Systems Engineering Design

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September 16, 2009

Systems Engineering

A System Is ...

Simply stated, a system is an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective.

Systems Engineering Is...

Systems engineering consists of two significant disciplines: the technical knowledge domain in which the systems engineer operates, and systems engineering management.

It is an interdisciplinary approach that encompasses the entire technical effort, and evolves into and verifies an integrated and life cycle balanced set of system people, products, and process solutions that satisfy customer needs.

Systems Engineering

Systems Engineering Management Entails...

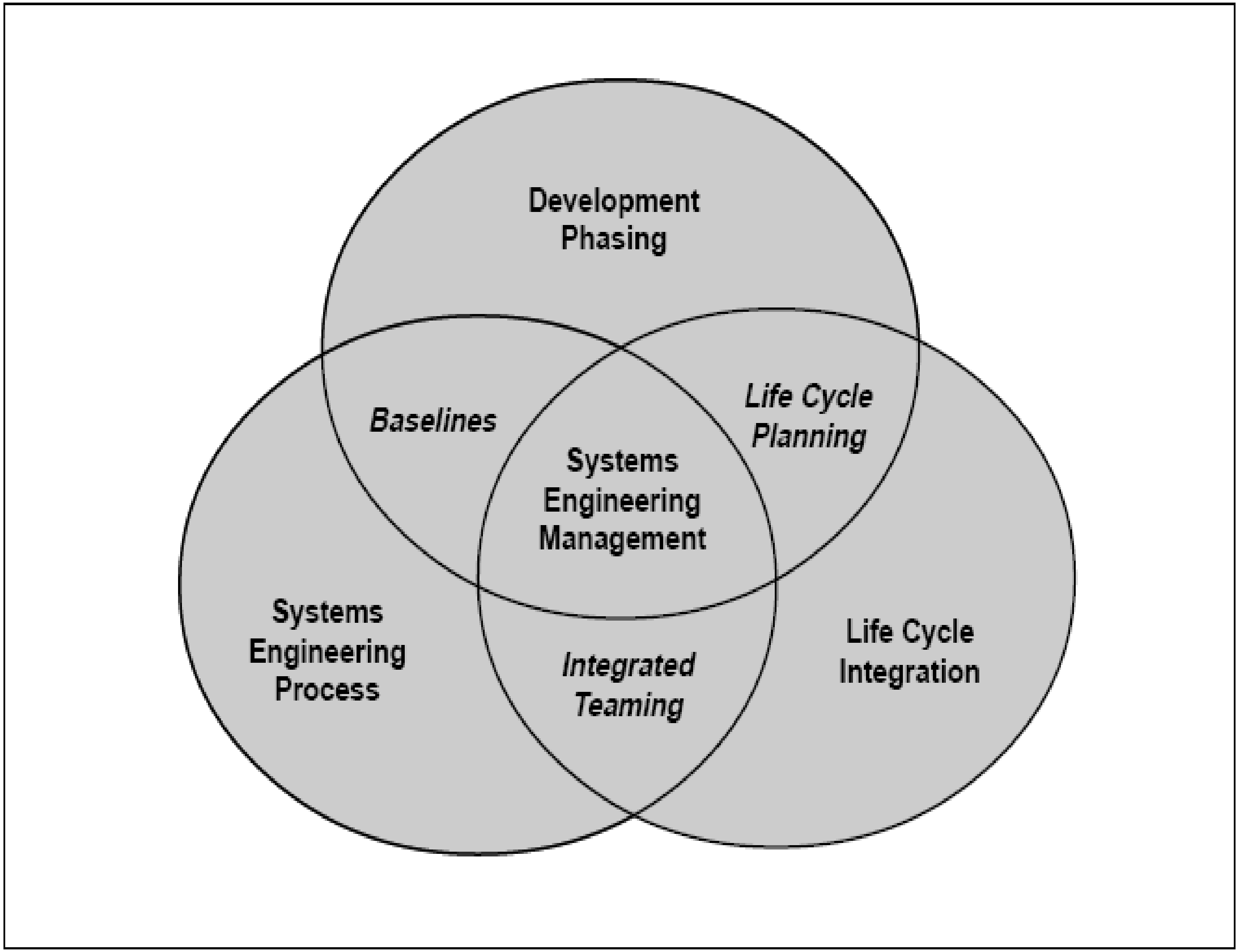
Systems engineering management is accomplished by integrating three major activities:

• Development phasing that controls the design process and provides baselines that coordinate design efforts,

• A systems engineering process that provides a structure for solving design problems and tracking requirements flow through the design effort, and

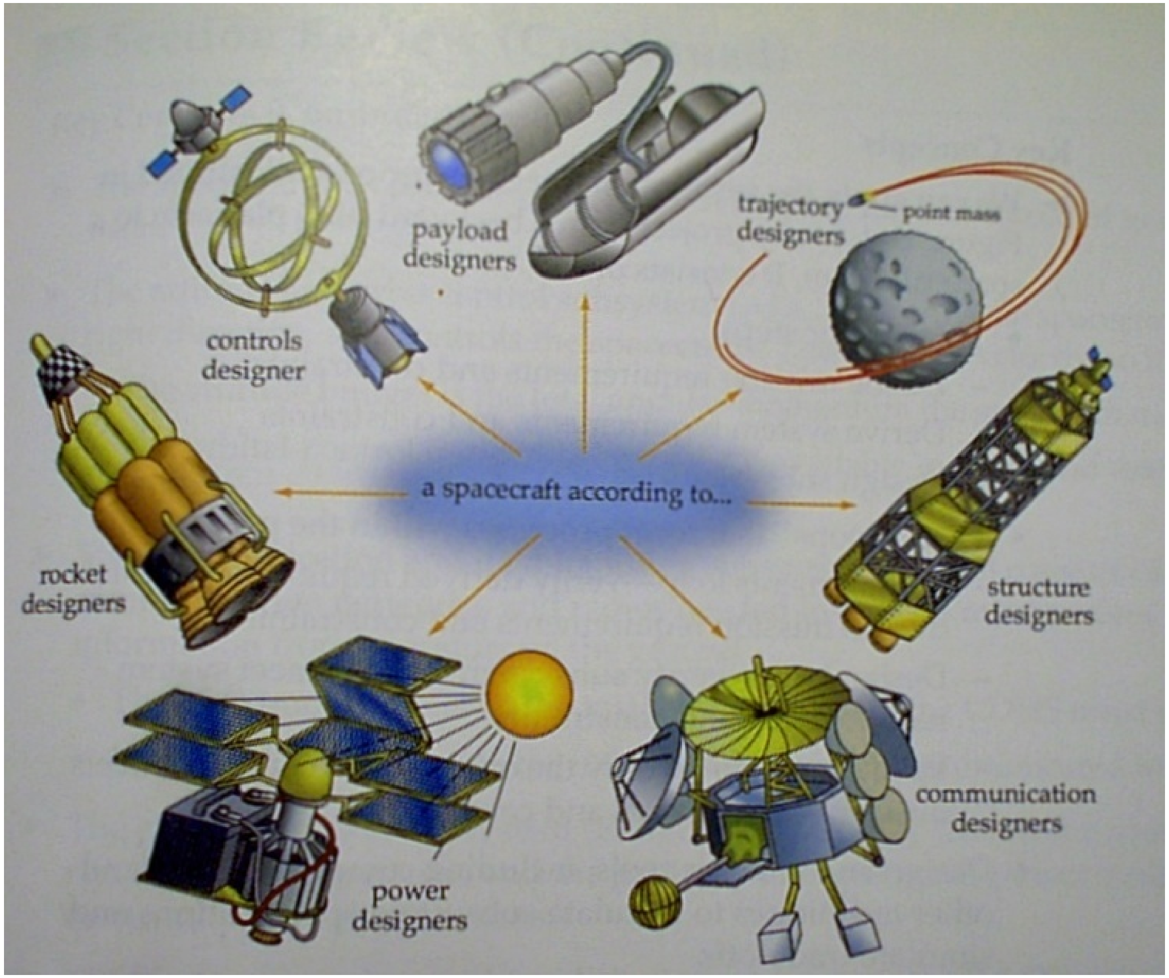
• Life cycle integration that involves customers in the design process and ensures that the system developed is viable throughout its life.

Systems Engineering



Three Activities of Systems Engineering Management

Systems Engineering

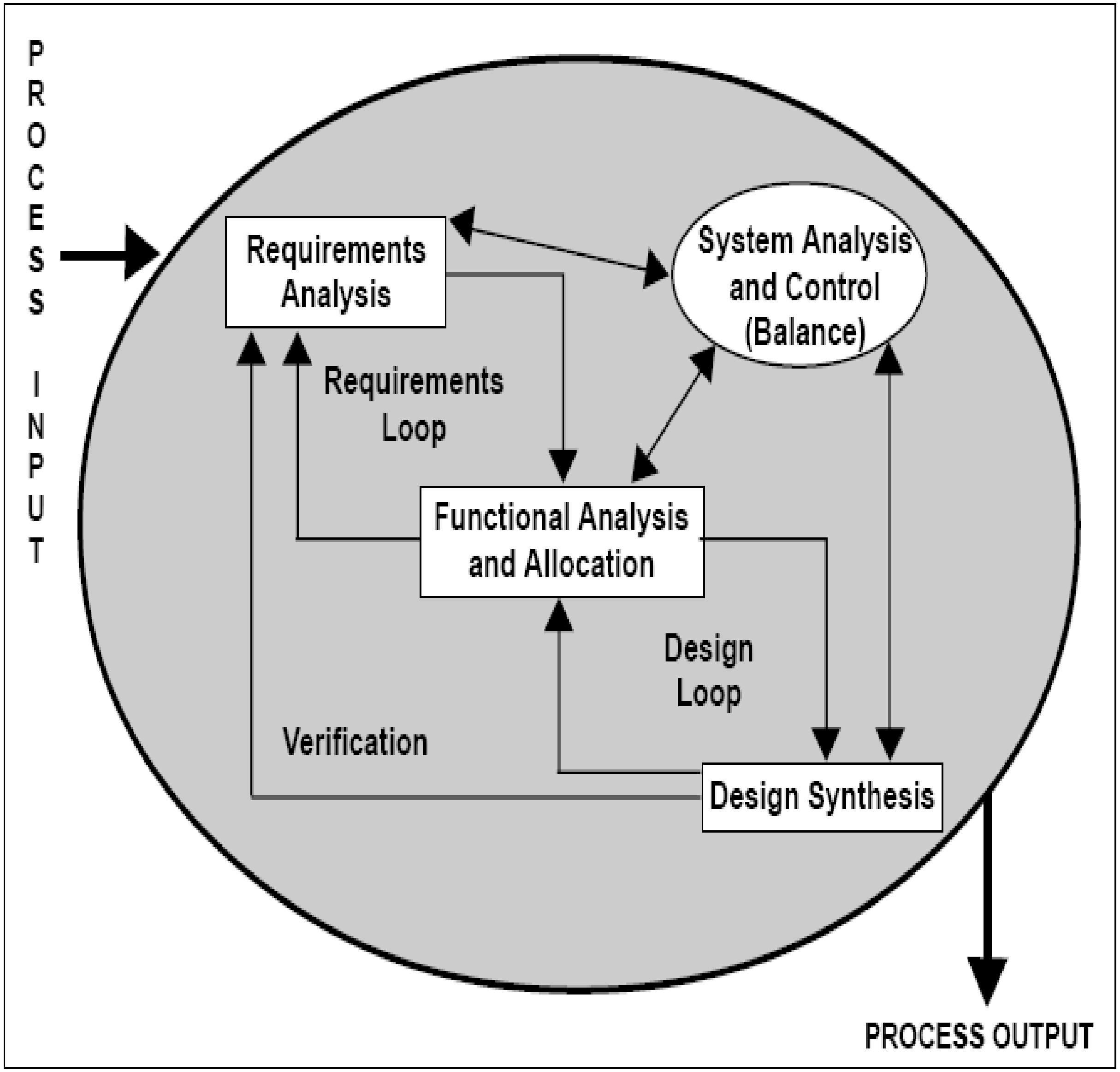


… "a spacecraft according to …

• **Sometimes individual subsystem designers get so focused on their subsystem designs that they lose sight of the overall mission objectives and requirements**

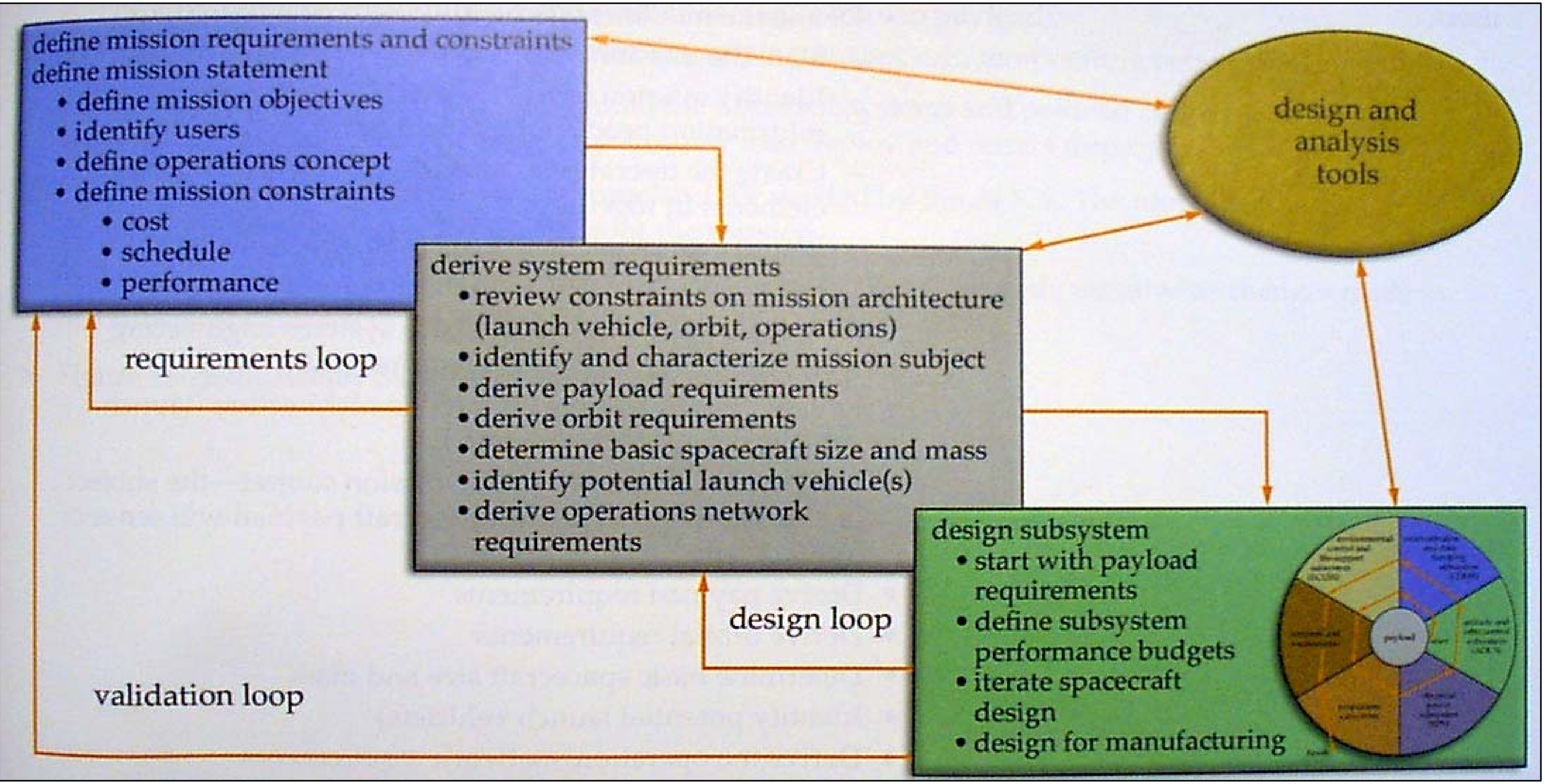
• **Good systems engineering coordinates the activities of disciplinary groups with disparate design objectives**

Systems Engineering Process



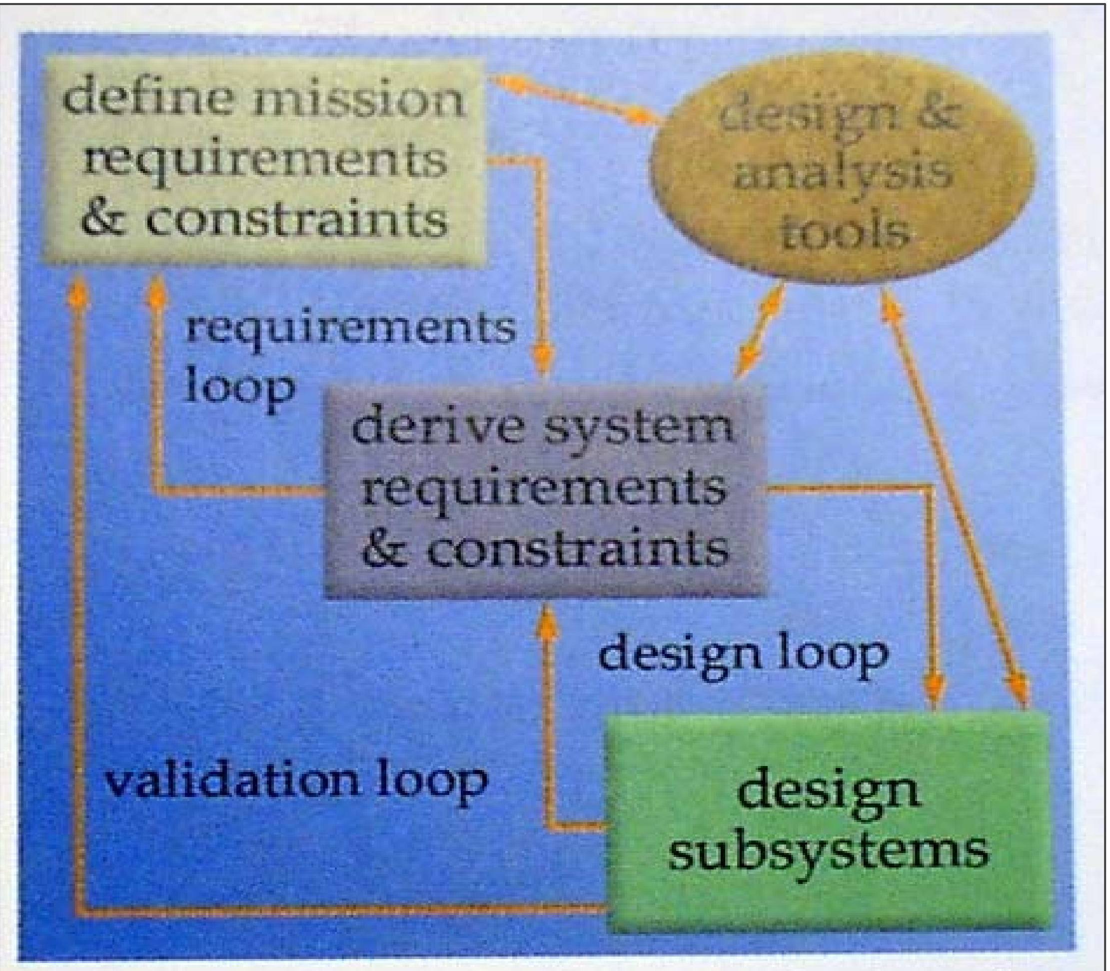
The Systems Engineering Process

Systems Engineering Process



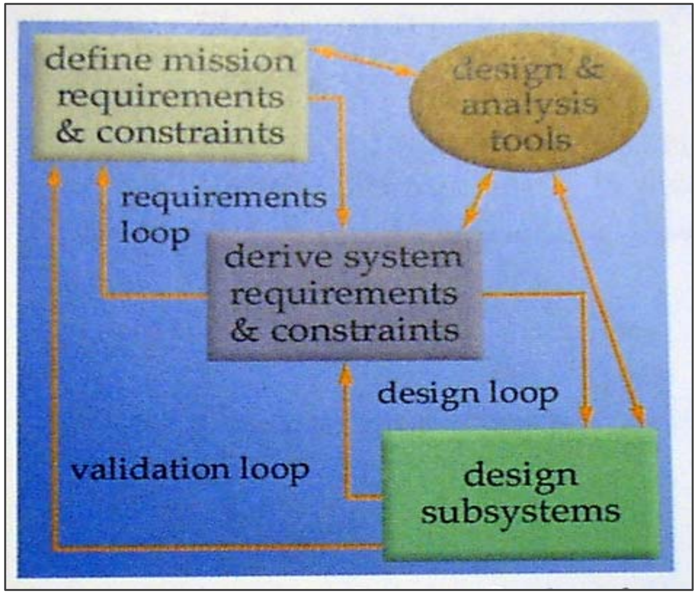
• By following a well-defined process, systems engineers design systems that meet mission requirements, while staying within budget and conforming to constraints

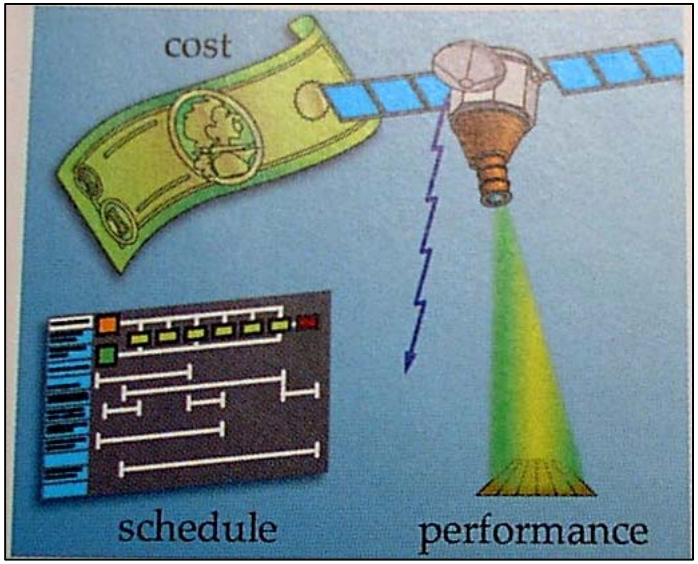
Systems Engineering Process



- Systems Engineering is a fundamental process that can be used to design anything from a backyard grill to a crewed-space platform.
- Each step utilizes established design and analysis tools.
- The process is iterative.
- Between process steps there are "feedback loops" to review decisions made in previous steps.

Systems Engineering Process



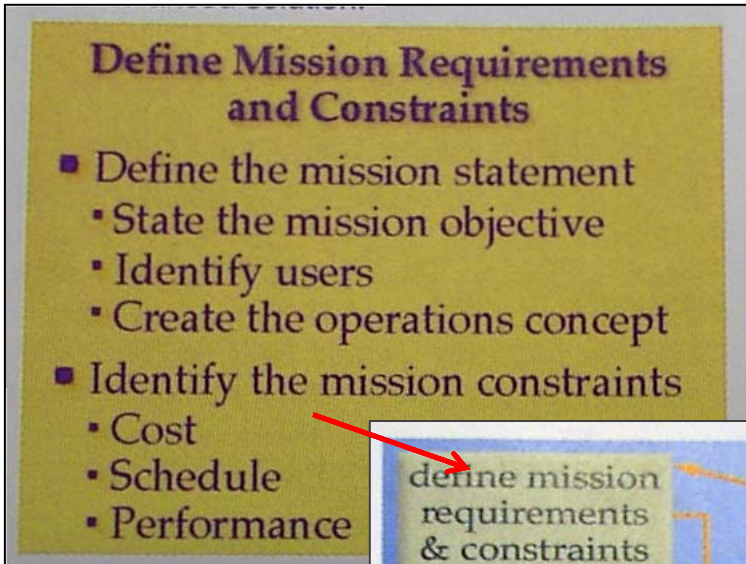


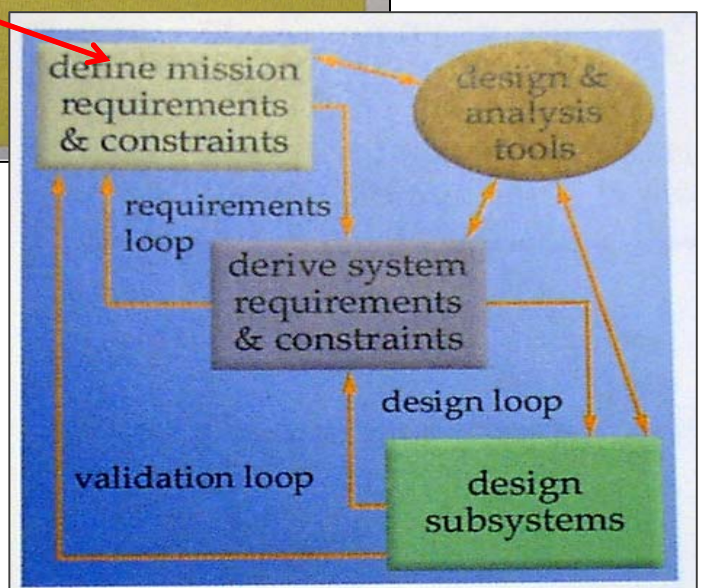
Cost, Schedule, Performance

- **3-D trade space that mission must operate within.**

- **Systems engineers continually trade competing objectives to achieve well-balanced solution -- “optimal” solution often not-achievable**

Systems Engineering Process





- **First phase in design process is to define the mission requirements, objectives, and constraints.**

- **Often documented and detailed in the mission "Objectives and Requirements Document."** ***(ORD)***

Types of Requirements
Technical Management

- Customer
  - Facts and assumption defining expectations
- Functional
  - The task that must be accomplished
- Performance
  - The extent to which a requirement must be executed
- Design
  - The requirements derived from technical data
- Derived
  - The requirements are derived from implied, higher-order requirements
- Allocated
  - The requirement is derived from dividing a higher level requirement

Types of Requirements
Operational

Operational distribution or deployment: Where will the system be used?

Mission profile or scenario: How will the system accomplish its mission objective?

Performance and related parameters: What are the critical system parameters to accomplish the mission?

Utilization environments: How are the various system components to be used?

Effectiveness requirements: How effective or efficient must the system be in performing its mission?

Operational life cycle: How long will the system be in use by the user?

Environment: What environments will the system be expected to operate in an effective manner?

Operational Requirements – Basic Questions

Good Requirements

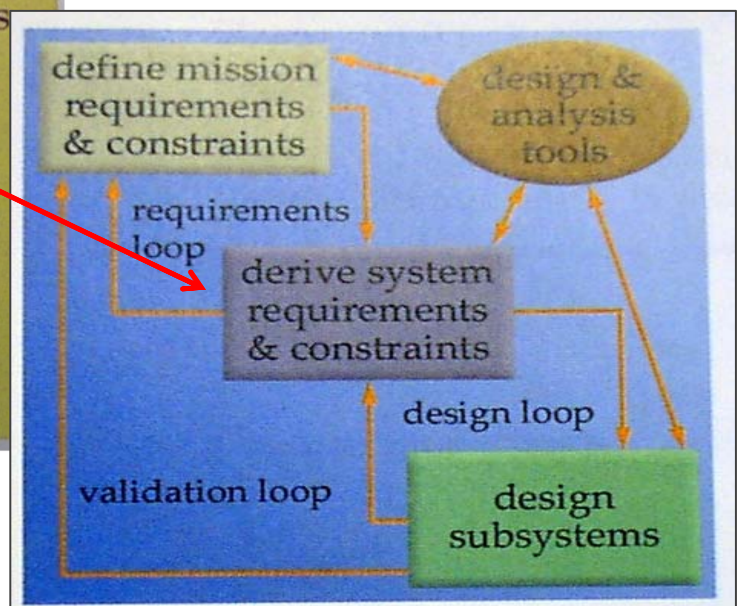
- Achievable
- Verifiable
- Unambiguous
- Complete
- Consistent
- Needs

Requirements Analysis

Derive the System Requirement

- Review the constraints on mission architecture (launch vehicle, orbit, operations, etc.)
- Identify and characterize the mission subject
- Derive payload requirements
- Derive orbital requirements
- Determine basic spacecraft size and mass
- Identify the potential launch vehicle(s)
- Derive operations systems requirements

- **Second phase of the design is to define the required sub-systems, and derive their requirements to meet the programmatic mission requirements**



"Derived Requirements"

Requirements Analysis

Requirements analysis involves defining customer needs and objectives in the context of planned customer use, environments, and identified system characteristics to determine requirements for system functions.

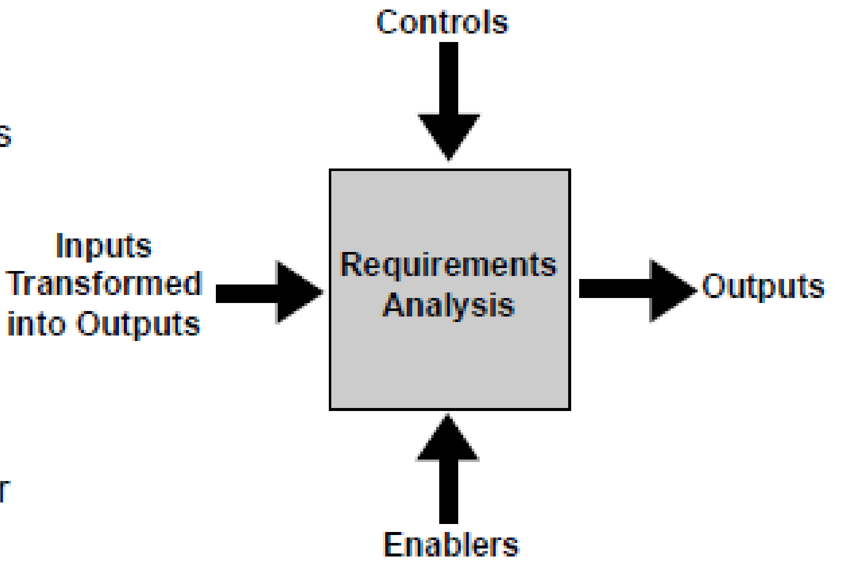
Requirements analysis is conducted iteratively with functional analysis to optimize performance requirements for identified functions, and to verify that synthesized solutions can satisfy customer requirements.

In general, Requirements Analysis should result in a clear understanding of:

- Functions: What the system has to do,
- Performance: How well the functions have to be performed,
- Interfaces: Environment in which the system will perform, and
- Other requirements and constraints.

Requirements Analysis

- **Inputs converted to putputs:**
  - Customer requirements
  - Mission and MOEs (MNS, ORD)
  - Maintenance concept and other life-cycle function planning
  - SE outputs from prior development efforts
- **Controls:**
  - Laws and organizational policies and procedures
  - Military specific requirements
  - Utilization environments
  - Tech base and other constraints
- **Enablers:**
  - Multi-disciplinary product teams
  - Decision and requirements database including system/configuration item descriptions from prior efforts
  - System analysis and control



Inputs to Requirements Analysis

Requirements Analysis

1. Customer expectations
2. Project and enterprise constraints
3. External constraints
4. Operational scenarios
5. Measure of effectiveness (MOEs)
6. System boundaries
7. Interfaces
8. Utilization environments
9. LIfe cycle
10. Functional requirements
11. Performance requirements
12. Modes of operation
13. Technical performance measures
14. Physical characteristics
15. Human systems integration

IEEE P1220 Requirements Analysis Task Areas

IEEE 1220

Clause 4 - General Requirements

1. Apply the SEP
2. Policies and procedures
3. Plans and schedules
4. Strategies
5. Models and prototyping
6. Integrated database
7. Integrated data package
8. Specification tree
9. Drawing tree
10. System breakdown structure
11. Integrate inputs
12. Technical reviews
13. Quality management
14. Product and process improvement

Clause 6 – The SEP

1. Requirements Analysis
2. Requirements Validation
3. Functional Analysis
4. Functional Verification
5. Synthesis
6. Design Verification
7. Systems Analysis
8. Control

IEEE 1220

System Definition		Concept, plans, interfaces, risks, quality factors, specs, baselines, reviews
Subsystem Definition	Preliminary Design	Subsystem definition, plans, interfaces, risks, quality factors, specs, baselines, reviews
	Detailed Design	Component definition, plans, interfaces, risks, quality factors, specs, baselines, reviews
	Fabrication Assembly Integration and Test	System integration and test; Analyze fix and retest; Plans, specs, baselines, reviews and audits
Production – Customer Support		Correct deficiencies; Ensure proper waste handling; Apply SEP on fielded products

Analysis Questions

- What are the reasons behind the system?
- What are the customer expectation?
- What do users expect?
- What is their level of expertise?
- With what characteristics must the system comply?
- What are the interfaces?
- What functions will be performed?
  - Expressed in customer terms
- With what characteristics must the system comply?
- What will be the final form?
  - Model, Prototype, Mass Production

Requirements Analysis Outputs

- Operational View
  - Needs Definition
  - System Mission Analysis
  - Sequences
  - Environments
  - Conditions/Events to Respond to
  - Constraints
  - Mission Performance
  - Job Task Roles
  - Operator Structure
  - Interfaces with Other Systems

Requirements Analysis Outputs

- Functional View
  - System Functions
  - System Performance
    - Qualitative, Quantitative, Timeliness
  - Tasks/Actions to be Performed
  - Inter-function Relationships
  - Functional Relationships
  - Performance Constraints
  - Interface Requirements
  - Verification Requirements

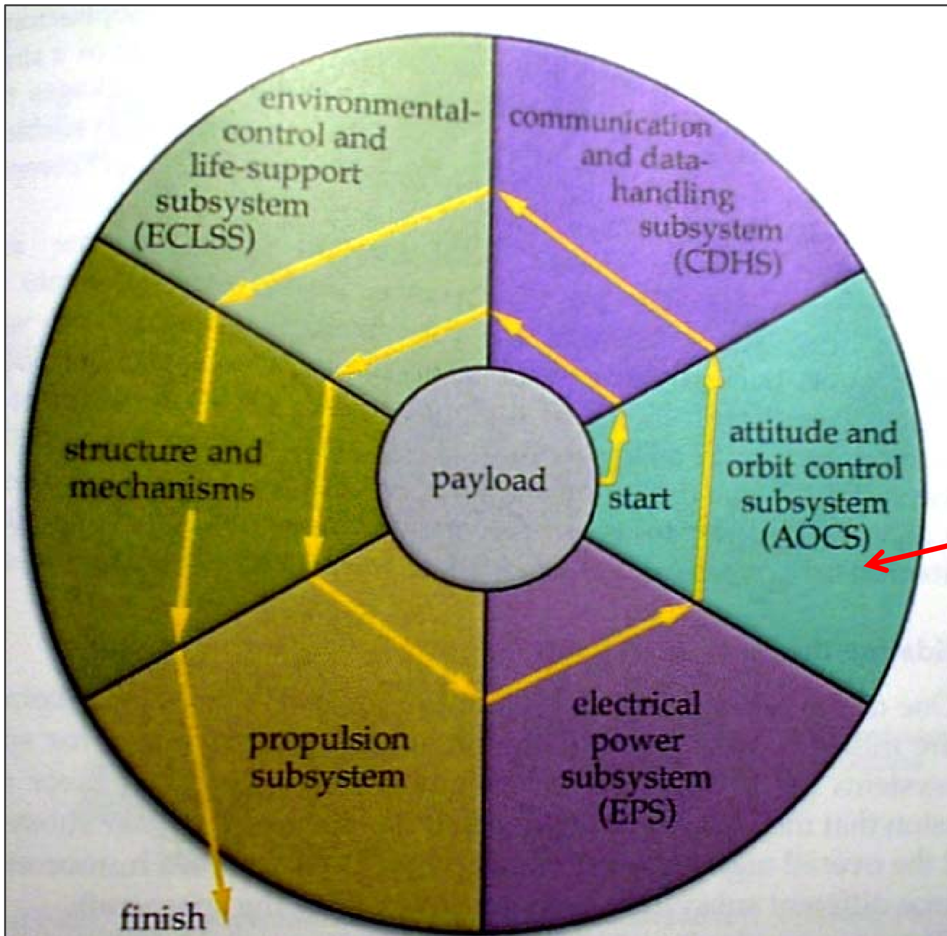
Requirements Analysis Outputs

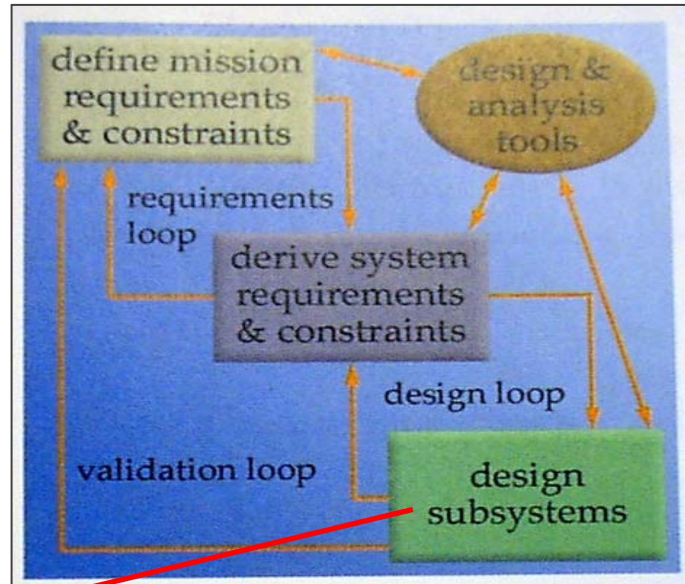
- Physical View
  - System Configuration
    - Interface Description
    - Operator Controls
    - Require Operator Skill Level
  - User Characterization
    - Special Operating Conditions
    - Movement/Visual Limitations
  - System Physical Limitations
    - Capacity, Power, Size, Weight
    - Technology Limitations
    - Equipment Supply
    - Reusability
    - Standards

Outputs Summary

- Initial need statements are seldom defined clearly
- Considerable life cycle customer collaboration is needed to produce an acceptable requirements document
- Requirements are a statement of the problem to be solved. Unconstrained and non-integrated requirements are seldom sufficient for a good design
- Requirements will conflict, trade studies are necessary to produce a balanced set of requirements leading to a feasible solution to customer requirements

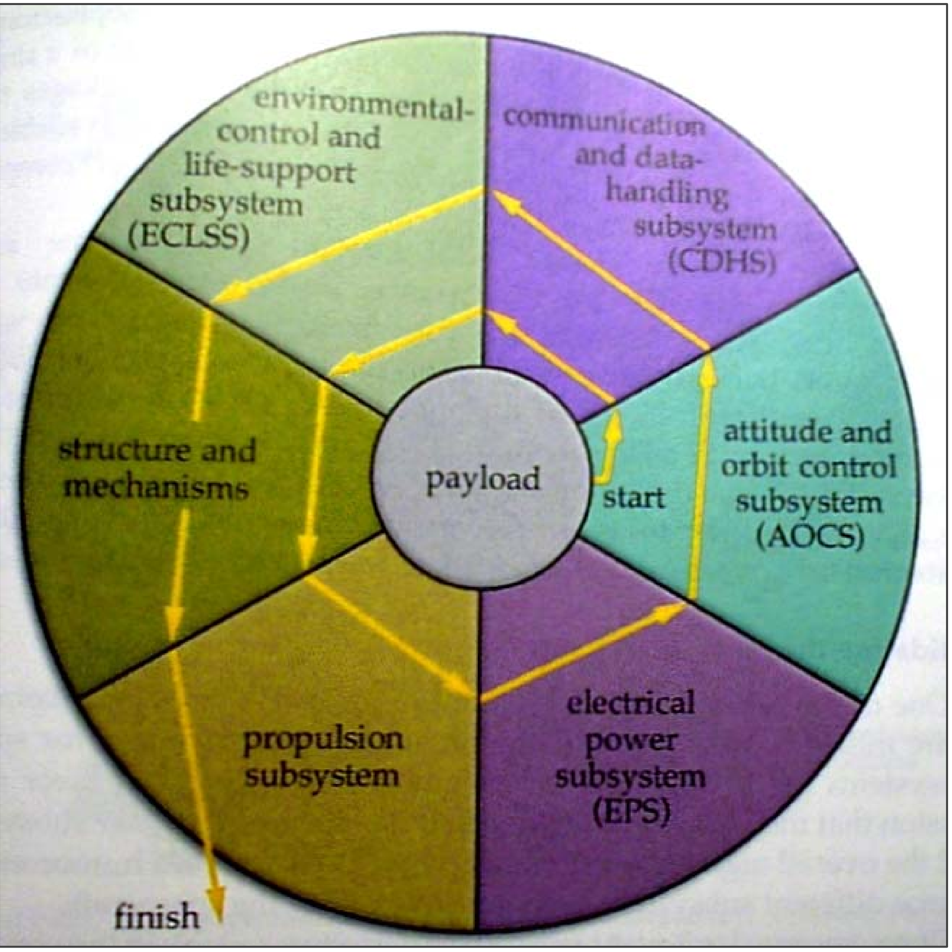
Subsystem Design





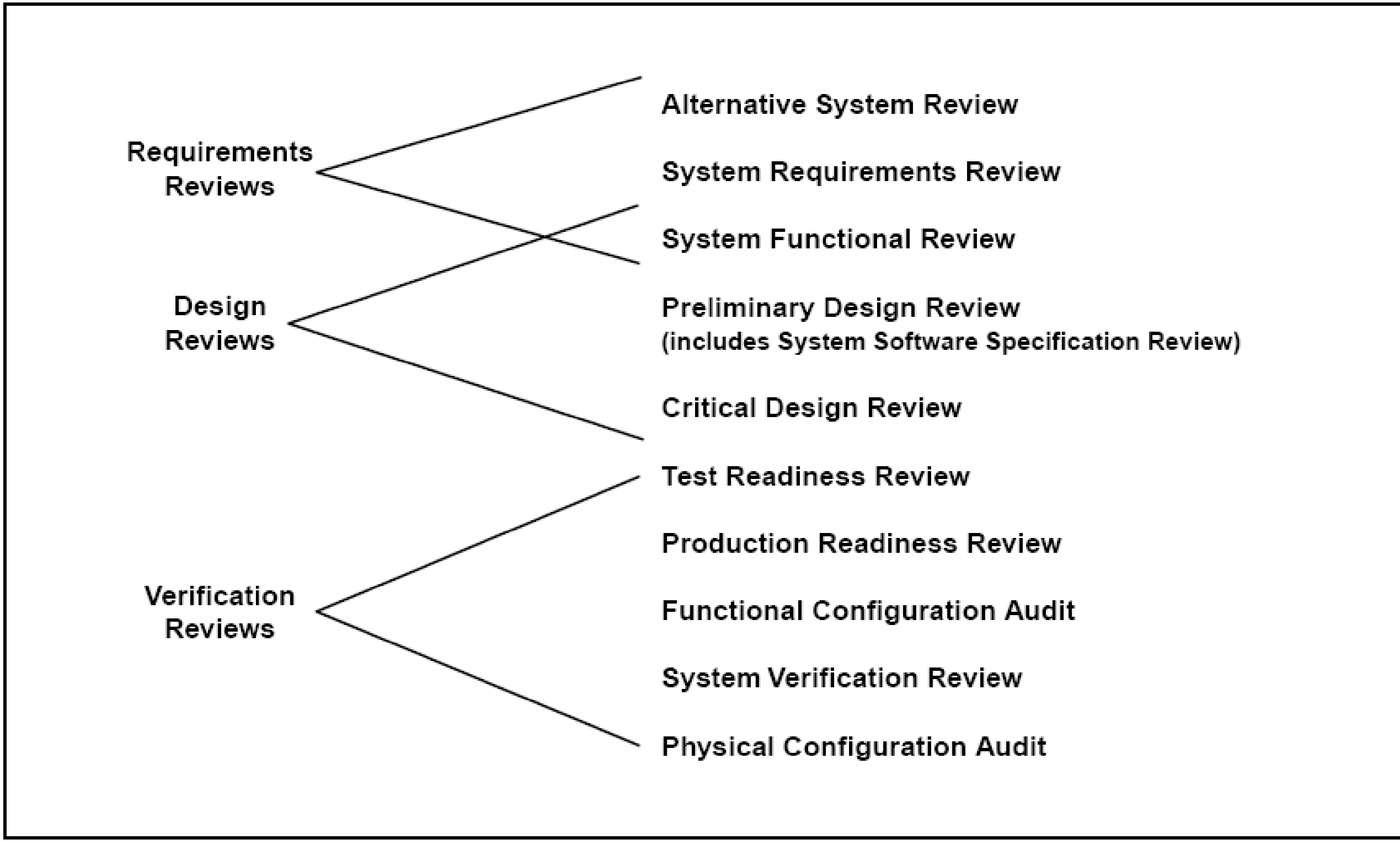
- Subsystem design process follows a distinct order and development hierarchy

Subsystem Design



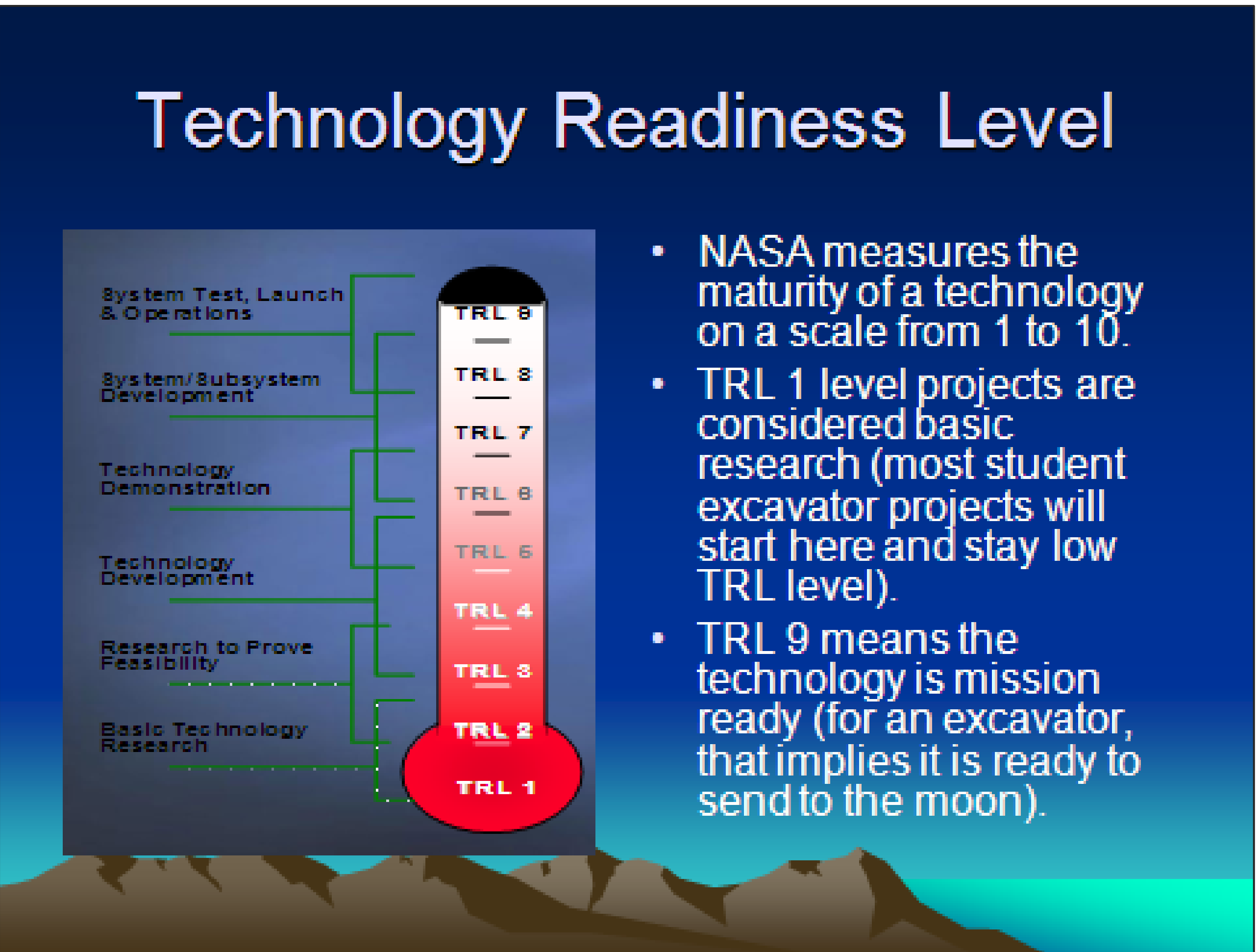
- Subsystem design chart shows the interdependence of all of the spacecraft subsystems.
- When the design of one sub-system is modified, then it typically become necessary to adjust the designs of some or all of the other sub systems.
- In extreme cases, the payload sometimes needs to be modified as the result of a mandated sub-system change.

Subsystem Design



Typical System-Level Technical Reviews

Subsystem Design



- **Designing sub-systems using high TRL components is a good way to reduce or mitigate programmatic risk.**
- **High TRL systems have "heritage" and offer increased reliability and (hopefully) enhanced ease of integration.**

Subsystem Design

- **Cardinal Sub-system Design Rules:**
  - *Integrate when can (high TRL)*
  - *Design and fabricate when you must*
  - *Low TRL sub-systems require significant testing and evaluation before integration*
  - *Low TRL's can "fight" each other and have potential to seriously impact overall design budget and schedule!*

- **High TRL systems have "heritage" and offer increased reliability and (hopefully) enhanced ease of integration.**

Technology Readiness Level

Technology Readiness Level	Description
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in simulated environment. Examples include "high fidelity" laboratory integration of components.

Technology Readiness Level

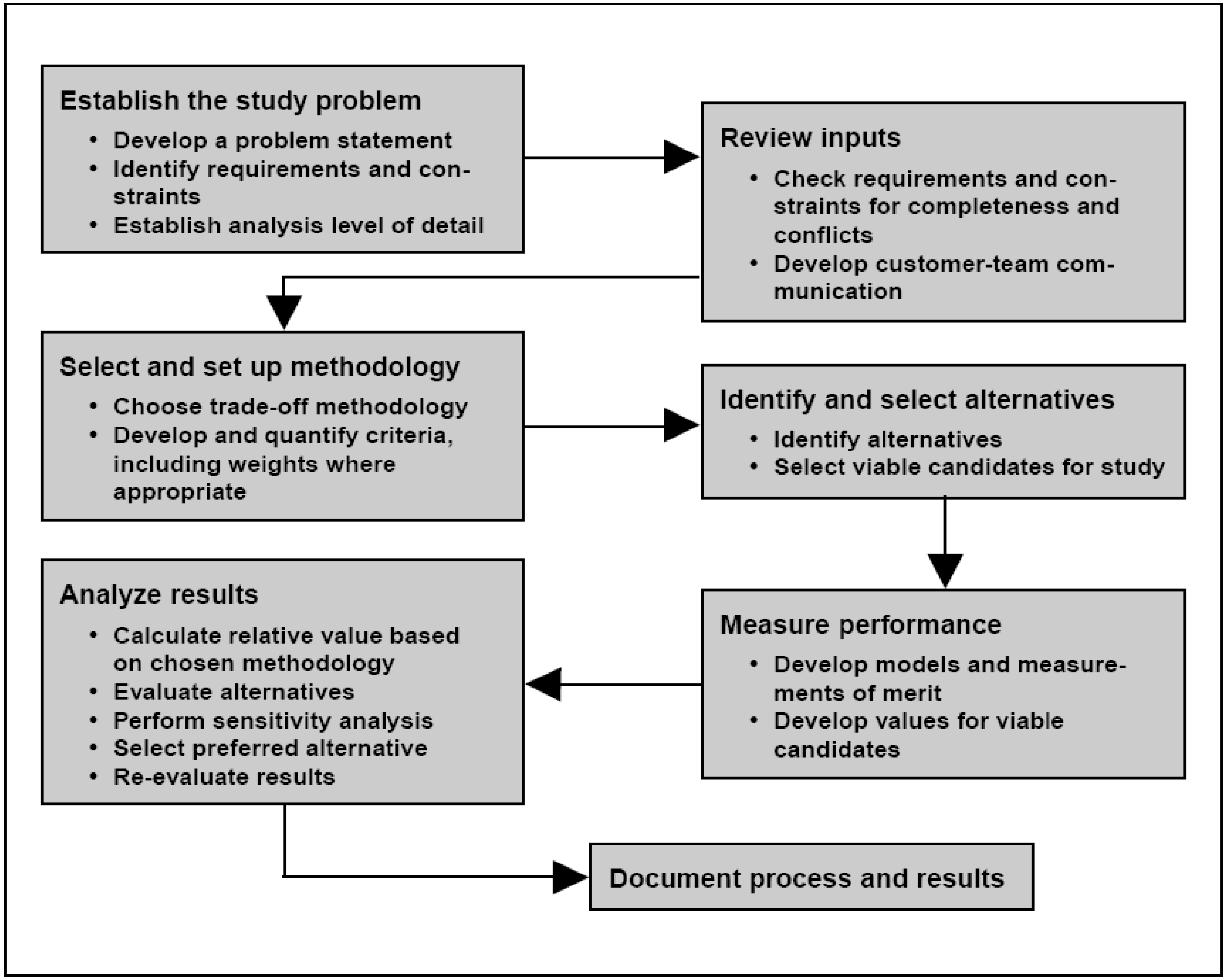
Technology Readiness Level	Description
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond the breadboard tested for level 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in a simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from level 6, requiring the demonstration of an actual system prototype in an operational environment. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this level represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

(continued)

Trade Studies

- Trade study is a tool used to help choose the best solution among alternatives.
- Numerical values are given based on weight factors and a normalization scale for the evaluation criteria.
- Evaluation criteria are important factors that are included in trade study.
- Weight factors are used to dictate how important the evaluation criteria are relative to each other.
- The choice of weight factors and normalization scale are extremely important to this process.
- Normalization scale creates a constant interval scale that allows us to set a numerical for each of the evaluation criteria (e.g. cost, mass, volume, power consumption legacy, ease of use).

Trade Studies



Trade Study Process

Steps to a trade study

1. Define the problem.
2. Define constraints on the on the solutions.
3. Find 3-5 solutions
4. Define evaluation criteria.
5. Define weight factors
6. Define normalization scale
7. Populate trade matrix
8. Rank the solutions

Trade Studies

Decision Factors / Alternatives	Range Wt. = 2.0		Speed Wt. = 1.0		Payload Wt. = 2.5		Weighted Total
	U	W	U	W	U	W	
Transport System 1	.8	1.6	.7	.7	.6	1.5	3.8
Transport System 2	.7	1.4	.9	.9	.4	1.0	3.3
Transport System 3	.6	1.2	.7	.7	.8	2.0	3.9
Transport System 4	.5	1.0	.5	.5	.9	2.25	3.75

Key: U = Utility value
W = Weighted value

Trade Studies

Comparison of Controllers for CubeSat

Microcontroller vs. FPGA Trade Study

MCU vs. Antifuse FPGA Trade Study V1.0					
Criteria	**Weight (%)**	**Microcontroller**	**Grade**	**Antifuse FPGA**	**Grade**
Radiation Tolerance	30%	Logical	2	Physical (rad hard by design)	5
Programming Language	20%	C	4	VHDL or Verilog	2
Power consumption	15%	16.5 mW	4	<16.5 mW	5
Cost per unit	10%	$15.05	4	$30	2
Initial Cost	5%	$0.00	5	$500	2
In Flight Programmable	5%	Yes	5	No	1
CubeSat Legacy	15%	Extensive	3	Unknown	1
Average Score			**3.8571**		**2.57143**
Weighted Score			**3.35**		**3.15**

Keys to Holding a Successful Meeting

- Meetings are essential to any team effort, be it designing a rocket system, or launching a new cosmetic product

- Done properly, meetings can quickly disseminate information, solve problems, create consensus, and get everyone “on the same page”

- Done improperly, meetings can bog down, cause dissention, delay, and sometimes cripple a project.

- Every meeting must a specific purpose – before arranging a meeting one need to think precisely about what it is that needs to be accomplished.

Keys to Holding a Successful Meeting

- **Typical Meeting Purposes**
  - **Brainstorming new ideas**
  - **Developing an idea or plan**
  - **Having a progress update**
  - **Technical interchange**
  - **Considering options and making a collective decision**
  - **Selling something to a potential buyer**
  - **Building a relationship with somebody**

There may be a mixture of objectives and desired outcomes for a particular meeting; however, primary objectives should kept clearly in mind and those should prioritized above others.

Keys to Holding a Successful Meeting

1. Invite the right people. Make sure these people attend.

2. Start with a clear objective for the meeting. Particularly with routine meetings, it's tempting to hold the meeting because it's “checking a box”, but what are you really trying to accomplish? People don't actually bond very much in unproductive meetings that lack clear objectives.

3. Set up a written agenda in advance. As you build the agenda, do your best to assess how long it will take to address each topic. As a guideline, assume that if the goal is to make a decision, it will take four times longer than if the goal is to simply provide a status report.

Keys to Holding a Successful Meeting

4. **Formally track problem-solving and decision-making discussions. Appoint someone to take notes at the beginning of the meeting. Formally archive meeting notes in a data base with access to participating team members.**

5. **Formal Tracking Tools:**

   a. Action Items – Requests for Action (RFA)

   Who is assigned action?

   When is action due?

   Who are action's "customers"

   b. Information Items – Requests for Information (RFI)

   Who provided the information and verification?

   When is action due?

   Who needs the information

Keys to Holding a Successful Meeting

6. **Log and Track RFAs RFIs .. Don't let people "off the hook" require that action forms be formally CLOSED.**

7. **End each meeting with a "consensus" check. Is everyone clear on assigned actions, and due dates. FORMALLY set a tentative time and date for a follow-up meeting, and who needs to be in attendance at this meeting. Log that follow up meeting time.**

More Information

- NASA Systems Engineering Handbook
  - http://education.ksc.nasa.gov/esmdspacegrant/Documents/NASA%20SP-2007-6105%20Rev%201%20Final%2031Dec2007.pdf
- US DOT Systems Engineering Handbook
  - http://ops.fhwa.dot.gov/publications/seitsguide/index.htm
- US DoD Systems Engineering Handbook
  - http://www.dau.mil/pubs/pdf/SEFGuide%2001-01.pdf
- NASA Systems Engineering Design Course – Utah State University Mechanical and Aerospace Engineering; Dr. S. Tony Whitmore
  - http://www.neng.usu.edu/classes/mae/5900/frameset_for_design_class_webpage