THERMAL & FLUIDS

ANALYSIS WORKSHOP

GSFC · 2015

Systems Engineering

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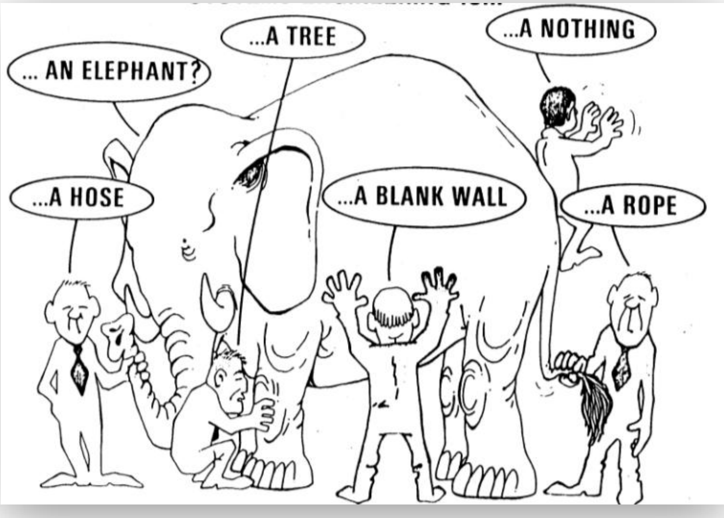
What is Systems Engineering?

- What’s a System?: The combination of elements that function together to produce the capability to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose.



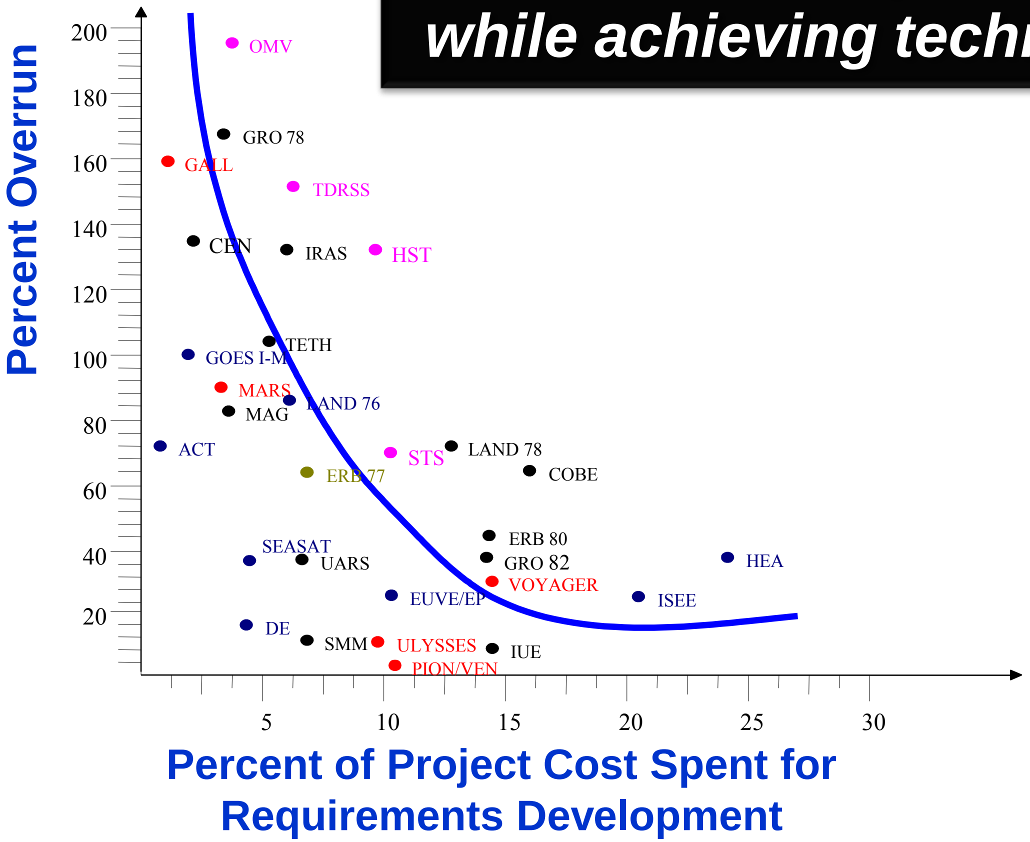
- Why does everyone has a different idea of what’s Systems Engineering?
- Systems Engineering involves breaking a complex problem up into smaller, more manageable pieces.

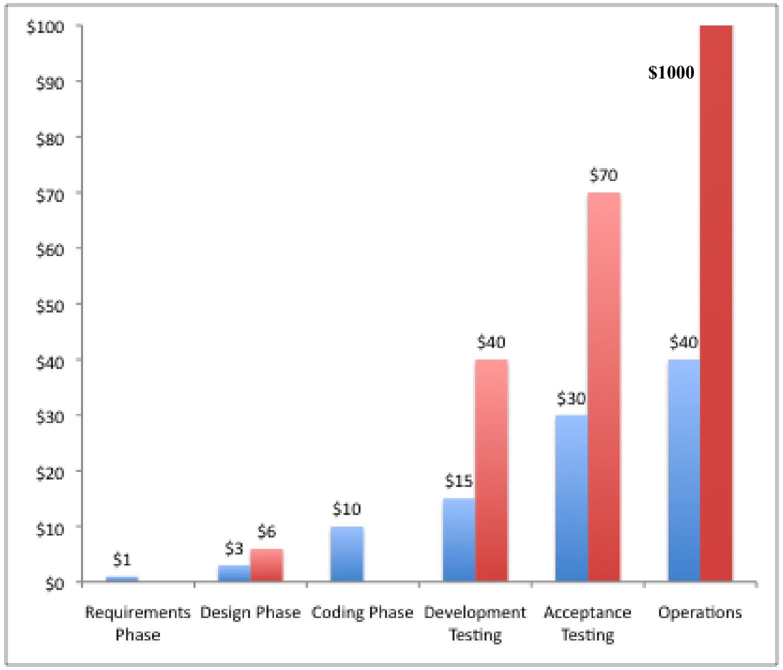
Systems Engineering Functions

- Systems Engineering functions (Sarah A. Sheard, *1996 INCOSE Symposium)*:
  - Requirements Owner
  - System Designer
  - System Analyst
  - Validation/Verification Engr.
  - Logistics/Ops Engineer
  - Glue Among Subsystems
  - Customer Interface
  - Technical Manager
  - Information Manager
  - Process Engineer
  - Coordinator
  - Classified Ads SE

What’s the Motivation?

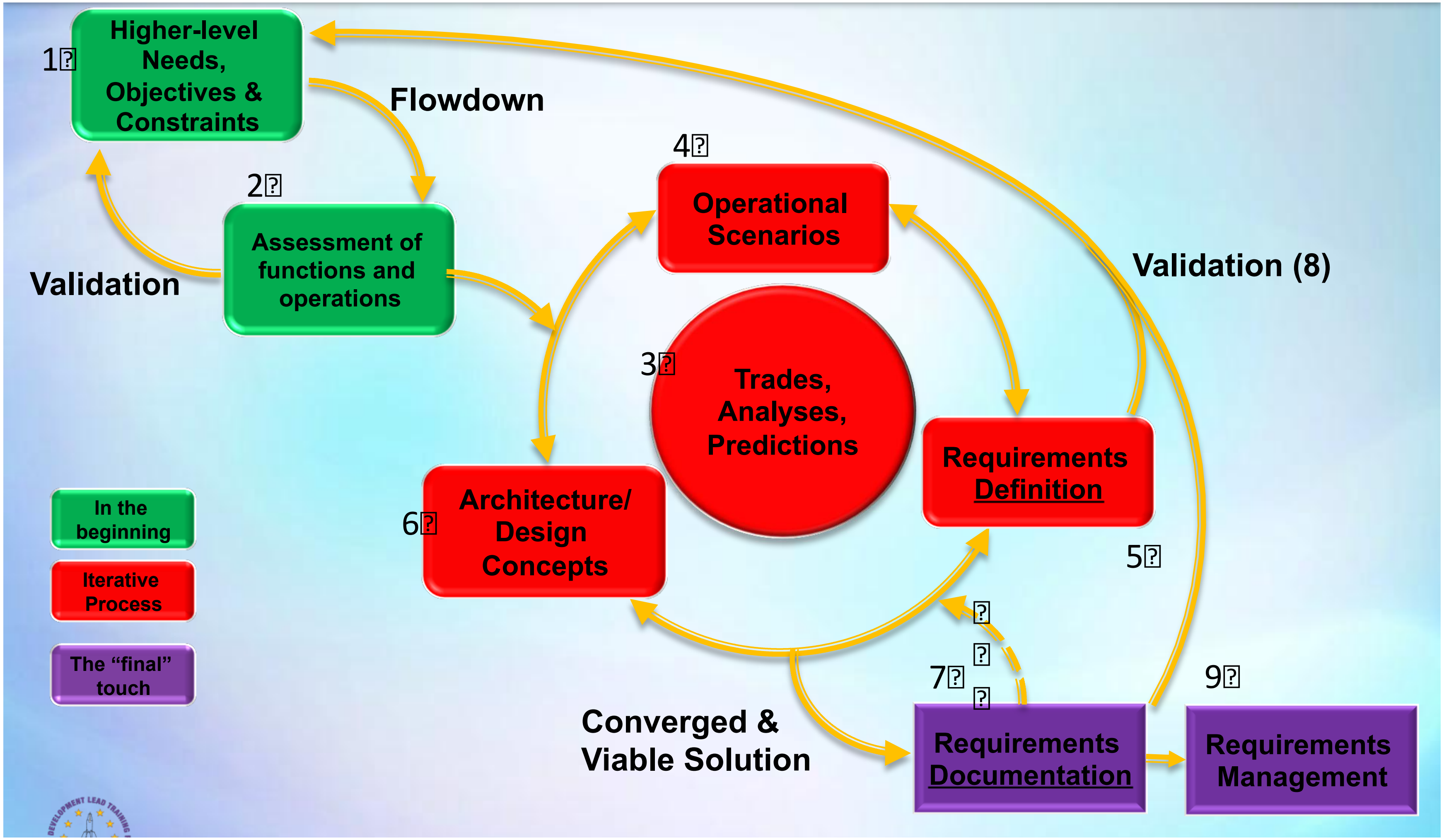
NASA’s current paradox is cost control while achieving technical performance.





Relative Cost of Requirement Errors (“Extra Time Saves Money,” Warren Kuffel Computer Language, December 1990)

Systems Design and Requirements Development Flow



1 Higher-level Needs, Objectives & Constraints

Flowdown

2 Assessment of functions and operations

Validation

4 Operational Scenarios

3 Trades, Analyses, Predictions

5 Requirements Definition

Validation (8)

6 Architecture/ Design Concepts

Converged & Viable Solution

7 Requirements Documentation

9 Requirements Management

🟩 In the beginning

🟥 Iterative Process

🟪 The “final” touch

Requirements

- Use the word “shall” when defining requirements and only for requirements:
  - “The attitude control system shall point the instrument boresight to within 6 arc seconds of the commanded attitude.”
  - Make it clear to the reader exactly what must be done.
- Requirements should be:
  - Measurable
    - Avoid vague statements like “shall point as accurately as possible”
  - Verifiable
    - If no one can demonstrate that a system does or does not meet a requirement, then there is no requirement
- Document rationale!
  - Capture the why while it is fresh.
  - Enable future changes—people are afraid to change things they don’t understand.
  - Challenge “borrowed” or legacy requirements – “we’ve always done it that way” is not a justification

Requirement Examples (1)

- Don’t use ambiguous terms
  - The ATLAS laser shall generate laser pulses at approximately 10kHz repetition frequency.
  - *The ATLAS laser shall generate laser pulses at a 10kHz +/- 0.3 kHz repetition frequency*
- Positively stated
  - The transmitter shall not allow radiation of the second harmonic to be greater than 20dB.
  - *The transmitter shall suppress radiation of the second harmonic by greater or equal to 20dB.*
- Keep one thought
  - The ATLAS laser shall generate laser pulses with a center wavelength of 532 nm +/- 15nm at 10kHz +/- .3kHz repetition frequency.
  - *The ATLAS laser shall emit light at 532nm nm +/- 15nm.*
  - *The ATLAS laser shall generate laser pulses at a 10kHz +/- 0.3 kHz repetition frequency.*

Requirement Examples (2)

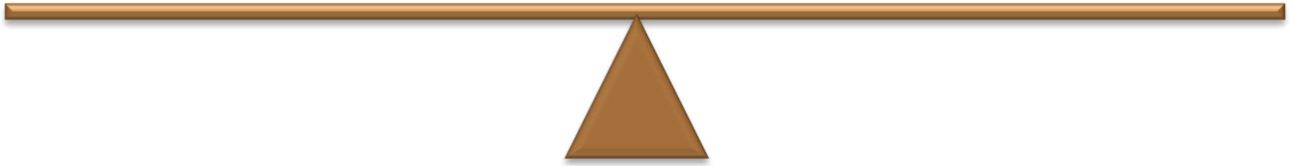
- Use consistent terminology
  - The ATLAS transmitter shall generate laser pulses at a 10kHz +/- 300Hz repetition frequency.
  - The ATLAS laser shall generate laser pulses at a 10kHz +/- 0.3kHz repetition frequency.
- Avoid “people do” statements
  - The operator shall send stored data to the science team.
  - *The Ground System shall transmit stored data to the science database upon user request.*
- Avoid implementation specific
  - The ATLAS laser shall use an intermittent signal disruption to generate laser pulses at a 10kHz +/- 0.3 kHz repetition frequency.
  - *The ATLAS laser shall generate laser pulses at a 10kHz +/- 0.3 kHz repetition frequency.*

Optimal Number of Requirements

- The Quantity & Quality (level of detail) of requirements evolve with time.

- **Too Few or too late requirements under constrains the design solutions.**
- **Progress, but not focused resulting in the design not converging to an implementation**

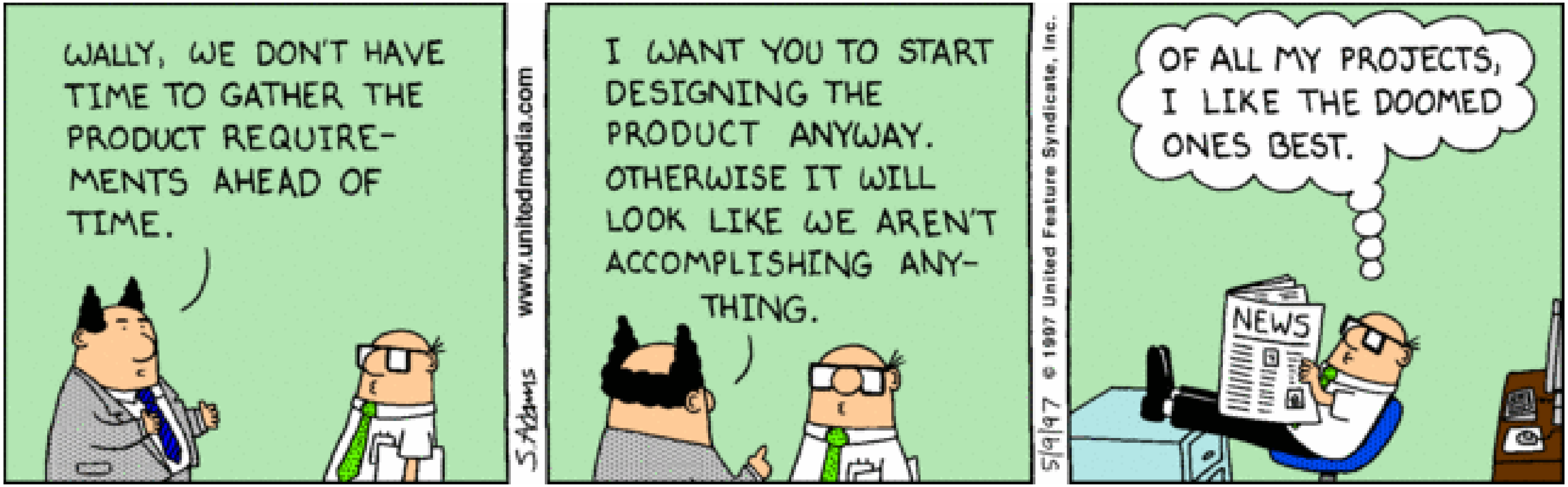
- **Too Many or too early requirements over constrains the design solutions**
- **Progress choked because any decision results in a violation of a requirements.**



- If you cannot recall from memory your requirements, you probably have too many.

We have an obligation to close paperwork of each and every requirement, don't get carried away and needlessly create busy work for yourself!

Don’t Let This Happen To You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OF ALL MY PROJECTS, I LIKE THE DOOMED ONES BEST.
NEWS

In order to control cost and schedule, we need to discipline ourselves to do the upfront work before getting into the fun technical work.

THERMAL IN SPACE SYSTEMS

Elements of Space Systems Design

- Orbital Dynamics
- Structures and Mechanisms
- Attitude Control
- Electrical Power
- Thermal
- Command and Data Handling
- Propulsion
- Communications
- Information Systems/Software
- Space Environment
- Launch Vehicle
- Instruments/Payloads
- Reliability
- Safety
- Operations
- Disposal
- Project management
- Maintenance
- Storage
- Verification (system built right?)
- Validation (right system built?)
- …

How Other Disciplines Interface with Thermal

Mechanical
- Selection of Materials
- Mounting Design
- Thermal Hardware Locations
- Radiator Accommodation
- TVAC (Deployment, Mechanisms)
- Surface Coating Specification
- STOP Analysis
- Geometry Files for Modeling
- Integration

Electrical/Power
- Power Resources (Htrs, TECs, etc)
- Thermal Dissipations
- Grounding/ESD Requirements
- Voltage Requirements
- Thermal Sensor Capability
- Heaters Services
- TVAC (PDU, Solar Arrays, etc)
- Integration

Optical
- Predicts for STOP/Pointing
- Temp Control for Stability & Focus

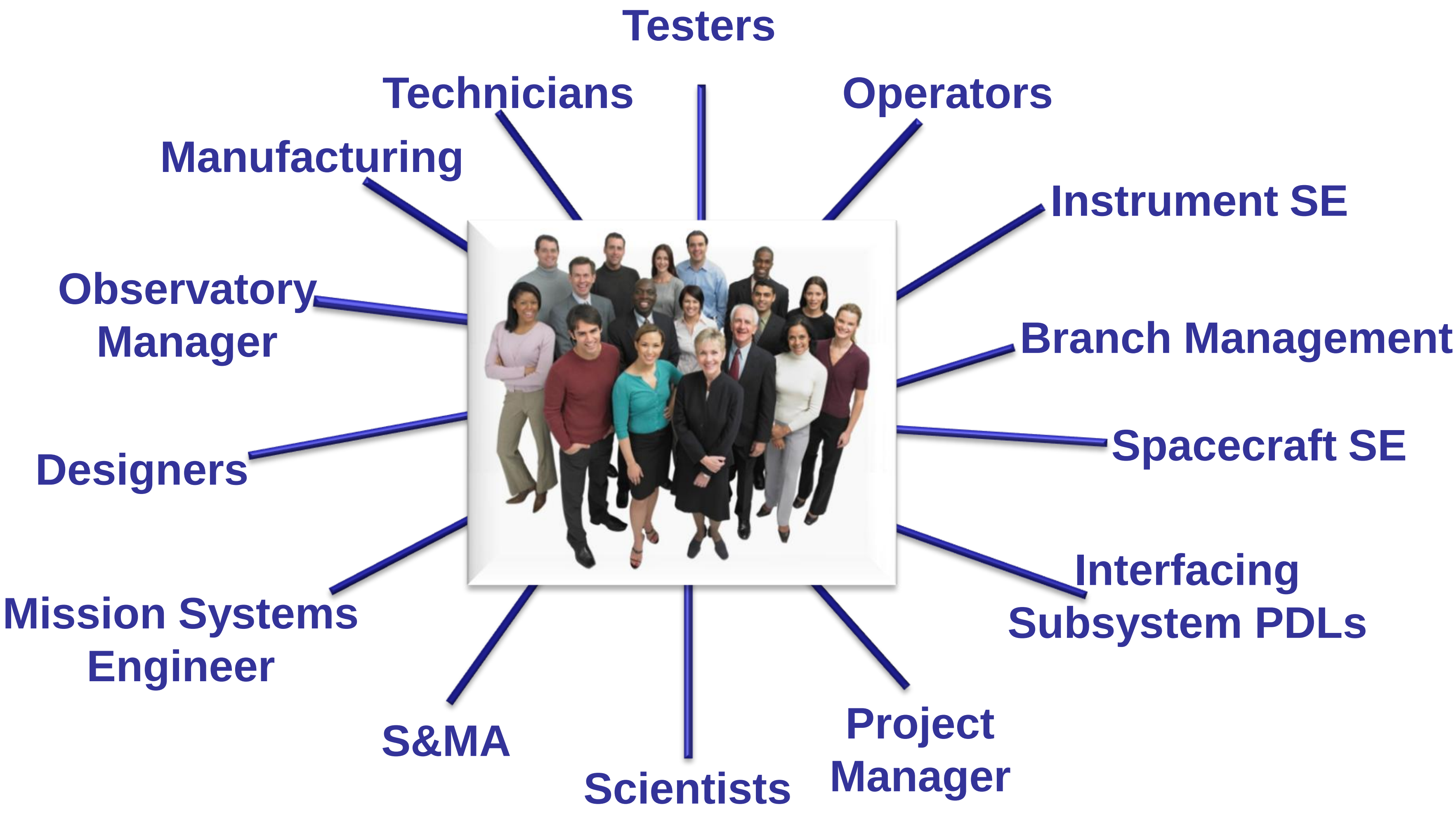
GNC
- Orbit Requirements
- Pointing Requirements
- TVAC (Reaction Wheels, etc)

Software
- Monitoring and Limits
- Temperature Control
- Autonomous Commands

Contamination/Coatings
- Material and Coatings Selection
- Temp Predicts & Geometry Model for Contamination Analysis
- Properties for Thermal Analysis
- Coating and Tape Application
- TVAC Requirements

Your Systems Engineering team should serve as a bridge or facilitator among all Disciplines.

Be Aware of Your Stakeholders



Testers

Technicians

Operators

Manufacturing

Instrument SE

Observatory Manager

Branch Management

Designers

Spacecraft SE

Mission Systems Engineer

Interfacing Subsystem PDLs

S&MA

Scientists

Project Manager

Observation Strategy & Operations Concept

- Thermal plays a very important role in these early phases of the mission
- How the system will be used in many respects drives the architecture
  - Earth orbit selection given instruments' observations
  - Planetary, e.g., extreme hots or extreme colds
  - Many instruments' performance depends on cold temperatures and/or tight stability
- Many requirements will fall out of the ops concept.
  - Temperature ranges and stability
  - Modes of operations over different phases
    - Launch operations
    - Orbit maneuvers
    - Calibration scans
    - Ground testing, e.g., heat pipe orientations

Ops Driven Thermal Requirements (1)

- Example:
  - Aquarius/SAC-D orbit selection
    - Instrument needed to observed the night side “all the time”
    - Room temperature detectors but <100mK stability, >7-days
    - Selection of sun-synch 6am orbit, very stable and ample power
  - ICESat-2 orbit selection
    - Instrument wants to map as much of the poles as possible AND provide high sampling
    - Optics benefit from good thermal control (not to tight)
    - Orbit selected provides a highly variable thermal environment, tough job!
    - Instrument thermal control discussed but not implemented, too much power. Optical systems have to deal with temperature variations. Optical systems struggle to meet performance.
    - Systems free up resources and a clever solution of a “thermal oven” for critical optics is implemented

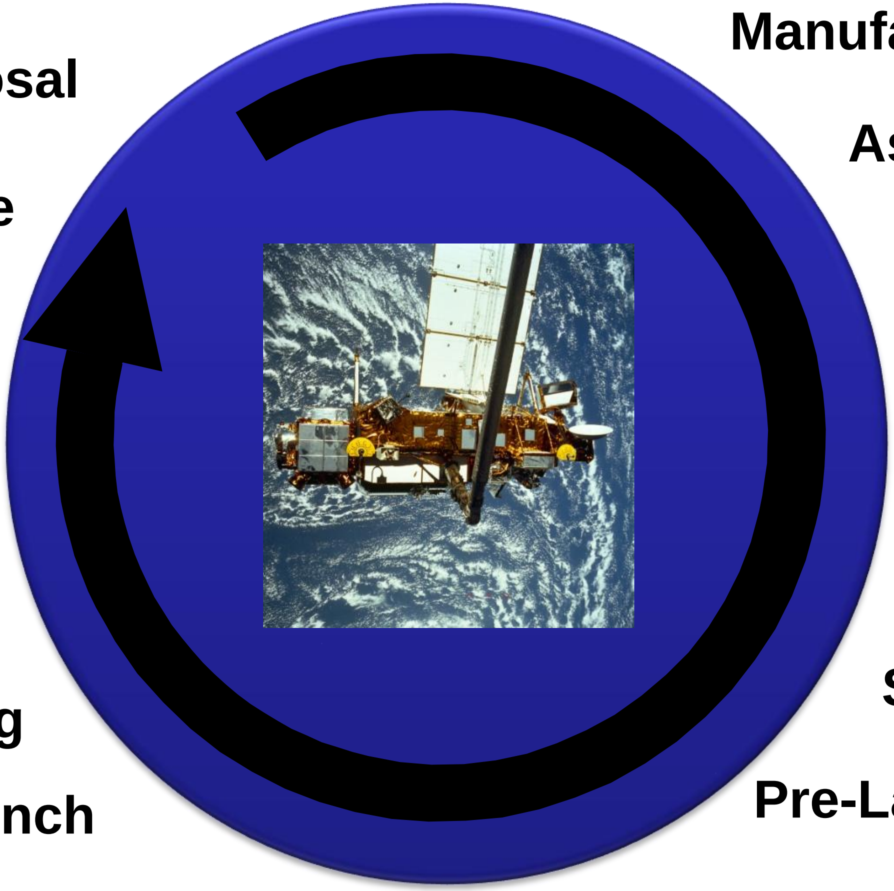
Ops Driven Thermal Requirements (2)

- Example:
  - JWST
    - Orbit at L-2 driven by high sensitivity of instruments
    - Detector technology necessitates cryogenic temperatures
    - Huge deployable sunshield
  - Solar Probe Plus
    - First mission to fly on Sun’s corona. Feeling hot, hot, hot!
    - The entire architecture is driven by the harsh environment

Working with Systems

- Above all else ask questions!
  - Communication is key, maintain good dialog
  - Don’t just expect to be handed requirements. Get involved in developing them.
  - It is important to understand what really matters, don’t get hung up on secondary minor issues, stay focused
  - Requirements are not sacrosanct, negotiate. The objective is for the system to work, not just your subsystem.
- Example: LRO lunar eclipses
  - Lot of back-and-forth about what lunar eclipses we had to design to survive
  - Systems originally wanted to design for any and all eclipses, high complexity
  - Negotiated to survival of only the predicted eclipses in the baseline (1 year) and extended (1 extra year) missions

Consider All Lifecycle Phases



Design & Analysis

Manufacturing

Assembly

Verification & Test

Higher level I&T (e.g., S/C)

Transportation

Storage

Pre-Launch Checkout

Launch

On-Orbit Commissioning

On-Orbit Operations Nominal & Off Nominal

Maintenance

Disposal

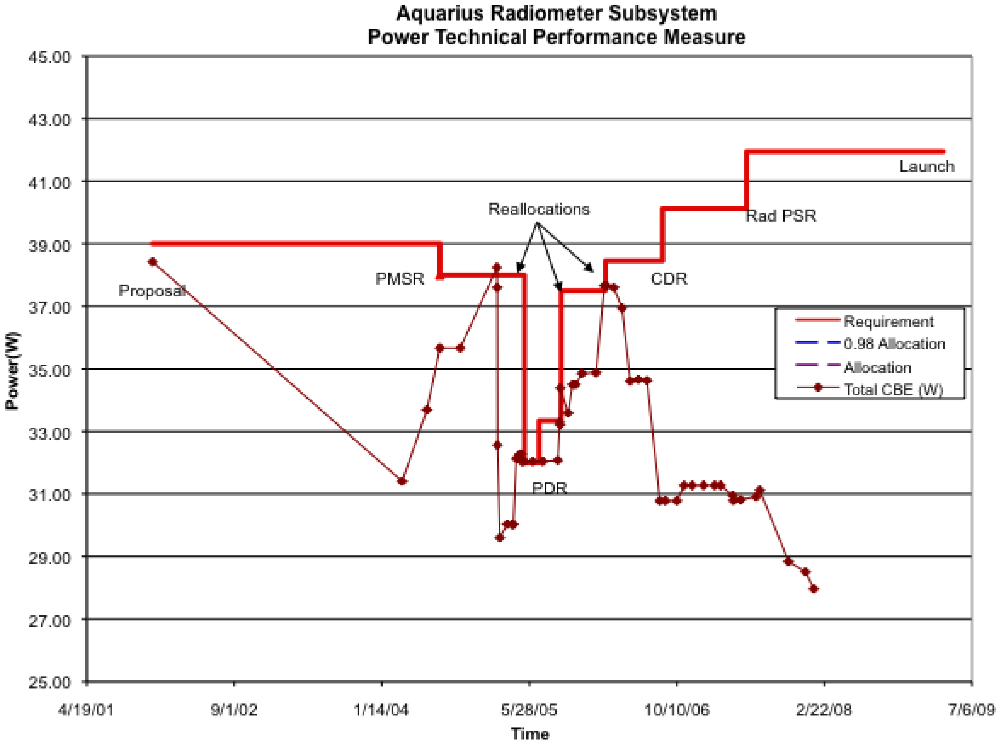
Include all phases of lifecycle.

Electrical vs Thermal Dissipation (1)

- Be mindful electrical and thermal dissipation are not always the same
  - Many s/s do not thermally dissipate all the electrical power
  - Example: Power Distribution Unit
    - Takes in 28V distributes secondary voltages
    - Ideally all power in goes out, i.e., 100% efficiency
    - Clearly efficiency is not ideal so only the conversion losses are dissipated in the box, in addition to internal dissipation from its C&DH
- Conservative power estimates
  - Not uncommon for component PDLs to worst-case power dissipation during analysis
  - Leads to lots of radiator to handle high loads …
  - … which then gets too cold in eclipse requiring lots of make up heaters…
  - … and then needs more power which is not cheap.
  - Again, good dialog and communication of assumptions is necessary!

Electrical vs Thermal Dissipation (2)

- Example of power history over development
  - Not uncommon for system to come in under estimates given “stacked” worse-case assumptions
  - Conservative, yes, but there’s a price to be paid

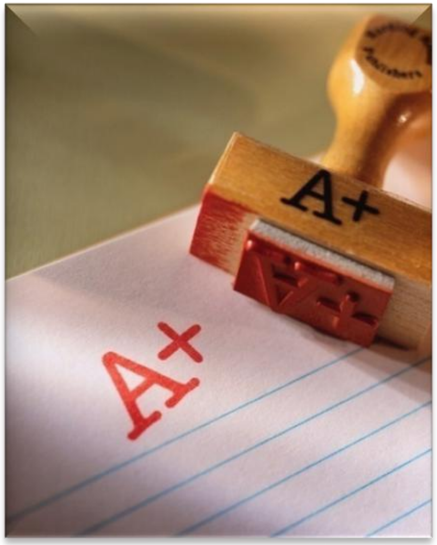


STOP Analysis

- Structural Thermal Optical (STOP) Analysis
  - – Critical function for instruments
  - – By necessity a highly integrated systems activity
  - – Good coordination and documentation a must
- Example: JWST
  - – A preliminary STOP analysis was needed to derive requirements for the primary mirror adjustment stages
  - – TVac testing later validated that analysis

Verification vs Validation

- System Verification
  - Did I build the thing right?
  - Example:
    - After H/W build
      - Pass/fail tests against requirements



- System Validation
  - Did I build the right thing?
  - Should occur throughout all phases of development
  - Example:
    - During Requirement Development
      - Do I have the right requirements?
      - Are the requirements complete and correct?
    - On-Orbit, e.g., commissioning phase
      - Are we getting the science we needed?

NASA Mission Class

- NASA Mission Risk Classifications are established by NPR 8705.4
  - Considers factors like criticality to the Agency Strategic Plan, national significance, availability of alternative research opportunities, success criteria, magnitude of investment, and other relevant factors.
- Class D: Low Priority, High Risk
  - Rapid development, proof-of-concepts, lower costs
    - E.g., ISS payloads
- Renewed emphasis on risk-based decisions
  - Many of our “standard” rules or processes are consistent with Low Risk
  - IF agreed by Agency, can/should adjust for a higher risk posture
    - Have to be addressed during Formulation Phase NOT after

Class D Examples

- NASA Goddard developed the Class D Constitution
  - *The application of processes and policies adapted for a design- and build-to-requirements approach and the risk aversion associated with higher classification missions (Class C, B and A) is having a negative impact on cost and performance for Class D missions.*
  - The underpinnings of the Class D initiative are:
    - Greater attention upfront to the credibility of proposals
    - Clear and focused lines of accountability
    - Short reporting and communication channels
    - Ownership by the team
    - Expert advice and stewardship
- Examples:
  - CATS: Build-to-cost approach
    - Leverage existing instrument designs
    - Use commercial parts where possible
  - NICER: Operational flexibility
    - Point-anywhere observations but limiting when due to thermal

KEY ISSUES IN SPACE SYSTEMS

Key Issues– Heritage vs New Developments

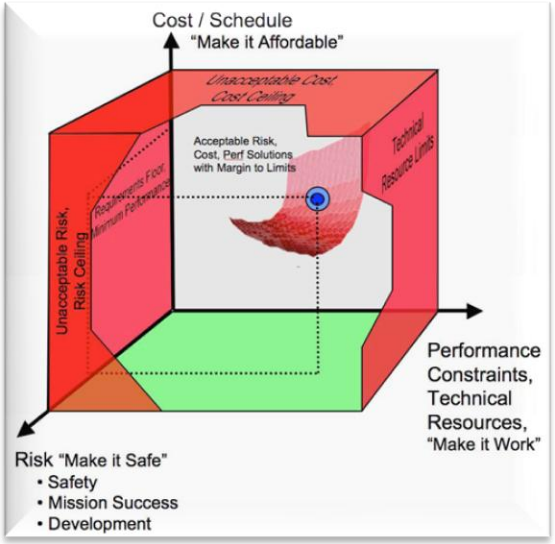
- Using the word “heritage” is probably one of the quickest ways of getting in trouble and starting off the wrong foot when it comes to resource planning.
- “In the space business, no two systems can be the same; heritage is imperfect at best and usually less than we think.”
  - *From “Some Things You Always Needed to Know About Systems Engineering but Didn’t Know You Needed to Know”, M.G. Ryschkewitsch, Schneebaum Colloquium GSFC, September 2008*
- It is more prudent to use prior designs as a <u>starting point</u> for the Requirements and Basis of Estimate. This is very different than bypassing our homework on the basis that “it’s been done before”.
- EVERY claim to heritage must be substantiated and presumed not to be until shown otherwise.

Key Issues – "Good Enough"

- The objective is to achieve convergence according to the evaluation criteria.
    - "Make it work" = technical and performance
    - "Make it safe and reliable" = risk
    - "Make it affordable" = cost and schedule.

Overachieving is not necessarily a good thing. As PDL, you need to find the design sweet spot.

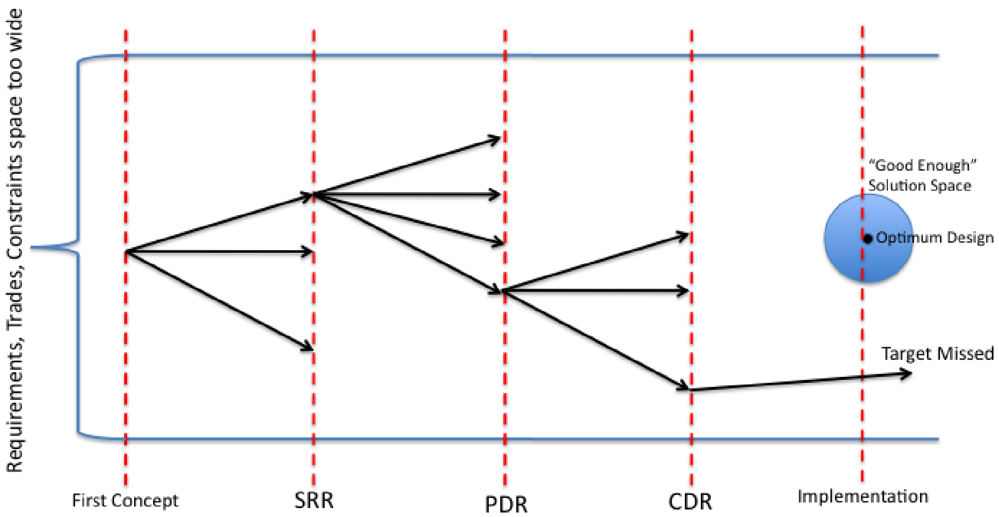
Optimization is a SYSTEM issue, not per subsystem



Good Enough Example

- Example:
  - TIRS radiator
    - Cryocooler-based system with many unknowns at the time
    - Conservative estimate of cyrocooler performance and thermal parasitics led to a rather large radiator with half or more of it blanketed for launch. Not optimized but the right decision for a schedule-constrained project.
    - How about TIRS2?
      - It is a lot more cost effective to do an exact repeat of the radiator rather than "optimize" it given its large blanketed area. Again, not optimized but the right decision for a cost-constrained project.
  - Use of off-the-shelf hardware
    - LRO over-sized reaction wheels
      - Developed by GPM
      - Overkill in performance and not "optimized"
      - Availability made it best choice for a schedule-constrained project

Over or Under Constraining the Solution Space



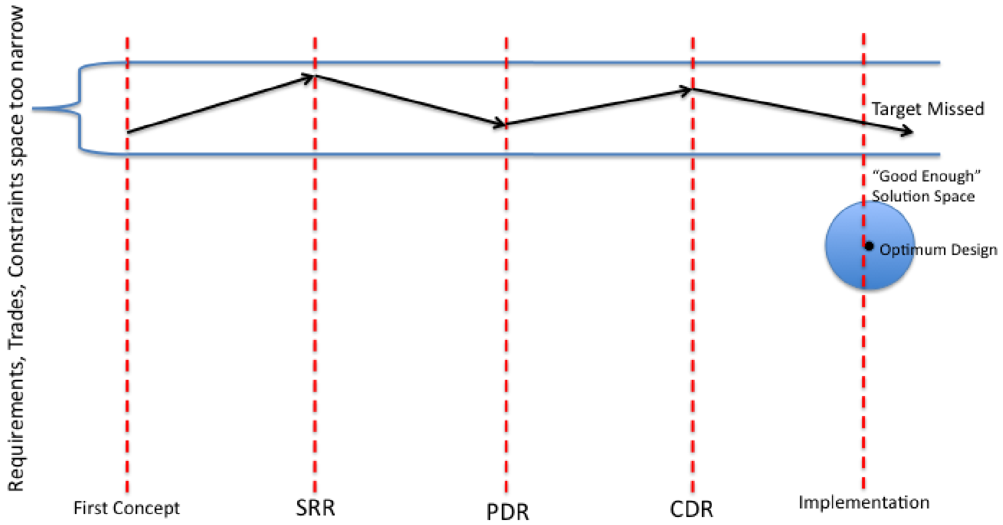
Requirements, Trades, Constraints space too wide
"Good Enough" Solution Space
Optimum Design
Target Missed
First Concept
SRR
PDR
CDR
Implementation

Under-constrained Solution Space

- Usually results in too many options being considered.
- Target may be hit or missed.
- Potential for large gyrations on the design.
- Cost and schedule inefficient.

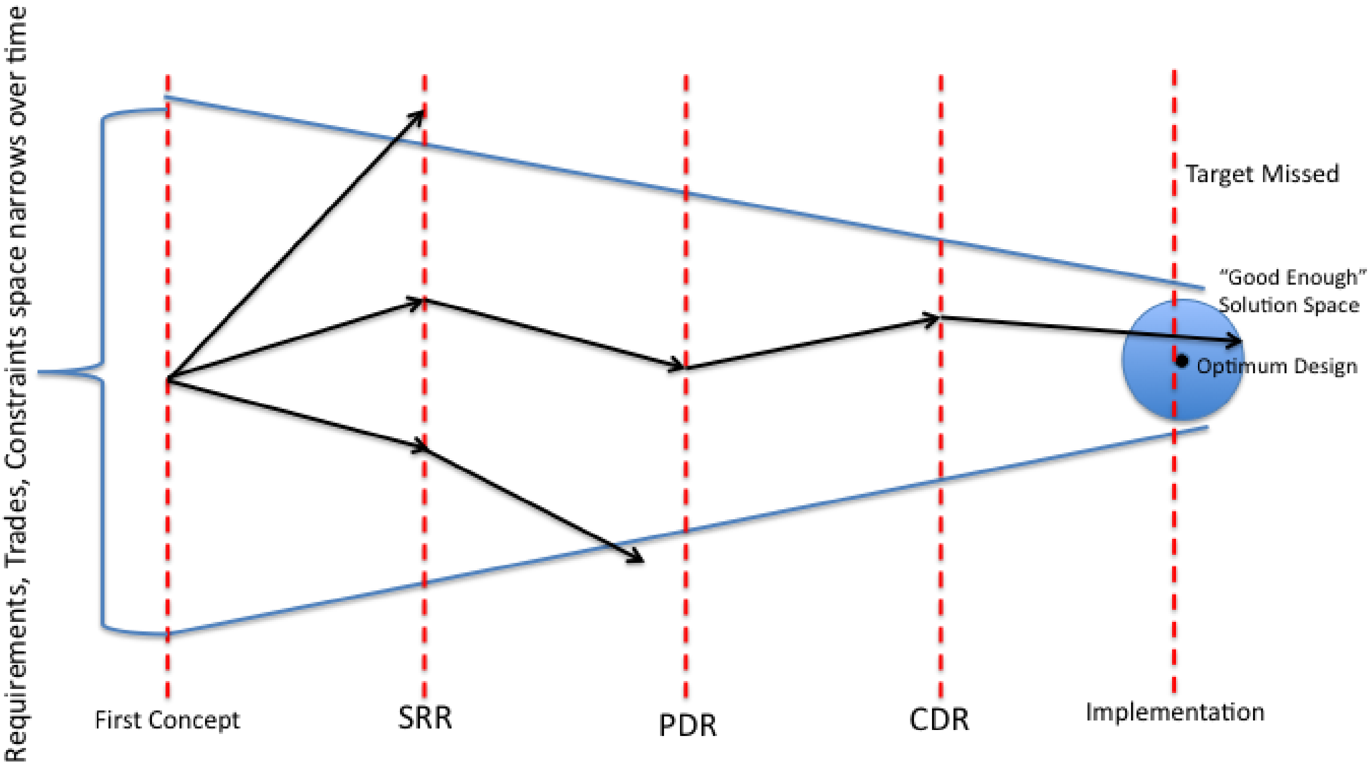
Over-constrained Solution Space

Perhaps minimal gyrations on the design, which appears cost and schedule efficient, but may never have a chance to hit target.



Requirements, Trades, Constraints space too narrow
Target Missed
"Good Enough" Solution Space
Optimum Design
First Concept
SRR
PDR
CDR
Implementation

"Optimally" Constraining the Solution Space



Optimally-constrained Solution Space

Reduces gyrations on the design over time, allowing control of cost and schedule while assuring we can hit the target.

Key Issues - Technical Performance Measures

- Primary measures: mass, power
  - Mass is cost!!!
  - Power generation requires mass, power system components are generally long-lead items.
- Other significant measures: data rate, pointing
  - Data rate impacts memory, processor, downlink (number of ground station contacts, downlink rate, transmitter power)
  - Pointing impacts type of sensors and actuators, which impacts mass and power
- Allocate and track

Key Issues - Safehold

- Out of power and it is dead.
- If it cooks or freezes, it will be dead.
- If we can’t talk to it, it might as well be dead.

- So, safehold must:
  - Be power and thermally safe
  - Allow communication
  - Be more reliable/robust than normal mode: it is your safety net

Key Issues - Margin

- Covers the unknown and the unknowable.
- Launches are substantially riskier than flying in an airplane, because rockets have very little margin:
  - An unexpected event or failure usually means the end of a space mission, while an aircraft can usually get back to the ground safely.
  - Space missions cannot afford the margin of a commercial airliner—too much energy is required to get to orbit.
- Margin costs money, so there is always pressure to reduce margin.
- Use good judgment and the experience of others to judge how much margin is appropriate.
  - Margins must be reasonable and commensurate with mission risk posture.

FINAL THOUGHTS

Lessons Learned

- Most problems are due to poor communication.
  - Create mechanisms for raising issues/concerns promptly and bring them to closure.
- Interface tests early and often will save you money.
- Don’t count on people reading documents.
- It’s the things you aren’t looking at that bite you in the rear.
- Discrepancies and disputes are an indicator of a mistake or a misunderstanding. Don’t brush them off—probe into the matter.
- You will re-learn some lessons others have already learned—try to keep that to a minimum as best you can.

Some More Advice

- Always look for the things you haven’t thought of, especially during testing.
- Perform tests to make sure it will work, not just because someone told you that the test is required.
- Test it in the configuration in which you will fly it.

- Always ask yourself if your answer makes sense.

- Always ask questions—understand why. No matter what you do, you can make better decisions if you understand the situation better.