An Overview of Systems Engineering at JPL

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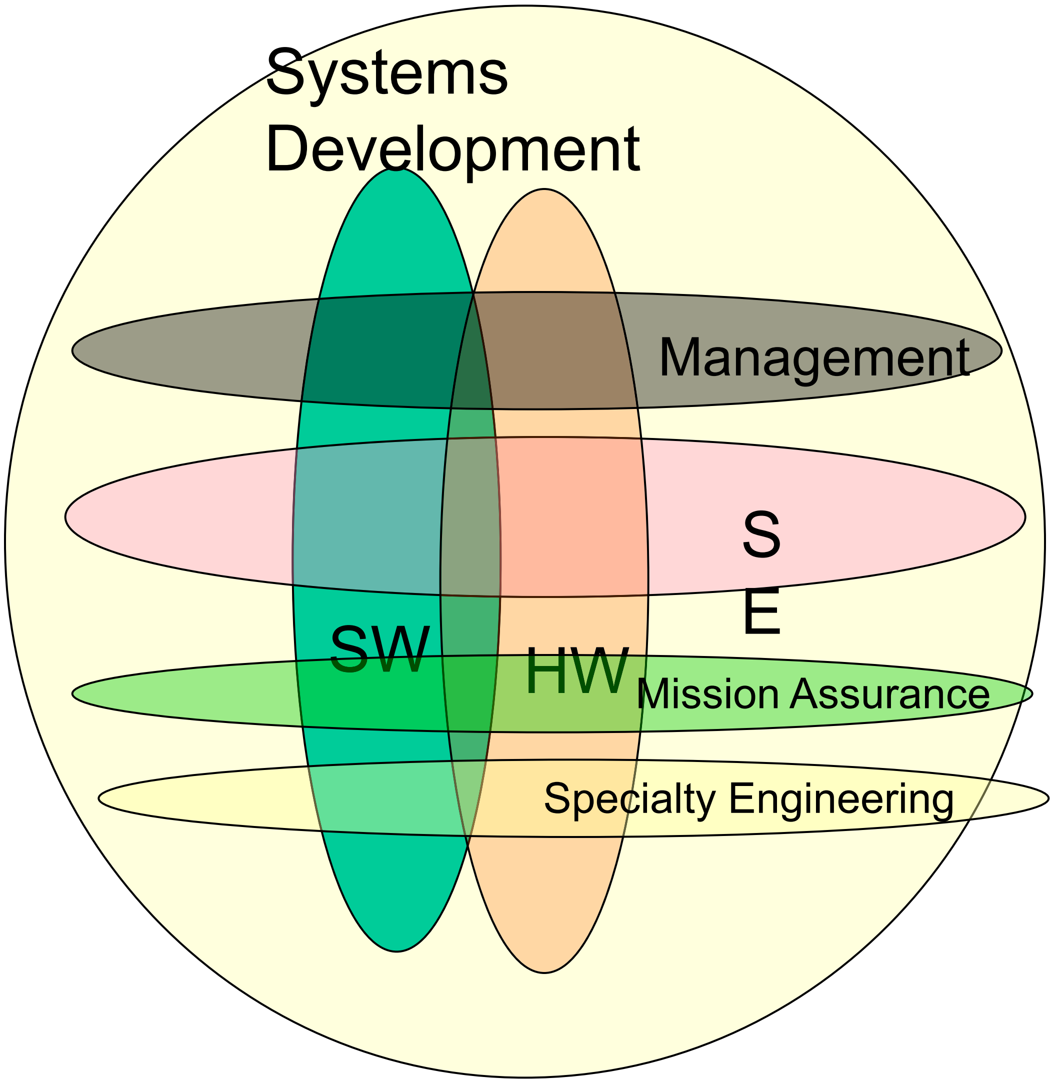
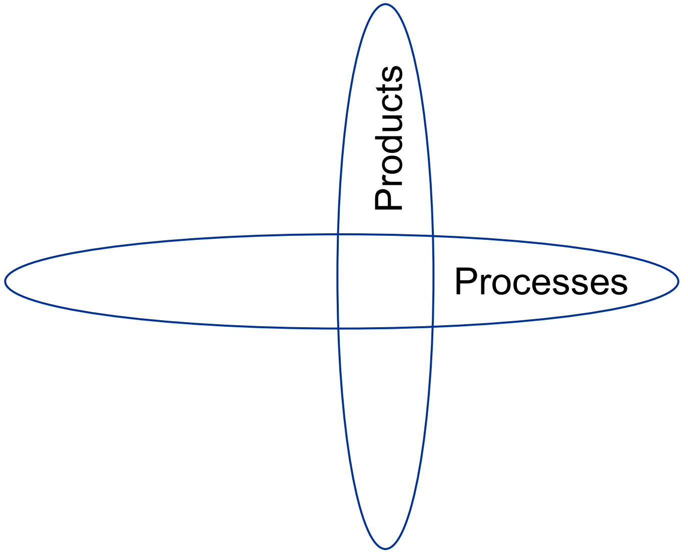
What is System Engineering At JPL?

- System Engineering is comprised of mixture of talents and behaviors that blend the various necessary disciplines together in a cohesive fashion in order to achieve and validate the desired objectives and requirements.
- System Engineers take ownership, at every level, of the entire product
  - Project
  - Flight System
  - Instrument
  - Subsystem
- System Engineers are the technical “conscience” of the Project
- System Engineering is a mixture of people, processes, and tools applied with technical knowledge and penetration into the substantive details of the development of a product
- Finally, System Engineering is all about leadership

Systems Engineering and Systems Development Distinction





Systems engineering is *only one* of the key activities that needs to be planned prior to embarking on the development of a system

Systems Engineering at JPL

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The JPL systems engineering process is defined to include the following 10 technical functions:

1. Architecting
2. Requirements
3. Analyze and Characterize the Design
4. Technical Resources and Performance Management
5. Interfaces
6. Verification and Validation
7. Manage Risk
8. Reviews and Systems Engineering
9. Requirements and Design Management and Control
10. Systems Engineering and Task Management

The highly valued personal behaviors of JPL systems engineers include the following:

1. **Leadership**
   - Has ability to influence
   - Has ability to work with a team
   - Has ability to trust others
2. **Communications**
   - Communicates the vision and technical steps needed to reach implementation
   - Communicates through story telling and analogies
   - Has ability to mentor and coach
   - Has ability to advance an idea
3. **Attitudes**
   - Has intellectual self-confidence
   - Is intellectually curious
4. **Problem Solving and Systems Thinking**
   - Has ability to effectively listen and translate information
5. **Technical Acumen**
   - Has ability to think critically
   - Has ability to manage change
   - Has ability to manage risk

Practiced across full life cycle, technical scope, and at all levels in a flight project

JPL Systems Engineering Practices

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What

- A body of requirements on how JPL practices systems engineering (SE)
  - Similar to the Software Development Requirements (DocID 57653)
  - Invoked via Flight Project Practices 6.4 (revised)
  - ~10 requirements for each SE function
- A process architecture

Why

- Reduce development and operations risk of our flight projects
- Improve the efficiency of the implementation of systems engineering
- Initiate a JPL “standard”
- Become aligned with NASA requirements and profession best practices (SE NPR, GSFC SE Directive, INCOSE, IEEE…)

When

- Rev 1 released Spring 06
- Currently in revision cycle

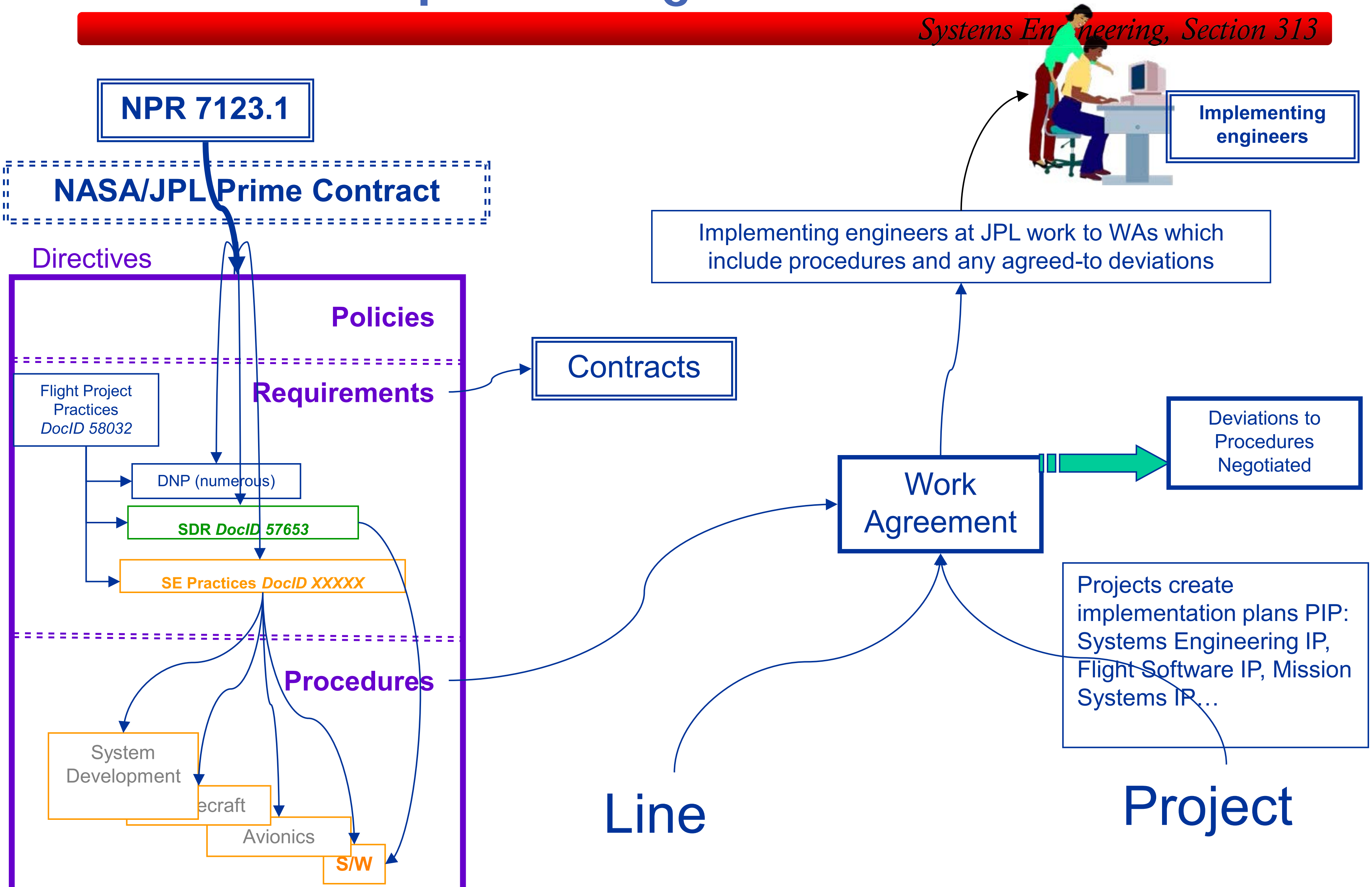
Who

- Led and championed by SE “function masters” from across the Lab

How

- Infused into our standard processes
- Taught in our Education Classes and OJT programs

Implementing SE Practices

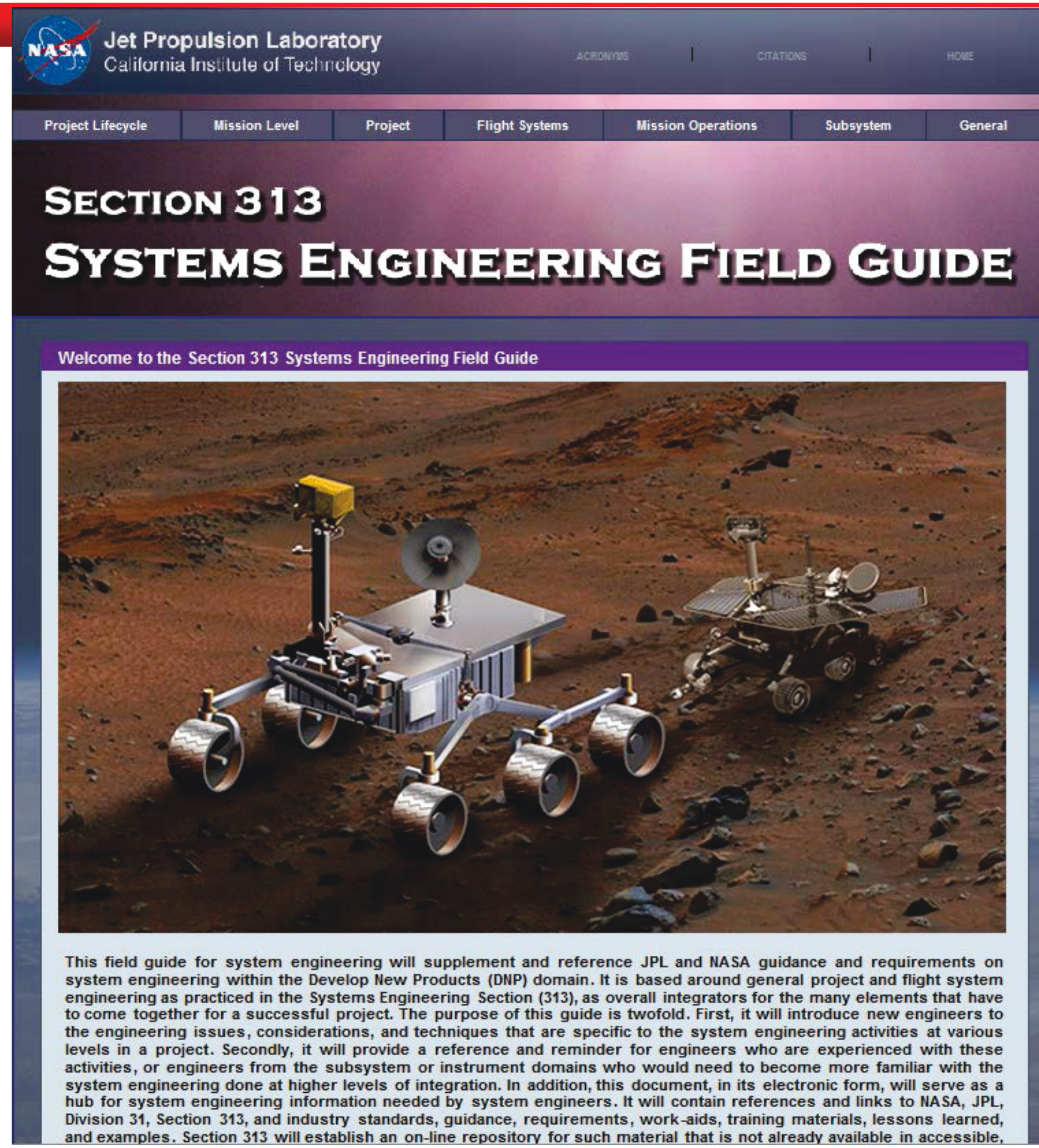


Implementing the System Engineering Field Guide

Home Page

The System Engineering Field Guide focuses on the “**How to**” of System Engineering more the “**what**”

This sets it apart from and is, arguably, more useful than, a suite of System Engineering procedures



Where System Engineering is Performed within a Typical Project

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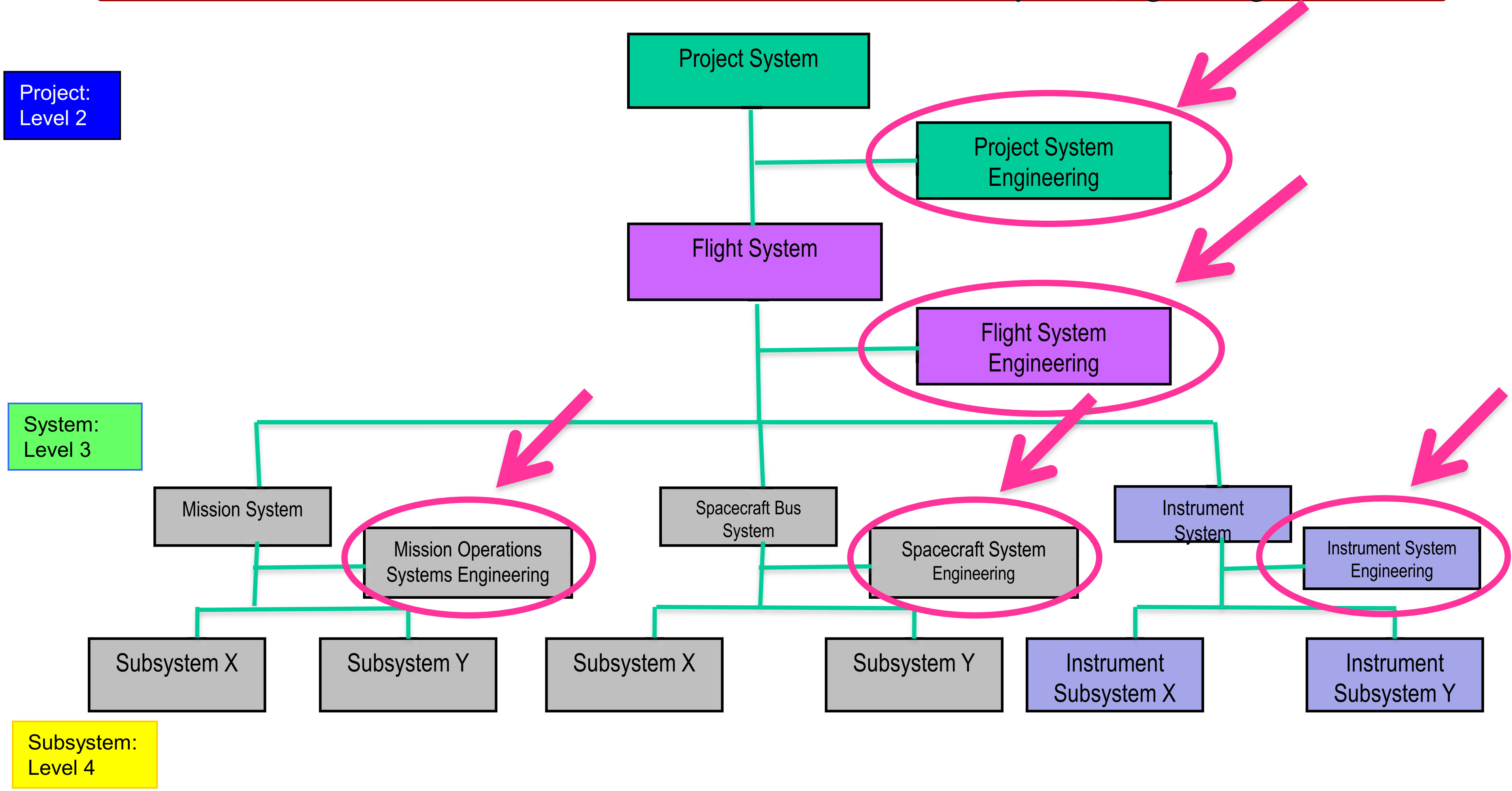

Example: Flight System Engineering Products

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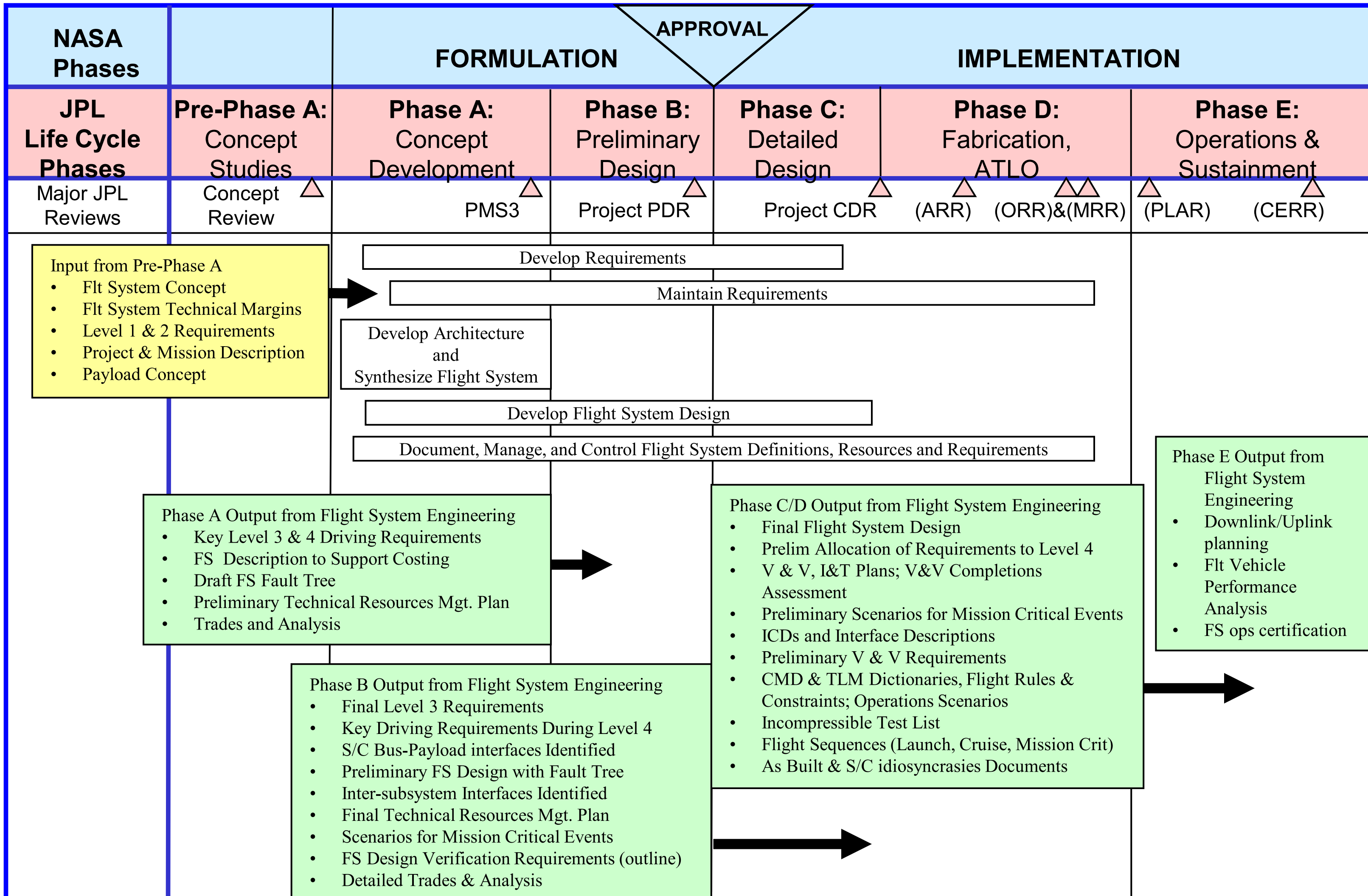

Developing the Flight System Architecture

- Development of Flight System Architecture consistent with:
  - Predetermined or Mandated Elements
    - Specification of Functional Capabilities
    - Specification and Clarification of Interfaces and Constraints
  - Inheritance
    - Identify and Assess Origin and Pedigree
    - Applicability and Required Adaptations
  - Design Requirements of Associated Elements
  - Risk Posture
    - Risk Identification and Mitigation
  - Cost and Schedule
  - Institutional Requirements
    - Design Principles; Flight Project Practices; etc.
  - Resource Constraints
    - Mass, Power, Memory, Bandwidth, Link Margins, etc.
- Systems Analyses for Architectural Design and Requirements Definition
  - Flight System/Ground System Trade Studies
  - Alternative Architecture Options
  - Mission Phase unique Analyses
  - Requirements analyses to identify cost, risk, schedule, and performance drivers

Example: System Engineering Trade Studies

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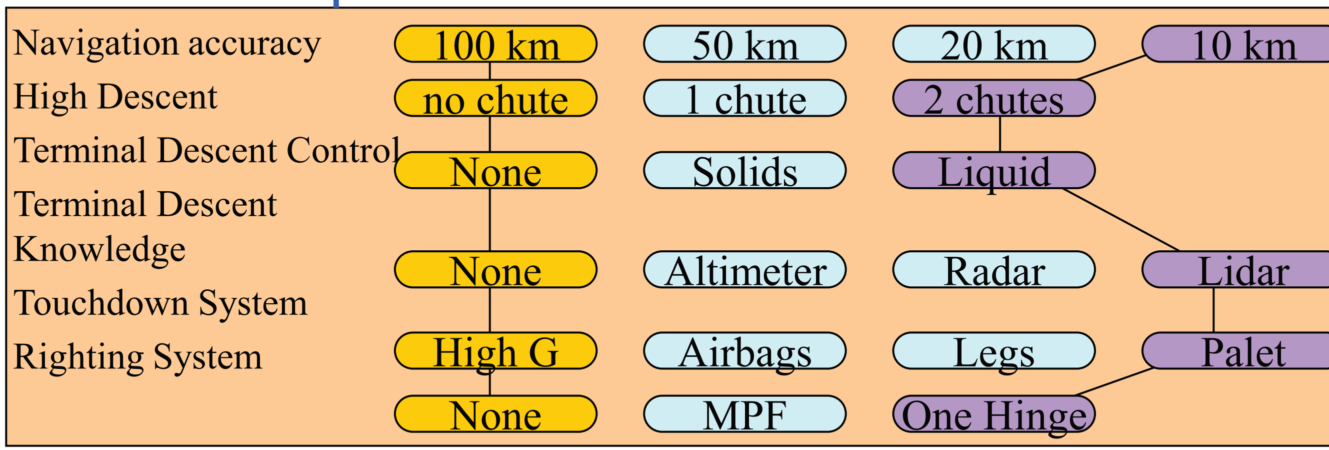
Trade Studies : To achieve balance among constraints such as cost, risk, schedule, and performance

- Project-level trades
- Support Flight-system-level trades
- Support Development of Methodologies



Example: Entry Descent and Landing Option Space

Example: Mars Lander + Telesat Design Options

Option	1	2	3	4	5
Description	Baseline: separate launches	1 launch, separate after launch	1 launch, separate at Entry -n days	1 launch, separate at Entry -1 hr	1 launch, on-orbit delivery
Cruise Stage Functions	Both vehicles	Both vehicles	Telesat plus Lander for n days	Telesat only	Telesat plus Lander deorbit
Telesat final Orbit	Full options	Full options	Constrained	Constrained	Constrained
Risks		R1	R1, R2	R1, R2, R3	R1, R2
Delta Cost	N/A	-$$$	-$$	-$$$$	-$
Injected Mass					

Sources for System Requirements

- Higher-level requirements
  - Especially science requirements
- Use cases
- User needs and objectives
  - Performance
  - Supportability
  - Measures of effectiveness
  - Environments
  - Constraints
- Technology integration
- Requirements applied through specifications and standards
  - JPL Design Principles
  - JPL Flight Project Practices
  - JPL Systems Engineering Practices
  - NASA, IEEE standards, etc.
- Concept studies
- Operational goals/constraints
  - Affordability
  - Interoperability
  - Intraoperability
  - Upgrades/system evolution
  - Component reuse
  - Legacy constraints
- Output requirements from prior development efforts
- Other sources
  - Legal
  - Physics
  - JPL program office
  - Part or subsystem capabilities

Generic FS Requirements Hierarchy

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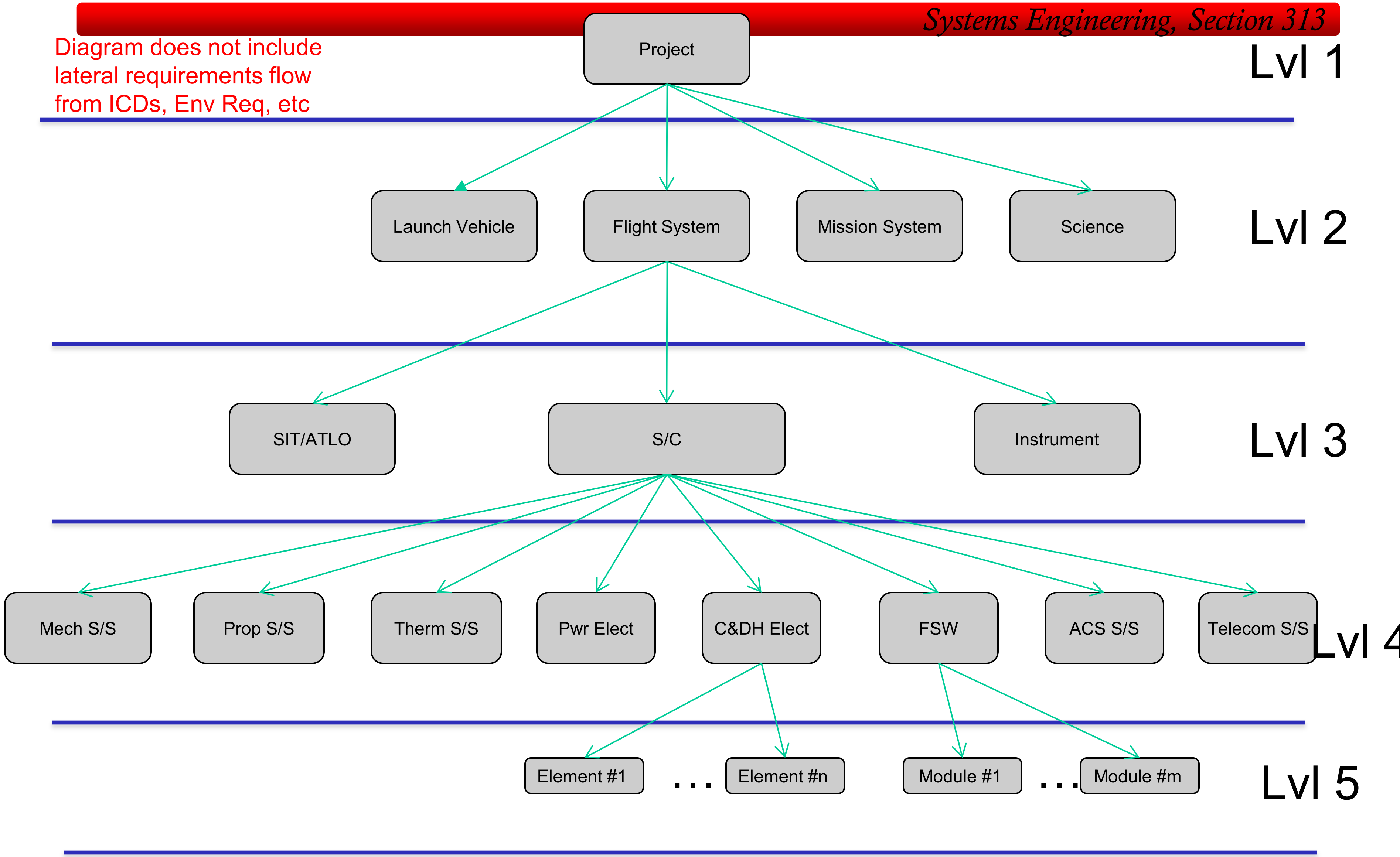
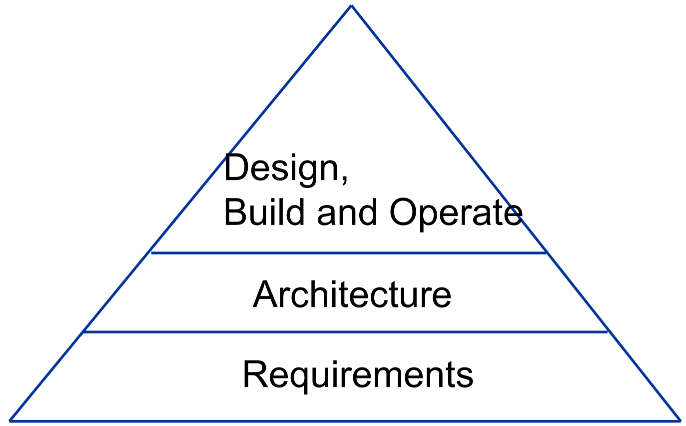
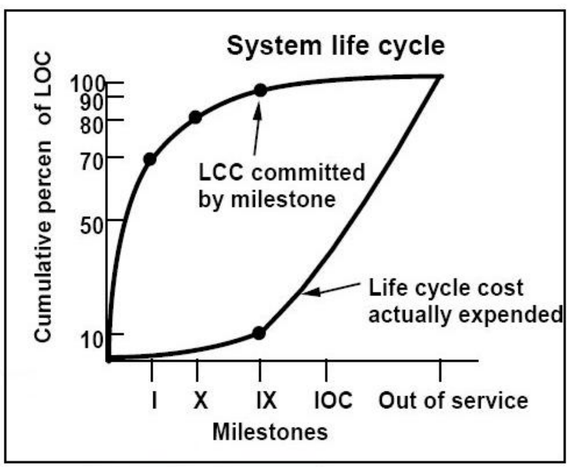
Diagram does not include lateral requirements flow from ICDs, Env Req, etc



Why Requirements Are Important



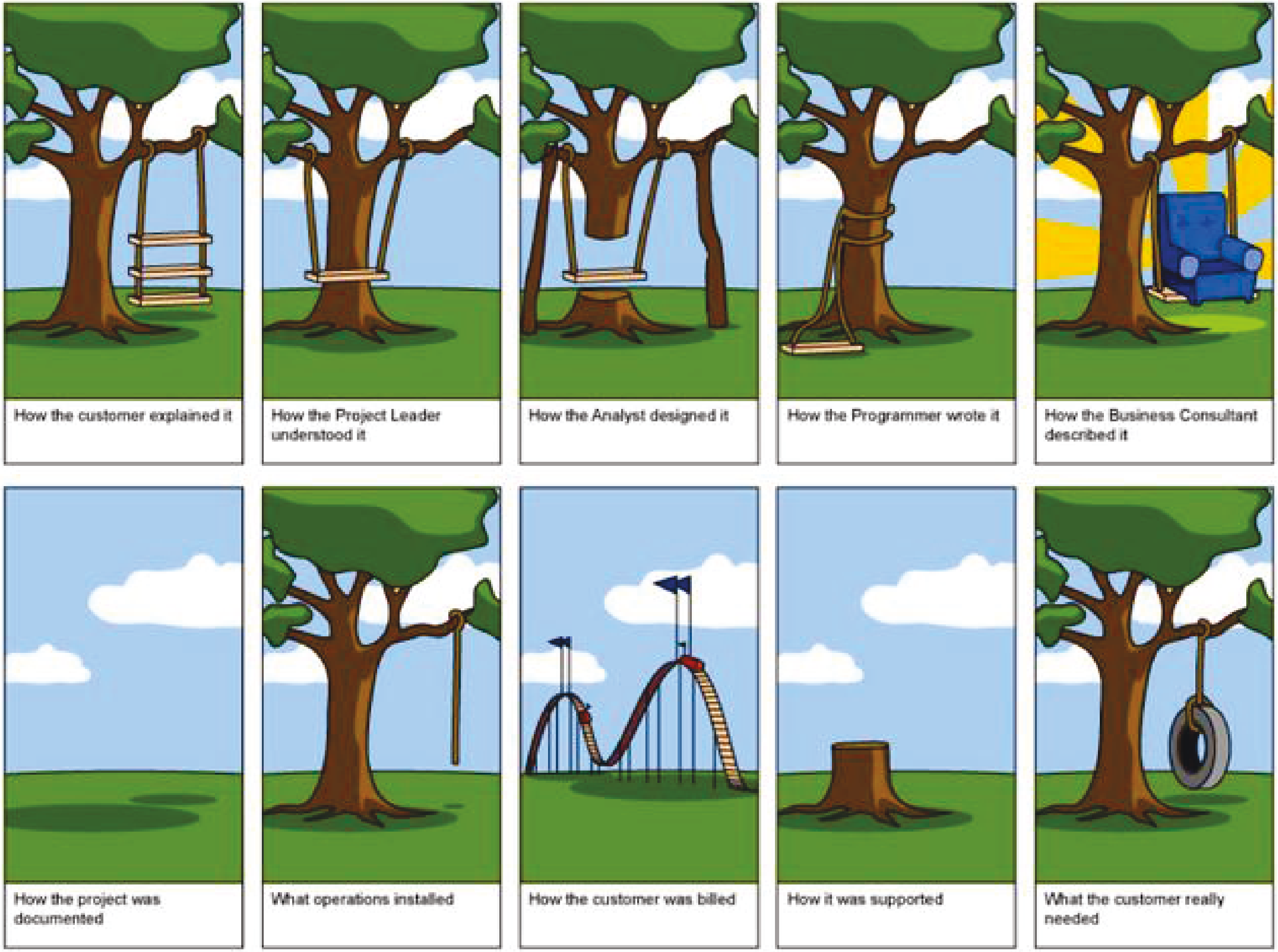
Good requirements are the foundation for success



Early decisions have a big impact

- What did you sign up for?
- How do you know when you are done?
- Will your customer be happy?

Rationale for Well-Developed Requirements



How the customer explained it

How the Project Leader understood it

How the Analyst designed it

How the Programmer wrote it

How the Business Consultant described it

How the project was documented

What operations installed

How the customer was billed

How it was supported

What the customer really needed

Developing the System Design

- Support Development of the System Design
  - Contribute to the Creation and "Wear the Big Hat" for what the System is and How it Works
  - Ensure Consistency with Requirements
- System Design Specification
  - Identify/Specify "Other" Systems within the System
    - Fault Protection
    - System level FSW
  - Specification of Subsystems and Interfaces
  - Consider flight/ground trades, mission-level trades, cross-instrument trades
  - Specification of Required Technical Resources (e.g. mass, power, memory, etc.)
  - Trade Studies
    - Impacts of Changes to Cost, Technical Performance, and Risk
    - Cross Subsystem Issues
      - Including Flight Software
- Maintain Technical Awareness for the System as a Whole
  - Cost, Technical Performance, and Risk Consistent with Requirements
  - Risk Trades and Analysis
  - Configuration Control/Management
- Support and Contribute to the Definition of System Nomenclature including Product Reference System

Developing the Cross-Subsystem System Design

- Development of Strategies for Managing Resources shared across the System
  - Mass, mass properties
  - Power/energy
  - Memory, CPU
  - Link margin
  - Power switches
  - Pyro-circuits
  - Error budgets (performance, alignment, dynamics & control, etc.)
  - Other expendables (cycles, fuel, etc.)
- Definition of Interfaces
  - Flight to Ground ICDs, Spacecraft to Instrument, etc.
  - Inter-System ICDs (Mechanical, Thermal, Electrical, Data etc.)
    - Assure implementation of interfaces with System Peers
  - Definition and Documentation of Interfaces between Subsystems

Developing the Cross-Subsystem System Design (cont.)

Development of Requirements on the System that cannot be met by any one Subsystem acting alone

- Functional Areas – Examples such as:
  - High level FSW behaviors
  - Entry, Descent and landing (EDL)
  - Orbit Insertion
  - System Fault Protection
    - System Fault Tolerance, cross-strapping and redundancy
- Phased System Engineering
  - Uses elements of the Flight system for the achievement of specific operations
    - E.g., Launch, Cruise, EDL, Surface Ops
- Risk Trades
- Integrated software/sequence interactions
- Command and Telemetry Dictionaries
- Flight Rules
- Electrical Interface SE (include Circuit Analysis and Grounding)

Example: Flight System Engineer Interactions with Subsystems

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CONSTRAINTS
- 313 Flight Systems Engineering Procedure
- Institutional Standards, Guidelines,
- FPP, DP & Procedures

Flight System Engineering Level 3

- Develop Flight System Requirements
- Define Flight System Architecture
- Design Flight System
- Define and Control Interfaces
- Allocate, Track & Control Technical Resources
- Perform Technical Analysis
- Maintain System Margins
- Verify FS Design vs. Requirements
- Validate FS Design
- Manage and control FS Risk
- Ensure review of FS Design
- Manage & Control Flight System Design, Configuration and Risk

RESOURCES
- DNP Process & Customer Support
- Previous Project's Flight System Engineering Materials
- DOORS
- Section 313 Reference Library
- Infrastructure

→

- Flight System Architecture & Design
- Level"3" Requirements & Requirements Allocated to Level "4"
- Level "3" Interface Agreements, Descriptions & Boundary Conditions
- Flight System Performance Requirements
- Block, Data Flow & State Diagrams
- Flight System Resource Estimates
- FS Schedule
- FS Risk Parameters
- FS Performance, Mass, Power Resources
- Margin Assessments and Spares Policies
- Flight System V & V Requirements & Implementation
- Process Control and Configuration Mgt. (ECRs, PFRs, etc.)

←

- Detailed Subsystem Design
- Detailed analysis and models
- Interface details and designs
- Allocation reports
- Capabilities against requirements
- Subsystem schedules and deliverables
- End Item Data packages

CONSTRAINTS
- Division Work Agreements
- Institutional Standards, Guidelines,
- FPP, DP & Procedures

PEM Support at Level 4

- Develop Subsystem Requirements
- Design Subsystem
- Define and Control Interfaces
- Allocate, Track & Control Technical Resources
- Perform Technical Analysis
- Verify Subsystem Design vs. Requirements
- Manage and control Subsystem Risk
- Ensure review of Subsystem S Design
- Manage & Control Subsystem Design, Configuration and Risk
- Maintain Subsystem margins

RESOURCES
- Documented Processes
- Previous Project's Engineering Materials
- Discipline specific tools
- Institutional Infrastructure

System Technical Resources

- SEs supports the Development and Tracking of Technical Resource Allocations
  - Mass, Power, Memory, Telecom Link Margins, CPU Utilization, Bus Bandwidth, Switches, etc.
  - Allocations from System to Subsystems
  - Margins Tracked per Design Principles
    - Allocations and Current Best Estimates (CBEs)
      - Margin (%) = ([Allocation - CBE]/Allocation)*100
    - Required Margins vary across the Development Cycle
      - Decrease with Increasing Knowledge as approach Launch
  - Resource Problem Resolution
    - Minimize Impacts across System
      - Internally Re-balance within Allocation
    - Renegotiate Allocation with Flight System
      - Flight System may Increase Allocation with Release from Reserve
      - Subsystem may Return Excess Allocation

Flight System Change Control

- SEs Lead the Change Control Process
  - Documents and Designs "Frozen" consistent with Project Plans
    - Changes Require adherence to Formal Process
      - Engineering Change Request (ECR)
      - Impact Assessment
      - Review
      - Approval (or Denial)
      - Authorization to Implement Change
      - Revision and Reissue of Updated Document
    - Ensure Complete Assessment and Identification of All Impacts and Affected Parties
    - Orderly Control and Communication of Changes
  - Problems found with Flight Equipment during VnV efforts are managed and tracked in Problem Failure Reports (PFRs)
    - Finding out and fixing the cause, fixing and closing out PFRs before Launch is the monumental task of the VnV effort before launch

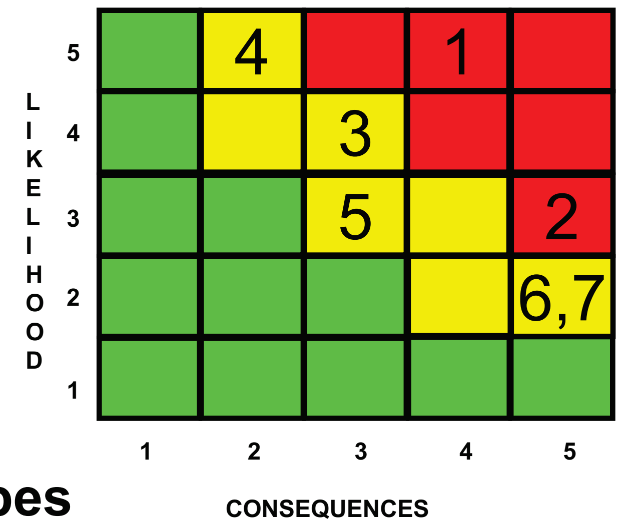
Defining Fault Tolerance & Redundancy as Driven by Flight Project Practices

- Fault analysis' efforts, to determine possible failure modes and to scope / design requisite fault protection mechanisms
- Coordinated support for required level of System Fault Tolerance and use of redundancy and cross-strapping prior to PDR
- Contribute to (for Projects with single fault tolerant policy):
  - List of potential single point failures (SPF) prior to PDR; keep and report on list of accepted SPFs
  - Assess likelihood of SPFs
  - Explore mitigation options for credible SPFs; perform system trades

System Risk Management

- Identify and assess consequence and likelihood of Flight System Risks (including effect on performance, margins and reserves)
- Keep and report Top 10 (+/-) Flight System technical concerns lists
- Brainstorm, assess and organize Flight System descope options

Risks



Descopes

Item	Cost Savings	Impacts	Latest Decision Date
Eliminate 1 testbed	$	Limited verification of X	November
Nadir measurements only	$$	Few targeted observations	January

Conduct Reviews

- Reviews are Conducted throughout the Development Cycle
  - Key Milestones
    - Life Cycle - KDPs (e.g., PMSR, PDR, CDR, SIR, LRR)
  - Peer Reviews at the System and Subsystem Levels
    - Involve Experts
    - Preparatory for Major Milestone Reviews
    - Early Identification of Issues/Concerns
  - Ad Hoc as Appropriate
    - Assess Progress
    - Respond to Actions
    - Transition Points

System Verification and Validation

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Verification: demonstrates that the system Satisfies its design requirements

- Testing is the preferred method of verification (T)
- If analysis or simulation: results must be independently verified (A)
- If inspection: performed on the final, as-built configuration (I)
- If demonstration: performed via physical action (D)

Requ men	Funct Own	Requir	Veri... Meth	Test F Venu	Inco pres ible
329	FS Level 3	Flight Software shall ...	Test	Testbed	TBD
331	FS Level 3	The Flight shall ...	Test	ATLO (Both	System
332	FS Level 3	All Flight H shall be	Test	ATLO (Both	System
333	FS Level 3	The Payloads shall be	Test	Testbed	TBD
335	FS Level 3	Thermal shall	Test	ATLO (Both	System TBD
339	FS Level 3	FSW shall...	Test	Testbed	TBD
389	FS Level 3	Telecom shall	Test	ATLO (Both	System
495	FS Level 3	The System shall be ca	Demonstration	Testbed	No
604	FS Level 3	The cruise system ...	Analysis	Flight System	Unknown

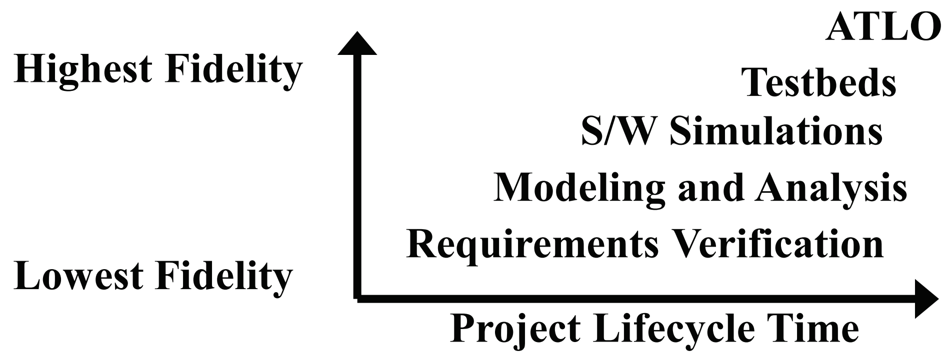
Example V & V Matrix

Validation: demonstrates that the system actually performs as intended

- Mission design validation: simulate enabling sequences
  - For launch and early cruise, validation requires the flight vehicle and the launch version of the flight software
- Navigation design is validated by peer review by subject matter experts

Capability	Capability Dem... ATL Tes	Miss Scen Tes	OR	Ost
Pre-Launch Capabilities				
[illegible]				
Launch/Ascent/Separation Recovery Capa				
[illegible]				
Engineering Housekeeping Capabilities				
[illegible]				
Primary Mission Capabilities				
[illegible]				

Verification Approaches



- - Requirements based
- - Utilizes a combination of:
  - 1)Modeling and simulation
  - 2) Testbeds
  - 3)Testing on the Flight Article
- - Verifies interfaces between lower level Subsystems
  - - Includes concurrence by SE of S/S verifications
- - Culminates in Assembly, Test and Launch Operations (ATLO)
- - Flight environmental requirements
  - E.g., “shake and bake”-

Summary of System Engineering @ JPL

- System Engineers are involved in all phases of the project lifecycle
- System Engineers “OWN” the technical challenges
- Systems Engineers lead the definition & allocation of requirements, functions and interfaces through an iterative design & verification/validation process
- Lead System Risk Management
  - Identification, Assessment, Mitigation and Close Out
- Lead/support Verification and Validation (V&V)
  - Planning
  - Implementation
  - Integration and Test
- Launch and Operations
  - Launch Vehicle Interfaces and Environments
  - Launch Hold Criteria
  - Launch Readiness
  - Flight Rules
  - Command and Telemetry Dictionaries
  - Early In-flight Operations

- This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.