The Art and Science of Systems Engineering*

The Scope of Systems Engineering

The Personal Characteristics of Good Systems Engineer

Summary

This work culminates years of experience in systems engineering and focused discussions among NASA leadership, systems engineers, and systems engineering trainers across the Agency. One consistent theme in these experiences and discussions is that NASA uses many definitions and descriptions of systems engineering. We use the terms and job titles of chief engineer, mission systems engineer, systems engineering and integration manager, system architect, vehicle integration, and so on for various pieces of the complete systems engineering function. We need to agree on a common understanding of systems engineering. In addition, no matter how we divide the roles and responsibilities among people, we must ensure that those roles and responsibilities are clear and executed as a functional whole. **Our objectives are to provide a clear definition of systems engineering, describe the highly-effective behavioral characteristics of our best systems engineers and make explicit the expectations of systems engineers at NASA.**

Systems engineering is both an art and a science. We can compare systems engineering to an orchestra and its ability to perform a symphony. Most people understand what music is, but not everyone can play an instrument. Each instrument requires a different level of expertise and skill. Some musicians spend their entire careers mastering a single instrument, which is good because each one needs to be played well. But sophisticated music involves many different instruments played in unison. Depending on how well they come together, they may produce beautiful music or a terrible cacophony.

We can think of a symphony as a system. The musicians apply the science of music: they follow the process of translating notes on a page to play their instruments. But an orchestra conductor, a maestro, must lead them to connect the process of playing to the art of creating great music. Maestros do a lot more than just keep time! They:

* Systems engineering is a critical core competency for successful NASA missions. This paper summarizes the collective wisdom of some of NASA's best technical minds on the subject. So here the word "we" represents all contributors to this effort: Michael Bay, Bill Gerstenmaier, Mike Griffin, Jack Knight, Wiley Larson, Ken Ledbetter, Gentry Lee, Michael Menzel, Brian Muirhead, John Muratore, Bob Ryan, Mike Ryschkewitsch, Dawn Schaible, Chris Scolese, and Chris Williams. Among them, they have more than 390 years—almost four centuries—of experience in aerospace and systems engineering.

- Know and understand music—such matters as pitch, rhythm, dynamics, and sonic qualities—as well as the capabilities of various instruments and musicians
- Are necessary once the orchestra reaches a certain size and complexity
- Have typically mastered one or more musical instruments
- May be composers
- Select and shape the music that an orchestra plays
- Interpret a composer's music in light of the audience
- Strive to maintain the integrity of the composer's intentions
- Organize and lead the musicians
- Are responsible for the success of the performance

The systems engineer is like the maestro, who knows what the music should sound like (the look and function of a design) and has the skills to lead a team in achieving the desired sound (meeting the system requirements). Systems engineers:

- Understand the fundamentals of mathematics, physics, and other pertinent sciences, as well as the capabilities of various people and disciplines
- Have mastered a technical discipline and learned multiple disciplines
- Must understand the end game and overall objectives of the endeavor
- Create a vision and approach for attaining the objectives
- May be architects or designers
- Select and shape the technical issues to be addressed by multidisciplinary teams
- Must often interpret and communicate objectives, requirements, system architecture, and design
- Are responsible for the design's technical integrity
- Organize and lead multidisciplinary teams
- Are responsible for the successful delivery of a complex product or service

A great systems engineer completely understands and applies the art of **leadership** and has the experience and scar tissue from trying to **earn** the badge of **leader** from his or her team.

Harold Bell
NASA Headquarters

The similarities between maestros and systems engineers are useful in describing the latters' desired behavioral characteristics and capabilities.

Systems engineering is the art and science of developing an operable system that meets requirements within imposed constraints. This definition is independent of scale, but our discussion here focuses on developing complex systems, such as aircraft, spacecraft, power plants, and computer networks.

Systems engineering is holistic and integrative. It incorporates and balances the contributions of structural, mechanical, electrical, software, systems safety, and power engineers, plus many other, to produce a coherent whole. Systems engineering is about tradeoffs and compromises, about generalists rather than specialists.

Systems engineering is not only about the details of requirements and interfaces among subsystems. Such details are important, of course, in the same way that accurate accounting is important to an organization's chief financial officer. But accurate accounting does not distinguish between a good financial plan and a bad one, nor help to make a bad one better. Similarly, accurate control of interfaces and requirements is necessary to good systems engineering, but no amount of care in such matters can make a poor design concept better. **Systems engineering is first and foremost about getting the right design**—and then about maintaining and enhancing its technical integrity, as well as managing complexity with good processes to get the design right. We define interfaces in a system design to minimize unintended interactions and simplify development and operations—and then we document and control the design. Neither the world's greatest design, poorly implemented—nor a poor design, brilliantly implemented—is worth having.

The principles of systems engineering apply at all levels. For example, engineers who are developing an avionics system must practice creative design and interface definition to achieve their goals. Similar activities are essential to the architecture, design, and development of elements and subsystems across the broad spectrum of NASA developments. But for the remainder of this discussion, we use the term "systems engineering" in the context of complex, multidisciplinary system definition, development, and operation.

In his 2007 presentation, "Systems Engineering and the 'Two Cultures' of Engineering," Mike Griffin describes how the complexities of today's aerospace systems and the ways they fail have led to branching within the industry. For our purpose, we divide systems engineering into technical leadership and its ally, systems management.

- Technical leadership focuses on a system's technical design and technical integrity throughout its lifecycle
- Systems management focuses on managing the complexity associated with having many technical disciplines, multiple organizations, and hundreds or thousands of people engaged in a highly technical activity

Once a credible design and architecture are established, the systems engineer's job is to maintain technical integrity throughout the complex system's very rigorous and challenging lifecycle phases.

Robert Ryan,
Marshall Space Flight Center

Technical leadership, the *art* of systems engineering, balances broad technical domain knowledge, engineering instinct, problem solving, creativity, leadership, and communication to develop new missions and systems. It is the system's complexity, and severity of its constraints—not just its size—that drives the need for systems engineering.

NASA systems are often large and complex, so they require systems engineers to work in teams and with technical and other professional experts to maintain and enhance the system's technical integrity. The creativity and knowledge of all of the people involved must be brought to bear to achieve success. Thus leadership and communications skills are often as important as technical acumen and creativity. This part of systems engineering is about doing the job right.

For large complex systems, there are literally millions of ways to fail to meet objectives, even after we have defined the "right system." It is crucial to work all the details completely and consistently and ensure that the designs and technical activities of all the people and organizations remain coordinated—art is not enough.

Systems management is the *science* of systems engineering. Its focus is on rigorously and efficiently managing the development and operation of complex systems. Effective systems management requires applying a systematic, disciplined engineering approach that is quantifiable, recursive, repeatable, and demonstrable. Here the emphasis is on organizational skills, processes, and persistence. Process definition and control are essential to effective, efficient, and consistent implementation. They demand a clear understanding and communication of the objectives, and vigilance in making sure that all tasks directly support the objectives.

> Systems management provides a framework for problem solving...creative problem solving for complex systems.
>
> *Dinesh Verma,*
> *Stevens Institute of Technology*
>
> One of the biggest challenges for a systems engineer of a large complex project is to "bring order from chaos."
>
> *Chris Hardcastle,*
> *Systems Engineering and Integration Manager, NASA's Constellation Program,*
> *Johnson Space Center*

Systems management applies to developing, operating, and maintaining integrated systems throughout a project or program's lifecycle, which may extend for decades. Since the lifecycle may exceed the memory of the individuals involved in the development, it is critical to document the essential information.

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.

The Scope of Systems Engineering

Since the late 1980's, many aerospace-related government and industry organizations have moved from a hard-core, technical leadership culture (the art) to one of systems management (the science). History has shown that many projects dominated by only one of these cultures suffer significant ill consequences. Organizations that focus mainly on systems management often create products that fail to meet stakeholder objectives or are not cost effective. The process often becomes an end unto itself, and we experience "process paralysis." Organizations that focus solely on technical issues often create products or services that are inoperable, or suffer from lack of coordination and become too expensive or belated to be useful.

To achieve mission success, we must identify and develop systems engineers that are highly competent in both technical leadership and systems management. That is why we focus on the complete systems engineer, who embodies the art **and** science of systems engineering across all phases of aerospace missions—a type reflected in Figure 1. In any project, it is critical that systems engineering be performed well during all lifecycle phases. The scope of systems engineering and the associated roles and responsibilities of a systems engineer on a project are often negotiated by the project manager and the systems engineer. The scope of systems engineering and the activities for which the systems engineer is both responsible and accountable should be understood and documented early in the project.

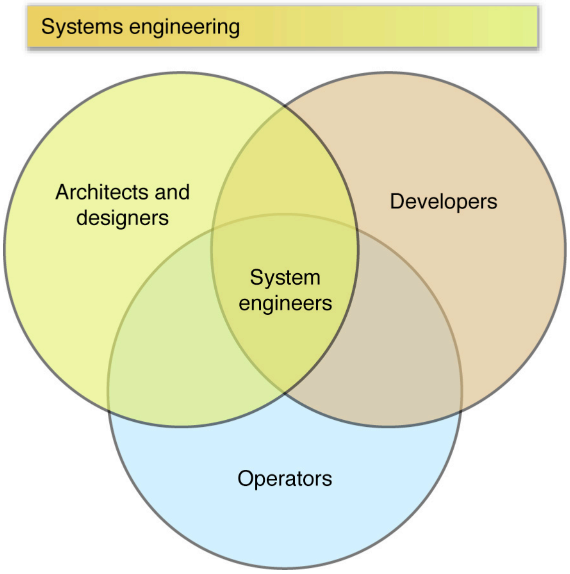

Figure 1. **The Scope of Systems Engineering.** Systems engineers often focus on one lifecycle phase like architecture and design versus development or operations, but good systems engineers have knowledge of and experience in all phases.

Here we describe the characteristics, some innate and others that we can develop, that enable select people to "systems engineer" complex aerospace missions and systems—to design, develop, and operate them. Then, we focus on how to further develop NASA's systems engineers to help them deal better with the complexities of sophisticated missions and systems.

The Personal Characteristics of Good Systems Engineers

Figure 2 depicts the personal behavioral characteristics of effective systems engineers.

Intellectual curiosity. Perhaps the most important personal characteristic of successful systems engineers is *intellectual curiosity*. People who prefer boundaries around their work to be comfortable, know what they know, and enjoy a focused domain may want to consider another occupation. Systems engineers continually try to understand the what, why, and how of their jobs, as well as other disciplines and situations that other people face. They are always encountering new technologies, ideas, and challenges, so they must feel comfortable with perpetual learning.

> People who have "systems engineer" in their title, regardless of the modifiers —project, program, flight system, and so on—are responsible for everything.
>
> *Gentry Lee, Jet Propulsion Laboratory*

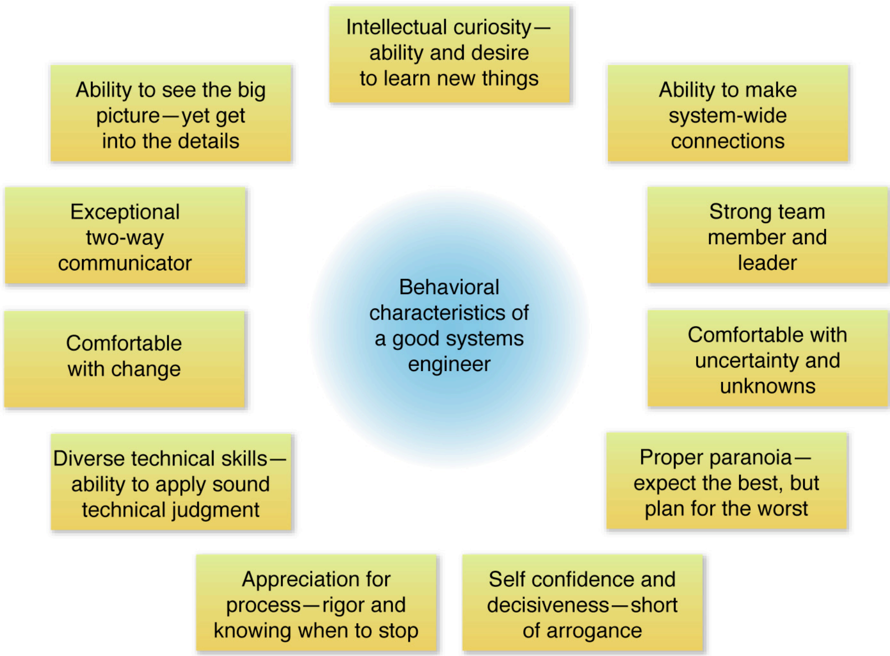

Figure 2. **Characteristics of a Good Systems Engineer.** The characteristics are shown in decreasing priority from top to bottom. Some of them are innate, whereas others can be learned and honed.

Ability to see the big picture. Good systems engineers maintain a *big-picture perspective*. They understand that their role, though always significant, changes throughout a project's lifecycle. At any point in the lifecycle the systems engineer must be fully cognizant of what has been done, what is necessary, and what remains to be done. Each phase has a different emphasis:

- Concept—mission and systems architecture, design, concept of operations, and trade studies
- Development—maintaining technical integrity throughout all lifecycle phases: preliminary design review, critical design review, verification, validation, and launch
- Operations—making sure that the project meets mission requirements and maintains technical integrity

Systems engineers pay particular attention to verification and validation. Verification answers the question: "Did we build our system right?" If we are successful, it proves our product meets the requirements. We emphasize the hard-earned lesson, "Test like you fly, fly like you test." Validation, on the other hand, answers the question: "Did we build the right system?" If we are successful, the system does what it is supposed to do, which often goes well beyond just meeting requirements!

Good systems engineers are able to "translate" for scientists, developers, operators, and other stakeholders. For example, "Discover and understand the relationship between newborn stars and cores of molecular clouds," is meaningful to a scientist. But developers and operators would better understand and use this version: "Observe 1,000 stars over two years, with a repeat cycle of once every five months, using each of the four payload instruments." The systems engineer that knows the project's objectives, helps determine how to meet them, and maintains the system's technical integrity throughout its lifecycle has a good chance of succeeding. A corollary is to check everyone's understanding of each other to make sure the team truly IS on the same page.

Ability to make system-wide connections. First-rate systems engineers understand the *connections* among all elements of a mission or system. They must often help individuals on the team see how their systems and related decisions connect to the bigger picture and affect mission success. The Chandra X-ray Observatory offers a practical example of these connections. The star tracker's designer must understand that the star tracker is part of an attitude control system—specifically, of an attitude estimator used to take precisely pointed observations—and that the star tracker's output determines whether or not the proper images are obtained. If the designer does not understand this, the project is in trouble. Good systems engineers can anticipate the impact of any change injected into the system or project, and describe the nature and magnitude of the impact throughout their system.

Exceptional two-way communicator. *Communications skills* are the great enabler. Systems engineers need to be able to get out of their offices and communicate well—listen, talk, and write. George Bernard Shaw once stated that England and America are "two countries separated by a common language," but engineers are separated by their **separate** languages—even more so since the advent of electronic communications. Systems engineering helps bridge the communication gaps among engineers and managers with consistent terms, processes, and procedures. A key to success is the ability to see, understand, and communicate the big picture, and be effective in helping others develop a big-picture view.

Strong team member and leader. Here we distinguish between management and leadership, realizing that a systems engineer must be skilled in both.

So far, we have described the characteristics that good systems engineers share. Ideally, as they gain experience, they are able to deal with more complex systems through

- Breadth of technical knowledge and expertise, combined with execution excellence
- Passion for the mission and challenges, combined with force of personality and leadership ability
- Creativity and engineering instinct —ability to sense the right way to attack a problem while appreciating inherent risks and implications
- Ability to teach and influence others

While management and leadership are related and often treated as the same, their central functions are different. Managers clearly provide some leadership, and leaders obviously perform some management. However, there are unique functions performed by leaders that are not performed by managers. My observation over the past forty years...is that we develop a lot of good managers, but very few leaders. Let me explain the difference in functions they perform.

- A manager takes care of where you are; a leader takes you to a new place
- A manager is concerned with doing things right; a leader is concerned with doing the right things
- A manager deals with complexity; a leader deals with uncertainty
- A manager creates policies; a leader establishes principles
- A manager sees and hears what is going on; a leader hears when there is no sound and sees when there is no light
- A manager finds answers and solutions; a leader formulates the questions and identifies the problems

James E. Colvard

Comfortable with change. Systems engineers should be *comfortable with change*. They understand that change is inevitable. They anticipate change, are able to understand how it affects their systems, and deal with those effects properly, usually without losing sleep at night.

The number of changes must decrease with time. If projects continue to change, they will never get to the launch pad. This is particularly true with requirements. While it is undesirable to freeze them too early, it is much more likely that requirements will continue to change way too long. ...At some point, the design must be implemented, at which time “change” is the enemy.

Ken Ledbetter, NASA Headquarters

Comfortable with uncertainty. A companion characteristic is being *comfortable with uncertainty*—indeed, embracing uncertainty. We usually do not know when we will finish a task, or even a mission. We know requirements are not complete, so we have to interpret them. This is the simple side of uncertainty. But uncertainty has a more complex side, so a strong background in probability and statistics is important. A good systems engineer understands and encourages quantification of uncertainty. For example, if the mission objective is to land a probe on a comet, the location and severity of jets or debris may be unknown or the comet’s albedo may be uncertain. The systems engineer must be able to work with a team to design a system that accommodates the uncertainties.

Proper paranoia. Another important characteristic is *proper paranoia*: expecting the best, but thinking about and planning for the worst. This suggests that the systems engineer is constantly checking and crosschecking selected details across the system to be sure that technical integrity is intact.

Diverse technical skills. A systems engineer must be able to apply sound technical principles across *diverse technical disciplines*. Good systems engineers know the theory and practice of many technical disciplines, respect expert input, and can credibly interact with most discipline experts. They also have enough demonstrated engineering maturity to delve into and learn new technical areas that should be integrated into the system. They must be strong *technical leaders*, in addition to having broad technical competence. Systems engineers must meet the special challenge of commanding diverse technical knowledge, plus managing, **and** leading effectively!

Self confidence and decisiveness. Systems engineers must have well-earned *self-confidence*. They know what they know and are aware of what they do not know, and are not afraid to own both. It does not mean systems engineers never make mistakes. We have all made mistakes...at least occasionally.

> Commission, not omission. This should be written on the door of every systems engineer. There is no excuse for omission. A systems engineer does not need authority from anyone to investigate anything. The systems engineer's job is the whole space. You go out, you make decisions. If someone tells you to stop, you use your communication skills and listen.
>
> *Gentry Lee, Jet Propulsion Laboratory*

Appreciate the value of process. Good systems engineers *appreciate process*. That does not mean systems engineering is just one process, plus another, plus another—like recipes in a cookbook. Let us look back at our metaphor. To create the music of a symphony, musicians use their instruments, musical scores, and notes. These tools provide them with a common frame of reference, help them keep proper time, and allow the orchestra to work together to create beautiful music. Processes serve the same purpose for the systems engineer. But just providing sheets of music to a group of musicians does not guarantee a great orchestra. While each orchestra uses the same tools and many have very skilled musicians, they do not all sound like the New York Philharmonic.

Herein lies the art—how well does the maestro lead the people and use the tools provided? Maestros know how to bring out the best in their musicians; they know how to vary the tempo and the right moment to cue the horn section to draw in the listeners. The same is true for systems engineers. We must all use processes to get the job done, but it is what we DO with the processes and talents of the team that matters.

Summary

Systems engineering is a crucial core competency within NASA. Systems engineering has two key components: technical leadership, the art, and systems management, the science, that are necessary for mission success. Technical leadership balances broad technical domain knowledge, engineering instinct, problem solving, creativity, leadership, and communication to develop and maintain new missions and systems at NASA.

Systems management's focus is on rigorously and efficiently managing the development and operation of complex systems. Effective systems management requires applying a systematic, disciplined engineering approach that is quantifiable, recursive, repeatable, and demonstrable. Here the emphasis is on organizational skills, processes, and persistence.

Systems engineering at NASA is most successful when there is a healthy balance of technical leadership and systems management engaged in a project.

Systems engineers are a critical resource for the Agency, and as such, we are dedicated to develop highly capable systems engineers that are able to lead and manage our missions and systems.