Exploring the Art and Science of Systems Engineering

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***Abstract*—** 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? Some say that the art of systems engineering is about designing systems that not only function well, but that are also elegant, beautiful and engaging. What does that mean? How can you tell when a system has been designed with that holistic "art" component? This paper[1] attempts to answer these questions by exploring various ways of looking at the Art and Science of Systems Engineering.

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1. 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? Some say that the art of systems engineering is about designing systems that not only function well, but that are also elegant, beautiful and engaging. What does that mean? How can you tell when a system has been designed with that holistic "art" component? This paper attempts to answer these questions by exploring various ways of looking at the Art and Science of Systems Engineering.

This exploration is akin to the famous poem by John Godfrey Saxe about the six blind men of Indostan exploring the elephant [26]. Each man touches a single part of the elephant – side, tusk, trunk, knee, ear and tail – and draws conclusions about the animal as a whole. The poem concludes with these lines:

> "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!"

In the same way, although each theory or view of the Art and Science of Systems Engineering has some validity, none by itself tells the whole story. However, when considered together, they provide some illumination on the "elephant" of systems engineering. Also, they all lead to the conclusion that to be truly effective, we must balance both the Art and the Science of Systems Engineering.

To further explore the concept of the Art and Science of Systems Engineering, let us consider a completely different field and draw an analogy. Let us consider figure skating at the winter Olympics. Olympic figure skaters are given scores for their "free skate" or long programs based on five components: skating skills, transitions, performance/ execution, choreography and interpretation [24]. Most of us are not skilled experts like the Olympic judges, nor are we able to articulate the subtle nuances separating the particular techniques and style points, but we know an excellent program when we see it. We know it's not just about the difficulty of the jumps, spins, and steps or even the beauty of the music and the costumes. There is an "art", a flow, a synthesis of technique, aesthetics, and poise that defines a true Olympic champion figure skater. Similarly, we know a robust and elegant system design when we see it. We also know when it is painfully absent. Also, many of us have been on teams that "got the job done, but it wasn't pretty." Why is that? What distinguishes these two outcomes?

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2. BRAIN HEMISPHERE DICHOTOMY

One way of characterizing the Art and Science of Systems Engineering is to consider the two hemispheres of the human brain and how each hemisphere contributes to systems thinking and design.

Left Hemisphere of Brain

Let's look at the usual functions and characteristics of the left hemisphere of the brain.

- **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
- Controls the right side of the body [16]

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

Right Hemisphere of Brain

Now let's look at the usual functions and characteristics of the right hemisphere of the brain.

- **Simultaneous** – sees many things at once
- **Intuitive**, aesthetic
- **Non-verbal** activities
  - Recognizes and interprets facial expressions, intonation and 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"
- Controls the left side of the body [16]

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

Six Essential R-Directed Aptitudes

In his book *A Whole New Mind*, Daniel Pink identifies what he calls six essential R-directed aptitudes. He believes that anyone can master these six "senses". But those who master them first will have a huge advantage. [16]

1. Design -- Not just function, but also design (beautiful and engaging)
2. Story -- Not just argument, but also story (a compelling narrative)
3. Symphony -- Not just focus, but also symphony (synthesis, "big picture")
4. Empathy -- Not just logic, but also empathy (forge relationships, care for others)
5. Play -- Not just seriousness, but also play (laughter, games, humor)
6. Meaning -- Not just accumulation but also meaning (purpose, transcendence)

Thus, in the brain dichotomy paradigm, the left hemisphere of the brain which uses logic, is detail oriented and focuses on *what* is said in words, is how the Science of Systems Engineering is done. And the right hemisphere of the brain which is "big picture" oriented, involves symbols and images, and specializes in context and *how* things are said, is how the Art of Systems Engineering is accomplished.

Active Corpus Collosum

The corpus collosum attaches the left brain hemisphere to the right brain hemisphere as shown in Figure 1 [5]. A systems engineer must be able to use both sides of his or her brain, and be able to switch between them. Good SEs can consider the technical issues as well as be visionary. They can be creative with new mission designs, but be tempered by costs and reality. SEs need to be "visionary skeptics." 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., the feasibility of a Venus Sample Return mission. [9]

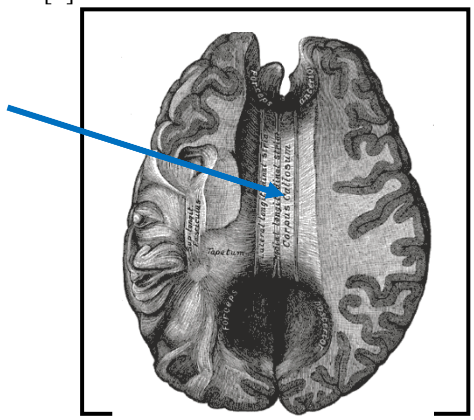


Figure 1 Brain with Corpus Collosum

3. LEADERSHIP VS. MANAGEMENT DICHOTOMY

Since systems engineering involves both technical leadership and systems management, another way of characterizing the Art and Science of Systems Engineering would be to consider the difference between leadership and management as discussed in business literature.

Transformational Leadership

Transformational leadership can be characterized as follows:

- 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. [20]

Leading the organization involves:

- Visioning and networking
- Focusing effort
- Being team oriented
- Building shared vision
- Facilitating change sensitively
- Supporting a development culture

Leadership tends to involve visionary thinking, a 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*. [20]

Transactional Management

Transactional management can be characterized as follows:

- 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.

Managing the organization involves:

- 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*. [20]

Nick Malik, in his blog focused on enterprise architecture and service oriented architecture, aptly clarifies the tension between leadership and management and shares his experience as follows [21]. "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 is. The toughest part really, is knowing when to lead and when to manage." [21]

In summary, leadership is characterized as transformational, strategic, visionary and focused on setting direction, motivating and inspiring. Management is characterized as transactional, tactical, operational and focused on control and problem solving. In the leadership/management paradigm, the Art of Systems Engineering would be considered as technical leadership, and the Science of Systems Engineering would be considered as systems management.

This concept is supported by the NASA Art and Science of Systems Engineering Monograph [17]. The monograph characterizes the Art of Systems Engineering as Technical Leadership and intuitive thinking that:

- 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

It characterizes the Science of Systems Engineering as Systems Management and analytic thinking that:

- Involves rigorously and efficiently managing the development and operation of complex systems
- Emphasizes organizational skills, processes and persistence.

4. PROCESS-BASED DICHOTOMY

NASA Systems Engineering NPR

The NASA Systems Engineering NPR (7123.1A) [8, 23] identifies 17 technical processes in three broad categories: system design processes, product realization processes and technical management processes, as shown in Table 1.

In the process-based dichotomy, the system design and product realization processes are considered the Art of Systems Engineering since they involve technical leadership. Then the technical management processes are considered the Science of Systems Engineering since they involve systems management.

NASA Systems Engineering Handbook

In addition, the NASA Systems Engineering Handbook [18] includes a Venn diagram delineating the task split between systems engineers and project managers as shown in Figure 2. The technical management activities in the overlapping area clearly fall into the systems management or project control area.

The "Two Cultures" of Engineering

Former NASA Administrator Dr. Michael Griffin discusses what he calls the "two cultures" of engineering – engineering design vs. engineering science or analysis. He defines systems engineering as "the art and science of developing an operable system capable of meeting requirements within imposed constraints. The definition is somewhat independent of scale, and so these words are useful only if one understands that it is the big-picture view which is taken here." [7]

Table 1 NASA SE NPR Technical Processes

Possible Art vs. Science of SE	**Process Category, Subcategory & 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 ? **Systems Management**	**Technical Management Processes** **Technical Planning Process** 10. Technical Planning **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

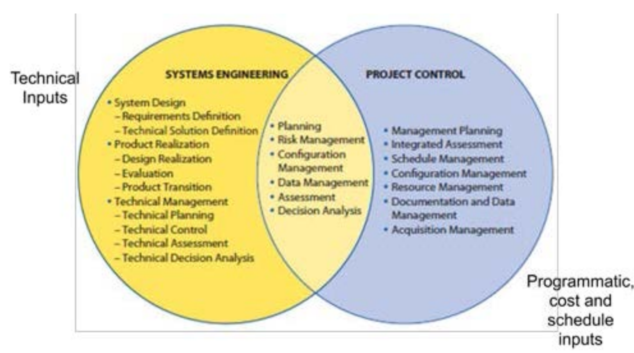


Figure 2 NASA SE Handbook SE vs. PM Activities

Griffin further defines systems engineering as "a holistic, integrative discipline, wherein the contributions of structural engineers, electrical engineers, mechanism designers, power engineers, and many, many more disciplines are weighted and considered and balanced, one against another, to produce a coherent whole that is not dominated by the view from the perspective of a single discipline. System engineering is about tradeoffs and compromises, about generalists rather than specialists." [7]

"System engineering is not about the details of requirements and interfaces between and among subsystems. Such details are important, of course. . . Accurate control of interfaces and requirements is necessary to good system engineering, but no amount of care in such matters can make a poor design concept better. System engineering is about getting the right design." [7]

"System engineering is the link which has evolved between the art and science of engineering. The system engineer designs little or nothing of the finished product; rather, he seeks a balanced design in the face of opposing interests and interlocking constraints. The system engineer is not an analyst; rather, he focuses analytical resources upon those assessments deemed to be particularly important, from among the universe of possible analyses which might be performed, but whose completion would not necessarily best inform the final design. There is an art to knowing where to probe and what to pass by, and every system engineer knows it." [7]

Griffin emphasizes that "there remains an artistic side of engineering, and it is fully as much an art for its practitioners as any painting, sculpture, poem, song, dance, movie, play, culinary masterpiece, or literary work. The difference between the cultural and engineering arts lies not so much in the manner of creation of a given work, but in the standards by which that work is judged." [7]

In this refinement of the process-based dichotomy, the Art of Systems Engineering involves system design, and the Science of Systems Engineering involves analysis and all other engineering details, such as requirements and interfaces.

The Art of Systems Architecting

In their book *The Art of Systems Architecting*, Maier and Rechtin [10] discuss the foundations of modern systems architecting. They define a systems approach as "one that focuses on the system as a whole, specifically linking value judgments (what is desired) and design decisions (what is feasible) . . . Taking a systems approach means paying close attention to results, the reasons we build a system. Architecture *must* be grounded in the client's /user's / customer's purpose . . . It is the responsibility 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." Further, they characterize systems architecting as "a process driven by a client's purpose or purposes . . . Clearly, if a system is to succeed, it must satisfy a useful purpose at an affordable cost for an acceptable period of time." Systems architecting "strives for fit, balance and compromise among the tensions of client needs and resources, technology, and multiple stakeholder interests." They conclude that "the best systems architects are indeed artists in what they do . . . The wisdom that distinguishes the great architect from the rest is the insight and the inspiration, that combined with well-chosen methods and guidelines and fortunate circumstances, creates masterworks." [10]

In this further refinement of the process-based dichotomy, the Art of Systems Engineering is even more restricted than just the System Design processes, and is limited to *only* the System Architecting components of system design, and then everything else belongs in the Science of Systems Engineering.

Art of Systems Engineering Throughout Project Life-Cycle

Yet, another view maintains that elements of the Art of Systems Engineering are practiced throughout the entire project life-cycle, only to a greater degree and with more prominence in the early phases, as shown in Table 2 below.

Table 2 Art of SE throughout Project Life-Cycle Phases

NASA Project Life-Cycle Phase	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

Millennium Challenge – Formal Process vs. Agile Intuition

In 2002, the US Military conducted some military exercises using two teams: the Blue Team consisted of the U.S. Joint Forces Command (USJFCOM) and the Red Team represented an opposing team supposedly from the Middle East. The "Blue Team" was characterized as a high tech team with access to computer systems, databases, formal decision making tools, processes, protocol, sophisticated communication systems, real-time maps, etc. They had a strict chain of command, lots of information to process and many discussions to figure out what was going on. [4]

The Red Team led by a "rogue Commander of a Middle East country," played by Lt. Gen. Ret. Paul Van Riper, USMC, was characterized as a low-tech, agile team with basic communications, flexible planning, rapid cognition, and a fast response to changing conditions. They prided themselves on being "in command and out of control." Their Commander and senior leadership provided overall guidance and intent. However, their forces in the field were to use their own initiative and be innovative. [4]

Over the course of the exercises, the Red Team thoroughly trounced the Blue Team in just three days! Analysis of the results yielded the following insights. The Blue Team was "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." Van Riper concluded that "If you get too caught up in the production of information, you drown in the data. . . .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. . . . Truly successful decision making relies on a balance between deliberate and instinctive thinking." [4]

So what are we to conclude from these military exercises? When the Blue Team focused solely on the Science of Systems Engineering and technical expertise, and seemingly ignored the holistic Art of Systems Engineering and the intuitive aspects, they were quickly and easily defeated.

5. Behavior and Skills Dichotomy

NASA Systems Engineering Behavior Study Report

In 2008, NASA conducted an agency-wide study of the behaviors of highly regarded systems engineers [2], [19]. In the behavior dichotomy, these specific behaviors are categorized as ones supporting the Science of Systems Engineering while others are viewed as supporting the Art of Systems Engineering. Table 5 delineates the top level themes of leadership, attitudes and attributes, communication, problem solving and technical acumen, along with 40 middle competencies from the NASA study. The vast majority of these competencies could be characterized as supporting the Art of Systems Engineering. Some of the specific behaviors that support the Art of Systems Engineering include:

1. **System Integrity:** Understands the integrity of the system is a primary role.
2. **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.
3. **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.
4. **Requirements:** Studies, understands, and articulates the project's overall objectives.
   - Knows what the system must do and be in order to accomplish its objectives.
5. **Priorities:** Sets technical priorities in order to maintain the balance for the problems at hand while achieving system requirements.
6. **Issues:** Looks for and anticipates problems or issues in the system in places that may not be covered with the right kind of data to make a decision.
7. **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.

Some of the specific behaviors that support the Science of Systems Engineering include:

1. **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.
2. **Risk:** Develops risk mitigation strategies for addressing problems, should they arise.
3. **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.

"Hard" Engineering Skills vs. "Soft" People Skills

In addition, most people agree that technical skills alone are necessary, but not sufficient, to be an effective and successful systems engineer. They reason that there is also a need for leadership, team building, communication, and other "soft" skills. [11, 12, 13, 14] In this skills dichotomy, technical or "hard" engineering skills would support the Science of Systems Engineering, and "soft" people skills would support the Art of Systems Engineering.

"Hard" engineering (technical) skills include the following categories and skills: [25]

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

"Soft" people skills include the following categories and skills: [25]

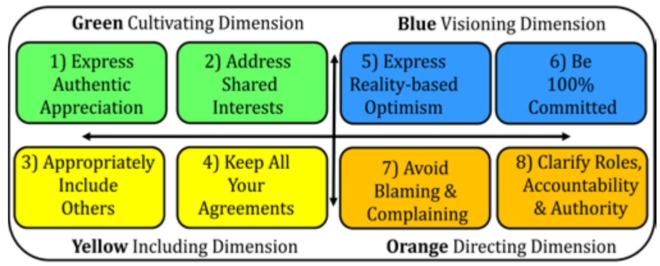
- **Problem Solving and Decision Making**
  - Problem Identification, Solution, Escalation
  - Timely Decisions, Follow Through
- **Vision and Leadership**
  - "Big Hat", "Big Picture" Approach
  - Clear Picture of Problem
  - Ownership of Problem
- **Dealing with People**
  - Staffing, Team Selection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

The above skill sets were derived from the results of multiple interviews with managers and team members at JPL in response to the question, "What skills would you like the people who work with and for you to have?" [25]

4-D Systems Dimensions and Behaviors

Yet another way of looking at the "soft" skills needed by engineers and project teams is defined by Charles Pellerin in *How NASA Builds Teams* [15]. He identifies four dimensions and eight behaviors (shown in Figure 3) that are necessary and sufficient for high performance.

Figure 3 4-D Systems' Dimensions and Behaviors



These behaviors have been used in assessments of over 500 teams, and provide a baseline for comparing a team's performance to results in the database, divided into quintiles from low to high performance. He believes that, to be successful, each *person* and *team* must develop basic skills in *all* four dimensions.

Pellerin states that each person has an innate preference for one of the four dimensions, which are based on Jung's deciding and information preferences. He uses these dimensions to categorize personality types as shown in Table 3. He believes that "not only is it important to address all four dimensions" but that "there is a necessary sequence, namely cultivating, including, visioning and directing."

Table 3 4-D Systems' Personality Types

"Green" Cultivating	**"Blue" Visioning**
• People Builders • Care about people and universal values • Stewards for others, families, values • Support others • Success while caring for people	• Idea Builders • Care about concepts • Creative ideas • Demand excellence • Freedom • Success through excellence and innovation
"Yellow" Including	**"Orange" Directing**
• Team Builders • Care about relationships • Harmony • Collaboration • Dislike conflict • Success through teamwork	• System Builders • Care about organization • Discipline, rigor • Focus on process and control • Success through process and consistency

Strengths-Based Leadership Domains

Another way of looking at skills and behaviors is through the leadership domains and strengths themes defined by Rath and Conchie in their book entitled *Strengths-Based Leadership* [28] which is based on extensive research by Gallup. These are shown in Table 4, and for the purpose of comparison, use the same color codes as the 4-D Systems dimensions to show the similarities. A description of each of the 34 strengths is given in Table 6 [27]. Rath states that it "serves a team well to have a representation of strengths in each of these four domains." In contrast to Pellerin, however, Rath believes that "*individuals* need not be well-rounded, [but] *teams* should be."

Table 4 Gallup's Four Domains of Leadership Strength and Corresponding Themes

Influencing	Strategic Thinking
Activator Command Communication Competition Maximizer Self-Assurance Significance Woo	Analytical Context Futuristic Ideation Input Intellection Learner Strategic
Relationship Building	**Executing**
Adaptability Developer Connectedness Empathy Harmony Includer Individualization Positivity Relator	Achiever Arranger Belief Consistency Deliberative Discipline Focus Responsibility Restorative

In this Strengths view, the Art of Systems Engineering would involve the strengths in the influencing and relationship building domains. This would be especially true in the formulation phase during stakeholder interactions when translating science objectives into measurement requirements and then into instrument requirements. The ideation, futuristic and strategic themes of the strategic thinking domain would be used for the Art of Systems Engineering as well, especially when developing an architecture and exploring design alternatives. The Science of Systems Engineering would involve the executing domain with emphasis on the arranger, discipline, focus and restorative themes.

6. SUMMARY

In summary, we've explored several different ways of looking at the "elephant" called systems engineering and the implications for the Art and Science of Systems Engineering, namely:

- Brain Hemisphere Dichotomy:
  - Right brain (R-directed thinking) vs. Left brain (L-directed thinking)
- Leadership vs. Management Dichotomy
  - Transformational Leadership vs. Transactional Management
  - Technical Leadership vs. Systems Management
- Process-Based Dichotomy:
  - SE NPR: Technical Management Processes vs. System Design and Product Realization Processes
  - System Design vs. Engineering Analysis
  - System Architecture vs. System Design
  - Art of SE Throughout Project Life-Cycle Phases
  - Formal Processes and Technology vs. Agile Methods and Intuition
- Behavior and Skills Dichotomy:
  - NASA SE Behavior Study Competencies
  - "Hard" Engineering (Technical) Skills vs. "Soft" People (Management) Skills
  - 4-D Systems Dimensions and Behaviors
  - Strengths-Based Leadership Domains

Implications and Recommendations

The author concludes that each of the above dichotomies has elements of legitimacy and fleshes out portions of the systems engineering "elephant." What, then, are the implications for systems engineers and their managers? While some of the traits of a good systems engineer are innate, many can be developed and enhanced. Some recommendations for potential next steps to strengthen one's abilities in the Art of Systems Engineering, based on each of the four dichotomies, are given below.

1. <u>Determine brain dominance</u>. 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 [29].

    a. If the assessment reveals limited capacity for right-brained thinking, then that would tend to indicate that one's ability to perform some needed SE skills such as holistic, "big picture" thinking is also limited.

    b. For those interested in developing their brains based on cutting edge neuroscience, resources are available at the Mind Media website [30] under Brain Power and Brain Enhancement, and from Lumosity, a developer of cognitive training and learning games [31]. In particular, cognitive training with a task called Dual N-Back has been shown to enhance fluid intelligence – the ability to creatively solve new problems.

2. <u>Seek leadership training and resources</u>. Since an important part of systems engineering involves technical leadership, ways to develop leadership

and influence skills should be actively pursued. Numerous courses and books on leadership are available. Anything by leadership "guru" John Maxwell is a good place to start [11], [12], [13].

3. Learn systems architecture principles. Since an important part of systems engineering includes systems architecture and design, training in this area is essential. Again courses and books on systems architecture are readily available. Maier and Rechtin's seminal work is definitely worth exploring [10].

4. Develop or enhance appropriate "soft" skills. The eight behaviors identified by Pellerin [15] 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 [32].

5. Seek opportunities to receive mentoring and coaching. Since some aspects of SE are "better caught than taught," having a good mentor or more senior systems engineer to observe and interact with is very instructive. Also, coaching is particularly valuable in inculcating the valuable systems engineering behaviors.

In conclusion, while there are many views on what constitutes the Art and the Science of Systems engineering, they are really two sides of the same coin. Most people agree that technical skills alone are necessary, but not sufficient, to be an effective and successful systems engineer. We must balance both the Art and the Science of Systems Engineering. As Griffin concludes [6], "Anything less results in systems not worth having, or that fail to function or perform."

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8.0 Acronyms and Abbreviations

JPL	Jet Propulsion Laboratory
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirements
OCE	Office of the Chief Engineer
PM	Project Manager
SE	Systems Engineering
SEA	Systems Engineering Advancement Project
SEWG	Systems Engineering Working Group
V&V	Verification and Validation

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Biography

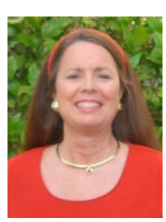

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Table 5 Results of NASA Systems Engineering Behavior Study

Top Level Themes	Art of SE ?	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
Communication	*	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
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
Technical Acumen		Possesses Technical Competence and Has Comprehensive Previous Experience
		Learns from Successes and Failures

Table 6 Gallup's 34 StrengthsFinder Themes

Theme Name	Theme Description
Achiever	Have a great deal of stamina and work hard; satisfied being busy and productive
Activator	Can make things happen by turning thoughts into action
Adaptability	Prefer to "go with the flow"; "now" people who take things as they come
Analytical	Search for reasons and causes; able to think about all factors that might affect a situation
Arranger	Can organize and likes to figure out how all the pieces and resources can be arranged for maximum productivity
Belief	Have certain core values that are unchanging and give a defined purpose for their life
Command	Have presence and can take control of a situation and make decisions
Communication	Find it easy to put their thoughts into words; good conversationalist and presenter
Competition	Measure their progress against the performance of others; strive to win
Connectedness	Have faith in the links between all things; believe there are few coincidences
Consistency	Are keenly aware of the need to treat people the same; set up clear rules and adhere to them
Context	Enjoy thinking about the past and understand the present by researching history
Deliberative	Take serious care in making decisions and choices and anticipate obstacles
Developer	Recognize and cultivate the potential in others; spot signs of improvements
Discipline	Enjoy routine and structure; create order
Empathy	Can sense the feelings of other people by imagining themselves in others' lives or situations
Focus	Can take a direction, follow through, and make the corrections necessary to stay on track; prioritize then act
Futuristic	Are inspired by the future and what could be; inspire others with visions of the future
Harmony	Look for consensus; don't enjoy conflict; seek areas of agreement
Ideation	Are fascinated by ideas; able to find connections between seemingly disparate phenomena
Includer	Are accepting of others; show awareness of those who feel left out and make an effort to include them
Individualization	Are intrigued with the unique qualities of each person; have a gift for figuring out how different people can work together
Input	Have a craving to know more; like to collect and archive all kinds of information
Intellection	Are characterized by their intellectual activity; are introspective and appreciate intellectual discussions
Learner	Have a great desire to learn and want to continuously improve
Maximizer	Focus on strengths as a way to stimulate personal and group excellence
Positivity	Have an enthusiasm that is contagious; are upbeat and can get others excited about what they are doing
Relator	Enjoy close relationships with others; find deep satisfaction in working hard with friends to achieve a goal
Responsibility	Take psychological ownership of what they say they will do; committed to stable values
Restorative	Are adept at dealing with problems; good at figuring out what is wrong and resolving it
Self-Assurance	Feel confident in their ability to manage their own lives; possess an inner compass
Significance	Want to be very important in the eyes of others; are independent and want to be recognized
Strategic	Create alternative ways to proceed; can quickly spot relevant patterns and issues
Woo	Love the challenge of meeting new people and winning them over; like to make a connection with another person

Legend: Executing Influencing Relationship Building Strategic Thinking