2012 IEEE Aerospace Conference Session 13.04

National Aeronautics & Space Administration

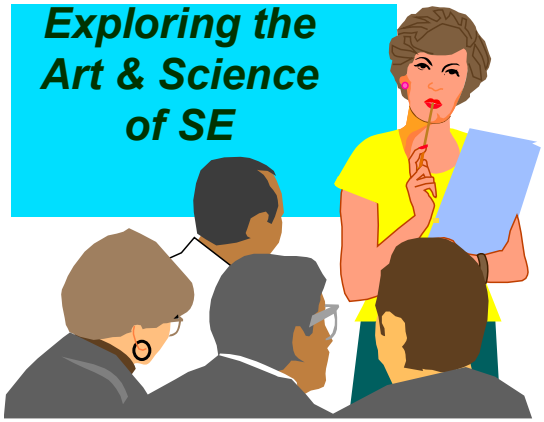
Exploring the Art and Science of Systems Engineering

Wednesday, March 7, 2012
Big Sky, MT

Author: P. A. "Trisha" Jansma
Presenter: C. Jeff Leising
Jet Propulsion Laboratory
California Institute of Technology

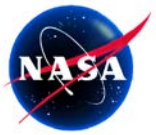
Topics To Be Covered

- Introduction
- Brain Hemisphere Dichotomy
- Leadership vs. Management Dichotomy
- Process-Based Dichotomy
- Behavior & Skills Dichotomy
- Summary & Recommendations



Contact info. for Trisha Jansma:
Telephone (818) 354-0647
e-mail Patti.A.Jansma@jpl.nasa.gov

The work described in this presentation was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration (NASA).

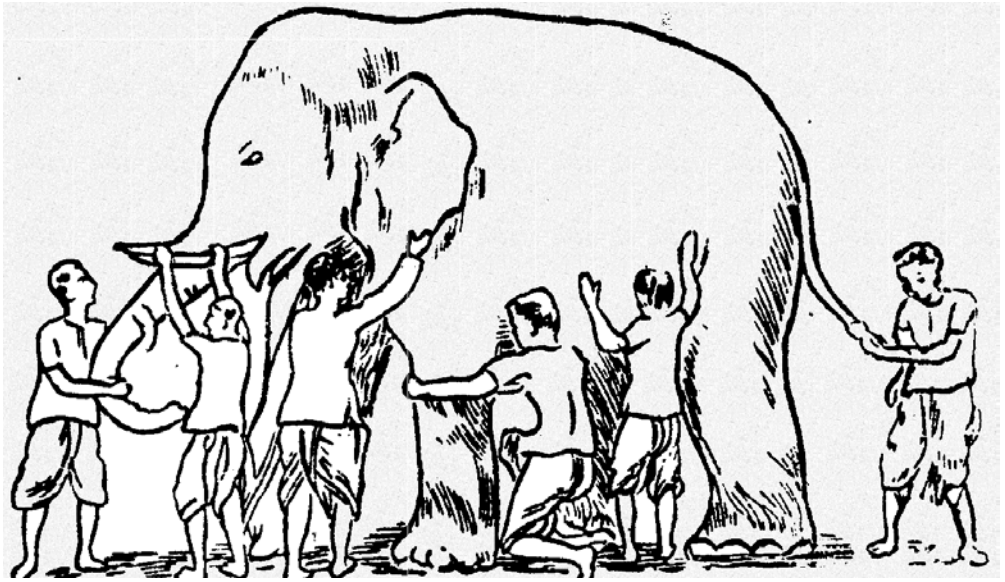


Introduction

- There has been much discussion of late in the NASA systems engineering community about the fact that systems engineering cannot be just about process and technical disciplines.
- The belief is that there is both an Art and Science to systems engineering, and that both aspects are necessary for designing and implementing a successful system or mission.
- How does one go about differentiating between and characterizing these two aspects?

Analogy of Six Blind Men and the Elephant

- Each man touches a single part of the elephant and draws conclusions about the animal as a whole.
  - side, tusk, trunk, knee, ear and tail



"And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,

Though each was partly in the right,
And all were in the wrong!"

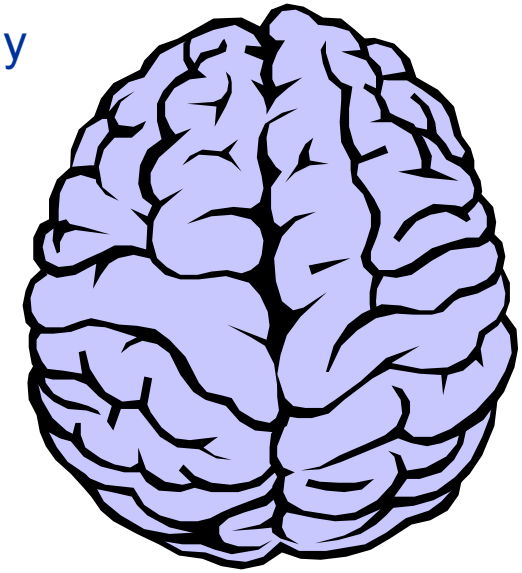
We're going to explore the "elephant" of Systems Engineering.

John Godfrey Saxe, *The Poems of John Godfrey Saxe, Complete Edition,*
(The Blind Men and the Elephant) James R. Osgood and Co, Boston, ©1873

Brain Hemisphere Dichotomy -1

Left Hemisphere of Brain

- Controls right side of body
- **Sequential** – recognizes serial events
- **Logical**, rational
- **Verbal** activities
  - Talking, understanding speech, reading and writing
- Specializes in **text** – *what* is said
  - Objective
  - Literal meaning
- **Analyzes** the details (parts)
  - Analyzes information
  - Breaks the whole into parts
  - Converges on a single answer
  - Focuses on categories
  - Grasps details



Daniel Pink, *A Whole New Mind: Why Right-Brainers Will Rule The Future*, Riverhead Books, New York, ISBN 1-57322-308-5, ©2006

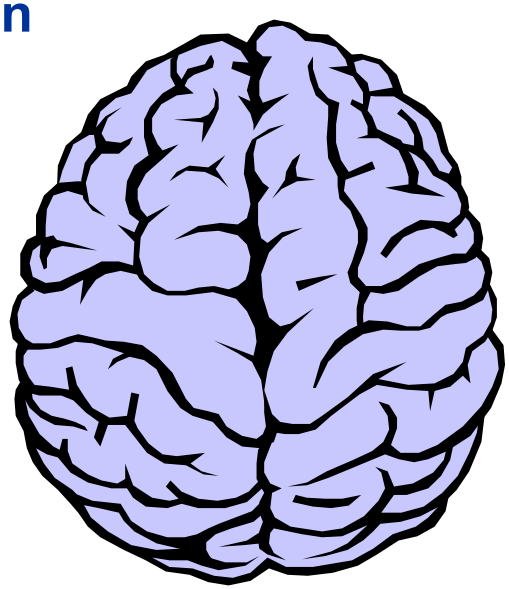
Right Hemisphere of Brain

- Controls left side of body
- **Simultaneous** – sees many things at once
- **Intuitive**, aesthetic
- **Non-verbal** activities
  - Recognizes and interprets facial expressions, intonation & emotional cues
- Specializes in **context** – *how* it is said
  - Subjective
  - Comprehends metaphors
- **Synthesizes** the "big picture" (whole)
  - Puts isolated elements together to perceive things as a whole (holistic)
  - Diverges into a Gestalt (organized whole)
  - Focuses on relationships
  - Sees the "big picture"

Brain Hemisphere Dichotomy -2

Left Hemisphere of Brain
L-Directed Thinking

- Uses logic
- Detail oriented
- Facts rule
- Words and language
- Present and past
- Math and science
- Can comprehend
- Knowing
- Acknowledges
- Order/pattern perception
- Knows object name
- Reality based
- Forms strategies
- Practical
- Safe



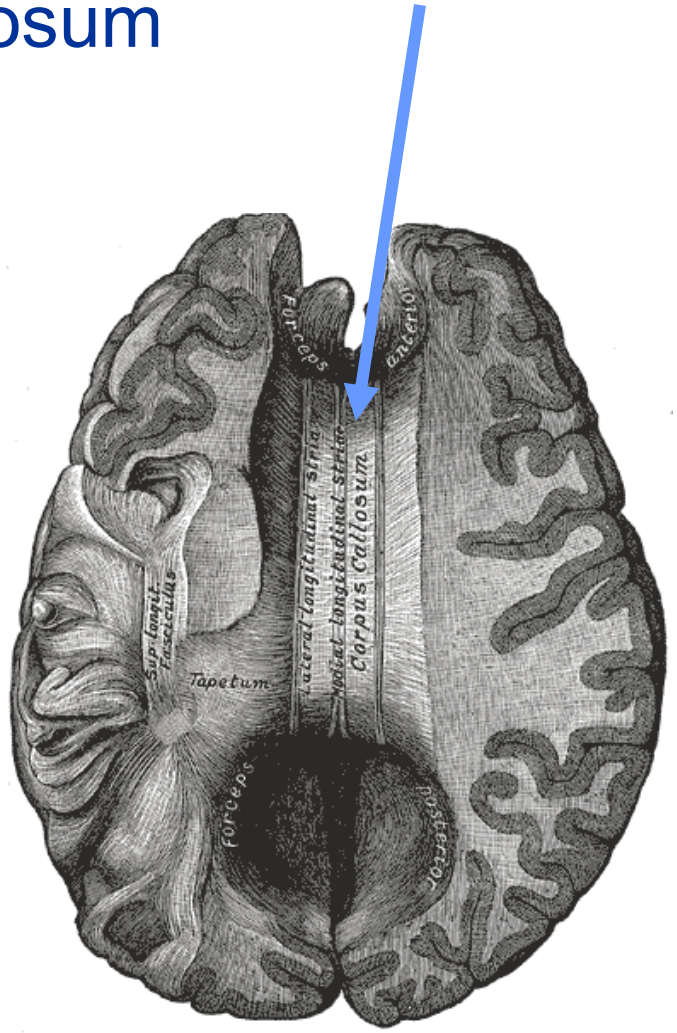
http://www.news.com.au/perthnow/story/0,,22492511-5005375,00.html?from=valueAdd

Right Hemisphere of Brain
R-Directed Thinking

- Uses feeling
- "Big picture" oriented
- Imagination rules
- Symbols and images
- Present and future
- Philosophy and religion
- Can "get it", i.e., meaning
- Believes
- Appreciates
- Spatial perception
- Knows object function
- Fantasy based
- Presents possibilities
- Impetuous
- Risk Taking

Systems Engineers Must Have An Active Corpus Callosum

- The corpus callosum attaches the left brain hemisphere to the right brain hemisphere.
  - Left brain: mathematical, logical, deductive
  - Right brain: aesthetic, intuitive, inductive
- SEs must be able to use <u>both</u> sides of their brain, and be able to switch between them.
  - Can consider the technical issues as well as be visionary
  - Can be creative with new mission designs, but be tempered by costs and reality
- SEs need to be a "visionary skeptic."
  - Sometimes the intuitive burst needs to pass over to the skeptic and ask how much it will cost, or if it is even possible.
    - e.g., feasibility of a Venus Sample Return mission.



Gray's Anatomy Fig. 733

SE When the Canvas Is Blank
by B. Gentry Lee, 2007

Leadership vs. Management Dichotomy -1

- **Transformational Leadership**
  - Strategic
  - Provides vision and direction
  - Moves organization forward
  - Sets the direction
  - Motivates and inspires
  - Defines the culture of the organization
- Leaders need to “get on the balcony” to spot operational and strategic patterns within the organization.
- Leadership has to do with creating things in the first place.
  - It is about coping with change and helping others to adapt to a volatile world.

- **Transactional Management**
  - Tactical
  - Day to day management
  - Sustains status quo
  - Operational
  - Develops the capacity to achieve the plan
  - Controls and problem solves
  - Instills the culture in the organization
- Managers get caught up in the field of action. It means hard choices and responsible follow up.
- Management has to do with planning and organizing, coping with complexity, process and procedures.

http://www.performancecoachinginternational.com/resources/articles/leadershipvsmanagement.asp

Leadership vs. Management Dichotomy -2

- **Leading** the organization
  - Visioning and networking
  - Focusing effort
  - Being team oriented
  - Building shared vision
  - Facilitating change sensitively
  - Supporting a development culture
- **Leadership** tends to involve visionary thinking, belief that with great risk comes great reward, achievement of goals by inspiring and motivating followers, and possessing the qualities that mirror the organization's mission and vision.
- **Leaders** are inspirational, motivational, visionary, big-picture and long-term focused.
- **Leaders lead people.**

- **Managing** the organization
  - Managing the service
  - Planning and organizing
  - Being goal oriented
  - Promoting innovation
  - Making sound judgments
  - Ensuring quality
- **Management** tends to involve direction of day-to-day operational tasks, management and maintenance of budgets and deadline oriented, directing teams to achieve goals by establishing objectives.
- **Management** is operational, task oriented, budget conscious and mindful of deadlines.
- **Managers manage tasks.**

http://www.performancecoachinginternational.com/resources/articles/leadershipvsmanagement.asp

Leadership vs. Management Dichotomy -3

- It is often said that if you are in a group of explorers hacking through a thick jungle, the **manager** is worried about cutting a straight and efficient path, while the **leader** is climbing the trees to make sure that you are going in the right direction.
  - Fact is, you need both.
- When I describe architecture, sometimes I need to **lead**.
  - Sometimes it is about insuring that the direction is the right one. I need to make sure that we are keeping the correct things visible as the goal, and staying focused on the elements that will get us there, while staying tuned to the "snares" that would prevent progress.
- Other times, I need to **manage**.
  - I need to write the document, create the diagram, lead the team meeting, enter rows in the schedule. It's day to day, “block and tackle” stuff. It's taking my turn at point.
    - It is not creative, but it is necessary.
- This distinction applies whether you have direct reports, or you are in a position of influence. The rules really aren't different, even though the balance of motivations are.
- **The toughest part, really, is . . .**

  knowing when to lead and when to manage.

Nick Malik Inside Architecture MSDN Blog
http://blogs.msdn.com/nickmalik/archive/2007/08/27/leadership-vs-management.aspx

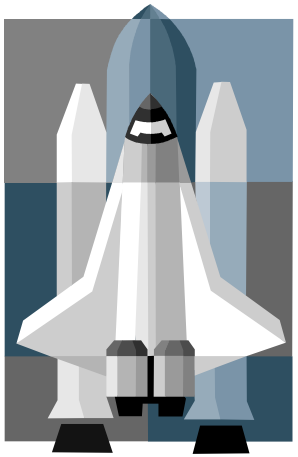
Leadership vs. Management Dichotomy -4
NASA Art and Science of SE Monograph

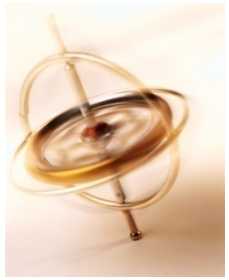
Science of SE

- Systems **Management**, Analytic
  - Involves rigorously and efficiently managing the development and operation of complex systems
    - Emphasis is on organizational skills, processes and persistence.

Art of SE

- Technical **Leadership**, Intuitive
  - Balances broad technical domain knowledge, engineering instinct, problem solving, creativity, leadership and communication to develop new missions and systems.
    - Focuses on a system's technical design and technical integrity throughout its life-cycle





NASA Art and Science of System Engineering Monograph 2008

Process-Based Dichotomy – NASA SE NPR -1

Possible Art vs. Science of SE	Process Category	Process Subcategory and Common Technical Processes
Art of SE ? **Technical Leadership**	**System Design Processes**	**Requirements Definition Processes** 1. Stakeholder Expectations Definition 2. Technical Requirements Definition **Technical Solution Definition Processes** 3. Logical Decomposition 4. Design Solution Definition
	Product Realization Processes	**Design Realization Processes** 5. Product Implementation 6. Product Integration
		Evaluation Processes 7. Product Verification 8. Product Validation
		Product Transition Process 9. Product Transition
Science of SE ?	**Technical Management Processes**	**Technical Planning Process** 10. Technical Planning
Systems Management		**Technical Control Processes** 11. Requirements Management 12. Interface Management 13. Technical Risk Management 14. Configuration Management 15. Technical Data Management
		Technical Assessment Process 16. Technical Assessment
		Technical Decision Analysis Process 17. Decision Analysis

Refinements on Art of SE

Process-Based Dichotomy -2
Further Narrower Refinements

- Two Cultures of Engineering
  (M. Griffin)
  - Engineering design vs. Engineering science or analysis
  - Defines systems engineering as "the art and science of developing an operable system capable of meeting requirements within imposed constraints."
  - Art of Systems Engineering involves system design
  - Science of Systems Engineering involves analysis and all other engineering details, such as requirements and interfaces.
- Art of System Architecting
  (M. Maier & E. Rechtin)
  - "Architecture *must* be grounded in the client's/user's/customer's purpose . . . It is the responsi-bility of the architect to know and concentrate on the critical few details and interfaces that really matter and not to become overloaded with the rest."
  - Art of Systems Engineering is limited to *only* the System Architecting components of system design
  - All other aspects of SE belong in the Science of Systems Engr.

Process-Based Dichotomy -3
Art of SE Throughout Project Life-Cycle Phases

NASA Project Life-Cycle Phases	How the Art of Systems Engineering May Be Practiced
Pre-Phase A: Concept Studies	Creative exploration of concepts, strategies and mission options; prioritizing issues, risks and making appropriate tradeoffs
Phase A: Concept & Technology Development	Constructive stakeholder interactions when translating science objectives into measurement requirements and then into instrument requirements
Phase B: Preliminary Design & Technology Completion	Selection of system architecture, particularly for a clean, elegant design that optimally addresses opposing interests and constraints
Phase C: Final Design & Fabrication	Knowing where to probe in the design and technical details; ensuring technical integrity
Phase D: System Assembly, Integration & Test, Launch	Holistic system approach to integration and V&V; creative problem solving and anomaly repairs; prioritizing issues/risks
Phase E: Operations & Sustainment	Creative and robust responses to operational challenges, spacecraft and payload anomalies, science discoveries, and changes in budgets and/or expectations
Phase F: Closeout	Capture of appropriate lessons learned; possible follow-on missions and use of mission data

Behavior and Skills Dichotomy -1
Results of NASA SE Behavior Study

Top Level Themes	Middle Competencies
Leadership	
*	Appreciates/Recognizes Others
*	Builds Team Cohesion
*	Understands the Human Dynamics of a Team
*	Creates Vision and Direction
*	Ensures System Integrity
*	Possesses Influencing Skills
	Sees Situations Objectively
*	Coaches and Mentors
	Delegates
	Ensures Resources are Available

Attitudes & Attributes	
	Remains Inquisitive and Curious
*	Seeks Information and Uses the Art of Questioning
*	Advances Ideas
	Gains Respect, Credibility, and Trust
	Possesses Self-Confidence
*	Has a Comprehensive View
	Possesses a Positive Attitude and Dedication to Mission Success
	Is Aware of Personal Limitations
*	Adapts to Change and Uncertainty
*	Uses Intuition / Sensing
*	Is Able to Deal with Politics, Financial Issues, and Customer Needs

* Utilizes Art of SE, 27 of 40 competencies

Behavior and Skills Dichotomy -2
Results of NASA SE Behavior Study (Cont.)

Communi-cation	
*	Listens Effectively and Translates Information
*	Communicates Effectively Through Personal Interaction
*	Facilitates an Environment of Open and Honest Communication
*	Uses Visuals to Communicate Complex Interactions
*	Communicates Through Story Telling and Analogies
*	Is Comfortable With Making Decisions
Technical Acumen	
	Possesses Technical Competence and Has Comprehensive Previous Experience
	Learns from Successes and Failures

Problem Solving & Systems Thinking	
*	Identifies the Real Problem
*	Assimilates, Analyzes, and Synthesizes Data
*	Thinks Systemically
*	Has the Ability to Find Connections and Patterns Across the System
*	Sets Priorities
*	Keeps the Focus on Mission Requirements
*	Possesses Creativity and Problem Solving Abilities
	Validates Facts, Information and Assumptions
	Remains Open Minded and Objective
	Draws on Past Experiences
	Manages Risk

* Utilizes Art of SE, 27 of 40 competencies

Behavior and Skills Dichotomy -3
Specific SE Behaviors from NASA Study

Science of SE

- **Technical Competence**: Possesses a strong, fundamental understanding of engineering principles with a cross-disciplinary background
  - Demonstrates the depth of technical knowledge and expertise necessary to perform, manage, and coordinate work-related activities.
- **Risk:** Develops risk mitigation strategies for addressing problems, should they arise.
- **Tools and Models:** Keeps abreast of current analytical tools and models by knowing where to find them, when to apply them, and how to use them.

Art of SE

- **System Integrity:** Understands the integrity of the system is a primary role.
- **Big Picture:** Seeks to understand the big picture and interrelationship of the parts. Moves without boundaries from one topic to another, to discover what else needs to be known, what might be overlooked.
- **Intuition:** Uses both intuition and sensing when evaluating a problem or making a decision. Does not rely solely on data.
  - May use "gut feeling" if data is inconclusive.
- **Requirements:** Studies, understands, and articulates the project's overall objectives.
  - Knows what the system must do and be in order to accomplish its objectives.
- **Priorities:** Sets technical priorities in order to maintain the balance for the problems at hand while achieving system requirements.
- **Team Cohesion:** Knows that resolving differing opinions is important to clarify the problem and foster better understanding.
  - Works to ensure vigorous debate is allowed among people with different views, goals, and objectives to build a common framework.

NASA Systems Engineering Behavior Study, Oct. 2008

Recommendations for Enhancing the Art of SE

1. Determine brain dominance.
   - A quick, inexpensive way to determine personal brain dominance and auditory/visual preferences is to use Brainworks, a self-assessment tool developed by Synergistic Learning Inc., available on-line.
   - If the assessment reveals limited capacity for right brain R-directed thinking, then that would tend to indicate that one's ability to perform some essential systems engineering skills such as holistic, "big picture" thinking is also limited.
2. Seek leadership training and resources.
   - Since an important part of systems engineering involves technical leadership, ways to develop leadership and influence skills should be actively pursued.
   - Anything by leadership "guru" John Maxwell is a good place to start.
3. Learn systems architecture principles.
   - Since an important part of systems engineering includes systems architecture and design, training in this area is essential. Courses and books on systems architecture especially Maier and Rechtin's book *The Art of Systems Architecting* are worth exploring.
4. Develop or enhance appropriate "soft" skills.
   - The eight behaviors identified by Pellerin in *How NASA Builds Teams* are a good place to start, especially since workshops and coaching are available to learn these skills. Also both team and individual assessments are available to provide feedback and monitor progress.
5. Seek opportunities to receive mentoring/coaching.
   - Since some aspects of systems engineering are "better caught than taught," having a good mentor or more senior systems engineer to observe and interact with is very instructive.
   - Coaching is particularly helpful for inculcating the valuable systems engineering behaviors.

Important Caveat

- It is important to keep in mind that there is no such thing as one ideal, ***perfect*** systems engineer prototype that ***everyone*** should strive for.
  - There is not ***one*** particular attribute or personality.
  - It would be a mistake to select or train using some "cookie cutter" assembly line approach.
- Different projects and project managers are looking for different mixes of skills in a systems engineer, depending on the size of the system, the nature and complexity of the mission, and the phase of the life-cycle.
  - A "hands-on" Project Manager would likely want a systems engineer who focuses on providing the necessary "glue" function for the project.
  - A more "hands-off" Project Manager would likely want the systems engineer to "step up" and do more creating and influencing.
- There is a range of customers, and consequently, they are looking for different mixes of skills. One size does not fit all.

Balancing the Art and Science of SE

It takes <u>both</u> of these ingredients to make NASA a success.

Science of SE

Systems Management, Analytic, Analysis, Decomposition, Drill Down

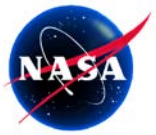
Left Brain
(language, sequential reasoning, rational, logical, analytic)

Art of SE

Technical Leadership, Intuitive, Synthesis Holistic, Big Picture

Right Brain
(nonverbal, nonlinear, instinctive, recognizes patterns & emotions)

To succeed, we must blend technical leadership and systems management into *complete* systems engineering. Anything less results in systems not worth having or that fail to function or perform.



Backup Slides

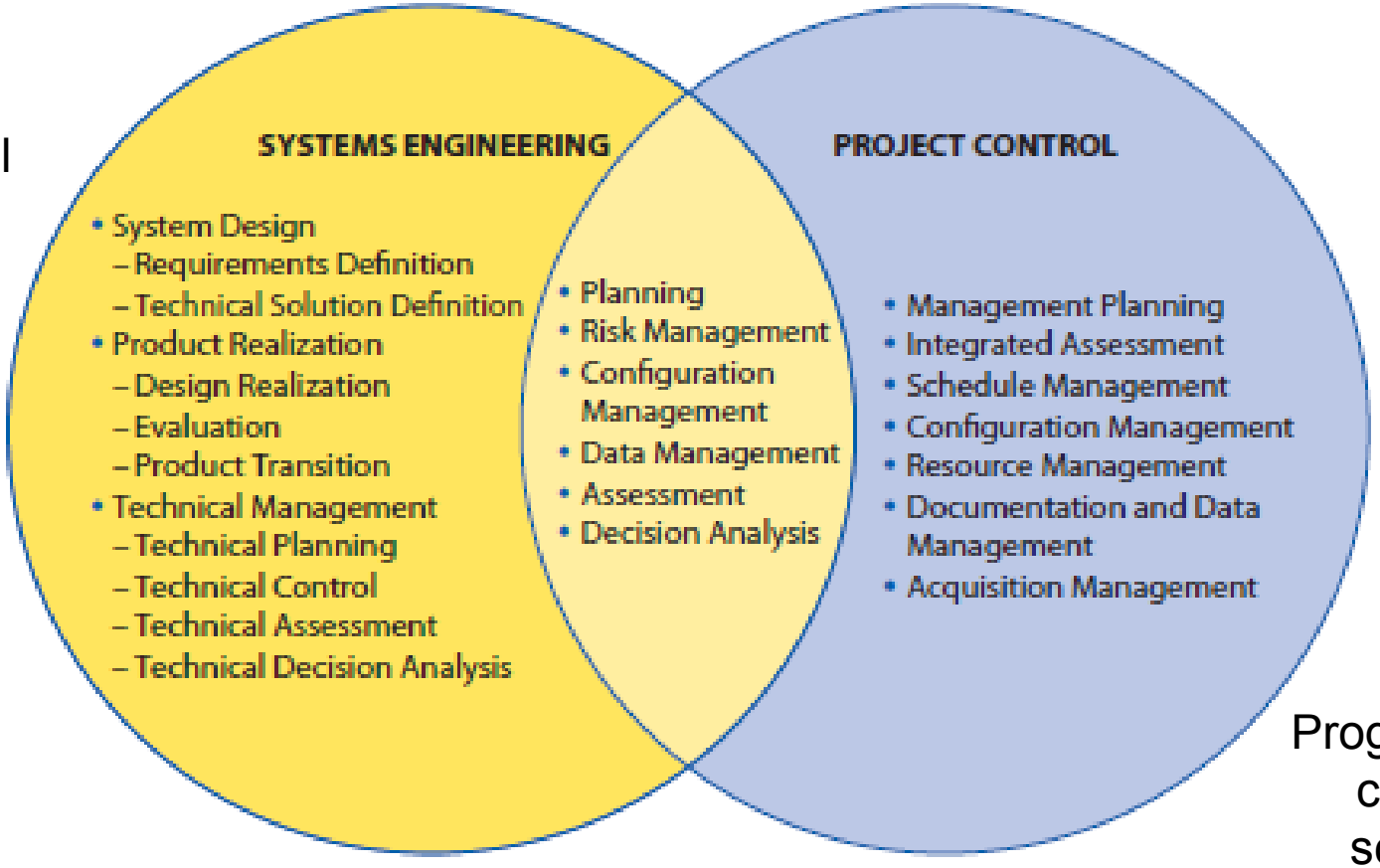
Six Essential Right Brain R-Directed Aptitudes

- **Design**
  - Not just function, but also design (beautiful and engaging)
- **Story**
  - Not just argument, but also story (a compelling narrative)
- **Symphony**
  - Not just focus, but also symphony (synthesis, “big picture”)
- **Empathy**
  - Not just logic, but also empathy (forge relationships, care for others)
- **Play**
  - Not just seriousness, but also play (laughter, games, humor)
- **Meaning**
  - Not just accumulation but also meaning (purpose, transcendence)
- Anyone can master these six “senses”.
  - But those who master them first will have a huge advantage.

Daniel Pink, *A Whole New Mind: Why Right-Brainers Will Rule The Future*, Riverhead Books, New York, ISBN 1-57322-308-5, ©2006

Project Management: Systems Engineering and Project Control

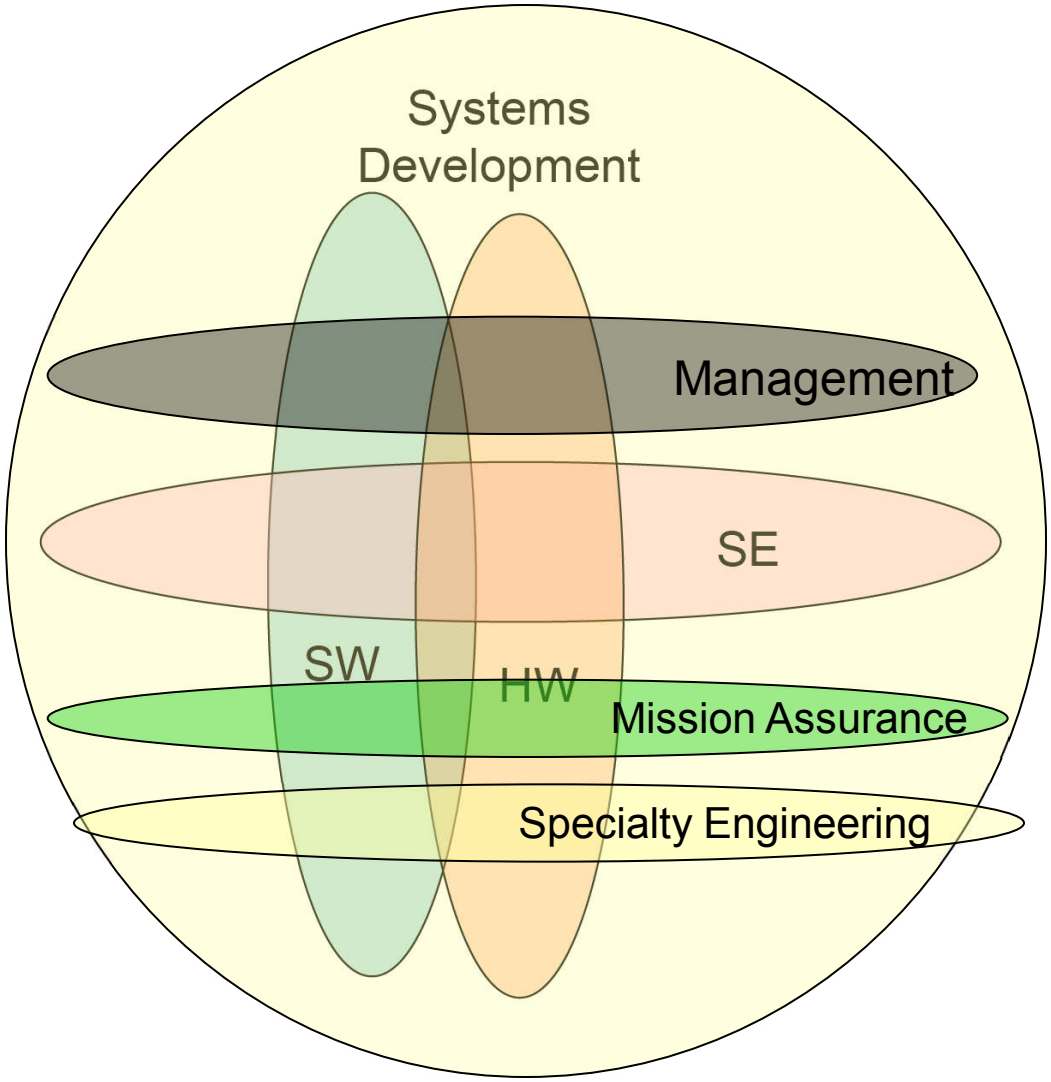
Technical Inputs

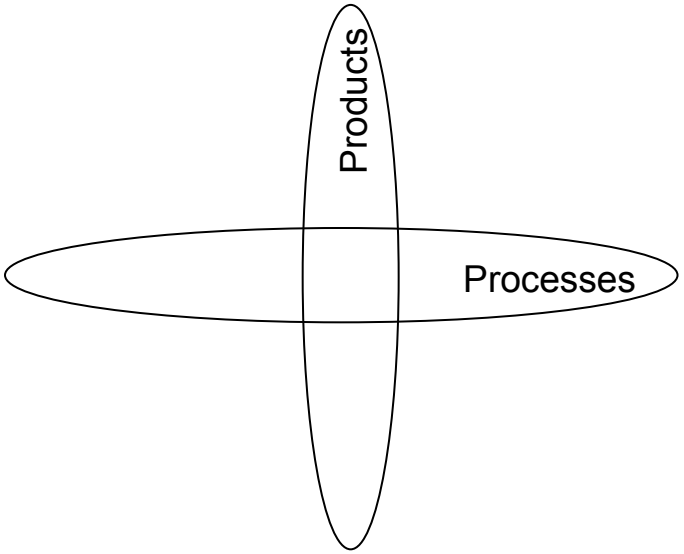


Programmatic, cost and schedule inputs

NASA Systems Engineering Handbook, NASA/SP-2007-6105 Rev. 1, pg. 4

Systems Engineering and Systems Development Distinction





Systems Engineering (SE) is one of the processes used during the development of systems

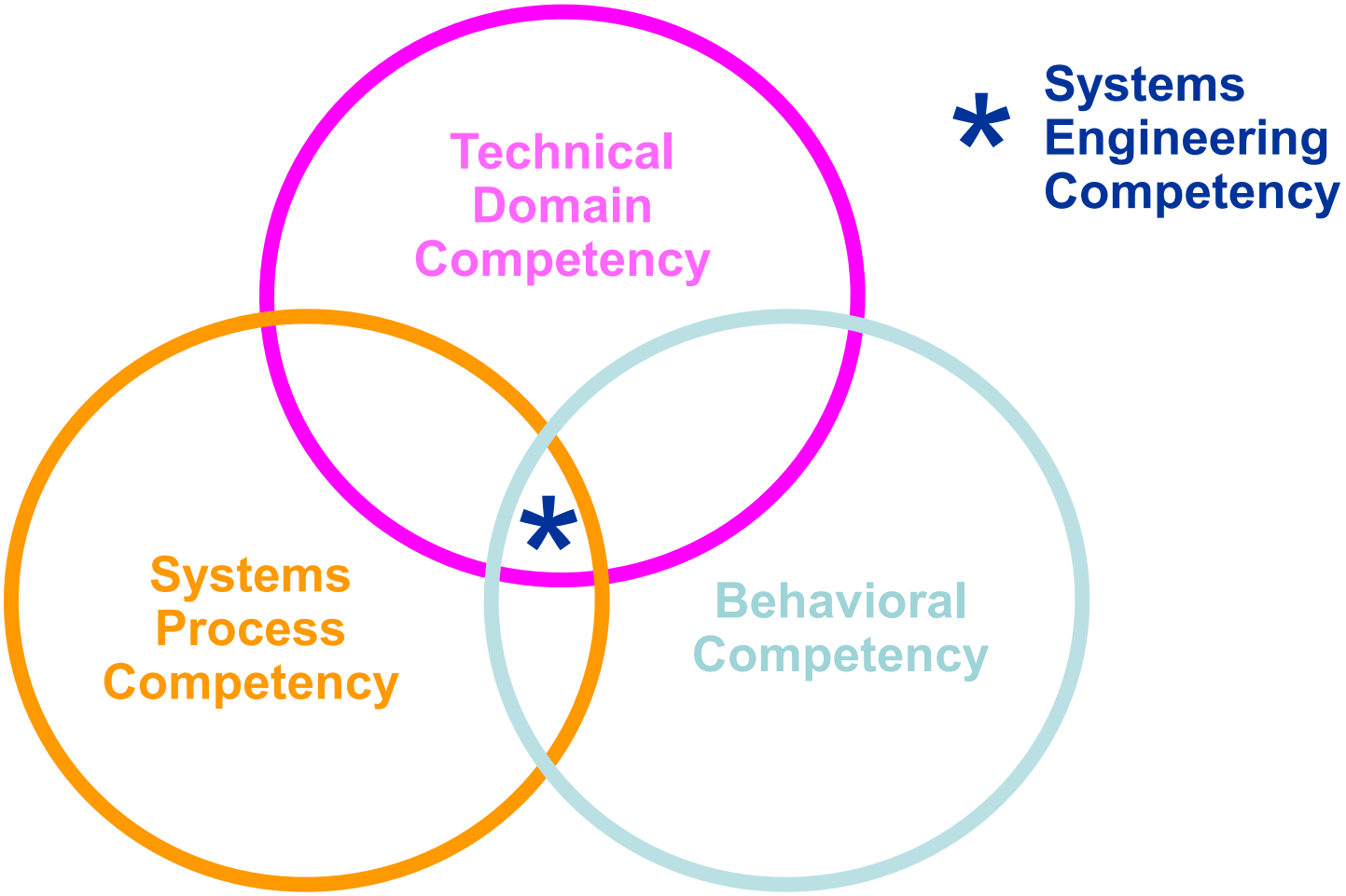
Millennium Challenge 2002 Exercise

- Blue Team – U.S. Joint Forces Command (USJFCOM)
  - High tech team with access to computer systems, databases, formal decision making tools, processes, protocol, sophisticated communication systems, real-time maps, etc.
  - Strict chain of command, lots of information to process and many discussions to figure out what was going on.
- "They were so focused on the mechanics and the process that they never looked at the problem holistically. In the act of tearing something apart, you lose its meaning.
- "If you get too caught up in the production of information, you drown in the data."
  Lt. Gen. Ret. Paul Van Riper, USMC as quoted in *Blink* (pg. 125, 144)

- Red Team – Rogue Commander of Middle East country
  - Low-tech, agile team with basic communications, flexible planning, rapid cognition, fast response to changing conditions
  - "In command and out of control"
    - Commander and senior leadership provided overall guidance and intent
    - Forces in the field were to use their own initiative and be innovative.
- "When we talk about analytic vs. intuitive decision making, neither is good or bad. What is bad is if you use either of them in an inappropriate circumstance."
  Lt. Gen. Ret. Paul Van Riper, USMC as quoted in *Blink* (pg. 143)
- "Truly successful decision making relies on a balance between deliberate and instinctive thinking." *Blink* (pg. 141)

Malcolm Gladwell, *Blink: The Power of Thinking Without Thinking*, Little, Brown and Co., New York, ISBN 0-316-17232-4, ©2005

Behavior and Skills Dichotomy – Competencies of Systems Engineering



Behavior and Skills Dichotomy
Managerial or "Soft" Categories and Skills

- **Project Planning and Tracking**
  - Task Planning, Task Allocation
  - Schedule Development, Tracking
  - Budget Development, Tracking
- **Problem Solving and Decision Making**
  - Problem Identification, Solution, Escalation
  - Timely Decisions, Follow Through
- **Vision and Leadership**
  - "Big Hat", "Big Picture" Approach
  - Clear Picture of Problem
  - Ownership of Problem
- **Dealing with People**
  - Staffing, Team Selection
  - Team Building
  - Conflict Resolution
  - Delegating
  - Negotiating
  - Challenging, Inspiring, Motivating
- **Communicating and Reporting**
  - Presentations, Reviews, Reports
  - Customer Focus & Awareness
  - Sponsor Interface
  - Open Communication with
    - Team, Management
  - Meeting Management

Technical or "Hard" Categories and Skills

- **Technical Management**
  - Cost Estimation
  - Risk Management
  - Project Planning
  - Development Environments
  - Project Monitor & Control
  - Measurement, Metrics
  - Quality Assurance
  - Configuration Management
- **Systems Engineering**
  - Requirements Definition & Analysis
  - Tradeoffs, Tailoring, Prioritizing
  - System Architecture
  - System Verification & Validation
    - Analysis, Simulation & Testing Approaches
  - Processes, Procedures, CMMI, ISO
- **Software Engineering**
  - Software Architecture
  - Software Design
  - Software Reliability and Safety
  - Software Implementation
  - Application Domain-Specific Knowledge
  - Methodologies, Tools, & Processes
  - Languages, OS, DBMS
  - Software Verification & Validation
  - Software Technology Awareness
- **Hardware Engineering**
  - Hardware Architecture & Design
  - Hardware Safety & Handling
  - Firmware
  - Hardware Test & Validation
  - Hardware Technology Awareness

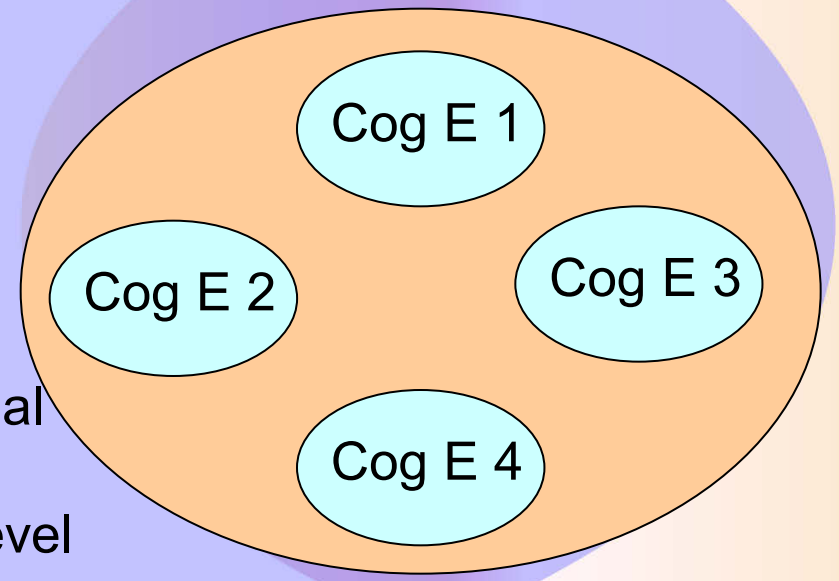
Exploring the Art and Science of SE

- We've explored several different ways of looking at the Art and Science of SE:
  - Right brain (R-directed thinking) vs. Left brain (L-directed thinking)
  - Leadership vs. Management
    - Technical Leadership vs. Systems Management (monograph)
  - SE NPR: Technical Management Processes vs. System Design and Product Realization Processes
  - Processes and technology vs. agile and responsive
  - SE Behaviors
  - "Hard" Engineering (Technical) Skills vs. "Soft" Engineering (People/Management) Skills
- While there are many views on what constitutes the Art and the Science of SE, they are really two sides of the same coin. Most people agree:
  - **Technical skills alone are necessary but not sufficient to be an effective and successful systems engineer.**

Role Distinctions Between Manager, Cog E and SE

Manager

- Delivery
- Decision maker
- Staffing
- Budget $
- Schedule
- Contracts
- Team & organizational behaviors
- Interacts with next level managers, peers
- Penetrates the design

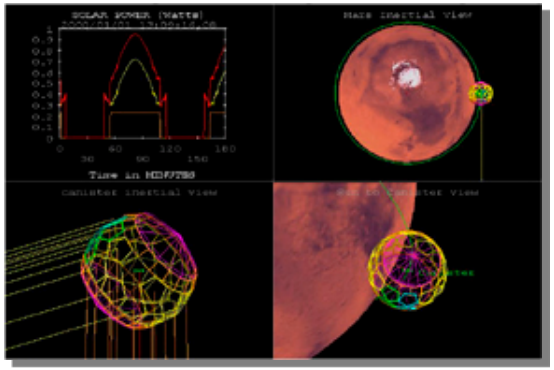


Systems Engineer

- Architecture
- Requirements
- Interfaces
- dB, W, SNR, kg
- Perf model & trades
- V&V
- Risk
- Manage change
- Recommends actions
- Interacts with next level up and peers
- Penetrates the design

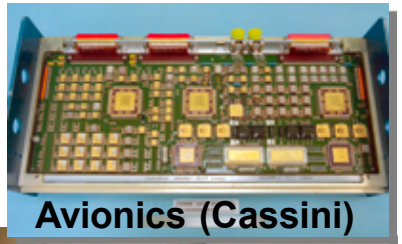
End to End Capabilities Needed for Robotic Missions

Project Formulation - Team X



Mission Design

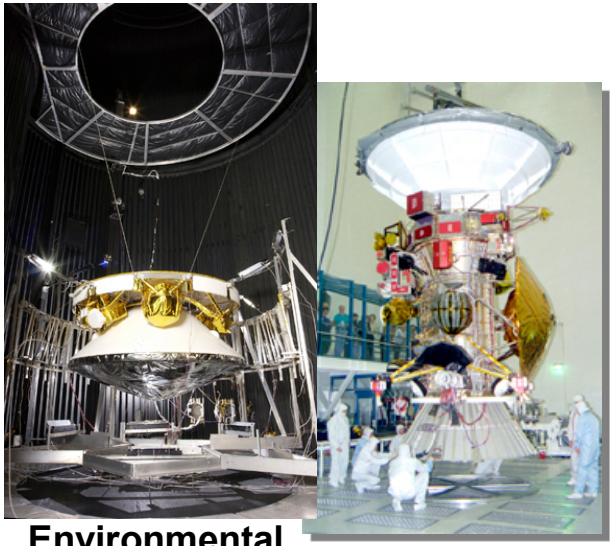
Spacecraft Development



Avionics (Cassini)

Large Structures (SRTM)

Ion Engine (DS-1)



Integration and Test

Environmental Test

Real Time Operations

Art & Science of Systems Engineering Panel at 2009 NASA PM Challenge

Science of SE

- Systems management
- Processes
- Systematic methods
- Quantitative approach

The application of SE is life-cycle dependent.
Applying the art of SE is an art!

Systems Engineering Advancement Research Initiative (SEAri) at MIT http://seari.mit.edu/ Dr. Donna H. Rhodes, Director and Principal Research Scientist

Art of SE

- Creativity
- Communication skills
- Creative problem solving
- Technical leadership
- Engineering intuition
- Intellectual curiosity
- Essence
- Comfortable with uncertainty
- Personality to be a great leader
- Architecture
- Can't keep them in a box
- Organizational enablers of trade space exploration
- Anticipatory and options-based thinking
- Situational Leadership

Behaviors of Good Systems Engineers

1. Has Intellectual Curiosity
2. Sees The “Big Picture” View
3. Sees Connections
4. Is Comfortable With Change
5. Is Comfortable With Uncertainty
6. Has “Proper Paranoia”
7. Keeps Track of Resources & Margins
8. Has Good Communication Skills
9. Has Self-Confidence and Energy
10. Has Appreciation For Process

NASA Art and Science of System Engineering Monograph 2008,
“So You Want To Be A Systems Engineer” by B. Gentry Lee