Falcon Rockets and Engines

Falcon 1, Falcon 9 and Falcon Heavy

Jim Rauf

SPACEX

1 Introduction: topics , some basics and rocket pioneers

2 SpaceX founding , Musk's vision, facilities, organization, personnel

3 SpaceX and NASA commercial funding

4 **Falcon rockets and engines , Falcon 1, Falcon 9 and Falcon Heavy**

5 Dragon spacecraft , Cargo Dragon and Crew Dragon

6 Super Heavy booster and engines and Starship spacecraft

7 Starship competition for Artemis Moon Human Landing System

8 Musk's Mars vision , plans , challenges and SpaceX summary

Falcon 1

- **Falcon 1** was SpaceX's first launch vehicle
- It stood 68 feet tall and 5.5 feet in diameter
- It was propelled into **low Earth orbit (LEO)** by a single **Merlin IC** engine
- Payload capacity up to ~1,010 pounds
- **Falcon 1** was designed to minimize price per launch for low-Earth-orbit satellites, increase reliability, and optimize flight environment and time to launch
- It also was used to verify components and structural design concepts that would be used in the **Falcon 9**
- **SpaceX** idea was to begin with the smallest useful orbital rocket , the **Falcon 1**
- It required less money, etc versus a larger more complex rocket system
- It was financed by SpaceX
- "Crawl before you run"

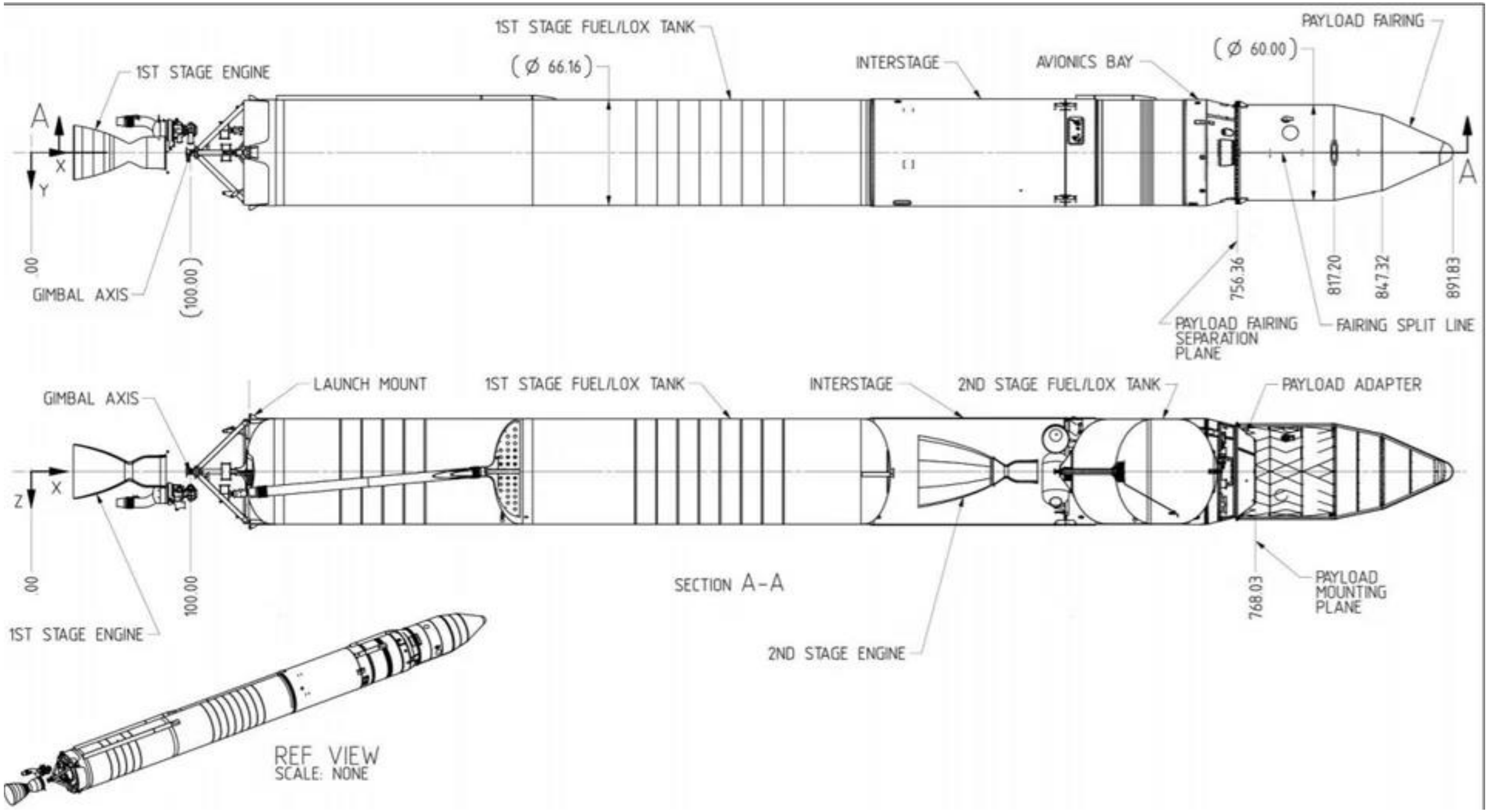
Falcon 1

- The first stage was made from friction-stir-welded 2219 aluminum alloy (aluminum –copper family)
- Used a common bulkhead between the LOX and RP-1 tanks, as well as flight pressure stabilization
- Transported safely without pressurization but gains additional strength when pressurized for flight
- The parachute system, built by **Irvin Parachute Corp-oration**, uses a high-speed drogue chute and a main chute
- The first two launches, the **Falcon 1** used a **Merlin 1A** engine
- An improved to create the **Merlin 1C** was first flown on the third **Falcon 1** flight, and on the first 5 flights of the **Falcon 9**
- The **Falcon 1** first stage was powered by a single pump-fed **Merlin 1C** engine burning **RP-1** and **liquid oxygen** providing 92,000 lbf of sea-level thrust and a specific impulse of 245 s (vacuum I_{sp} 290)
- The first stage burns for around 169 seconds

Falcon 1

- The second stage tanks were built with a cryogenic-compatible 2014 aluminum alloy
  - With the plan to move to aluminum-lithium alloy on the Falcon 1e
- The helium pressurization system pumps propellant to the engine, supplies heated pressurized gas for the attitude control thrusters, and is used for zero-*g* propellant accumulation prior to engine restart
- The **Kestrel** engine includes a titanium heat exchanger to pass waste heat to the helium, thereby greatly extending its work capacity
- The pressure tanks are composite overwrapped pressure vessels made by Arde corporation with Inconel alloy and are the same as those used in the Delta III.[22]
- The second stage was powered by a pressure-fed Kestrel engine with 7,000 lbf of vacuum thrust and a vacuum specific impulse of 330 sec

Falcon 1


1ST STAGE FUEL/LOX TANK
(Ø 66.16)
1ST STAGE ENGINE
INTERSTAGE
AVIONICS BAY
PAYLOAD FAIRING
(Ø 60.00)
A
X
Y
.00
GIMBAL AXIS
(100.00)
756.36
817.20
847.32
891.83
PAYLOAD FAIRING SEPARATION PLANE
FAIRING SPLIT LINE
GIMBAL AXIS
LAUNCH MOUNT
1ST STAGE FUEL/LOX TANK
INTERSTAGE
2ND STAGE FUEL/LOX TANK
PAYLOAD ADAPTER
Z
X
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100.00
SECTION A-A
768.03
PAYLOAD MOUNTING PLANE
1ST STAGE ENGINE
2ND STAGE ENGINE
REF VIEW
SCALE: NONE

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Falcon 1 Launch Attempts

Flight No	Date / time (UTC)	Launch site	Payload	Payload mass	Orbit	Customers	Launch outcome
1	24 March 2006, 22:30	Omelek Island	FalconSAT-2	19.5 kg	LEO (Planned)	DARPA	Failure
	Engine failure at T+33 seconds. Loss of vehicle FalconSAT-2 landed in a storage shed near the launch site						
2	21 March 2007, 01:10	Omelek Island	DemoSat		LEO (Planned)	DARPA	Failure
	Successful first-stage burn and transition to second stage, maximal altitude 289 km. Harmonic oscillation at T+5 minutes. Premature engine shutdown at T+7 min 30 s. Failed to reach orbit						
3	3 August 2008, 03:34	Omelek Island	Trailblazer PRESat Nanosail-D Explorers	4 kg	LEO (Planned)	ORS NASA NASA Celestis[42]	Failure
	Residual stage-1 thrust led to collision between stage 1 and stage 2						
4	**28 September 2008, 23:15**	**Omelek Island**	**RatSat**	**165 kg**	**LEO**	**SpaceX**	**Success**
	Initially scheduled for 23–25 Sep, carried dummy payload – mass simulator, 165 kg (originally intended to be RazakSAT.						
5	**14 July 2009, 03:35**	**Omelek Island**	**RazakSAT**	**180 kg**	**LEO**	**ATSB**	**Success**

Falcon 1 July 14,2009 Launch Success

Liquid Propellants

- Liquid oxygen LOX
  - Oxidizer
  - -297F
- Liquid hydrogen LH2
  - Fuel
  - -423 F
- Methane CH4
  - Fuel
  - -258 F
- RP-1 Kerosene $C_nH_{2n+1}OH$
  - Fuel
  - Room temperature
- Alcohol $CH_3{-}CH_2{-}CH_2{-}OH$
  - Fuel
  - Room temperature

- Liquid propellant rockets are more “efficient” than solid propellant rockets
- They have higher specific impulse values

$$I_{\mathrm{sp}} = \frac{v_{\mathrm{e}}}{g_0},$$

$$v_{\mathrm{e}} = g_0 \cdot I_{\mathrm{sp}},$$

$$F_{\mathrm{thrust}} = v_{\mathrm{e}} \cdot \dot{m},$$

	V e m/s	Isp
Space Shuttle Solid Rocket Booster	2,500	250
Liquid oxygen-liquid hydrogen	4,400	450
Liquid oxygen- liquid methane	3,333	363

SPACEX First Engine Kestrel

- **Kestrel** was an LOX/RP-1 pressure-fed rocket engine
- It was developed in the 2000s for upper stage use on the **Falcon 1** rocket
- It used the same **pintle** architecture as the **Merlin** engine but does not have a **turbopump** and is fed only by tank pressure
- It was **ablatively cooled** in the chamber and throat and **radiatively cooled** in the nozzle, which was fabricated from a high strength **niobium alloy**
- Thrust vector control is provided by electro-mechanical actuators on the engine dome for pitch and yaw
- Roll control (and attitude control during coast phases) is provided by helium cold **gas thruster**s
- A **TEA-TEB** pyrophoric ignition system is used to provide multiple restart capability on the upper stage

Kestrel Engine

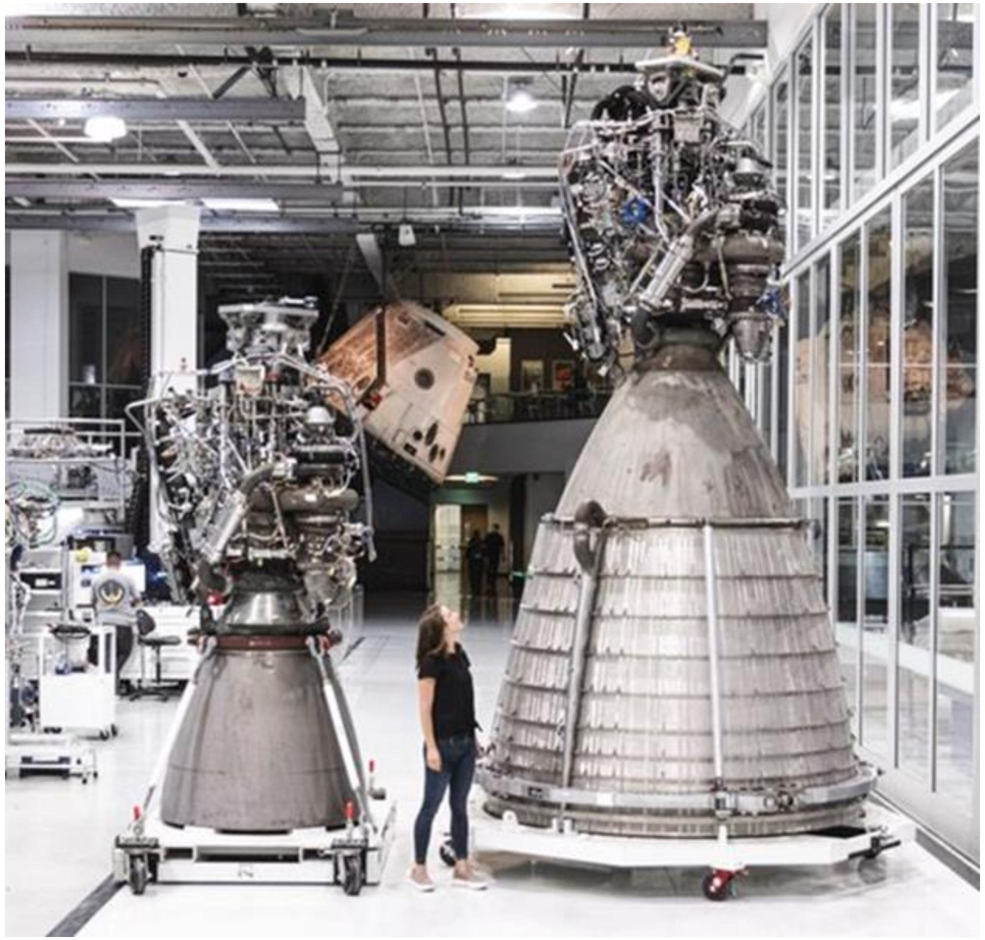
- First flight 2006
- Last flight 2009
- Designer **Tom Mueller**
- Liquid-fuel engine
- Propellant LOX / RP-1
- Cycle Pressure fed
- Thrust, vacuum 6,300 lb
- Thrust-to-weight ratio 65:1
- Chamber pressure 135 psi
- Specific impulse 317 seconds
- Dry weight 115 lb

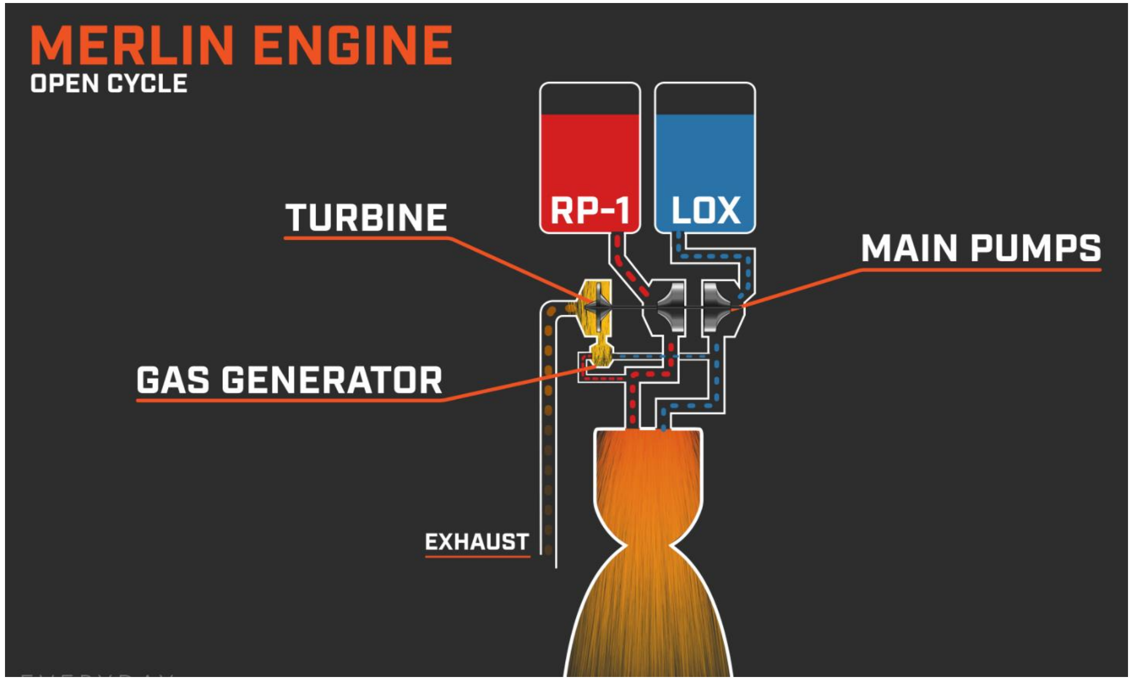
Merlin engines

- Merlin rocket engines powering falcon rockets were developed for recovery and reuse
- The engines are **gimbaled** and have **throttle** and **restart capability** https://www.grc.nasa.gov/WWW/k-12/rocket/Images/pitch.gif
- They utilize **cooled rocket-grade kerosene (RP-1**) and chilled **liquid oxygen** in a gas-generator power cycle
- A **Turbopump** feeds the propellant, heated helium pressurizes the fuel tank
- Dual redundant **TEA-TEB** pyrophoric igniters provide restart reliability.
- The **Merlin 1D** (**M1D**) for sea-level has 854 kilonewtons thrust
- The **Merlin 1D Vac** (**MVac**) for vacuum has 981 kilonewtons thrust
- **Merlins** have thrust-to-weight ratio of approximately 200:1
- The **Merlin 1D has** increased fatigue life, improved nozzle and combustion chamber thermal margins counts
- It is also easier to manufacture by decreasing the parts count and labor hours
- Each **Merlin** engine is assigned one processing unit employing three computers - a triple redundant design
- The engines use an open-cycle or **gas-generator power cycle**
- A **gas-generator cycle** burns some of the propellant to generate exhaust driving a turbine that power the **RP-1** and **LOX** pumps, then expelled to the atmosphere or vacuum
- Propellants are supplied by a **single-shaft**, **dual-impeller turbopump** spinning at 36,000 RPM, and produces 10,000 horsepower
- The turbopump supplies the **hydraulic actuators** with high-pressure fluid eliminating the need for a separate hydraulic drive system
- **M1D** engines have a smaller exhaust section and 16:1 expansion nozzle primarily for ascent from Earth
- **MVac** engine has a larger expansion nozzle of 165:1 to maximize efficiency in the vacuum
- The expansion nozzle is by **radiative cooling**

Merlin engines

- Nine **Merlin 1D** engines were fitted to the **Falcon 9** first stage and one to it second stage
- They engines are produced at a rate of eight per month with plans to increase the production to 400 per year





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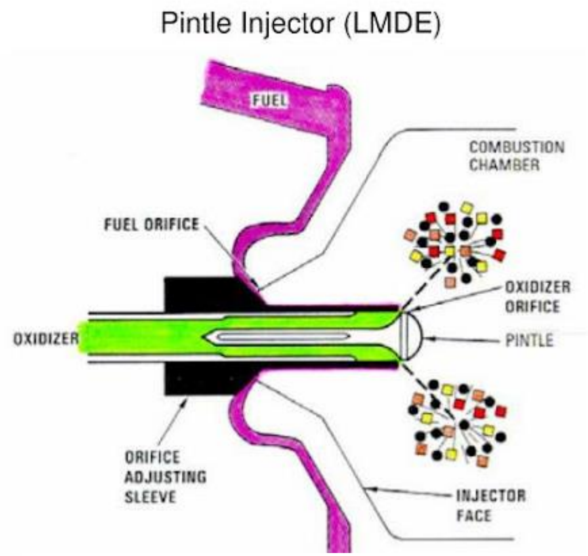
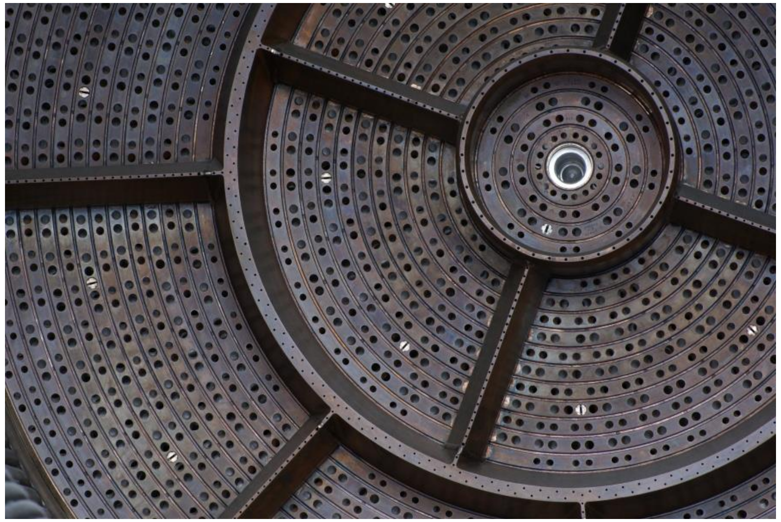
Merlin Engine

Pintle Propellant Injection



Pintle Injector Cold flow Testing for SpaceX's Raptor engine.

Advantages	Disadvantages	Rockets using these injectors
Throttle able	Wall compatibility problems	LEM decent engine, SpaceX Merlin engine,BE-3 engine, Grasshopper engine,Kesterl Engine of Falcon 9 second stage.
Proven dependability	No correlations for level of mixing and spray size.	
Simple structure and easy to manufacture		
Large thrust per element		
Good Combustion stability		
Wider spray angles enables single injection element instead of multiple elements and subsequent weight reduction.		



F-1 Engine Propellant Injector

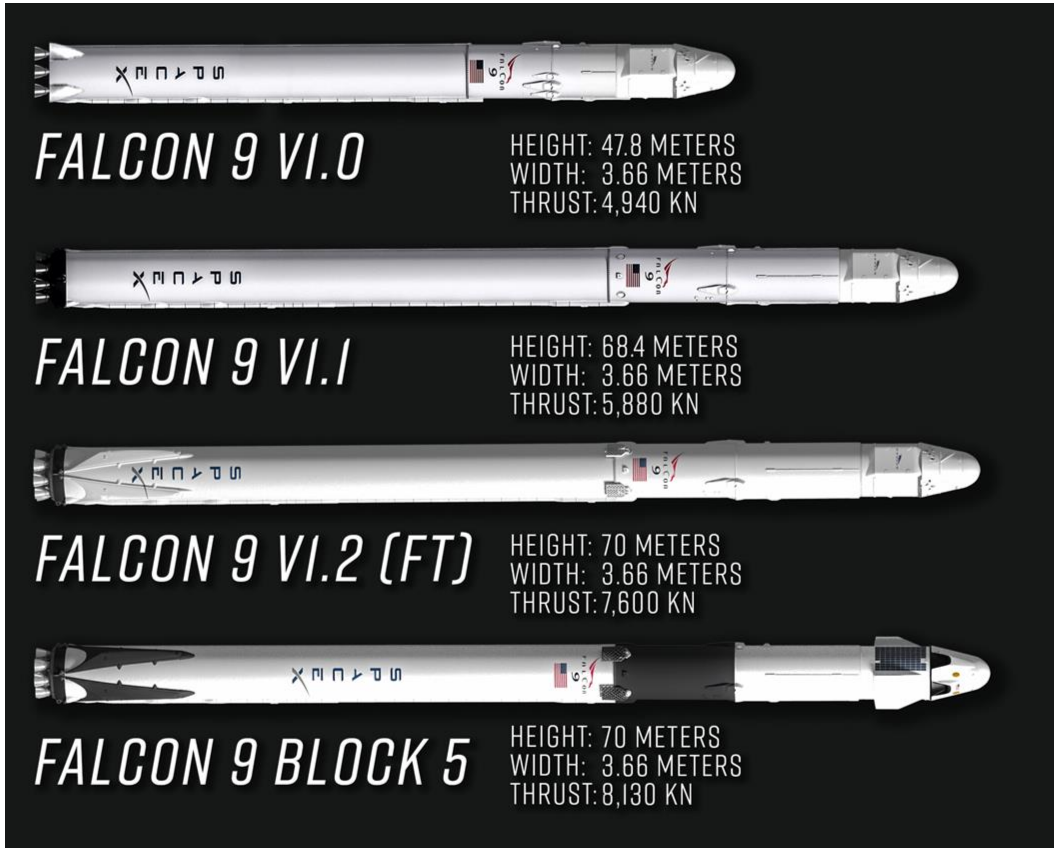
Falcon 9

- **Falcon 9** is a **two-stage** launch vehicle powered by **liquid oxygen (LOX**) and **rocket-grade kerosene (RP-1**)
- Its payload can be either a **satellite** enclosed in a **fairing** or a **SpaceX Dragon** spacecraft
- **Falcon 9** has been updated several times
- Its current version is the **Full Thrust Block 5** configuration which first flew in spring 2018
- **Falcon 9 Block 5** architecture focused on improving performance, reliability, and life of the vehicle, as well as ensuring the vehicle's ability to meet critical government crewed and non-crewed mission requirements
- Engine performance, additional thrust, on both stages was increased
- Thermal protection shielding was modified to support rapid recovery and refurbishment
- Avionics designs, thrust structures, and other components were upgraded for commonality, reliability, and performance

Falcon 9 Block 5

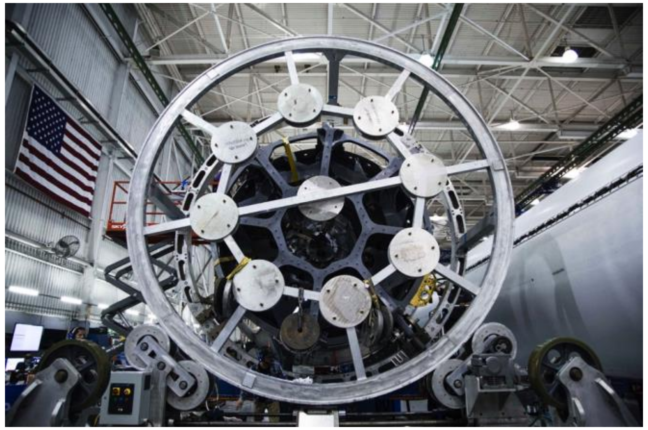
Falcon 9

- First stage thrust is 1.71 million pounds at liftoff
    - Nine **Merlin** sea level engines
- Second stage thrust is 210,000 pounds
    - One **Merlin** vacuum engine
- The **Falcon 9** is designed to fly up to ten times without refurbishing and up to 100 times with periodic refurbishing
- The **Falcon 9** payload capability is:
    - 50,265-pounds to **Low-Earth Orbit (LEO)**
    - 18,300-pounds to **Geosynchronous Transfer Orbit (GTO)**
    - 8,860-pounds on a **Mars** trajectory



Falcon 9 Engine Mounts Octaweb

- The metal **Octaweb** structure that houses the **Merlin** engines is vital to the **Falcon 9's** first stage
- Earlier versions of the rocket had nine engines arranged in three rows of three
- With the **Octaweb**, eight engines are clustered in a circle around a central one
- The **Octaweb** reduces the length and weight of the **Falcon 9** thrust structure, simplifying the rocket's design and assembly
- Streamlining the manufacturing process ultimately keeps launch costs down



Falcon 9 Specs

First stage

Height	41.2 m / 135.2 ft
Height (with interstage)	47.7 m / 156.5 ft
Diameter	3.7 m / 12 ft
Empty Mass	25,600 kg / 56,423 lb
Propellant Mass	395,700 kg/ 872,369 lb
Structure Type	LOX tank: monocoque
	Fuel tank: skin and stringer
Structure Material	Aluminum lithium skin; aluminum domes
Landing Legs	Number: 4
	Material: carbon fiber; aluminum honeycomb
Number Of Merlin Engines	9 sea level
Propellant	LOX / RP-1
Thrust At Sea Level	7,607 kN / 1,710,000 lbf
Thrust In Vacuum	8,227 kN / 1,849,500 lbf
Specific Impulse (sea-level)	283 sec.
Specific Impulse (vacuum Sec)	312 sec.
Burn Time	162 sec.
Ascent Attitude Control - Pitch, Yaw	Gimbaled engines
Ascent Attitude Control - Roll	Gimbaled engines
Coast/Descent Attitude Control	Nitrogen gas thrusters and grid fins

Second stage

Height	13.8 m / 45.3 ft
Diameter	3.7 m / 12.1 ft
Empty Mass	3,900 kg / 8,598 lb
Propellant Mass	92,670 kg / 204,302 lb
Structure Type	LOX tank: monocoque
	Fuel tank: skin and stringer
Structure Material	Aluminum lithium skin; aluminum domes
Number Of Merlin Engines	1 vacuum
Propellant	LOX / RP-1
Thrust	981 kN / 220,500 lbf
Specific Impulse (vacuum)	348 sec
Burn Time	397 sec
Ascent Attitude Control - Pitch, Yaw	Gimbaled engine and nitrogen gas thrusters
Ascent Attitude Control - Roll	Nitrogen gas thrusters
Coast/Descent Attitude Control	Nitrogen gas thrusters

Sample mission profiles for Falcon 9 and Falcon Heavy are shown in Figure 8-10 and Figure 8-11, and sample Falcon 9 timelines for a GTO mission and LEO mission are shown in Table 8-3 and Table 8-4. Note: each flight profile is unique and will differ from these examples.

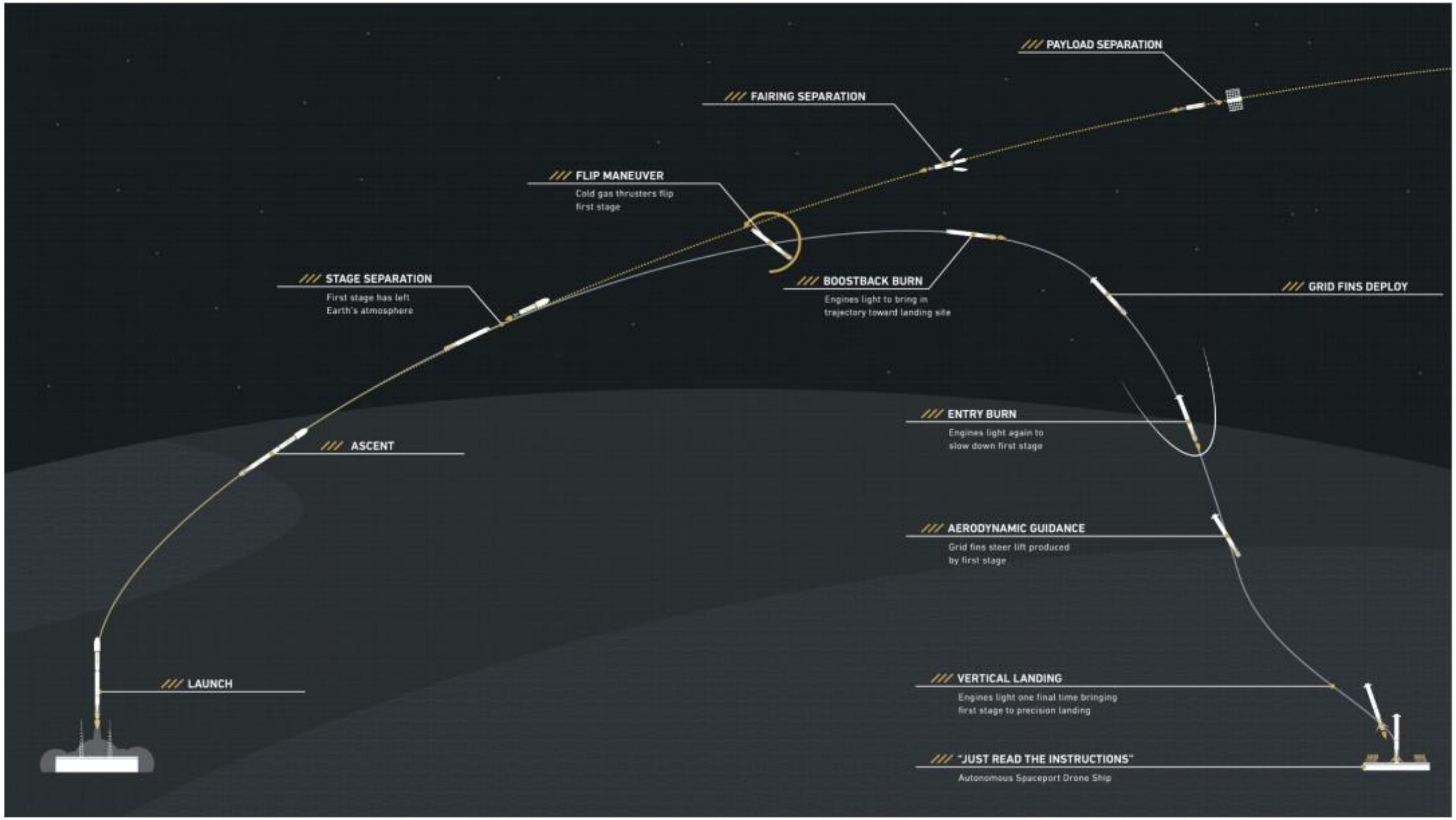
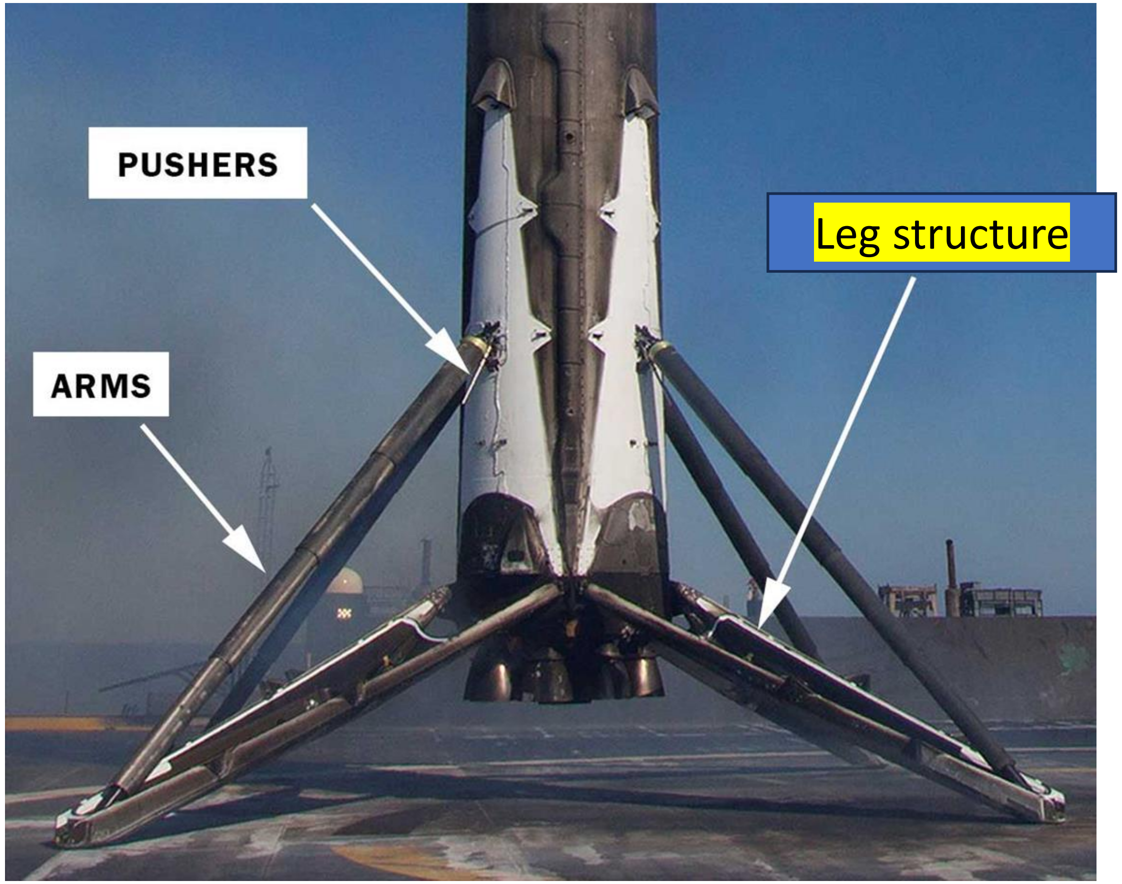


Figure 8-10: Falcon 9 sample mission profile

SPACEX Falcon 9 Landing Legs



SPACEX Falcon 9 Grid Fins Second Stage and Landing

https://www.youtube.com/watch?v=Aq7rDQx9jns

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Falcon 9 Horizontal Integration Facility

- **SpaceX** doesn't build the **Falcon 9** in Florida, it's just assembled there
- Most of the rocket's parts are built in the company's factory in Hawthorne, California
- The **Falcon 9** components, including fuselages and engines, are shipped by truck to various test stands before eventually ending up at **NASA's Kennedy Space Center** in Florida
- In Florida, the pieces are mated in **SpaceX's Horizontal Integration Facility**, a large hangar within sight of launchpad **39A**

Falcon 9 First Stage Landing

- The most exciting part of any **Falcon 9** launch might be the landing, specifically that of the first stage onto a floating barge
- The **Falcon 9's** first stage includes four small carbon-fiber landing legs stowed flat against its fuselage
- After the rocket goes through staging, the first stage begins its fall through the atmosphere
- Cold gas thrusters near the top flip the rocket around so it's upright
- Then the stage engine fires briefly, just enough to slow its fall
- As the stage approached its target, the legs deploy
- In the very final phases of its descent, three of the nine Merlin engines fire one last time for what **SpaceX** calls the 'boostback burn'
- The stage slows even further, almost hovering as it makes a soft touchdown
- This landing sequence **entirely automated**, with the rocket stage responding to real-time data

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Falcon 9 Post-flight

- After its successful landing, the **Falcon 9's** first stage is returned to the **Horizontal Integration Facility** where it can be checked out, refurbished, and readied for another launch
- Reusing the stage is much cheaper than building a new one for every launch
- The SES-10 mission in March 2017 was the first time a core stage of an orbit-capable rocket has been reused, and the ***cost was "substantially less than half" of what it would have cost to build a brand new stage***

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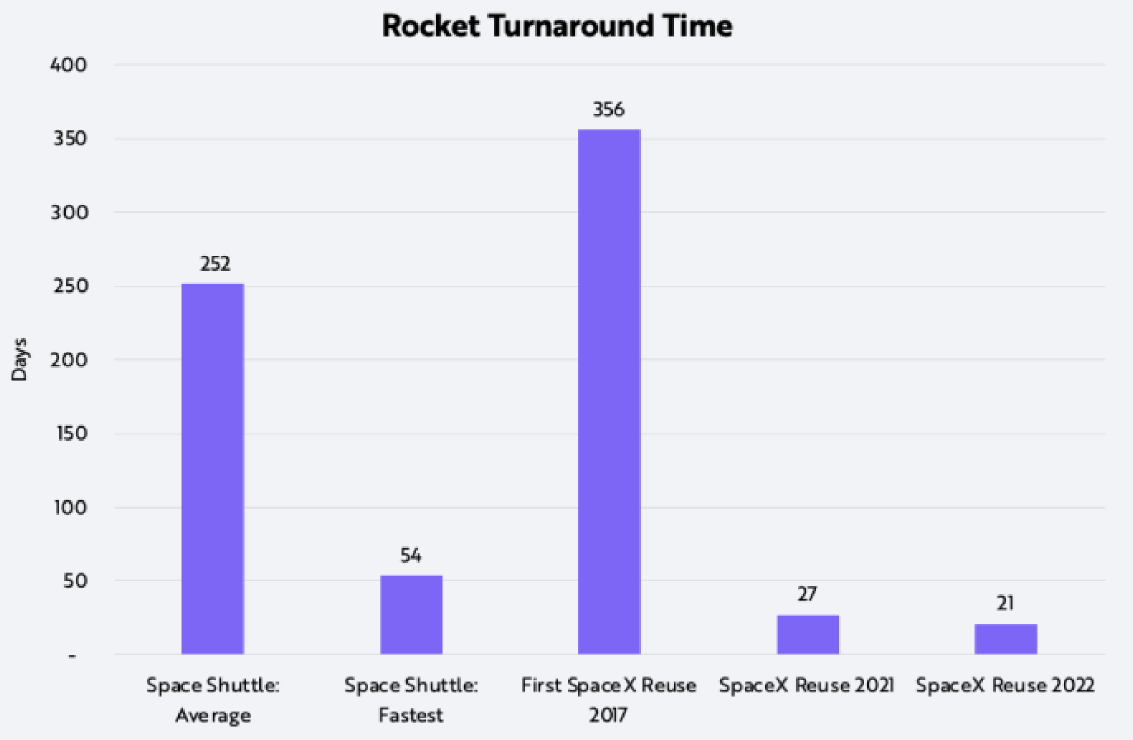
Falcon 9 Turn Around Time

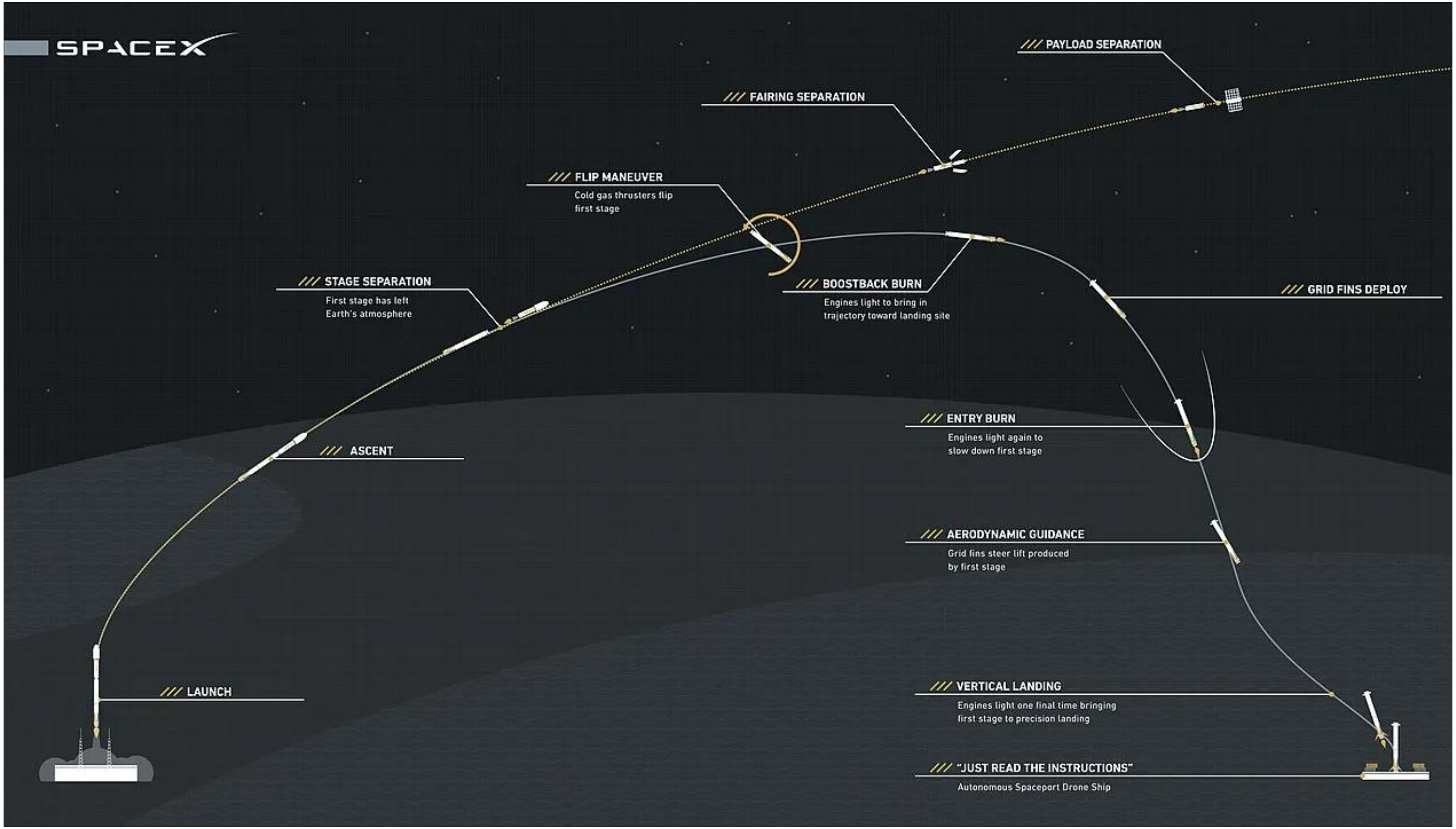
- **Rapid rocket reusability** is key to lowering launch costs and turbocharging space exploration
- In the last year alone, **SpaceX** reduced rocket reuse time from 27 to 21 days, as shown below
- If the cost were to correlate with time, which seems likely, that suggests that the **cost to refurbish** the first stage of the **Falcon 9** rocket has dropped from **~$13 to ~$1 million** during the past five years
- This improvement, along with other reusability developments, suggests the cost-per-kilogram to **LEO** of a reused **Falcon 9** is ~**$800**, compared to ~**$2,700** for a new **Falcon 9**
- It cost between **$450 million** and **$1.5 billion** per launch to refurbish the **Space Shuttle**



Source: ARK Investment Management LLC, 2022; Ehttps://www.reddit.com/r/spacex/wiki/cores#wiki_b1049; https://www.nasa.gov/pdf/537939main_ss-launches-080311.pdf. For informational purposes only and should not be considered investment advice or a recommendation to buy, sell, or hold any particular security.

- **Launches** **261**
- **Landings** **219**
- **Reflights** **194**

Falcon 9



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/// PAYLOAD SEPARATION
/// FAIRING SEPARATION
/// FLIP MANEUVER
Cold gas thrusters flip first stage
/// STAGE SEPARATION
First stage has left Earth's atmosphere
/// BOOSTBACK BURN
Engines light to bring in trajectory toward landing site
/// GRID FINS DEPLOY
/// ENTRY BURN
Engines light again to slow down first stage
/// ASCENT
/// AERODYNAMIC GUIDANCE
Grid fins steer lift produced by first stage
/// VERTICAL LANDING
Engines light one final time bringing first stage to precision landing
/// LAUNCH
/// "JUST READ THE INSTRUCTIONS"
Autonomous Spaceport Drone Ship

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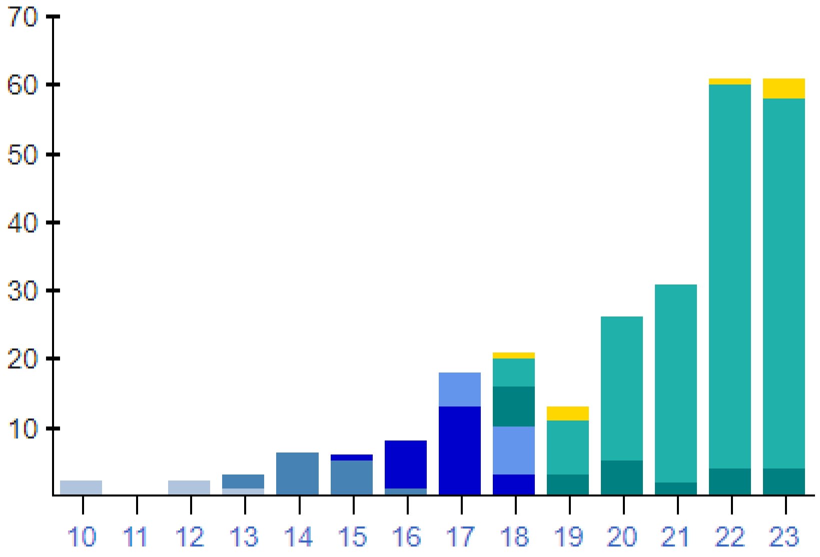
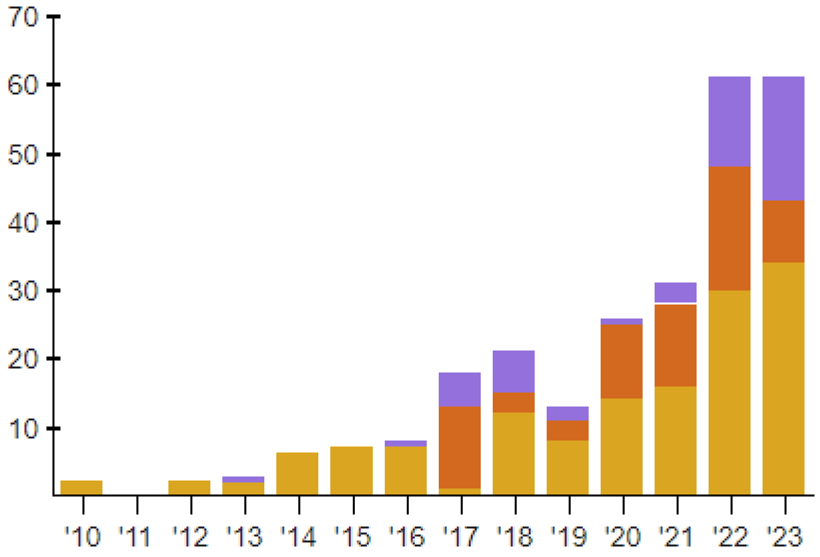
Falcon 9

Rocket configurations [edit]



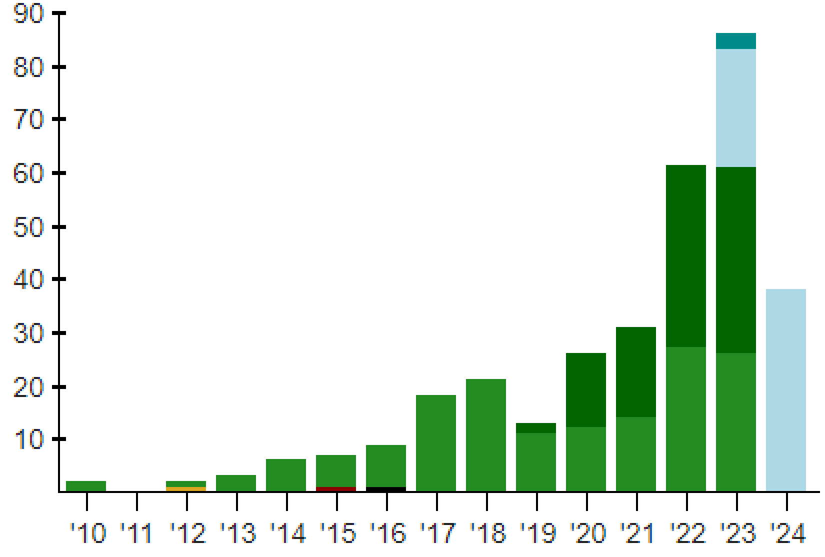
Launch sites [edit]



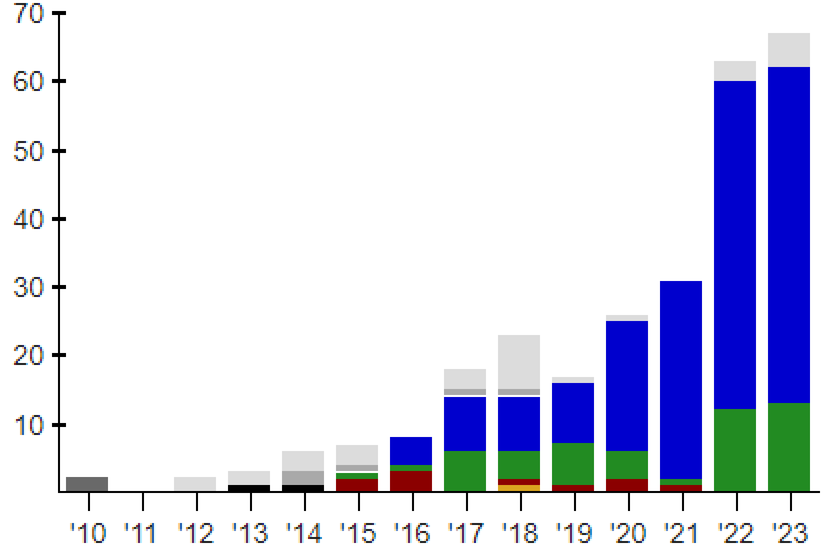
- Falcon 9 v1.0
- Falcon 9 v1.1
- Falcon 9 Full Thrust
- Falcon 9 FT (reused)
- Falcon 9 Block 5 (new)
- Falcon 9 Block 5 (reused)
- Falcon Heavy
- CCSFS, SLC-40
- KSC, LC-39A
- VSFB, SLC-4E

Falcon 9

Launch outcomes [edit]



Booster landings [edit]



- Loss before launch
- Loss during flight
- Partial failure
- Success (commercial and government)
- Success (Starlink)
- Planned (commercial and government)
- Planned (Starlink)

- Ground-pad failure
- Drone-ship failure
- Ocean test failure[i]
- Parachute test failure[ii]
- Ground-pad success
- Drone-ship success
- Ocean test success[iii]
- No attempt

i. ^ Controlled descent; ocean touchdown control failed; no recovery
ii. ^ Passive reentry failed before parachute deployment
iii. ^ Controlled descent; soft vertical ocean touchdown; no recovery

Falcon Heavy

- **Falcon Heavy** is a partially reusable super heavy-lift launch vehicle that can carry cargo into Earth orbit, and beyond
- The rocket consists of a **center core** on which **two Falcon 9 boosters** are attached, and a **second stage** on top of the center core
- **Falcon Heavy** has the second highest payload capacity of any currently operational launch vehicle behind **NASA's Space Launch System (SLS)**
- **Falcon Heavy's** maiden launch on 6 February 6, 2018,
- As a dummy payload, the rocket carried a **Tesla Roadster** belonging to **Elon Musk**, with a mannequin dubbed "*Starman*" in the driver's seat
- The second **Falcon Heavy** launch occurred on April 11, 2019
- All three booster rockets successfully returned to Earth
- The third Falcon Heavy launch successfully occurred on June 25, 2019
- Since then, **Falcon Heavy** has been certified for the **National Security Space Launch (NSSL**) program
- **Falcon Heavy** is not human rated by **NASA**
- **SpaceX** intends to have the **Starship/Super Heavy** vehicles human rated

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Falcon Heavy

- **First Stage**
- Three cores make up the first stage of Falcon Heavy
- The side cores, or boosters, are connected on the nosecone, the interstage, and on the **octaweb**
- Shortly after liftoff the center core engines are throttled down
- After the side cores separate, the center core engines throttle back up to full thrust
- Falcon Heavy's first stage incorporates 27 Merlin engines across three aluminum-lithium alloy rocket cores containing liquid oxygen and rocket-grade kerosene (RP-1) propellant
- Falcon Heavy generates more than 5 million pounds of thrust at liftoff
  - NUMBER OF ENGINES 27
  - THRUST AT SEA LEVEL 5,130,000 lbf
  - THRUST IN VACUUM 5,548,500 lbf

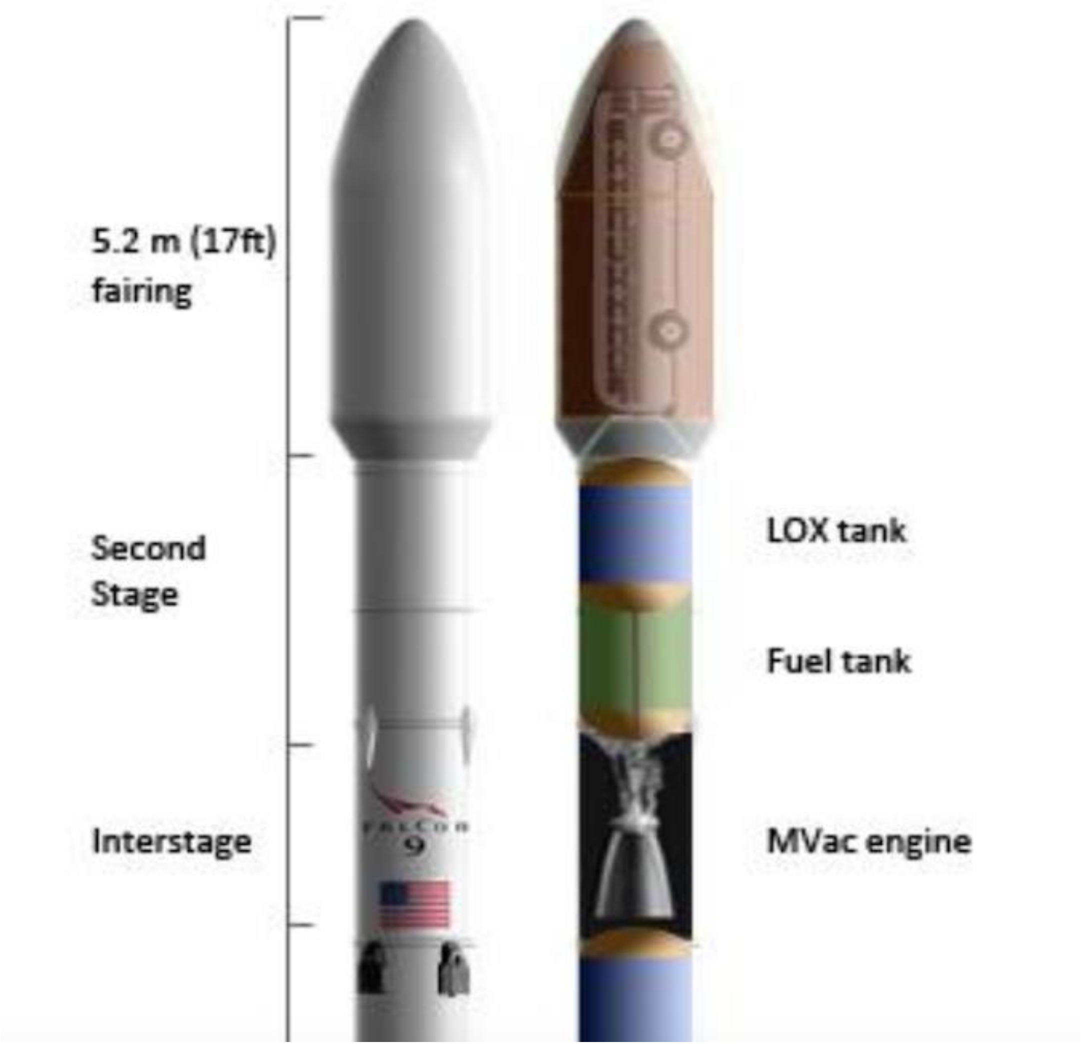
HEIGHT	229.6 ft
WIDTH	39.9 ft
MASS	3,125,735 lb
PAYLOAD TO LEO	140,660 lb
PAYLOAD TO GTO	58,860 lb
PAYLOAD TO MARS	37,040 lb

Falcon Heavy

- **Interstage**
- The interstage is a composite structure that connects the center core on the first stage and second stages and holds the release and separation system.
- **Grid fins**
- Falcon Heavy is equipped with 12 hypersonic grid fins
- Four on each booster, positioned at the base of the interstage or nosecone which orients by moving the center of pressure during reentry

Falcon Heavy

- **Second Stage**
- **Falcon Heavy** draws upon **Falcon 9's** proven design, which minimizes stage separation events and maximizes reliability
- The second-stage **Merlin Vacuum Engine** delivers the rocket's payload to orbit after the main engines cut off and the two first-stage cores separate.
  - NUMBER OF ENGINES 1
  - BURN TIME 397 sec
  - THRUST 220,500 lbf
- **Payload Fairing**
- Made of a carbon composite material, the fairing protects satellites on their way to orbit
- **SpaceX** is recovering fairings for reuse on future missions.
  - HEIGHT 43 ft
  - DIAMETER 17.1 ft
- Falcon Heavy
  - **Launches 7**
  - **Landings 13**
  - **Reflights 10**



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Falcon Heavy Assembly at Launch Site

SPACEX Falcon Heavy Liftoff and Landing

Twenty-seven Merlin engines firing during launch of Arabsat-6A in 2019

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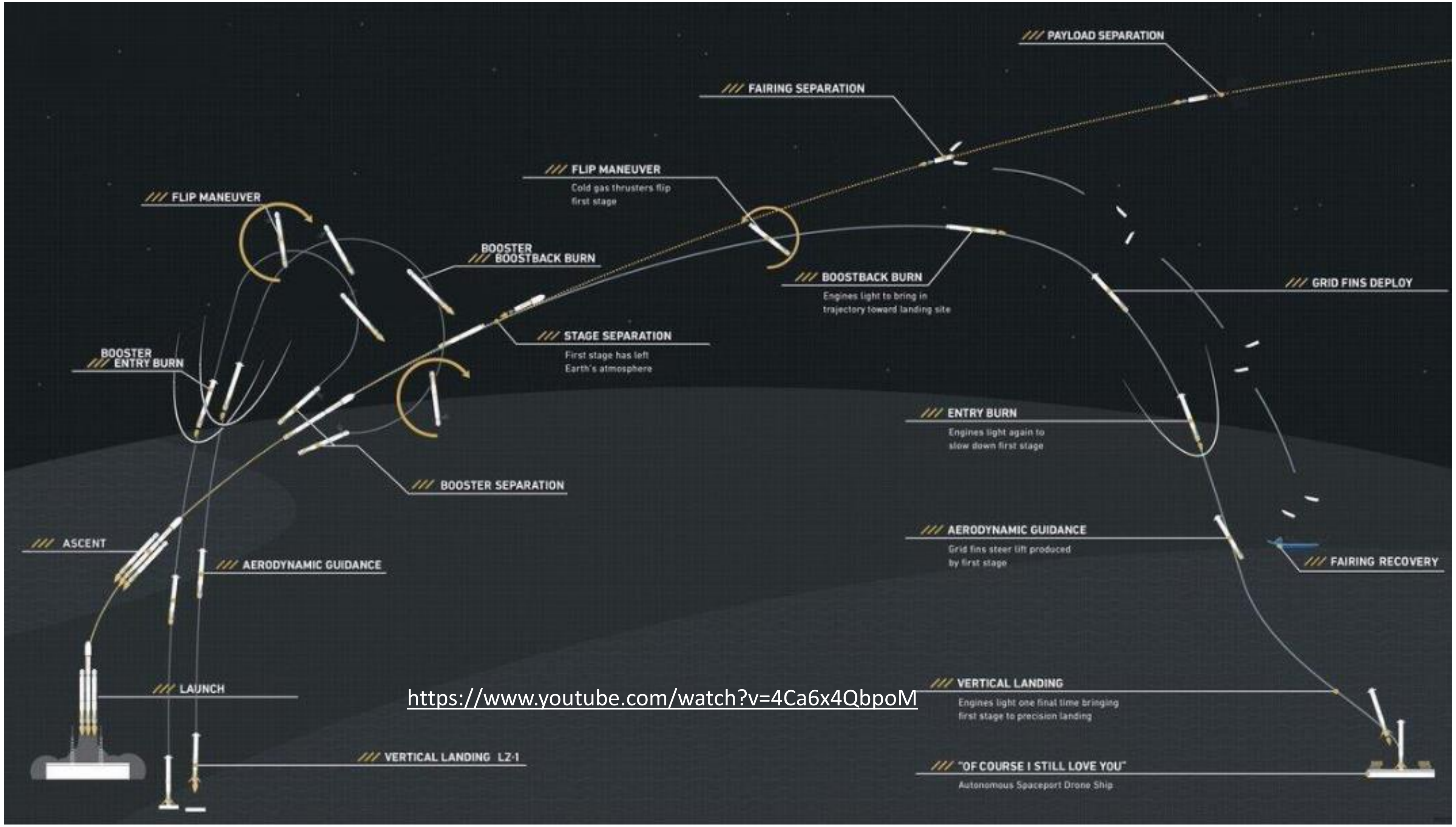
Falcon Heavy Flight Profile



https://www.youtube.com/watch?v=4Ca6x4QbpoM

Figure 8-11: Falcon Heavy sample mission profile

1	Introduction: topics , some basics and rocket pioneers
2	SpaceX founding , Musk's vision, facilities, organization, personnel
3	SpaceX and NASA commercial funding
4	Falcon rockets and engines , Falcon 1, Falcon 9 and Falcon Heavy
5	**Dragon spacecraft , Cargo Dragon and Crew Dragon**
6	Super Heavy booster and engines and Starship spacecraft
7	Starship competition for Artemis Moon Human Landing System
8	Musk's Mars vision , plans , challenges and SpaceX summary