System Engineering:

A Traditional Discipline in a Non-traditional Organization

Corporate Overview

- Founded with the singular goal of providing highly reliable space transportation
- Tech-style Organization—Flat and Fast
- 1,750 employees and growing
- Nearly 1 million sq. ft. of offices, manufacturing and production in Hawthorne, California
- >1 square mile (2.5 square km) state-of-the-art Propulsion and Structural Test Facility in central Texas
- Launch sites at Cape Canaveral and Vandenberg
- Commercial launch site nearing selection

SLC-40, Cape Canaveral

Central Texas

Hawthorne (Los Angeles) Headquarters

SLC 4, Vandenberg

SpaceX Large Scale Developments

FALCON

DRAGON

Falcon 1	Falcon 9	Falcon Heavy	Dragon Spacecraft

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Falcon Launch Vehicle Evolution

Falcon 1

Falcon 9
Dragon

Falcon 9
5.2 m Fairing

Falcon Heavy
5.2 m Fairing

- F1 and F9 share similar architecture
- F1 and early F9 use nearly the same Merlin 1C engine
- Advanced F9 uses evolution (Merlin 1D)
- Evolved family of software and avionics
- Similar launch and ground operations
- Lessons learned from Falcon 1 applied to Falcon 9

- Falcon Heavy's first stage will be made up of three nine-engine cores, which are used as the first stage of the Falcon 9
- Same second stage as Falcon 9.
- Falcon Heavy can deliver 53 metric tons to Low Earth Orbit
- Cross-feeding of propellant leaves core stage nearly full on booster separation

Five Successes in a Row

Falcon 1
Flight 4
28 Sep 2008

Falcon 1
RazakSAT
14 Jul 2009

Falcon 9
Demo Flight 1
4 Jun 2010

Falcon 9 Demo Flight 2
Dragon COTS C1
8 Dec 2010

Falcon 9 Demo Flight 3
Dragon COTS C2
22 May 2012

33 Merlin engines flown successfully

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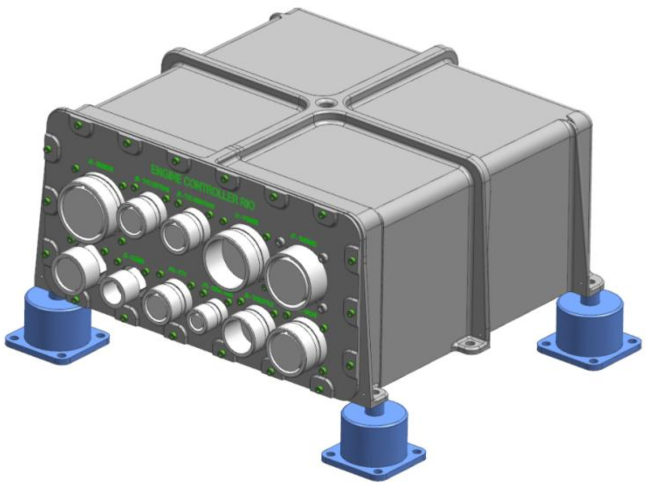
Premise: Systems Engineering is a discipline established to protect the enormous investment of large scale, complex system development by anticipating and solving integration problems ahead of time

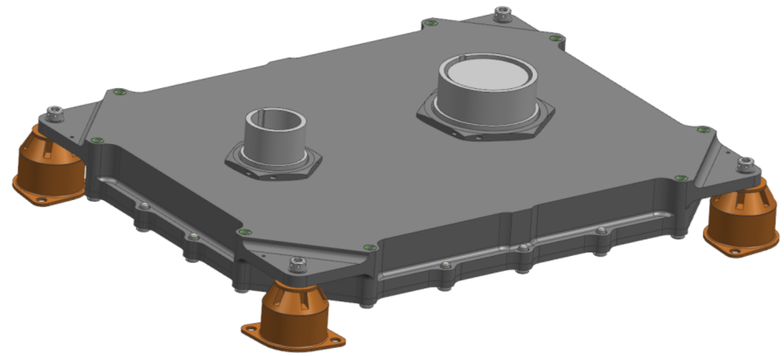
And yet--history has shown that humans are very poor at anticipating all potential integration problems, especially in new systems

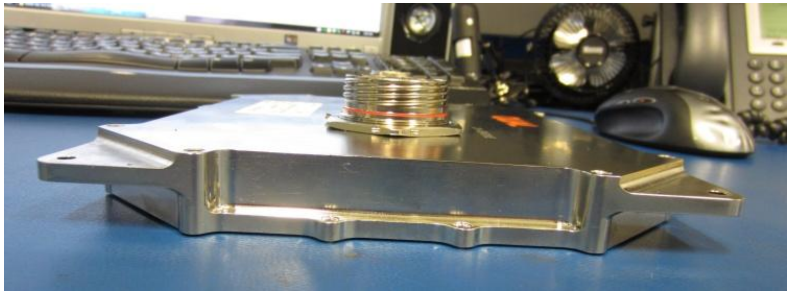
Central Philosophy

- SpaceX is a systems oriented culture whose goal is the engineering and integration of reliable and safe systems
- SpaceX operates on the philosophy of Responsibility—no engineering process in existence can replace this for getting things done right, efficiently
- There is an important balance between heavy up front systems engineering and rapid prototyping to reduce systems risk—tipping point heavily dependent on organizational agility, cost of iteration, and the ability to trade lower level requirements
- Because we can design-build-test at low cost (21st century infrastructure) we can afford to learn through experience rather than consuming schedule attempting to anticipate all possible system interactions
- Design a testable system and test what you fly!
- **Test rigorously and at multiple levels of integration—including right before service**

Some Examples of “Iterative Design”: Engine Controller







Previous Design → Current Design

Some Examples of “Iterative Design ”: Engine

Previous Design

Current Design

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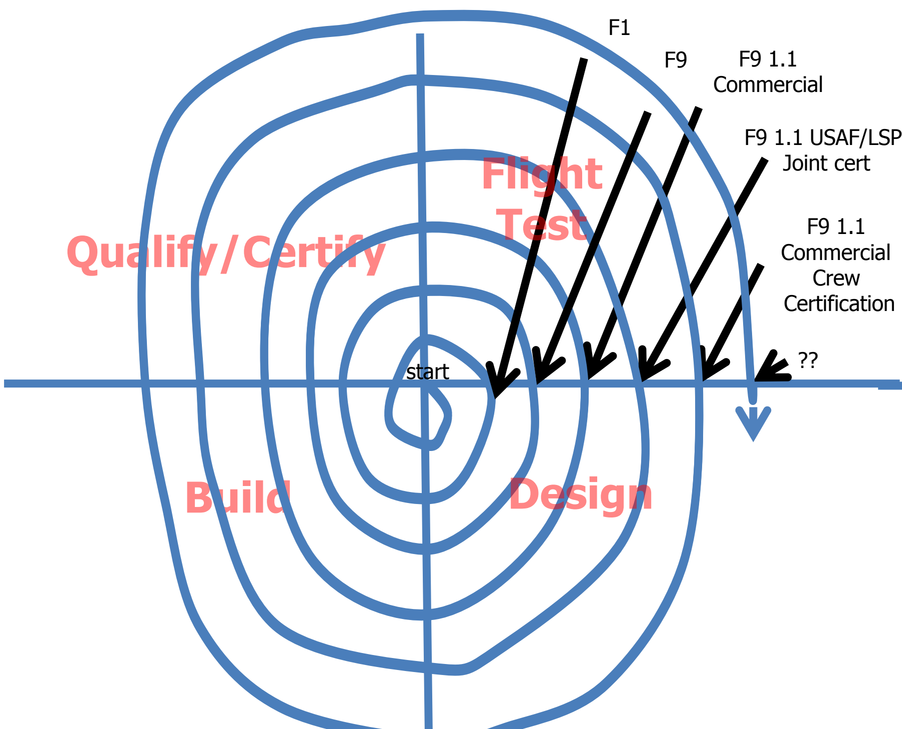
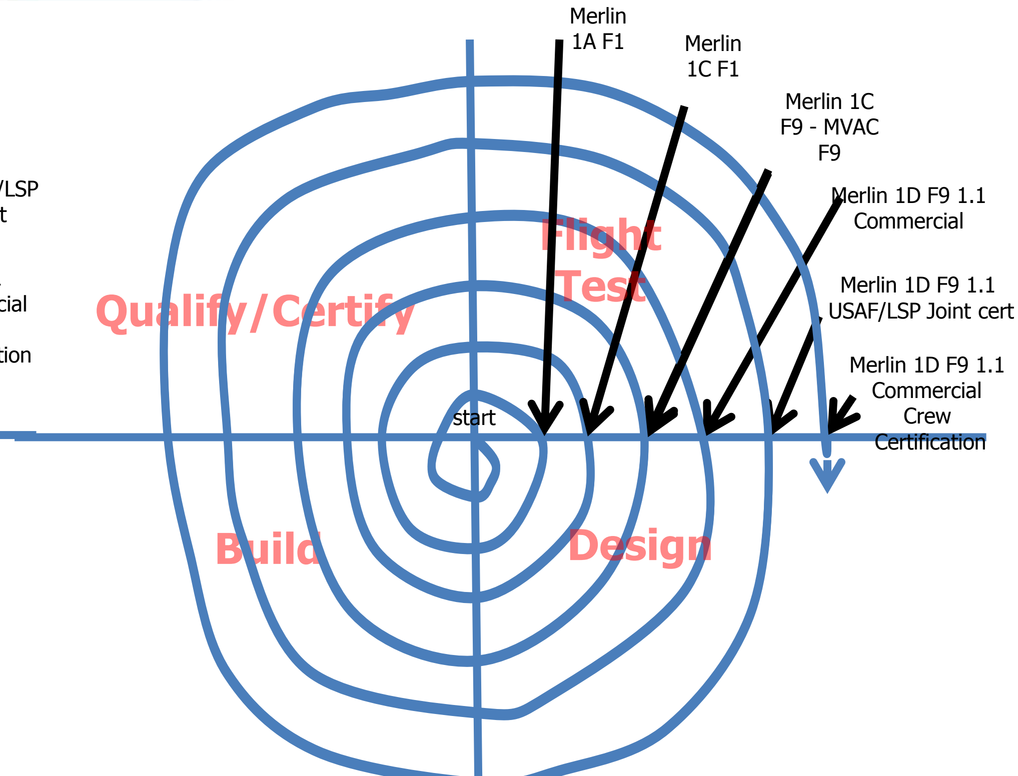
Maintain continuous design heritage in development with within rapid spiral methodology





Falcon 1 and Falcon 9

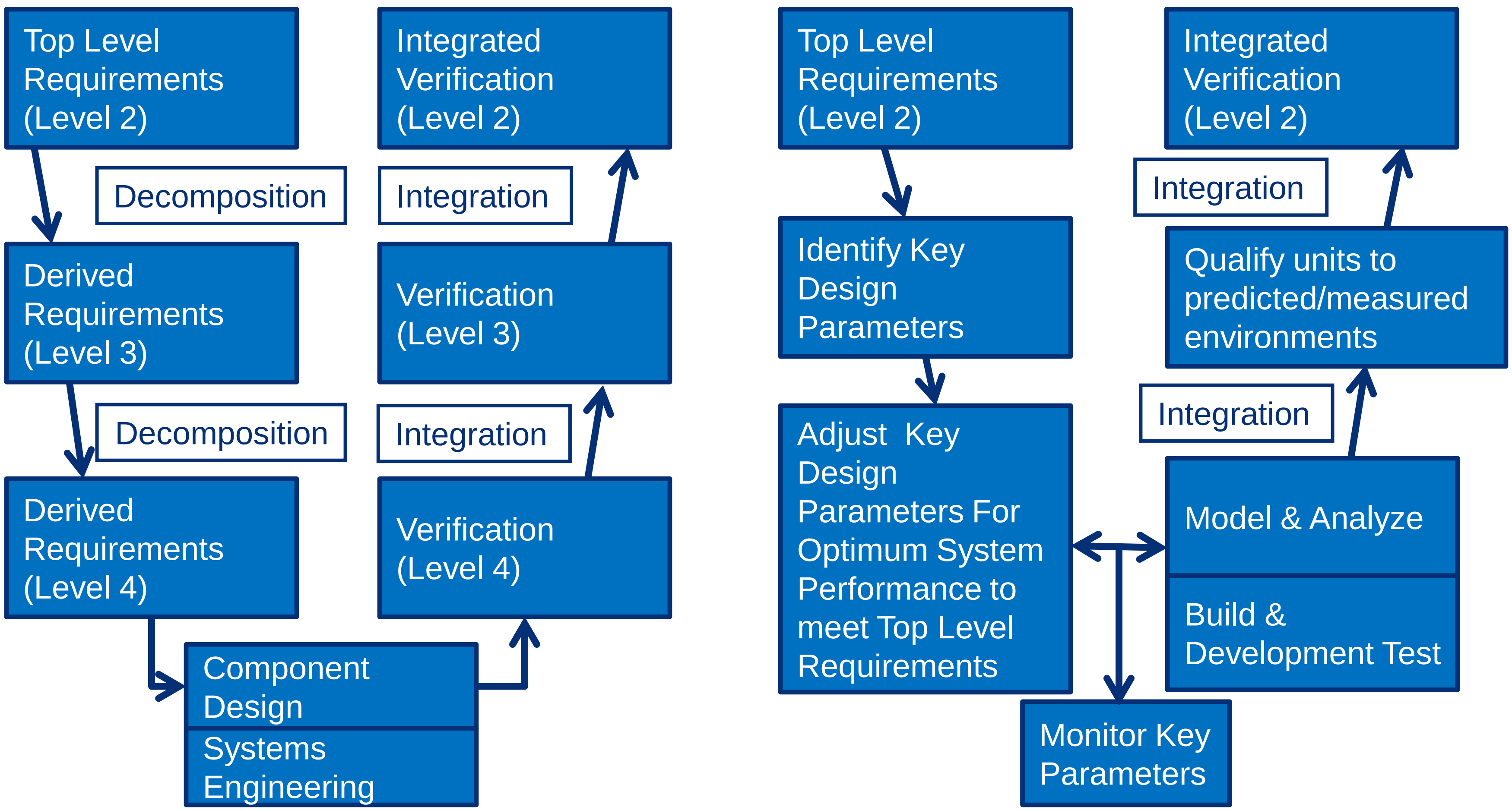
Merlin 1A (Falcon 1), Merlin 1C (Falcon 1 & 9) and Merlin 1C Vacuum (Falcon 9)

More Specifics:

- Distribute systems level tasks to departments to get departments focused on systems thinking
- Follow up with a network of integrators spread throughout the company
- User requirements are tracked and verified but everything below these requirements is constantly traded and optimized during the design phase
- Use modern 21st century information system tools to replace traditional control boards as forum for discussion and integration – use a paradigm more similar to social networking
    - Focus on TOOLS NOT RULES
- **Test rigorously and often**

User requirements are tracked and verified but everything below these requirements is constantly traded and optimized during the design phase

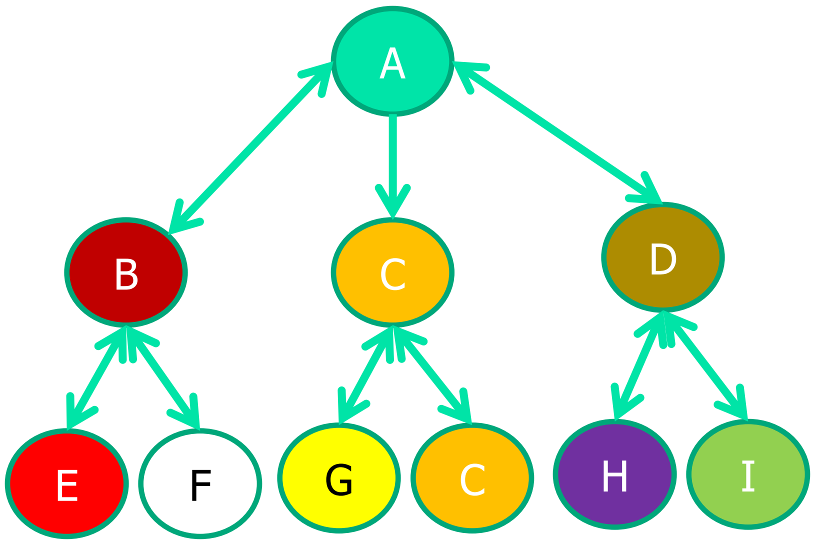
Traditional Vee / SpaceX



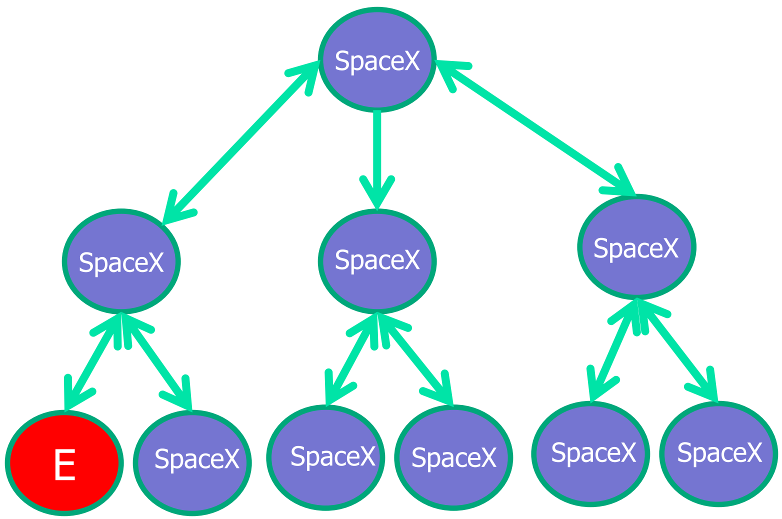
Possible to trade key design parameters between subsystems to optimize results because designers not separated by contract-subcontract bounds

Speed of *Key Design Parameter Trades* enhanced because of limited subcontracts

Traditional



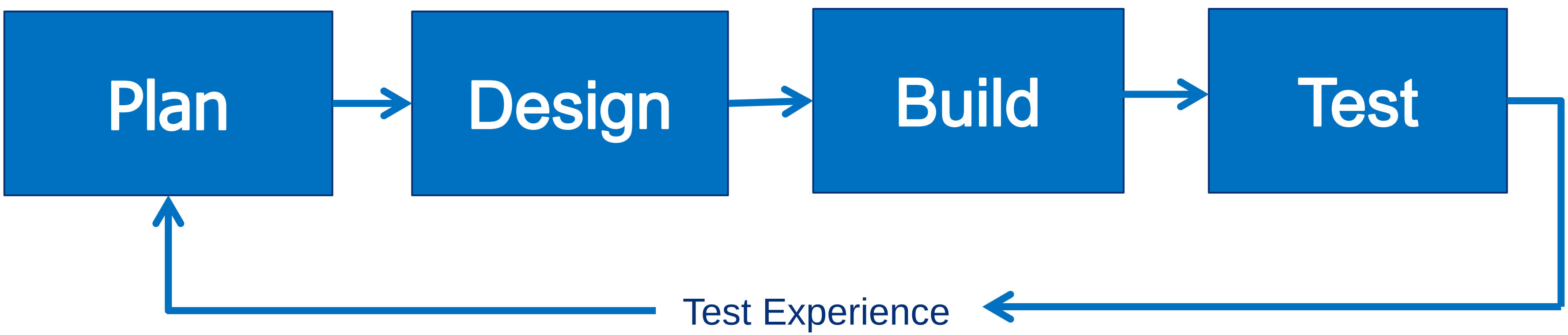
If SpaceX performed traditional decomposition



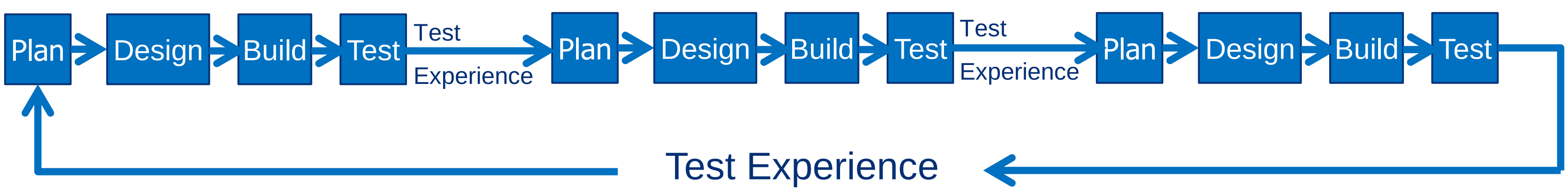
>70% of rocket dry mass is built in-house at SpaceX from raw materials

SpaceX learns through experience rather than attempting to anticipate all possible system interactions

Traditional Developments Use Single Cycle to Product—This Mandates Heavy Systems Engineering to Protect the Design-Build-Test Investment



SpaceX relies on rapid design-build test cycles to inform design by experience

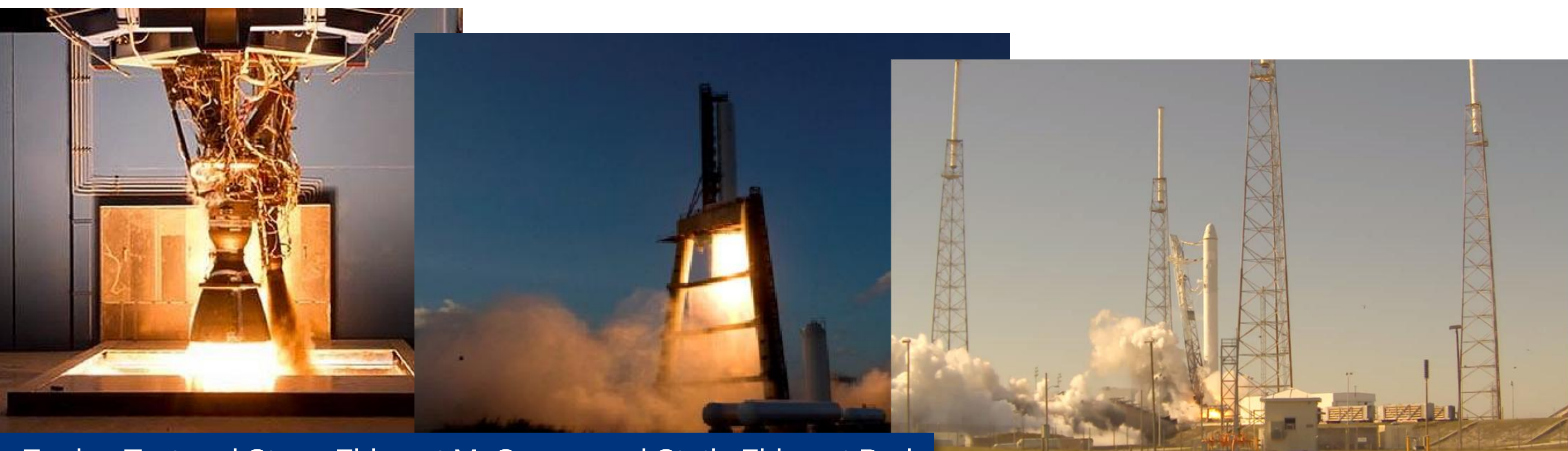


Documentation and process becomes more formal as systems move into later cycles
Final qualification, first flight and production

Test Like You Fly, Test *What* You Fly

Integrated testing tools are a key investment and provide points where integration is assessed and ensured using a “Test Like You Fly” approach

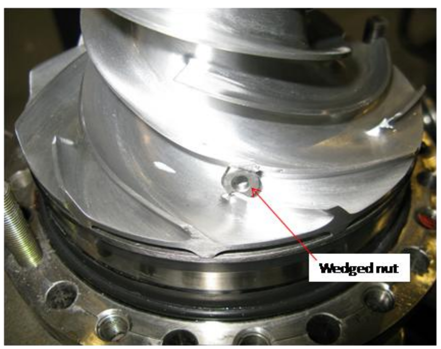
- Ironbirds at Hawthorne – hardware–software integration
- McGregor engine test – engine and avionics integration in real dynamics environment
- McGregor stage test firing– tanks, plumbing, avionics and propulsion integration in real dynamics environment
- Launch Site Hardware in the Loop Simulations - hardware-software integration with all system components
- Launch Site Wet Dress Testing and Static Fire - hardware-software integration with all system components in real dynamics environment



Engine Test and Stage Firing at McGregor and Static Firing at Pad

Flexible test hierarchy increases formality as product matures

- Development Tests used to determine hardware capability in excess of requirements and to find weaknesses (running at extended temperatures, ultimate strength tests)
- Qualification tests demonstrate hardware performance limits (worst case flight conditions plus required factor of safety or margins). Qualification tests are performed every design/environment combination
- Acceptance Tests verify workmanship and functionality. All hardware acceptance tested
- HITL – Hardware in the Loop – shows hardware-software integration. Run for every hardware-software change



M1C Merlin Engine Foreign Object Ingestion Demonstration Test

Thermal qualification of F9 separation system

Development Test – Composite Overwrap Pressure Vessel Ultimate

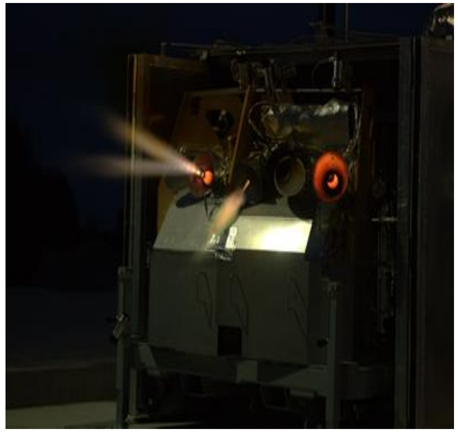
Thermal qualification test of Dragon Claw – connection between Dragon and Trunk

F9 First Stage Qualification Tank at McGregor, TX

Second Stage Acceptance Test Flight 3 – McGregor, TX

Component, Assembly and End to End Testing

Dragon Trunk – Falcon 9 Second Stage Separation Qualification Test



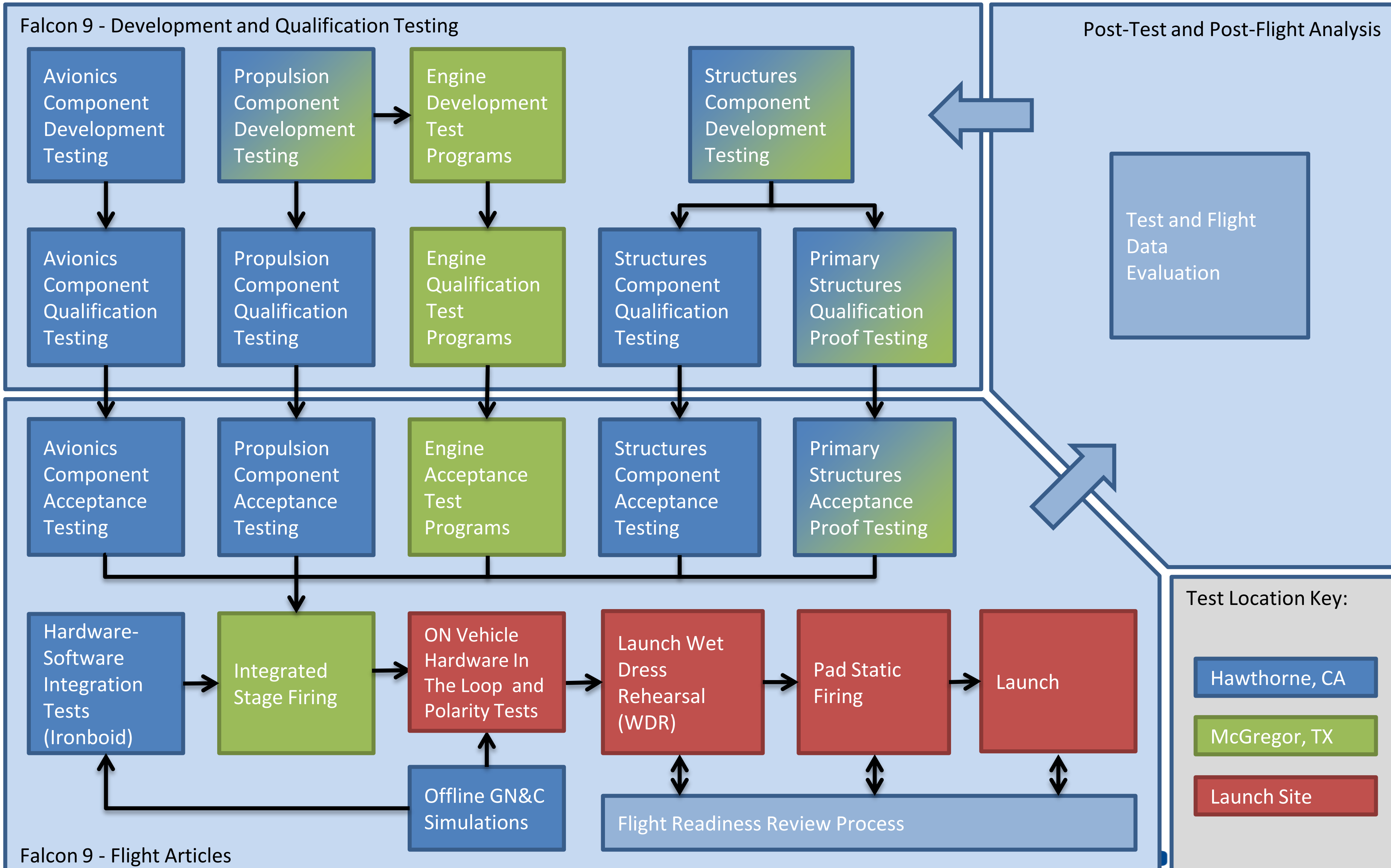
Draco (Dragon Thruster) Acceptance Testing

Merlin Nozzle Carbon Coating Development Test

DragonEye – Dragon Rendezvous Thermal Sensor) Shuttle Development Flight Test

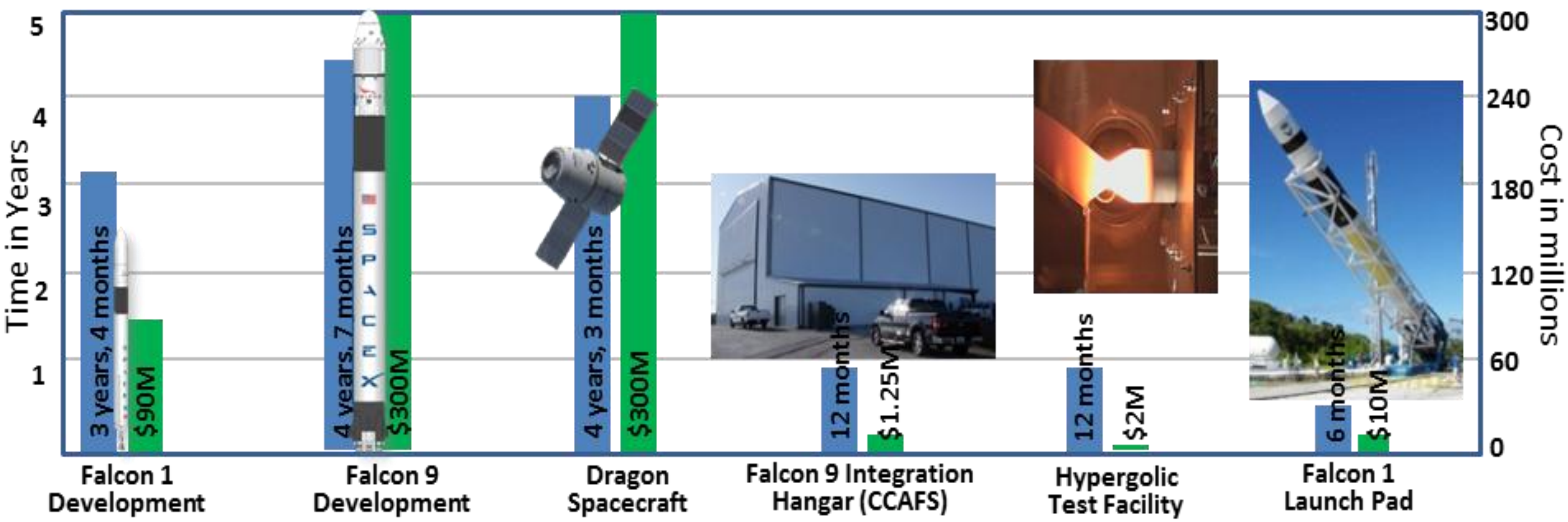
Space Station End To End Communications Testing

Test Process at SpaceX



Closing Thoughts

- It is difficult to build a creative high performance engineering culture
- It is really easy to ruin the creativity and performance by ***too much*** organization, rules and process
- SpaceX is achieving a good balance of creativity and systems engineering for agility and affordability

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