Mission costs: Past, Present, Future

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Humans to Moon and Mars Seminar
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Past Missions

Project Mercury and Gemini

Project Mercury

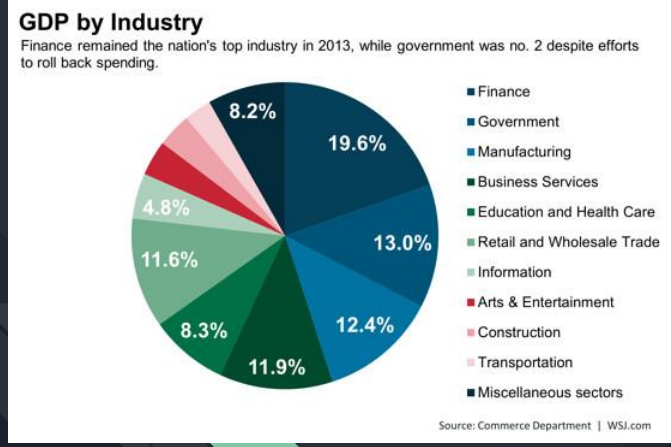
- 1959-1963
- Goal of putting a person into orbit and returning them safely
- $277 million in 1965 —> **$2.3 billion today**
- 6 piloted missions —> **$383 million per flight**

Project Gemini

- 1962-1967
- $1.3 billion in 1967 —> **$10 billion today**
- 10 piloted missions —> **$1 billion per flight**
- Each Gemini mission was roughly twice as expensive as a Mercury mission

The Apollo Program

- 1961-1972
- In 1973, NASA reported a cost of $25.4 billion to congress
  - —> **$146.9 billion today**
- 11 piloted missions —> $13.4 billion per mission
- Only 6 landings —> $24.5 billion per landing
- An Apollo-type effort would take up 3.6% of the 2017 US GDP



	original $	Adjusted 2019 $	Relative GDP $
Spacecraft	8.1 billion	81.3 billion	194.8 billion
Launch Vehicles	9.4 billion	99.0 billion	243.4 billion
Development & Operations	3.1 billion	28.7 billion	66.9 billion
Direct costs	**20.6 billion**	**209.0 billion**	**505.2 billion**
Construction of Facilities, Salaries, & Overhead	5.2 billion	54.8 billion	136.2 billion
Total Apollo	**25.8 billion**	**263.8 billion**	**641.4 billion**
Robotic Lunar Program	907.0 million	10.3 billion	26.1 billion
Project Gemini	1.3 billion	14.1 billion	34.8 billion
Total Lunar Effort	**28.0 billion**	**288.1 billion**	**702.3 billion**

Table 2. Costs of the Apollo lunar effort, adjusted for inflation to 2019 dollars using the NNSI and relative GDP share. Detailed numbers available in the source data. Source data.

The Apollo Program

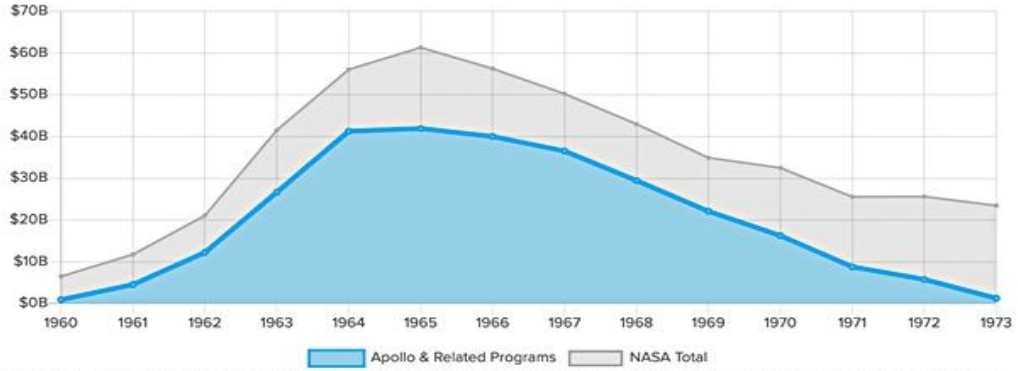


Figure 1. Project Apollo and related programs obligations per year, measured against total NASA obligations for fiscal years 1960—1973. All amounts adjusted for inflation to 2019 dollars using NASA's New Start Index (NNSI).

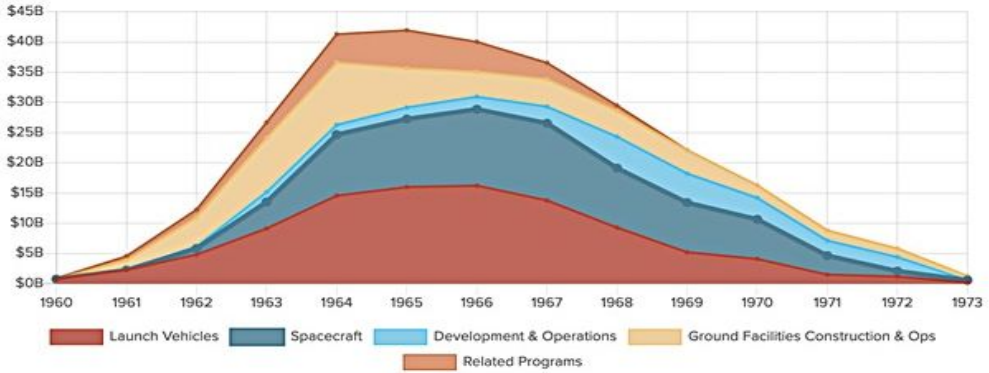
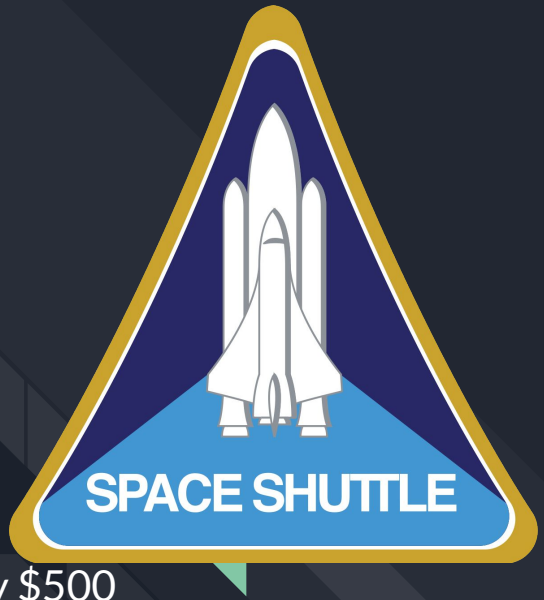


Figure 2. Cost of Project Apollo and related programs, by major sub-program, for fiscal years 1960 to 1973. All amounts adjusted for inflation to 2019 dollars using NASA's New Start Index (NNSI). Source data.

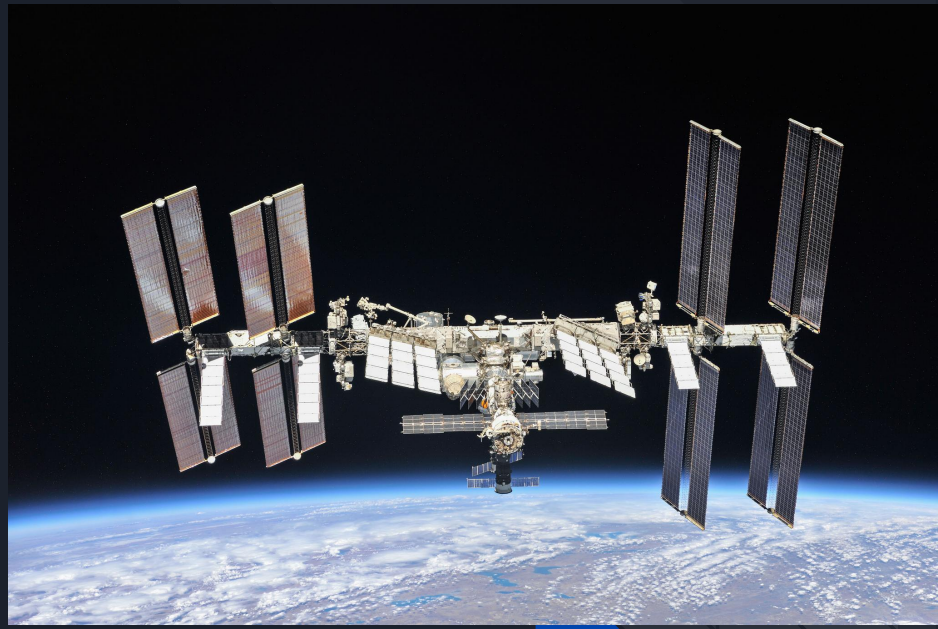
The Shuttle Program

- 1972-2011
- Total Cost: **$224 billion**
- 135 flights —> $1.7 billion per flight
- 1973 budget estimates (in 2019 dollars)
    - $49 billion in development costs
    - $10.6 million per flight
- According to NASA, the actual cost in 2011 per flight was roughly $500 million
- Why so expensive?
    - Final design was 20% heavier than the original concept
    - Large maintenance costs on the thermal protection tiles
    - Less launches per year than originally planned
        - 12 flights per year planned; average was 4.5/yr
        - Much higher cost per launch

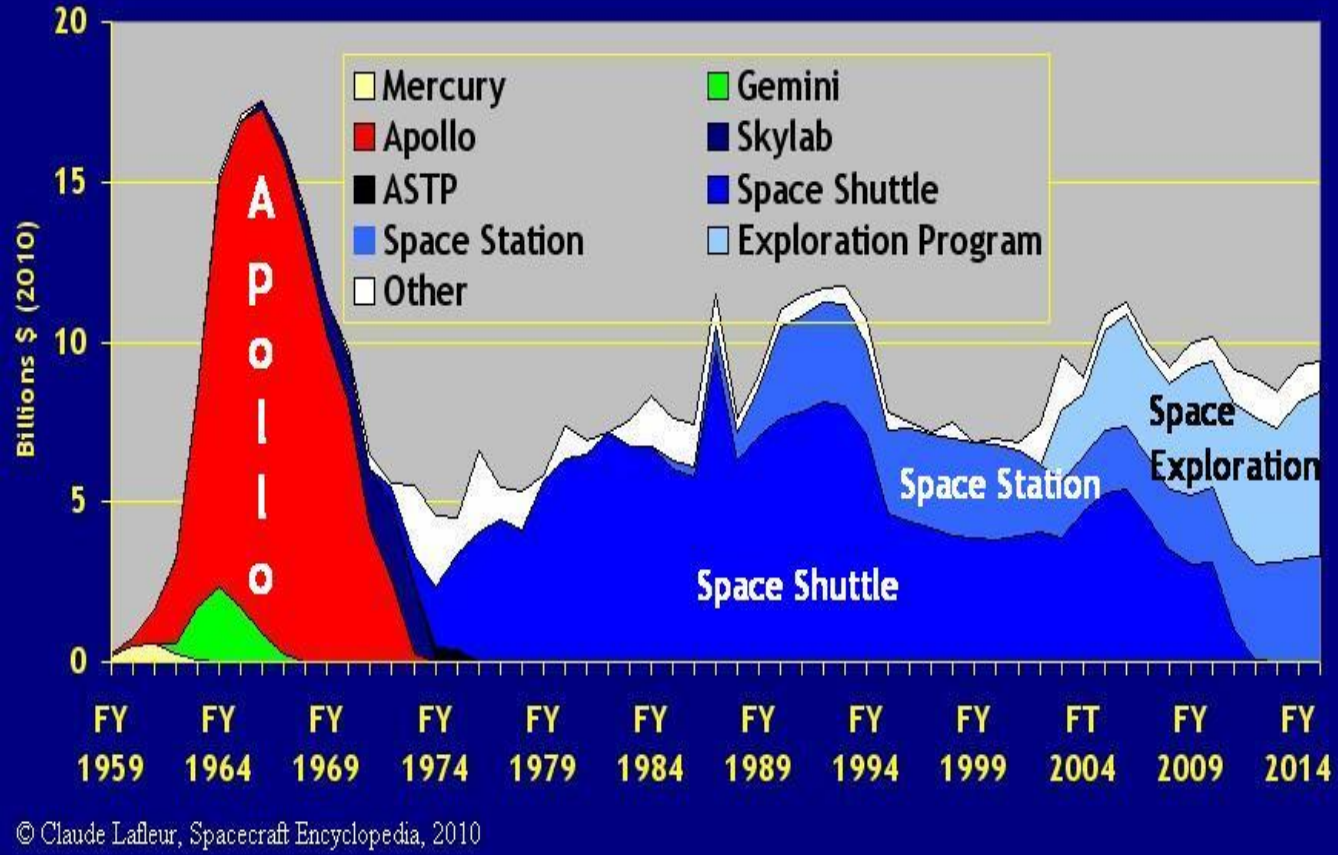


The International Space Station

- 1985-present
- NASA budgeted ~$85 billion through 2015
- International partners also contributed
    - Russia: $ 14.1 billion
    - Europe and Japan: $11.8 billion
    - Canada: $2.4 billion
- 36 shuttle flights needed to build the station
    - Roughly $1.6 billion each —> $57.6 billion
- Total Cost (through 2015): **~$171 billion**



U.S. Piloted Programs Funding, 1959-2015 (2010$)



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Program	Period	Current cost (a) (millions $)	End of Program Cost (b) (millions $)	Cost in 2010 $ (c) (billions $)
Mercury	1959-1963	269	277	1.6
Gemini	1962-1967	1,282	1,342	7.2
Apollo	1959-1973	20,443	29.3	109
Skylab	1966-1974	2,256	2,786	10
Apollo-Soyuz	1972-1975	245	258	1
Space Shuttle	1972-2012	123,031	198,569	199
Space Station:				150
• NASA Funding	1985-2015	58,695	72,102	
• Shuttle flights	1998-2010	n/a	53,374	126
• Int'l Parthners	1986-2015			24
Exploration Programs	2003-2015	46,208	n/a	48
Total	1959-2015	274,757	n/a	486

a) Adding yearly costs without taking into account inflation. See Tables below.
b) Adding yearly costs taking into account inflation. See Tables below.
c) Adding yearly costs in 2010 $ (rounded). See Tables below.
* See International Space Station Total Cost below.

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- From 1959-2015, $572 billion dollars spent on piloted programs
- The total GDP over that time is roughly $590 trillion

Current Missions

How are missions scoped at NASA?

NASA's **Science Mission Directorate (SMD)** is responsible for funding robotic, science-focused missions

Four divisions:

- Astrophysics
- Heliophysics
- Earth Science
- Planetary Science

Directed vs. Competed Missions

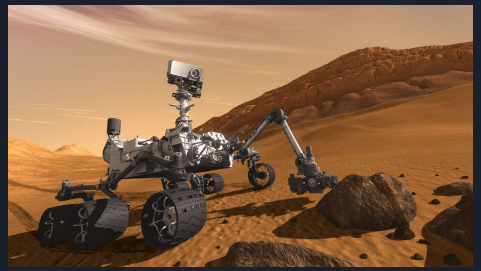
The biggest scale and most expensive robotic missions NASA operates are the **large strategic science missions** (aka Flagship missions)

These missions are found across all four divisions of the SMD, and are assigned to a specific institution (usually a NASA center)

Smaller scale robotic missions tend to be **competed**, or **PI-driven**, meaning that NASA provides funding calls periodically with a certain amount of budget, and selects missions proposed by PI-led teams that fall within those budgetary constraints

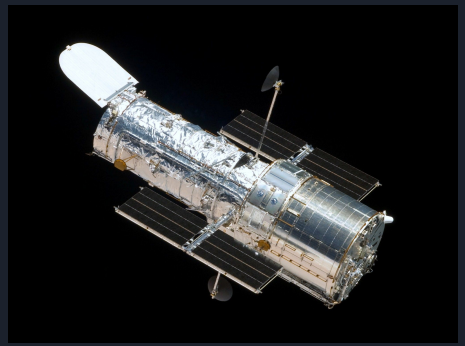
Examples of Flagship Missions

Planetary Science:
Mars Science Laboratory
($2.5B)



Earth Science:
Aqua ($1.3B)

Astrophysics:
Hubble Space Telescope
($9.2B)



Heliophysics:
Parker Solar Probe
($1.5B)

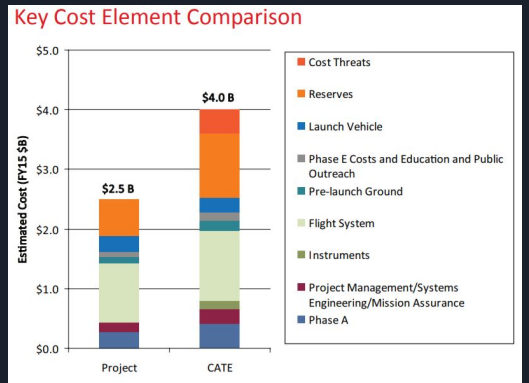
Current Classes of PI-Led Missions in the Planetary Science Division

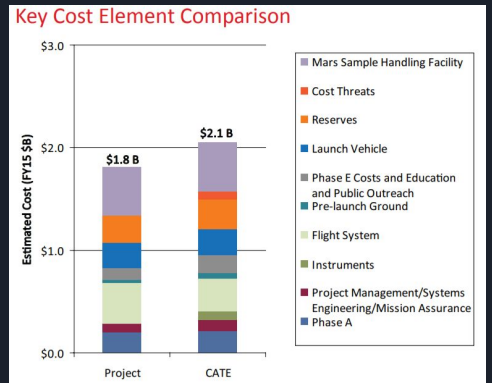
- Discovery program
  - Roughly offered once every two years
  - Cost-cap of ~$450 million (excluding launch + post-launch costs)
  - Examples: Mars Pathfinder, Dawn, InSight, Psyche
- New Frontiers program
  - Roughly offered twice a decade
  - Cost-cap of ~$850 million (excluding launch + post-launch costs)
  - Examples: New Horizons, Juno, OSIRIS-REx, Dragonfly

Decadal Survey

- In the Decadal Surveys (used to direct NASA's science mission priorities over the next decade), detailed cost estimates are performed both by the project team itself and an independent auditor (guess which number is usually higher)
- These costs inform whether science goals could be accomplished within a PI-led category, or if they need a specially funded flagship mission

Mars Sample Return Lander + Ascent Vehicle

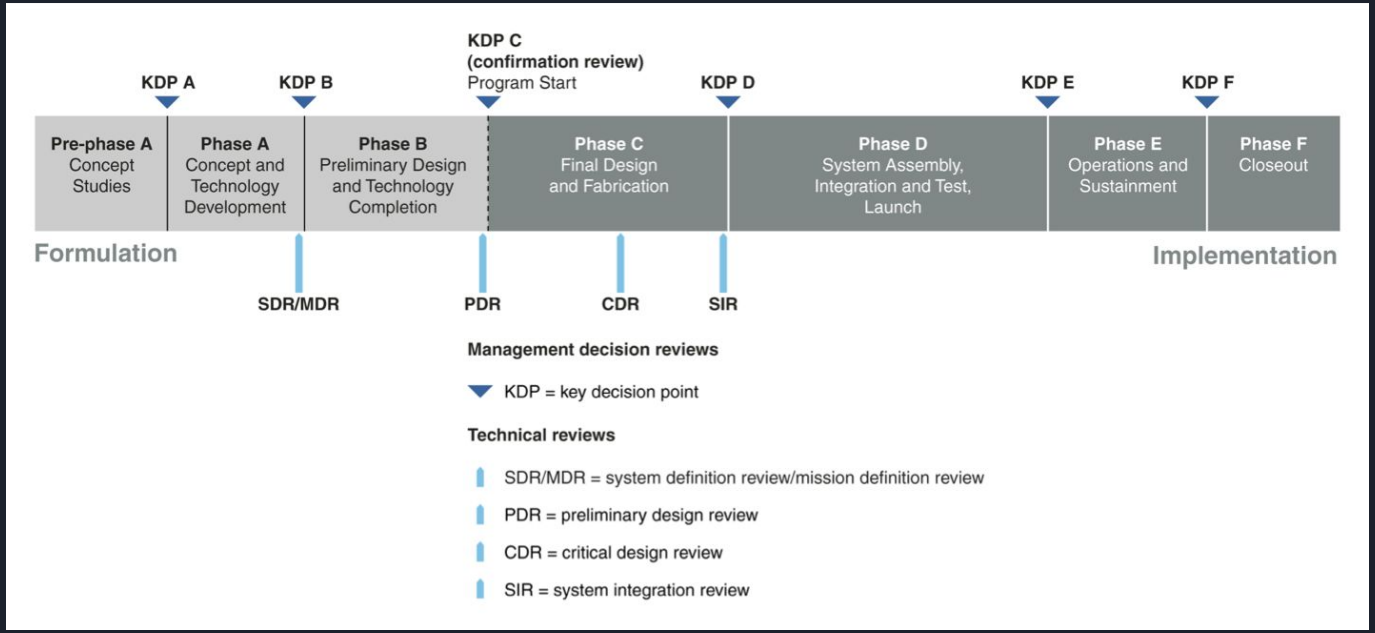




Mars Sample Return Orbiter + Entry Vehicle

Budgetary Deep Dive:
Flagship Mission (Mars Science Laboratory)

NASA Mission Lifecycle



Project Cost Summary

Mission Phase	Budget Allocation
Formulation (Phases A & B)	$515.1M planned, $515.5M actual
Development (Phases C & D)	$968.6M planned, $1,802.0M actual
Operations (Phase E)	$158.5M planned, $158.8M actual
Life-Cycle Cost (Primary Mission)	$1,642.2M planned, $2,476.3M actual

Budget overage due to unforeseen problems + missed launch window (thought to directly contribute ~$137M to total mission cost)

A Wide Array of Instruments

Instrument	Subcontractor
MastCam	Malin Space Science Systems
ChemCam	Los Alamos National Laboratory
MAHLI	Malin Space Science Systems
APXS	Canadian Space Agency
CheMin	NASA Ames
SAM	NASA Goddard
RAD	Southwest Research Institute
MARDI	Malin Space Science Systems
DAN	Russian Space Agency
REMS	Spanish Space Agency

And a Wide Array of Subsystems

Subsystem/Task	Subcontractor
Propulsion	In House (JPL)
Thermal	In House (JPL)
Telecom	In House (JPL)
Mechanical	In House (JPL)
Sample Acquisition/Sample Processing and Handling	In House (JPL)
Avionics	In House (JPL)
Launch Vehicle	United Launch Alliance
Flight Software	In House (JPL)

And a Wide Array of Subsystems

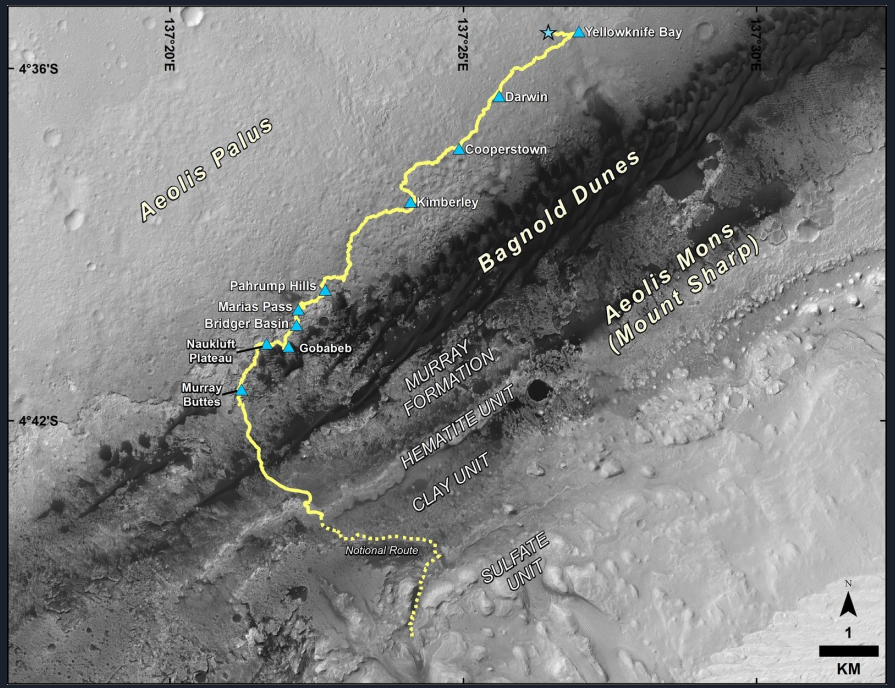
Subsystem/Task	**Subcontractor**
Assembly, Test & Launch Operations	In House (JPL)
Guidance, Navigation & Control	In House (JPL)
Launch Operations	NASA Kennedy
Multi-Mission Radioisotope Thermoelectric Generator	U.S. Department of Energy

Extended Missions

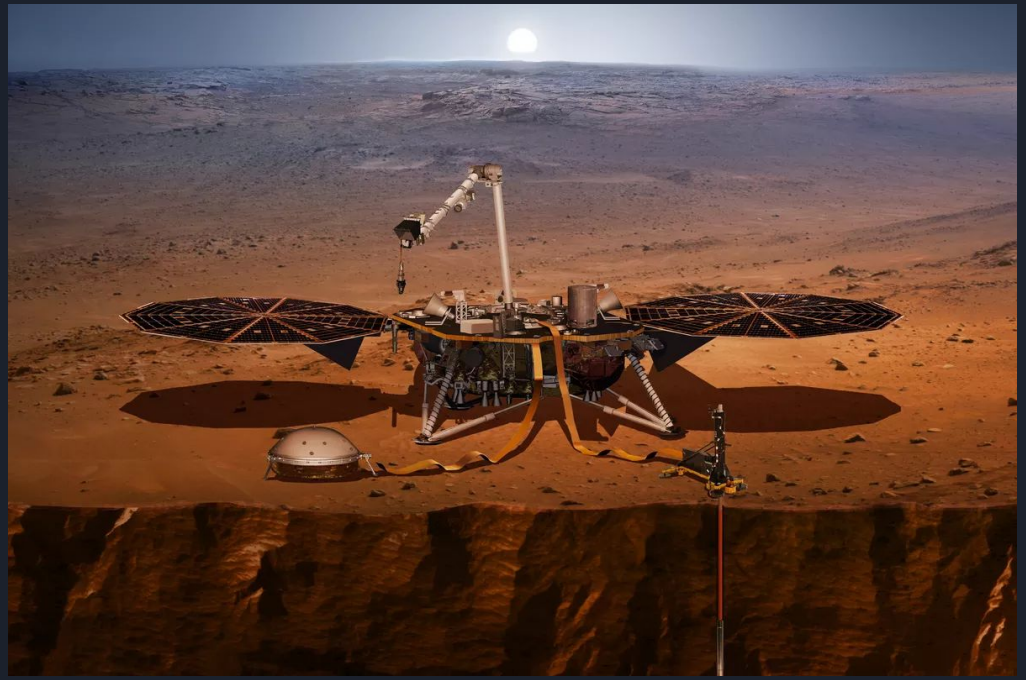
Curiosity is currently in its 2nd extended mission

Primary mission: 2 years

Extended missions add to the mission cost (~$50M per year in operations costs), but if a Flagship can still gather science, NASA will almost always fund it



Budgetary Deep Dive:
Discovery Mission (Mars InSight)

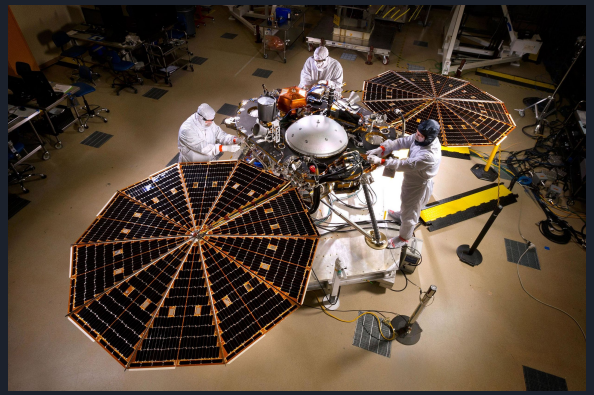


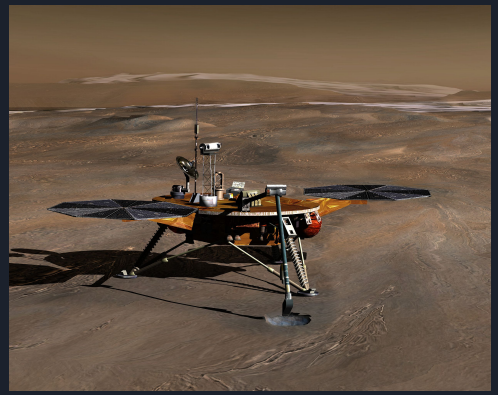
Competition for Discovery 12

- 28 proposals submitted for the Discovery Program's 12th call
- Downselected to 3 - each awarded $3M for pre-phase A studies
  - InSight - P.I. Bruce Banerdt, NASA JPL
  - TiME - P.I. Ellen Stofan, Johns Hopkins APL
  - Comet Hopper - P.I. Jessica Sunshine, NASA Goddard
- InSight selected in August 2012 with cost cap of $425M (not including launch vehicle or operations costs) - scheduled for launch in 2016

Subcontractors

- Unlike Curiosity, JPL would not be handling the construction of the spacecraft bus in-house
- Lockheed Martin Space Systems would manufacture InSight, using legacy design from the Phoenix lander to reduce risk/cost
- Instruments provided by German and French Space Agencies





The Final Cost

- Cost cap of $425M
- Estimated total cost of $675M (including Atlas V 401 launch + operations costs)
- Due to a persistent vacuum failure in the SEIS instrument (built by CNES), launch was delayed from 2016 to 2018
- This was associated with a cost overrun of roughly $150M, leading to a final price tag of $825M

Future Missions

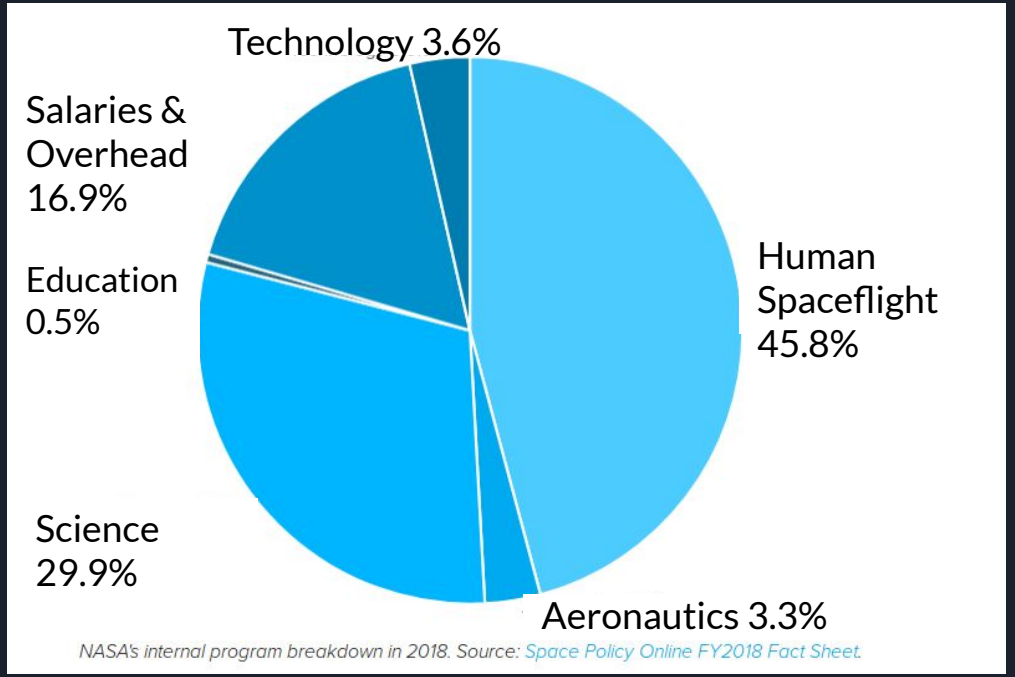
NASA’s budget breakdown at present

Total 2019: $21.5 billion

Human spaceflight: $9.8 billion

Science: $6.4 billion

Consider:
What size budget would NASA need for Artemis or a human Mars mission?



NASA's internal program breakdown in 2018. Source: Space Policy Online FY2018 Fact Sheet.

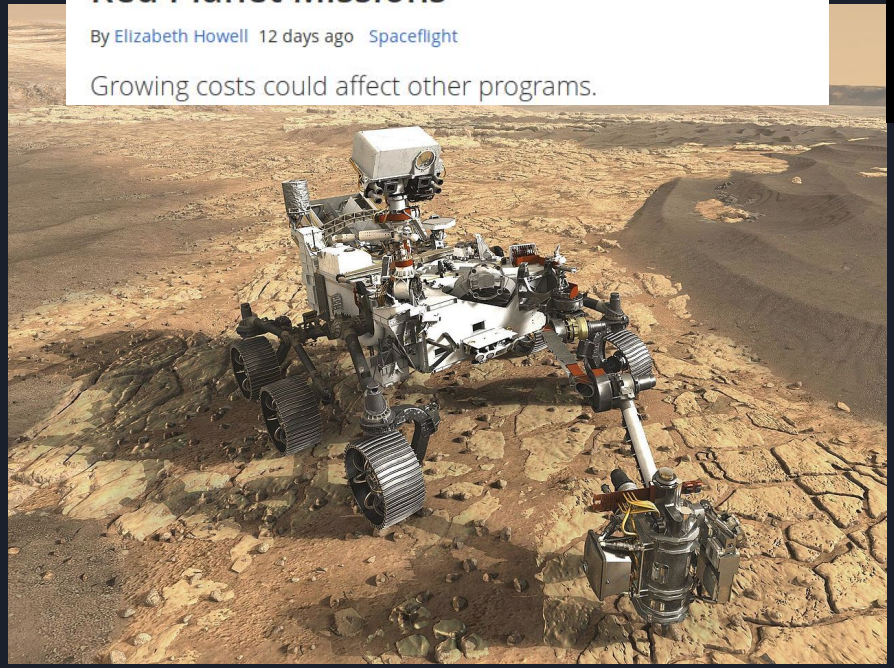
https://www.planetary.org/get-involved/be-a-space-advocate/nasa-budget.html

When budgets balloon

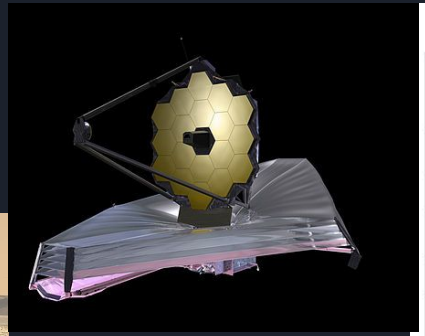
Mars 2020 Rover Cost Could Starve Other Red Planet Missions

By Elizabeth Howell 12 days ago Spaceflight

Growing costs could affect other programs.



James Webb Space Telescope



Then-planned launch and costs

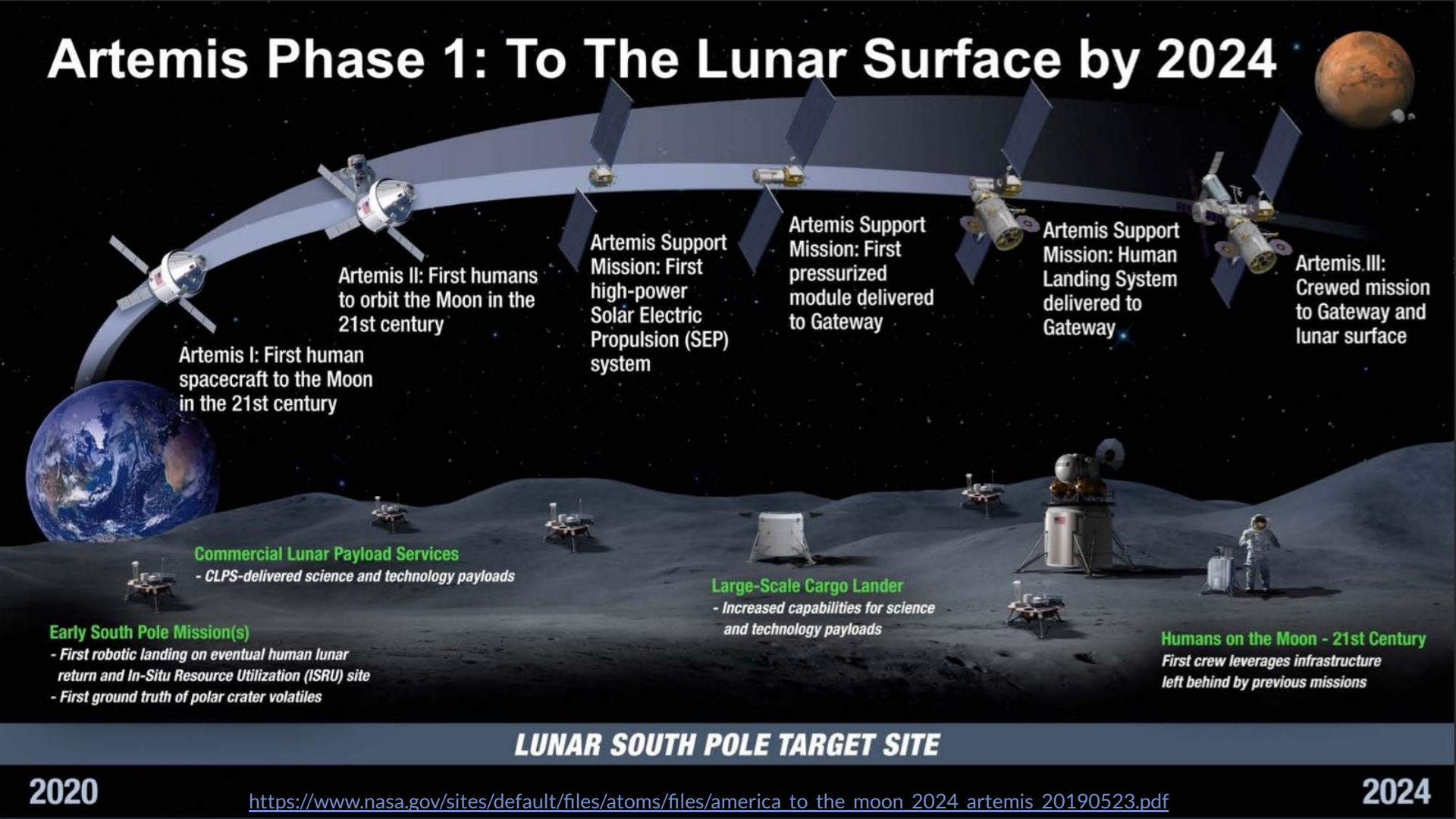
Year	Planned launch	Budget Plan (Billion USD)
1997	2007[73]	0.5[73]
1998	2007[77]	1[48]
1999	2007 to 2008[78]	1[48]
2000	2009[36]	1.8[48]
2002	2010[79]	2.5[48]
2003	2011[80]	2.5[48]
2005	2013	3[81]
2006	2014	4.5[82]
2008, Preliminary Design Review		
2008	2014	5.1[83]
2010, Critical Design Review		
2010	2015 to 2016	6.5[*citation needed*]
2011	2018	8.7[84]
2013	2018	8.8[85]
2017	2019[86]	8.8
2018	2020[87]	≥8.8
2018	2021[88]	9.66

"JWST is always 2 years away"

Artemis: Initial budget estimates

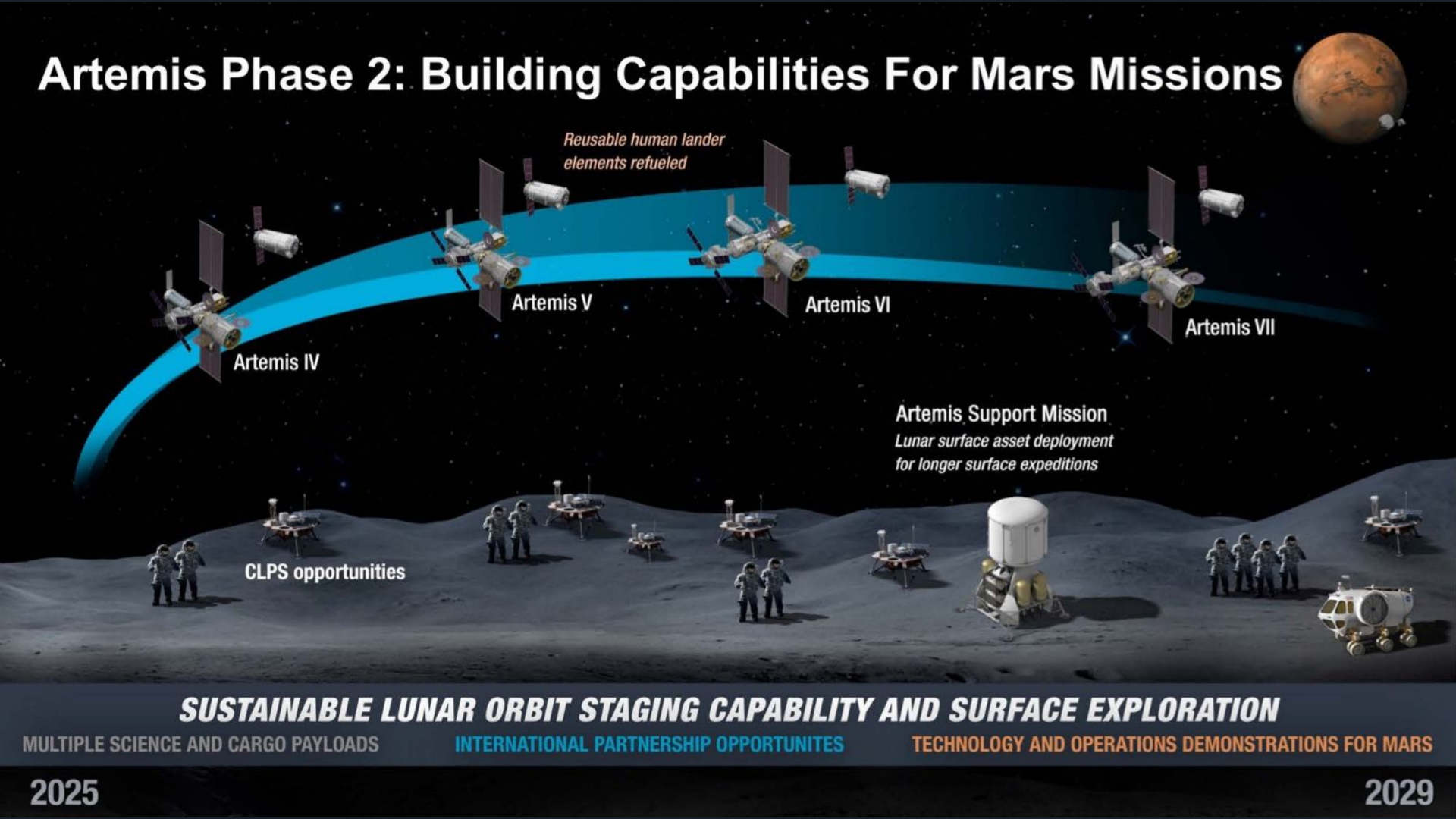
- $20-30 billion in total (not including Space Launch System, Orion command module)
  - $4-6 billion per year IN EXCESS of other NASA budget
  - Only $1.6 billion extra requested for 2020
- Context:
  - Apollo program: $136 billion (today's $)
  - Each Apollo: $22.6 billion (today's $)

Artemis Phase 1: To The Lunar Surface by 2024



https://www.nasa.gov/sites/default/files/atoms/files/america_to_the_moon_2024_artemis_20190523.pdf

Artemis Phase 2: Building Capabilities For Mars Missions



SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION

MULTIPLE SCIENCE AND CARGO PAYLOADS | INTERNATIONAL PARTNERSHIP OPPORTUNITES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

2025 2029

Fermi Problem Activity: Mars Mission Budget

Mars Mission Design Reference Architecture 5.0:

1. 2 cargo Mars Transfer Vehicles (MTV)
2. 1 crew MTV
3. In Situ Resource Utilization (ISRU) unit
4. Habitats
5. Mars Ascent Vehicle (MAV)

Mission basics:

- 7 year timespan
- Astronauts return to Earth alive
- ~400 kg sample returned

Helpful numbers (today's $):

- Each Apollo mission: $22 billion
- Entire Apollo program: $136 billion
- ISS: $100 billion

Estimate the cost of this mission!
(Order of magnitude)

Mars Mission cost: McNutt & Delamere 2017

$1 trillion (± a bit) (50x current NASA budget)

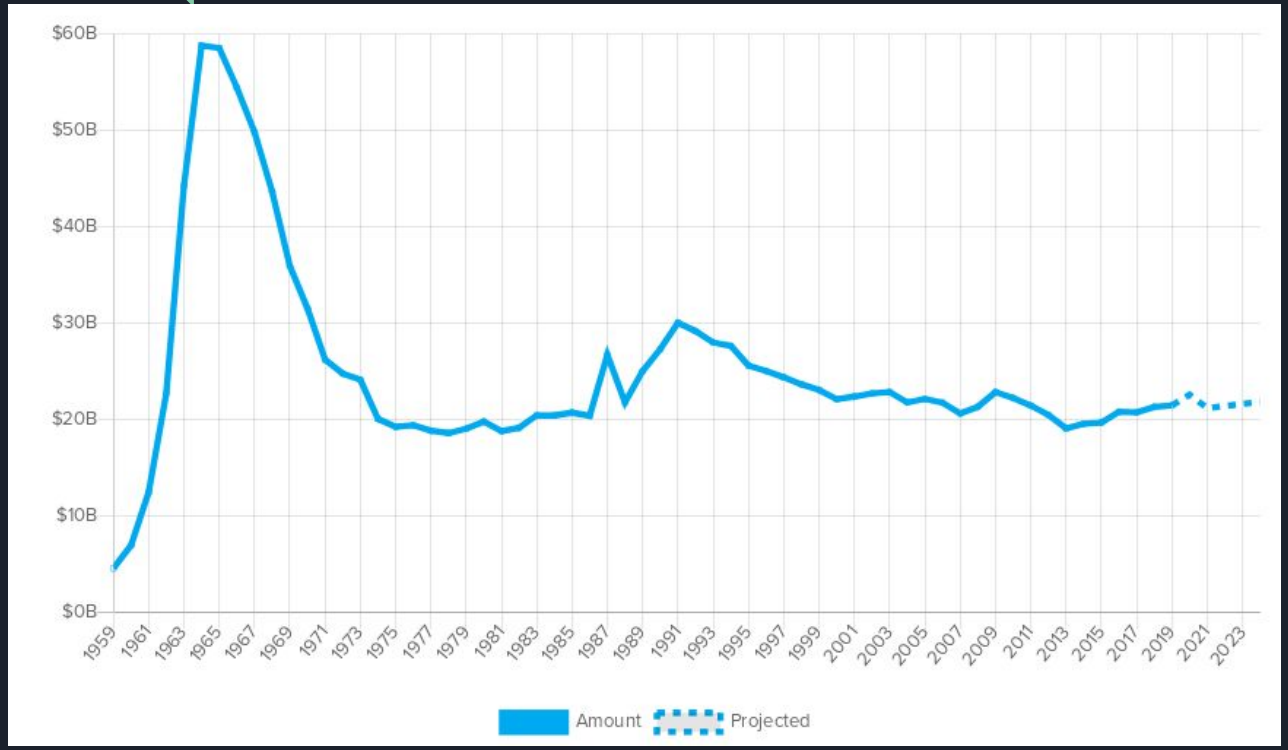
How?

1. Approximation based on ISS cost, mass, use
2. Scaling up from Apollo missions

Why?

- Mass
- Fuel and storage of fuel
- Orbital and solar cycles
- Reusable hardware
- Radiation shielding
- No resupply option
- Food/water/waste recycling
- Crew health maintenance
- Social changes
- ……..

In perspective:
Cumulative NASA budget ≅ $1.6 trillion



(Integrated by eye)

Total =
$25 billion * (2013-1959) +
½ * (1971-1962) * $35 billion

Takeaway: Sending humans to Mars is an expensive and hard problem. NASA cannot pick up the whole tab without support.

https://www.planetary.org/get-involved/be-a-space-advocate/nasa-budget.html

Summary

Past missions

- Going to space is expensive especially when you have infrastructure to build and new technologies to develop

Current missions

- Spacecraft are complicated and almost always cost more than you initially project

Future missions

- Budgets are really hard to project. Artemis and human Mars mission could be vulnerable to

References

Past Missions

- A new accounting for Apollo: how much did it really cost?
- Columbia Accident Investigation Board Public Hearing
- US Real GDP by Year
- Costs of US piloted programs
- Van Pelt, Michael (2005). *Space tourism: adventures in Earth's orbit and beyond*. Springer. pp. 75–76

Current Missions

- NASA's Management of the Mars Science Laboratory Project
- NASA Assessments of Selected Large-Scale Projects
- NASA Selects Investigations for Future Key Planetary Mission
- 2013 Planetary Science Decadal Survey
- Mission to Mt. Sharp - MSL Extended Mission Plan
- InSight Lander: Probing the Martian Interior

Future Missions

- What is NASA's Budget?
- Artemis cost estimate won't be ready until 2020
- NASA's Artemis Program
- NASA announces plans for new $1.5 billion Mars rover
- Mars 2020 Rover Cost Could Starve Other Red Planet Missions
- NASA's James Webb Telescope Likely To Be Delayed Yet Again
- JWST - Cost and Schedule Issues
- Human Exploration of Mars Design Reference Architecture 5.0
- McNutt, R. L., & Delamere, W. A. (2017). Human Exploration of Mars: Cost Realities of a First Mission. 68th International Astronautical Congress, (September).