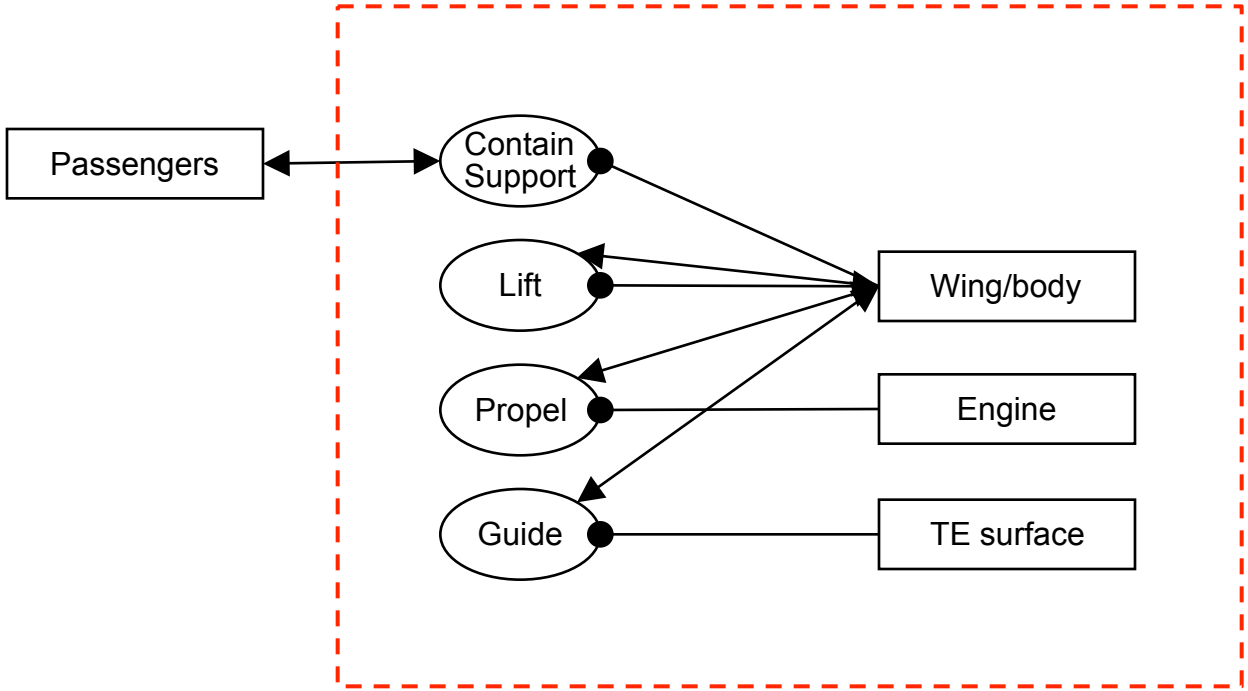
Relationships: Form and Function

- Interactions occur when operands are shared
- Emergence is in interaction

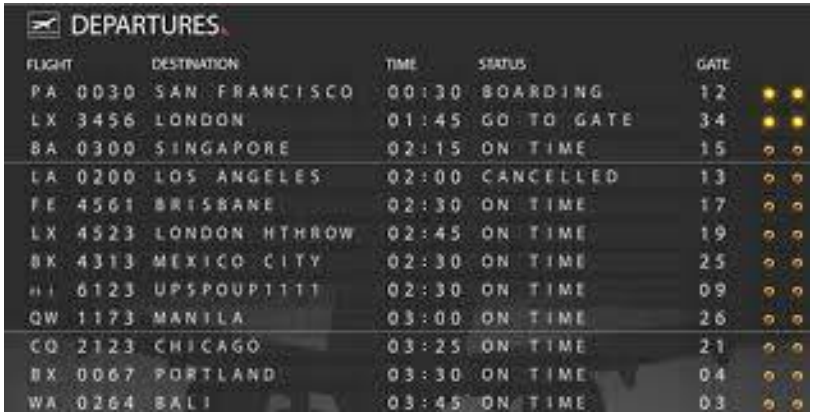


Relationships: Form and Function

- **A different concept brings different interaction**

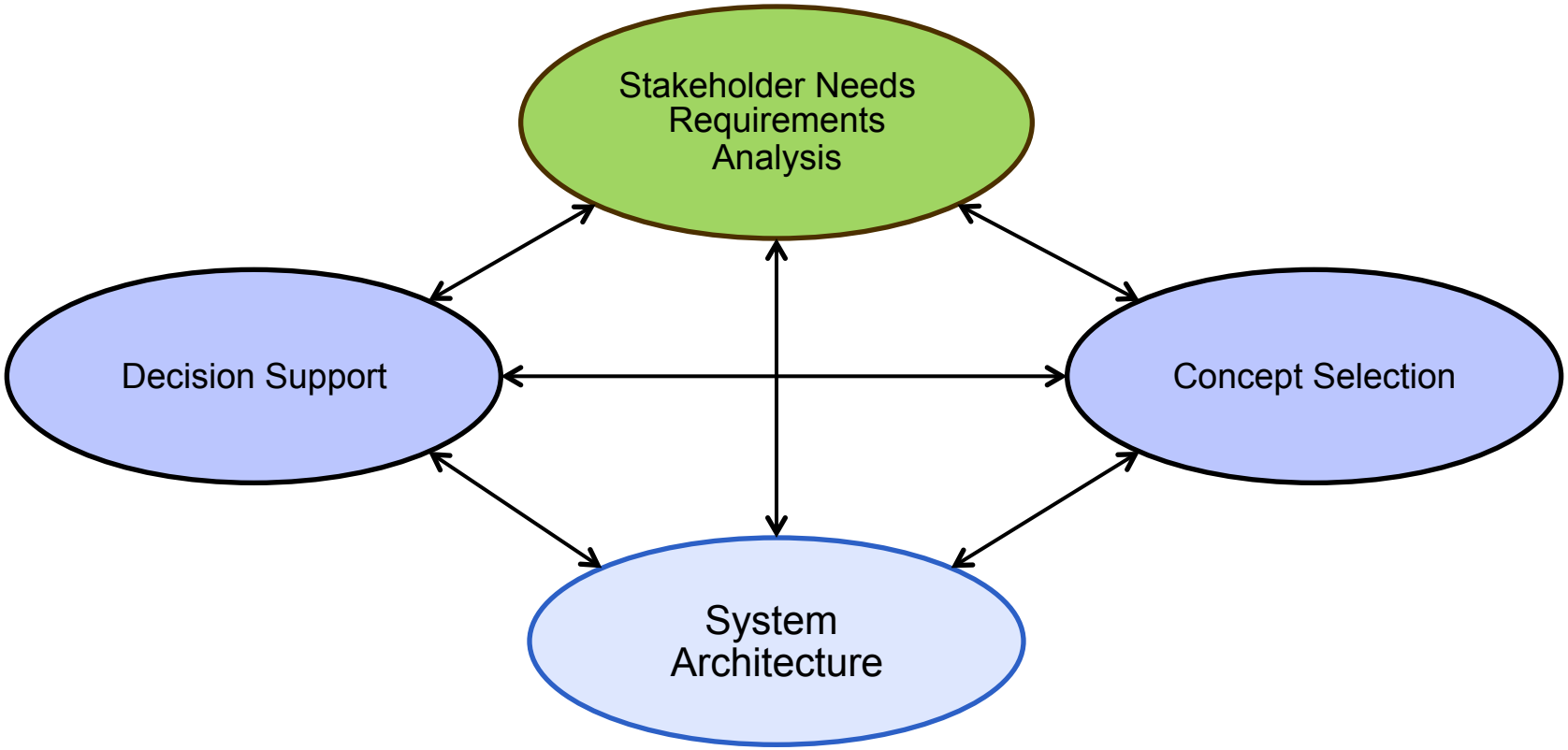


Desired Emergence?



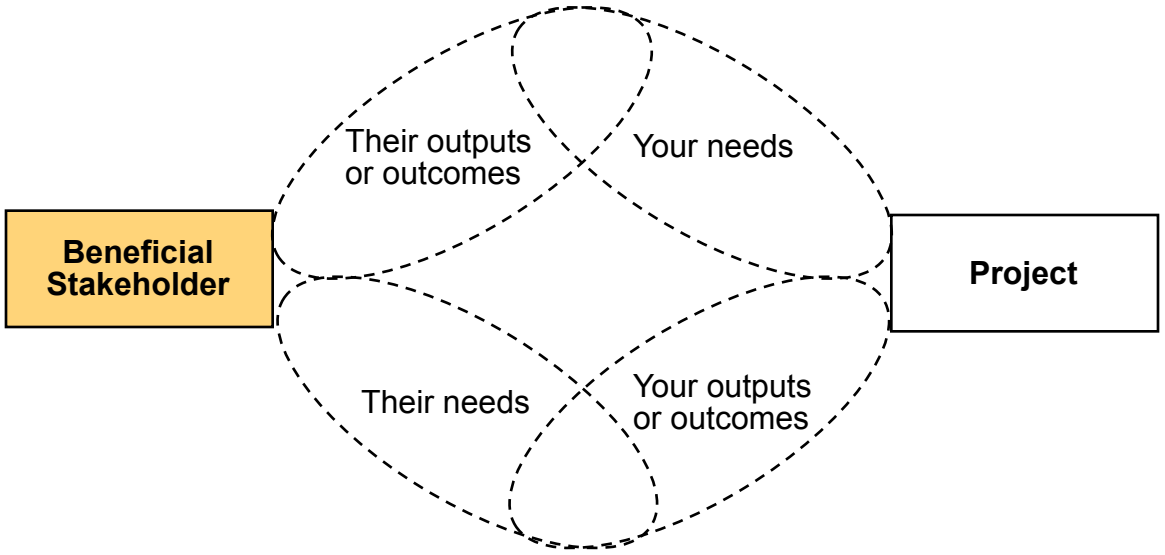
- **Emergence can be predicted *a priori* by:**
  - **Precedent**
  - **Experimentation**
  - **Modeling**
- **For other systems, only human reasoning can be relied on to predict emergence – functional modeling helps guide us**

Comprehensive Analysis of System Architectures



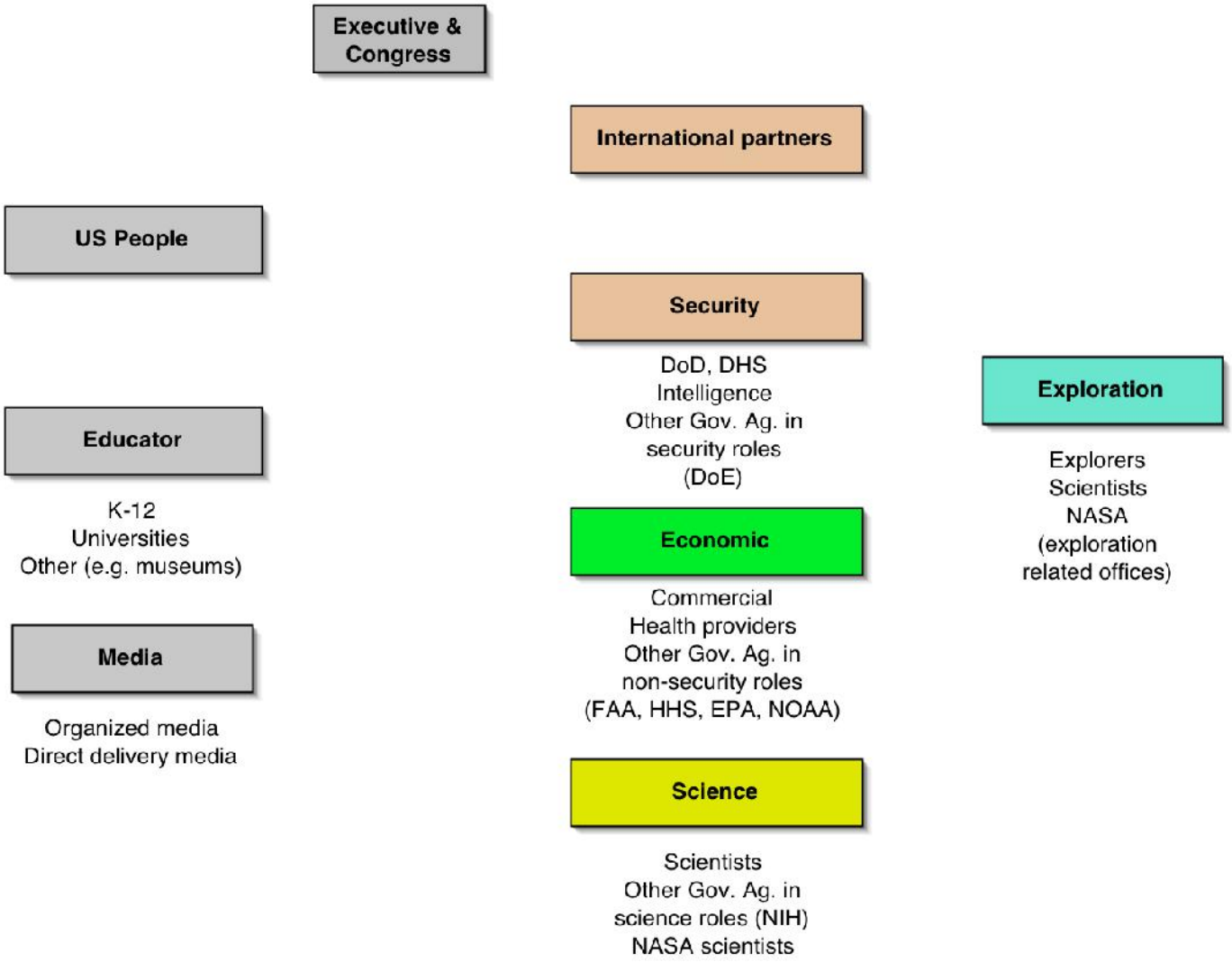
- **These all systems! Use system thinking**
- **Requirements and concepts are intellectual stepping stone**

Exchange Model of Stakeholder Interaction



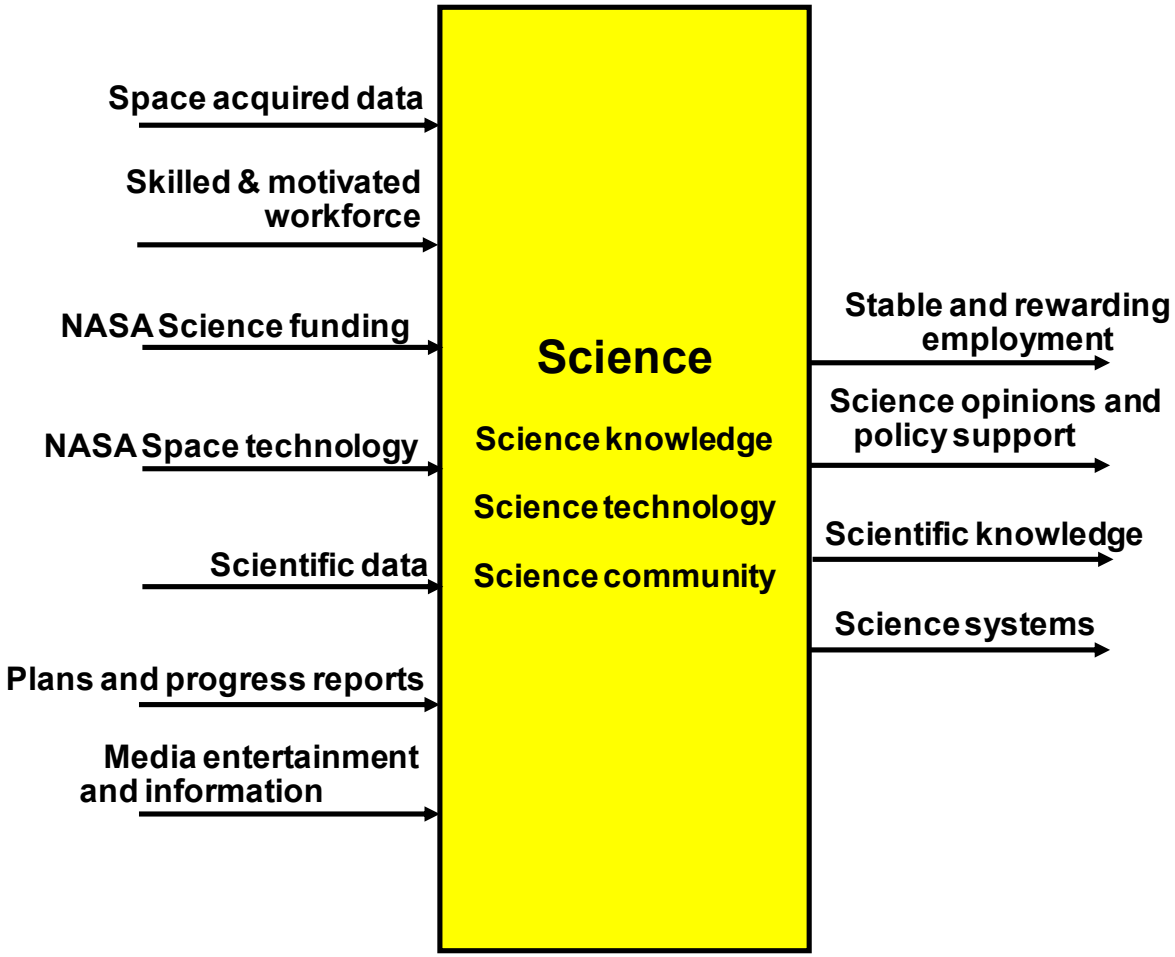
- **Value** is delivered in an exchange - **benefit at cost**
- Successful exchange with a stakeholder occurs when:
  - Your outputs or outcomes meet their needs (benefit to them)
  - Their outputs or outcomes meet your need (cost to them)
- **A Principle:** the basis of stakeholder engagement

Identify Stakeholders for Human Space Exploration

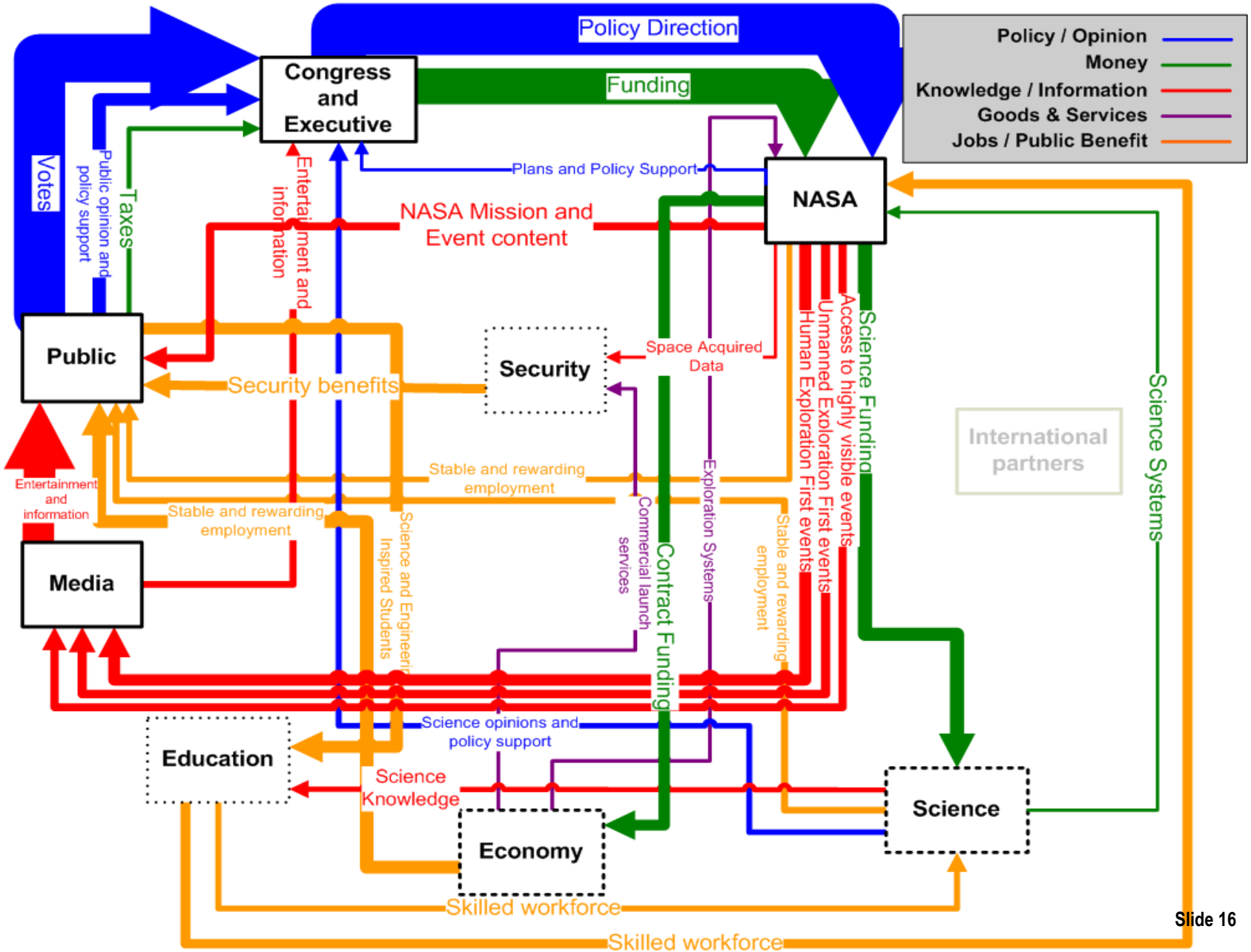


Model Needs of Each Stakeholder

- Identify the needs of stakeholders, and what flows to them to satisfy that need
- Assess the relative importance of the flow to the stakeholder
- Create a network model of the stakeholder community with the project as the central node
- Analyze to gain insight into the delivery of value in the network



Modeling Value Flow in Stakeholder Network



Key Architectural Decisions

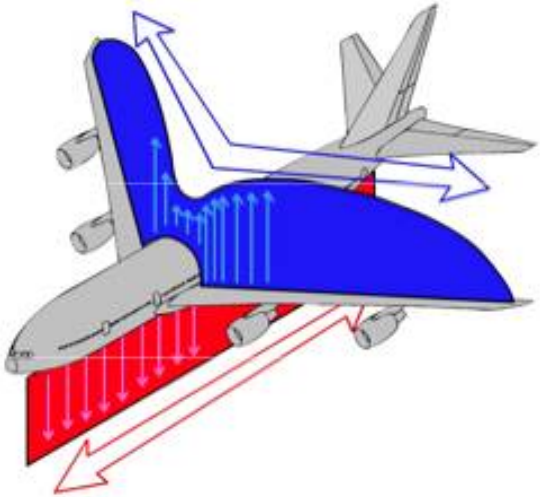
Tube and Wing Family

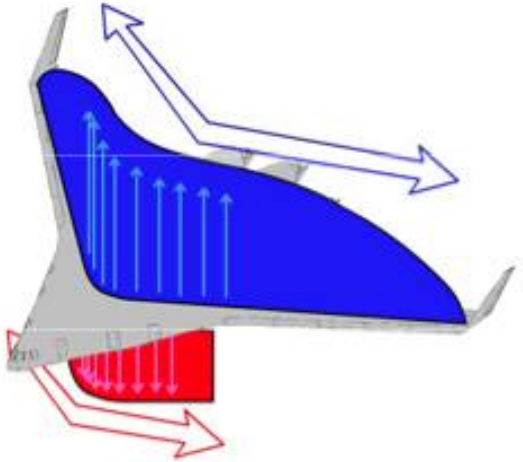
What are the key architectural features that separate these two designs?

What are the decisions?

Architectural?
Sensitive?
Connected?

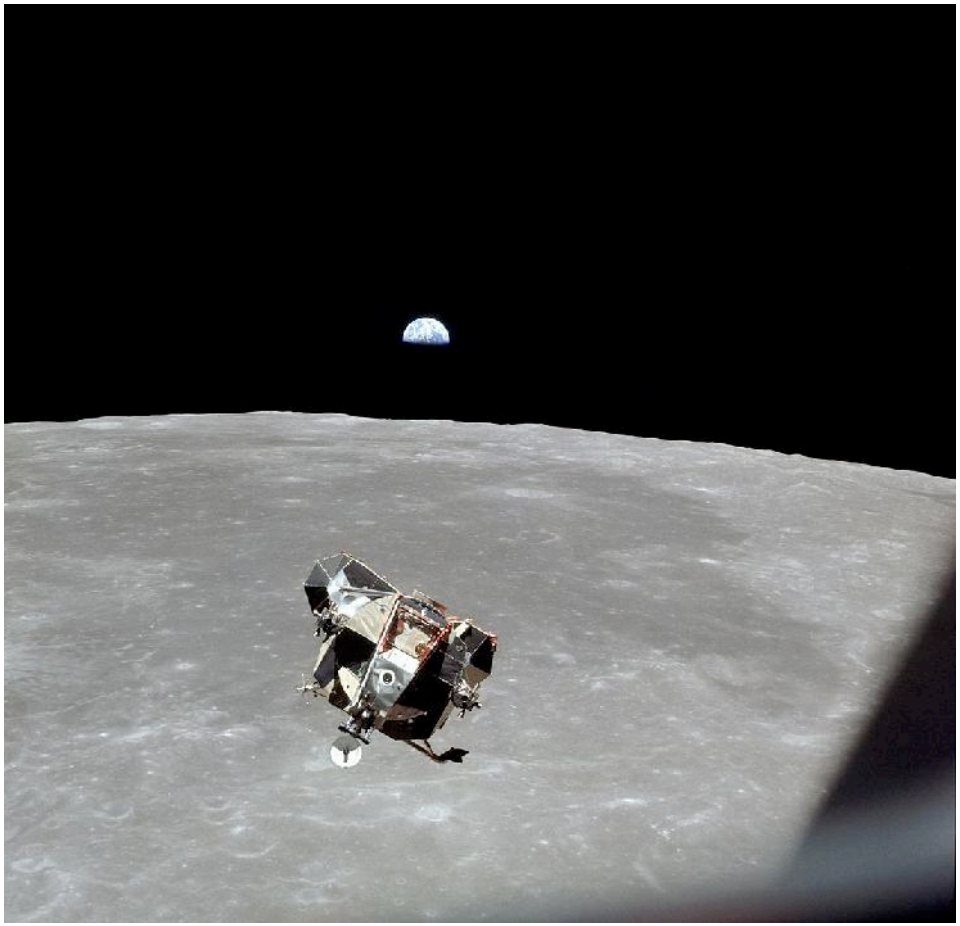
BWB Family





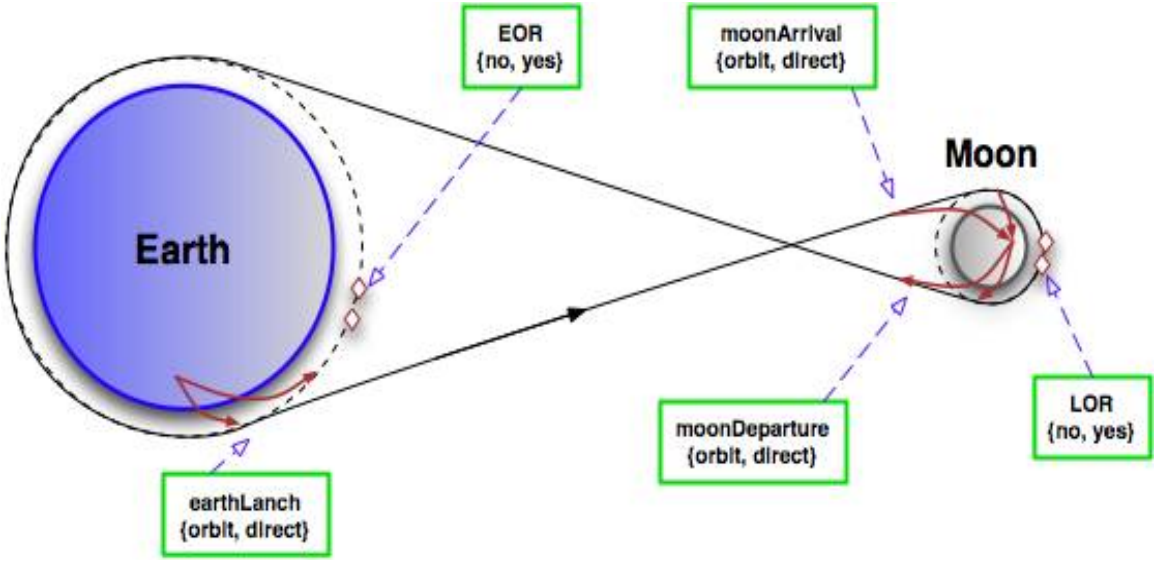
Credit: Robert Liebeck / Boeing

Apollo Architecture – What are the Decision?



Source: http://www.hq.nasa.gov/alsj/a17/AS17-145-22261HR.jpg

Identifying the Decisions and Choices – Apollo



- **Mission parameters:**
  - **Mission mode related (Earth launch, EOR, Moon arrival, LOR, Moon departure)**
  - **Command Module Crew: 2 or 3?**
  - **Lunar Module Crew: N/A, 1, 2 or 3?**
- **Fuel/propulsion type related:**
  - **Service module fuel: cryogenic or storable?**
  - **Lunar module fuel: N/A, cryogenic or storable?**

- The three major categories of mission modes are captured : Direct, EOR, and LOR.

9 Decisions !

Representing the Decisions and Choices

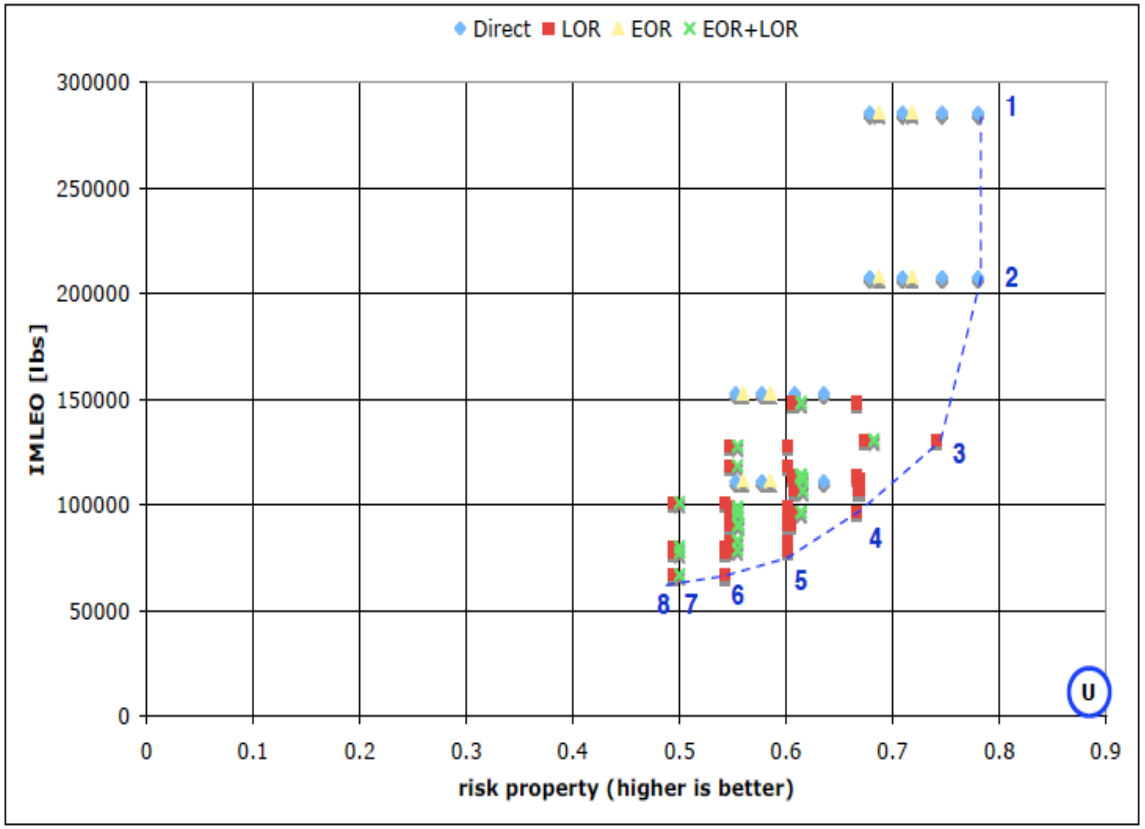
shortID	Decision	alt A	alt B	alt C	alt D
EOR	Earth Orbit Rendezvous	no	yes		
earthLaunch	Earth Launch Type	orbit	direct		
LOR	Lunar Orbit Rendezvous	no	yes		
moonArrival	Arrival at Moon	orbit	direct		
moonDeparture	Departure from Moon	orbit	direct		
cmCrew	Command Module Crew	2	3		
lmCrew	Lunar Module Crew	0	1	2	3
smFuel	Service Module Fuel	cryogenic	storable		
lmFuel	Lunar Module Fuel	NA	cryogenic	storable	

Trade Analysis

Scenario Analysis

Non - dominated Feasible Solutions

- **IMLEO vs. mission success probability**



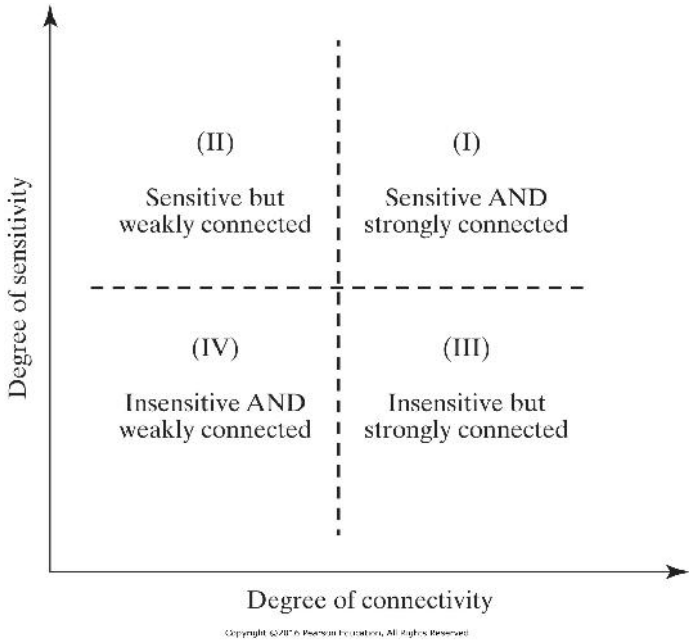
Prob of mission success

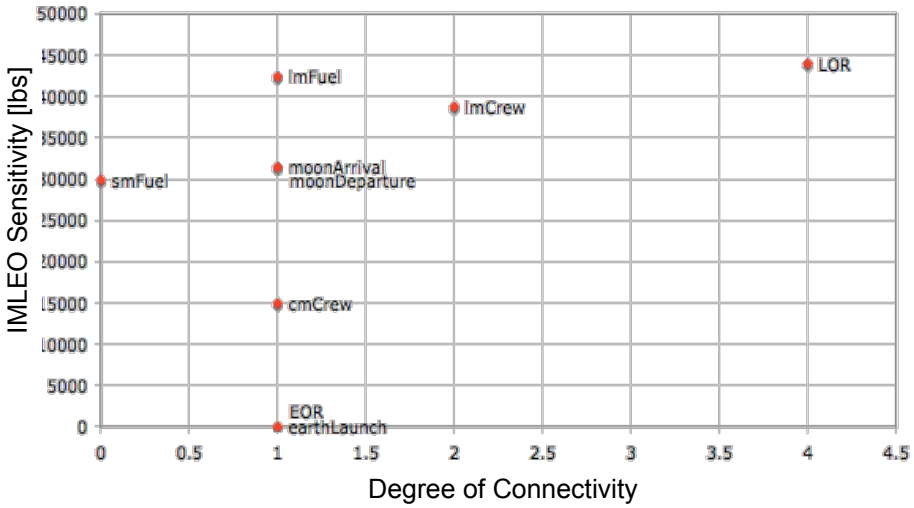
Points on the Pareto front:

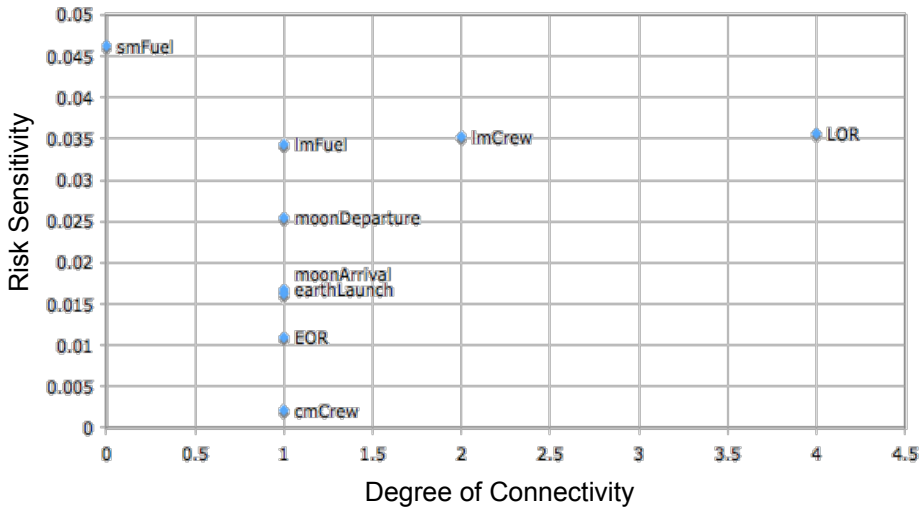
- **Point 1: <u>von Braun-like</u>: Direct Mission, with 3 crew, storable propellants**
- **Point 2: Direct with 2 crew, storable propellants**
- **Points 3, 4, 5, 6: LOR missions.**
- **Point 3 is <u>Apollo-like</u>: LOR mission, storable propellants, 3 crew, 2 to surface**
- **Point 7: EOR mission, 2 crew with cryogenic propellants**
- **Point 8: <u>Soviet-like:</u> min mass configuration, LOR, 2 crew, 1 to surface,.**

About 3 Good Architectures

Decision Space View: helps us understand decision sequence





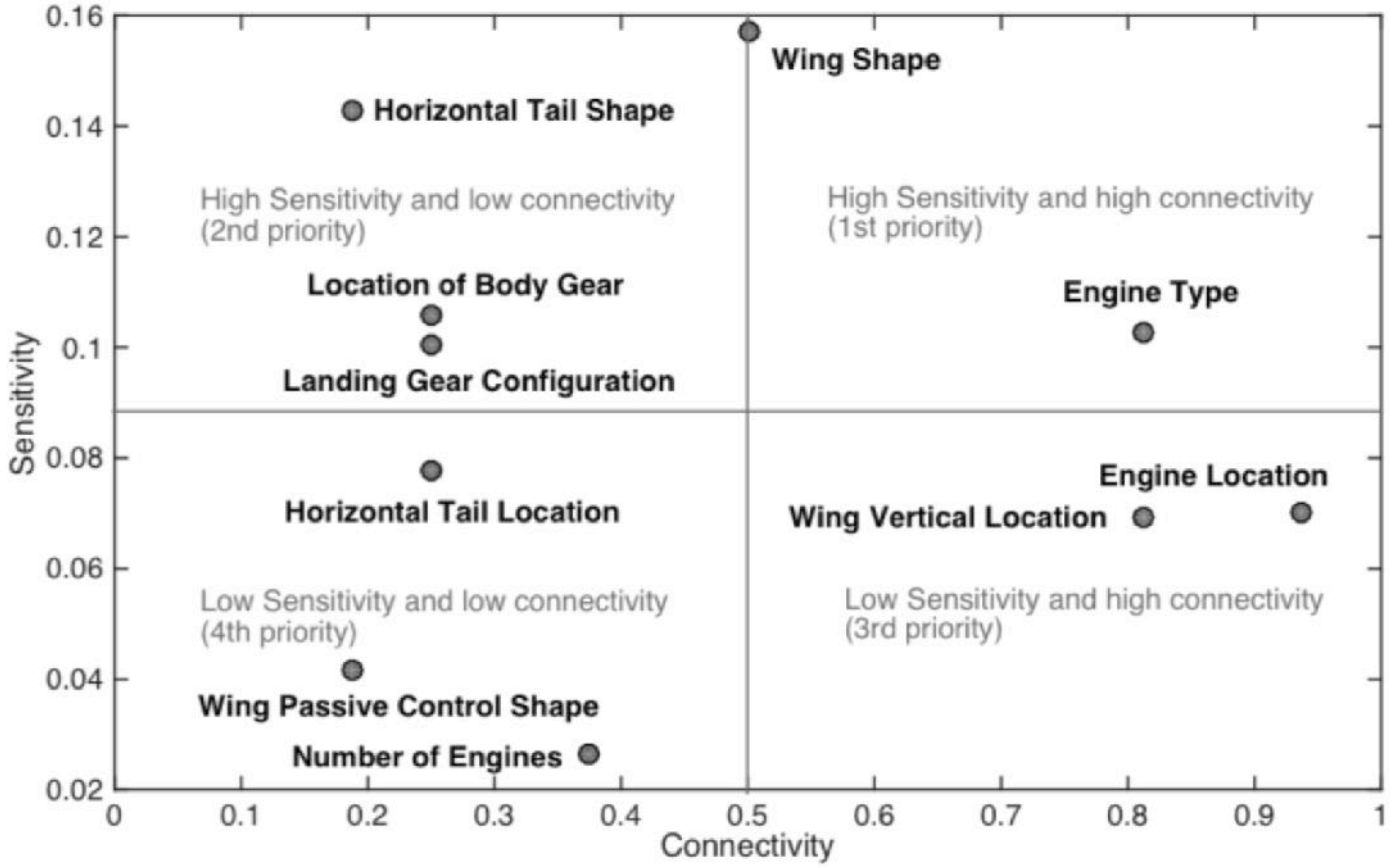


Decision Space

	Function 1: Lifting payload					
Wing	Wing Vertical Location	High Wing	Mid Wing	Low Wing			
	Wing Shape	Rectangular	Tapered	Delta	Swept Back	Elliptical	
	Passive Control Shape	Dihedral	Anhedral	Straight			
	Function 2: Accelerating payload						
Engines	Engine Type	Piston Prop	Turboprop	Turbofan	Turbojet		
	Number of Engines	1	2	3	4		
	Engine Location	Inside Vertical Tail	Side of fuselage aft of wing	Under Wing	Above Wing	In Wing etc.	
	Function 3: Maintaining stability						
Stabilizer	Vertical Location	Fuselage (Inverted-T)	Vertical Tail (T-Tail)				
	Shape	Swept back	Tapered	Straight	Elliptical		
	Function 4: Taxiing payload						
Landing gear	Landing gear Arrangement	Single Main	Tail Dragger	Tricycle	Tricycle w/ triple body gear		
	Location of stowed landing gear	In the Wing	Wing Podded	In the Fuselage	Fuselage Podded	Wing-Fuselage	In Nacelle

Includes 157 production 30+ seat civil transports since the DC3 (in 45 distinct architectures)

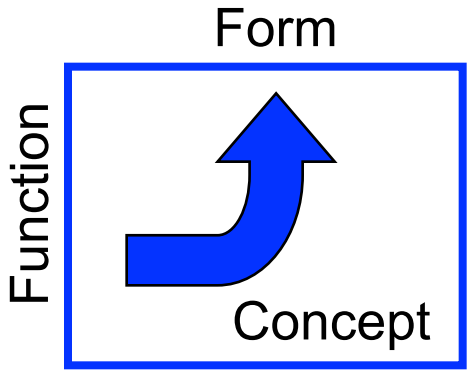
Decision Space View: helps us understand key decisions



- **Sensitivity is based on real historical data for a metric that includes fuel efficiency, T/W, V_{cruise} , price**

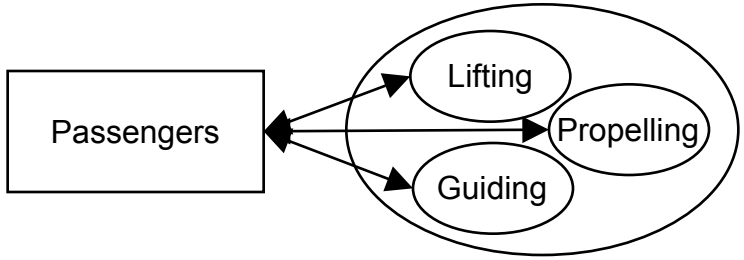
Concept - Definition

- **A product or system vision, idea, notion or mental image which maps Function to Form**
- **Embodies *principle of operation***
- **Includes an *abstraction of form***
- **Concept rationalizes the structure of the architecture (Imrich)**
- **Establishes the solution-specific vocabulary - it is the beginning of the architecture**



Concept Exploration - Transporting

- **Concepts vary by the assignments of the principle internal functions to form**



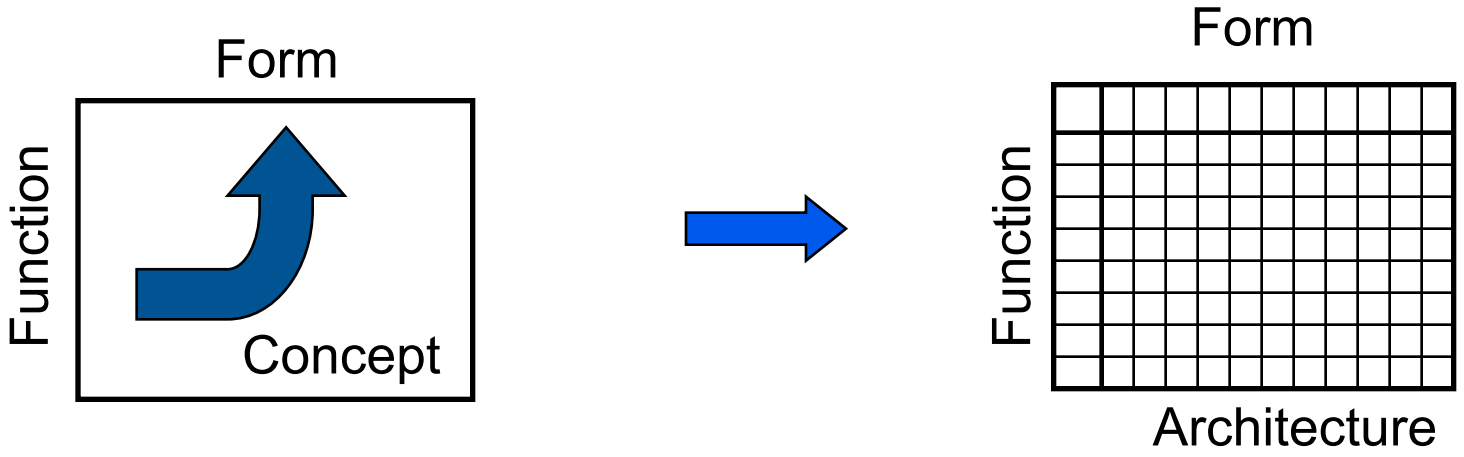
Function:	Internal Function:	Form	Form 2
Transporting payload	Lifting	Wheels	Wing
	Propelling	Wheels	Air breathing engine
	Guiding	Wheels	TE surfaces

Exercise: Concepts

Delivered process	Internal processes	Instrument	Car	?	?	?
Transporting	Lifting	Wheels	x	x		
		Wings				
		Propeller			x	
		Closed hull				x
	Propelling	Wheels	x	x		
		Propeller			x	x
	Guiding	Wheels	x			
		“Ground”		x		
		Rudder/TE				x
		Propeller			x	

Concept

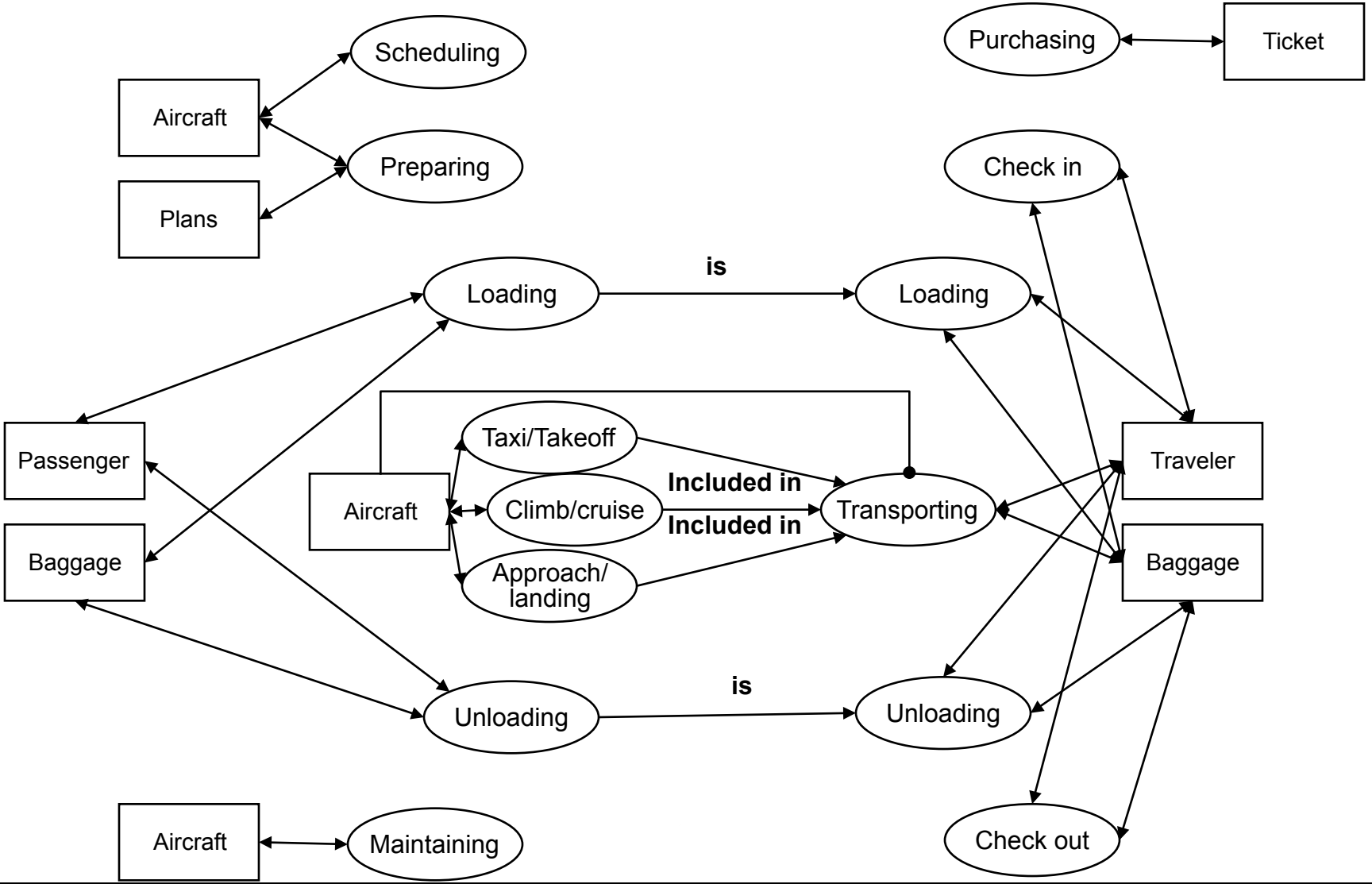
Concept to Architecture



- **Concept is a system vision, which maps Function to Form**
- **Contains first level functions and form**

- **Architecture includes the details of the assignment of function to form**
- **Process flow, internal operands, internal processes, interface definition**

Concept of Operations of the Aircraft (left) and of the Service of Air Transportation (right).



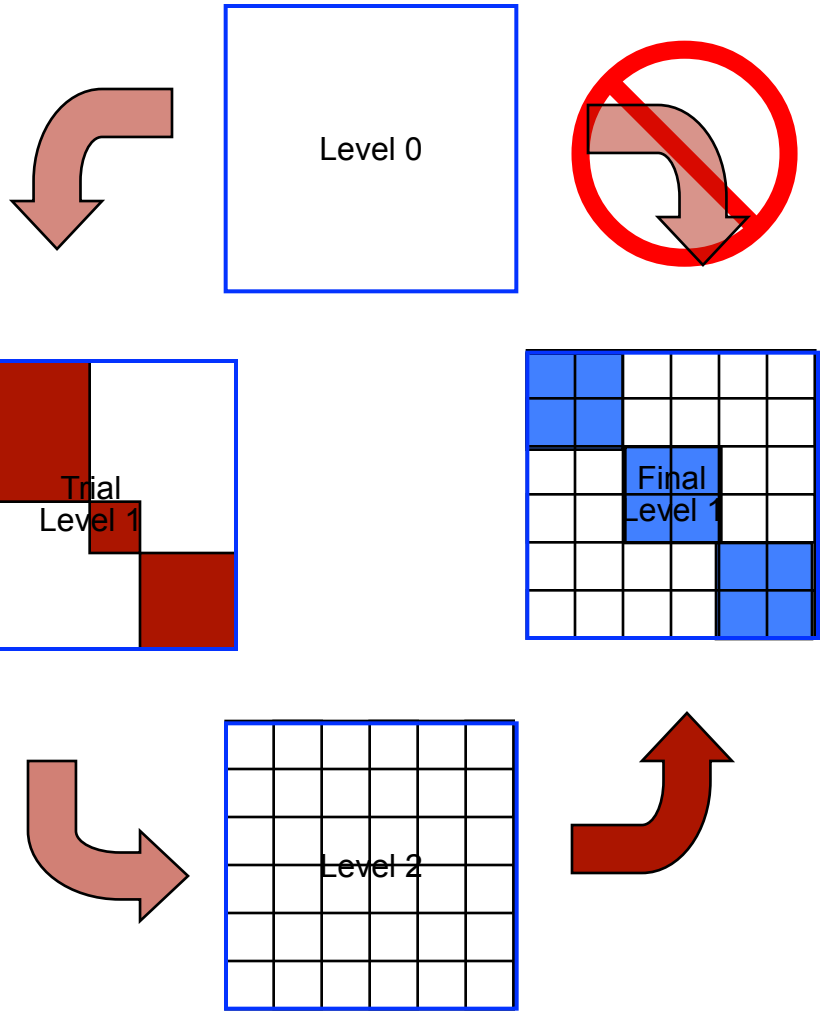
Decomposition of Function

- Successive decomposition from 1 to 28 functions
- Ordered roughly by sequence
- Only one level 2 function is “transporting passenger”
- Is this a good decomposition?

Level 0	Level 1	Leevel 2
transporting	ticketing	linking learning reserving purchasing amending
	checking in	arriving airport issuing checking inspecting examining alerting changing
	loading	loading embarking storiing
	transporting	informing entertaining nourising
		transporting
		conveying shipping evacuating
	unloading	collecting disembarking unloading
	checking out	collecting departing airport crediting
1 function	6 functions	28 functions

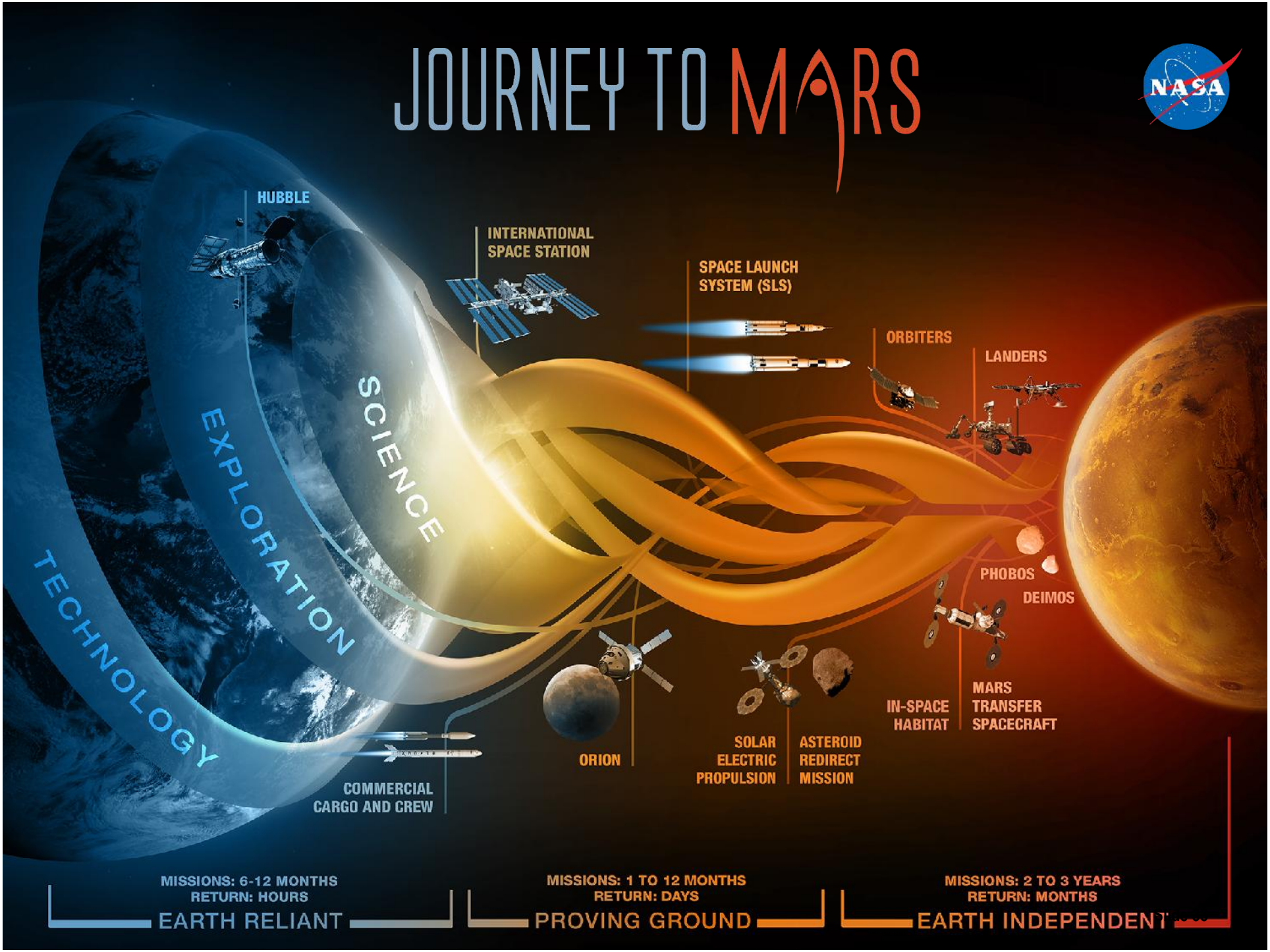
Creating the Final Level 1 Architecture

- The final level 1 architecture is not found by working down to level 1 from level 0, but working up from level 2
- "2 down, 1 up"
- Start with the system at level 2
- Find appropriate modularization at level 1
- That will balance all of the important considerations and (hopefully) find that they cleave along the same "planes"



- This is modularization by functional interaction
- Must also consider from, integration, legacy, suppliers, etc.
- Good modularization is a key step to making complex systems less complicated

		Reservation					Ticket			Passenger							Checked Bags					Carry Bags				Secondary			
		linking	learning	reserving	purchasing	amending	changing	issuing	crediting	arriving at airport	inspecting	embarking	transporting	disembarking	evacuating	departing airport	checking	loading	shipping	unloading	collecting	examining	storing	conveying	collecting	alerting	informing	entertaining	nourishing
Cluster 1	linking	2	2	2	2	2	2	1	1	1	1	1	0	1	1	1	2	0	0	0	1	1	1	0	1	1	1	1	1
	learning	2	3	3	2	3	2	1	1	1	1	1	0	1	1	1	2	0	0	0	1	1	1	0	1	1	1	1	1
	reserving	2	3	4	3	4	3	2	2	1	2	1	0	1	1	1	3	1	0	1	2	2	1	0	1	1	1	1	1
	purchasing	2	2	3	4	4	4	3	2	1	2	1	0	1	1	1	3	1	0	1	2	2	1	0	1	1	1	1	1
	amending	2	3	4	4	5	4	3	2	1	2	1	0	1	1	1	3	1	0	1	2	2	1	0	1	1	1	1	1
Cluster 2	changing	2	2	3	4	4	5	4	2	1	2	2	0	2	2	1	3	1	0	1	2	2	2	0	1	2	1	2	2
	issuing	1	1	2	3	3	4	4	2	0	1	1	0	1	1	0	2	1	0	1	1	1	1	0	0	1	0	1	1
	crediting	1	1	2	2	2	2	2	2	0	1	0	0	0	0	0	2	1	0	1	1	1	0	0	0	0	0	0	0
Cluster 3	arriving at airport	1	1	1	1	1	1	0	0	4	1	3	1	3	2	4	1	1	1	1	2	1	2	1	2	1	1	1	1
	inspecting	1	1	2	2	2	2	1	1	1	3	1	0	1	1	1	2	1	0	1	2	2	1	0	1	1	1	1	1
	embarking	1	1	1	1	1	2	1	0	3	1	4	1	4	3	3	1	0	0	0	1	1	3	1	2	2	1	2	2
	transporting	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	disembarking	1	1	1	1	1	2	1	0	3	1	4	1	4	3	3	1	0	0	0	1	1	3	1	2	2	1	2	2
	evacuating	1	1	1	1	1	2	1	0	2	1	3	1	3	3	2	1	0	0	0	1	1	2	0	1	2	1	2	2
	departing airport	1	1	1	1	1	1	0	0	4	1	3	1	3	2	4	1	1	1	1	2	1	2	1	2	1	1	1	1
Cluster 4	checking	2	2	3	3	3	3	2	2	1	2	1	0	1	1	1	4	1	0	1	3	2	1	0	1	1	1	1	1
	loading	0	0	1	1	1	1	1	1	1	1	0	0	0	0	1	1	2	1	2	2	1	0	0	0	0	0	0	0
	shipping	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0
	unloading	0	0	1	1	1	1	1	1	1	1	0	0	0	0	1	1	2	1	2	2	1	0	0	0	0	0	0	0
	collecting	1	1	2	2	2	2	1	1	2	2	1	0	1	1	2	3	2	1	2	4	2	1	0	1	1	1	1	1
Cluster 5	examining	1	1	2	2	2	2	1	1	1	2	1	0	1	1	1	2	1	0	1	2	3	1	0	1	1	1	1	1
	storing	1	1	1	1	1	2	1	0	2	1	3	0	3	2	2	1	0	0	0	1	1	3	1	2	2	1	2	2
	conveying	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0
	collecting	1	1	1	1	1	1	0	0	2	1	2	0	2	1	2	1	0	0	0	1	1	2	1	2	1	1	1	1
Cluster 6	alerting	1	1	1	1	1	2	1	0	1	1	2	0	2	2	1	1	0	0	0	1	1	2	0	1	3	1	2	2
	informing	1	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1	2	1	1
	entertaining	1	1	1	1	1	2	1	0	1	1	2	0	2	2	1	1	0	0	0	1	1	2	0	1	2	1	3	2
	nourishing	1	1	1	1	1	2	1	0	1	1	2	0	2	2	1	1	0	0	0	1	1	2	0	1	2	1	2	3


JOURNEY TO MARS
NASA
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
IN-SPACE HABITAT
MARS TRANSFER SPACECRAFT
ORION
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
COMMERCIAL CARGO AND CREW
MISSIONS: 6-12 MONTHS
RETURN: HOURS
EARTH RELIANT
MISSIONS: 1 TO 12 MONTHS
RETURN: DAYS
PROVING GROUND
MISSIONS: 2 TO 3 YEARS
RETURN: MONTHS
EARTH INDEPENDENT

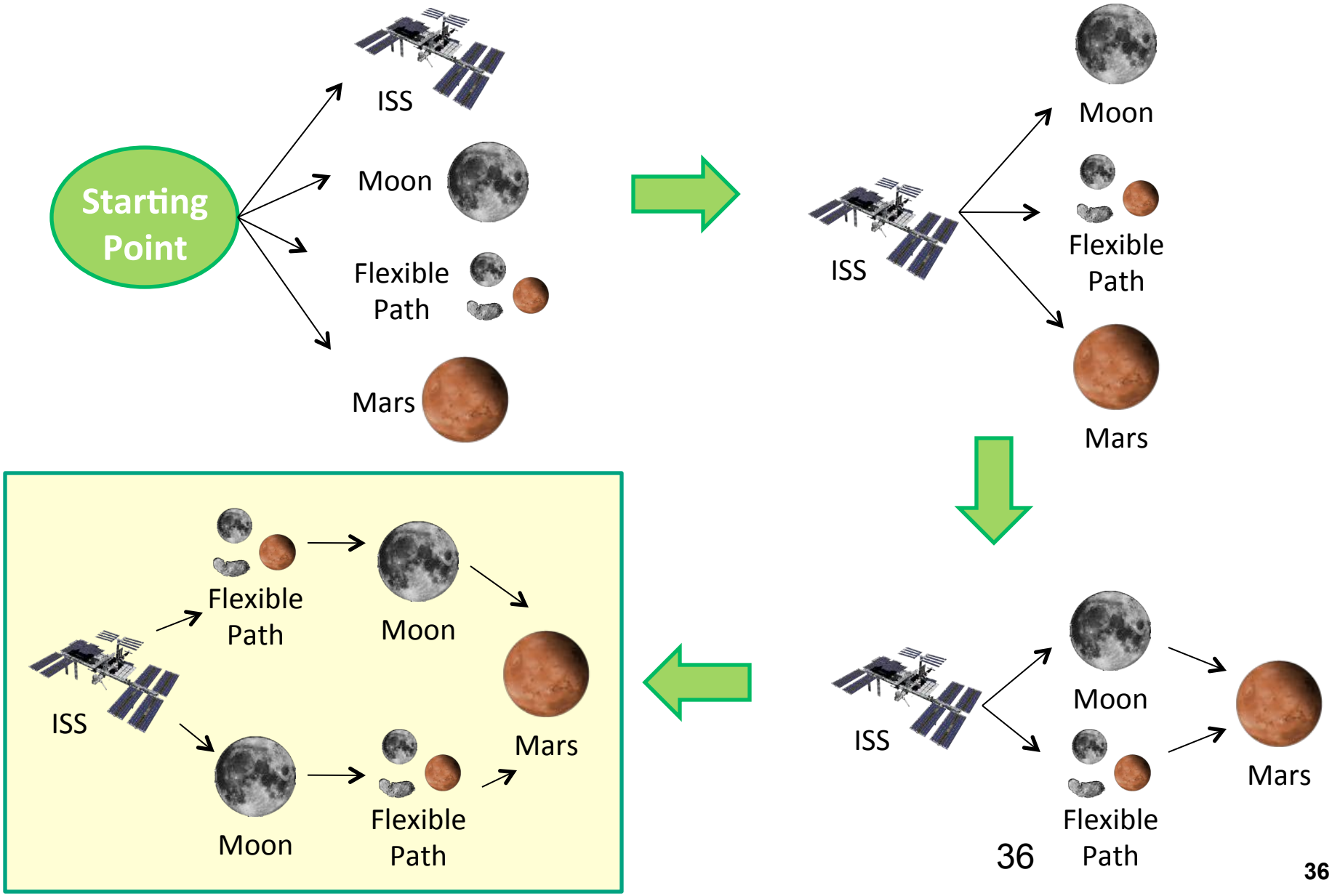
Augustine Human Space Flight Committee 2009: Stakeholder Based Evaluation Measures

Evaluation Measure	Traceability				Criteria
	Space Act	VSE 2004	GES 2007	OSTP 2009	
Exploration Preparation	✓	✓	✓	✓	Capable systems and ops for robust exploration beyond LEO
Technology Innovation	✓	✓	✓	✓	Enable new modes of exploration and leadership in innovation
Science Knowledge	✓	✓	✓	✓	Aligned with goals of scientific community
Expanding Human Civilization		✓	✓		Sustained human presence off planet, and protection of Earth
Public Engagement			✓	✓	Motivate and inspire; Societal benefits, regular new accomplishments
Economic Expansion	✓	✓	✓	✓	Growing profitable industrial base and commercial engagement
Global Partnership	✓	✓	✓	✓	Leverage & expand Intl partnerships

Decisions that Frame Policy

1. What is the phase out plan of the Shuttle?
   - As planned in 2012, extend?
2. What is the future of the ISS?
   - End in 2015, extend to 2020?
3. What is the strategy for exploration beyond LEO?
   - Moon first, flexible
4. Should the government developed launch system be based on:
   - NASA Ares, Ares lite, direct shuttle derivative or an EELV heritage systems?
5. How should crew be carried to LEO (ISS in particular)
   - Commercial or US Government supplied

High Level Decision Evolution of the Committee



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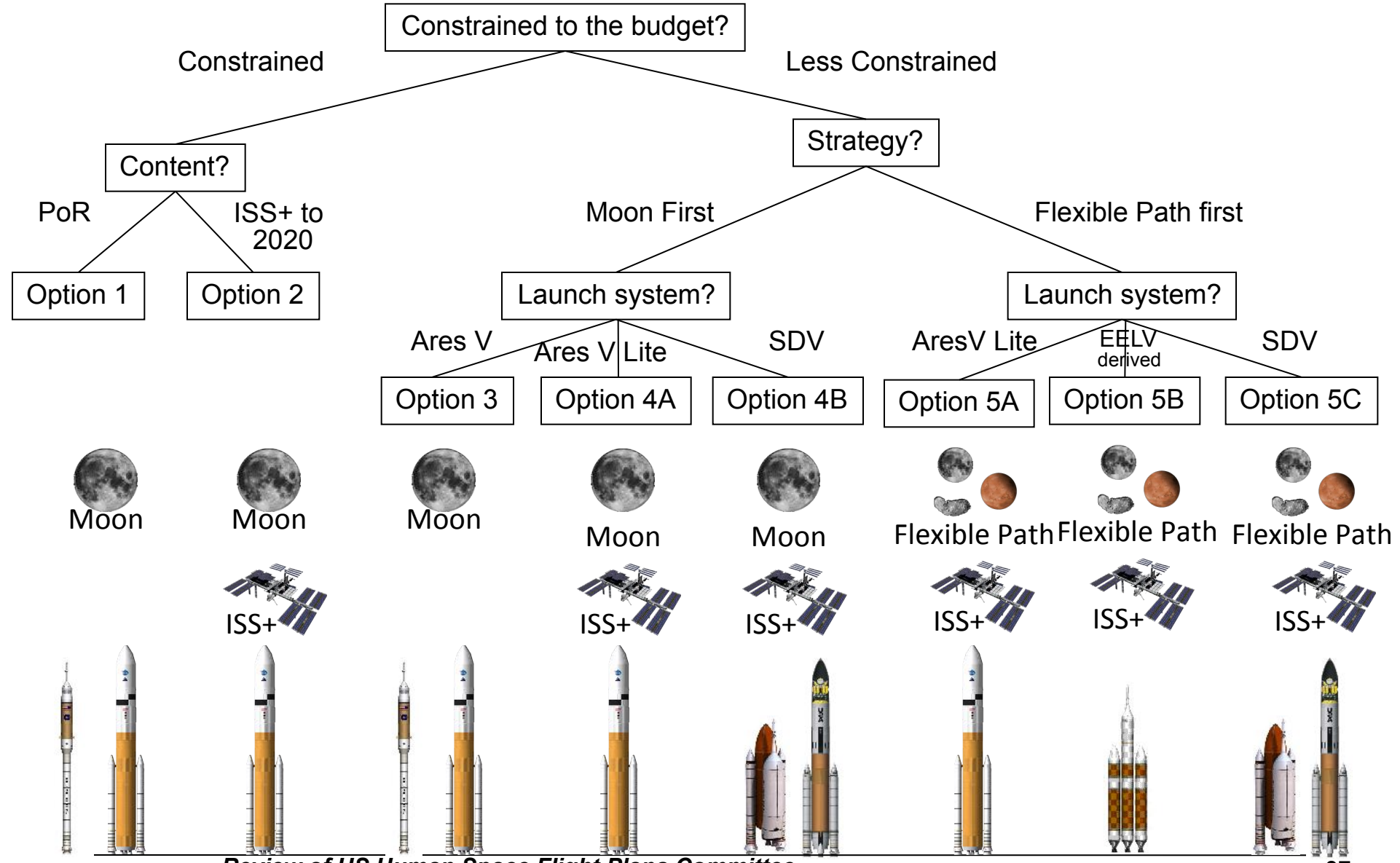
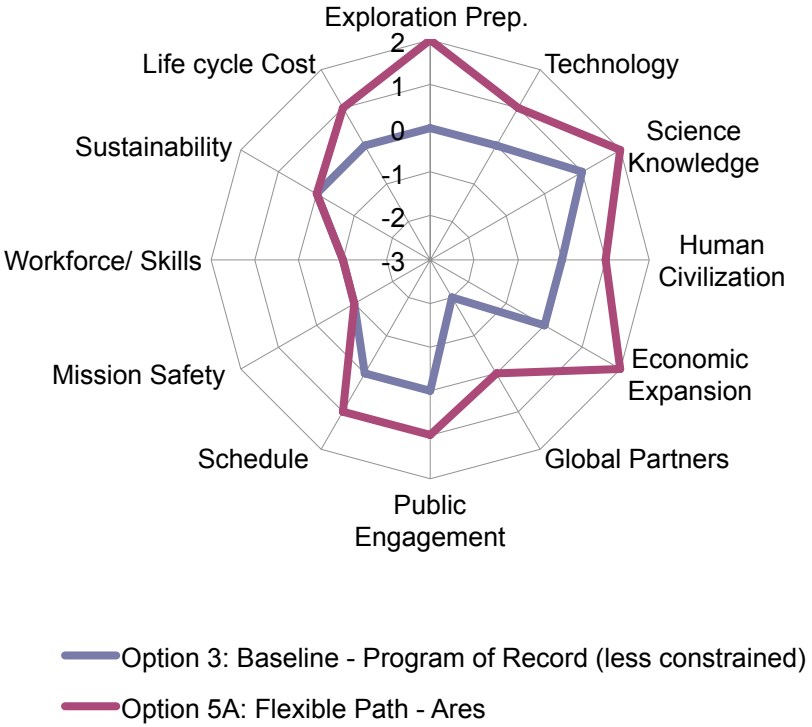
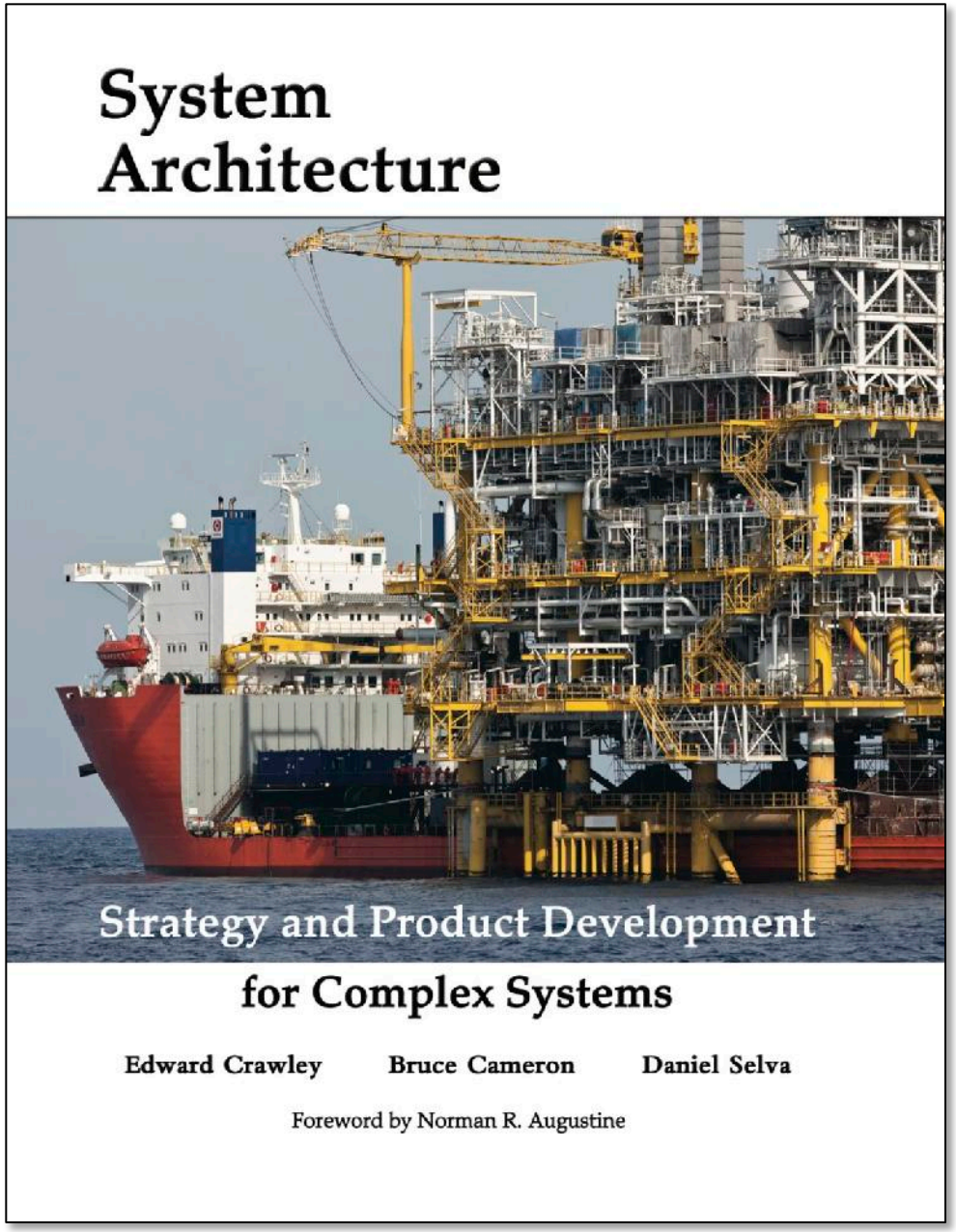
Suggested Integrated Option Decision Analysis



Relative Value Analysis – Baseline vs. Flexible Path (Ares V Lite) Less Constrained Options

- The Flexible Path (with Ares V Lite) dominates the Baseline:
  - Exploration preparation (much mor capable launch system)
  - Technology (investment)
  - Science (more places visited)
  - Human civilization (ISS extension)
  - Economic expansion (in space commercial elements and crew)
  - Global partnerships (ISS)
  - Public engagement (more new things)
  - Schedule (out of LEO sooner)
  - Life cycle costs
- This is a significant difference in benefi. for the same investment!





Outcomes

- Developed a rigorous engineering discipline with design principles, semantically exact ISO approved notation, and some ability to compute
- Applied successfully to technical systems of wide variety
- Educated thousands of young and mid career professionals
- Created texts and online education

References

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- Dori, Model-Based Systems Engineering with OPM and SysML Springer 2016
- Augustine, Report of the US Human Space Flight Plans Committee, NASA 2009
- MITx: Architecture and Systems Engineering - http://web.mit.edu/professional/digital-programs/online-course/syseng/index.html