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EE584 – S/C Design and Systems Engineering

Lecture 1

Systems Engineering Overview

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Based on the lecture "Fundamentals of Systems Engineering"
By Prof. Olivier L. de Weck MIT/EPFL

Overview

- **Systems Engineering (SE) Overview**
  - A bit of history
  - The “V”-Model
  - SE Standards and Handbooks
  - Challenges of current practice
- **Stakeholder Analysis**
  - Identifying Stakeholders
  - CONOPS
  - Stakeholder Value Network (SVN) Analysis

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An example of a system: Swiss F/A-18 Program

Image Source: https://www.vtg.admin.ch/fr/organisation/cdmt-op/fa/kdt-stv/cap/fa18-solo-display.html

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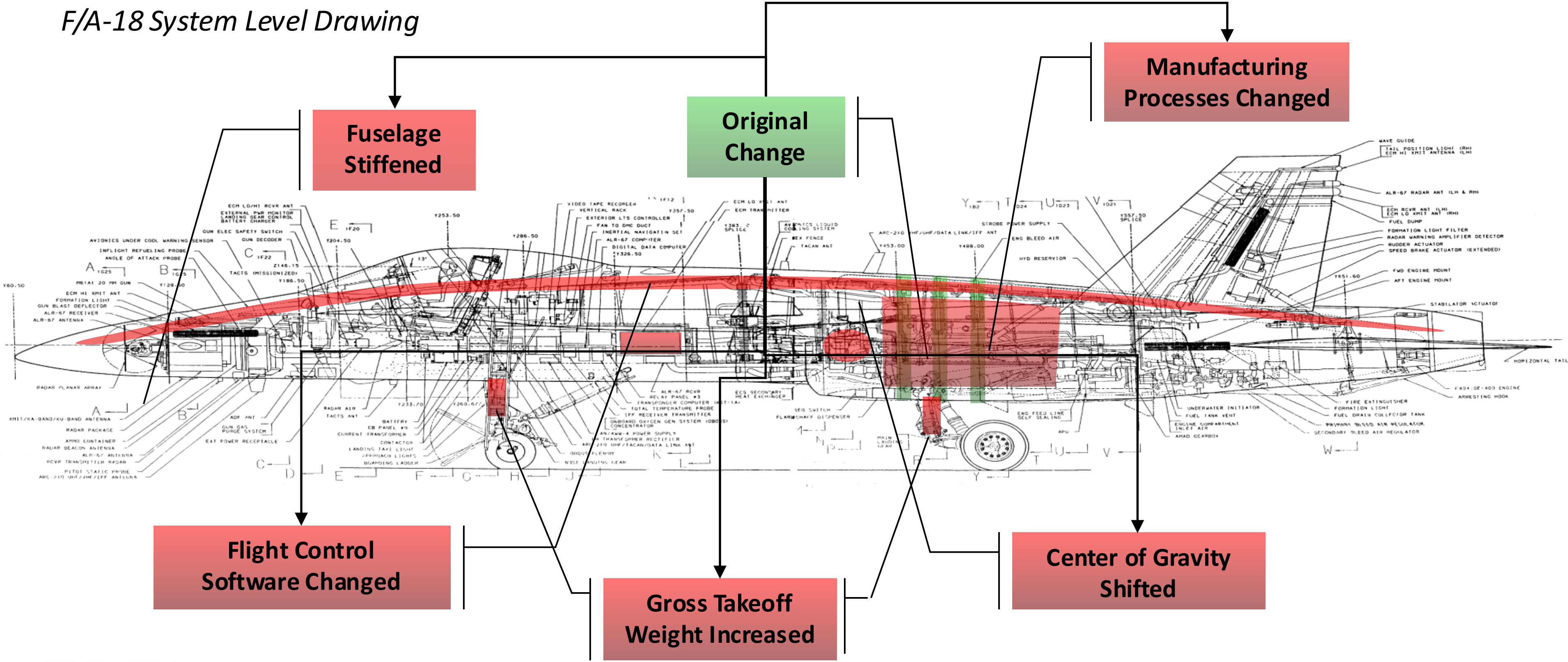
F/A-18 Complex System Change

F/A-18 System Level Drawing



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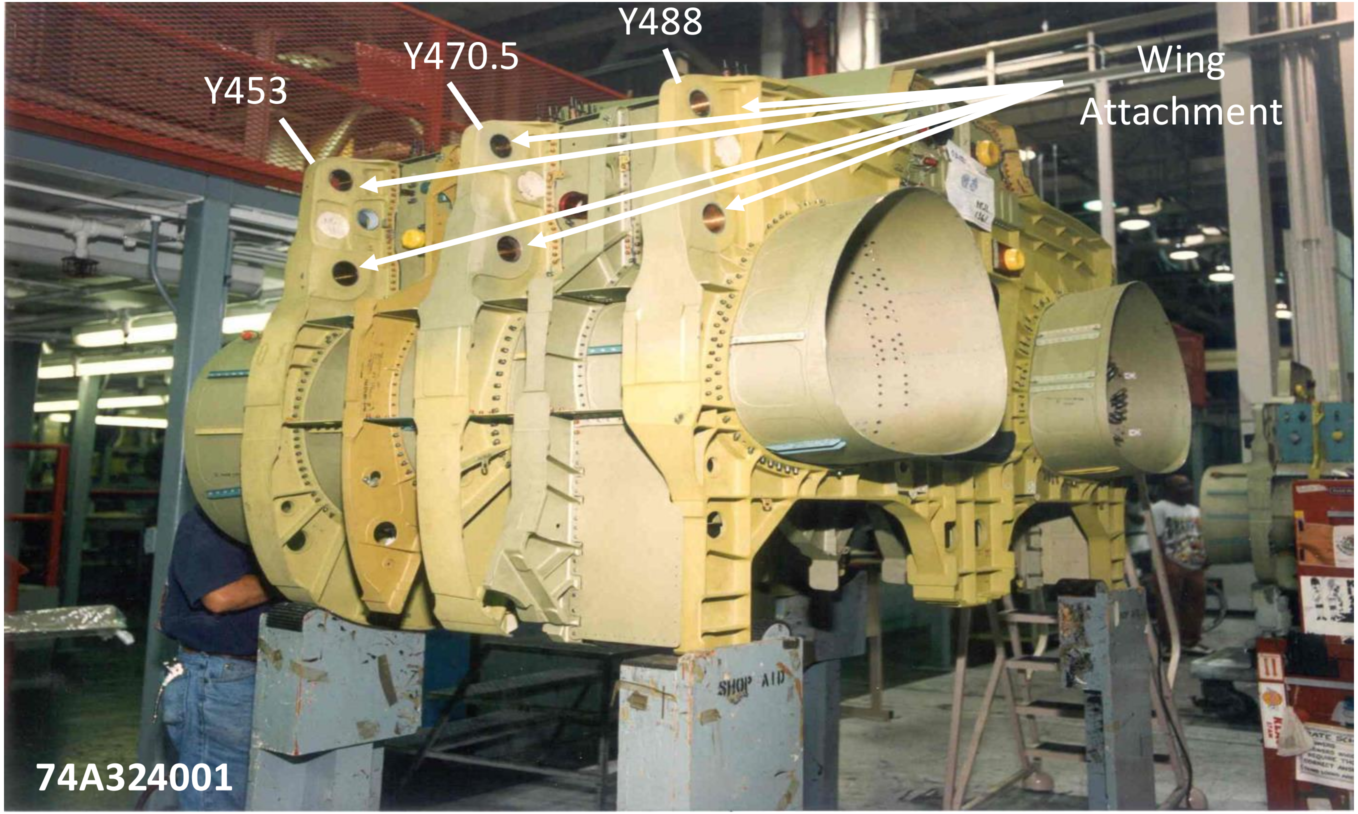
F/A-18 Center Barrel Section



Lessons Learned from Swiss F/A-18 Program

- **High-performance aircrafts are very complex internally … propulsion, avionics, structures …**
- **Changing requirements can have ripple effects because everything is tightly coupled**
  - It is difficult to predict the totality of system interactions ahead of time
- **The "whole" system is much more than the air vehicle: logistics, training, incl. simulators etc..**
- **People matter a lot: contracts, culture, incentives ….**

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Motivation for this introduction to SE

- Aerospace Systems deliver important functions to society … air transportation, defense, sensing, exploration …
- Complex "machines" with thousands of unique parts and potentially millions of interactions
  - **Many aerospace systems require 6+ levels of decomposition to arrive at indivisible parts that cannot be taken "a-part"**
- Humans play an important role as designers, operators, beneficiaries, maintainers ….
- Best Practices have emerged since the 1960's and are continuously evolving … documented in standards/handbooks
- Limitations of "traditional" SE
  - **System Safety**
  - **Typical program cost and schedule overruns** … Boeing Dreamliner 787 delays …
- Systems Engineering is also penetrating in other industries
  - Automobiles, Software, Medical Devices ….

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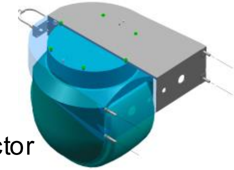
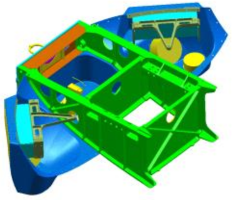
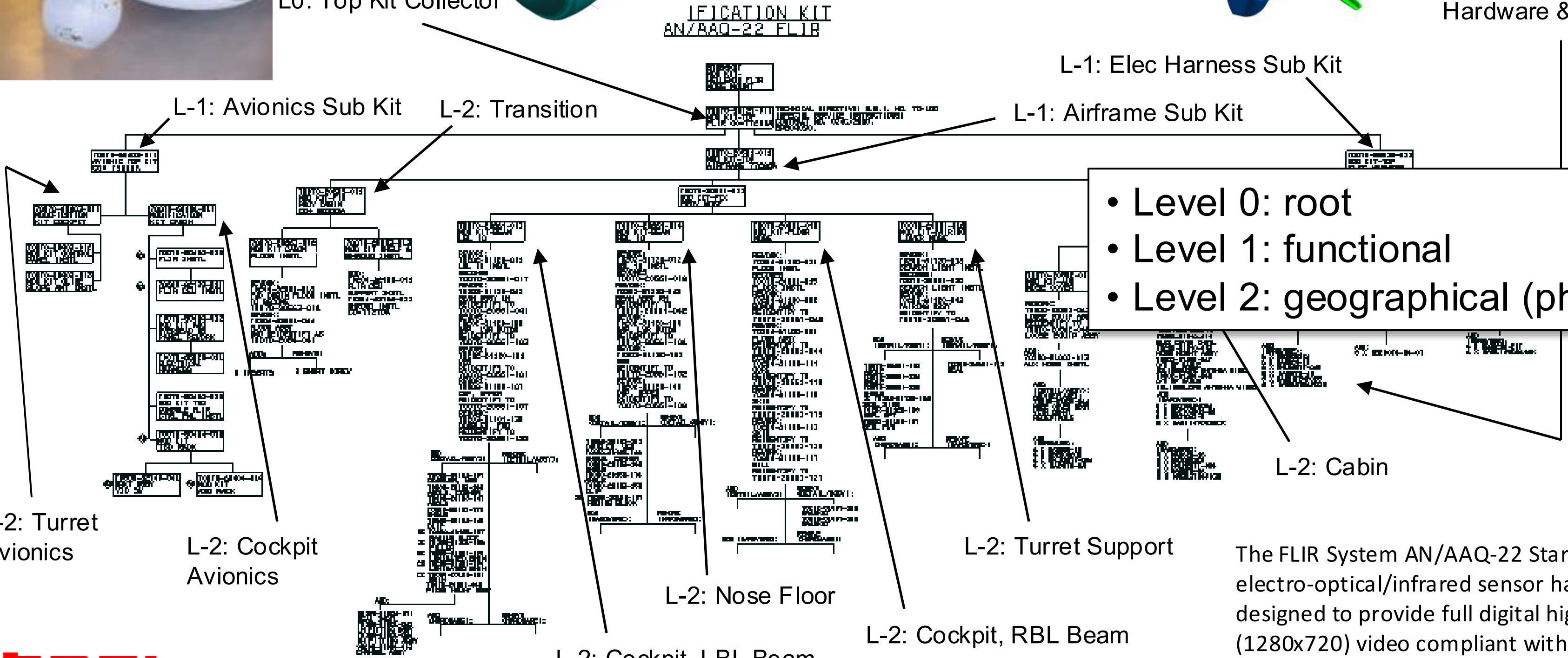
Example: FLIR System for Aircraft

FLIR = Forward Looking Infrared







- Level 0: root
- Level 1: functional
- Level 2: geographical (physical)

The FLIR System AN/AAQ-22 Star SAFIRE electro-optical/infrared sensor has been designed to provide full digital high-definition (1280x720) video compliant with US and NATO specifications.

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Why do we need system decomposition?

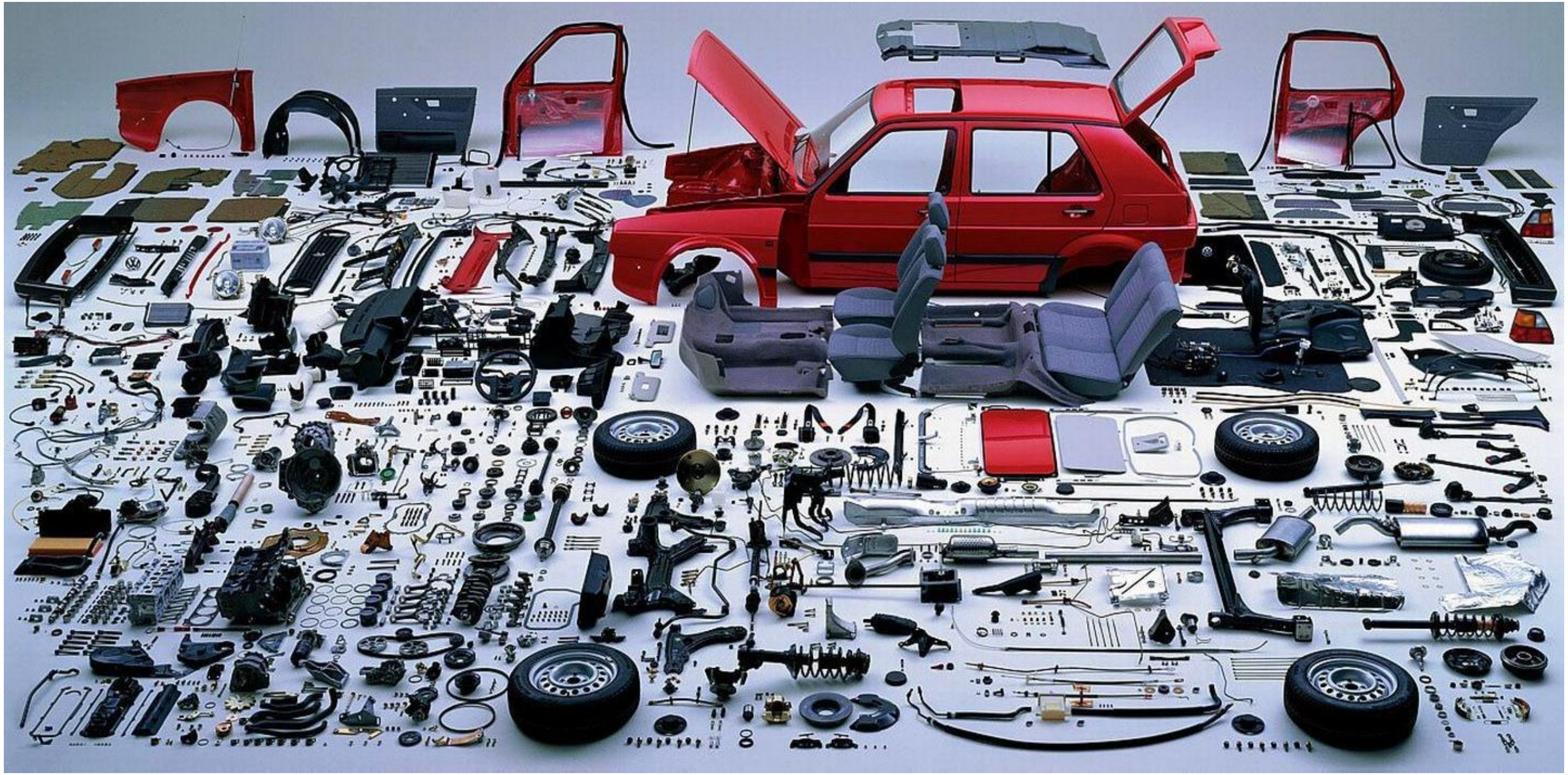

Photo: Hans Hansen - o.T. (separated Golf/Car), 1988 / Camera Austria

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Concept Question

- **How many levels of decomposition (depth of drawing tree) do we need to describe the car shown in the previous picture?**
  - 1
  - 2
  - 3
  - 4
  - 5
  - 6
  - >6
  - This question does not make sense to me

Submit your answer within 1 minute at the following URL
http://tiny.cc/seintro01

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System Complexity

Assume 7-tree [Miller 1956]
http://www.musanim.com/miller1956/

- **How many levels in drawing tree?**

$$\#levels = \left\lceil \frac{\log(\#parts)}{\log(7)} \right\rceil$$

		~ # parts	*# levels*	
▪ Screwdriver	(B&D)	3	1	simple
▪ Roller Blades	(Bauer)	30	2	↓
▪ Inkjet Printer	(HP)	300	3	
▪ Copy Machine	(Xerox)	2,000	4	
▪ Automobile	(GM)	10,000	5	
▪ Airliner	(Boeing)	100,000	6	complex

Source: Ulrich, K.T., Eppinger S.D. , Product Design and Development Second Edition, McGraw Hill, 2nd edition, 2000, Exhibit 1-3

Overview

- **Introductions**
  - Personal Introductions
  - Course Introduction
- **Systems Engineering (SE) Overview**
  - A bit of history
  - The “V”-Model
  - SE Standards and Handbooks
  - Challenges of current practice
- **Stakeholder Analysis**
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How would you define Systems Engineering?

- **Turn to your neighbor and discuss for about 5 minutes:**
  - What is your definition of Systems Engineering?
  - Can you agree amongst yourselves?
  - What are the key elements of a definition?

- **We will sample after about 5 minutes !**

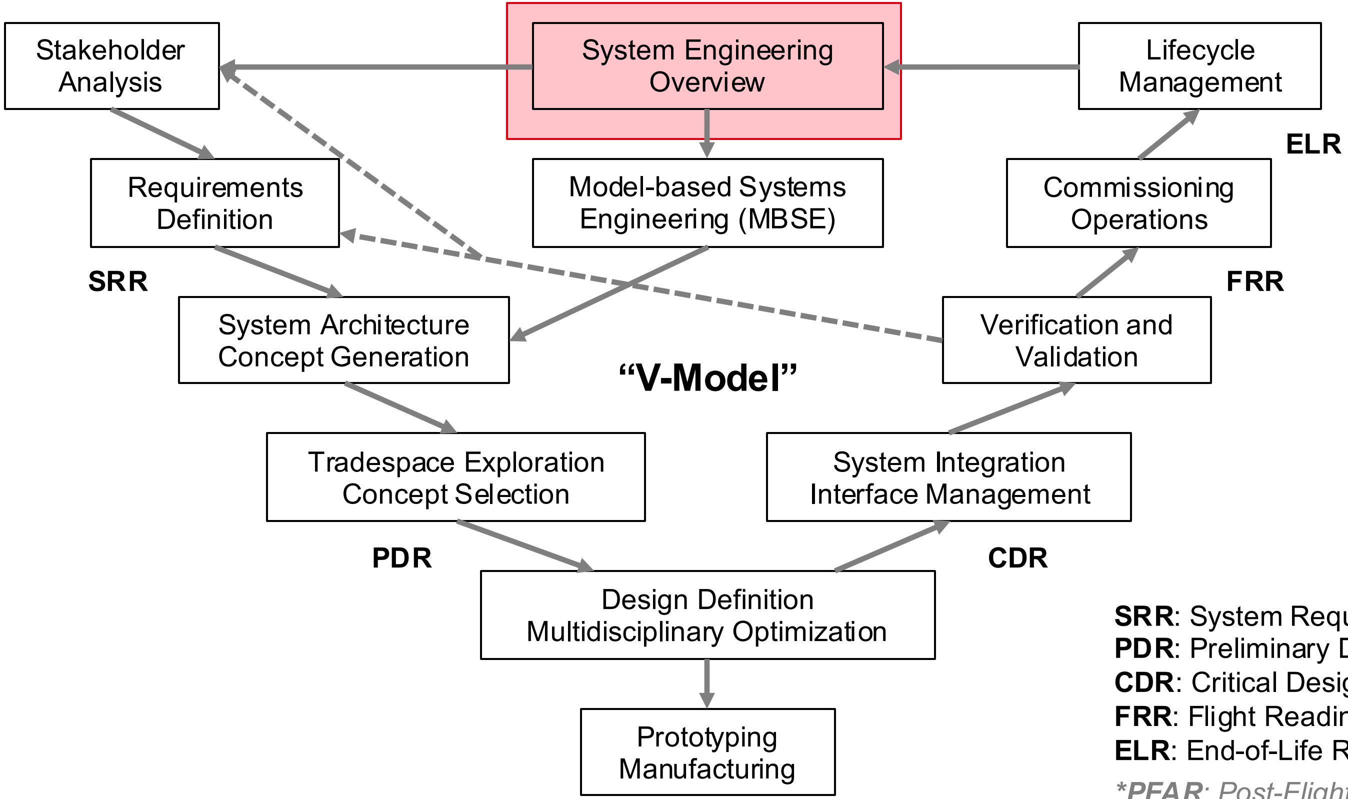
A bit of SE History

- **Systems Engineering has been informally practiced since antiquity**
  - Great Wall of China, Egyptian Pyramids, Roman Aqueducts
  - Mainly a “workforce” problem to build large infrastructures
- **The term “Systems Engineering” can be traced back to Bell Labs (1940s)**
  - https://en.wikipedia.org/wiki/Bell_Labs
  - Beginning of new methods to better handle complexity
- **Formal Systems Engineering really started after WWII**
  - 1950’s and 1960s: Cold War, Apollo Lunar Program, ICBMs etc…
  - Complex Engineering Systems: Air Traffic Control, High Speed Rail, Nuclear ..
  - Mainly (paper) document-based: requirements, specifications, test plans etc…
- **Early Pioneers**
  - Arthur D. Hall, Kelly Johnson, Simon Ramo, Eberhardt Rechtin, Andrew Sage, Margaret Hamilton, and others
- **1995 Founding of International Council for Systems Engineering (INCOSE)**
- **Since ~2000: Development of new Model-Based-Systems-Engineering (MBSE). Need to accelerate SE and better handle complexity**

Some Definitions of SE

- "Systems engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals." - *NASA Systems Engineering Handbook, 1995*.
- "An interdisciplinary approach and means to enable the realization of successful systems" - *INCOSE handbook, 2004*
- More recently the scope of SE has broadened:
  - Design of Enterprises, Infrastructure Networks etc…

The famous "V-Model" of Systems Engineering



SRR: System Requirements Review
PDR: Preliminary Design Review
CDR: Critical Design Review
FRR: Flight Readiness Review
ELR: End-of-Life Review*

****PFAR**: Post-Flight Assessment Review*

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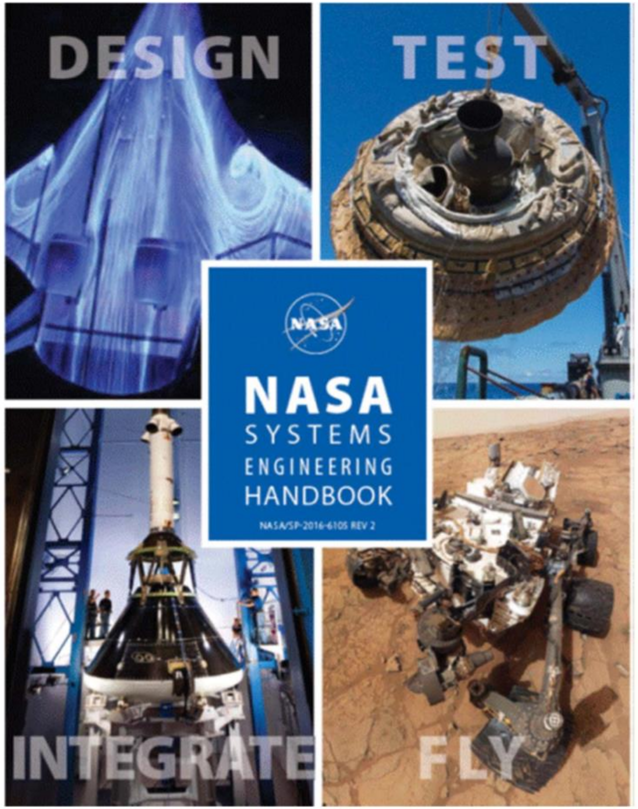
NASA/SP-2016- 6105 Rev 2

- **"Bible" for Systems Engineering at NASA**
- **Makes the bridge from "typical" guidance back to NASA Systems Engineering Process (NPR 7123.1)**
  - Guidance from practitioners
    - Written by practitioners for practitioners
  - "How" vs "What"
- **2nd Revision of**
  - Original practice/methodology from 1995 (basic)
- **Abridged version of:**
  - Expanded Guidance on Systems Engineering Volumes 1 & 2
  - Updates SP-2007-6105 Rev 1
- **Provides top-level guidance for Systems Engineering best practices; it is not intended in any way to be a directive**



https://www.nasa.gov/connect/ebooks/nasa-systems-engineering-handbook

European Space Standards

- **ECSS – European Cooperation for Space Standardization**
  - Space engineering – System engineering general requirements ***ECSS-E-ST-10C Rev.1***
  - Space engineering – Verification *ECSS-E-ST-10-02C Rev.1*
  - Space engineering – Technical requirements specification *ECSS-E-ST-10-06C*
  - Space engineering – Interface management *ECSS-E-ST-10-24C*
  - Space project management – Project planning and implementation *ECSS-M-ST-10C Rev.1*
  - Space Management – Organization and conduct of reviews *ECSS-M-ST-10-01C*
  - …

https://ecss.nl


ECSS-E-ST-10C Rev.1
15 February 2017

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space engineering

System engineering general requirements

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands

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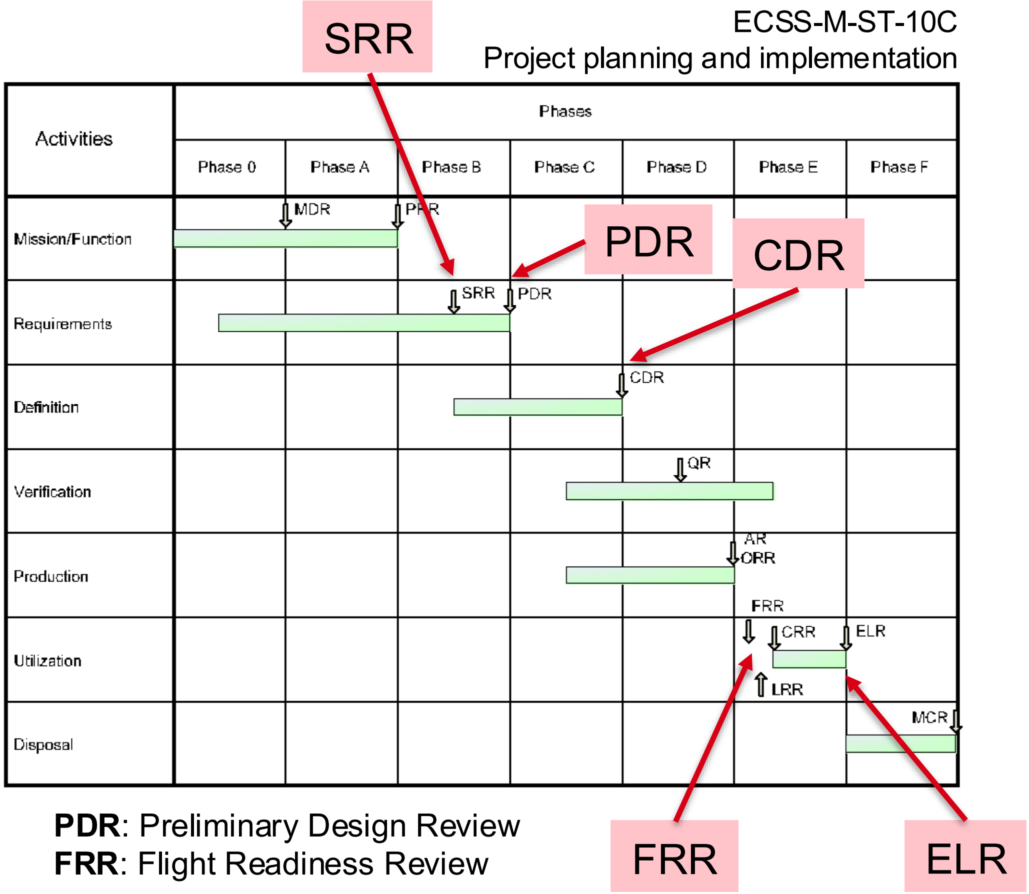
The life cycle of space projects - ESA

- Phase 0 - Mission analysis/needs identification
- Phase A - Feasibility
- Phase B - Preliminary Definition
- Phase C - Detailed Definition
- Phase D - Qualification and Production
- Phase E - Utilization
- Phase F - Disposal

ECSS-M-ST-10C
Project planning and implementation



SRR: System Requirements Review
CDR: Critical Design Review
ELR: End-of-Life Review

PDR: Preliminary Design Review
FRR: Flight Readiness Review

SE Standards and Handbooks

- **Systems Engineering Standards**

  1) **NASA Systems Engineering Handbook**, NASA/SP-2016-6105, Rev 2, 2016
  2) **INCOSE Systems Engineering Handbook**, A Guide for System Lifecycle Processes and Activities, version 5, International Council on Systems Engineering (INCOSE), June 2023
  3) **ISO/IEC/IEEE 15288:2023**, Systems and software engineering - System life cycle processes; Ingénierie des systèmes et du logiciel - Processus du cycle de vie du système – May 2023 edition
  4) **ECSS-E-ST-10C Rev.1** – European Systems Engineering Standard, http://www.ecss.nl/, February 2017

These are suggestions based on our best knowledge/experience. Feel free to make additional suggestions as the literature in SE is growing fast.

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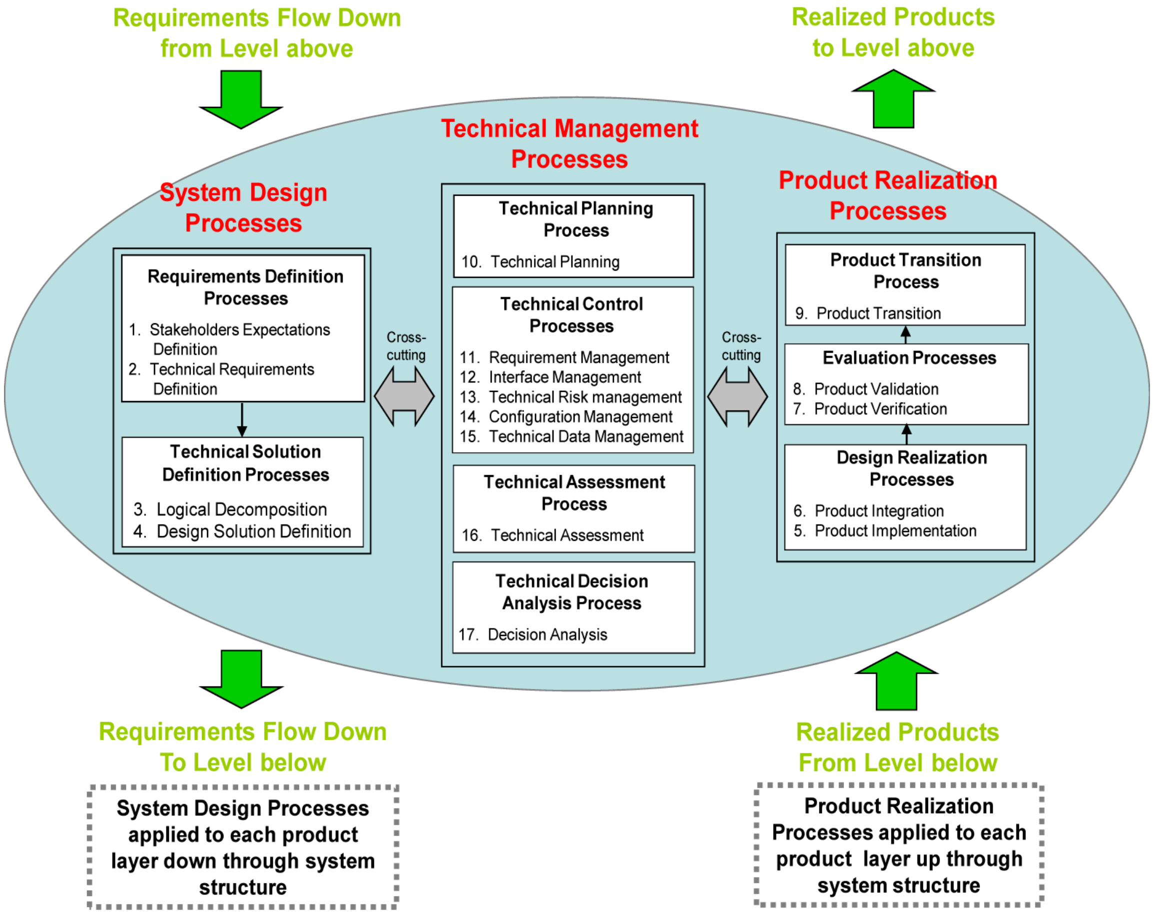
The NASA Systems Engineering "Engine"



From
NASA Procedural Requirements

NPR 7123.1B

Challenges of current practice …

Behavioral Characteristics of a Good Systems Engineer

- Intellectual Curiosity – ability and desire to learn new things
- Ability to make system-wide connections
- Comfortable with uncertainty and unknowns
- Proper Paranoia – expect the best, but plan for the worst
- Strong team member and leader
- Self Confidence and Decisiveness – short of arrogance
- Appreciation for Process – rigor and knowing when to stop
- Exceptional Two-way Communicator
- Diverse Technical Skills – ability to apply sound technical judgment
- Comfortable with change
- Ability to See the Big Picture – yet get into the details

Challenges of current practice …

- **NASA and other formal Systems Engineering processes are very helpful and valuable, but …**
  - Assume mostly “clean sheet” design, but many real projects are modifications of previous systems
    - How to do “redesign”, use legacy or COTS components etc…?
  - Assume that system/mission requirements and stakeholder needs are known and stable over time, but in reality they (can) change over time (new administrations …)
    - Impact of externalities (e.g. policy) is underrepresented
  - Effect of design iterations and rework on budgets and project outcomes is more important than the linear “waterfall” or “stagegate” process suggests
    - – See NRC Study on Cost and Schedule Growth in NASA’s Earth and Space Science Missions (see next chart).
  - Etc…etc…

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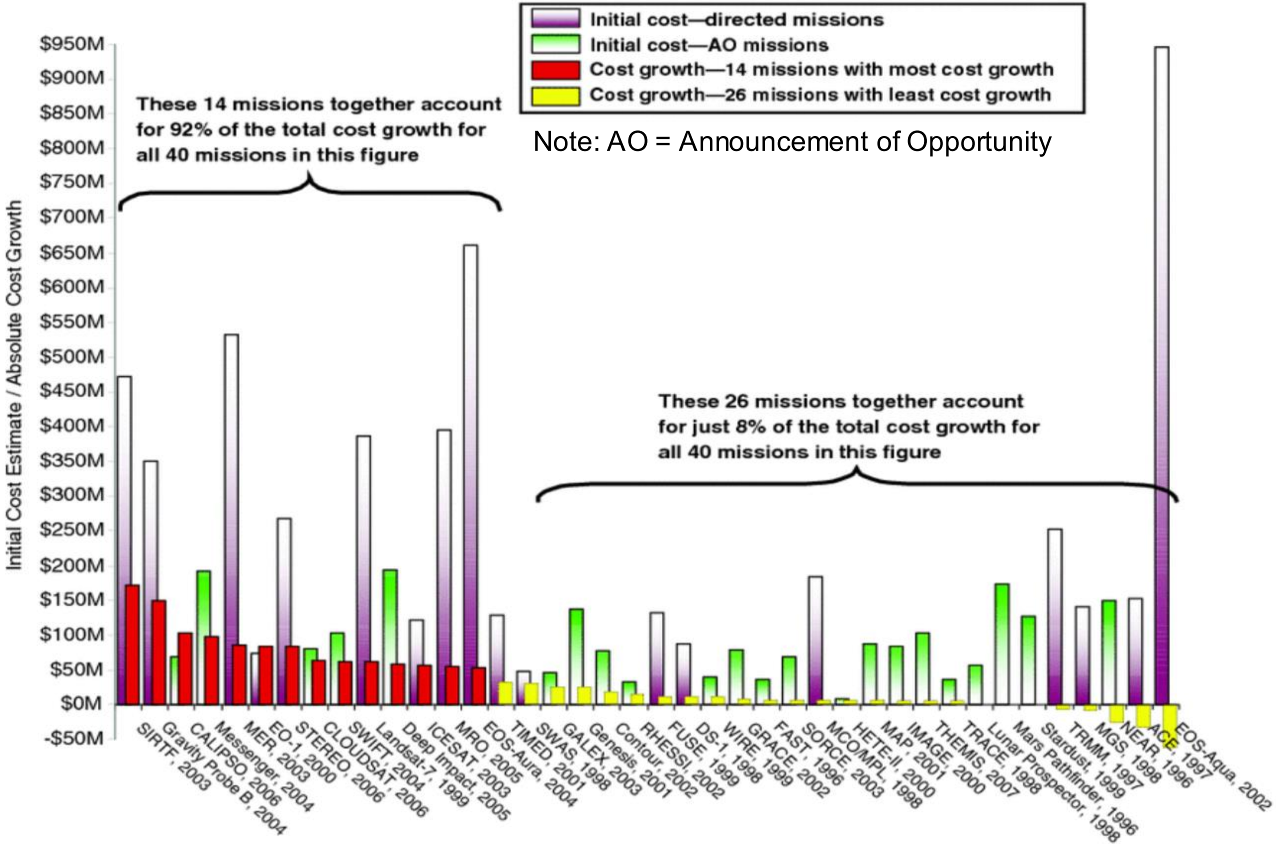
Ranking of 40 NASA science missions in terms of absolute cost growth in excess of reserves



Sega R., de Weck O.L, et al. ,"Controlling Cost Growth of NASA Earth and Space Science Missions" By Committee on Cost Growth in NASA Earth and Space Science Missions, National Research Council (NRC) of the National Academy of Sciences, ISBN-13: 978-0-309-15737, Washington .D.C., July 2010

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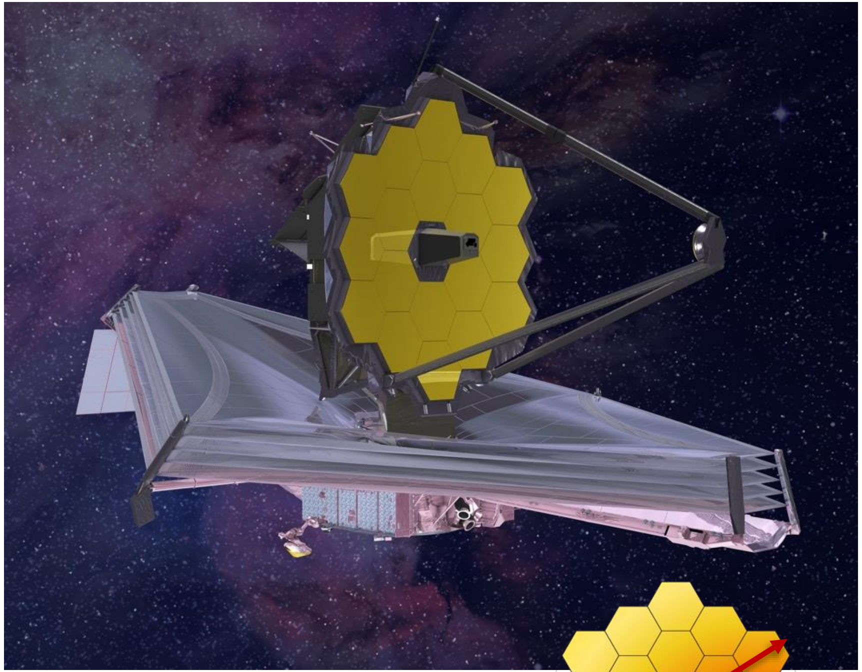
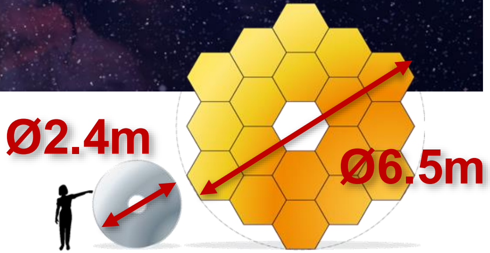
James Webb Space Telescope (JWST)



Credits: Northrop Grumman



Credits: Bobarino, based on NASA image

Development began in **1996**

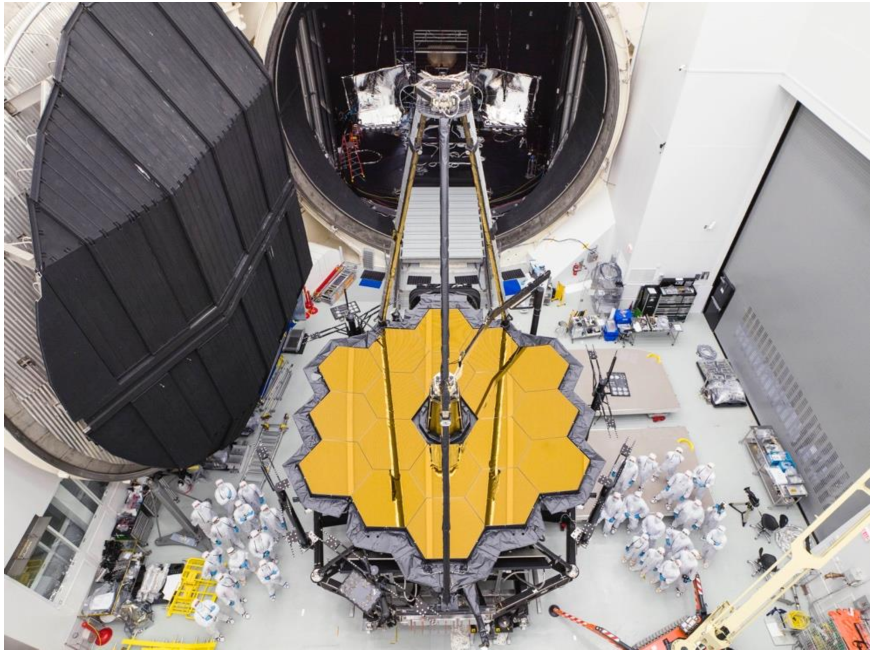
Original launch: **2007**

Launch: Dec. **2021**

Budget 500 M$

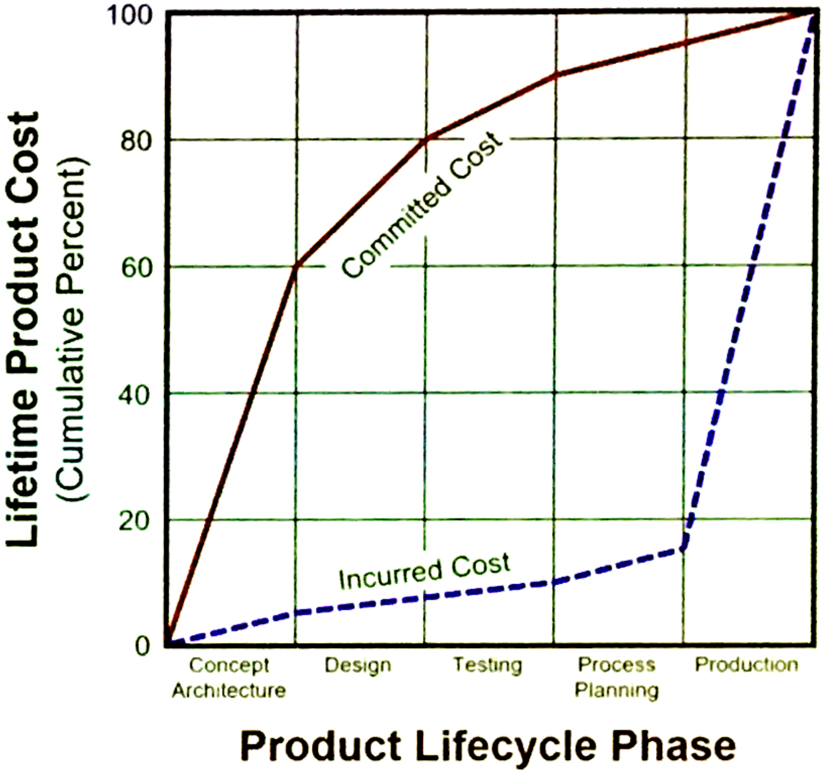
20x

Budget 10 G$



Credits: NASA/Chris Gunn

Product Lifecycle Costs



Dr. David Anderson,
Design for Manufacturability (2014)