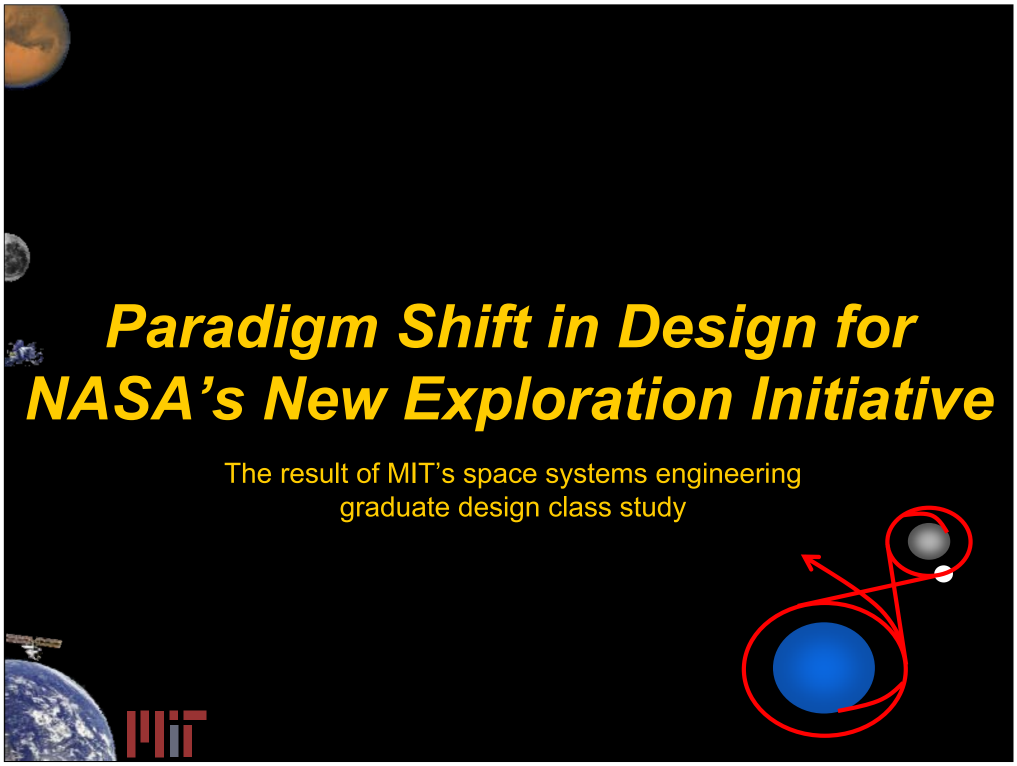
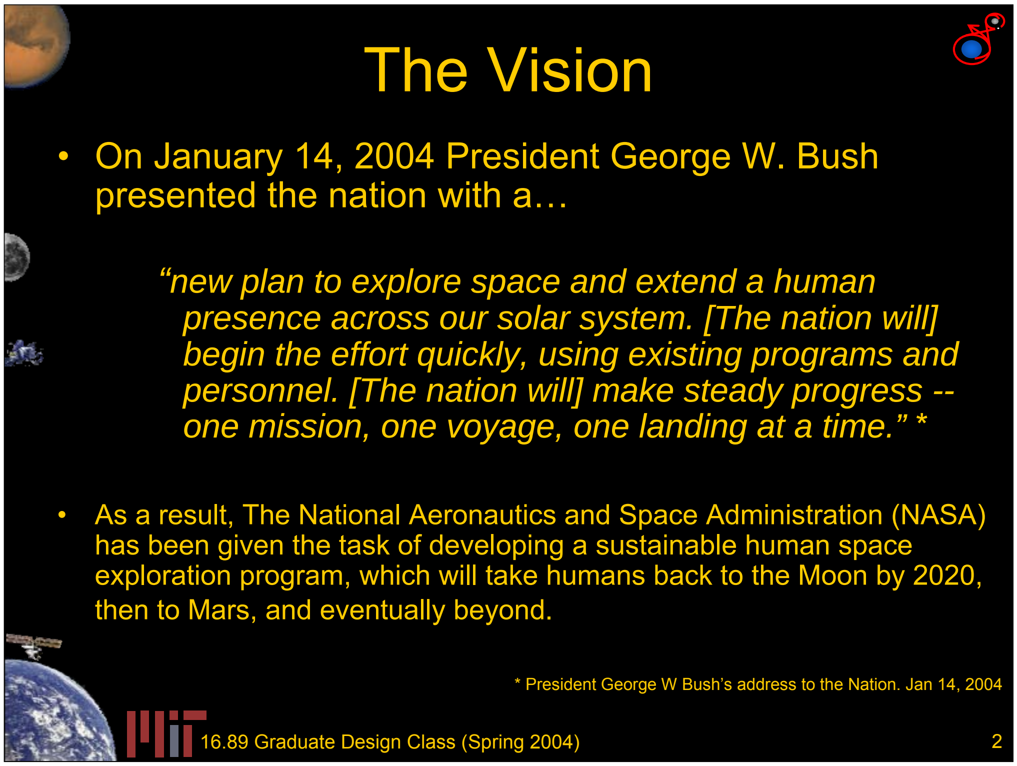
16.89J / ESD.352J Space Systems Engineering
Spring 2007



Welcome….

The following presentation outlines the results of MIT's graduate space systems design class study of NASA's new exploration system.

The presentation focuses on how the new exploration initiative should be designed, as opposed to the more common single-point design.



On Jan 14, 2004 President Bush presented the nation with a new vision for space. President Bush's Vision called for NASA to develop a sustainable space exploration system which would bring the US back to the moon no later than the year 2020, with the goal of traveling to Mars, and then eventually beyond.

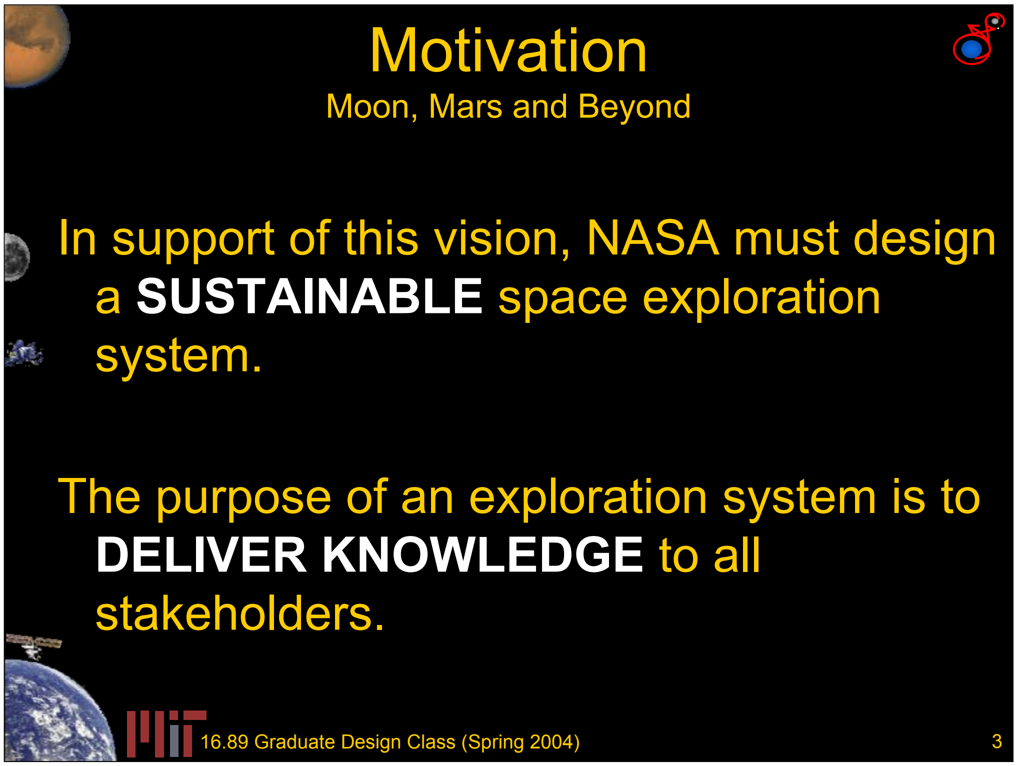
However, the new directive for NASA raises to main questions:

1. What does the design of a sustainable space exploration system consist of and how can NASA go about designing this system.

Maybe even more general of a question is, What is a sustainable space system?

2. For the past couple of decades, NASA's main focus has no been on exploring. This raise the question of what is to be gained by an exploration system.

What is the goal of exploration? How does one value an exploration system?



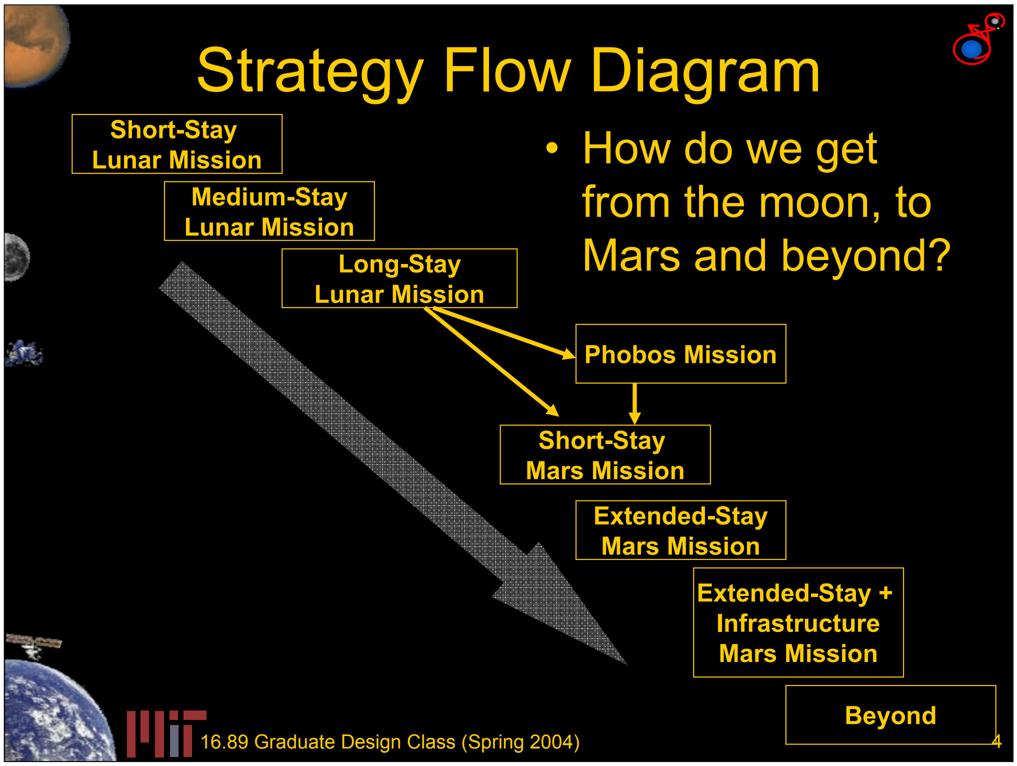
The motivation behind MIT's graduate space systems design class report is to describe how NASA's should focus it's design methodologies towards the design of the new space exploration initiative.

The two main points of the presentation are:

NASA must develop a rigorous design method focusing on the development of a SUSTAINABLE space exploration system

- and -

NASA must understanding that the purpose of an exploration system is to deliver knowledge to the stakeholders

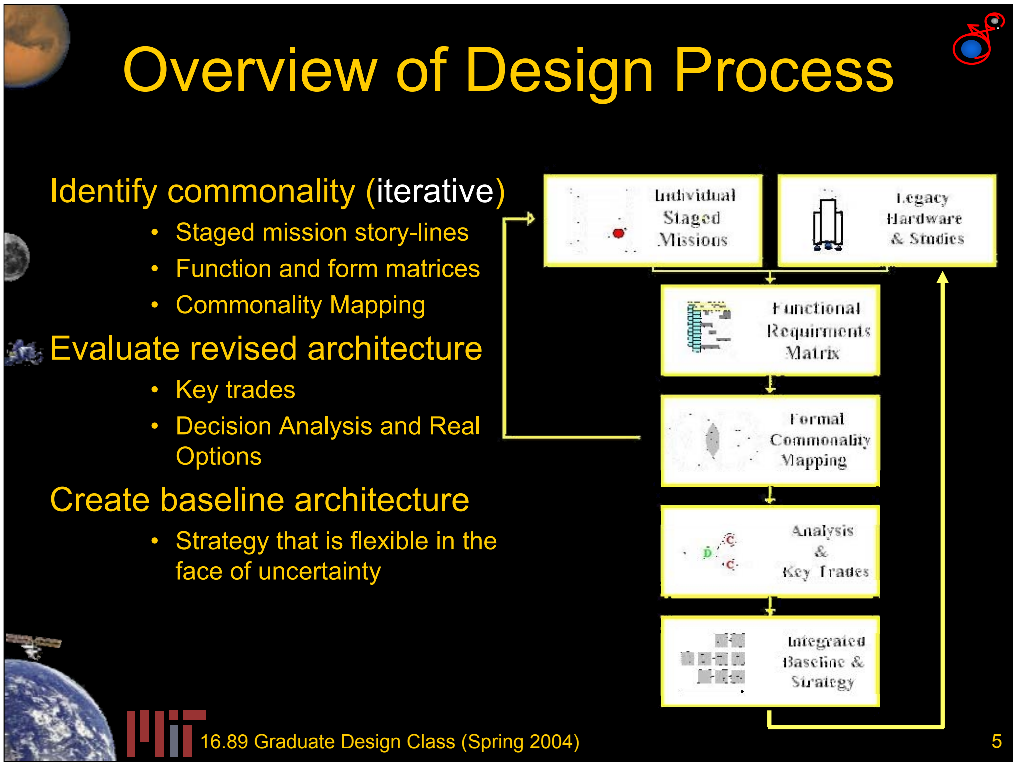


What is the goal of the design? How does one being the design process?

The first step in designing the new exploration initiative is to develop a strategy, a way in which the development process will be implemented. President Bush laid out two main milestones for the new exploration initiative. The first step in the nations exploration path will be to return to the Moon. The next step will be to use what was learned at the moon and then use that knowledge to go onto Mars.

But how should NASA reach these two goals while maintaining a sustainable space system. MIT graduate design class has viewed strategy as an evolutionary path of increasingly difficult missions, each one building on the next. The first step will be to regain the capability of the Apollo program by returning to the moon, but only for a small period of time. The next step will be to perform longer science gathering and technology test-bed missions. The last phase of moon missions is long duration mission that utilizes a semi-permanent habitation facility, similar to that which would be required for Mars.

Once the Moon test-bed missions have been completed, or policy has shifted, the next step will be a short mars mission. The evolutionary path for Mars will be similar to that of the moon with each mission building on the previous. With the Mars there exists the option of a pre-mission to the Martian moon phobos. A mission to phobos could be used as a technology demonstrator much like Apollo 8 was used. However, in this case the crew could gain additional knowledge with phobos instead of simply orbiting Mars.



Once the strategy was completed, the nest step was to complete a design process.

This presentation will describe one way in which NASA could go about designing a sustainable space system.

Note that at this point in time this is only a conceptual design methodology. This design methodology is not the answer to the problem, but simply one way in which NASA could proceed.

The design process starts out by looking at existing studies, legacy hardware and by defining individual staged missions.

The next step is then to define the different capabilities, or “functions”, that are required to complete the individual missions.

Once the required functions have been complied, generic forms are created to perform these functions. (Form Function mapping)

After completing the form/function mapping, the forms are compared across all the missions in an attempt to define any common elements. The above process is repeated several times.

Note that the examples in this presentation are the results of one pass through this iteration.

Once an appropriate amount of iteration has been performed, modern analysis tools are applied to the designs. These analysis tools consist of, but are not limited to decision analysis, scenario planning, utility theory, and real options theory.

The last step is to combine all the design decisions into an integrated strategy for the development path of the exploration system

The remainder of this presentation focuses on the class' proposed design methodology and how that system should be evaluated with respect to knowledge.

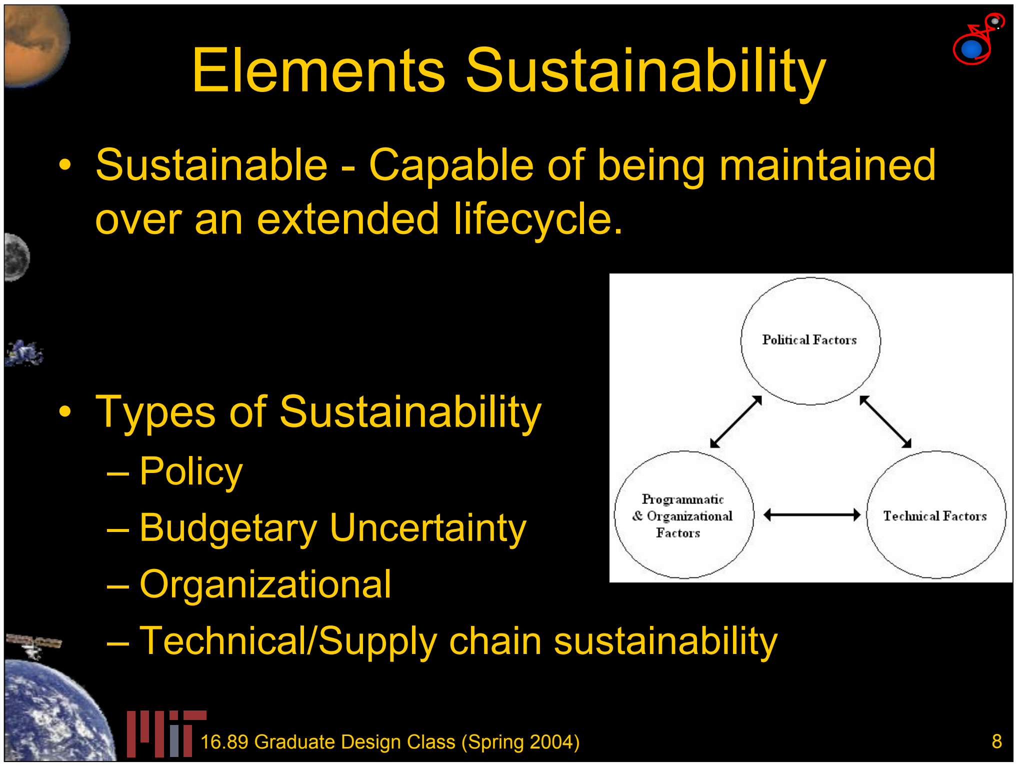
The next section will discuss the characteristics that make a system sustainable

The following section will focus on how knowledge is the deliverable in an exploration system and how knowledge pertain to the design of NASA's new exploration system

The final section of the presentation will go over the proposed deign process. This section will focus on developing individual mission strategies, form/function mapping to identify common elements, and modern analysis tools with which to evaluate the designs.

Sustainability

Sustainability and Extensibility

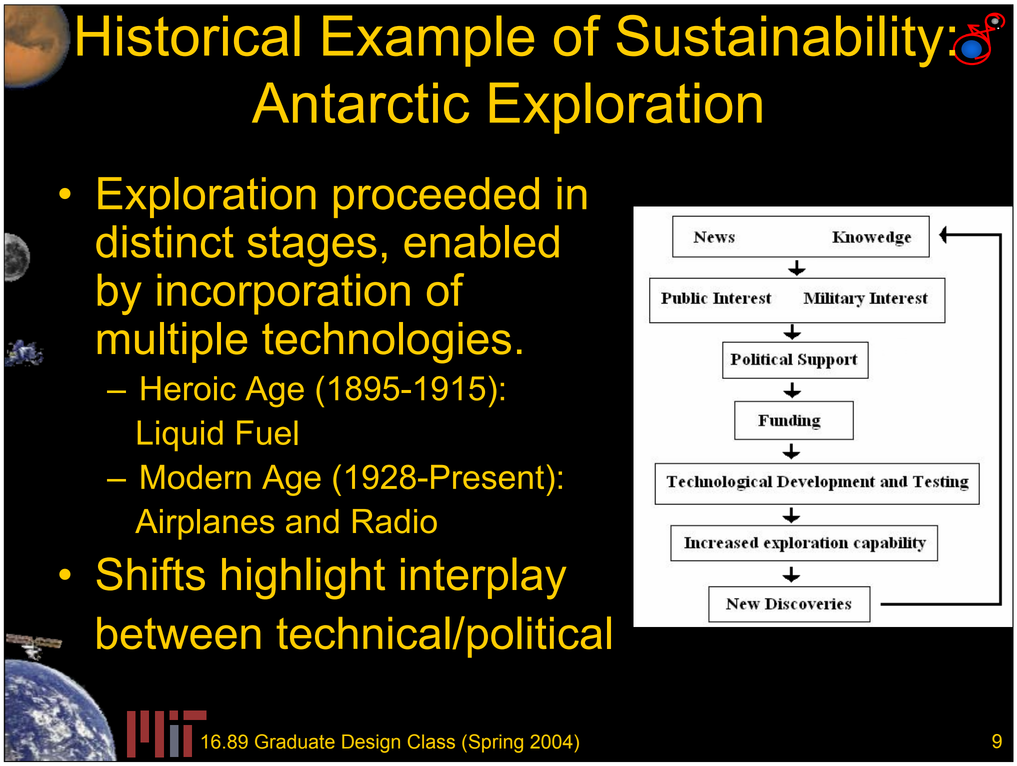


Sustainability can be looked at as a systems capability to be maintained over an extended lifecycle. Sustainability comes in many different types, but some of the more common types of sustainability consist of a system reaction to policy, budgetary, organizational, and technical/supply chain uncertainties. The different types of sustainability interact with one another and form a cyclic relationship What is important to understand is that a system must account for all these form of sustainability if the system will be sustainable into the future.

In an attempt to better understand what it takes to be a sustainable space infrastructure, we will first look at what is not a sustainable space architecture. There are two example of non-sustainable space architectures: they are the Apollo and shuttle programs.

•The Apollo program can be viewed as non-sustainable due to the high costs associated with the design and a shift in policy. Apollo was not a sustainable system because it could not be maintained by the current budget in the face of policy change.

•The Shuttle is not sustainable due to the shuttle's inflexibility towards new technology and the high maintenance / operations cost. The high costs and constraints of associated with the refurbishment of the shuttle have made it very difficult for new technology to be infused into the system.

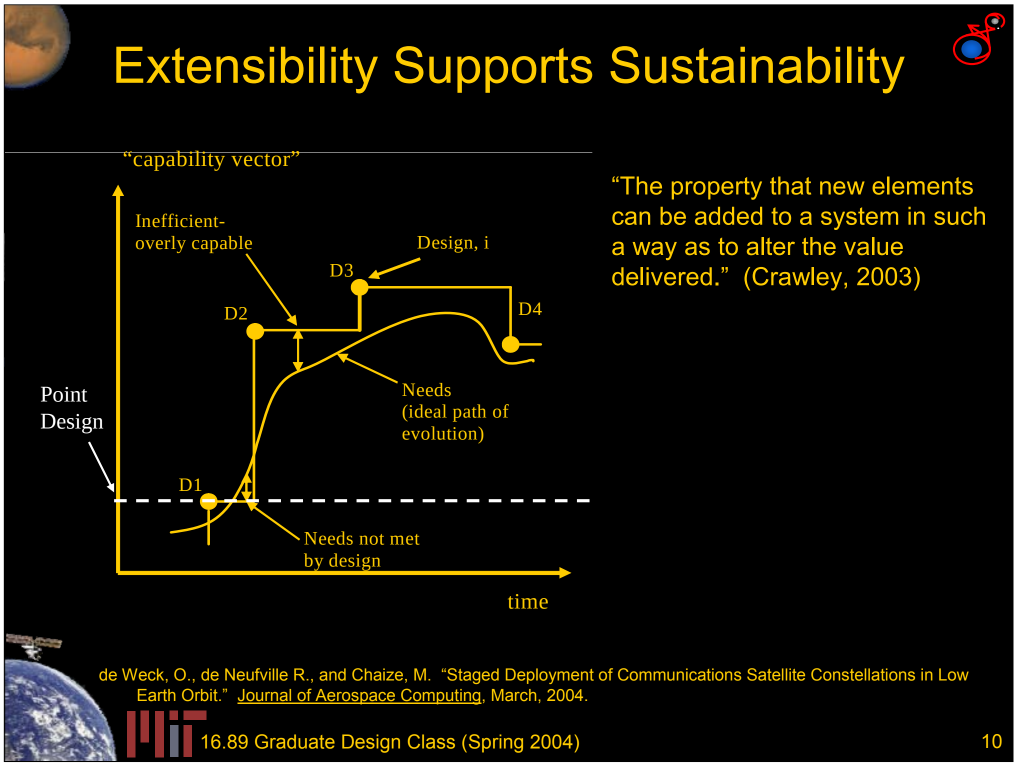


An example of a sustainable exploration program is the exploration of Antarctica. The interesting fact about Antarctica is that Antarctica was never designed to be sustainable, but evolved into a sustainable program.

This evolution can be seen by the two ages of Antarctica exploration; the Heroic and Modern age. The transition was in part due to the infusion of new technologies (More than one technology come together: the airplane and the radio). However, the reason for the shift between periods was due to the interaction of technical and political factors. It is this interaction that allowed a new era of Antarctican exploration to begin.

Finally, the exploration Antarctica is still being maintained today because the system is able to evolve with the changes in new technology and political issues.

Today, we find ourselves on a similar edge to a new era in space exploration. Over the past decade new technologies have been developed that will aid in the exploration of space. With President Bush's speech, political interests have aligned themselves with these new technologies in support of space exploration. More recently, NASA is being reorganized as a response to the new space exploration initiative. So, All the key ingredients exist for a shift towards a new era of sustainable space exploration.



Finally another attribute of a sustainable design is that the system is extensible into the future. Above is a conceptual example of how developing an extensible system supports sustainability.

In the graph you can see a plot of the demand for capability vs time. Notice that throughout time the desired, or ideal, capability can either increase or decrease.

At one point in time, traditional design methods would results in a single point design with a given capability. This capability could be either above or below the current demand.

As time goes on the, ideal capability of the system changes and the traditional point design is no longer ideal.

Under these circumstance the common approach to take would be to develop another point design, say D2, in order to meet the current demand.

The idea behind extensibility is that the system is flexible to changes in the future . For example: initially our extensible design might have the same capability as our point design, D1. However, the design of the extensible system is such that as the demand changes the system can be modified, at a lower cost, such that it's capability can be raised or lowered. The significance of this extensible design is that a single design can be modified such that it meets current demand throughout time, as opposed to being forced to design new single-point systems over and over again.

In real life, it would not be possible for an extensible system for following the ideal capability demand path precisely. Therefore, the evolution of any extensible system is more than likely to happen in jumps or spurts, very much in the same way computer software manufactures release new version of computer code.

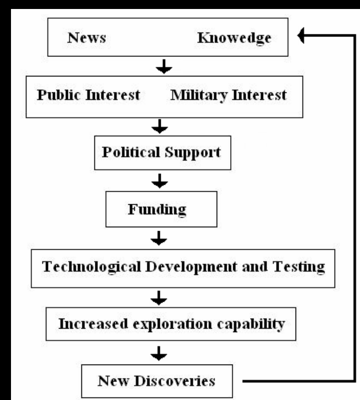
The point to take away is that extensible systems, by their nature, support sustainability. Because the future is uncertain, extensible systems can react to changes in demand and therefore can be sustained into the future.

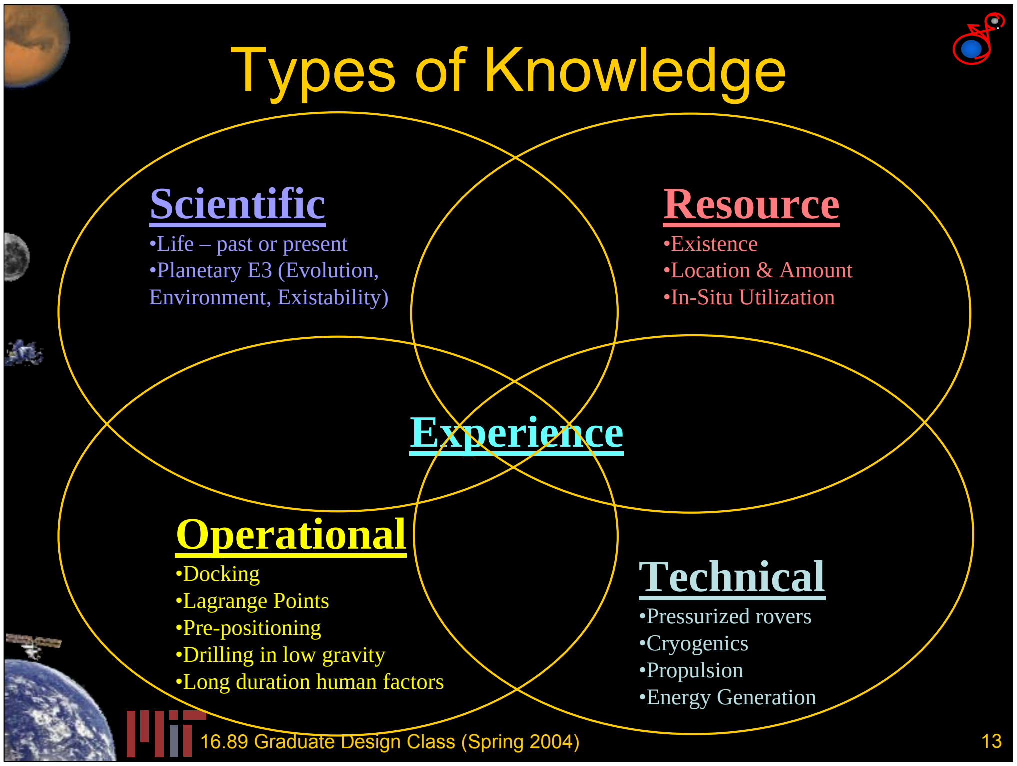
Knowledge

The product of any exploration system

The Knowledge View

- Why do humans explore?
  - To expand the knowledge of our surroundings
  - To improve the technological leadership of the United States
  - To inspire interest in science and technology
- The knowledge gained by the space infrastructure is the value-added delivery to the beneficiary
  - Scientists
  - Technologists/Explorers
  - Public and Commercial Enterprises
- Knowledge drives the exploration cycle




Types of Knowledge
Scientific
•Life – past or present
•Planetary E3 (Evolution, Environment, Existability)
Resource
•Existence
•Location & Amount
•In-Situ Utilization
Experience
Operational
•Docking
•Lagrange Points
•Pre-positioning
•Drilling in low gravity
•Long duration human factors
Technical
•Pressurized rovers
•Cryogenics
•Propulsion
•Energy Generation
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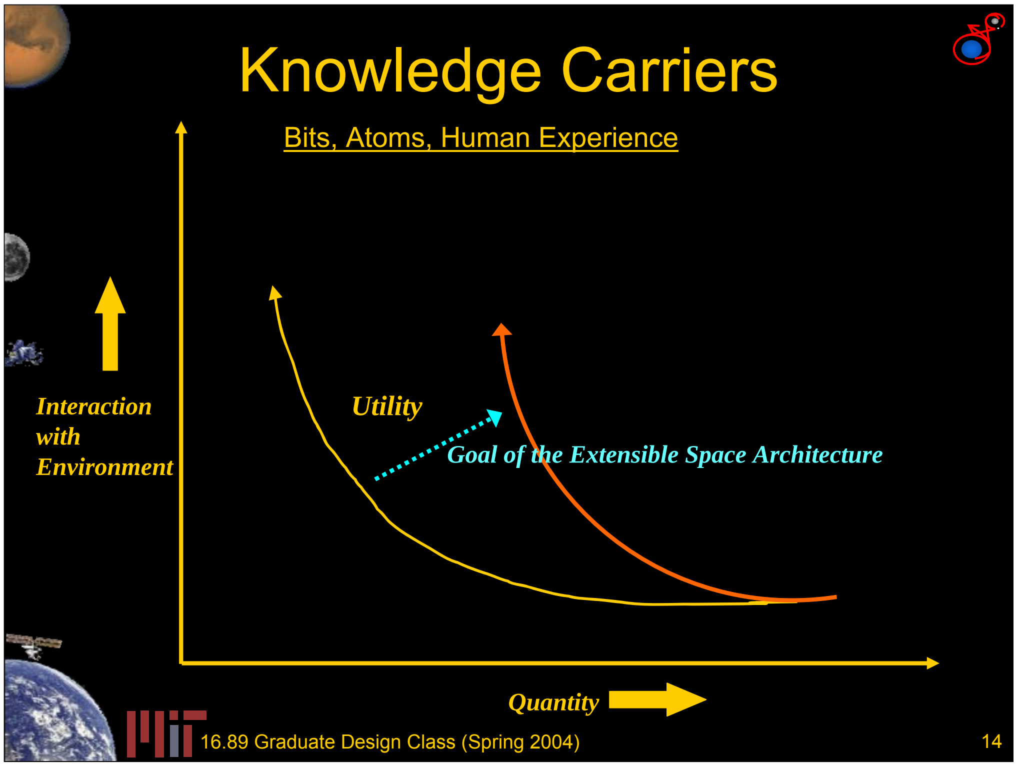


Listed in increasing utility and increasing ‘difficulty’

Bits

- Passive – non interactive. Ex: picture
- Active – interacting with the environment, taking a measurement, sending data back

Samples

- Implied discoveries – weathered rock showing past existence of water
- Direct Proof → rock with a pocket of water in it

Human Experience

- The adage “a picture is worth a thousand words” does not apply
- Really “the experience is worth a thousand pictures”

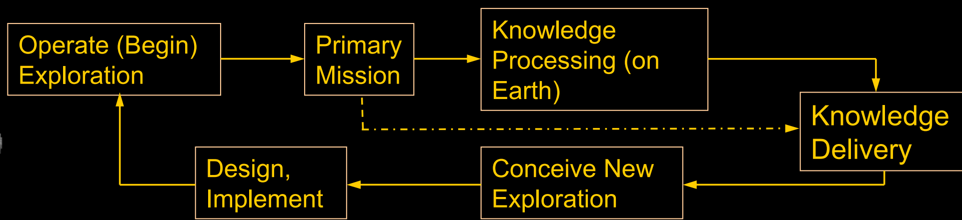
http://marsrovers.jpl.nasa.gov/spotlight/

Orion nebula from: http://sparky.rice.edu/~hartigan/astr542/astr542.html

www.fpsoftlab.com/ saturn3d.htm

http://www-curator.jsc.nasa.gov/curator/lunar/lunar.htm

Knowledge Delivery Cycle



For Sustainability, Knowledge Delivery Time (Latency & Throughput) must be factored into the Exploration System design

Mars Global Surveyor (MGS)

(Sept 1997 - orbit around mars)
- ('Recent' Mars water paper – Aug 2000)

Knowledge Delivery Time (KDT) = 35 months

('Recent' Mars water paper – Aug 2000)
- (Indirect verification by MER – March 2004)

KDT = 43 months

→ **Total MGS KDT = 78 months (>6.5 years)**

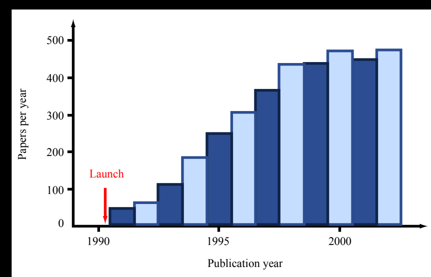
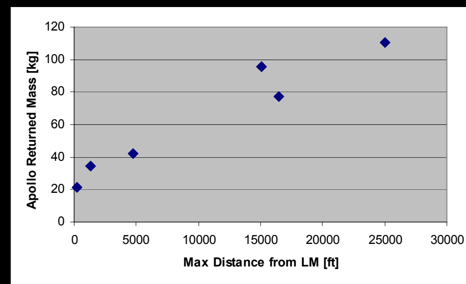


Image by MIT OpenCourseWare. Adapted from Beckwith, 2003.

Apollo Case Study

- Apollo is an example of how infusing new technology into a baseline architecture can affect knowledge returned
- Knowledge returned ~ sample mass
- Amount of knowledge driven by exploration time, exploration distance
- Large jump in exploration coverage from Apollo 14 to 15
- Apollo 15 is the first to have a rover



	Samples Returned (kg)	cost (94$M)	%kg inc from previous	%cost inc from previous
Apollo 11	21.6	1360		
Apollo 12	34.3	1389	59	2.1
Apollo 14	42.3	1421	23	2.3
Apollo 15	77.3	1581	83	11.3
Apollo 16	95.7	1519	24	-4
Apollo 17	110.5	1536	15	1
	381.7			

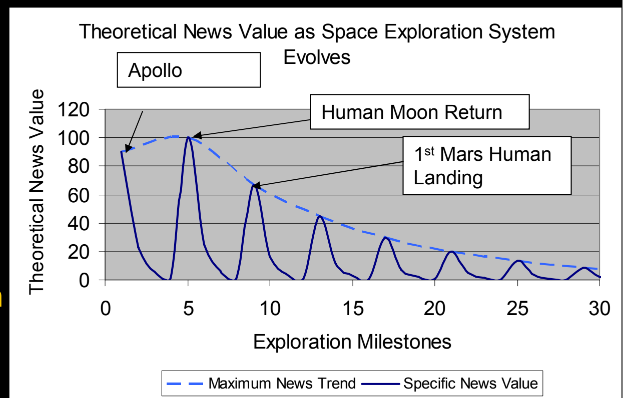
Knowledge Vs. News

Repeated but similar successes generate decaying news value over time.

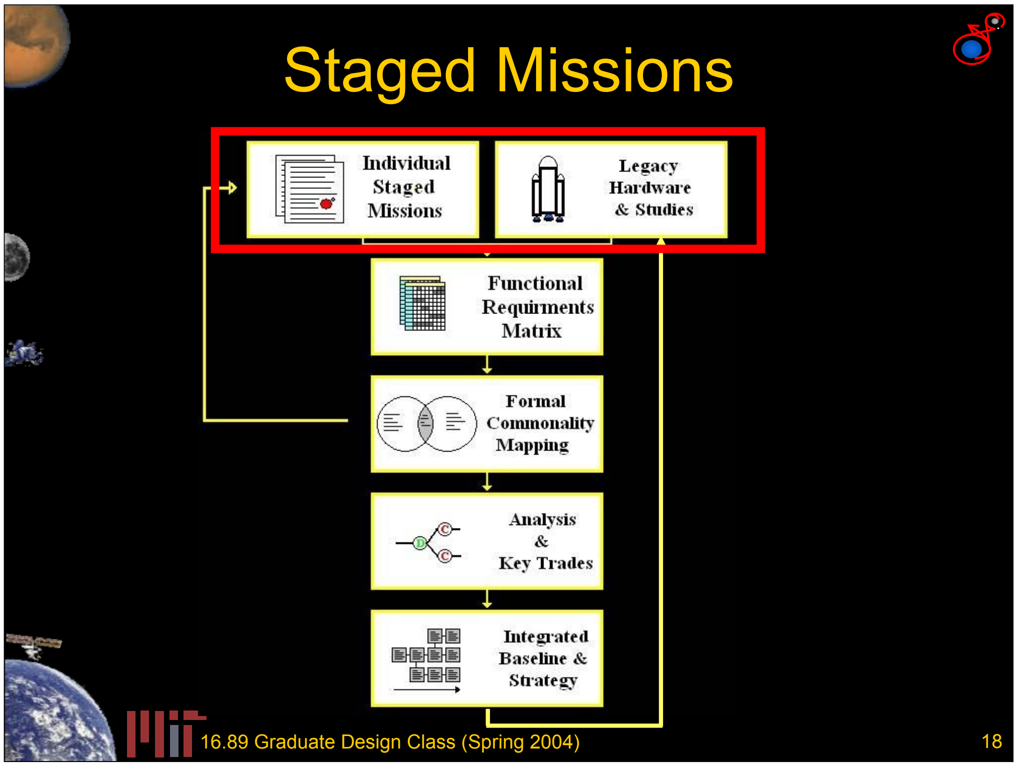
<u>Breakthrough Scenario</u>

Personal connections with exploration system

Permanent or semi-permanent settlements will generate interest between people on Earth and explorers



- For a sustainable exploration system → effective knowledge delivery system → Public receives knowledge separate from media


Staged Missions
Individual Staged Missions
Legacy Hardware & Studies
Functional Requirments Matrix
Formal Commonality Mapping
Analysis & Key Trades
Integrated Baseline & Strategy
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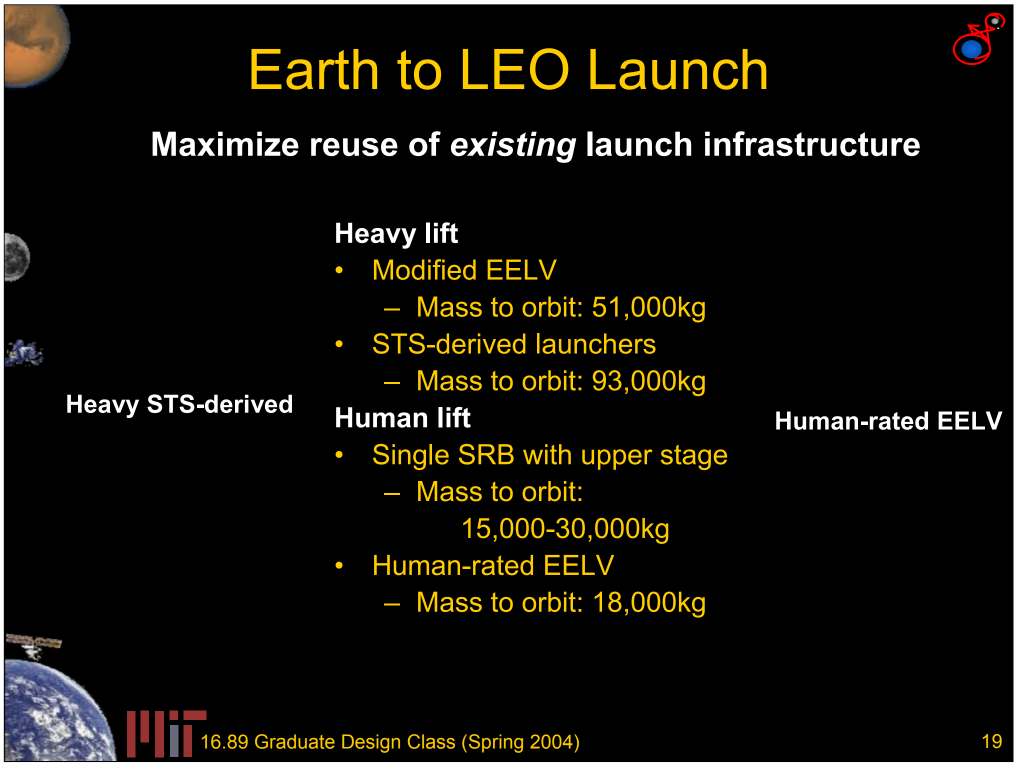


All mass to orbit numbers are to LEO 28.8

After calculating the capabilities that could be achieved with a different configurations of legacy hardware including: STS launchers (a shuttle stack replacing the orbiter with a payload pod) derived , SRB derived launchers (a solid rocket booster from the shuttle with a large cryogenic second stage on top), Foreign launchers (such as the heavy versions of the A5), the EELV families (evolved expendable launch vehicles, the Atlas V and Delta IV families), EELV derived approaches, and completely new systems. We have come to the conclusion that the most attractive technically and also the most cost effective architecture should be built around two launchers. A heavy one for cargo only based on the STS and lifting about 100 metric tons to LEO. And a Heavy EELVs such as the Delta IV Heavy for transporting Humans.

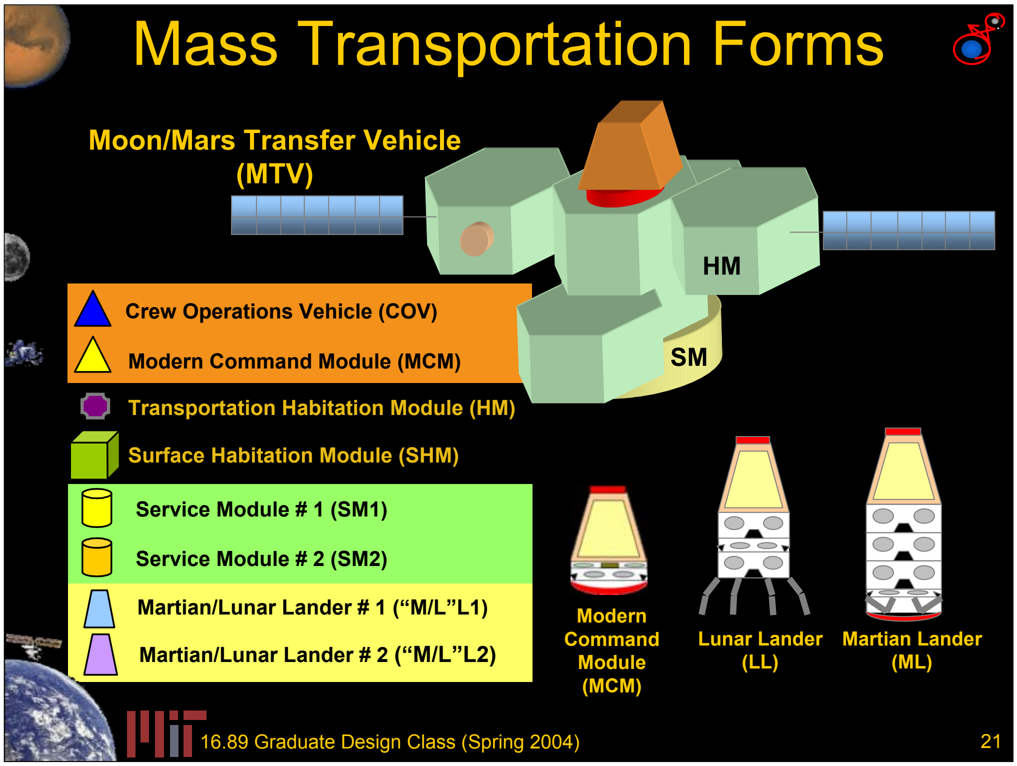
This is for your info in case they ask questions about this:

The engines of the STS derived would not be reusable and would use exactly the same ones that the DeltaIV Heavy, that is three RS68s. This allows economy of scale.

After separation from the external tank a cryogenic upperstage provides the last part of the Delta-IV. It is a cryogenic upper stage similar to that of the Apollo third stage and it is the most complex part that has to be developed.

Extensible System Strategy

- Knowledge must be transferred in the form of "**bits and atoms**"
  - A communications architecture will aid in knowledge return and support exploration system operations
  - An extensible set of forms will deliver mass to and from the Earth
- A continuum of individual mission profiles are possible for each destination
  - Missions divided into three classes per destination
    - **Moon:** Short, Medium and Extended
    - **Mars:** Short, Extended and Extended+
    - **Outlier mission:** Phobos



Common forms are **highlighted**.

The *Crew Operations Vehicle (COV)* is functionally similar to the Apollo Command Module, capable of transporting a crew of three and supporting the crew for a short duration mission. The *Habitation Module (HM)* is an extensible habitable volume, made up of **separable modules**. This module can sustain life for long duration missions. When these two modules dock, they form the *Crew Exploration System (CES)*. The *Service Module (SM)* is capable of providing propulsion for transiting the crew from Earth to destination or destination to Earth. In combination with the COV and HM, this module is defined as the *Moon/Mars Transfer Vehicle (MTV)*. The *Mars Landers (ML)* or the *Lunar Landers (LL)* are functionally similar to the Apollo type lander (slightly different forms for Moon and Mars) and capable of transporting three crewmembers from orbit to the surface and back into orbit. In addition to containing the crew during launch and transferring the three crewmembers to the HM in LEO, the *Modern Command Module (MCM)* is functionally similar to the COV, but can return crew back to Earth from LEO at the end of the mission. These modules are summarized in Table 1.

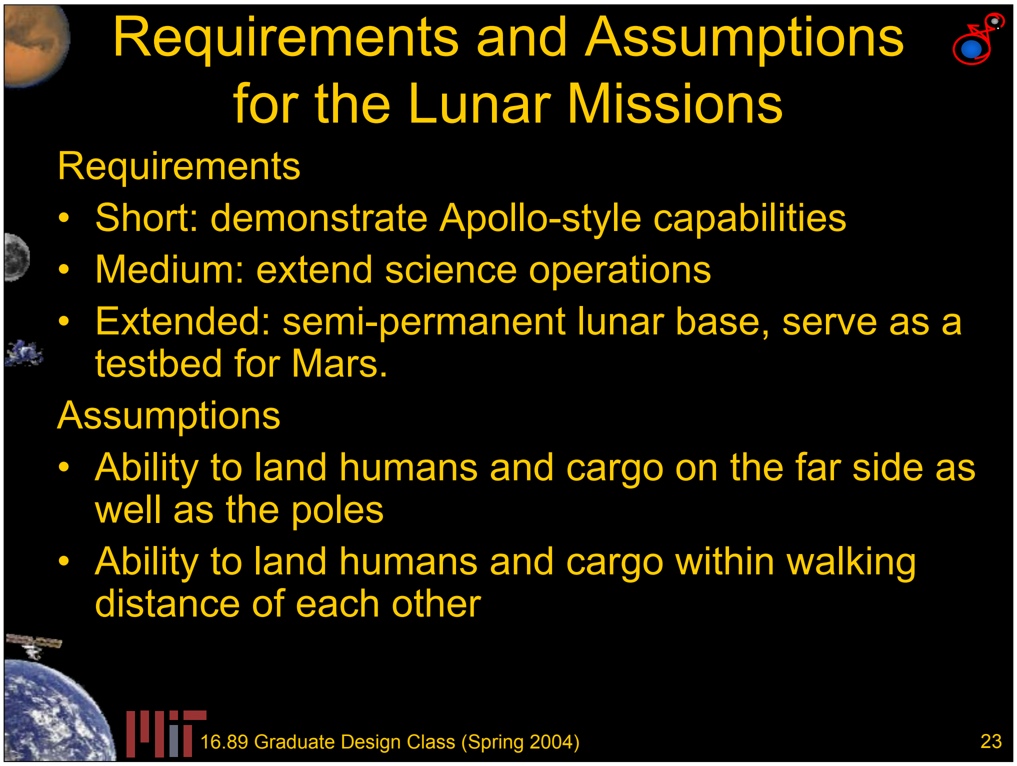
Requirements and Assumptions – All Missions

Requirements

- To gain knowledge by exploring the solar system using an affordable and sustainable space exploration system

Assumptions

- Capability for electric propulsion pre-positioning
- Technologies developed for:
  - Storing cryogenic chemical fuel
  - Radiation and low-gravity countermeasures
  - Advanced spacesuit

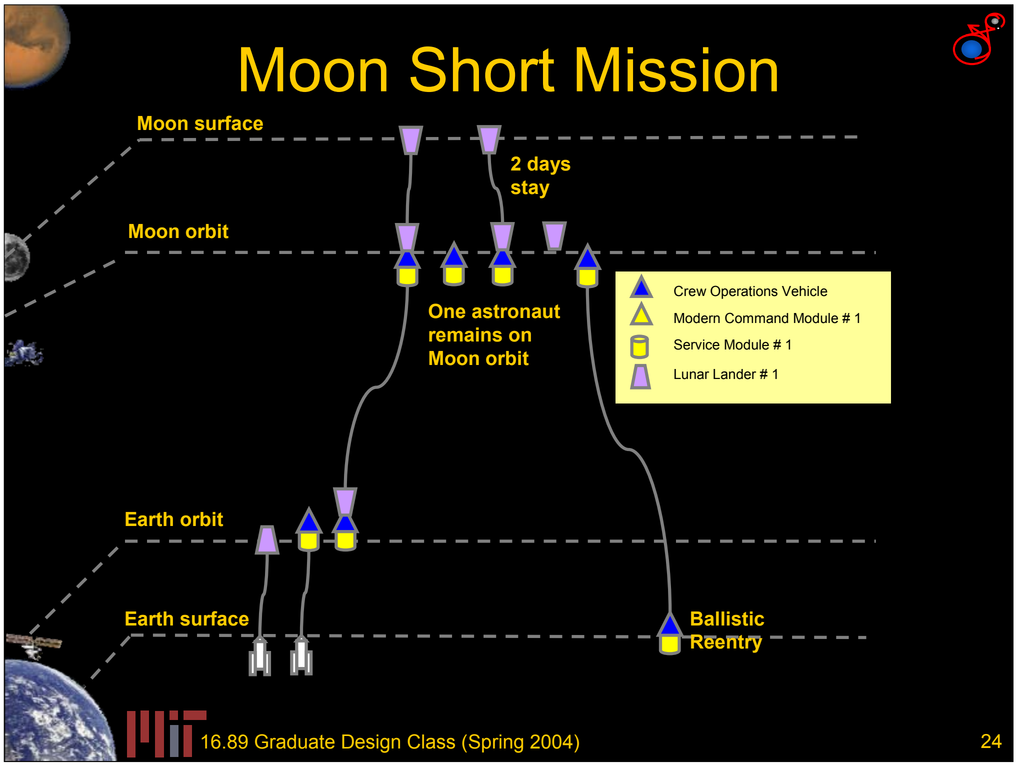


Capability:

Launch, transfer, rendezvous, land

Life support, communications, operations

1. Demonstrate, 2. Scientific, 3. Semi-permanent base.


Moon Short Mission
Moon surface
2 days stay
Moon orbit
One astronaut remains on Moon orbit
Crew Operations Vehicle
Modern Command Module # 1
Service Module # 1
Lunar Lander # 1
Earth orbit
Earth surface
Ballistic Reentry
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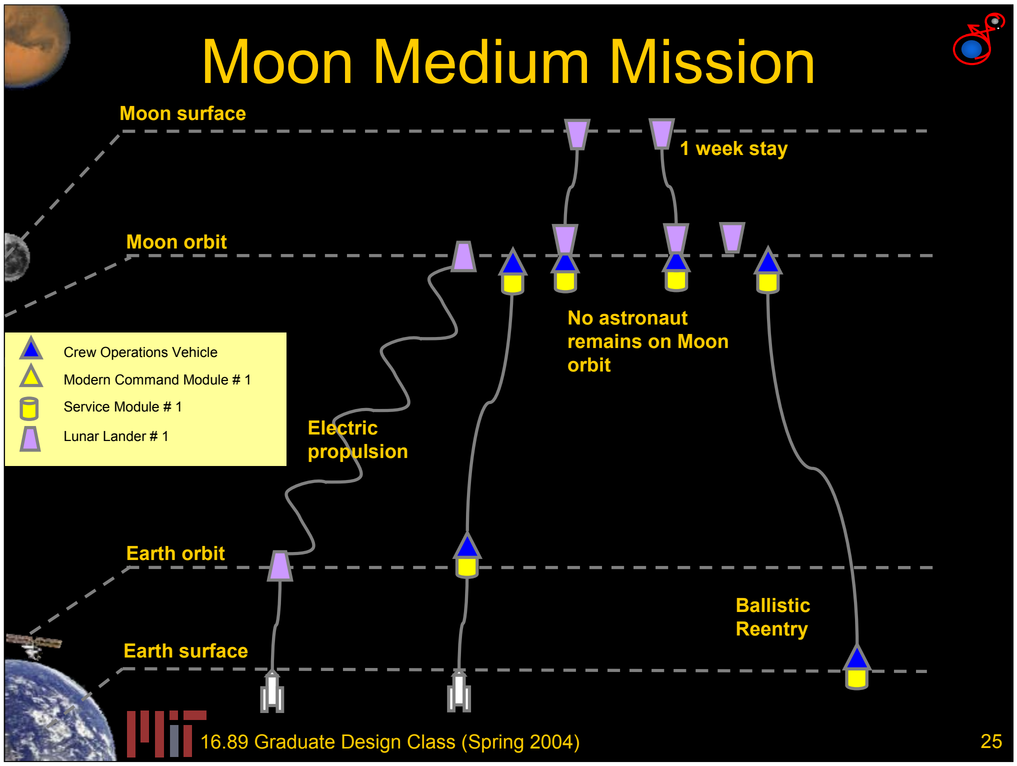
Moon Medium Mission
Moon surface
1 week stay
Moon orbit
No astronaut remains on Moon orbit
Crew Operations Vehicle
Modern Command Module # 1
Service Module # 1
Lunar Lander # 1
Electric propulsion
Earth orbit
Ballistic Reentry
Earth surface
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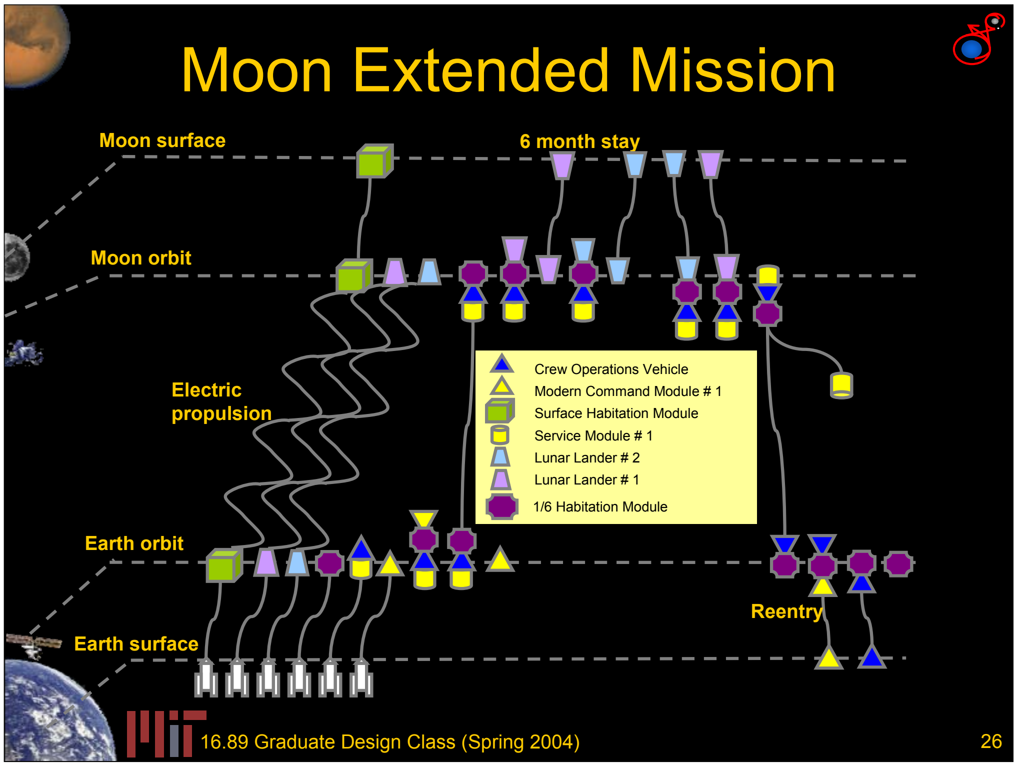
Moon Extended Mission
Moon surface
6 month stay
Moon orbit
Electric propulsion
Crew Operations Vehicle
Modern Command Module # 1
Surface Habitation Module
Service Module # 1
Lunar Lander # 2
Lunar Lander # 1
1/6 Habitation Module
Earth orbit
Reentry
Earth surface
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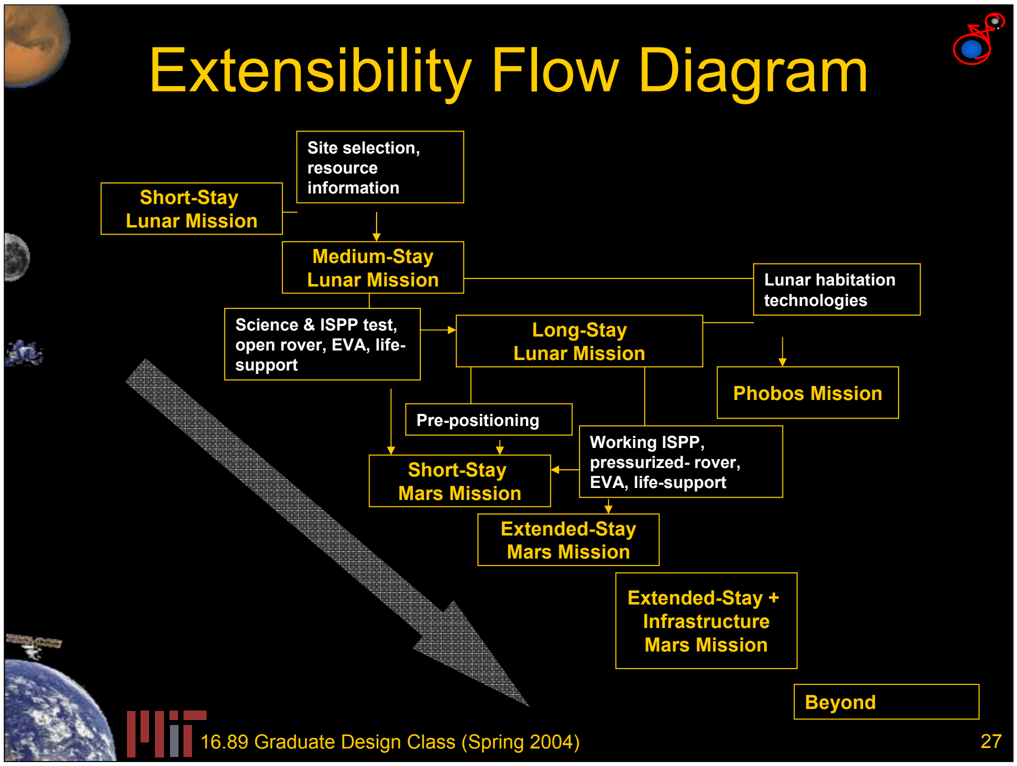
Extensibility Flow Diagram
Site selection, resource information
Short-Stay Lunar Mission
Medium-Stay Lunar Mission
Lunar habitation technologies
Science & ISPP test, open rover, EVA, life-support
Long-Stay Lunar Mission
Phobos Mission
Pre-positioning
Working ISPP, pressurized- rover, EVA, life-support
Short-Stay Mars Mission
Extended-Stay Mars Mission
Extended-Stay + Infrastructure Mars Mission
Beyond
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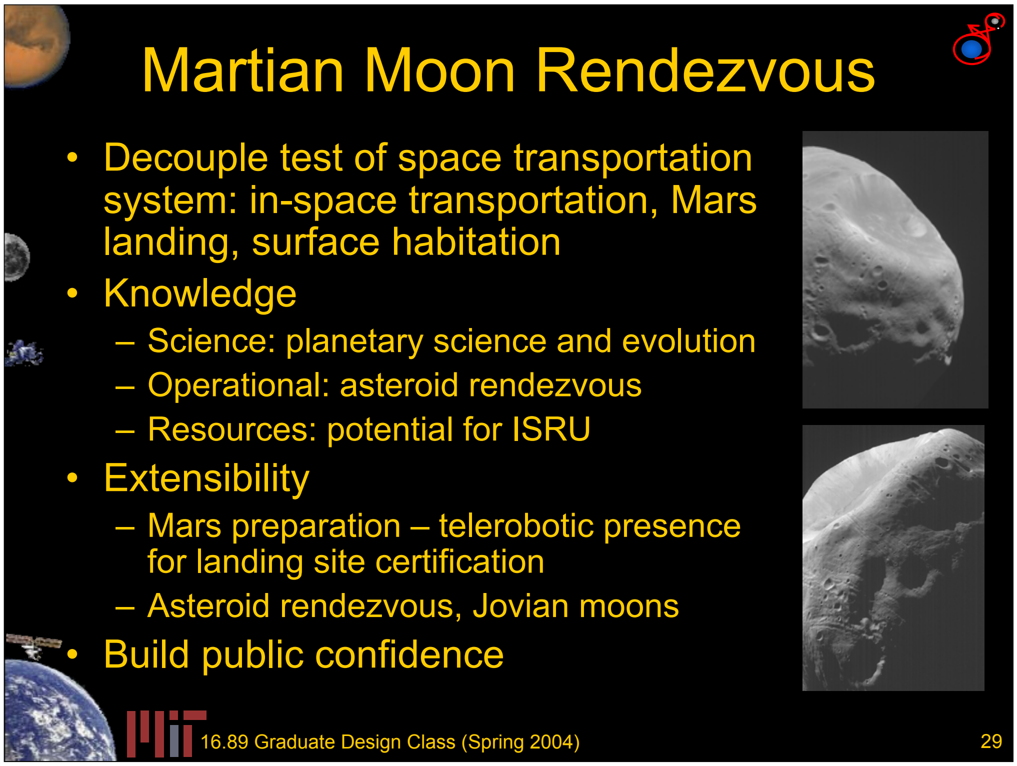
Mars Baseline Design Overview

Mission Evolution

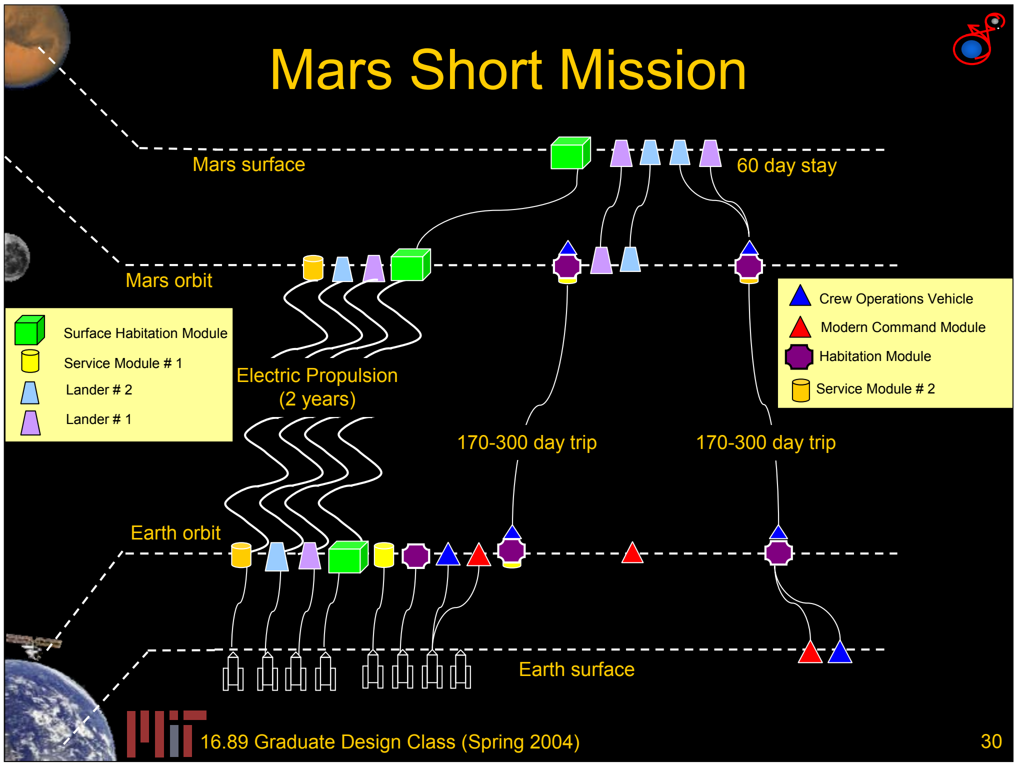
- Phobos
  - demonstrate in-space transportation
- Short stay
  - demonstrate in-space transportation, landing, surface habitation
- Extended stay
  - science, technology test
- Extended stay + infrastructure
  - develop semi-permanent base, technology test for further exploration

Assumptions

- Crew size of 6
- Chemical propulsion for crew transfer
- Electric propulsion for pre-positioned elements
- Precision landing ability



Operational: like an asteroid rendezvous but with precisely known ephemeris data



Mars Short Mission
Mars surface
60 day stay
Mars orbit
Surface Habitation Module
Service Module # 1
Lander # 2
Lander # 1
Electric Propulsion
(2 years)
170-300 day trip
170-300 day trip
Crew Operations Vehicle
Modern Command Module
Habitation Module
Service Module # 2
Earth orbit
Earth surface
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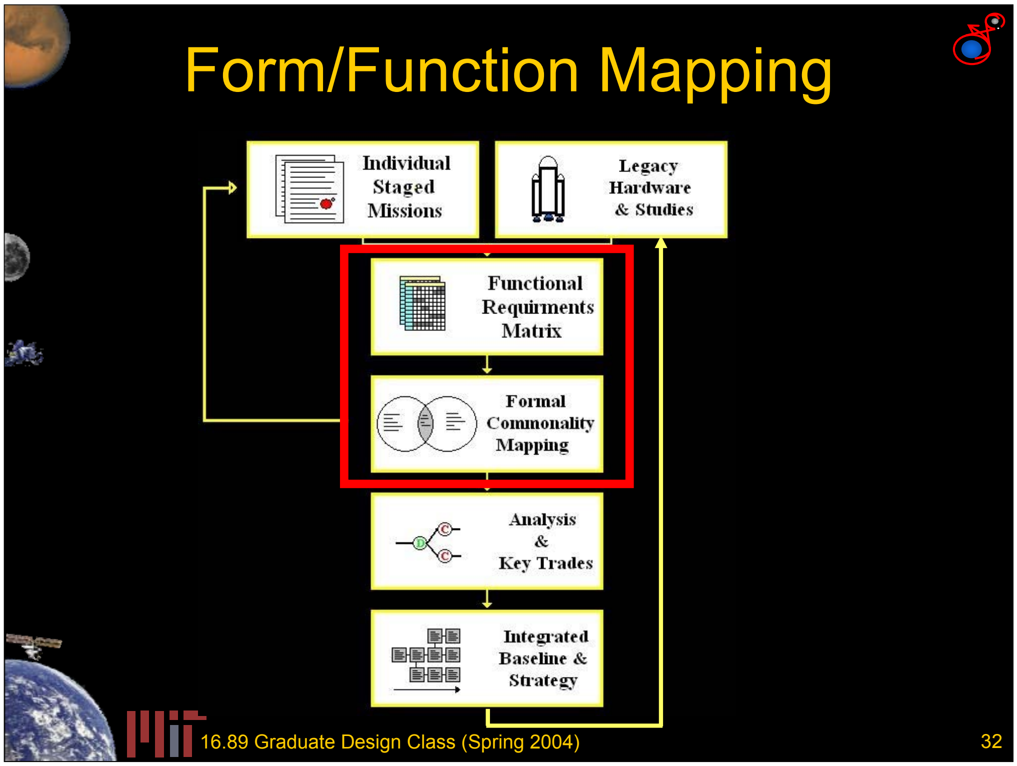
Short stay vs. Extended stay

SHORT STAY	EXTENDED STAY
Opposition class, Venus flyby	Conjunction class, Fast transfer
Surface stay 30-60 days	Surface stay 600 days
EVA, unpressurized rover	Pressurized rover, range ~500km
Knowledge return: Science, Operational, Technology Test, Resources	Knowledge Return: Science – longer term experiments, increased range, Operational

EXTENDED STAY + INFRASTRUCTURE

If Mars remains an interesting destination from a science, operations, or technology testing perspective, subsequent Mars missions will develop infrastructure to facilitate surface stays and exploration at reduced cost.


Form/Function Mapping
Individual Staged Missions
Legacy Hardware & Studies
Functional Requirments Matrix
Formal Commonality Mapping
Analysis & Key Trades
Integrated Baseline & Strategy
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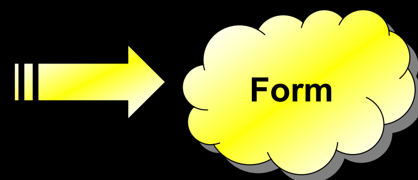
Commonality Mapping

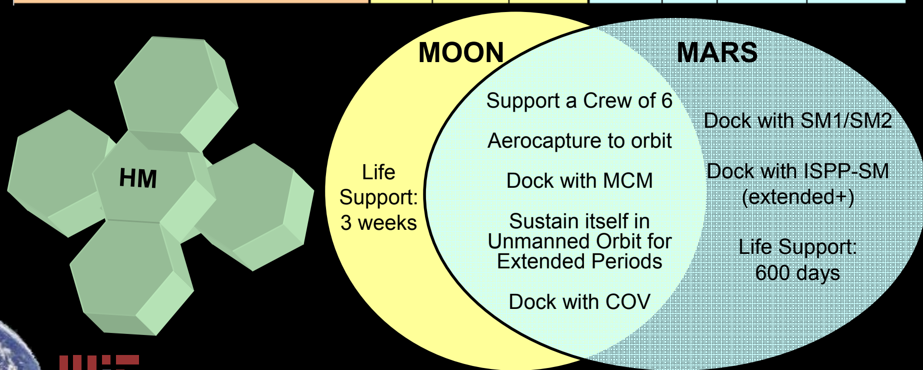
- Goal of commonality
  – Enhance system **sustainability** through **extensibility**
- Step 1
  – Identify required functions for each mission
- Step 2
  – Map required functions to forms
- Step 3
  – Identify opportunities to incorporate commonality

Form	Mission #1	Mission #2	Mission #3	Mission #4
Function #1	X	X	-	X
Function #2	-	X	-	-
Function #3	X	X	X	X
Function #4	X	X	-	-
Function #5	-	X	-	-



Habitation Module

Habitation Module (HM)	Moon			Mars			
	Short	Medium	Extended	Phobos	Short	Extended	Extended+
Support a Crew of 6	-	-	X	X	X	X	X
Human Life Support for 3 weeks	-	-	X	-	-	-	-
Human Life Support for 360 days	-	-	-	-	-	X	X
Human Life Support for 600 days	-	-	-	X	X	-	-
Aerocapture to Orbit	-	-	X	-	X	X	X
Dock with COV	-	-	X	X	X	X	-
Dock with SM1/SM2	-	-	-	X	X	X	-
Dock with MCM	-	-	X	X	X	X	-
Dock with Landers	-	-	X	X	X	X	-
Dock with ISPP-SM	-	-	-	-	-	-	X
Unmanned in Orbit for Extended Period	-	-	X	X	X	X	X



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ISPP-SM = In-situ Propellant Production – Service Module

Following the Mars study performed by Larson (1999), the mass of the HM was calculated as ~55,000kg for a crew of six, depending on a number of critical factors (mission duration, type of radiation protection, life support, supplies, aeroshield and power requirements).

The use of truncated octahedrons increases spacecraft flexibility and was inspired by work from Nadir, Bounova & de Weck. The use of truncated octahedrons,

– Allow 3-D objects to pack together without voids,

– Permit the highest ratio of volume to surface area of all close packing 3D shapes (no voids) to be utilized, and

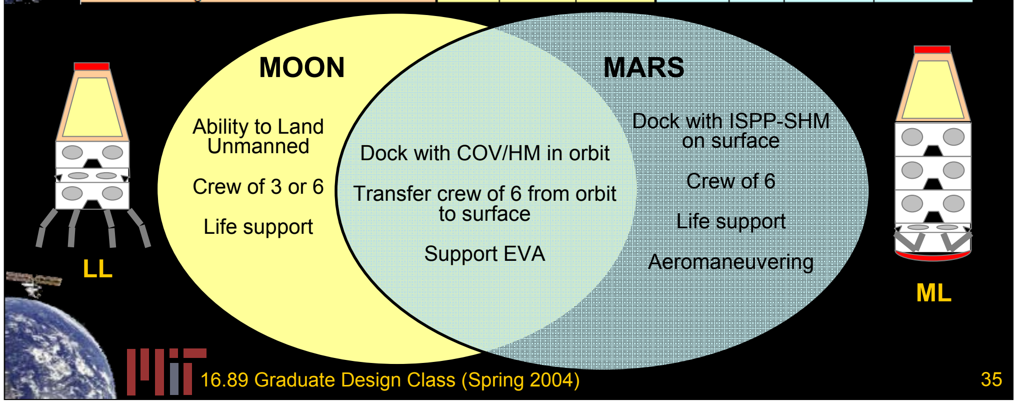
- Allow for significant modular spacecraft design flexibility

Six octahedrons were combined in two groups of three and platform, forming one large volume required for a Mars mission. Based on Larson (1999), it was assumed that a habitable volume of 20m^3 per person was required for a 6 crew, 6-month mission. For this analysis, 30m^3 was specified per person. It was also assumed by Larson (1999) that 33% of the total volume was assumed to be habitable. Therefore, a total volume of 540m^3 could be created by 6 octahedrons, each with a 5.6m diameter.

An interesting observation is the number of different forms that must have docking capabilities with the HM. Since the HM module will be docking with the COV, SM1,

Lander Functions

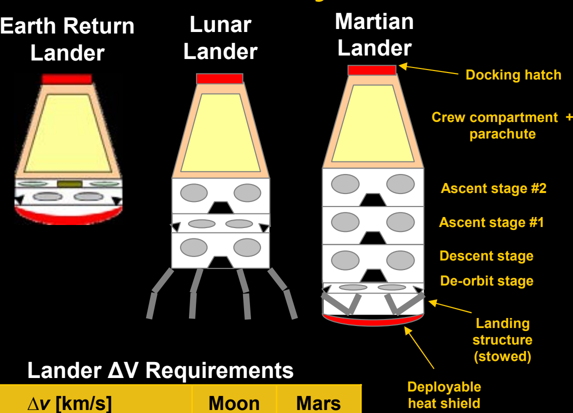
Landers (LL/ML)	Moon			Mars			
	Short	Medium	Extended	Phobos	Short	Extended	Extended+
Dock with COV/HM in Orbit	X	X	X	-	X	X	-
Dock with ISPP-SHM on Surface	-	-	-	-	-	X	-
Transfer crew of 6 from Orbit to Surface and Back	-	-	X	-	X	X	-
Transfer crew of 3 from Orbit to Surface and Back	X	X	-	-	-	-	-
Support EVA	X	X	X	-	X	-	-
Life support for 3 crew members	X	X	-	-	-	-	-
Life support for 6 crew members	-	-	X	-	X	X	-
Life support for 2 days	X	X	X	-	-	-	-
Life support for 5 days	-	X	-	-	X	X	-
Life support for 2 weeks	-	X	-	-	-	-	-
Aeromanuevering	-	-	-	-	X	X	-



For comparison purposes, it is clear that common functions are shared. When common functions exist, extensibility will benefit the overall group of missions to the Moon and Mars. The lander must dock with the COV or the COV/HM in both lunar and Martian orbit. As well, the lander must deliver a crew of 6 to the surface for all of the Mars missions and some of the Moon missions. If two identical landers are chosen instead of a single, larger lander, the impact of this decision can be observed by evaluating whether or not the new option satisfies the functional requirements. If all of the functions are deemed satisfied, only then was the impact of the decision not critical. As can be expected, a wide range of requirements are made for the landers, but many of these requirements are specified by only one of the seven missions, making it difficult to justify changing the baseline form. Indeed, the landers are a mission critical piece of hardware and must be highly reliable. Therefore, when considering extensibility of such a device, it may be beneficial to target the lander design for the most difficult landing mission, thereby ensuring a robust, if over-designed, form for the other missions. This has the effect of increasing net reliability while still maintaining an extensible form. The idea of designing a non-optimal form now such that it may be optimal when used in a different manner or location stands as one of the cornerstones of extensibility.

Lander Commonality

- Martian and Lunar Lander designs take advantage of opportunities to implement commonality
  - **Common** components
    - Crew compartment
  - **Similar** components
    - Propulsion modules
  - **Different** components
    - Parachute
    - Deployable landing structure
    - Heat shield



Lander ΔV Requirements

Δv [km/s]	Moon	Mars
De-orbit	0.019	0.111
Descent and Landing	1.862	0.630
Ascent and Rendezvous	1.834	4.140

Note: Δv values are shown only for propulsive mission phases. Aeromanuevering and parachutes are assumed for Martian descent.

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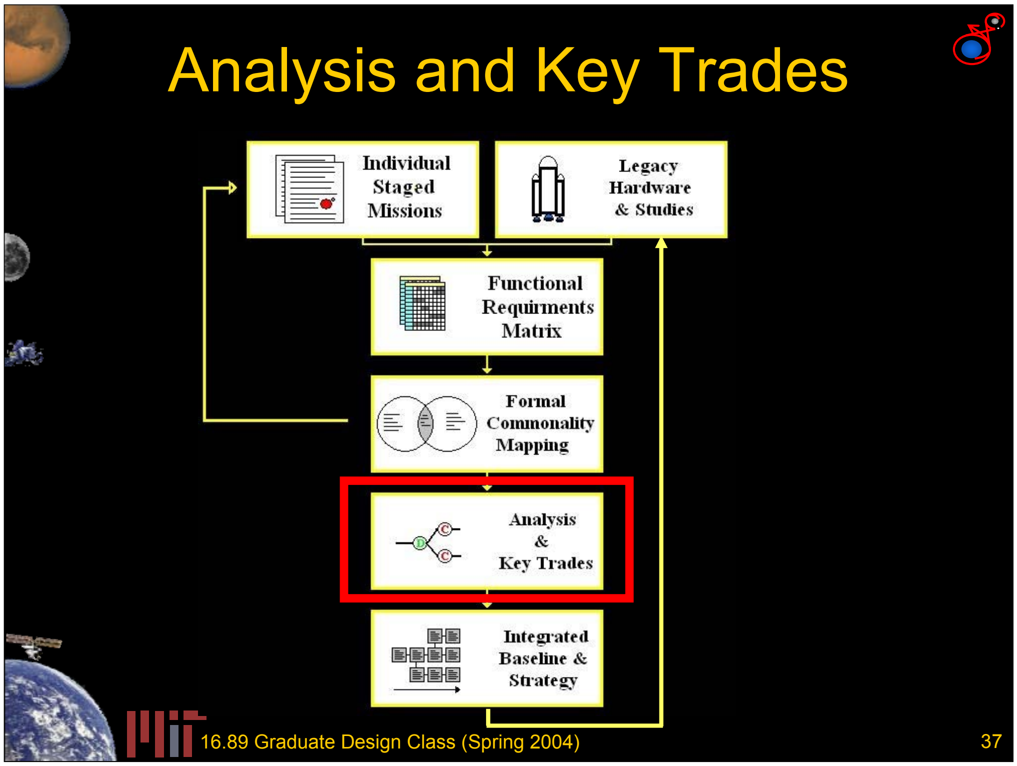
Stage 1 (powered descent delta_V) includes ±4.5 km lateral translation capability for dispersion accommodation and landing target site redesignation.

An effort was made to keep as much similarity between the lunar and Martian Landers as possible. However, since the environment on the Moon and Mars is so different, only a portion of each Lander design is identical. This is the crew compartment. The rocket stages are similar because they use the same propulsion technology but vary in size (significantly differnet deltaV requirements). The major differences are the parachute, heat shield, and deployable landing structure required for the Martian Lander.


Analysis and Key Trades
Individual Staged Missions
Legacy Hardware & Studies
Functional Requirments Matrix
Formal Commonality Mapping
Analysis & Key Trades
Integrated Baseline & Strategy
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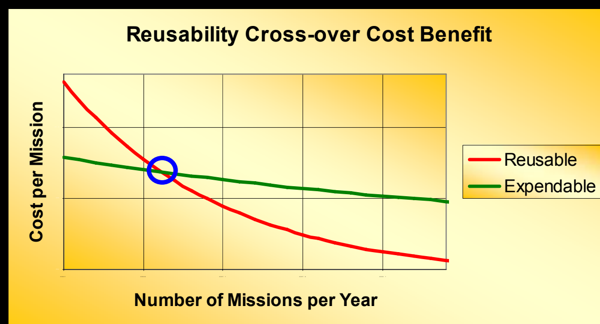
Reusability

Reusability for sustainability

- Cost benefit over the long term
- Greater initial investment required to develop reusable system
- Difficult to implement and justify (Shuttle Transportation System)

Reusability opportunities

- Mass transportation vehicle
- Martian and Lunar Landers



For first use, Lander and propellant are pre-positioned using electric propulsion

For later uses, propellant for re-fueling is transferred to Lander using electric propulsion

Mass Increase for reusability

30% Increase in Mass => 1 use till benefit

90% Increase in Mass => 4 uses till benefit

Lunar Mission Trajectories

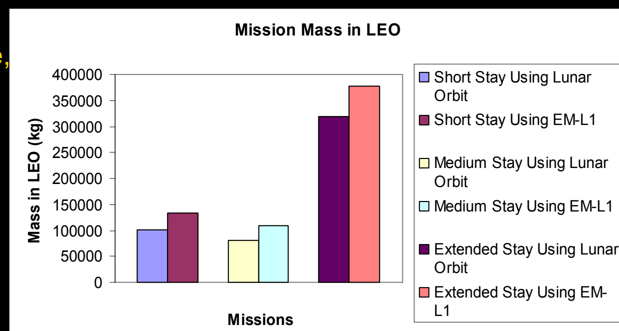
Assumptions

Using Lunar Orbit ← Less mass in LEO

- Any latitude landing site & no free-return trajectory OR
- Equatorial landing site & free-return trajectory

Using EM-L1

- Any latitude landing site, but increases ΔV by ~11%



But what if you need to reach high latitude landing sites with a free-return trajectory?

Lunar Mission Trajectories

Reaching Polar Landing Sites with Free-Return Trajectory

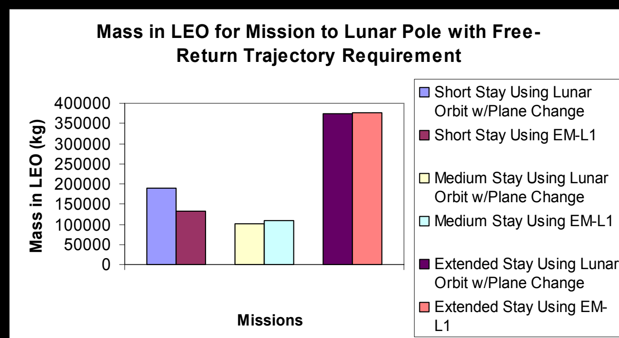
Using Lunar Orbit with Plane Change

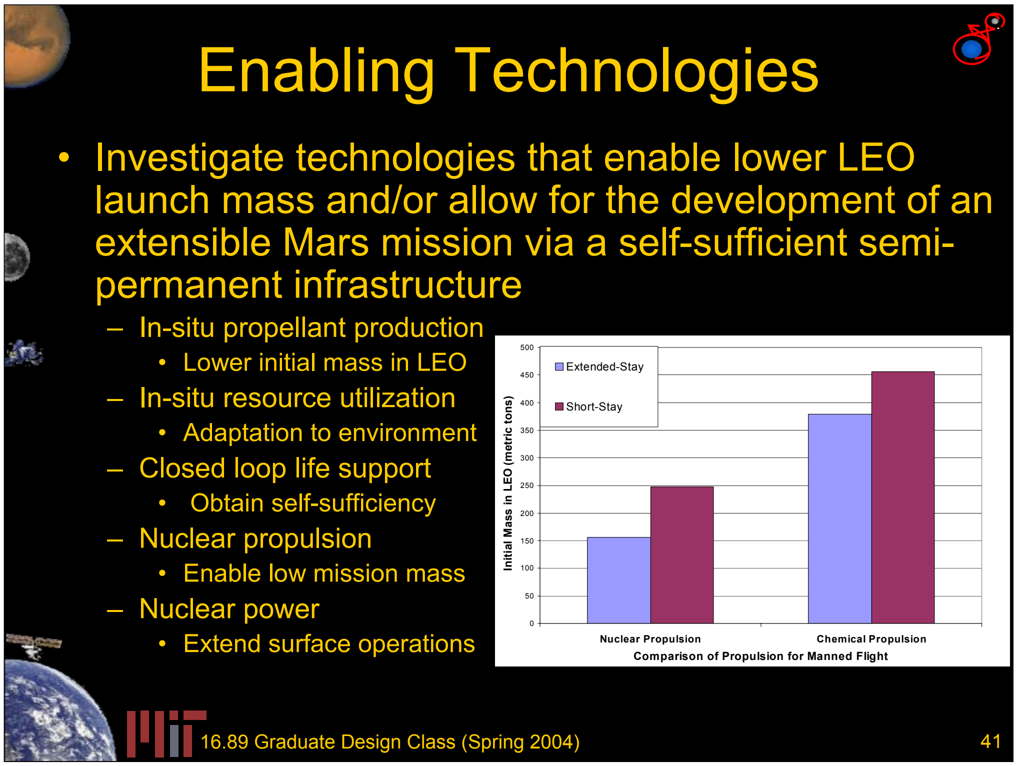
- Any latitude landing site & free-return trajectory
- Requires less total mission ΔV than EM-L1 for landing sites < 39 degrees from lunar equator

Using EM-L1

- Any latitude landing site

Mass in LEO dependent on mission architecture, total mission ΔV not a good indicator.



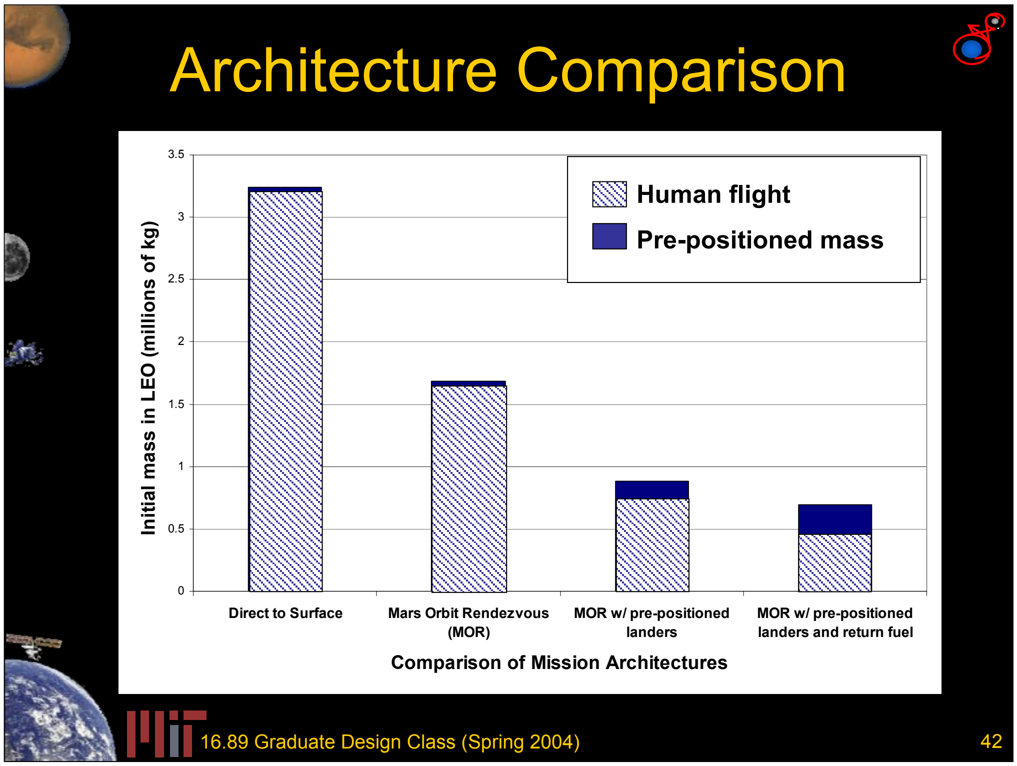


ISPP→ allows for a reduced IMLEO and utilizes the Martian environment to enable sustained exploration at low mission cost (over time)

ISRU → reduces IMLEO and takes advantage of available resources → useful for future missions (i.e solar radiation for power, soil for radiation shielding, water from the permafrost)

Closed loop life support → provides for self-sufficiency, and increased knowledge for adjusting to environment…..also increase crew mental health

Nuclear power → 100kw – class nuclear reactors can provide an effective means of power for life support to enable extended surface operations and increase mission flexibility.

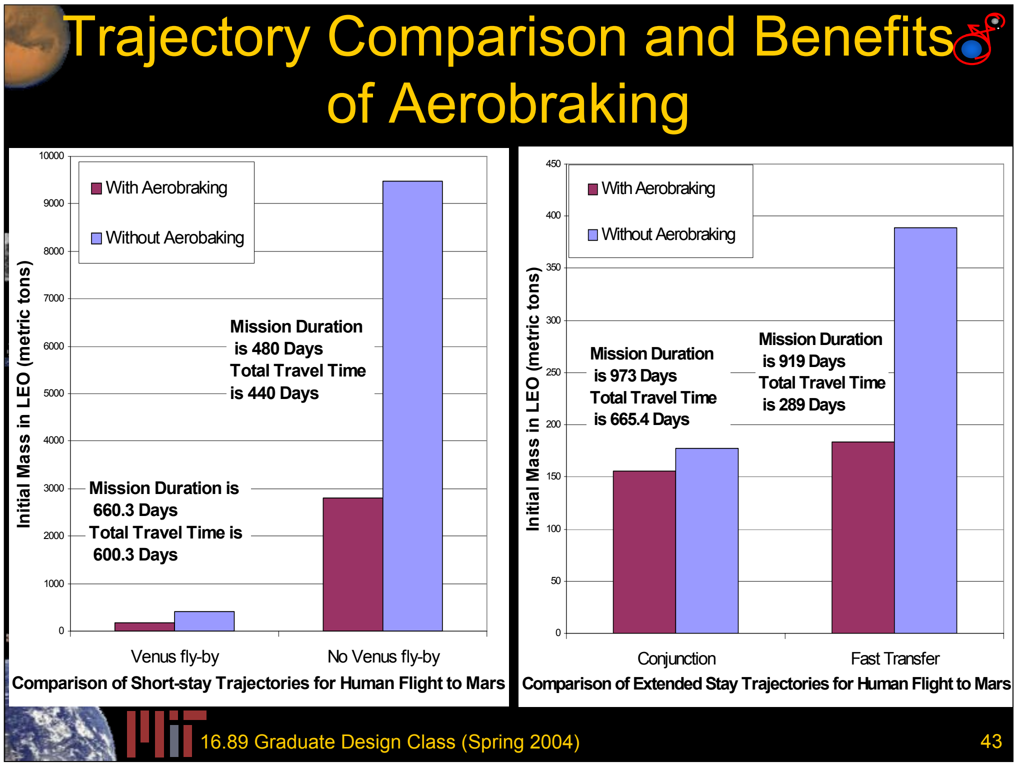


IMPORTANT POINT= MOR3 (return fuel, landers, and S.H are pre-positioned by EP and the IMLEO is the LEAST for this type)

Assumptions: No aerobraking at Mars, direct entry at Earth, includes IMLEO for EP pre-positioned elements. The DV's refer to the Opposition w/ Venus fly by.

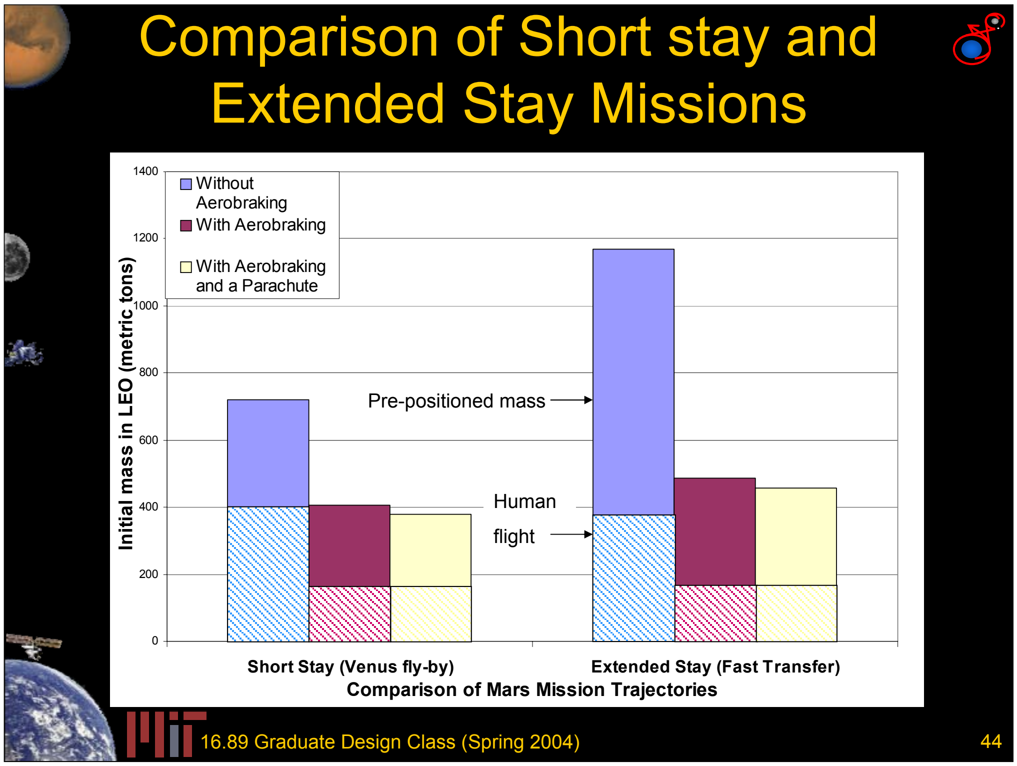
Names of architectures NOVA = Direct to surface, MOR = MOR, but we bring landers and return fuel…the only thing pre-positioned is the Surface Hab, MOR2 = landers and S.H are pre-positioned, MOR3 = Landers, S.H. and RETURN FUEL are pre-positioned.

All pre-positioning of elements is done by electric propulsion Specific power of 150 W/kg, efficiency =.7, specific impulse 3200 sec. This means that the IMLEO for the human missions is EVEN less for MOR3 than MOR2….



Important things… the Venus fly-by is the only feasible option for short stay….even w/ aerobraking, the 2milliion kg in LEO is prohibitive. Notes: This is only for the manned trajectory, assuming MOR3 (pre-positioning of landers, earth return fuel, and S.H.) Thus, the IMLEO of all pre-positioned elements are not included in these numbers. You want to note that 1) No Venus fly-by, even w/ aerobraking is too large. 2) That aerobraking reduce IMLEO for all missions (conjunction too, but not enough to be shown on this plot) 3) That the difference in IMLEO for Conjunction and Fast transfer w/ aerobraking is small enough (Fast transfer have higher mass) but the Total travel time is much shorter.

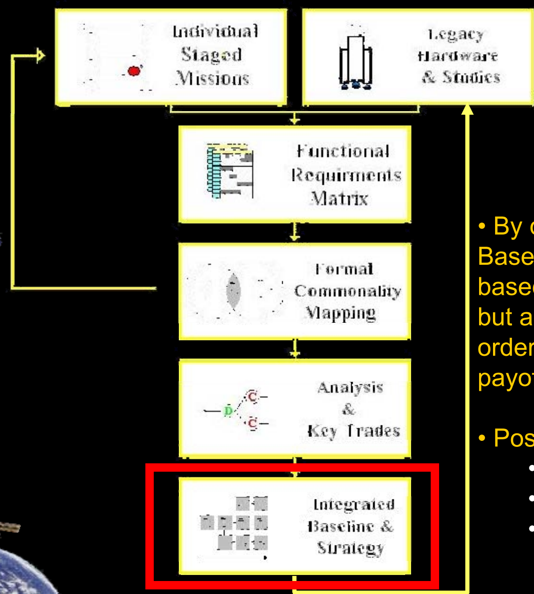
Other notes: The Venus fly-by may have other issues, such as increased radiation from the inner Earth orbit pass, but allows for 60 day stays. Fast transfer has very long stays on the surface, but the reduced time of flight allows for each transfer leg to be equivalent to some of the ISS stays, so that zero gravity and space radiation are no longer unknowns.



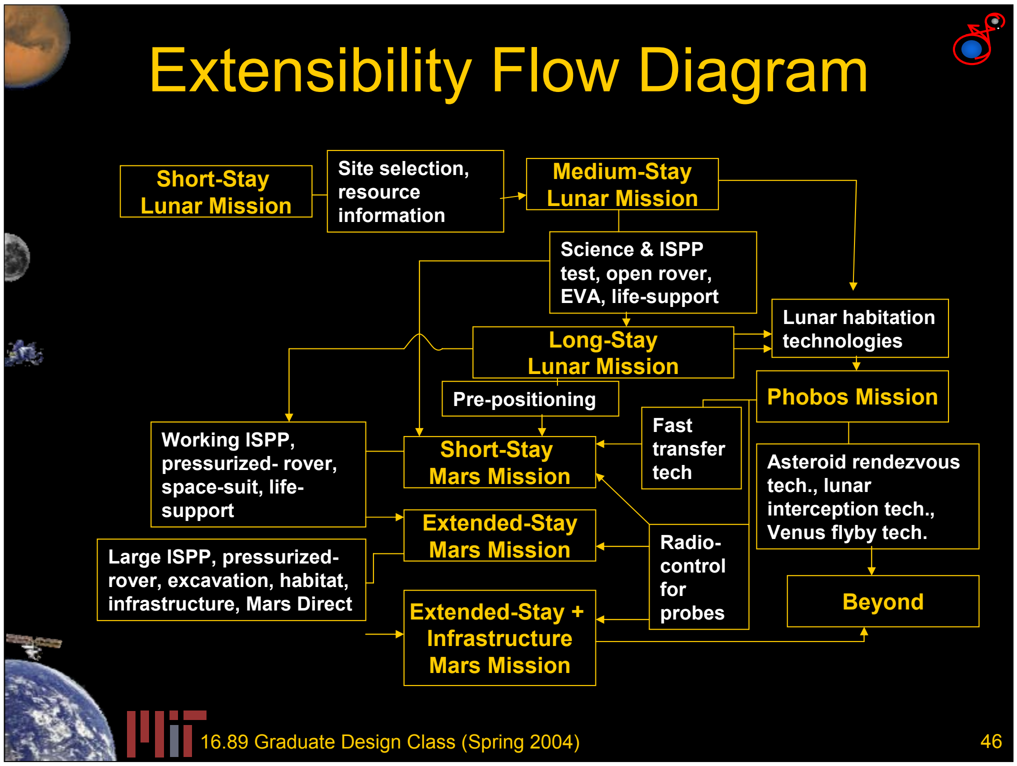
These numbers include the IMLEO for the total mission (including pre-posititioned elements). Short stay = opposition w/ venus fly-by. Extended stay = fast transfer

IMPORTANT TO NOTE that parachute and aerobraking EVEN BETTER. Also, With aerobraking Short stay and long stay comparable!!!!

Integrate Baseline Strategy



- By doing this analysis upfront, a best Baseline architecture could be chosen, based not only on an optimal point design but also on the what-ifs scenarios in order to reduce risks and increase payoffs
- Possible tools for such an analysis are
  - **Utility Theory**
  - **Analytic Deliberative process**
  - **Decision Analysis**


Extensibility Flow Diagram
Short-Stay Lunar Mission
Site selection, resource information
Medium-Stay Lunar Mission
Science & ISPP test, open rover, EVA, life-support
Lunar habitation technologies
Long-Stay Lunar Mission
Phobos Mission
Pre-positioning
Fast transfer tech
Working ISPP, pressurized- rover, space-suit, life-support
Short-Stay Mars Mission
Asteroid rendezvous tech., lunar interception tech., Venus flyby tech.
Extended-Stay Mars Mission
Radio-control for probes
Large ISPP, pressurized-rover, excavation, habitat, infrastructure, Mars Direct
Beyond
Extended-Stay + Infrastructure Mars Mission
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Overview of Scenario Planning

- Scenario: A deviation from the anticipated state of nature.
- Used to determine the degree to which a system responds to environmental change
  - Critical contingencies may be planned into the final design
- Baseline strategy was evaluated against each of these scenarios
  - Options exercised allowing for significant adaptability to constraints imposed by scenario's parameters
- Seven sample scenarios total, two representative scenarios selected for presentation

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Scenarios

1. ***<u>NASA policy change</u>***
2. **Space race II**
3. **Catastrophic exploration system failure**
4. ***<u>Nuclear propulsion available</u>***
5. **Asteroid fear becomes public, political interest**
6. **Practical methods for lunar resource extraction become available.**
7. **Signs of life discovered on Mars**

Scenario: NASA Policy Change

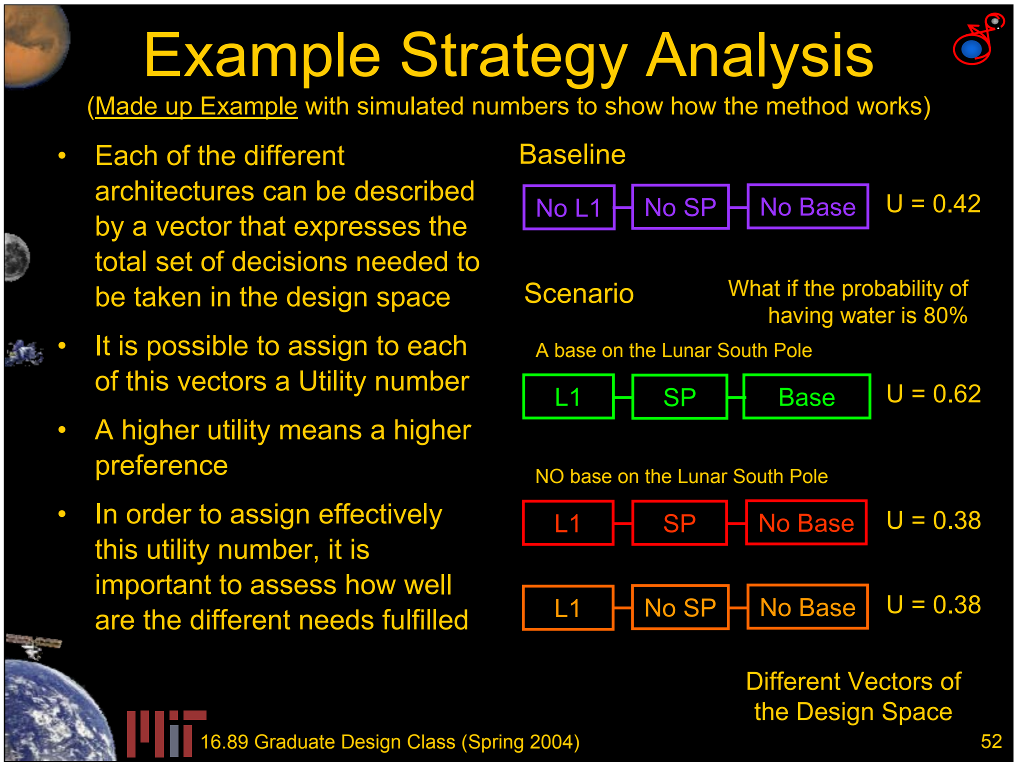
- Description: Budget cut due to lack of public interest. NASA restricted to education and Earth-monitoring activities.
- Response: Very little can be done in the face of restrictive policy directives.
  - Knowledge collected before budget cut will inspire future generations to continue space exploration.
- Prevention strategy: Public interest must be maintained. Regular (e.g. yearly) milestones and frequent press releases are recommended.
  - Frequent milestones serve as points for program to self-evaluate and to address new information. Contributes to sustainable and extensible program.
  - Associated trade: How much money should be spent on public awareness of NASA activities?

Scenario: Nuclear Propulsion

- Description: Nuclear propulsion technology is developed and becomes mainstream.
- Response: Modular architecture of propulsion system allows for creation of new nuclear propulsion service with little redesign required for rest of system.
- Benefits realized: Shorter transit times to Mars result in decrease in initial mass to LEO and human factors-related benefits.
  - Modular, extensible system allows for ready utilization of new, upgraded technology.
  - Associated real option: Design capability to easily transition from current to other propulsion?

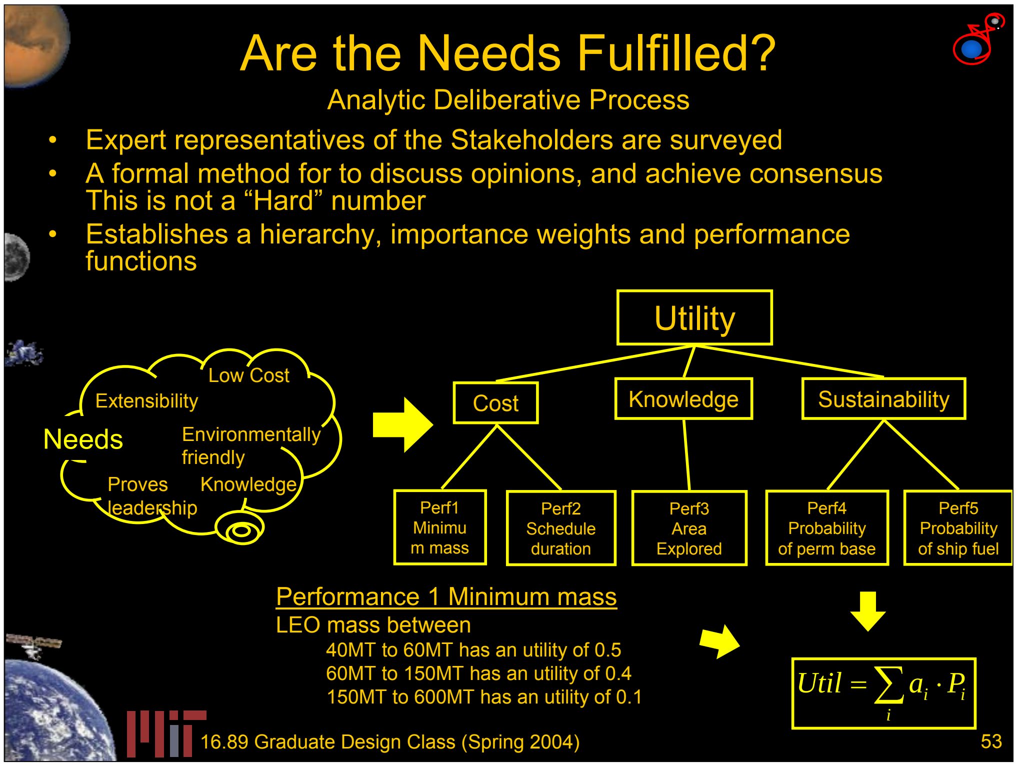
Econometric Tools for Strategy

- Architecture as a n-dimensional vector
- Utility is a function from the vectorial space into a 0 to 1 number
- Assign utilities based on stakeholders survey
- Scenarios are States of Nature
- The most likely Scenario are the assumptions for the Baseline
- Architecture answers to alternative scenarios are valued through Real Options



Different vectors will express different decisions of the design space. The design space is as deep as we intend that the whole system to be, including all the different decisions to be taken: modules size, number of expeditions, amount of budget available, technologies to be used, etc

A utility can be assigned to every of this architectures in the sense that a Rational Decision maker will always choose the one with the higher utility. This number does not have units, it just expresses preference



The needs as expressed by the stakeholders can have different levels of importance and can be contradictory.

An order is needed, and some merit figures need to be found

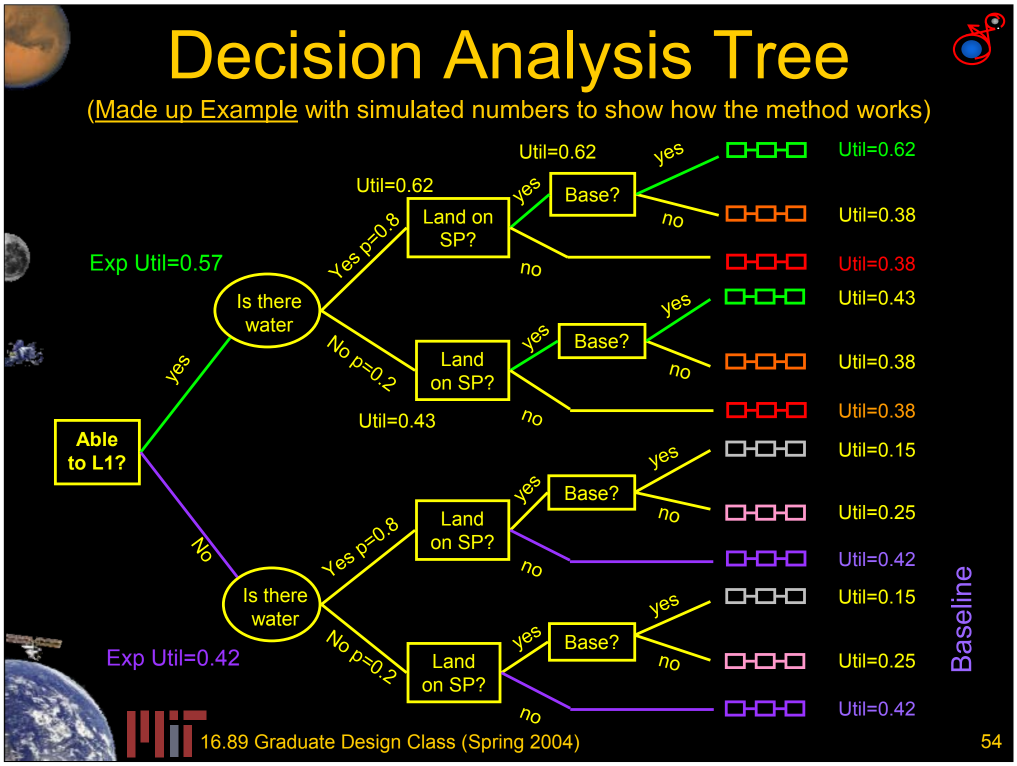
To do so a hierarchy is established, and the needs are arranged in a tree like structure. At the lowest level, there will be a set of performance measures. Some of them will be "hard physics" but others will just be constructed scales, such as "a level 3 of probability of shipping fuel from the moon"

To assess the preference, and the relative utility of each level or hard physics value, a set of experts who represent the decision maker stakeholders are surveyed about their preferences. These stakeholders range from the technical field to the political one, in order to synthesize the objectives of all the parties involved.

For each performance, pairwise comparisons is surveyed, and through some math, a function that maps levels to preferences, (and thus utilities) is found. A similar pairwise comparisons is done at the categories, and therefore a set of weights for this performances and categories is found (Sigma below)

These weights and functions are not absolute numbers, they just express the opinions of a group of people.

This method for the same reason is not a hard number, but instead a tool to argue, and discuss, but to focus on an objective, and get a compromise solution.



The set of decisions that define an architecture are taken overtime, and are therefore possible to be arranged in a tree, with branching points each time a decision has to be taken. The decisions are drawn as squares at our tree diagram.

Another point where the design space branches is at Chance nodes. At these nodes a certain event, the outcome of an external event gets to be known. Previous to that we do know though, the probabilities of the different results. These points are drawn as circles in our diagram.

Once we established the tree, we use the Utility function already identified to assign utilities to each architecture. At each Decision node the DM will choose the higher utility, at each chance node, using the probabilities, an expected utility is assigned.

We arrive at the case that by choosing to get the ability to go to L1 the expected utility is 0.574, and by not choosing it is 0.417. Therefore the DM will choose to have that capability in this very simplified example

Real Options Analysis

(Made up Example with simulated numbers to show how the method works)

- Option: "The right but not the obligation to take action in the future"
- The what-if scenario analysis allows us to negotiate with risks

What-if "the prob of having water is 80%"
Should we "buy" the option to go to L1?

	Lands on South Pole	No South Pole
Able to go to L1	U=0.57	U=0.38
Not able to go to L1	**U=0.42**	**U=0.42**

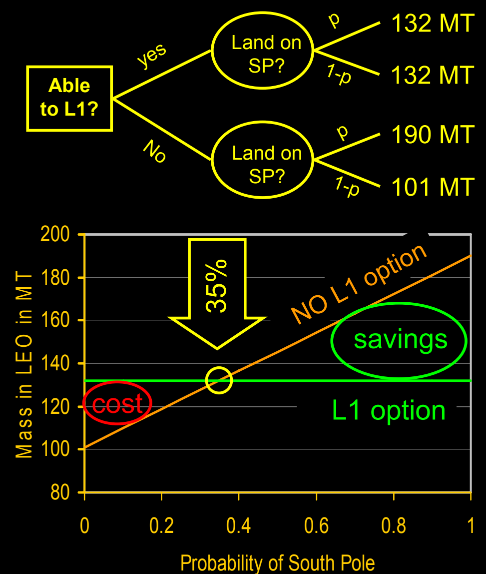
The potential benefit of that option is realized when we actually go to L1

The cost of the option is the difference between the sure utility we had and the lower utility we will get if we don't use it

Real Options
Sensitivity Analysis on Mass

- Analysis of
  - Expected Mass vs
  - probability of accessing the South Pole
- Switching point: 35% probability of pole access
- "Expected Mass" as surrogate for cost

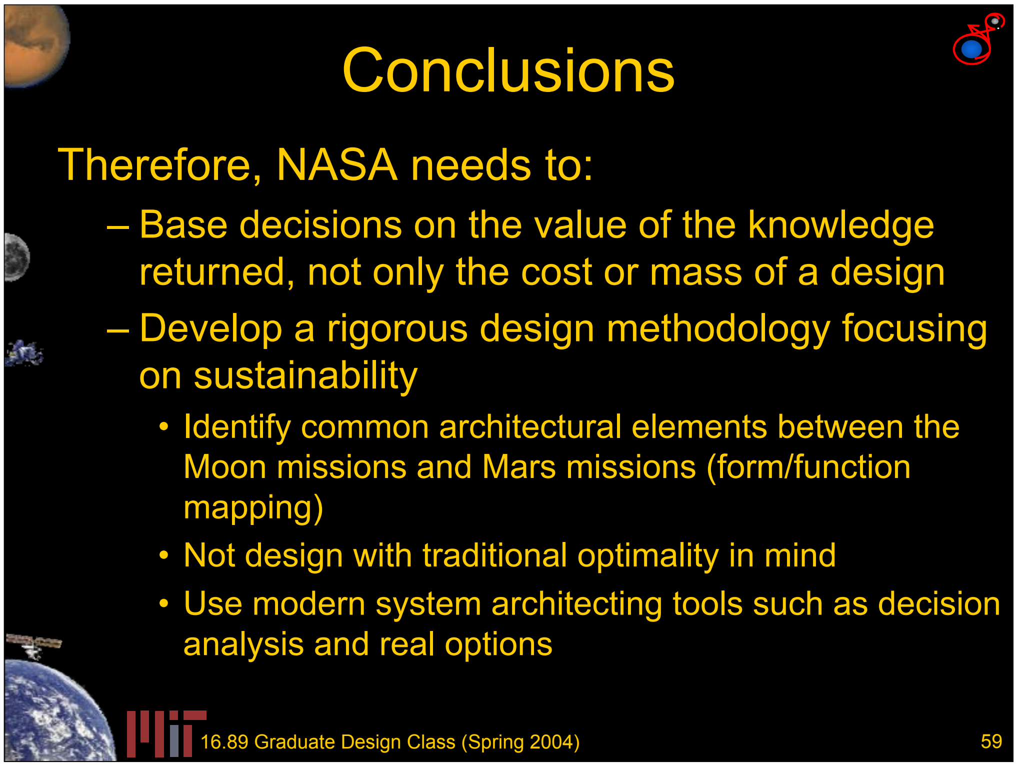
- This are "real" numbers
- Assumption: poles are accessed with a free return trajectory



Conclusions

Conclusions

- ***Sustainability should be incorporated at all levels of the space exploration architecture.***
- ***NASA needs to focus on the acquisition, transfer, and processing of knowledge.***



Conclusions

NASA needs to incorporate sustainability into every level of the design of the space exploration architecture.

Then talk about how to do it quantitatively….there may be a process.

-by applying form function mapping (re-highlight the process)

-highlight commonality idea

“not just” the cost or mass of the design

Use Modern system architecting tools such as scenario planning, decision analysis and real options analysis


Questions?

Backup Slides

Mars Mission Design Background

- Von Braun (1952), 90 Day Study (1989) – Large scale programs with orbiting facilities, on-orbit assembly, high cost
- New paradigm: “living off the land”, Zubrin’s Mars Direct, NASA DRM (late 1990’s) drastically reduced cost and IMLEO

Backup Slide 1 DSN Capabilities

SIZE (meters)	TYPE	LOCATION	I.D. (Station)	S-BAND UP	S-BAND DOWN	X-BAND UP	X-BAND DOWN	K-BAND UP	K-BAND DOWN	RCVR. TYPE
26	E. O.[1]	Goldstone	DSS-16	2025-2120[9]	2200-2300	-	8400-8500[14]	-	-	MFR
26	E. O.[1]	Canberra	DSS-46	2025-2120[9]	2200-2300	-	8400-8500[14]	-	-	MFR
26	E. O.[1]	Madrid	DSS-66	2025-2120[9]	2200-2300	-	-	-	-	MFR
34	BWG1[1,3]	Goldstone	DSS-24	2025-2120[11]	2200-2300	7145-7190[9] 7190-7235[9,6]	8400-8500	-	10/23/06[5,7]	DTT
34	BWG1[1,3]	Canberra	DSS-34	2025-2120[11]	2200-2300	7145-7190[9] 7190-7235[9,6]	8400-8500	-	04/11/05[5,7]	DTT
34	BWG1[1,3]	Madrid	DSS-54	2025-2120[11]	2200-2300	7145-7190[9] 7190-7235[9,6]	8400-8500	-	08/01/07[5,7]	DTT
34	BWG2[3]	Goldstone	DSS-25	-	-	7145-7190[9] 7190-7235[9,6]	8400-8500	34200-34700[4]	31800-32300	DTT
34	BWG2[3]	Goldstone	DSS-26	-	-	7145-7190[9] 7190-7235[9,6]	8400-8500	-	31800-32300[2]	DTT
34	BWG2[3]	Madrid	DSS-55	-	-	7145-7190[9] 7190-7235[9,6]	8400-8500	-	31800-32300[2]	DTT
34	HEF[3]	Goldstone	DSS-15	-	2200-2300	7145-7190[9]	8400-8500	-	TBD[5,7]	DTT
34	HEF[3]	Canberra	DSS-45	-	2200-2300	7145-7190[9]	8400-8500	-	TBD[5,7]	DTT
34	HEF[3]	Madrid	DSS-65	-	2200-2300	7145-7190[9]	8400-8500	-	TBD[5,7]	DTT
34	HSB[1]	Goldstone	DSS-27	2025-2120[10]	2200-2300	-	-	-	-	MFR/DTT
70	D. S.[3]	Goldstone	DSS-14	2110-2120[11,12] 2090-2094[13]	2270-2300	7145-7190[9]	8400-8500	-	TBD[5,7]	DTT
70	D. S.[3]	Canberra	DSS-43	2110-2120[11,12] 2090-2094[13]	2270-2300	7145-7190[9]	8400-8500	-	TBD[5,7]	DTT
70	D. S.[3]	Madrid	DSS-63	2110-2120[11,12] 2090-2094[13]	2270-2300	7145-7190[9]	8400-8500	-	TBD[5,7]	DTT

By E. Luers

Table from:http://rapweb.jpl.nasa.gov/Planning/SERCAP_Antennas_2004.pdf

Backup Slides 2
Power/Data rate numbers

Earth->Moon				Non earth Dish size		Data rate1		Power		Data rate1		Power		Data rate1		Power	
380000	km			1	m	0.06933	mbits/sec	0.01	W	0.6933	mbits/sec	0.1	W	3.4667	mbits/sec	0.5	W
L4->Moon		Moon dish		Sat dish													
380000	km	1	m	1	m	0.06933	mbits/sec	0.3888	W	0.6933	mbits/sec	3.888	W	3.4667	mbits/sec	19.44	W
Marst -> Earth																	
Large				Mars dish		Data rate1		Power		Data rate1		Power					
401300000	km			3	m	0.034721	mbits/sec	7.96	W	0.34720833	mbits/sec	79.6	W				
Small																	
55700000	km																

Trade: Crew Launch Escape

Tower Escape

- To consist of Launch-escape motor, Tower-jettison motor, and Pitch-control motor
- Operational through pad and solid boost phase, then jettisoned (120,000 ft)
- Pros: Reliable, flight-tested (Apollo)
- Cons: Expensive, 5-6% reduction in LEO payload mass for EELV

Ejection Seats

- Occupant-seat combination rapidly decelerated due to ram air force
- Operational to Mach 2.6 and 30,000 ft assuming q-force survivability of Russian Zvezda K-36D fighter ejection seat
- Pros: Well-developed technology
- Cons: 91 kg/astronaut payload reduction

Tractor Seats

- Crewman pulled from orbiter by a rocket attached via an elastic pendant
- Pros: Lighter and less voluminous than a tower escape or an equivalent ejection seat system, used extensively during Vietnam
- Cons: Aerodynamic "blow-back" causes unsuccessful extraction at altitudes above 15000 ft, 45 kg/astronaut payload reduction

No Escape

Pros

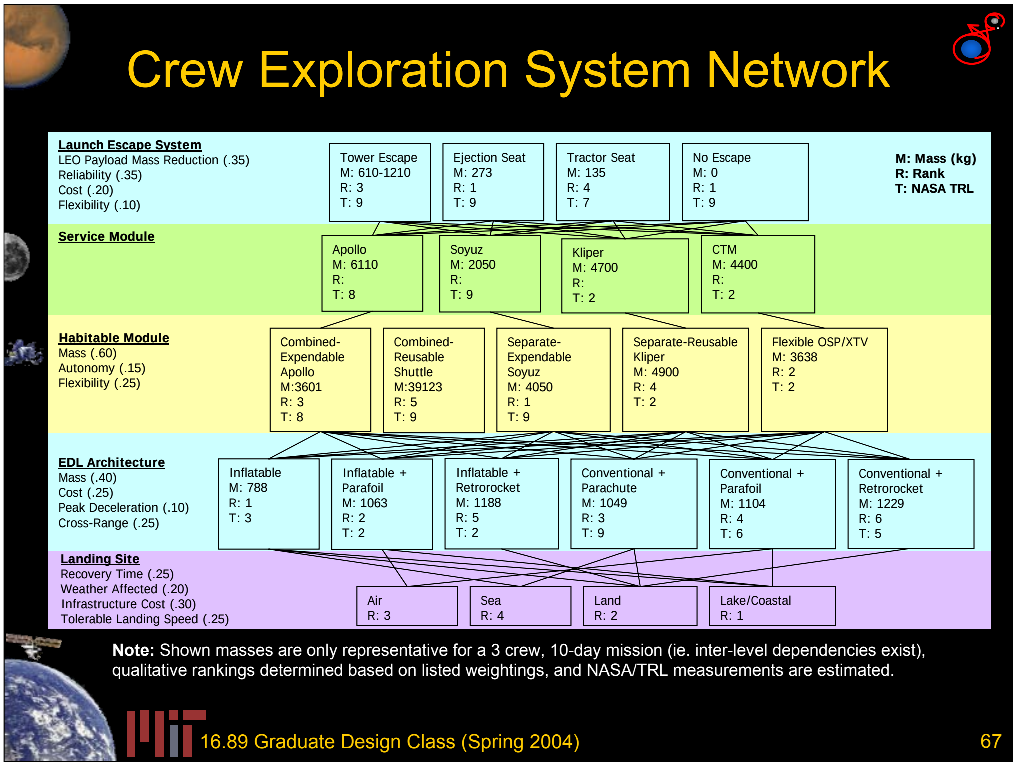
- Hundreds or thousands of additional payload mass delivered to LEO each launch
- Cost savings

Cons

- Reduction in crew safety
- Politically unacceptable?

Rover Development

Category	Unmanned Precursor	Short-Stay	Long-Stay	Long-Stay + Infra.
Automated, Autonomous	**R**	**n/a**	**n/a**	**n/a**
Remote Controlled	**n/a**	**O**	**O**	**O**
Unpressurized	**n/a**	**R**	**R**	**O**
Pressurized (2)	**n/a**	**n/a**	**O**	**R**



Emphasize that inter-level dependencies exist (eg. mass of reentry system depends on habital module). Links between levels represent preferable or feasible options. For example, the lake/coastal landing site option requires a reentry system with a large cross-range capability for precisely landing into a small body of water (inflatable or parafoil). More information provided in the EDL (entry, descent, and landing) and Landing site slides.

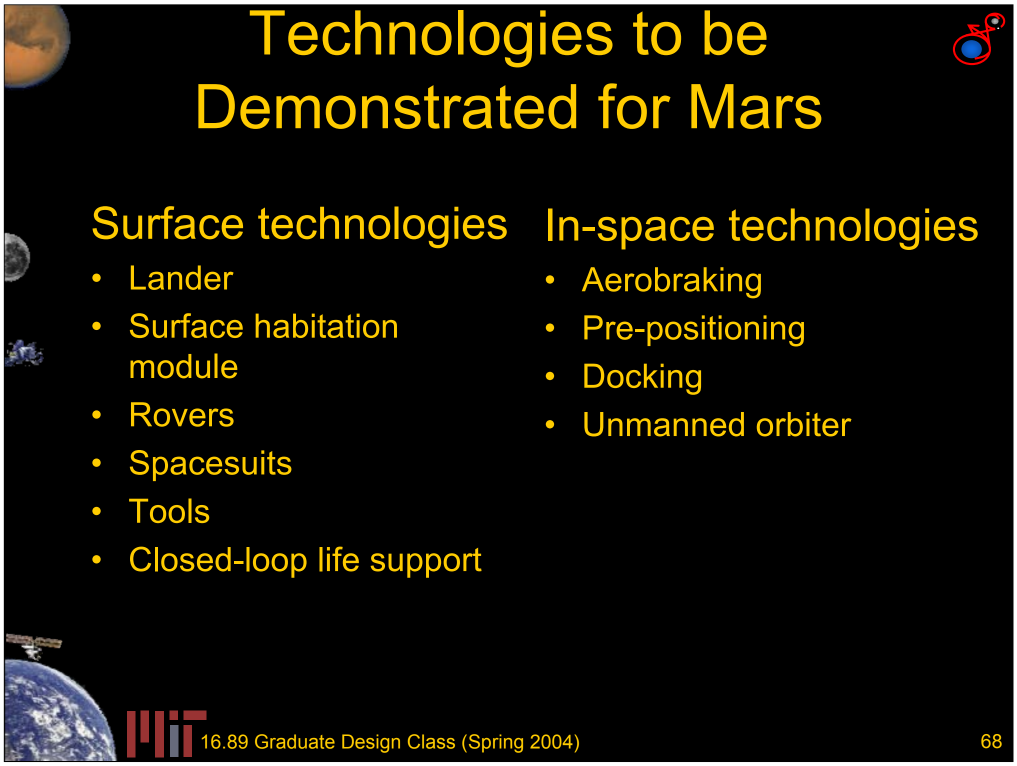
Three metrics were used: mass, TRL, Rank.

Rank was used because it enables

-to have a normalized comparison across elements. For example, launch escape system shouldn't be chosen for the same reason than EDL elements. Each element of the CES (each row in the network) has its own criteria.

-To compare each option into a row with different metrics… while trying to assess each option as objectively as possible for trading different measure of performance/priority

-To be able to weigh the metrics in order to make the right decision given what is the priority (it can be cross-range or peak deceleration for EDL architecture… then depending on the priority, you can weigh the metric so that the final ranking reflects more this priority)



Lander

Slow descent engines

Ascent stages

Reduced gravity

Life support

Ability to land unmanned

Surface Habitation Module

Life support

Pre-positioning

Surface manipulation, docking

Rovers

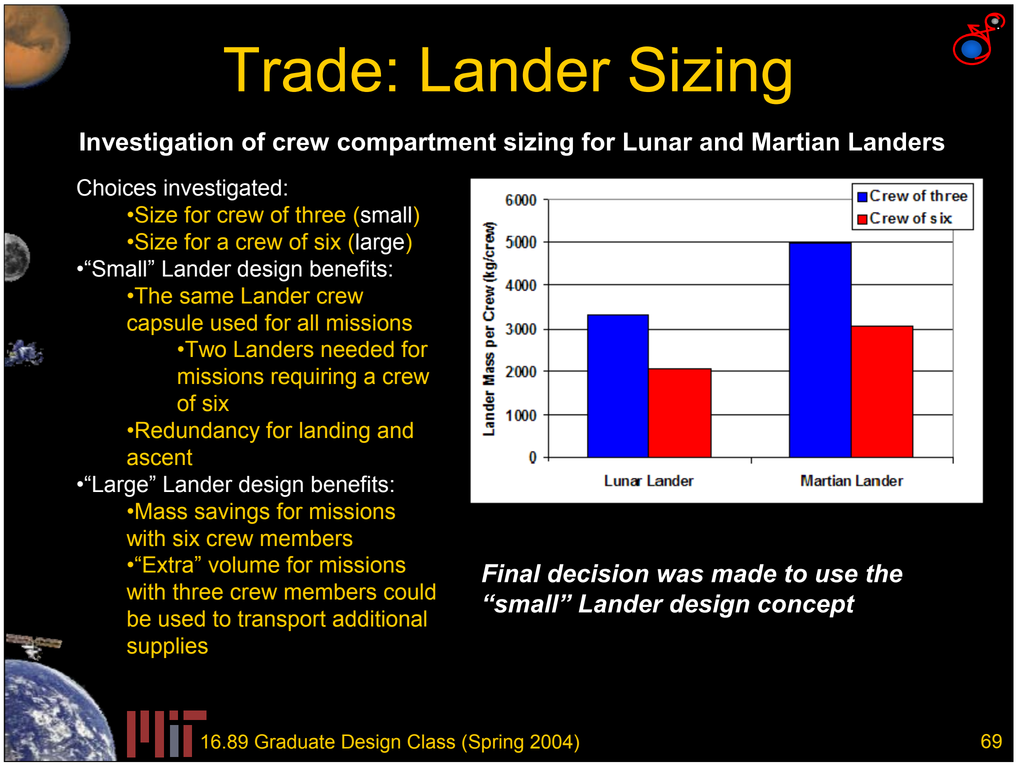
Range

Habitability

Science capabilities

Spacesuits, Tools, Closed-loop life support

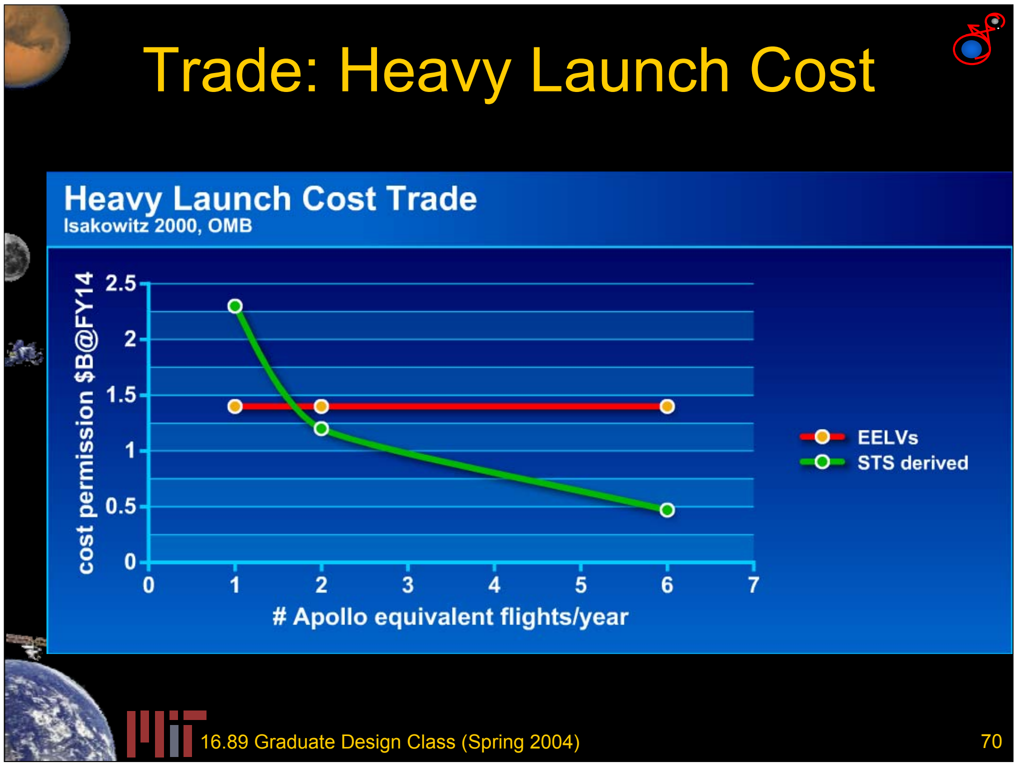
Aerobraking (only 1/8 of HM plus COV for Moon)



A trade study was performed to examine the tradeoffs between using a 3-person or a 6-person Lander design. Since crew sizes of 3 and 6 are planned for the various lunar and martian missions, a vehicle that can accommodate 3 or 6 crew would be ideal. The benefits of using a 3-person Lander is that you minimize mass for 3-person crew sizes and for 6-person crew sizes, you have added redundancy for the landing and ascent portions of the mission since there will be two small Landers being used.

The advantages of the six-person Lander are a mass savings per crew member for the missions that have six crew members and the ability to bring more cargo along with the crew to the surface if there is a crew of three (the extra volume can be filled with extra equipment).

Finally, the 3-person Lander concept was chosen. This was a difficult decision and mainly the result of needing to freeze the requirements at a certain point in our abbreviated design process.



This graph shows the cost per flight of a whole Apollo class mission (short stay) to the moon. It compares two approaches one using many heavy EELVs (Delta-IV Heavy) to launch the mission in chunks, the other sending the astronauts in a separate EELV and the cargo on a Heavy STS derived.

Using data from Isakowitz and the consumer price index of the Office of Management and Budget we have put all the cost data into FY14. Because the EELV has other (good) customers, such as the NRO or the DoD, the cost of an EELV will not depend dramatically on the flight rate. Whereas the STS based system has high fixed costs.

For a mission to the Moon that can be done with a single STS derived and a EELV for the crew or with up to six EELVs. According to our cost data the break even point where it costs the same to do the mission with many launches or with a single one is around 1.7 Apollo equivalent missions a year.

Therefore EELVs are attractive if one wants only to do a plant the flag a year. However for a sustained commitment to human exploration it becomes clear that an STS derived is much more cost effective. For instance a mission to Mars in terms of launch requirements is equivalent of about 6 Apollos. It would be three times as expensive to launch it with a fleet of EELVs.

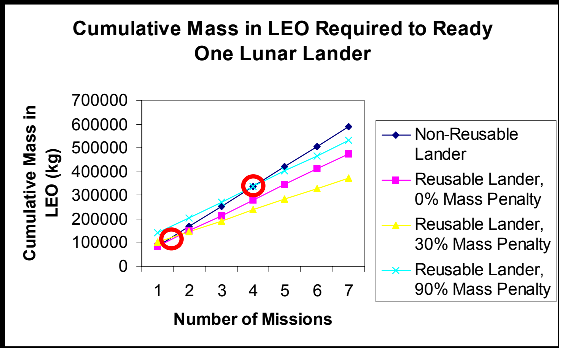
Reusability of a Lunar Lander

Assumptions

- For first use, Lunar Lander and propellant are pre-positioned using electric propulsion
- For second use, propellant for re-fueling is transferred to Lunar Lander using electric propulsion

Mass Increase for reusability

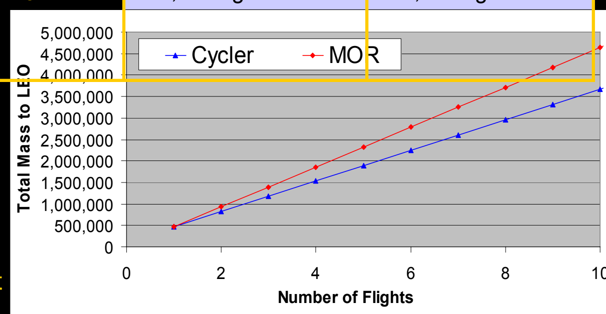
- 30% Increase in Mass => 1 use till benefit
- 90% Increase in Mass => 4 uses till benefit



Cycler Vs Staged Transportation Design

Generic Mars transfer design	Cycler mass at LEO	Staged mass at LEO
No pre-positioning of return fuel & no aerobraking	>>10,000,000 kg	740,000 kg
Pre-positioning of return fuel & no aerobraking	~6,000,000 kg	464,000 kg
No pre-positioning of return fuel & aerobraking	~1,200,000 kg	740,000 kg
Pre-positioning of return fuel & aerobraking	472,000 kg	464,000 kg

Important: This does not mean that the transportation system should be designed as a cycler, but that aerobraking and pre-positioning technologies should be researched in order for the option of a cycler to exist



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For a generic Mars transfer Mission, the table shows the resulting LEO masses for a staged and cycler transportation system for four different test cases:

1. No pre-positioning and No Aerobraking
2. Pre-positioning and No Aerobraking
3. No pre-positioning and Aerobraking
4. Pre-positioning and Aerobraking

A staged system is comparable to the Apollo style missions. At the end of each burn a stage is dropped and therefore a staged system would consist of multiple stages. Additionally once the staged system returned to earth, the vehicle would re-enter the earth's atmosphere and do a direct descent to earth.

In a cycler system there is only one stage and there is no staging. The advantage behind the cycler system is that this system does no change throughout its mission and therefore could be re-used in the next mission, hence the cycler is seen as a reusable system. Due to the reusable nature of the cycler, fuel must be provided to the cycler during the mission and the cycler must re-enter earth orbit once the vehicle returns to earth. The requirement of re-establishing earth orbit is a major fuel and mass requirement on the system and only shows promise in the case of aerobraking and return fuel pre-positioning.

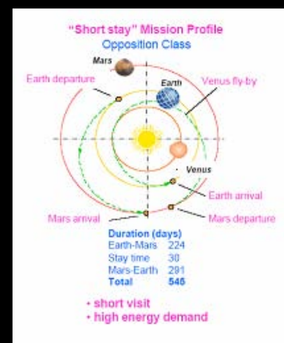
Another benefit of the cycler system is that the delta V required for a Mars mission, in the aerobraking and pre-positioning case, is approximately equal to that of a moon mission (~8km/s roundtrip). This means that if a cycler was developed, a common design and vehicle could be used to conduct both moon and mars missions.

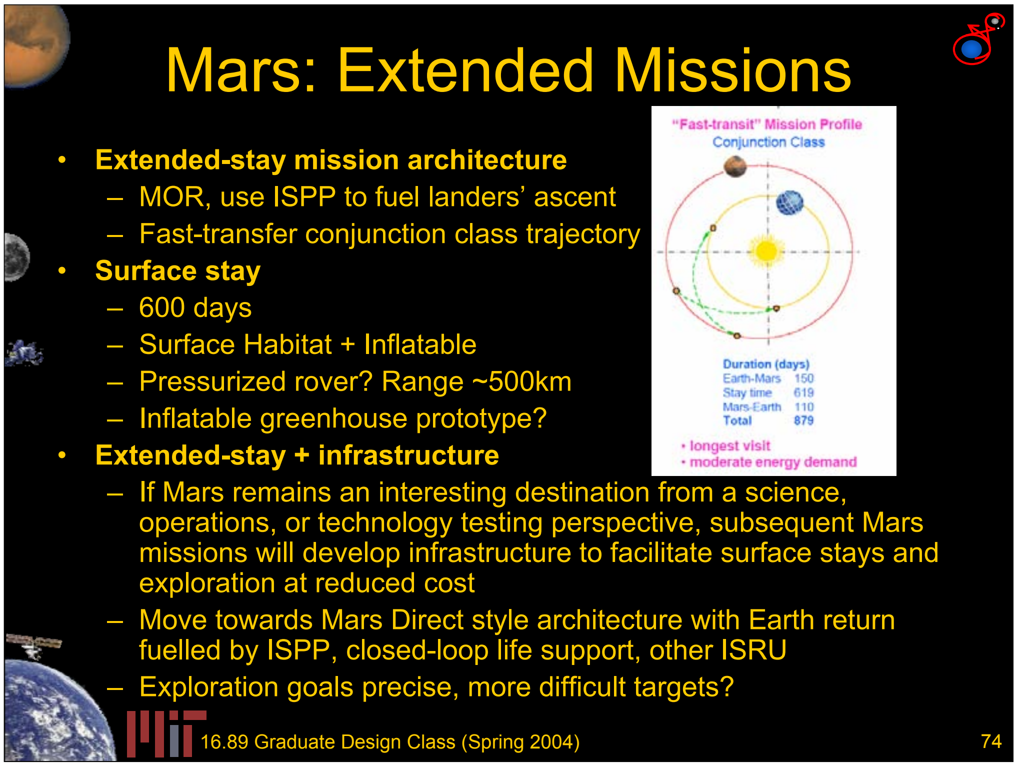
The Chart show the results of the fourth cases as a function of the number of mission. You can see that because of the reusable nature of the cycler design, the total mass at LEO for the cycler becomes less and less to that of the Staged design.

The major take away is not that the transportation system should be designed as a cycler, but that the transportation system should initially be designed as a staged system that would be capable of being modified into a cycler type system. Additionally, before any decisions concerning building a cycler system would be considered, research into aerobraking and pre-positioning must be conducted and proved successful.

Comparison: Short to Extended

- **Architecture**
  - MOR
  - Opposition class trajectory with Venus fly-by
- **Surface stay**
  - 30-60 Days
  - Surface Hab pre-positioned
  - EVA suits and unpressurized rover
- **Mission goals**
  - Science
  - Improve operational knowledge in preparation for future missions
  - Aerobraking
  - Search for resources
- **Mission options**
  - Human verification of ISPP test
  - Test other enabling technologies





ISPP to fuel lander's ascent assuming successful test during short-stay mission