Chapter 1
Overview of Systems Engineering

"Systems engineering" is a relatively young discipline compared to the earlier, well-known engineering disciplines of engineering, such as electrical, civil, and mechanical. The term can be traced back to Bell Telephone Laboratories in the 1940s.[1] In 1990, the professional society National Council on Systems Engineering (NCOSE) was formed; the name changed in 1995 to the International Council on Systems Engineering (INCOSE).[2] Educational programs at that time began adding systems engineering as adjuncts to the specific engineering discipline, evolving into separately identified programs in systems engineering.

1.1 What is Systems Engineering?

In order to answer the question "what is systems engineering?" one must first define the component words. "Engineering" is to layout or construct; to contrive or plan with more or less skill or craft; to guide the course of events. A "system" is a regularly interacting group of items that form a unified whole; an organized set of doctrines, ideas, or principles usually intended to explain the arrangement of the working of a systematic whole. The INCOSE handbook definition of a system is "a combination of interacting elements organized to achieve one or more stated purposes."

"Systems engineering" is focused on considering the whole job or problem. It involves global or universal optimization, finding the "best" answer, making the best plans, starting with your eyes on the finish, and telling the complete story at the appropriate level for the right audience. Before a system is optimized (designed), the objectives must be known. An understanding of what "best" means is needed. Is it "best" performance or just meeting requirements? Is it lowest cost, fastest delivery, lowest risk (performance, cost, and schedule), best valued, longest lived, or a balance of all the above?

The INCOSE handbook definition of systems engineering reads as follows:

> Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem. Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.

Systems engineering should be thought of as providing guidelines, not a strict one-size-fits-all recipe. This is especially true for the current application for large astronomical systems that have no existing book, i.e., owner's manual. A group of experienced NASA personnel prepared a white paper entitled "The art and science of systems engineering,"[3] in which they identify technical leadership as the art of systems engineering, balancing broad technical-domain knowledge, engineering instinct, problem solving, creativity, leadership, and communication to develop new missions and systems. The system's complexity and severity of its constraints—not just its size—drive the need for systems engineering. The science of systems engineering is system management, which uses a disciplined approach that has a clear understanding and communication of objectives and ensures that all tasks directly support the objectives. The emphasis is on overseeing the development and operation of complex systems, utilizing organizational skills, processes, and persistence.

Systems engineering acts as a hub of activity and interaction. The central objective for systems engineering is the system as a whole and mission success achieved with a balanced approach. The domains of activity and interaction around systems engineering are management, engineering, technical, political/legal, human, and social; Fig. 1.1 illustrates how they overlap.

The central problem of systems engineering involves the design and execution of a system capable of producing worthy (new) science with the following constraints:

- Under-defined or improperly defined problem,
- New designs or technology,
- Complexity,
- Imperfect parts,
- Finite funds, and
- Finite time (e.g., celestial schedule, graduation, or retirement).

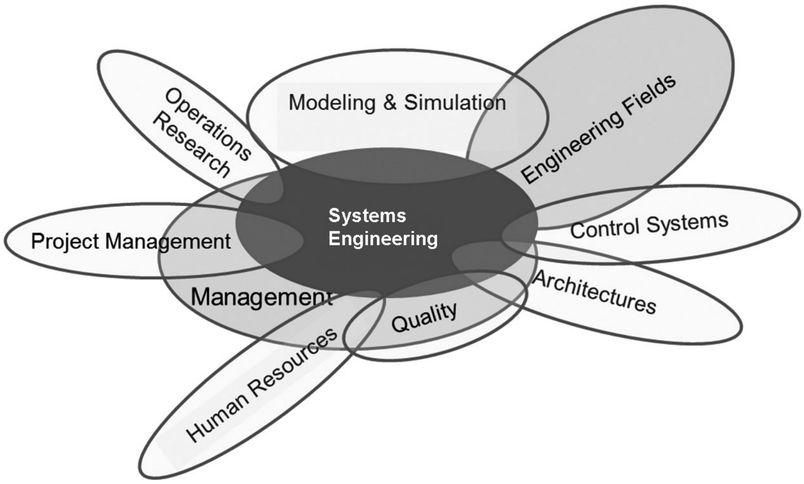

Figure 1.1 Systems engineering occurs at the technical hub of activity for the many specialties that collectively support a mission.

Systems engineering for astronomical (scientific) instruments comes with some special or unique aspects. Scientific instruments are generally intended to do something new or better than previously achieved, i.e., push the state of the art beyond the existing literature. Lots of new or nonrecurring engineering means that it may be harder than incremental improvements in other areas of engineering.

Process, orthodoxy, imagination, and rigor: in the literature, much is said of process. It is important but never a substitute for doing the right work at the right time. Many systems-engineering processes are intended to apply to all situations, and by necessity they are very general and do not apply well to development activities. These processes are good guidelines but should not be taken as inviolate statutes. Note these processes, but be ready to deviate from them if necessary. Be able to defend the position with well-presented rationale:

"Good processes do not make good products,
good people making good decisions do."

Getting the right answer means asking the correct question. Many problems that confront a systems engineer, especially with very complex systems, are posed with the best knowledge at the time with respect to fundamental scientific questions and how the system operates. However, knowledge advances. While working through the problems, engineers should always reconsider, "are we solving the right problem in light of what we know NOW?" This question applies to all phases of a program or project. It is more than acceptable—it is required that the question being addressed be reconsidered if new information demands it.

1.2 What Makes a Good Systems Engineer?

The following traits are essential for a good systems engineer:

- Displays curiosity. Has multidisciplinary knowledge with a wide range of technical skills and enjoys interdisciplinary problems.[4]
- Possesses a "big-picture" view. Conversant with the fundamental questions and is "science smart." Has a comprehensive understanding of the system and how it operates.
- Sees connections. Has an N^2 view and knows the $\delta x_i/\delta x_j$ for all i, j.
- Uses the power of approximations anchored to underlying physics.
- Comfortable with change and uncertainty. Knows probability and statistics, and understands how to handle uncertainties. Can juggle chaos and options.
- Expresses skepticism. Has an active imagination with a proper level of paranoia. A multi-dimensional risk analyst who understands failure modes and effects, and who can manage fault tolerance.
- Pays attention to resources, margins, and reserves. Understands the capabilities beyond requirements and the partials for scientific return and for cost.
- Appreciates the art of systems engineering.
- Appreciates process with an understanding of the toolkit, but knows that tools do not make an artist.
- Displays self-confidence and high energy. Hardworking and not easily discouraged.
- Demonstrates self-motivation (it is the systems engineer's job to turn over the rocks).
- Likes people and has good communication skills.

A good systems engineer possesses a combination of both technical and nontechnical skills. Chapter 8 will expand on the nontechnical aspects that are important to systems engineering, including communication, organizational, and management skills. The first skill covers the many forms of communication, from formal writing intended for other professionals to communicating informally to peers and the nontechnical lay community. The latter two skills range from setting priorities and organizing the documentation structures to interpersonal skills and conducting effective meetings.

1.3 How Does Systems Engineering Relate to Astronomical Telescopes and Observatories?

The relationship between systems engineering and astronomical telescopes and observatories involves their fundamental scientific goals. Chapter 6 presents the role of scientific goals in systems engineering by utilizing the concept of "science systems engineering" put forward by Nobel Laureate Ricardo Giaconni.[5]

The process analyzes the scientific question(s) being asked in all its dimensions to clearly define the goals and develop concepts for the instrumentation and data needed to answer the question(s). This process results in new systems and scientific instruments intended to do something new or better than previously achieved. Systems engineering must manage the process from the early identification and definition of the scientific problem to the execution of a successful mission that can provide answers to the corresponding scientific research questions. These endeavors are typically large and require sizeable teams for effective systems engineering to be successful. The challenge is to find a balance between the scientific return, engineering maturity, and mission cost while keeping in mind the excitement of the first item.