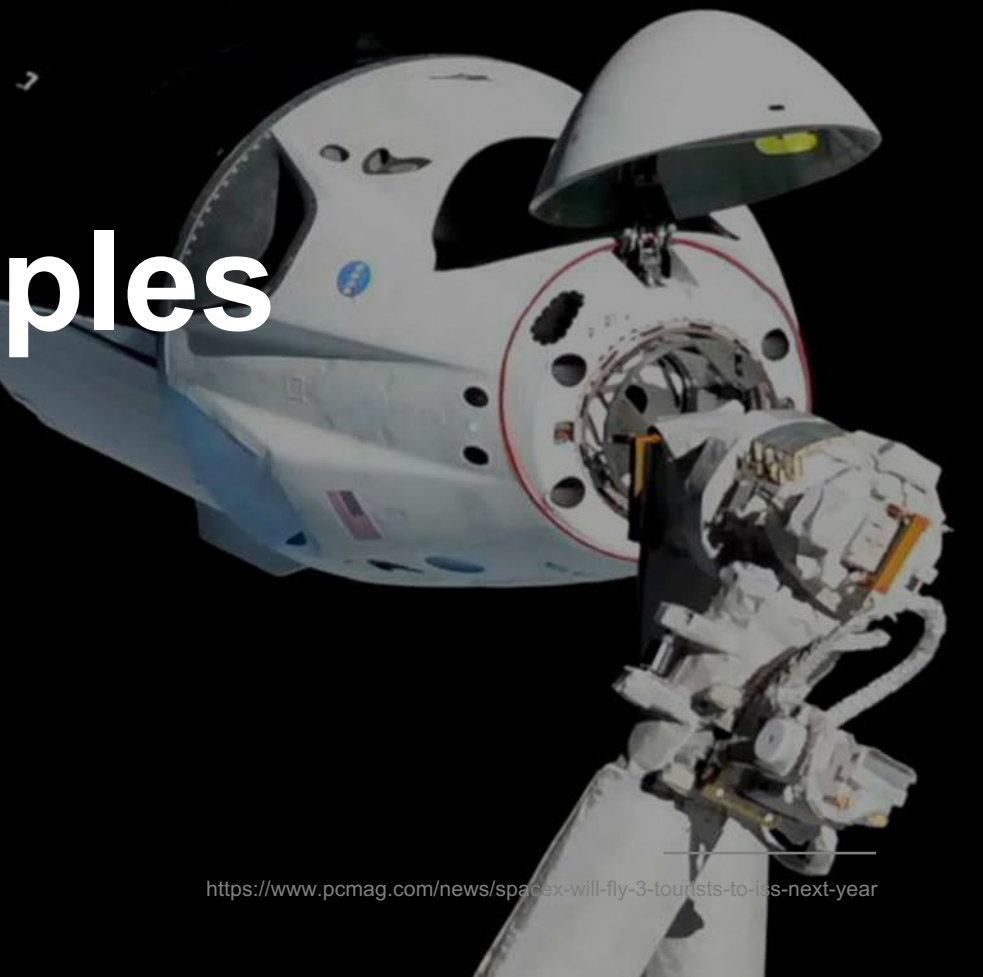
06/16/20 Version 5

NSW Venture Studio

SpaceX Insights and Industry Design Principles

Cesar Lopez | Darae Kim | Devya Ramanathan | Eric Haddleton | Yuanyuan Hu



https://www.pcmag.com/news/spacex-will-fly-3-tourists-to-iss-next-year

NOKIA

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NSW Venture Studio | **2020 Internship Team**

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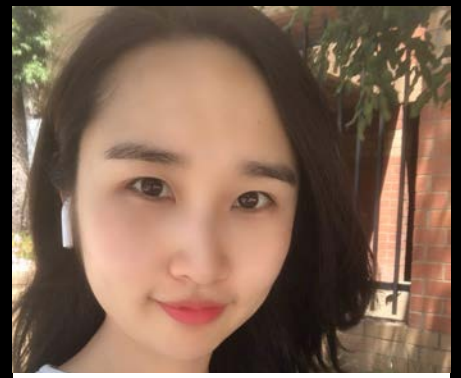

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Executive Summary

1. Business Model

The SpaceX business model focuses on reducing bureaucracy and eliminating the red tape that has become synonymous with the space industry through organizations such as NASA.

They manufacture their parts in-house whenever possible, which reduces the impact of costly contracts with other private companies.

In addition, they will sometimes purchase commercial off-the-shelf (COTS) products, reusing products from other industries in their spacecraft.

2. User Experience

SpaceX uses feedback in order to gain insights on what needs to be improved, specifically with the UI displays and the crew suits.

From rapid iterations, they are able to test various scenarios to provide for the Most-Advanced-Yet-Acceptable (MAYA) technology in the space industry today.

3. Technology

SpaceX is a company that has been focused on technological innovation from its inception.

While it is true that their designs are driven by user experiences and feedback, SpaceX’s success would not be possible without the technological innovation that ranges from triple redundancy of all their systems to an umbilical cord that connects the suits to the capsule.

Introduction to SpaceX

"SpaceX designs, manufactures and launches advanced rockets and spacecraft. The company was founded in 2002 to revolutionize space technology, with the ultimate goal of enabling people to live on other planets". [1]

Team

Led by CEO and Founder Elon Musk, SpaceX currently employs more than 8,000 people across the United States, ranging from suit designers to flight engineers.

Services & Vehicles

SpaceX's main products are its Falcon launching vehicles, Dragon spacecraft, and Starship. These vehicles will eventually serve both in space and on the earth.

History & Plan

SpaceX has made the fully reusable rocket Falcon 9 and has brought Tesla to space using Falcon Heavy. On May 30, 2020, the Falcon 9 and crew Dragon brought humans to the ISS. SpaceX's future plans include Moon & Mars colonization as well as using rockets for the earth transportation.

https://spaceflightnow.com/2016/12/13/spacexs-first-crewed-launch-moved-back-to-2018/

Key Designers Behind SpaceX

"You have to let people see you fail, and you have to push back when the critics use your early failures as an excuse to shut you down (...) This is why it is hard for national space agencies to adopt it. The geopolitics and domestic politics are brutal." [2]

SpaceX CEO Chief Engineer & Designer Elon Musk

https://www.bloomberg.com/news/articles/2019-11-13/elon-musk-s-german-factory-started-with-love-letter-from-berlin

Key Designers Behind SpaceX

Tom Mueller | Dragon Designer

Tom Mueller, a founding member of SpaceX, is a rocket designer and engineer in SpaceX. He helped create the Dragon spacecraft and spearheaded the creation of the Merlin engines. [3]

Jose Fernandez | Suit Designer

Having worked in the film industry since 1989, Jose Fernandez was asked by Musk to give the space suit a “heroic” look. [4]

https://www.cnbc.com/2019/01/25/tom-mueller-spacex-cto-who-makes-elon-musks-rockets-fly.html
https://world-today-news.com/jose-fernandez-the-mexican-american-artist-who-has-dressed-batman-and-the-spacex-astronauts/

Services

Sending people and cargo to Earth's orbit

*Contract signed with NASA [5] & three tourists

Delivering satellites to Earth's orbit

Mission to the Moon & Mars

Vehicles

Falcon 9 with Dragon

The world's first orbital class reusable rocket that uses 9 Merlin engines. [6]

Falcon Heavy

With 27 Merlin engines, it can lift 64 metric tons into orbit. [7]

Starship

Designed to be the most powerful launching vehicle and can carry more than 100 metric tons into Earth's orbit. [8]

Past Achievements

Key Milestone
Funding round






2002
Founded by Elon Musk

2006
$100M seed investment by Elon Musk

2008
$10M Series A

2008
Falcon 1's first Successful launch

2009
$15.03M Venture

$30.44 Series B

2010
Falcon 9's first maiden launch

2010
$50M Series C

2012
Dragon's first resupply mission to the ISS.

Contracts for 13 launches

2012
$30M Series D

2015
Falcon 9's successful landing on drones

2015
$1 Billion Series E

2018
Falcon Heavy brings a Tesla into space

2020
Crew Dragon brings two astronauts to ISS

Graph made based on Loïc Souêtre's article in medium [9] and Jonathan Corum's article from Nytimes [10]

https://www.nytimes.com/interactive/2018/science/spacex-falcon-launch.html
https://www.nasa.gov/sites/default/files/thumbnails/image/jsc2020e024483.jpg

Future Plans

2017*

Building Moon base

* Original Plan, deadline missed

2022

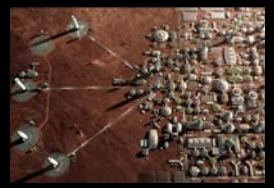
First Cargo Mission to Mars

Identify resources and hazards, build infrastructures

2024

2 Cargo & 2 Crew ship to Mars

Bring the first human and more equipment to Mars



2024-

Building Mars Base

(No specific time)

Earth to earth transportation

Moon

The first long term goal is to head to the moon -compared to Mars, it is much safer and cheaper.

Mars Colonization

Musk proposed a detailed plan for Mars colonization, and the goal is to reach Mars with the Starship by 2024.

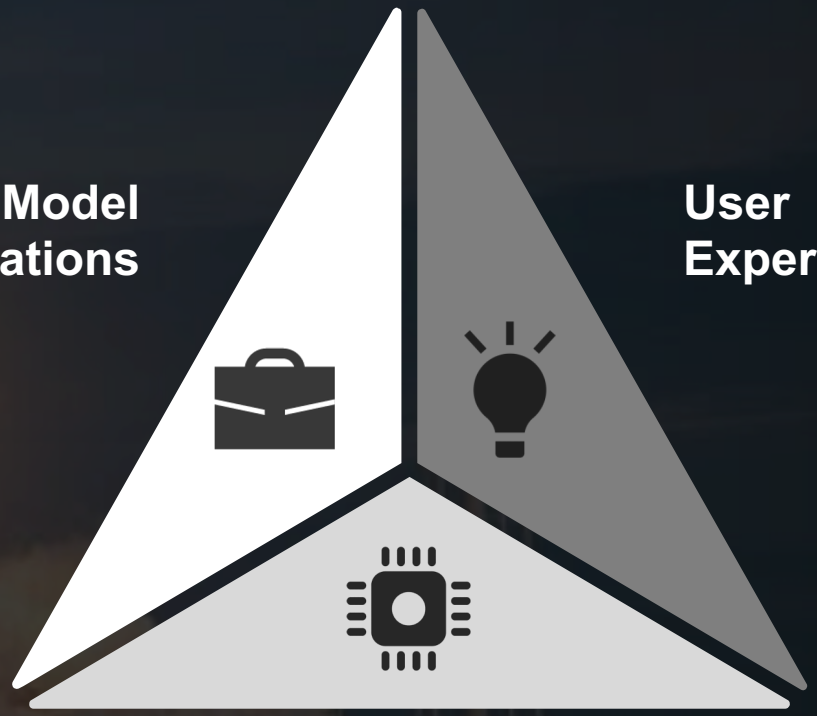
Earth transportation

Earth transportation is another long-term goal. Musk hopes that people will be able to travel anywhere in the world within 30 minutes.

Graph made based on SpaceX's Starship user guide [11]

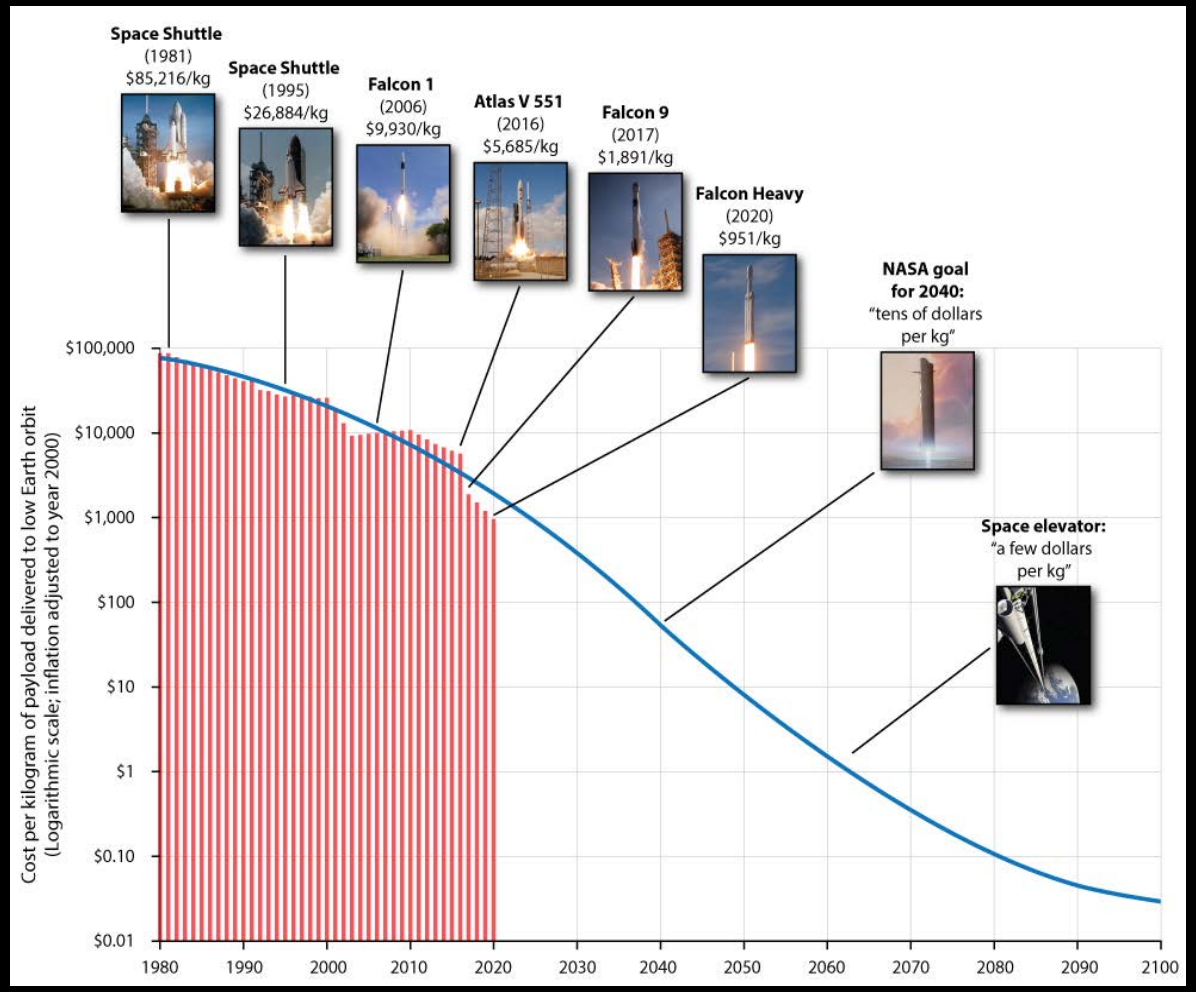
https://www.spacex.com/media/starship_users_guide_v1.pdf
https://www.tesmanian.com/blogs/tesmanian-blog/spacex-plans-to-get-you-anywhere-on-earth-in-an-hour-using-starship

What Makes SpaceX Different?



Business Model Innovations

- Until the emergence of SpaceX, private companies have been largely **unsuccessful** in the space industry.
- By shedding the **red tape** and **bureaucracy** that state-run organizations deal with and focusing on keeping costs low, SpaceX has developed a stable business model.
- Operating under the principles of **iterative design** allows SpaceX to focus on prototyping their ideas early in the design process, and adjust their designs as needed.
- By following a **commercial-off-the-shelf (COTS)** strategy, SpaceX has been able to reduce costs.

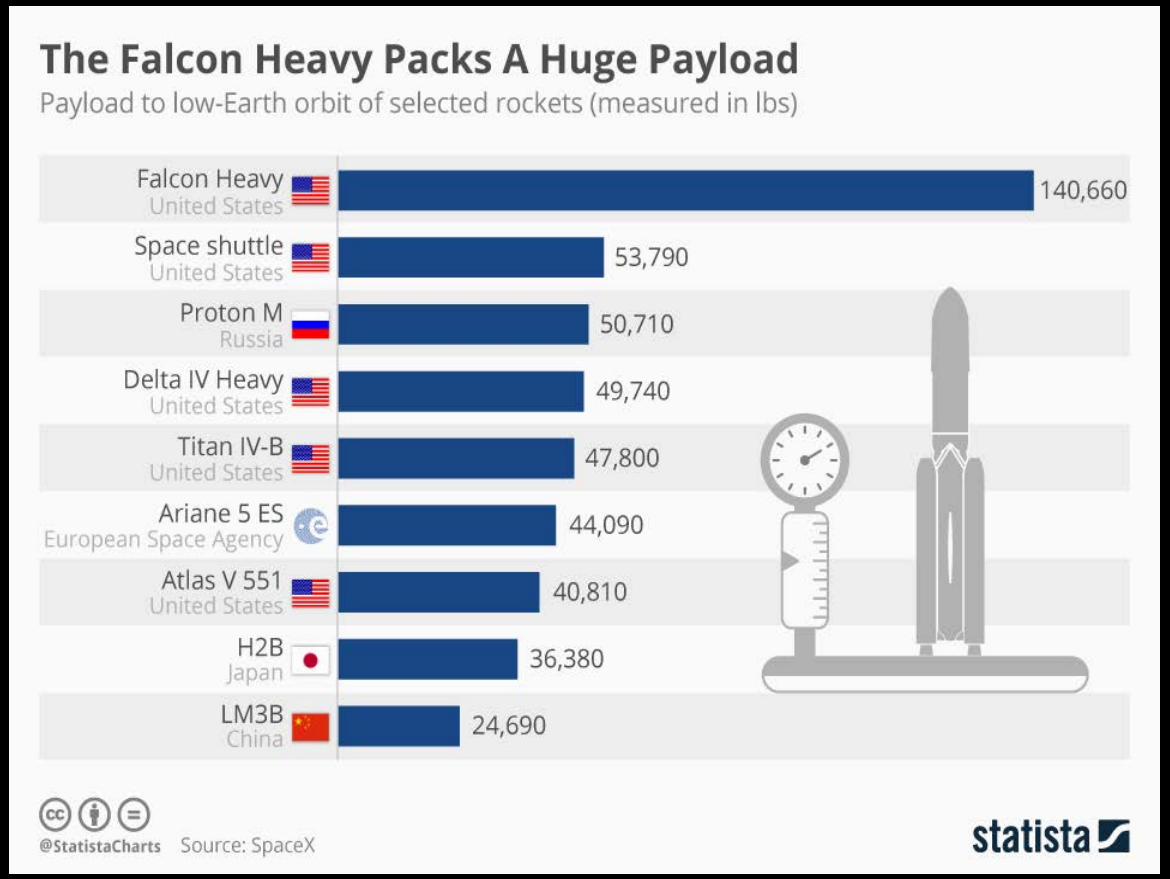


Cost of Access

Keeping Costs Low

- SpaceX aims to show that **simple design, reliability, and low costs** can all coexist. [12]
- In space travel, this is not really seen – NASA is perhaps a good example of the opposite of this (see high costs at the left).
- Countless missions and programs cancelled, resulting in taxpayer money going to waste, and a **waste of the public's ongoing interest in space travel**, with little result to show for it. [13]
- Founder Elon Musk has stated that his goal is for space travel to cost $500/pound or less [14], which was **achieved** by Falcon Heavy (see chart at left).

https://www.futuretimeline.net/data-trends/6.htm

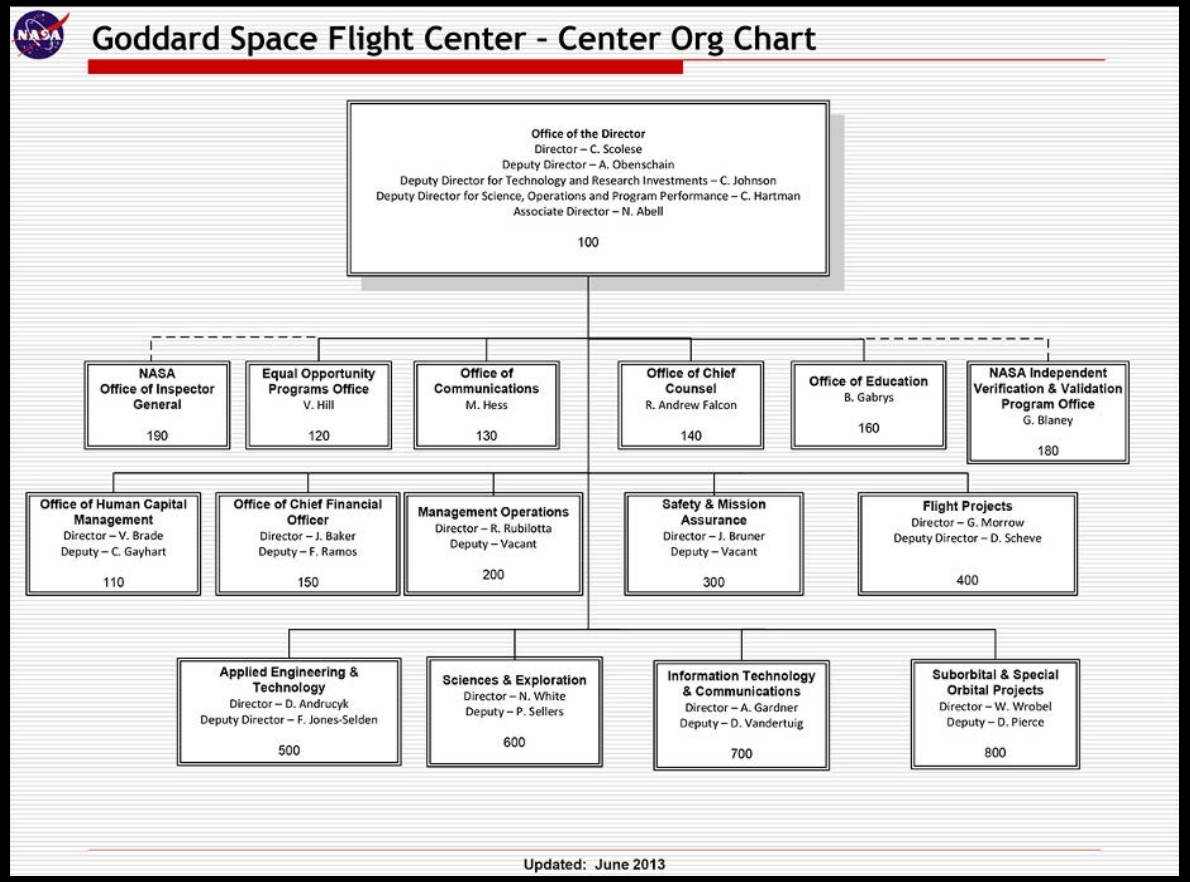


Cost of Access

Efficiency is Key

- A key part of SpaceX's ability to keep costs low is their decision to manufacture whatever they can **in house**, rather than subcontracting or purchasing expensive custom-built parts for space travel. [15]
- This also allows more control over quality, as well as for a **better feedback loop** between manufacturing teams and engineering teams.

https://www.statista.com/chart/12810/the-falcon-heavy-packs-a-huge-payload/



Simplified Corporate Structure

Left: The corporate structure for one of NASA's Flight Centers.

- The end result of this is a process that cuts out a lot of the red tape and bureaucracy that has plagued NASA for decades. [16]
- Organizations such as NASA have to go through many steps to secure funding for their projects, while SpaceX and other private companies have an easier path to the top for new ideas.
- This is difficult to avoid, however – some have expressed concern that **SpaceX is becoming bureaucratic** itself. [17]

https://www.nasa.gov/sites/default/files/center.org_.chart_.jpg

Commercial-off-the-Shelf

By following this strategy, among others, SpaceX has managed have the lowest cost per mission compared to other companies.

- The company made hatch handles from bathroom lock parts to save $1,470.
- Using race-car safety belts to strap in astronauts was **more comfortable and less expensive** than custom-built harnesses. [18]

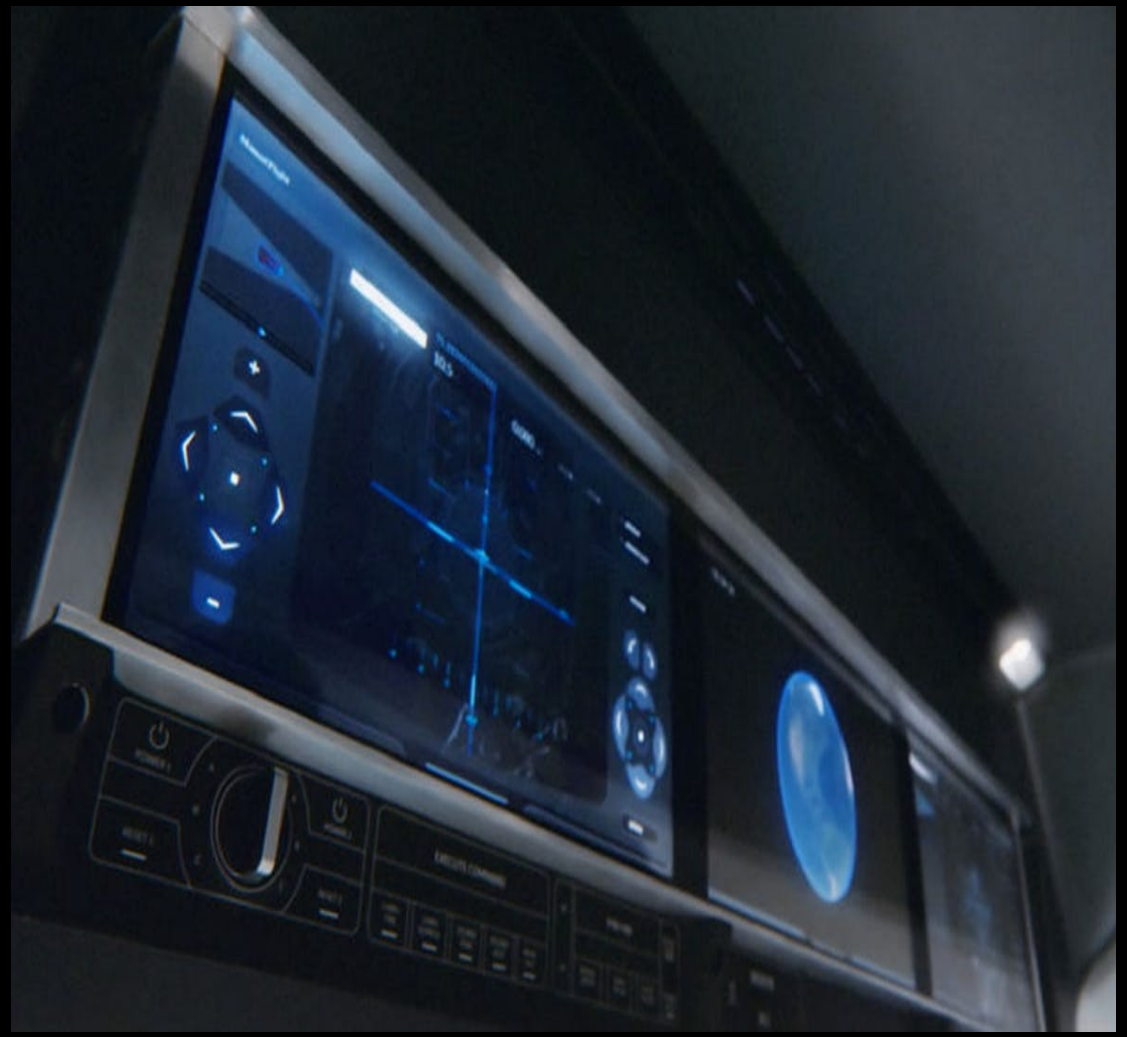
“I almost never heard NASA engineers talking about the cost of a part.”

- NASA Official Mike Horkachuck

https://www.humansinspace.org/introducing-spacex-dragon-v2/spacex-dragon-v2-preview-seat-belt-2/

User Experience

- SpaceX follows a **Human-Centered-Design (HCD) Process** to envision their goal of a 'fully autonomous' Dragon spacecraft [19], but in emergency situations the crew entirely has manual control.
- Main focus: **minimum-crew interaction**, emphasis on taking the crew up on flight in the **Most-Advanced-Yet-Acceptable way (MAYA).**
- Designed around well-versed comprehension of **crew tasks, environmental conditions,** and **situational awareness.** This helped to simplify many aspects of the experience, focusing mainly on **functionality.**



Dragon Interface

- **Physical buttons** for all emergency commands such as changing course or starting emergency protocol.
  - **'Execute' and 'Cancel'** aside from the displays. [19]
- Tests for **vibrations** and **visibility** during flight were also thought through beforehand, so crew members practiced using displays with suits and gloves on.
- Focusing on the most common space-related scenarios in order to provide a pleasant yet informative user experience of the displays in flight.
- **Many iterations came to play** while simplifying and modifying the Dragon UI.

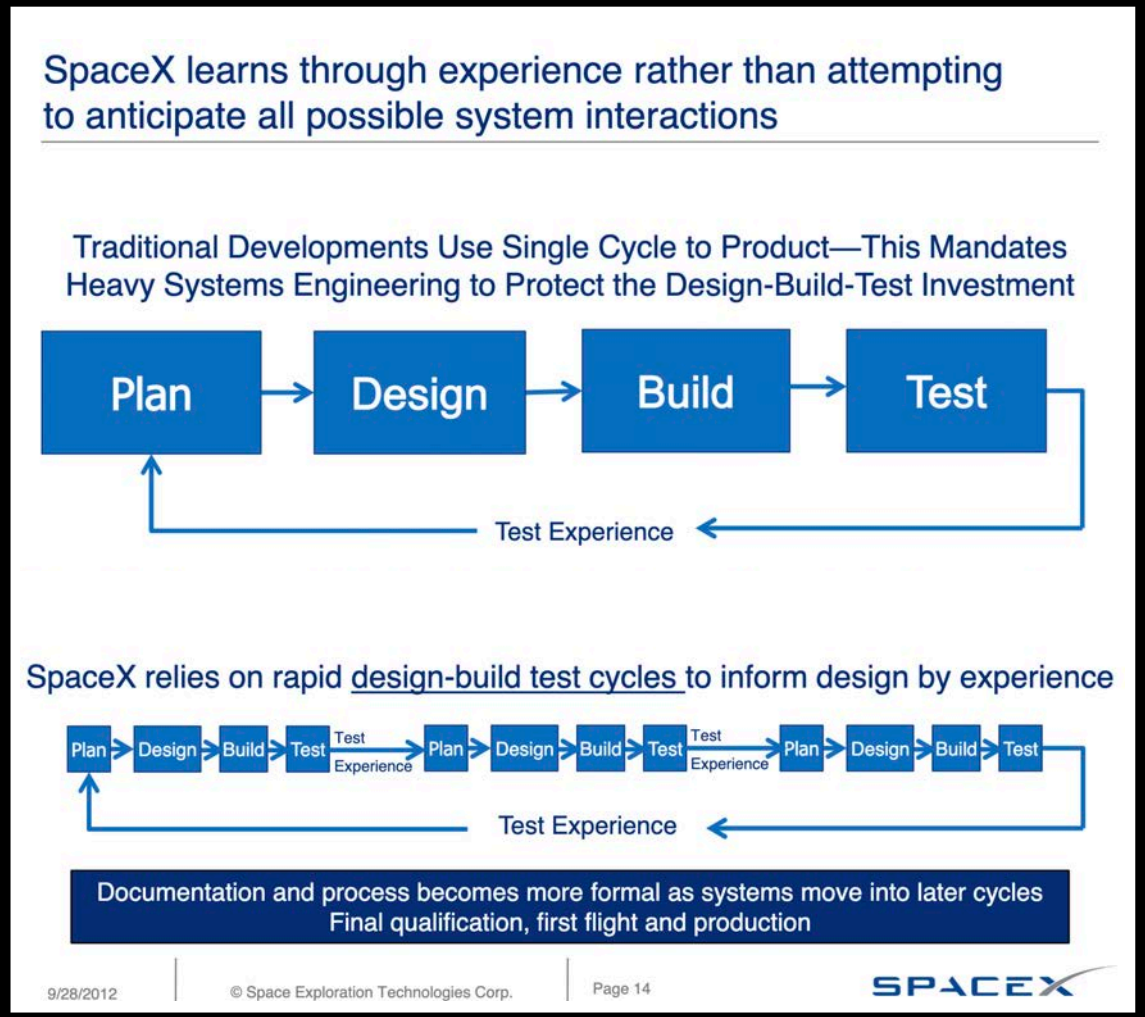
https://www.thedrive.com/news/22887/the-spacex-dragon-capsule-has-controls-like-a-tesla

Dragon Interface

- Principles used in designing the *Meridian,* a data analytics tool used to operate land-rover *Opportunity.*
- **Data must come with context**: Systems should allow users to see both an **overview** of information displayed, and more **in-depth detail** should they want it, while identifying and relating to the source of the data and other data points. [20]
  - *Dragon* crew must have context of data sources and relation to other data; else the data display is limited.

- **Surface issues early, with diagnostic tools if necessary:**
- Display should flag certain tasks and anomalies, **raising warnings in certain situations.**
  - *Meridian* tool to determine if surrounding objects are too close to rover, and a warning is displayed.
  - *Dragon* displays depict warnings when necessary, also allowing manual control use in emergency situations.

https://www.reddit.com/r/SpaceXLounge/comments/grs50n/dragon_user_interface/



SpaceX Design Process

- How SpaceX achieves their design goals through their constant feedback and experience loop.
- Crew Dragon attended a week-long Hackathon in which:
  - Crew members provided **feedback** of simulations throughout each day for manual piloting controls.
  - Engineers used feedback to **modify** and roll out **new builds** by the next morning. [19]
  - **Quick iterations** allow for a more **streamlined process**, providing for **positive crew display experiences**, and to focus on the important aspects of the display.

"System Engineering: A Traditional Discipline in a Non-Traditional Organization." *SpaceX*, 28 Sept. 2012, docplayer.net/12635684-System-engineering-a-traditional-discipline-in-a-non-traditional-organization.html.

Suits

Another example of how the design process directly affects the **user experience** of the crew.

Suits are **part of the vehicle** itself. [21]

- Optimization on **functionality,** not meant for much movement– main role to transport astronauts in flight.
- Connects to seat via an umbilical cord, allowing for gas exchange, air, and avionics.
- The suit gloves are retrofitted to comply with Dragon UI Displays. [22]
- Cooling system, foam-lined interior, hearing system all included inside.

Key part of iterating the suit was how to provide **comfort** while transporting the crew in **the safest way possible.**

Feedback and rapid iterations are an integral part of the SpaceX design process in order create **insightful user experiences.**

https://www.newscientist.com/article/2144989-elon-musk-shows-off-first-photo-of-spacex-space-suit/

What Sets SpaceX Apart From Their Competition?

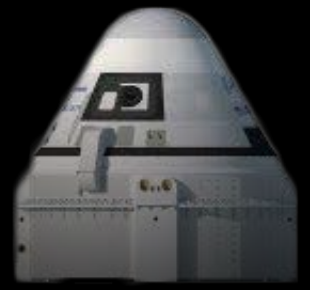
- Rockets: Powerful, **reusable** and cost-aware with an incredible safety system.
- Spacecrafts: **Autonomous**, safer, and focused on the user experience.
- Suits: **Comfortable**, outstanding and high-tech.
- Control center: A modern, **well-organized** mission control room
- The technology behind these designs puts SpaceX in a **leading position.**

Rockets

	SPACE SHUTTLE	SOYUZ	FALCON 9	ATLAS V
Company	NASA	РОСКОСМОС	SPACEX	ULA
Reliability (Succeed/launched)	98.5% (133/135)	96.9% (996/1028)	97.1% (67/69)	100%(79/79)
Reusable	No	No	Fully reusable	Yes after 6 months turnaround
Cost per seat	$43M if full of cargo $204M without cargo	$82 M	$58 M	$58 M
Fuel	Solid	Liquid	Liquid	Liquid

https://everydayastronaut.com/what-is-block-5-of-falcon-9-why-throw-non-block-5s-away/
[23,24]

Spacecraft



	SPACE SHUTTLE	SOYUZ	CREW DRAGON	STARLINER
Company	NASA	РОСКОСМОС	SPACEX	BOEING
Reusable	No	Yes	Yes	Yes
Abort	None	Tractor	Pusher	Pusher
Emergency thrusters	None	-	Integrated into the crew module allowing a guided abortion	They are at the service module
Landing	Land touchdown	Land touchdown	Ocean touchdown	Land touchdown

https://everydayastronaut.com/crew-dragon-vs-starliner/
[25,26]

Spacecraft interior

	SPACE SHUTTLE	SOYUZ	CREW DRAGON	STARLINER
Company	NASA	РОСКОСМОС	SPACEX	BOEING
Control	Buttons	Buttons	Touchscreens and Buttons	Buttons
Crew Capacity	5-7 astronauts	3 astronauts	7 astronauts	7 astronauts
Status	Retired	Active	Active	Active (uncrewed)
Movable Chairs	No	No	Yes	-

https://www.pinterest.com/pin/807199933183281018/
https://www.pinterest.com/pin/200832464611016311/
https://www.nationalgeographic.com/news/2012/4/120416-nasa-space-shuttle-discovery-smithsonian-360-tour-panorama-science/
[27]

Current suits

Space Shuttle Flight Suit
(1994-2011)

Sokol Launch and Entry Suit
(1973- Present)

Crew Dragon Flight Suit
(2020)

Starliner Flight Suit
(2021)

Key example of **form follows function** – differences in suit functionality, thus form is different.

NASA

Space Shuttle Flight Suit (1994-2011)

- 30Lb of weight & bulky design.
- Wear for only during liftoffs and landing.
- Able to perform spacewalk.
- Orange color design; Astronaut could be easily spotted in case they need to bail out.
- Enter from the back and zipped up.

JSC NPP Zvezda

Sokol Launch and Entry Suit (1973- Present)

- 22lb, originally designed for Russia's Soyuz spacecraft.
- Sharp, blue-lined design, similar to the space shuttle suit.
- Considered less of a spacesuit and more of a rescue suit.
- Supports an astronaut for up to two hours in case a spacecraft suddenly loses its pressurized atmosphere.

https://noosphereventures.com/space-fashion-how-new-spacesuits-keep-astronauts-safe-and-sound/ [28]

SPACEX

Crew dragon flight suit (2020)

- Lightweight, one-piece suit features a single connection pint between the suit and the vehicle.
- Not sustainable for space walk.
- 3D printed with solar radiation protect helmet.
- Flexible and specifically designed to be compatible with the touch screen device.
- Liquid cooling system + emergency breathing system.

BOEING

Starliner Flight Suit (2021)

- 12Lb of weight, made with lighter “breathable” materials.
- Flexible and touchscreen-sensitive gloves.
- Equipped with communication system in the suit.
- Helmet provides a wide-viewing angle.
- This suit is entered from the back and zipped up to wear.

https://www.businessinsider.com/spacesuit-design-history-timeline-changes-nasa-2018-3#boeing-cst-100-starliner-flight-suit-expected-in-2019-10 [29]

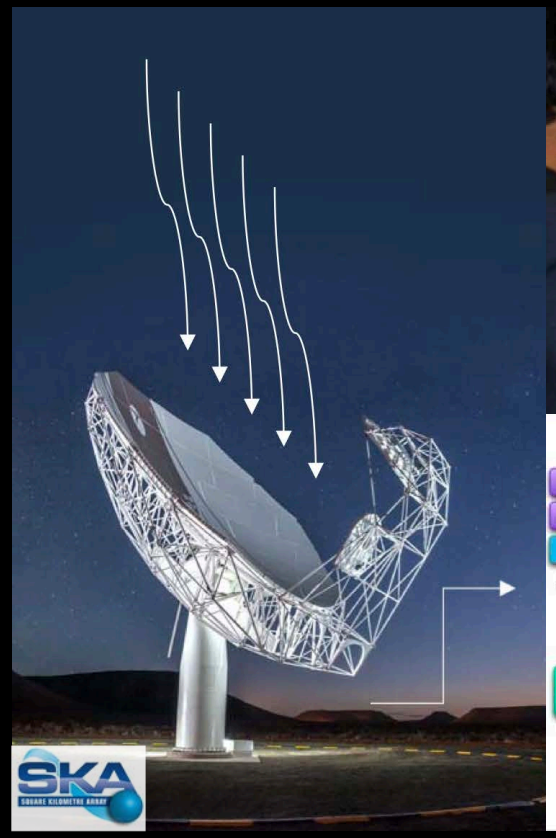
Control Centers

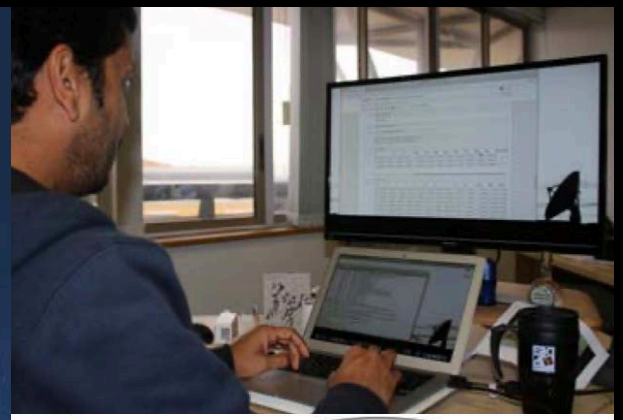
Company	NASA BOEING	ROSCOSMOS	SPACEX
Location	Houston, Texas	Moscow, Russia	Hawthorne, California
Workspace design	Windowless room & building, Dated look	Dated technology equipment, Resembles theater arrangement	Open and modern office-like atmosphere
Dress code	Business-casual dress code	Business casual	Free

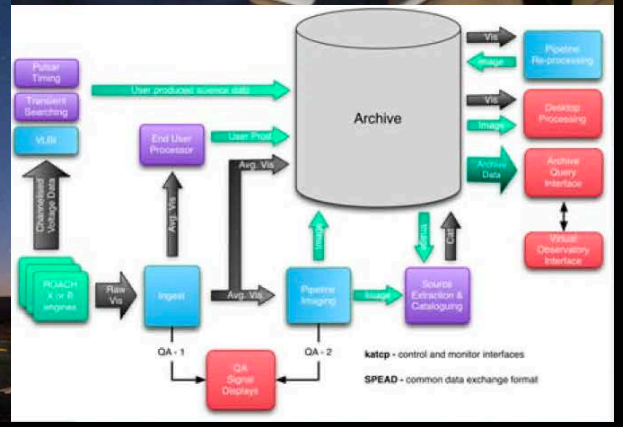
https://www.regus.com/work-us/inside-nasas-mission-control-the-worlds-coolest-workspace/ [31]
https://blogs.nasa.gov/spacex/2014/09/21/mission-and-launch-control-centers-across-the-country/ [32]

Technological innovations

- **Big Data. Hundreds of GB per mission**. After that, the data is reviewed to understand if the system behaves as intended. [18]
  - **Don’t remove data, even if it may not be used.** [20]
- **Triple redundancy** in almost every system. Losing a computer, a sensor, a thruster, actuators, etc. Is not a big deal for them because all those losses are compensated automatically by the **algorithm.**
- The Dragon state machine allows to switch **autonomously** from approach to breakout if certain failures are observed.







Big Data

By using Big Data tools, space agencies and companies are or will be able to make better and faster decisions and to unlock the mysteries of the universe.

- NASA is using Elasticsearch to analyze the data from the Curiosity sensors to predict if there is life in Mars or not.
- The Square Kilometer Array (SKA) project: an international effort to monitor the sky using a million of antennas. This array will generate 700 TB of data per second. [33]
- **Keep data even if it is not used:** It is very important to have context for the mission or to ease the decision making– this can be done by collecting tons of data, even if it is not used. It can help monitor system behavior and can identify anomalies. [20]

https://www.ft.com/content/f62ee814-f510-11e5-803c-d27c7117d132
https://www.sarao.ac.za/wp-content/uploads/2017/06/presentation_parliament_2017.pdf

Operational Environment	Commercial	Space	Avionics
Mission duration	Years	Years	Hours
Maintenance Intervention	Manual	Remote	After mission
Outage response time	Hours	Days (Cruise Phase)	Milliseconds
Resources -Power -Spare parts	-Unlimited -Unlimited	-Minimal -None	-Medium - After mission

Redundancy

Redundancy is very important on Spacecraft missions due to the duration and the harness the spacecrafts suffer along the mission.

- Left: A comparison table of the differences among commercial, space and avionics domains in terms of resources, duration, response time and so on that justifies the importance of redundancy in space missions. This is from the University of Carnegie Mellon. [34]
- In this table you can see how the number of possible faults within a space mission is higher and the possible impact too. That's why the redundancy is critical in these missions.
- NASA requirement for SpaceX mission was double redundancy. SpaceX has implemented triple redundancy in all their systems. [18]

https://www.cs.unc.edu/~anderson/teach/comp790/papers/Siewiorek_Fault_Tol.pdf

Autonomy

Working under hazardous conditions, on unknown environments and in long-term missions drives the necessity of increase the autonomy of the robots or spacecrafts to solve issues by themselves.

- Left: Picture of Autonomous Spaceport Drone Ship from SpaceX.
- The Dragon from SpaceX is a fully autonomous vehicle. It can change automatically from approach to break out if certain measures are taken. [18]
- Made in Space is developing in collaboration with NASA the Archinaut One, a robot which will be able to build its own extended solar panels and other tech like antennas, radiators and deflectors in orbit. [35]
- The Kuiper Belt exploration mission must operate in unknown environments and the robot equipment should survive against failures during decades. [36]

https://medium.com/@JerBarcellona/spacex-the-innovation-of-affordable-spaceflight-c083004d2719

Recap (1/2)
Top Design Principles

Rapid Prototype
- Fail Early, Fail Forward

SpaceX design process includes iterating quickly and using feedback from design to inform future iterations.

Failure of some iterations can benefit a company greatly, and SpaceX capitalizes on the failures to propel them forward.

Business Optimization
- Spend Smarter

SpaceX, in contrast with NASA and other public organizations in the space industry, has always made low cost and "affordable" space travel a priority in their work.

This resulted in reaching Elon Musk's goal of traveling to space for under $500/pound in 2020.

Human-Centered Design and Automation

SpaceX utilizes HCD to roll out advanced technological solutions to combat the various space-related scenarios that occur.

The company gathers data from the crew and uses human factors to create the most-advanced-yet-acceptable (MAYA) technology that caters to the astronauts needs.

Recap (2/2)
Top Design Principles

Data must come with context

All data should be traceable to the source and should contain some relation to other data values around it. If the data in the Dragon display causes confusion, the display is limited in what it can offer to the user.

Users should be able to gather context about the sources of some data to better equip themselves to make a decision for certain tasks.

Use Big Data, and keep the data

SpaceX uses hundreds of GB of data per mission in order to better inform themselves of the software's behavior. Even if data is not used, having the context to see many types of behavior can be to SpaceX's benefit– allowing a look into numerous possibilities-- and can help make decisions to solve problems should they arise.

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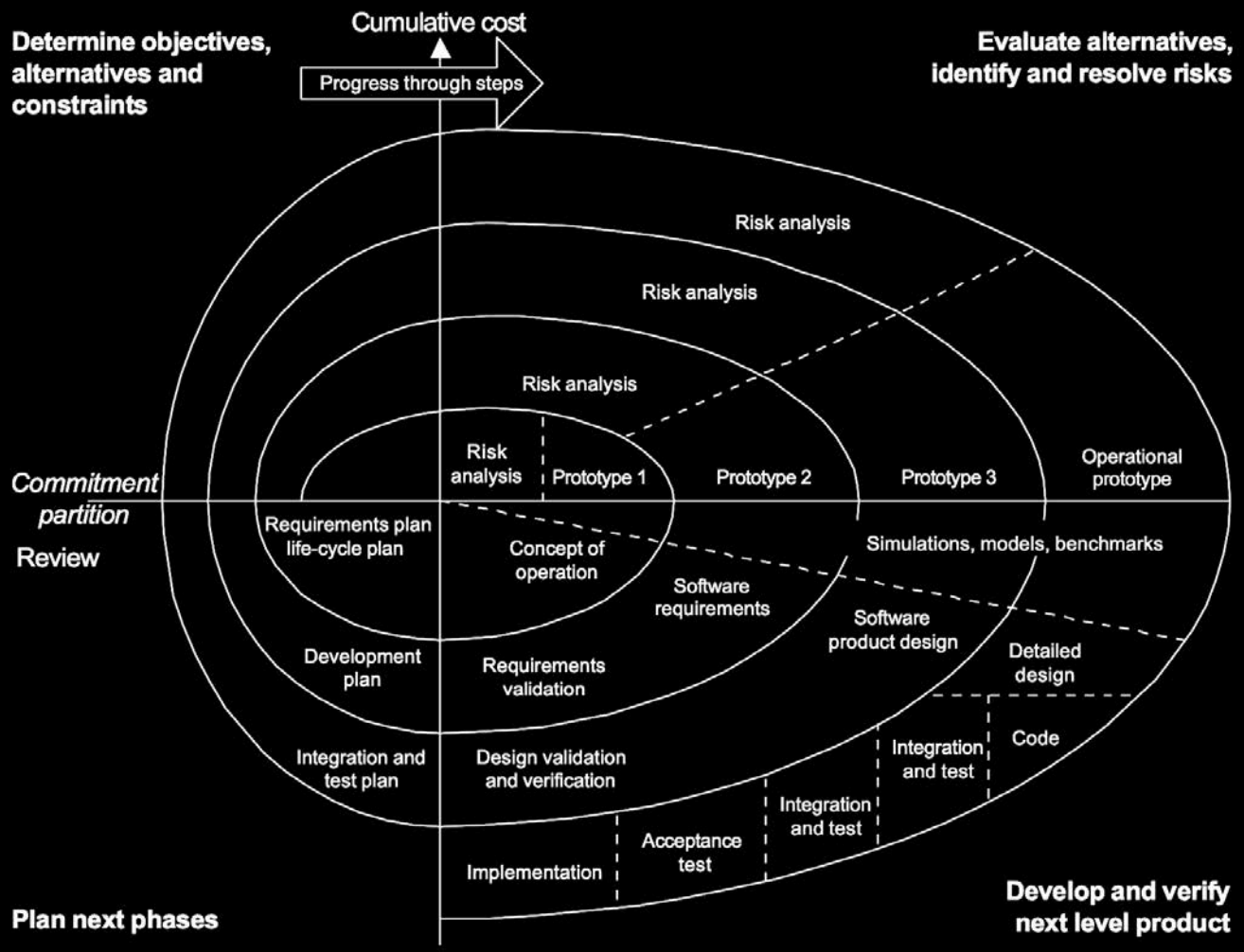
Questions?

Appendix

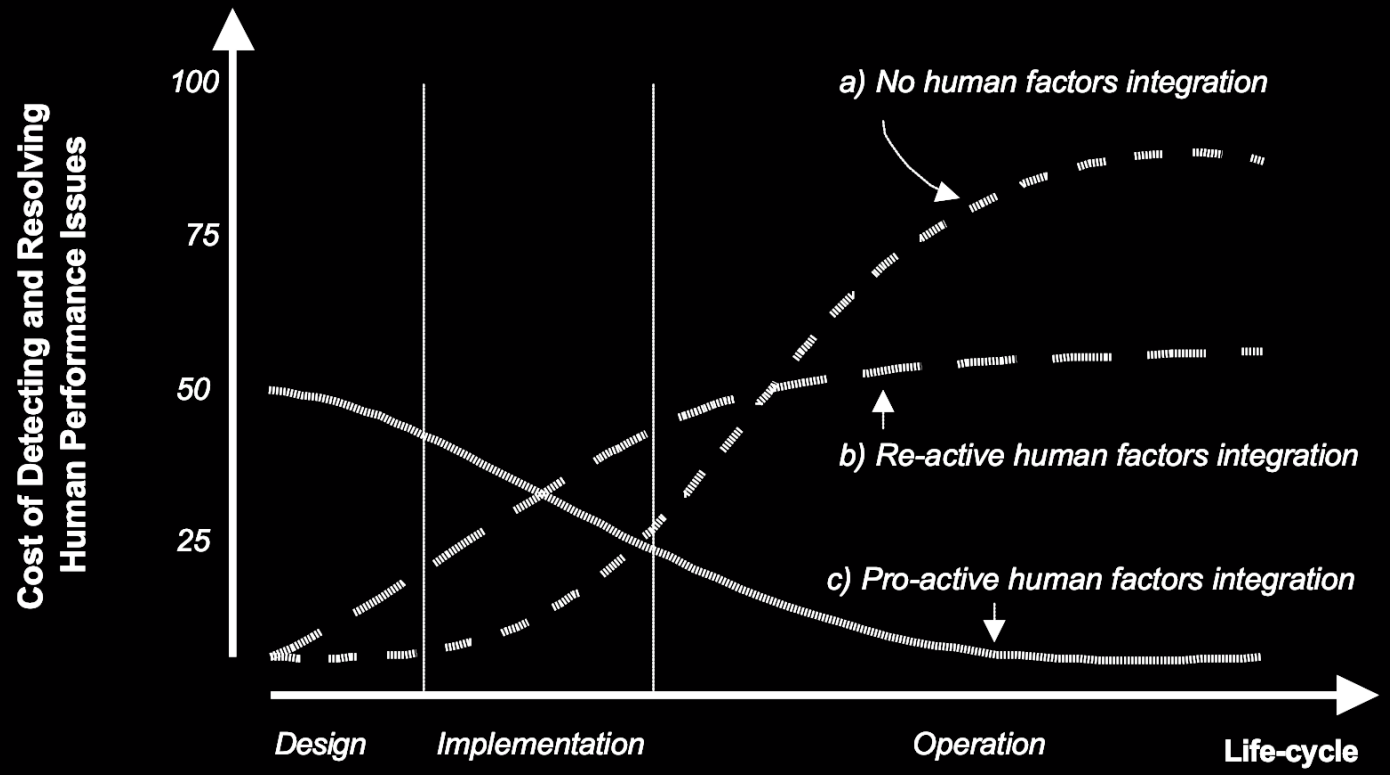


The iterative spiral model of system development (Boehm, 1988)

Iterative system development process

"The spiral model suggests that system development should be carried out in an iterative succession of phases gradually expanding the scope. The model suggests the early use of prototypes and risk modelling. "

http://www.idemployee.id.tue.nl/g.w.m.rauterberg/lecturenotes/HF99cost-report.pdf .



Cost scenarios of three different life-cycle strategies

Integrating human factors in the earlier stage can lower the cost for later implementation and operation.

"It is a matter of either paying up front for detecting and resolving the problems - or paying more later, which by all accounts, will be significantly more costly."

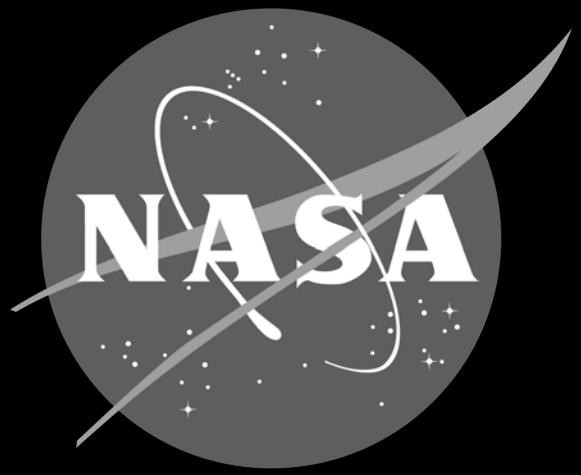
http://www.idemployee.id.tue.nl/g.w.m.rauterberg/lecturenotes/HF99cost-report.pdf .

"Pay now or pay more later" -- How involving human factors can help save money

" Involving human factors early in the process saves money by reducing redesign costs. Changes to a system costs less when made early in the development process. ***If human factors issues are not addressed users may refuse to use a system.***

A general rule of thumb is that ***for every $1 spent*** *on human factors early in the development cycle,* ***$100 is saved*** *on fixing the problem once the system is released (Gilb, 1988). Proper human factors engineering can* ***prevent many problems that cause cost overruns on software engineering projects****, substantially reducing cost overruns (Nielsen, 1993). "*

https://hf.tc.faa.gov/value-of-hf/ .
https://en.wikipedia.org/wiki/Federal_Aviation_Administration



NASA's Learning in Applying Design thinking to advance testing of autonomous aeronautics systems

- *"**For more complex problems**, the customer or user will not be able to provide all requirements and all information."*
- *"**Non-technical aspects** of the problem space may be significant and need to be addressed in the design."*
- *"Some of the best **data** may not be captured in numbers."*
- *"Learn how to use qualitative research methods and **continuously learn** about the users, the stakeholders, and the beneficiaries of the system and their context."*
- *"Simple, draft sacrificial prototypes can yield considerable insight for the users and stakeholders and will help the design team communicate."*
- *"Challenge your assumptions about the design concept by welcoming **early feedback."***
- *"Embrace **diversity of thought** instead of necessitating uniformity."*
- ***"Step-wise and predictable linear processes are not always better."***

https://hf.tc.faa.gov/value-of-hf/ .
https://en.wikipedia.org/wiki/Federal_Aviation_Administration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