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SYSTEMS ENGINEERING AND THE WORLD OF MODERN SYSTEMS

1.1 WHAT IS SYSTEMS ENGINEERING?

There are many ways in which to define systems engineering. For the purposes of this book, we will use the following definition:

The function of systems engineering is to *guide* the *engineering* of *complex systems*.

The words in this definition are used in their conventional meanings, as described further below.

To guide is defined as "to lead, manage, or direct, usually based on the superior experience in pursuing a given course" and "to show the way." This characterization emphasizes the process of selecting the path for others to follow from among many possible courses—a primary function of systems engineering. A dictionary definition of engineering is "the application of scientific principles to practical ends; as the design, construction and operation of efficient and economical structures, equipment, and systems." In this definition, the terms "efficient" and "economical" are particular contributions of good systems engineering.

The word "system," as is the case with most common English words, has a very broad meaning. A frequently used definition of a system is "*a set* of *interrelated*

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components working *together* toward some *common* objective." This definition implies a multiplicity of interacting parts that collectively perform a significant function. The term *complex* restricts this definition to systems in which the elements are diverse and have intricate relationships with one another. Thus, a home appliance such as a washing machine would not be considered sufficiently diverse and complex to require systems engineering, even though it may have some modern automated attachments. On the other hand, the context of an *engineered* system excludes such complex systems as living organisms and ecosystems. The restriction of the term "system" to one that is complex and engineered makes it more clearly applicable to the function of systems engineering as it is commonly understood. Examples of systems requiring systems engineering for their development are listed in a subsequent section.

The above definitions of "systems engineering" and "system" are not represented as being unique or superior to those used in other textbooks, each of which defines them somewhat differently. In order to avoid any potential misunderstanding, the meaning of these terms *as used in this book* is defined at the very outset, before going on to the more important subjects of the responsibilities, problems, activities, and tools of systems engineering.

Systems Engineering and Traditional Engineering Disciplines

From the above definition, it can be seen that systems engineering differs from mechanical, electrical, and other engineering disciplines in several important ways:

1. Systems engineering is focused on the system as a whole; it emphasizes its total operation. It looks at the system from the outside, that is, at its interactions with other systems and the environment, as well as from the inside. It is concerned not only with the engineering design of the system but also with external factors, which can significantly constrain the design. These include the identification of customer needs, the system operational environment, interfacing systems, logistics support requirements, the capabilities of operating personnel, and such other factors as must be correctly reflected in system requirements documents and accommodated in the system design.
2. While the primary purpose of systems engineering is to guide, this does not mean that systems engineers do not themselves play a key role in system design. On the contrary, they are responsible for leading the formative (concept development) stage of a new system development, which culminates in the functional design of the system reflecting the needs of the user. Important design decisions at this stage cannot be based entirely on quantitative knowledge, as they are for the traditional engineering disciplines, but rather must often rely on qualitative judgments balancing a variety of incommensurate quantities and utilizing experience in a variety of disciplines, especially when dealing with new technology.
3. Systems engineering *bridges* the traditional engineering disciplines. The diversity of the elements in a complex system requires different engineering disci-

plines to be involved in their design and development. For the system to perform correctly, each system element must function properly in combination with one or more other system elements. Implementation of these interrelated functions is dependent on a complex set of physical and functional interactions between separately designed elements. Thus, the various elements cannot be engineered independently of one another and then simply assembled to produce a working system. Rather, systems engineers must guide and coordinate the design of each individual element as necessary to assure that the interactions and interfaces between system elements are compatible and mutually supporting. Such coordination is especially important when individual system elements are designed, tested, and supplied by different organizations.

Systems Engineering and Project Management

The engineering of a new complex system usually begins with an exploratory stage in which a new system concept is evolved to meet a recognized need or to exploit a technological opportunity. When the decision is made to engineer the new concept into an operational system, the resulting effort is inherently a major enterprise, which typically requires many people, with diverse skills, to devote years of effort to bring the system from concept to operational use.

The magnitude and complexity of the effort to engineer a new system requires a dedicated team to lead and coordinate its execution. Such an enterprise is called a “project” and is directed by a project manager aided by a staff. Systems engineering is an inherent part of project management—the part that is concerned with guiding the engineering effort itself—setting its objectives, guiding its execution, evaluating its results, and prescribing necessary corrective actions to keep it on course. The management of the planning and control aspects of the project fiscal, contractual, and customer relations is supported by systems engineering but is usually not considered to be part of the systems engineering function. This subject is described in more detail in Chapter 5.

Recognition of the importance of systems engineering by every participant in a system development project is essential for its effective implementation. To accomplish this, it is often useful to formally assign the leader of the systems engineering team to a recognized position of technical responsibility and authority within the project.

1.2 ORIGINS OF SYSTEMS ENGINEERING

No particular date can be associated with the origins of systems engineering. Systems engineering principles have been practiced at some level since the building of the pyramids and probably before. (The Bible records that Noah’s Ark was built to a system specification.)

The recognition of systems engineering as a distinct activity is often associated with the effects of World War II, and especially the 1950s and 1960s when a number of textbooks were published that first identified systems engineering as a distinct discipline and defined its place in the engineering of systems. More generally, the recognition of systems engineering as a unique activity evolved as a necessary corollary to the rapid growth of technology, and its application to major military and commercial operations during the second half of the twentieth century.

The global conflagration of World War II provided a tremendous spur to the advancement of technology in order to gain a military advantage for one side or the other. The development of high-performance aircraft, military radar, the proximity fuse, the German VI and V2 missiles, and especially the atomic bomb required revolutionary advances in the application of energy, materials, and information. These systems were complex, combining multiple technical disciplines, and their development posed engineering challenges significantly beyond those that had been presented by their more conventional predecessors. Moreover, the compressed development time schedules imposed by wartime imperatives necessitated a level of organization and efficiency that required new approaches in program planning, technical coordination, and engineering management. Systems engineering, as we know it today, developed to meet these challenges.

During the Cold War of the 1950s, 1960s, and 1970s, military requirements continued to drive the growth of technology in jet propulsion, control systems, and materials. However, another development, that of solid-state electronics, has had perhaps a more profound effect on technological growth. This, to a large extent, made possible the still evolving "information age," in which computing, networks, and communications are extending the power and reach of systems far beyond their previous limits. Particularly significant in this connection is the development of the digital computer and the associated software technology driving it, which increasingly is leading to the replacement of human control of systems by automation. Computer control is qualitatively increasing the complexity of systems and is a particularly important concern of systems engineering.

The relation of modern systems engineering to its origins can be best understood in terms of three basic factors:

1. *Advancing Technology,* which provide opportunities for increasing system capabilities, but introduces development risks that require systems engineering management; nowhere is this more evident than in the world of automation. Technology advances in human–system interfaces, robotics, and software make this particular area one of the fastest growing technologies affecting system design.
2. *Competition,* whose various forms require seeking superior (and more advanced) system solutions through the use of system-level trade-offs among alternative approaches.
3. *Specialization,* which requires the partitioning of the system into building blocks corresponding to specific product types that can be designed and built by specialists, and strict management of their interfaces and interactions.

These factors are discussed in the following paragraphs.

Advancing Technology: Risks

The explosive growth of technology in the latter half of the twentieth century and into this century has been the single largest factor in the emergence of systems engineering as an essential ingredient in the engineering of complex systems. Advancing technology has not only greatly extended the capabilities of earlier systems, such as aircraft, telecommunications, and power plants, but has also created entirely new systems such as those based on jet propulsion, satellite communications and navigation, and a host of computer-based systems for manufacturing, finance, transportation, entertainment, health care, and other products and services. Advances in technology have not only affected the nature of products but have also fundamentally changed the way they are engineered, produced, and operated. These are particularly important in early phases of system development, as described in Conceptual Exploration, in Chapter 7.

Modern technology has had a profound effect on the very approach to engineering. Traditionally, engineering applies known principles to practical ends. Innovation, however, produces new materials, devices, and processes, whose characteristics are not yet fully measured or understood. The application of these to the engineering of new systems thus increases the risk of encountering unexpected properties and effects that might impact system performance and might require costly changes and program delays.

However, failure to apply the latest technology to system development also carries risks. These are the risks of producing an inferior system, one that could become prematurely obsolete. If a competitor succeeds in overcoming such problems as may be encountered in using advanced technology, the competing approach is likely to be superior. The successful entrepreneurial organization will thus assume carefully selected technological risks and surmount them by skillful design, systems engineering, and program management.

The systems engineering approach to the early application of new technology is embodied in the practice of "risk management." Risk management is a process of dealing with calculated risks through a process of analysis, development, test, and engineering oversight. It is described more fully in Chapters 5 and 9.

Dealing with risks is one of the essential tasks of systems engineering, requiring a broad knowledge of the total system and its critical elements. In particular, systems engineering is central to the decision of how to achieve the best balance of risks, that is, which system elements should best take advantage of new technology and which should be based on proven components, and how the risks incurred should be reduced by development and testing.

The development of the digital computer and software technology noted earlier deserves special mention. This development has led to an enormous increase in the automation of a wide array of control functions for use in factories, offices, hospitals, and throughout society. Automation, most of it being concerned with information processing hardware and software, and its sister technology, autonomy, which adds in capability of command and control, is the fastest growing and most powerful single influence on the engineering of modern systems.

The increase in automation has had an enormous impact on people who operate systems, decreasing their number but often requiring higher skills and therefore special training. Human–machine interfaces and other people–system interactions are particular concerns of systems engineering.

Software continues to be a growing engineering medium whose power and versatility has resulted in its use in preference to hardware for the implementation of a growing fraction of system functions. Thus, the performance of modern systems increasingly depends on the proper design and maintenance of software components. As a result, more and more of the systems engineering effort has had to be directed to the control of software design and its application.

Competition: Trade-offs

Competitive pressures on the system development process occur at several different levels. In the case of defense systems, a primary drive comes from the increasing military capabilities of potential adversaries, which correspondingly decrease the effectiveness of systems designed to defeat them. Such pressures eventually force a development program to redress the military balance with a new and more capable system or a major upgrade of an existing one.

Another source of competition comes with the use of competitive contracting for the development of new system capabilities. Throughout the competitive period, which may last through the initial engineering of a new system, each contractor seeks to devise the most cost-effective program to provide a superior product.

In developing a commercial product, there are nearly always other companies that compete in the same market. In this case, the objective is to develop a new market or to obtain an increased market share by producing a superior product ahead of the competition, with an edge that will maintain a lead for a number of years. The above approaches nearly always apply the most recent technology in an effort to gain a competitive advantage.

Securing the large sums of money needed to fund the development of a new complex system also involves competition on quite a different level. In particular, both government agencies and industrial companies have many more calls on their resources than they can accommodate and hence must carefully weigh the relative payoff of proposed programs. This is a primary reason for requiring a phased approach in new system development efforts, through the requirement for justification and formal approval to proceed with the increasingly expensive later phases. The results of each phase of a major development must convince decision makers that the end objectives are highly likely to be attained within the projected cost and schedule.

On a still different basis, the competition among the essential characteristics of the system is always a major consideration in its development. For example, there is always competition between performance, cost, and schedule, and it is impossible to optimize all three at once. Many programs have failed by striving to achieve levels of performance that proved unaffordable. Similarly, the various performance parameters of a vehicle, such as speed and range, are not independent of one another; the efficiency of most vehicles, and hence their operating range, decreases at higher speeds.

Thus, it is necessary to examine alternatives in which these characteristics are allowed to vary and to select the combination that best balances their values for the benefit of the user.

All of the forms of competition exert pressure on the system development process to produce the best performing, most affordable system, in the least possible time. The process of selecting the most desirable approach requires the examination of numerous potential alternatives and the exercise of a breadth of technical knowledge and judgment that only experienced systems engineers possess. This is often referred to as “trade-off analysis” and forms one of the basic practices of systems engineering.

Specialization: Interfaces

A complex system that performs a number of different functions must of necessity be configured in such a way that each major function is embodied in a separate component capable of being specified, developed, built, and tested as an individual entity. Such a subdivision takes advantage of the expertise of organizations specializing in particular types of products, and hence is capable of engineering and producing components of the highest quality at the lowest cost. Chapter 3 describes the kind of functional and physical building blocks that make up most modern systems.

The immensity and diversity of engineering knowledge, which is still growing, has made it necessary to divide the education and practice of engineering into a number of specialties, such as mechanical, electrical, aeronautical, and so on. To acquire the necessary depth of knowledge in any one of these fields, further specialization is needed, into such subfields as robotics, digital design, and fluid dynamics. Thus, engineering specialization is a predominant condition in the field of engineering and manufacturing and must be recognized as a basic condition in the system development process.

Each engineering specialty has developed a set of specialized tools and facilities to aid in the design and manufacture of its associated products. Large and small companies have organized around one or several engineering groups to develop and manufacture devices to meet the needs of the commercial market or of the system-oriented industry. The development of interchangeable parts and automated assembly has been one of the triumphs of the U.S. industry.

The convenience of subdividing complex systems into individual building blocks has a price: that of integrating these disparate parts into an efficient, smoothly operating system. Integration means that each building block fits perfectly with its neighbors and with the external environment with which it comes into contact. The “fit” must be not only physical but also functional; that is, its design will both affect the design characteristics and behavior of other elements, and will be affected by them, to produce the exact response that the overall system is required to make to inputs from its environment. The physical fit is accomplished at intercomponent boundaries called *interfaces*. The functional relationships are called *interactions*.

The task of analyzing, specifying, and validating the component interfaces with each other and with the external environment is beyond the expertise of the individual design specialists and is the province of the systems engineer. Chapter 3 discusses further the importance and nature of this responsibility.

A direct consequence of the subdivision of systems into their building blocks is the concept of modularity. Modularity is a measure of the degree of mutual independence of the individual system components. An essential goal of systems engineering is to achieve a high degree of modularity to make interfaces and interactions as simple as possible for efficient manufacture, system integration, test, operational maintenance, reliability, and ease of in-service upgrading. The process of subdividing a system into modular building blocks is called "functional allocation" and is another basic tool of systems engineering.

1.3 EXAMPLES OF SYSTEMS REQUIRING SYSTEMS ENGINEERING

As noted at the beginning of this chapter, the generic definition of a system as a *set* of *interrelated components* working *together* as an integrated whole to achieve some common objective would fit most familiar home appliances. A washing machine consists of a main clothes tub, an electric motor, an agitator, a pump, a timer, an inner spinning tub, and various valves, sensors, and controls. It performs a sequence of timed operations and auxiliary functions based on a schedule and operation mode set by the operator. A refrigerator, microwave oven, dishwasher, vacuum cleaner, and radio all perform a number of useful operations in a systematic manner. However, these appliances involve only one or two engineering disciplines, and their design is based on well-established technology. Thus, they fail the criterion of being *complex*, and we would not consider the development of a new washer or refrigerator to involve much systems engineering as we understand the term, although it would certainly require a high order of reliability and cost engineering. Of course, home appliances increasingly include clever automatic devices that use newly available microchips, but these are usually self-contained add-ons and are not necessary to the main function of the appliance.

Since the development of new modern systems is strongly driven by technological change, we shall add one more characteristic to a system requiring systems engineering, namely, that some of its key elements use advanced technology. The characteristics of a system whose development, test, and application require the practice of systems engineering are that the system

- is an engineered product and hence satisfies a specified need,
- consists of diverse components that have intricate relationships with one another and hence is multidisciplinary and relatively complex, and
- uses advanced technology in ways that are central to the performance of its primary functions and hence involves development risk and often a relatively high cost.

Henceforth, references in this text to an *engineered* or *complex* system (or in the proper context, just *system*) will mean the type that has the three attributes noted above, that is, is an engineered product, contains diverse components, and uses advanced technology. These attributes are, of course, in addition to the generic definition stated earlier and serve to identify the systems of concern to the systems engineer as those that require system design, development, integration, test, and evaluation. In Chapter 2, we explore the full spectrum of systems complexity and why the systems engineering landscape presents a challenge for systems engineers.

Examples of Complex Engineered Systems

To illustrate the types of systems that fit within the above definition, Tables 1.1 and 1.2 list 10 modern systems and their principal inputs, processes, and outputs.

TABLE 1.1. Examples of Engineered Complex Systems: Signal and Data Systems

System	Inputs	Process	Outputs
Weather satellite	Images	• Data storage • Transmission	Encoded images
Terminal air traffic control system	Aircraft beacon responses	• Identification • Tracking	• Identity • Air tracks • Communications
Track location system	Cargo routing requests	• Map tracing • Communication	• Routing information • Delivered cargo
Airline reservation system	Travel requests	Data management	• Reservations • Tickets
Clinical information system	• Patient ID • Test records • Diagnosis	Information management	• Patient status • History • Treatment

TABLE 1.2. Examples of Engineered Complex Systems: Material and Energy Systems

System	Inputs	Process	Outputs
Passenger aircraft	• Passengers • Fuel	• Combustion • Thrust • Lift	Transported passengers
Modern harvester combine	• Grain field • Fuel	• Cutting • Threshing	Harvested grain
Oil refinery	• Crude oil • Catalysts • Energy	• Cracking • Separation • Blending	• Gasoline • Oil products • Chemicals
Auto assembly plant	• Auto parts • Energy	• Manipulation • Joining • Finishing	Assembled auto
Electric power plant	• Fuel • Air	• Power generation • Regulation	• Electric AC power • Waste products

It has been noted that a system consists of a multiplicity of elements, some of which may well themselves be complex and deserve to be considered a system in their own right. For example, a telephone-switching substation can well be considered as a system, with the telephone network considered as a "system of systems." Such issues will be discussed more fully in Chapters 2 and 4, to the extent necessary for the understanding of systems engineering.

Example: A Modern Automobile. A more simple and familiar system, which still meets the criteria for an engineered system, is a fully equipped passenger automobile. It can be considered as a lower limit to more complex vehicular systems. It is made up of a large number of diverse components requiring the combination of several different disciplines. To operate properly, the components must work together accurately and efficiently. Whereas the operating principles of automobiles are well established, modern autos must be designed to operate efficiently while at the same time maintaining very close control of engine emissions, which requires sophisticated sensors and computer-controlled mechanisms for injecting fuel and air. Antilock brakes are another example of a finely tuned automatic automobile subsystem. Advanced materials and computer technology are used to an increasing degree in passenger protection, cruise control, automated navigation and autonomous driving and parking. The stringent requirements on cost, reliability, performance, comfort, safety, and a dozen other parameters present a number of substantive systems engineering problems. Accordingly, an automobile meets the definition established earlier for a system requiring the application of systems engineering, and hence can serve as a useful example.

An automobile is also an example of a large class of systems that require active interaction (control) by a human operator. To some degree, all systems require such interaction, but in this case, continuous control is required. In a very real sense, the operator (driver) functions as an integral part of the overall automobile system, serving as the steering feedback element that detects and corrects deviations of the car's path on the road. The design must therefore address as a critical constraint the inherent sensing and reaction capabilities of the operator, in addition to a range of associated human–machine interfaces such as the design and placement of controls and displays, seat position, and so on. Also, while the passengers may not function as integral elements of the auto steering system, their associated interfaces (e.g., weight, seating and viewing comfort, and safety) must be carefully addressed as part of the design process. Nevertheless, since automobiles are developed and delivered without the human element, for purposes of systems engineering, they may be addressed as systems in their own right.

1.4 SYSTEMS ENGINEERING AS A PROFESSION

With the increasing prevalence of complex systems in modern society, and the essential role of systems engineering in the development of systems, systems engineering as a profession has become widely recognized. Its primary recognition has come in companies specializing in the development of large systems. A number of these have established departments of systems engineering and have classified those engaging in the process as systems engineers. In addition, global challenges in health care, communications, environment, and many other complex areas require engineering systems methods to develop viable solutions.

To date, the slowness of recognition of systems engineering as a career is the fact that it does not correspond to the traditional academic engineering disciplines. Engineering disciplines are built on quantitative relationships, obeying established physical laws, and measured properties of materials, energy, or information. Systems engineering, on the other hand, deals mainly with problems for which there is incomplete knowledge, whose variables do not obey known equations, and where a balance must be made among conflicting objectives involving incommensurate attributes. The absence of a quantitative knowledge base previously inhibited the establishment of systems engineering as a unique discipline.

Despite those obstacles, the recognized need for systems engineering in industry and government has spurred the establishment of a number of academic programs offering master's degrees and doctoral degrees in systems engineering. An increasing number of universities are offering undergraduate degrees in systems engineering as well.

The recognition of systems engineering as a profession has led to the formation of a professional society, the International Council on Systems Engineering (INCOSE), one of whose primary objectives is the promotion of systems engineering, and the recognition of systems engineering as a professional career.

Career Choices

Systems engineers are highly sought after because their skills complement those in other fields and often serve as the "glue" to bring new ideas to fruition. However, career choices and the related educational needs for those choices is complex, especially when the role and responsibilities of a systems engineer is poorly understood.

Four potential career directions are shown in Figure 1.1: financial, management, technical, and systems engineering. There are varying degrees of overlap between them despite the symmetry shown in the figure. The systems engineer focuses on the whole system product, leading and working with many diverse technical team members, following the systems engineering development cycle, conducting studies of alternatives, and managing the system interfaces. The systems engineer generally matures in the field after a technical undergraduate degree with work experience and a master of science degree in systems engineering, with an increasing responsibility of successively larger projects, eventually serving as the chief or lead systems engineer for a major systems, or systems-of-systems development. Note the overlap and need to understand the content and roles of the technical specialists and to coordinate with the program manager (PM).

The project manager or PM, often with a technical or business background, is responsible for interfacing with the customer and for defining the work, developing the plans, monitoring and controlling the project progress, and delivering the finished output to the customer. The PM often learns from on the job training (OJT) with

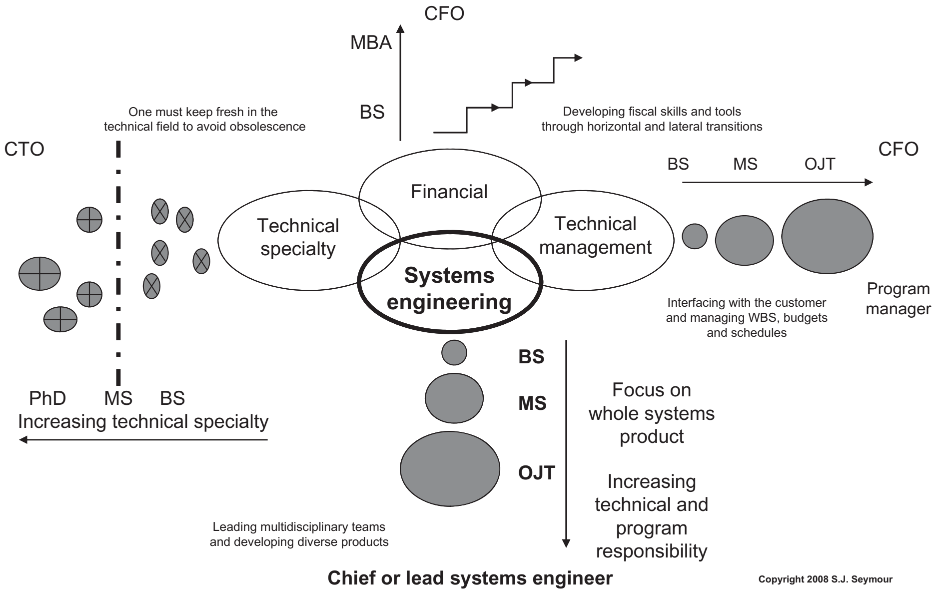


Figure 1.1. Career opportunities and growth.

projects of increasing size and importance, enhancing the toolset available with a master of science degree in technical/program management. While not exclusively true, the chief executive officer (CEO) frequently originates from the ranks of the organization's PMs.

The financial or business career path that ultimately could lead to a chief financial officer (CFO) position usually includes business undergraduate and master of business administration (MBA) degrees. Individuals progress through their careers with various horizontal and vertical moves, often with specialization in the field. There is an overlap in skill and knowledge with the PM in areas of contract and finance management.

Many early careers start with a technical undergraduate degree in engineering, science or information technology. The technical specialist makes contributions as part of a team in the area of their primary knowledge, honing skills and experience to develop and test individual components or algorithms that are part of a larger system. Contributions are made project to project over time, and recognition is gained from innovative, timely, and quality workmanship. Technical specialists need to continue to learn about their field and to stay current in order to be employable compared to the next generation of college graduates. Often advanced degrees (MS and PhDs) are acquired to enhance knowledge, capability, and recognition, and job responsibilities can lead to positions such as lead engineer, lead scientist, or chief technology officer (CTO) in an organization. The broader minded or experienced specialist often considers a career in systems engineering.

Orientation of Technical Professionals

The special relationship of systems engineers with respect to technical disciplines can be better understood when it is realized that technical people not only engage in widely different professional specialties, but their intellectual objectives, interests, and attitudes, which represent their technical orientations, can also be widely divergent. The typical scientist is dedicated to understanding the nature and behavior of the physical world. The scientist asks the questions "Why?" and "How?" The mathematician is usually primarily concerned with deriving the logical consequences of a set of assumptions, which may be quite unrelated to the real world. The mathematician develops the proposition "If A, then B." Usually, the engineer is mainly concerned with creating a useful product. The engineer exclaims "Voila!"

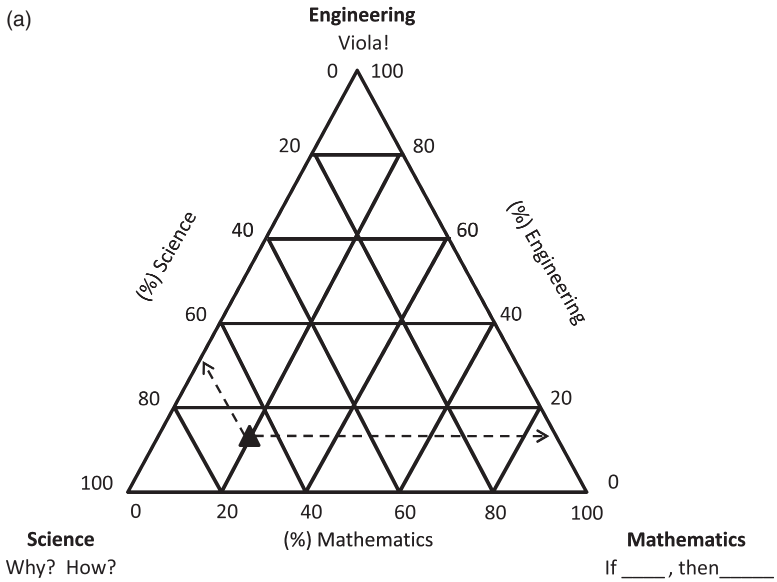
These orientations are quite different from one another, which accounts for why technical specialists are focused on their own aspects of science and technology. However, in most professionals, those orientations are not absolute; in many cases, the scientist may need some engineering to construct an apparatus, and the engineer may need some mathematics to solve a control problem. So, in the general case, the orientation of a technical professional might be modeled by a sum of three orthogonal vectors, each representing the extent of the individual's orientation being in science, mathematics, or engineering.

To represent the above model, it is convenient to use a diagram designed to show the composition of a mixture of three components. Figure 1.2a is such a diagram in which the components are science, mathematics, and engineering. A point at each vertex represents a mixture with 100% of the corresponding component. The composition of the mixture marked by the small triangle in the figure is obtained by finding the percentage of each component by projecting a line parallel to the baseline opposite each vertex to the scale radiating from the vertex. This process gives intercepts of 70% science, 20% mathematics, and 10% engineering for the orientation marked by the triangle.

Because the curricula of technical disciplines tend to be concentrated in specialized subjects, most students graduate with limited general knowledge. In Figure 1.2b, the circles representing the orientation of individual graduates are seen to be concentrated in the corners, reflecting their high degree of specialization.

The tendency of professional people to polarize into diverse specialties and interests tends to be accentuated after graduation, as they seek to become recognized in their respective fields. Most technical people resist becoming generalists for fear they will lose or fail to achieve positions of professional leadership and the accompanying recognition. This specialization of professionals inhibits technical communication between them; the language barrier is bad enough, but the differences in basic objectives and methods of thought are even more serious. The solution of complex interdisciplinary problems has had to depend on the relatively rare individuals who, for one reason or another, after establishing themselves in their principal profession, have become interested and involved in solving system problems and have learned to work jointly with specialists in various other fields.

(a)



(b)

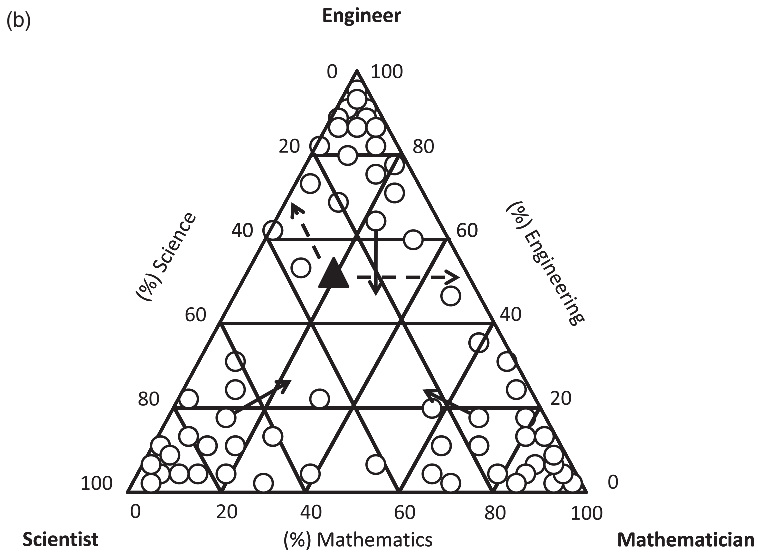


Figure 1.2. (a) Technical orientation phase diagram. (b) Technical orientation population density distribution.

The occasional evolution of technical specialists into systems engineers is symbolized in Figure 1.2b by the arrows directed from the vertices toward the center. The small black triangle corresponds to such an evolved individual whose orientation is 30% science, 50% engineering, and 20% mathematics, a balance that would be effective in the type of problem solving with which a systems engineer is typically involved. It is the few individuals who evolve into systems engineers or system architects who become the technical leaders of system development programs.

The Challenge of Systems Engineering

An inhibiting factor in becoming a professional systems engineer is that it represents a deviation from a chosen established discipline to a more diverse, complicated professional practice. It requires the investment of time and effort to gain experience and an extensive broadening of the engineering base, as well as learning communication and management skills, a much different orientation from the individual's original professional choice.

For the above reasons, an engineer considering a career in systems engineering may come to the conclusion that the road is difficult. It is clear that a great deal must be learned; that the educational experience in a traditional engineering discipline is necessary; and that there are few tools and few quantitative relationships to help make decisions. Instead, the issues are ambiguous and abstract, defying definitive solutions. There may appear to be little opportunity for individual accomplishment and even less for individual recognition. For a systems engineer, success is measured by the accomplishment of the development team, not necessarily the system team leader.

What Then Is the Attraction of Systems Engineering?

The answer may lie in the challenges of systems engineering rather than its direct rewards. Systems engineers deal with the most important issues in the system development process. They design the overall system architecture and the technical approach and lead others in designing the components. They prioritize the system requirements in conjunction with the customer to ensure that the different system attributes are appropriately weighted when balancing the various technical efforts. They decide which risks are worth undertaking and which are not, and how the former should be hedged to ensure program success.

It is the systems engineers who map out the course of the development program that prescribes the type and timing of tests and simulations to be performed along the way. They are the ultimate authorities on how the system performance and system affordability goals may be achieved at the same time.

When unanticipated problems arise in the development program, as they always do, it is the systems engineers who decide how they may be solved. They determine whether an entirely new approach to the problem is necessary, whether more intense effort will accomplish the purpose, whether an entirely different part of the system can be modified to compensate for the problem, or whether the requirement at issue can best be scaled back to relieve the problem.

Systems engineers derive their ability to guide the system development not from their position in the organization but from their superior knowledge of the system as a whole, its operational objectives, how all its parts work together, and all the technical factors that go into its development, as well as from their proven experience in steering complex programs through a maze of difficulties to a successful conclusion.

Attributes and Motivations of Systems Engineers

In order to identify candidates for systems engineering careers, it is useful to examine the characteristics that may be useful to distinguish people with a talent for systems engineering from those who are not likely to be interested or successful in that discipline. Those likely to become talented systems engineers would be expected to have done well in mathematics and science in college.

A systems engineer will be required to work in a multidisciplinary environment and to grasp the essentials of related disciplines. It is here that an aptitude for science and engineering helps a great deal because it makes it much easier and less threatening for individuals to learn the essentials of new disciplines. It is not so much that they require in depth knowledge of higher mathematics, but rather, those who have a limited mathematical background tend to lack confidence in their ability to grasp subjects that inherently contain mathematical concepts.

A systems engineer should have a creative bent and must like to solve practical problems. An interest in the job should be greater than an interest in career advancement. Systems engineering is more of a challenge than a quick way to the top.

The following characteristics are commonly found in successful systems engineers. They

1. enjoy learning new things and solving problems,
2. like challenges,
3. are skeptical of unproven assertions,
4. are open-minded to new ideas,
5. have a solid background in science and engineering,
6. have demonstrated technical achievement in a specialty area,
7. are knowledgeable in several engineering areas,
8. pick up new ideas and information quickly, and
9. have good interpersonal and communication skills.

1.5 SYSTEMS ENGINEER CAREER DEVELOPMENT MODEL

When one has the characteristics noted above and is attracted to become a systems engineer, there are four more elements that need to be present in the work environment. As shown in Figure 1.3a, one should seek assignments to problems and tasks that are

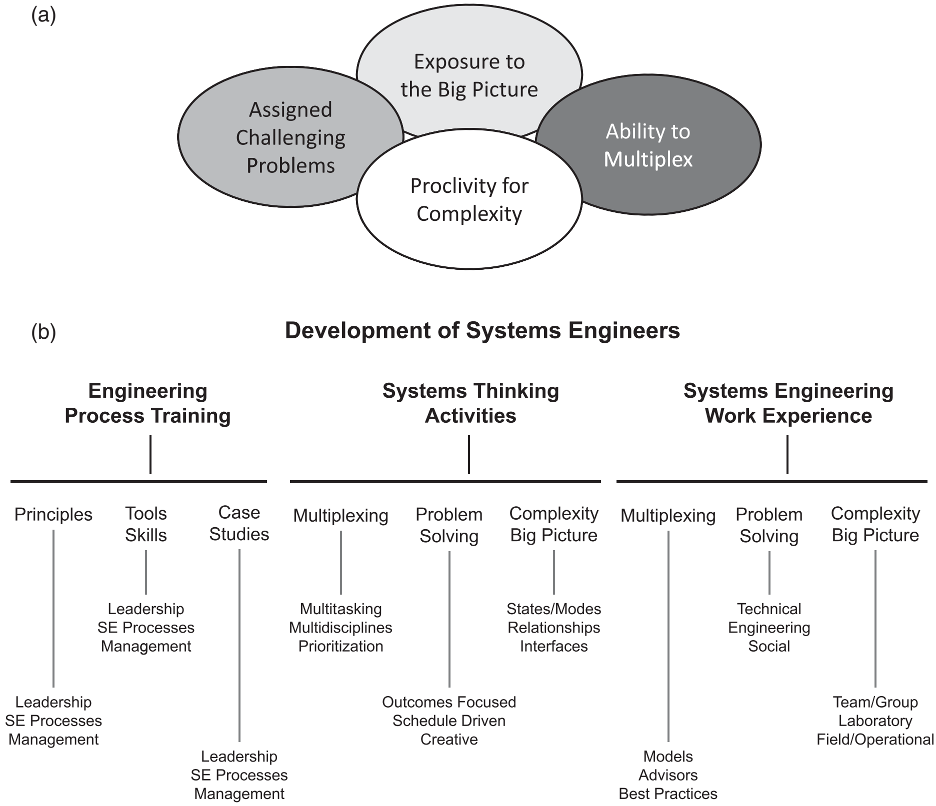


Figure 1.3. (a) Systems engineering (SE) career elements derived from quality work experiences. (b) Components of employer development of systems engineers.

very challenging and are likely to expand technical domain knowledge and creative juices. Whatever the work assignment, understanding the context of the work and understanding the big picture is also essential. Systems engineers are expected to manage many activities at the same time, being able to have broad perspectives but able to delve deeply into to many subjects at once. This ability to multiplex is one that takes time to develop. Finally, the systems engineer should not be intimidated by complex problems since this is the expected work environment. It is clear these elements are not part of an educational program and must be gained through extended professional work experience. This becomes the foundation for the systems engineering career growth model.

Employers seeking to develop systems engineers to competitively address more challenging problems should provide key staff with relevant systems engineering work experience, activities that require mature systems thinking, and opportunities for systems engineering education and training. In Figure 1.3b, it can be seen that the experience can be achieved not only with challenging problems but also with

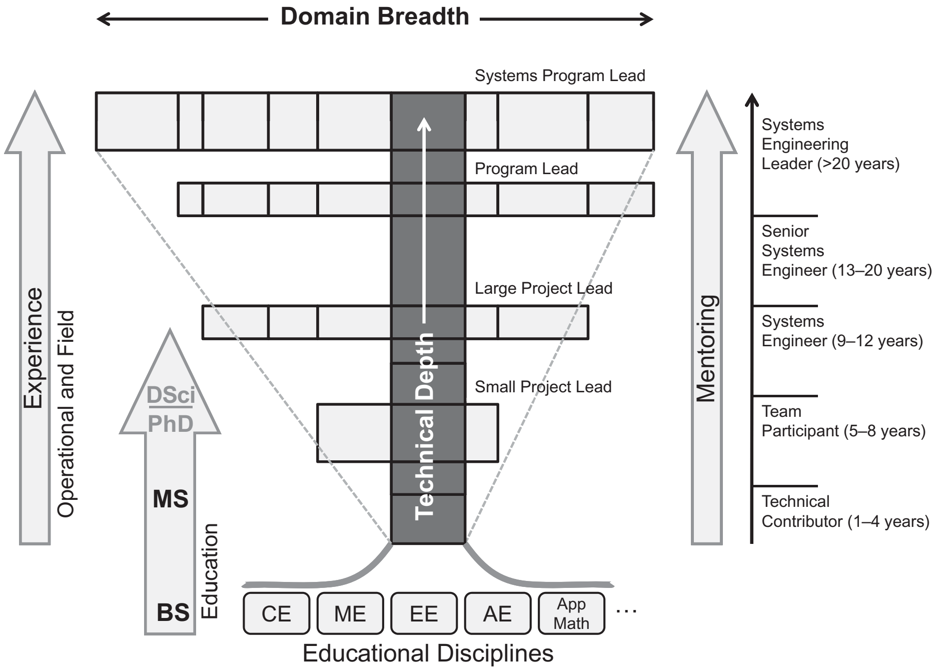


Figure 1.4. "T" model for systems engineer career development. CE, chemical engineering; ME, mechanical engineering; EE, electrical engineering; AE, aeronautical engineering; App Math, applied mathematics.

experienced mentors and real, practical exercises. While using systems thinking to explore complex problem domains, staff should be encouraged to think creatively and out of the box. Often, technically trained people rigidly follow the same processes and tired ineffective solutions. Using lessons learned from past programs and case studies creates opportunities for improvements. Formal training and use of systems engineering tools further enhance employee preparation for tackling complex issues.

Interests, attributes, and training, along with an appropriate environment, provide the opportunity for individuals to mature into successful systems engineers. The combination of these factors is captured in the "T" model for systems engineer career development illustrated in Figure 1.4. In the vertical, from bottom to top is the time progression in a professional's career path. After completion of a technical undergraduate degree, shown along the bottom of the chart, an individual generally enters professional life as a technical contributor to a larger effort. The effort is part of a project or program that falls in a particular domain such as aerodynamics, biomedicine, combat systems, information systems, or space exploration. Within a domain, there are several technical competencies that are fundamental for systems to operate or to be developed.

The T is formed by snapshots during a professional's career that illustrates in the horizontal part of the T the technical competencies at the time that were learned and used to meet the responsibilities assigned at that point in their career. After an initial experience in one or two technical domains as technical contributor, one progresses to increasing responsibilities in a team setting and eventually to leading small technical groups. After eight or more years, the professional has acquired both sufficient technical depth and technical domain depth to be considered a systems engineer. Additional assignments lead to project and program systems engineering leadership and eventually to being the senior systems engineer for a major development program that exercises the full range of the technical competencies for the domain.

In parallel with broadening and deepening technical experience and competencies, the successful career path is augmented by assignments that involve operational field experiences, advanced education and training, and a strong mentoring program. In order to obtain a good understanding of the environment where the system under development will operate and to obtain firsthand knowledge of the system requirements, it is essential for the early systems engineer professional to visit the "field site" and operational location. This approach is important to continue throughout one's career. A wide variety of systems engineering educational opportunities are available in both classroom and online formats. As in most engineering disciplines where the student is not planning on an academic career, the master of science is the terminal degree. Courses are usually a combination of systems engineering and domain or concentration centric focused with a thesis or capstone project for the students to demonstrate their knowledge and skills on a practical systems problem. Large commercial companies also provide training in systems engineering and systems architecting with examples and tools that are specific to their organization and products. Finally, the pairing of a young professional with an experienced systems engineer will enhance the learning process.

1.6 THE POWER OF SYSTEMS ENGINEERING

If power is measured by authority over people or money, then systems engineers would appear to have little power as members of the system development team. However, if power is measured by the influence over the design of the system and its major characteristics, and over the success or failure of the system development, then systems engineers can be more powerful than project managers. The sources of this power come from their knowledge, skills, and attitude. Each of these is discussed in the following paragraphs.

The Power of Multidisciplinary Knowledge

A major system development project is a veritable "Tower of Babel." There are literally dozens of specialists in different disciplines whose collective efforts are necessary to develop and produce a successful new system. Each group of specialists has its own language, making up for the imprecision of the English language with a rich set of acronyms, which convey a very specific meaning but are unintelligible to those outside the specialty. The languages, in turn, are backed up by knowledge bases, which the specialists use to ply their trade. These knowledge bases contain descriptions of the different materials peculiar to each discipline, as well as bodies of relationships, many of them expressed in mathematical terms, that enable the specialists to compute various characteristics of their components on the basis of design assumptions. These knowledge bases are also foreign to those outside the discipline.

Such a collection of multi-tongued participants could never succeed in collectively developing a new system by themselves, just as the citizens of Babylon could never build their tower. It is the systems engineers who provide the linkages that enable these disparate groups to function as a team. The systems engineers accomplish this feat through the power of multidisciplinary knowledge. This means that they are sufficiently literate in the different disciplines involved in their system that they can understand the languages of the specialists, appreciate their problems, and are able to interpret the necessary communications for their collective endeavor. Thus, they are in the same position as a linguist in the midst of a multinational conference, with people speaking in their native tongues. Through the ability to understand different languages comes the capability to obtain cooperative effort from people who would otherwise never be able to achieve a common objective. This capability enables systems engineers to operate as leaders and troubleshooters, solving problems that no one else is capable of solving. It truly amounts to a power that gives systems engineers a central and decisive role to play in the development of a system.

It is important to note that the depth of interdisciplinary knowledge, which is required to interact effectively with specialists in a given field, is a very small fraction of the depth necessary to work effectively in that field. The number of new acronyms that one has to learn in a given technical area is nearer to a dozen of the more frequently used ones than to a hundred. It also turns out that once one gets past the differences in semantics, there are many common principles in different disciplines and many similar relationships. For instance, the equation used in communications, connecting signal, noise, antenna gain, receiver sensitivity, and other factors, is directly analogous to a similar relationship in acoustics.

These facts mean that a systems engineer does not need to spend a lifetime becoming expert in associated disciplines, but rather can accumulate a working knowledge of related fields through selected readings, and more particularly, discussion with colleagues knowledgeable in each field. The important thing is to know which principles, relationships, acronyms, and the like are important at the system level and which are details. The power of multidisciplinary knowledge is so great that, to a systems engineer, the effort required to accumulate it is well worth the learning time.

The Power of Approximate Calculation

The practice of systems engineering requires another talent besides multidisciplinary knowledge. The ability to carry out “back of the envelope” calculations to obtain a “sanity check” on the result of a complex calculation or test is of inestimable value to the systems engineer. In a few cases, this can be done intuitively on the basis of past experience, but more frequently, it is necessary to make a rough estimate to ensure that a gross omission or error has not been committed. Most successful systems engineers have the ability, using first principles, to apply basic relationships, such as the communications equation or other simple calculation, to derive an order of magnitude result to serve as a check. This is particularly important if the results of the calculation or experiment turn out very differently from what had been originally expected.

When the sanity check does not confirm the results of a simulation or experiment, it is appropriate to go back to make a careful examination of the assumptions and conditions on which the latter were based. As a matter of general experience, more often than not, such examinations reveal an error in the conditions or assumptions under which the simulation or experiment was conducted.

The Power of Skeptical Positive Thinking

The above seemingly contradictory title is meant to capture an important characteristic of successful systems engineering. The skeptical part is important to temper the traditional optimism of the design specialist regarding the probability of success of a chosen design approach. It is the driving force for the insistence of validation of the approach selected at the earliest possible opportunity.

The other dimension of skepticism, which is directly related to the characteristic of positive thinking, refers to the reaction in the face of failure or apparent failure of a selected technique or design approach. Many design specialists who encounter an unexpected failure are plunged into despair. The systems engineer, on the other hand, cannot afford the luxury of hand wringing but must have, first of all, a healthy skepticism of the conditions under which the unexpected failure occurred. Often, it is found that these conditions did not properly test the system. When the test conditions are shown to be valid, the systems engineer must set about finding ways to circumvent the cause of failure. The conventional answer that the failure must require a new start along a different path, which in turn will lead to major delays and increases in program cost, is simply not acceptable unless heroic efforts to find an alternative solution do not succeed. This is where the power of multidisciplinary knowledge permits the systems engineer to look for alternative solutions in other parts of the system, which may take the stress off the particular component whose design proved to be faulty.

The characteristic of positive thinking is absolutely necessary in both the systems engineer and the project manager so that they are able to generate and sustain the confidence of the customer and of company management, as well as the members of the design team. Without the "can-do" attitude, the esprit de corps and productivity of the project organization is bound to suffer.

1.7 SUMMARY

What Is Systems Engineering?

The function of systems engineering is to guide the engineering of complex systems. And a system is defined as a set of interrelated components working together toward a common objective. Furthermore, a complex engineered system (as defined in this book) is (1) composed of a multiplicity of intricately interrelated diverse elements and (2) requires systems engineering to lead its development.

Systems engineering differs from traditional disciplines in that (1) it is focused on the system as a whole; (2) it is concerned with customer needs and operational environment; (3) it leads system conceptual design; and (4) it bridges traditional engineering disciplines and gaps between specialties. Moreover, systems engineering is an integral part of project management in that it plans and guides the engineering effort.

Origins of Systems Engineering

Modern systems engineering originated because advancing technology brought risks and complexity with the growth of automation; competition required expert risk taking; and specialization required bridging disciplines and interfaces.

Examples of Systems Requiring Systems Engineering

Examples of engineered complex systems include

- weather satellites,
- terminal air traffic control,
- truck location systems,
- airline navigation systems,
- clinical information systems,
- passenger aircraft,
- modern harvester combines,
- oil refineries,
- auto assembly plants, and
- electric power plants.

Systems Engineering as a Profession

Systems engineering is now recognized as a profession and has an increasing role in government and industry. In fact, numerous graduate (and some undergraduate) degree programs are now available across the country. And a formal, recognized organization exists for systems engineering professionals: the INCOSE.

Technical professionals have specific technical orientations—technical graduates tend to be highly specialized. Only a few become interested in interdisciplinary problems—it is these individuals who often become systems engineers.

Systems Engineer Career Development Model

The systems engineering profession is difficult but rewarding. A career in systems engineering typically features technical satisfaction—finding the solution of abstract and ambiguous problems—and recognition in the form of a pivotal program role. Consequently, a successful systems engineer has the following traits and attributes:

- a good problem solver and should welcome challenges;
- well grounded technically, with broad interests;
- analytical and systematic, but also creative; and
- a superior communicator, with leadership skills.

The “T” model represents the proper convergence of experience, education, mentoring, and technical depth necessary to become a successful and influential systems engineer.

The Power of Systems Engineering

Overall, systems engineering is a powerful discipline, requiring a multidisciplinary knowledge, integrating diverse system elements. Systems engineers need to possess the ability to perform approximate calculations of complex phenomena, thereby providing sanity checks. And finally, they must have skeptical positive thinking as a prerequisite to prudent risk taking.

PROBLEMS

1.1 Write a paragraph explaining what is meant by the statement “Systems engineering is focused on the system as a whole.” State what characteristics of a system you think this statement implies and how they apply to systems engineering.

1.2 Discuss the difference between engineered complex systems and complex systems that are not engineered. Give three examples of the latter. Can you think of systems engineering principles that can also be applied to nonengineered complex systems?

1.3 For each of the following areas, list and explain how at least two major technological advances/breakthroughs occurring since 1990 have radically changed them. In each case, explain how the change was effected in
(a) transportation,
(b) communication,
(c) financial management,
(d) manufacturing,
(e) distribution and sales,
(f) entertainment, and
(g) medical care.

1.4 What characteristics of an airplane would you attribute to the system as a whole rather than to a collection of its parts? Explain why.

1.5 List four pros and cons (two of each) of incorporating some of the latest technology into the development of a new complex system. Give a specific example of each.

1.6 What is meant by the term "modularity?" What characteristics does a modular system possess? Give a specific example of a modular system and identify the modules.

1.7 The section Orientation of Technical Professionals uses three components to describe this characteristic: science, mathematics, and engineering. Using this model, describe what you think your orientation is in terms of $x\%$ science, $y\%$ mathematics, and $z\%$ engineering. Note that your "orientation" does not measure your knowledge or expertise, but rather your interest and method of thought. Consider your relative interest in discovering new truths, finding new relationships, or building new things and making them work. Also, try to remember what your orientation was when you graduated from college, and explain how and why it has changed.

1.8 Systems engineers have been described as being an advocate for the whole system. Given this statement, which stakeholders should the systems engineer advocate the most? Obviously, there are many stakeholders and the systems engineer must be concerned with most, if not all, of them. Therefore, rank your answer in priority order—which stakeholder is the most important to the systems engineer; which is second; which is third?

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