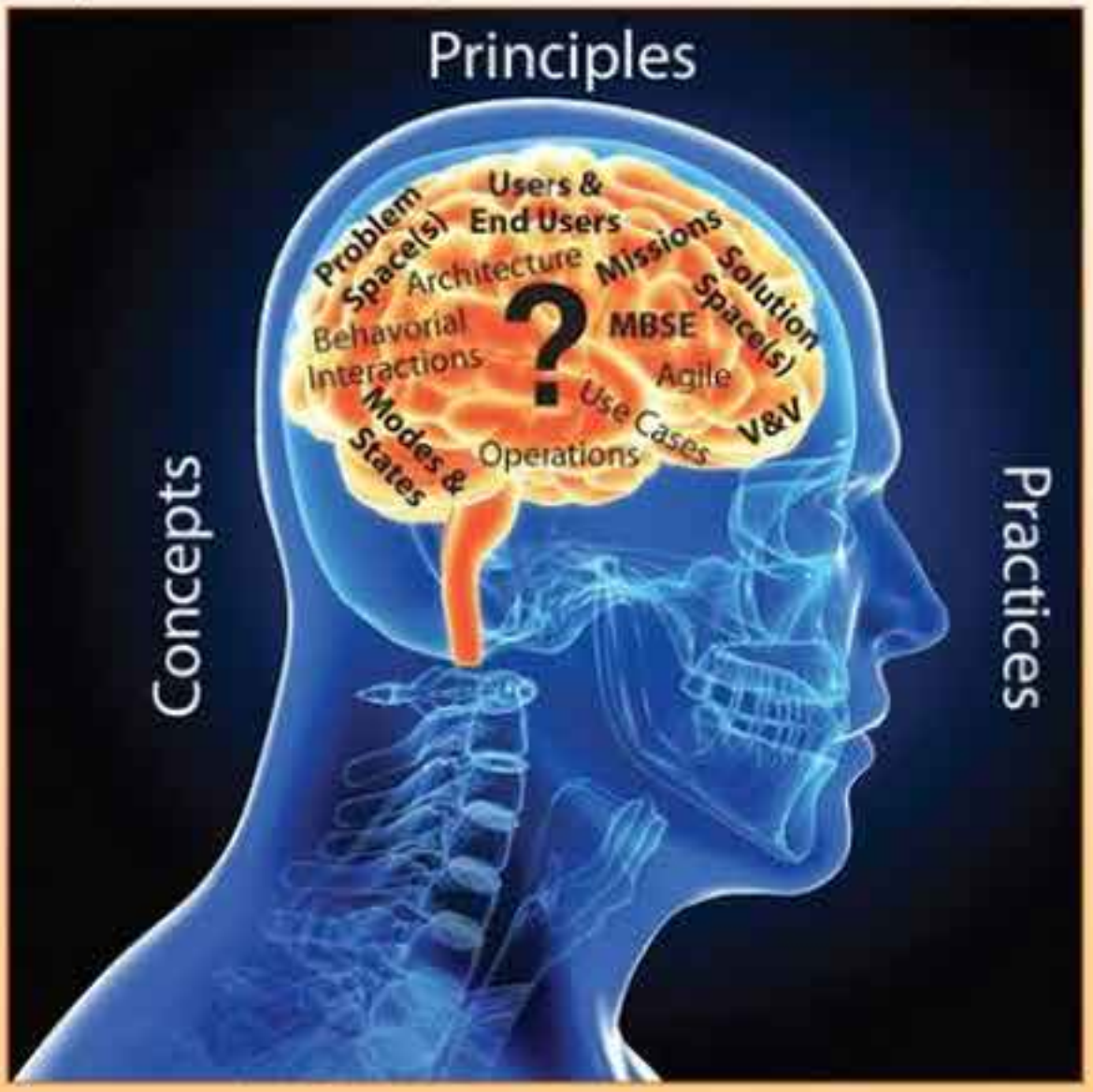
Wiley Series in Systems Engineering and Management
Andrew P. Sage, Series Editor

System Engineering

Analysis, Design, and Development



Charles S. Wasson
Wasson Strategics, LLC

Foreword by Norman Augustine
Former Chairman and CEO – Lockheed Martin Corporation
Former Under Secretary of the Army
Former Member of Princeton Engineering Faculty

WILEY

SYSTEM ENGINEERING ANALYSIS, DESIGN, AND DEVELOPMENT

WILEY SERIES IN SYSTEMS ENGINEERING AND MANAGEMENT

Andrew P. Sage, Editor

A complete list of the titles in this series appears at the end of this volume.

SYSTEM ENGINEERING ANALYSIS, DESIGN, AND DEVELOPMENT

Concepts, Principles, and Practices

CHARLES S. WASSON

WILEY

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data:

Wasson, Charles S., 1948-
System engineering analysis, design, and development : concepts, principles, and practices / Charles S. Wasson.
pages cm
Revised edition of: System analysis, design, and development. Hoboken, N.J. : Wiley-Interscience, 2005.
Includes bibliographical references and index.
ISBN 978-1-118-44226-5 (cloth)
1. System design. 2. System analysis. I. Title.
QA76.9.S88W373 2015
003–dc23

2014018409

Cover image courtesy of iStockphoto © cgtoolbox

Typeset in 10/12pt TimesLTStd by SPi Global, Chennai, India

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

1 2016

CONTENTS

FOREWORD

Norman R. Augustine

Arguably the most sought-after employees in engineering-oriented firms are systems engineers. This was certainly the case in the firm that I led at the time I led it, and I suspect that at least in this regard not much has changed. Of 82,000 engineers only a tiny fraction could have been categorized as "systems engineers;" nonetheless, they were the individuals who provided the "glue" in building our products and often were the ones that moved into management positions.

But, given the impact of their field, one can't help but ask why such individuals are so rare? One reason is that few universities even offer a degree in "systems engineering." (Most *high schools*, for that matter, don't even offer a *course* in what one might call "engineering.") Another reason is that it requires a rather special talent to cut across a broad set of disciplines—some of which would not even be categorized by most people as "technical." Further, in my experience, the best systems engineers are those who acquired a relatively deep understanding of at least one core discipline before moving into systems engineering. This seems to give them a grounding in dealing with the challenges one encounters when working with complex systems—but it also adds time to the educational process.

Further complicating matters, there is widespread disagreement, even in the profession itself, as to what constitutes "systems engineering." Is it an aspect of management? Does it have to do with the "ilities"—reliability, maintainability and availability? Does it have to do with the acquisition of major systems? Is it the process of conducting trade-offs between alternate approaches to carrying out a function or producing a design? Is it figuring out what something will cost? Is it the process of identifying solutions to a requirement … or is it determining what the requirement should be in the first place?

The answer is, "yes." It is all of these things … and more.

My own rather simplified definition of systems engineering is that it is the discipline of combining two or more interacting elements to fulfill a need. In this book, much greater insight will be given to the answer to this question. Many tools will also be presented that a systems engineer can use to address a broad spectrum of problems in design and analysis—all introduced in an understandable and carefully organized fashion.

One might conclude that with such a simple definition as the one I offer, systems engineering must be a fairly straightforward pursuit. Unfortunately, it is not. Consider the following: the simplest of all systems has only two elements, each of which can influence the other. Perhaps the canonical example would be (putting aside quarks and their cousins) a hydrogen atom. Furthermore, if one limits the interaction between the elements of the system to be binary ("on" or "off") but omni-interactive, it will readily be seen that the number of possible states of a two-element system will be just four. But if one expands the number of elements to merely seven or eight, the number of states virtually explodes.

Making matters still worse, many systems involve humans among their elements, adding unpredictability. All this is what makes it impossible to completely test a complex system in all of its possible states and makes the task of the systems engineer all the more critical. Further, among the humans affecting systems there are usually engineers, many of whom seem to embrace the code that "If it ain't broke … it needs more functions!"

To the designer of a component, say a fuel-control, the fuel-control is a system. Which it is. But to the designer of the jet engine into which the fuel control is incorporated, the

engine is the system. To an aeronautical engineer, the entire aircraft is the system. And it does not stop there … since to an engineer configuring an airline the system includes passengers, agents, airports, air traffic control, runways, and still more—what is often called a system of systems. Fortunately, there are techniques to deal with such challenges in systems of systems and these, too, are described in the pages that follow.

The discipline embodied in sound systems engineering practice can have an important impact on the utility of a system. For example, a few years ago a market survey found that airline passengers wished, among other things, to get to their destinations faster. To an aerodynamicist (my original field) that meant (presuming supersonic flight over land was, at least at that time, impracticable) flying faster, which in turn meant pressing even further against the sudden drag rise that occurs as one approaches the speed of sound. Thus, the effort began to develop a "near-sonic" airliner … a difficult and costly solution.

But systems engineers interpreted the passengers' desire quite differently. They deduced that what passengers really wanted was to get from, say, their homes to an office in a distant city, more rapidly. Decomposing the relevant time-line into such segments as driving to the airport, finding a place to park and clearing security, flying, recovering baggage, and driving to the destination, they concluded that any plausible increase in airspeed would be trivial in its impact on *overall* travel time and that one should focus not on a challenging aerodynamics problem but rather on such matters as expediting security inspection, handling baggage, and speeding ground transportation. The idea of a near-sonic aircraft was thus wisely, if belatedly, discarded.

As noted, this book provides the individual interested in systems engineering with a variety of techniques to deal with such problems, techniques that systems engineers (something into which I "evolved" during my career) in the past largely learned the costly way: O.J.T. Insights will be offered into such important tasks as defining requirements, decomposing requirements, managing software, root-cause analysis, identifying single-point failure modes, modeling, conducting trades, controlling interfaces, and testing for utility as opposed to simply satisfying a specification.

Many of the more important challenges facing America, and in most cases the world, are, in effect, massive systems engineering problems. These include providing healthcare; producing clean, sustainable, affordable energy; preserving the natural environment; growing the economy; providing national security; and rebuilding the nation's physical infrastructure.

In *Systems Engineering Analysis, Design and Development,* Charles Wasson has created a guide for the practitioner. This is not a philosophical treatise or an abstract, theoretical assessment. This is a book that is for the individual who faces every-day, practical challenges relating to the various aspects of systems engineering. It is not only an important teaching device, it is a reference book of lasting value.

The logic and techniques of systems engineering are truly ubiquitous in their applicability. Whether one works in engineering, venture capital, transportation, defense, communications, healthcare, cybersecurity, or dozens of other fields, understanding the principles of systems engineering will serve one well. After all, what is there in life that doesn't involve two or more elements that influence each other?

NORMAN R. AUGUSTINE

Retired Chairman & CEO, Lockheed Martin Corporation
Former Under Secretary of the Army
Former Member of Princeton Engineering Faculty

PREFACE TO THE SECOND EDITION

Welcome to the Second Edition of *System Engineering, Analysis, Design, and Development* written for anyone who is accountable for specifying, analyzing, designing, and developing systems, products, or services. This Second Edition is a landmark text intended to take System Engineering (SE) to new levels of 21st-Century System Thinking. Systems Thinking that goes beyond what some refer to as "outdated, old school, and parochial" paradigms such as "Engineering the (Hardware/Software) Box" promulgated by institutions and Enterprises.

Traditional "Engineering the Box" mindsets fail to approach SE&D from the standpoint of "Engineering the System" based on User capabilities and limitations. Contrary to public perceptions, system failures are often attributable to poor System Design – "Engineering the Box" – that influences "human error" publicized as the "root cause." The reality is system failures are typically the result of a series of latent defects in the System "Box" Design that lie dormant until the right set of enabling circumstances occur and proliferate via a chain of events culminating in an incident or accident. This text goes beyond traditional "Engineering the Box" and fosters Systems Thinking to broaden insights about how to "Engineer the System" and the "Box."

The Systems Engineering *concepts*, *principles*, *practices*, and problem-solving and solution-development *methods* presented in this text apply to any discipline irrespective of type of discipline. This includes:

1. System Engineers (SE);
2. Multi-discipline Engineers—Electrical, Mechanical, Software, BioMedical, Nuclear, Industrial, Chemical, Civil, and others.
3. Specialty Engineers—Manufacturing, Test, Human Factors (HF); Reliability, Maintainability, and Availability (RMA); Safety; Logistics; Environmental, and others.
4. System and Business Analysts.
5. Quality Assurance (QA) and Software QAs.
6. Project Engineers.
7. Project Managers (PMs).
8. Functional Managers and Executives.

System Engineering Analysis, Design, and Development is intended to fill the SE void in Engineering education and to provide the concepts, principles, and practices required to perform SE. Based on the bestselling, international award-winning First Edition, this Second Edition builds on those foundational concepts, principles, and practices. This text has three key objectives:

1. To help educate Engineers who have a vision of becoming an SE or a better SE through course instruction or self-study.
2. To equip discipline Engineers and System Analysts—EEs, MEs, SwEs, etc.—with SE *problem-solving and solution development methods* that help them better understand the *context* of their work within the overall framework of the system, product, or service they are Engineering.
3. To provide Project Managers (PMs) with an understanding of SE & Development (SE&D) to facilitate better project integration with Engineering.

During the past 70 years, Systems Engineering has evolved from roots in fields such Aerospace and Defense (A&D) and proliferated into new business domains such as energy; medical products and healthcare; transportation

—land, sea, air, and space; telecommunications; financial, educational, and many others. Worldwide awareness and recognition of Systems Engineering, its application, and benefits have placed it at the forefront of one of the most sought-after fields of study and employment. In 2009, *Money Magazine* identified Systems Engineering as #1 in its list of Best Jobs in America with a 10-year job growth forecast of 45%. Besides being #1, the criticality of this profession is in stark contrast to the second place job, which had a 10-year job growth projection of 27%.

Despite its rapidly expanding growth potential, Systems Engineering is still *evolving* in terms of its methodology, discipline, and application by Users. Its application in many Enterprises is often *ad hoc*, *experiential,* and characterized by semantics and methods that often exist in lofty marketing brochures and websites. Yet, produce limited objective evidence that SE has been performed. Based on the author's experience:

- Most Engineers, in general, spend from 50% to 75% of their total career hours on average making systems decisions for which they have little or no formal Systems Engineering coursework.
- Less than 3% of the personnel—one person out of 30—in most Enterprise SE organizations possess the requisite knowledge of the concepts, principles, and practices identified in this text.
- What most people and Enterprises perceive to be System Engineering (SE) is actually an *ad hoc, trial-and-error, endless loop*, Specify-Design-Build-Test-Fix (SDBTF) Paradigm. Compounding the problem is the fact that embedded within the SDBTF Paradigm is another *trial-and-error endless loop* Design Process Model (DPM) documented in the 1960s. Users of the SDBTF-DPM paradigm acknowledge it is *inconsistent*, *inefficient*, *ineffective*, and *chaotic* in developing systems, products, or services. Yet, they continue to employ it despite the fact that it is *not scalable* to moderate or large, complex systems projects.
- The underlying rationale to the SDBTF-DPM Paradigm is that since they have used it to to develop "systems," it must be—by definition—Systems Engineering. Based on those misperceptions, the SDBTF-DPM Paradigm becomes the "core engine" within an SE "wrapper." When the SDBTF-DPM Paradigm is applied to System Development and the deliverable system fails or the customer does not like the system, they *rationalize* the root cause to be … Systems Engineering.
- Within these Enterprises anyone who has electrically, electronically, or mechanically integrated two hardware components or compiled two software modules is "knighted" as a Systems Engineer by their manager whether they have exhibited SE skills and competence in the discipline or not … everyone is "Systems Engineer."

Frightening isn't it! Unfortunately, executives and managers are often unaware or refuse to acknowledge the existence of the SDBTF-DPM Paradigm as the defacto "SE Process" within their Enterprise.

These Enterprises are easily identifiable. Ignoring or oblivious to the problem, executives and managers will challenge the SDBTF-DPM Engineering Paradigm observation. They recite metrics that quantify how they have trained XX personnel in an SE short course, YY personnel obtained a Master's degree in SE or higher, and ZZ personnel have been certified as Systems Engineering professionals within the past year. This is mindful of an old cliché that "owning a paint brush does not make someone an artist."

Despite their proclamations, project performance issues traceable to a lack of true SE education or SE courses in Engineering education refute any evidence to the contrary. There are, however, Enterprises and professionals who do understand SE and perform it reasonably well. *What are the differences between Enterprises that perform SE well versus those where the SDBTF-DPM Engineering Paradigm thrives?*

First, SE knowledge is often learned *experientially* through personal self-study and "On-the-Job Training" (OJT). Despite its significance as a critical workplace Engineering skill, the fundamentals of SE are not taught as a course in most undergraduate Engineering programs. Undergraduate or graduate level courses that are labeled as SE: (1) often focus on Systems Acquisition and Management or (2) specialty engineering equation-based courses. These courses are fine … when staged and sequenced … after … a strong, requisite foundation in understanding what a system is coupled with the ability to perform the problem-solving and solution development to actually develop a system.

Secondly, Engineering has always wrapped itself in a cloak of equations; that's the perception of Engineering by many. 21st Century System Engineering and Development (SE&D) in industry and government demands a combination of *problem-solving and solution-development* decision-making *soft skills* that precede, enable, and facilitate the equation-based *hard skills*. Engineers erroneously "knighted" as SEs who spend their days *plugging* and *chugging* equations either have a highly specialized instance of SE, misplaced priorities, or simply do not understand what is required to develop a system on-schedule, within budget, and compliant with its technical requirements!

Missing is the requisite knowledge Engineers and System Analysts need to serve as a foundation for transforming a User's abstract operational needs into the physical realization of a system, product, or service. Most SEs will emphatically

state that is what they do. However, their *misinformed* perception of SE and actions reveal that they typically take a *quantum leap* from requirements directly to a physical solution and implementation (Figure 2.3). Due to a lack of a true system problem-solving and solution development methodology and skills, these efforts often result in failure or fall short of technical performance, especially in complex systems, and compliance to specification requirements.

Foundational SE knowledge requires competence in the following areas: (1) understanding and applying SE concepts, principles, and practices; (2) applying a proven *problem-solv*ing and *solution-development* methodology; (3) scaling SE practices to meet project resource, budget, schedule, and risk constraints; (4) structuring and orchestrating technical projects; and (5) leading multi-discipline Engineering and other types of System Development decision-making teams. Where true SE knowledge and skills are lacking, Engineering evolves into an *ad hoc*, *endless loop* of Build-Test-Fix with the peception that "if we create a design and tweak it enough, sooner or later we will get it right."

To address these and other issues, industry, government, and professional Enterprises have made great strides in establishing standards, Enterprise capability assessments, certification programs, etc. These are certainly *essential* for any type of discipline. However, they do not solve the *root problem* that exists concerning the lack of foundational SE knowledge. Specifically, *shifting*—correcting—the SDBTF-DPM Paradigm that permeates Enterprises, projects, and individual thinking due to a lack of substantive SE education beginning at the undergraduate level. *How do we solve the problem*?

This Second Edition builds on the author's experiences and incorporates readers' and instructors' feedback as well as advancements in SE. This includes (1) leading-edge topics and methods that enhance your knowledge and (2) provides a framework that supports pursuit of professional certification provided by organizations such as International Council on Systems Engineering (INCOSE), Enterprise level Capability Maturity Model Integration (CMMI) Assessments, and Enterprise Organizational Standard Processes (OSPs) traceability to ISO standards.

KEY FEATURES

Textbooks often include a "principles of" subtitle as marketing claims to lure readers. Readers read these texts from cover to cover and discover the lack of explicitly stated principles despite the claims. This text delivers on its Concepts, Principles, and Practices subtitle. The Second Edition:

- Includes approximately 365 principles, 231 examples, 148 author's notes, and 21 mini case studies that exemplify how to apply SE to the real world.
- Facilitates readability and quick location of key points of information based on icon-based visual aids used to highlight principles, heuristics, author's notes, mini case studies, cautions, warnings, etc.
- Consists of two levels of end-of-chapter exercises for undergraduate and graduate level course instructions: Level 1 Chapter Knowledge Exercises and Level 2 Knowledge Application Exercises.

Textbooks are often a one-time reading and disposed of on completion—donated to a library, sold back to a bookstore, or given away. It is the author's intent for this text to serve as a personal desk reference throughout your professional career subject to the evolution of SE standards, updates, etc. Professions, industries, and individuals evolve and inevitably change over time; however, fundamental systems concepts stand the test of time.

In summary, *System Engineering Analysis, Design, and Development* provides foundational SE knowledge based on the author's experience tempered by over 40 years in industry with some of the world's leading SE Enterprises and private consulting with small, medium, and large corporate clients. The next step is up to you and your Enterprise. Leverage these concepts, principles, and practices to achieve the next level of performance. Learn to *competently scale* this knowledge along with your own unique experience to meet each project's technical, resources, technology, budgetary, schedule, and risk constraints.

ACKNOWLEDGMENTS

Projects such as this demand a lot of time, inspiration, and support from a community of professionals that strive to advance the practice of the Systems Engineering. My sincere gratitude and appreciation to colleagues, instructors, authors, mentors, friends, and family who contributed to the success of the 1st Edition and to this 2nd Edition.

- Dr. Norman R. Augustine for his visionary leadership in Engineering worldwide and preparation of the Foreword.
- Readers, colleagues, instructors, and authors, – Brian Muirhead – Prof. Heinz Stoewer, Dr. Sven Bilen, Dr. Ricardo Pineda, Dr. Adeel Khalid, Dr. Kamran Moghaddam, Joe Stevens, Michael Vinarcik, Mark Wilson, Rebecca Reed, Dr. Marita O'Brien, Dr. Bud Lawson, Neill Radke, Christopher Unger, Matthew Eash, Dr. Kevin Forsberg, David Walden, James Highsmith, Dr. Barry Boehm, Dr. Rick Dove, Dr. Eric Honour, Dr. Bohdan Oppenheim, Dr. Stavros Androulakakis, Cork Heyning, David Swinney, John Bartucci, Charles Anding, Eileen Arnold, Dorothy McKinney, William D. Miller, Garry Roedler, James

Sturges, Sandy Friedenthal, Michael W. Engle, Dr. Terry Bahill, Dr. Herman Migliore, and Dr. Eric D. Smith.

- Mentors – Dr. Charles Cockrell, Dr. Gregory Radecky, Bobby Hartway, Danny Thomas, Dr. William H. McCumber, Dr. Wolter J. Fabrycky, Benjamin S. Blanchard, Dr. Tom Tytula, William F. Baxter, Dan T. Reed, Chase B. Reed, Bob Jones, and Kenneth King.
- Wasson Strategics, LLC's many valued clients and their visionary pursuit of Systems Engineering and Development (SE&D) excellence.
- Administrative and Clerical Support – Jean Wasson and Sandra Hendrickson for their outstanding work and performance, systems thinking, and focus on achieving excellence.
- Research Support – David Moore and his University of Alabama - Huntsville (UAH) Library staff – Michael Manasco and Doug Bolden, Victoria Hamilton – Clemson University Library, and Pam Whaley – Auburn University Library.
- John Wiley & Sons, Inc. – Brett Kurzman (Editor – 2nd Edition), Kari Kapone – Manager, Content Capture, and Alex Castro – Senior Editorial Assistant; Vishnu Priya (Production Editor); Lincy Priya (Project Manager) and team members; Nicole Hanley (Marketing); and George Telecki (Editor – 1st Edition).

Most of all … the 1st and 2nd editions of this text could not have been possible without my wife who provided reviews, comments, and unwavering support throughout this challenging project.

To Jean, my love … my sincere gratitude and appreciation … always and forever!

In summary, thank you—the readers, instructors, and professionals—for the opportunity to shift traditional, narrow-scoped, Engineering and Systems Engineering paradigms to a new level of multi-disciplined 21st Century System Thinking.

Charles Wasson
Wasson Strategics, LLC
August, 2015

ABOUT THE COMPANION WEBSITE

This book is accompanied by a companion website:

www.wiley.com/go/systemengineeringanalysis2e.

- Level 2 Knowledge Application Exercises
- Instructional Materials
  - Chapter-Based Learning Objectives
  - Links to News Articles and Technical Papers

INTRODUCTION—HOW TO USE THIS TEXT

System Engineering Analysis, Design, and Development by virtue of its broad application to any type of Enterprise or Engineered system, product, or service is written for Engineers—Hardware, Software, BioMedical Specialty, Test, Chemical, Nuclear, etc., System Analysts, Project Engineers, Project Managers, Functional Managers, and Executives who strive to achieve System Engineering & Development (SE&D) excellence. Across that spectrum are Engineers and Analysts who may be new to SE, simply interested in learning more about SE methods to apply to their own Engineering disciplines, or seasoned professionals who want to improve and advance the state of the practice of their existing skills.

This text is written to accommodate a broad range of audiences. Writing to fulfill the needs of readers across a diverse spectrum of disciplines can be challenging. Readers who are new to SE request detailed discussions; seasoned professionals request less discussion. To accommodate such a diverse audience with varying levels of knowledge and skills, this text attempts to achieve a *reasonable balance* between communicating *essential* information about SE concepts, principles, and practices while limiting the depth due to page count limitations. As a result, our discussions will *drill down* to a particular level and provide resource referrals for you to pursue via your own personal study.

SCOPE OF TEXT

Due to the broad range of *technical* and *managerial* activities required to perform Systems Engineering and Development (SE&D) coupled with the need to limit the page count, the scope of this text focuses primarily on the *technical* aspects of SE.

As its name communicates, this text is about *System Engineering Analysis, Design, and Development: Concepts, Principles, and Practices*. This text is not about designing integrated circuits or electronic circuit boards or selecting physical components—resistors, capacitors, etc. or their deratings; design of mechanical structures and mechanisms; design and coding of software; Modeling or Simulation (M&S); developing mathematical algorithms, etc. Instead, it provides the SE concepts, principles, and practices that are *essential* for discipline-based Engineers and Analysts who perform those activities to better understand the *context* of their work products in terms of its Users, requirements, architecture, design, trade-offs, etc.

PRIMARY STRUCTURE

System Engineering Analysis, Design, and Development is partitioned into three parts:

- Part 1—System Engineering and Analysis Concepts
- Part 2—System Design and Development Practices
- Part 3—Decision Support Practices

Be Advised: Each part has a specific purpose, scope, and interrelationship to the other parts as illustrated in Figure I.1. However, for purposes of this description, to understand *why* Part 1 exists, we need to first understand the scopes of Parts 2 and 3.

Part 2—System Design and Development Practices

Part 2—System Design and Development Practices—addresses multi-discipline SE *workflow* activities

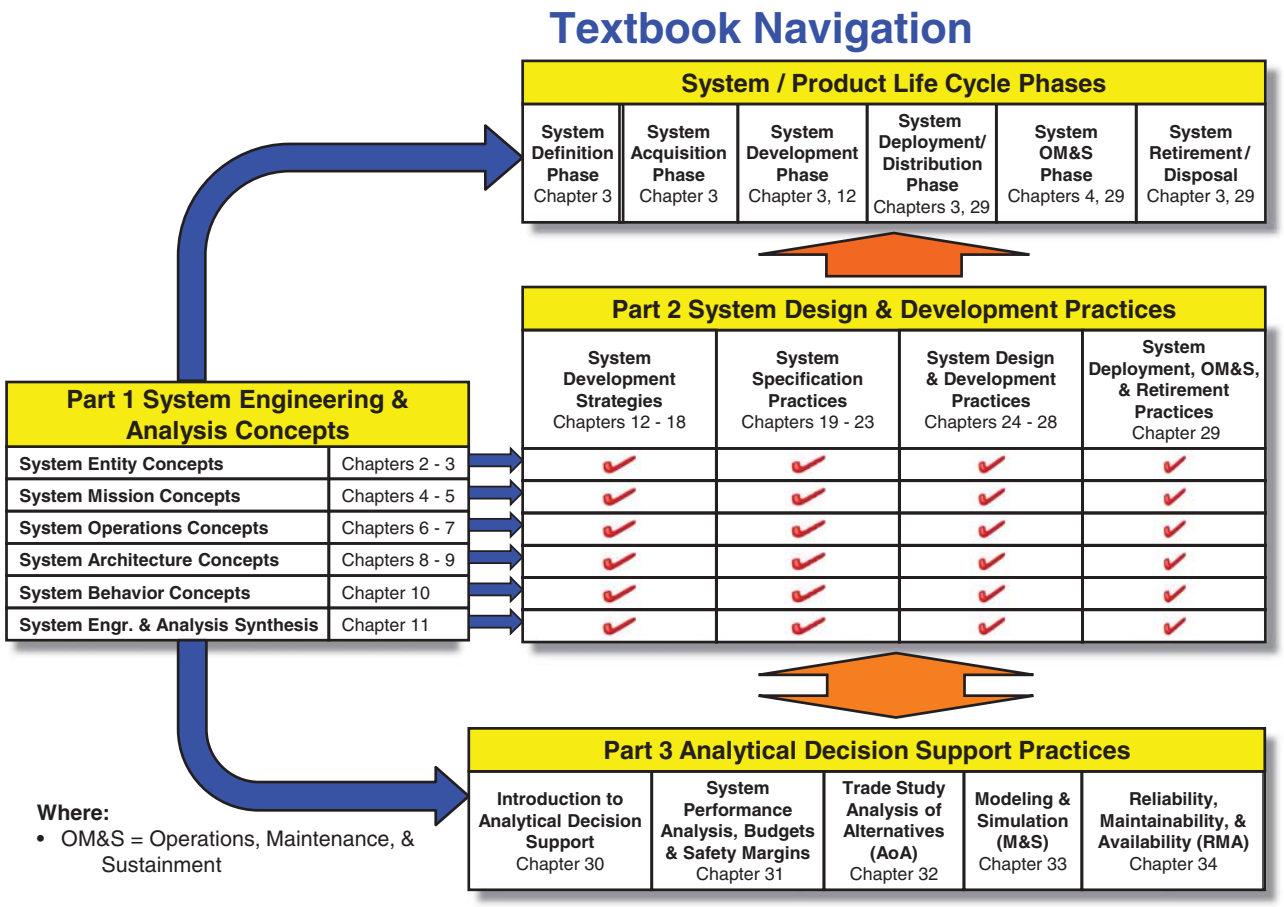


Figure I.1 Book Structure and Interrelationships

and practices required to engineer, develop, and deliver systems, products, or services. Part 2 is partitioned into four sets of SE practices that address how SE is performed not only during SE&D but also during operations performed by the User after delivery—System Deployment; Operations, Maintenance, & Sustainment (OM&S); and Retirement/Disposal. These include:

System Development Strategies

- Chapter 12 Introduction to System Development Strategies
- Chapter 13 System Verification and Validation (V&V) Strategy
- Chapter 14 The Wasson System Engineering Process
- Chapter 15 System Development Process Models
- Chapter 16 System Configuration Identification and Component Selection Strategy
- Chapter 17 System Technical Documentation Strategy
- Chapter 18 Technical Reviews Strategy

System Specification Practices

- Chapter 19 System Specification Concepts
- Chapter 20 Specification Development Approaches
- Chapter 21 Requirements Derivation, Allocation, Flow Down, and Traceability
- Chapter 22 Requirements Statement Development
- Chapter 23 Specification Analysis

System Design and Development Practices

- Chapter 24 User-Centered System Design (UCSD)
- Chapter 25 Engineering Standards of Units, Coordinate Systems, and Conventions
- Chapter 26 System and Entity Architecture Development
- Chapter 27 System Interface Definition, Analysis, and Control
- Chapter 28 System Integration, Test, and Evaluation (SITE)

System Deployment; Operations, Maintenance, and Sustainment (OM&S), and Retirement Practices

- Chapter 29 System Deployment; Operations, Maintenance, & Sustainment (OM&S); and Retirement

Part 3—Decision Support Practices

PART 3—DECISION SUPPORT PRACTICES—addresses multi-discipline SE practices such as System Analysis, Reliability, Maintainability, Human Factors, safety, etc. required to provide *timely* and *effective* decision support to the Part 2 decisionmaking practices. This includes development and assessment of rapid prototypes, Modeling and Simulations (M&S); proof-of-concept, proof-of-principle, and proof-of-technology demonstrations, to derive data to support SE&D decisions as well as to validate models and simulations. Part 3 is partitioned into the following chapters:

- Chapter 30 Introduction to Analytical Decision Support
- Chapter 31 System Performance Analysis, Budgets, and Safety Margins
- Chapter 32 Trade Study Analysis of Alternatives (AoA)
- Chapter 33 System Modeling & Simulation (M&S)
- Chapter 34 System Reliability, Maintainability, and Availability (RMA)

This brings us to the purpose of Part 1.

Part 1—System Engineering and Analysis Concepts

Most Enterprises, organizations, and projects perform the practices addressed in Parts 2 and 3. The problem is they employ the SDBTF-DPM Engineering Paradigm that is acknowledged to be *ad hoc, inefficient,* and *ineffective* as evidenced by poor performance in performing Parts 2 and 3. The reality is this is a *problem space*. PART 1—SYSTEM ENGINEERING AND ANALYSIS CONCEPTS—provides a *solution space* framework for *shifting* the SDBTF-DPM Engineering Paradigm to correct these shortcomings and serves as the foundational knowledge required to competently perform the practices in Parts 2 and 3.

Part 1 is partitioned into primary concepts that enable you to understand: *what* a system is: *why* it exists—missions; *how* the User envisions deploying, operating, maintaining, sustaining, retiring, and disposing of the system; *how* systems are structured architecturally; and *how* the User envisions system behavioral responses to mission interactions in its OPERATING ENVIRONMENT. Part 1 SYSTEMS ENGINEERING AND ANALYSIS CONCEPTS consists of the following:

System Entity Concepts

- Chapter 1 Systems, Engineering, and Systems Engineering
- Chapter 2 The Evolving State of SE Practice–Challenges and Opportunities
- Chapter 3 System Attributes, Properties, and Characteristics

System Mission Concepts

- Chapter 4 User Enterprise Roles, Missions, and System Applications
- Chapter 5 User Needs, Mission Analysis, Use Cases, and Scenarios

System Operations Concepts

- Chapter 6 System Concepts Formulation and Development
- Chapter 7 System Command and Control (C2) -Phases, Modes, & States of Operation

System Architecture Concepts

- Chapter 8 System Levels of Abstraction, Semantics, and Elements
- Chapter 9 Architectural Frameworks of the SOI & Its OPERATING ENVIRONMENT

System Behavior Concepts

- Chapter 10 Modeling MISSION and ENABLING SYSTEM Operations

System Engineering & Analysis Synthesis

- Chapter 11 Analytical Problem-Solving and Solution Development Synthesis

How to Use This Text

If you are reading this text for the first time … regardless of SE experience, you are encouraged to follow the sequence of Parts 1–3 and Chapters as sequenced. Understanding PART 1 SYSTEM ENGINEERING & ANALYSIS CONCEPTS is the critical foundation for understanding Parts 2 and 3. Figure I.1 serves as a roadmap for quickly locating and navigating the chapters.

Once you have read the text, you will be performing project work addressed in Part 2 SYSTEM DESIGN AND DEVELOPMENT PRACTICES or PART 3 ANALYTICAL DECISION SUPPORT PRACTICES. Figure I.1 facilitates navigation in the text by enabling you to easily refer back to more detailed discussions in the other Parts.

Undergraduate and Graduate Level Course Instruction

This textbook is structured to accommodate both *upper level undergraduate* and *graduate level* Engineering and other

courses. Depending on the (1) students and (2) the instructor's knowledge, skills, and industry experience, this text has also been designed to accommodate as much technical depth as the instructor wants to achieve. The instructor can treat the material as introductory or drill deeply into challenging topics.

Chapter Features

System Engineering Analysis, Design, and Development: Concepts, Principles, and Practices has been designed to incorporate specific features to facilitate readability and searches. In general, the textbook employs a common outline sequence of topics in each chapter.

- Chapter Introduction
- Definitions of Key Terms
- Approach to the Chapter (where necessary)
- Sectional Details and Discussions of Chapter Topics
- Chapter Summary
- Chapter Exercises
- References

Let's address some of the details of these features.

Definitions of Key Terms

The introduction to each chapter consists of Definitions of Key Terms that are relevant to the Chapter's discussion. Some of the definitions originate from military handbooks and standards. If you work in energy, medical, transportation, telecommunications fields, *avoid* the notion that these are not applicable to your work. As an SE, System Analyst, or Engineer, the mark of a true SE professional is the ability to work across business domains, understand the context of usage of definitions, their application, and what is to be accomplished. If your business domain or Enterprise has its own standards and definitions, *always* employ those in your work unless there is a compelling, authoritative reason to do otherwise.

Icon-Based Breakouts for Principles, Heuristics, Author's Notes, Examples, and Mini-Case Studies

SE, like most disciplines, is characterized by key points that are worthy of consideration. This includes principles, heuristics, author's notes, examples, and mini-case studies.

To facilitate readability, this text employs icon-based breakouts that also serve as easily identifiable navigation landmarks for referencing other chapters. For example, icons are encoded with XX.Y *syntax* reference identifiers where XX represents the chapter number and Y represents a sequential number indexed from the beginning of the chapter. Principle 12.4 represents Chapter 12 Principle #4, and so forth. The following is a list of icons for identifying principles, heuristics, author's notes, examples, cautions, and warnings that use this approach.

Principles represent a truth or law that governs reasoning and serves as a guide for action.

Principle I.1

Heuristic I.1 Heuristics represent "rules of thumb" that are not rigid but do provide insightful guidance that is worthy of consideration. As such, Heuristics are subject to exceptions depending on the circumstances.

Author's Note I.1

Author's Notes provide observations that highlight *subtle* or *noteworthy* aspects of a discussion concerning the context, interpretation, or application of a concept, principle, or practice. Your experiences may be different. You, your team, project, and Enterprise are wholly accountable for the decisions or lack of decisions you make and their consequences.

Examples illustrate a situation or practical application of a principle, heuristic, or SE practice.

Example I.1

Mini-Case Study I.1

Mini-Case Studies provide a brief description of a real-world situation, event, or incident that illustrates a principle, heuristic, example, or key point relevant to a topical discussion.

Reserved Words

Reserved words have unique *contexts* that differentiate them from general usage. For these terms, the text uses SMALL CAPS. For example, there is a *contextual* difference in referring to your SYSTEM (small caps) … versus … generic systems, products, or services (regular font). Reserved words occur in three categories of usage:

System Levels of Abstraction

Your SYSTEM, PRODUCT, SUBSYSTEM, ASSEMBLY, SUBASSEMBLY, and PART Levels.

System Types

Types of systems such as a System of Interest (SOI) composed of one or more Mission Systems and one or more Enabling Systems.

Environments

Your OPERATING ENVIRONMENT consisting of a NATURAL ENVIRONMENT, INDUCED ENVIRONMENT, or PHYSICAL ENVIRONMENT.

A Word of Caution I.1

Cautions are informed awareness notifications concerning conditions that represent potential risks that require special consideration. Remember—You, your team, project, and Enterprise are wholly accountable for the decisions or lack of decisions you make and their consequences.

Warning I.1

Warnings are risk-based situations that demand special attention, awareness, and recognition of decisions or conditions related to safety as well as statutes, regulations, ethics, etc. established by international, national, state, and local governments and organizations that carry severe penalties for violation. Remember – You, your team, project, and Enterprise are wholly accountable for the decisions or lack of decisions you make and their consequences.

CHAPTER EXERCISES

Chapter Exercises are provided in two forms:

- **Level 1 Chapter Knowledge Exercises**—Represent *essential* knowledge you should have learned from the chapter.
- **Level 2 Knowledge Application Exercises**—Represent *upper undergraduate level* and *graduate-level* exercises that challenge the reader's ability to apply Chapter knowledge to real world systems, products, or services. Level 2 Exercises are located on the text's companion website located at: www.wiley.com/go/systemengineeringanalysis2e

APPENDICES

This text consists of three Appendices:

- **Appendix A—Acronyms and Abbreviations**—Provides an alphabetic listing of acronyms and abbreviations used in the text.
- **Appendix B—INCOSE Handbook Traceability**—Provides a traceability matrix that links to the International Council on Systems Engineering (INCOSE) *Systems Engineering Handbook* (SEHv4, 2015) to chapters within this text.
- **Appendix C—Systems Modeling Language (SysML™) Constructs**—Provides a brief overview of SysML™ constructs used in the text. SE employs the Object Management Group's (OMG) Systems Modeling Language™ (SysML™), an extension of the OMG's Unified Modeling Language (UML™), to model Enterprise and Engineered systems, products, and services. This text uses some of the SySML™ features to illustrate SE and Analysis concepts.

As its title conveys, this text is about *System Engineering Analysis, Design, and Development*, not SysML™; that is a separate text and course. However, to facilitate your understanding, Appendix C provides a brief overview of SysML™ constructs used in figures of this text. For more detailed information about SysML™, refer to the OMG's website.

- *Note:* UML™ and SysML™ are either registered trademarks or trademarks of Object Management Group (OMG), Inc., in the United States and/or other countries.

SUMMARY

Now that we have established *How to Use the Text*, let's begin with Chapter 1 SYSTEMS, ENGINEERING, AND SYSTEMS ENGINEERING.

1

SYSTEMS, ENGINEERING, AND SYSTEMS ENGINEERING

Principle 1.1

SE Alpha–Omega Principle

SE *begins* and *ends* with the Users of a system, product, or service.

Have you ever purchased a commercial hardware and/or software product; contracted for development of a system, product, or service; or used a website and discovered that it:

- May have complied with its specification requirements but was not what you wanted, needed, or expected?
- Was difficult to use, unforgiving in accepting User inputs and errors, and did not reflect your thought patterns of usage?
- Consisted of an overwhelming number of *non-essential* features that were so distracting it was difficult to navigate?
- Buried commonly used features under several layers of linkable structures requiring numerous mouse clicks to reach and invoke?
- Has software updates that are incompatible with standard operating systems. The System Developer's customer service response was to post a question in an online "community forum." Then, wait (potentially forever) for some other "community User" to offer a solution as to how they solved the System Developer's problem?

Then, in frustration, you and millions of other Users question whether the System Developer and its designers ever bothered to communicate with and listen to the Users or marketplace to understand and comprehend:

- The jobs or missions the User is expected to perform to deliver the system's outcomes to their customers
- How the User expects to deploy, operate, maintain, sustain, retire, or dispose of the systems, products, services, or by-products required to perform those jobs or missions

Welcome to Systems Engineering (SE)—or more appropriately the lack of SE. If you talk with Users such as the ones in the examples above, you will often hear comments such as:

- Company XYZ needs to do a better job "Engineering" their systems, products, or services!
- System ABC needs some "SE!"

From an SE perspective, what emerges from a distillation of User comments are questions such as: *What is SE*? Answering this question requires understanding (1) *what is a system* and (2) *what is Engineering*. Then, *what is the interrelationship between Engineering and SE*?

System Engineering Analysis, Design, and Development: Concepts, Principles, and Practices, Second Edition. Charles S. Wasson.

Companion Website: www.wiley.com/go/systemengineeringanalysis2e

Opinions vary significantly for definitions of these terms and their context of usage. Industry, government, academia, professional, and standards organizations have worked for years to reach consensus definitions of the terms. To achieve a consensus—global in some cases—the wording of the definitions becomes so diluted and abstract that it has limited utility to the User communities the organizations serve. In some cases, the abstractness distorts User perceptions of what the terms truly encompass. For example, the definition of a *system* is a classic example.

The problem is exacerbated by a general lack of true Systems Engineering & Development (SE&D) courses that focus on *problem-solving and solution development* methods and Engineering. Unfortunately, many of the so-called SE courses focus on: (1) System Acquisition & Management - how to manage the acquisition of systems and (2) equation-based courses – "Engineering the box," not the system. This results in a major deficiency in Engineering knowledge and skills required to actually transform a User's abstract, operational need into the Engineering of a physical system, product, or service that meets those needs. *Should there be any surprise as to why User frustrations with systems, products, or services highlighted above occur*?

Given this backdrop, Chapter 1 establishes the foundational definitions for understanding what it means to perform SE addressed in Chapters 2–34.

1.1 DEFINITIONS OF KEY TERMS

- **Capability**—An explicit, inherent feature *initiated* or *activated* by an external stimulus, cue, or excitation to perform an action (function) at a specified level of performance until terminated by external commands, timed completion, or resource depletion.
- **Engineering**—"[T]he profession in which knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize economically the materials and forces of nature for the benefit of mankind" (Prados, 2007, p. 108).
- **Entity**—A generic term used to refer to an operational, logical, behavioral, physical, or role-based object within a system. Physical entities, for example, include PERSONNEL; EQUIPMENT items such as SUBSYSTEMS, ASSEMBLIES, SUBASSEMBLIES, or PARTS comprised of HARDWARE and/or SOFTWARE; PROCEDURAL DATA such as User's guides and manuals; MISSION RESOURCES such as *consumables* (water, fuel, food, and so on) and *expendables* (filters, packaging, and so on); and SYSTEM RESPONSES—performance-based outcomes—such as products, by-products, or services or FACILITIES.
- **Environment**—A general, context-dependent term representing the NATURAL, HUMAN SYSTEMS, or INDUCED Environments that in which a SYSTEM or ENTITY of Interest must operate and survive.
- **Ilities**—Specialty Engineering disciplines such as Reliability, Maintainability, and Availability (RMA); Sustainability; Safety; Security; Logistics; and Disposal.
- **System**—An integrated set of interoperable elements or entities, each with specified and bounded capabilities, configured in various combinations that enable specific behaviors to emerge for Command and Control (C2) by Users to achieve performance-based mission outcomes in a prescribed operating environment with a probability of success.
- **System Engineering (SE)**—The multidisciplinary application of analytical, mathematical, and scientific principles to formulating, selecting, developing, and maturing a solution that has acceptable risk, satisfies User operational need(s), and minimizes development and life cycle costs while balancing Stakeholder interests.

1.2 APPROACH TO THIS CHAPTER

Our approach to this chapter focuses on defining SE. Since the term SE is comprised of *System* and *Engineering*, we begin with establishing definitions for both of these terms as a precursor for defining SE.

Most definitions of a *system* are often too abstract with limited utility to the User. This text defines a *system* in terms of its attributes and success criteria—what a system is, why it exists, its compositional structure, what it accomplishes, under what conditions, and User expectations for success. Although systems occur in a number of forms such as Enterprise, social, political, and equipment, we focus on Enterprise and Engineered Systems.

One of the challenges in discussing systems is the need to differentiate systems, products, or services. We address those differences and relationships and provide examples. When systems are developed, they may be (1) new innovations (*unprecedented* systems) based on new or emerging technologies or (2) improvement on existing systems or technologies (*precedented* systems). We address the contexts of *unprecedented* versus *precedented* systems.

Based on establishment of what a *system* is, we introduce a commonly accepted definition of *Engineering* and then derive the definition of SE used in this text. Since people often are confused by the usage of *System* versus *SE*, we delineate the context of usage for these terms.

An introduction to SE is incomplete without some form of background description of its history. Rather than repeating

a set of dates and facts that have been documented in other texts, a more important point is understanding what has driven the evolution of SE. To address this point, we introduce an excellent source of SE history for those who want more detailed information. We elaborate this topic in more detail in Chapter 2.

Finally, we close Chapter 1 with a discussion of a key attribute of Systems Engineers—Systems Thinking.

Before we begin, a brief word concerning individuals and teams crafting statements—definitions, specification requirements, and objectives—to achieve consensus agreement is as follows:

When people or organizations develop definitions, attempts to simultaneously create *content* and *grammar* usually produce a result that only has a degree of acceptability. People typically spend a disproportionate amount of time on *grammar* and spend very little time on substantive *content*. We see this in development of plans and specifications, for example. Grammar is important, since it is the root of any language and communications. However, grammar is simply a mechanism to convey: (1) *content* and (2) *context*. "Word-smithed" grammar has *little or no value if it lacks substantive content or context*.

You will be surprised how animated and energized people become during grammar "word-smithing" exercises. After protracted discussions, others simply walk away from the chaos. For highly diverse terms such as a *system*, a good definition may begin with simply a bulleted list of descriptors concerning what a term *is* or *is not*. If you or your team attempt to create a definition, perform one step at a time. Obtain consensus on the key elements of *substantive content*. Then, structure the statement in a logical sequence and translate the substantive content into a grammar statement.

Let's begin our discussion with *What Is a System*?

1.3 WHAT IS A SYSTEM?

Merriam-Webster (2014) states that the term *system* originates from "late Latin *systemat-, systema,* from Greek *systēmat-, systēma,* from *synistanai* to combine, from *syn-* + *histanai* to cause to stand." Its first known use was in 1603.

There are as many definitions of a *system* as there are opinions. Industry, government, academia, and professional organizations over many decades have worked on defining what a system is in their context. If you analyze many of these definitions, most of the definitions have become so diluted due to "wordsmithing" to achieve a consensus of the user community, the remaining substantive content is almost nil. That is reality, not a critique! It is a very challenging task given a diverse set of views and levels of experience weighted toward those who are willing to participate.

The *definition* that emerges from these exercises accomplishes a different objective—obtain a consensus definition of what a User community believes a system is versus *what a system actually is* and *what its Users expect it to accomplish*. Additionally, the definitions are often *abstract* and *intermix* different types of information and levels of detail that may impress uninformed customers but are *technically incorrect*. Consider the following example.

Example 1.1 **Making Statements That Are Partially True but Technically Incorrect**

Definitions over the years loosely infer that a system is a collection of people, hardware, software, procedures, and facilities—for example, entities. Systems do encompass those entities. However, general definitions such as this crafted to achieve a consensus do not express what a system is, why it exists, who it serves, its operating conditions, required outcomes and performance, criteria for success, etc.

The intent here is not to critique established definitions. If they work for you and your organization, fine. However, let's establish a definition that expresses *what a system actually is*. This is a crucial step in establishing a foundation for understanding Chapters 2–34. Therefore, we establish the following definition of a *system*:

- **System**—An integrated set of interoperable elements or entities, each with specified and bounded capabilities, configured in various combinations that enable specific behaviors to emerge for Command & Control, C2 by Users to achieve performance-based mission outcomes in a prescribed operating environment with a probability of success.

The "system" definition above captures a number of key discussion points that define a *system*. A *system* is composed of two or more integrated entities that enable accomplishment of a higher-level purpose—emergence—that cannot be achieved by each of the entities on an individual basis. However, a *purpose* without some *measure of success*—an outcome and level of performance—has limited value to the User or its stakeholders. With the establishment of this theme as a backdrop, let's explore each of the definition's phrases individually to better understand what they encompass and communicate.

1.3.1 System Definition: "An Integrated Set of Interoperable Elements or Entities …"

Systems occur in a variety of forms that include Enterprise and Engineered Systems—equipment hardware and software, social systems, political systems, and environmental systems. This text focuses on two types of systems: Enterprise and Engineered. Let's define each of these terms:

- **Enterprise Systems**—Formal and informal industry, academic, governmental, professional, and nonprofit organizations such as corporations, divisions, functional organizations – departments such as accounting and engineering; projects, and others.
- **Engineered Systems**—Physical systems or products developed for internal use, commercial sale to the marketplace, or for contract development that require one or more Engineering disciplines and skillsets to apply mathematical and scientific principles to design and develop solutions

Since Engineered Systems are an integral part of our home and work lives, let's begin with those.

1.3.1.1 Engineered Systems Engineered Systems, in general, consist of equipment comprised of hardware and/or software, fluids (lubricants, coolants, etc.), gases, and other entities:

- Hardware entities, for example, include hierarchical levels such as PRODUCTS comprised of → SUBSYSTEMS comprised of → ASSEMBLIES comprised of → SUBASSEMBLIES comprised of → PARTS (Chapter 8).
- Software entities include hierarchical terms such as Computer Software Configuration Items (CSCIs) comprised of → Computer Software Components (CSCs) comprised of → Computer Software Units (CSUs) (Chapter 16).

1.3.1.2 Enterprise Systems Enterprise Systems are HIGHER-ORDER SYSTEMS (Chapter 9)—government, corporations, and small businesses—that:

- Employ Engineered Systems—manufacturing systems, vehicles, computers, buildings, and roads—to:
  - Produce and distribute consumer products and contract deliverable systems
  - Provide services such as retail sales; land, sea, air, or space transportation; utilities such as electrical power, natural gas, telephone, water, sanitation, and refuse; and medical, healthcare, financial, educational, and other services

As we shall see in Chapters 8 and 9, analytically:

- **Enterprise Systems** consist of hierarchical levels of abstraction (divisions, departments, branches, etc.) comprised of System Elements (Figure 8.13)—personnel, equipment (hardware and software), procedures, resources, behavioral outcomes, and facilities—that are integrated to perform Enterprise missions.
- **Engineered Systems** consist of hierarchical levels of abstraction (Figure 8.4)—SEGMENTS, PRODUCTS, SUBSYSTEMS, ASSEMBLIES, SUBASSEMBLIES, and PARTS.

Observe the terms Enterprise System *elements* and Engineered System *entities*. Application of these terms will become more important in follow-on chapters. The terms imply that these are discrete objects, which they are. However, remember the earlier point in the *system* definition … *comprised two or more entities in combination that enable accomplishment of a higher-level purpose that cannot be achieved by each of the entities on an individual basis*. The operative term *combination* means that the system elements or entities must be *integrated*—connected.

Integrating elements and entities is a *necessary* condition to leverage or exploit the combination of capabilities. However, suppose the entities are *incompatible*? Hypothetically, you could fill—*integrate*—diesel fuel or kerosene into a gasoline-based automobile's fuel tank. But that does not mean that the engine will perform. Due to the *incompatibility*, fuel station pump nozzles and vehicle fuel tank ports are purposely designed to preclude inadvertent mixing.

Being *compatible* may be a *necessary condition* for some system entities such as rigid mechanical interfaces or System Elements such as procedural consistency between equipment—hardware and software—and User or Operator Manuals. Being compatible, however, does not mean that they can communicate in a language that is intelligible and comprehensible. That leads us to the need for some systems to be … *interoperable*. Consider electronic financial transactions in which debit or credit cards, card readers, and computers must be not only *compatible* in terms of electronic protocols but also formatting in an intelligible language that enables each to understand and interpret what is being communicated—*interoperability*. For those types of systems, compatibility and interoperability are both *necessary* and *sufficient* conditions for success.

In summary, the foundation of a system begins with *an integrated set of interoperable* (*Enterprise System*) *elements* (personnel, equipment, procedures, resources, behavioral outcomes, and facilities) *or* (*Engineered System*) *entities* (PRODUCTS, SUBSYSTEMS, ASSEMBLIES, SUBASSEMBLIES, etc.). In either case, we refer to the *system* being analyzed or investigated as a System of Interest (SOI).

1.3.2 System Definition: "… Each with Specified and Bounded Capabilities …"

If a system requires *System Elements* or *entities* that are *compatible* and *interoperable*, how do we ensure that they are? This requires multi-discipline Engineering - SE - to *specify* and *bound* these operational, behavioral, and physical capabilities—*attributes*, *properties*, and *characteristics*

(Chapter 3)—via specification requirements as a starting point.

Observe usage of the term *capability*. Traditionally, the term *function*—as in *form, fit, and function*—has been used by Engineers to characterize *what* a system is expected to accomplish. However, there is a gross disparity between the true definition of a *function* and what the User expects the system to *accomplish*. Here's the difference.

A Word of Caution 1.1

Form, Fit, and Function: An Implied Catch Phrase for Failure!

The phrase *form, fit, and function*, which is deeply ingrained as a paradigm in everyday Engineering, is a well-intended concept that is subject to misinterpretation. By virtue of the sequence of terms, people sometimes interpret the phrase as the sequence of steps required to perform Engineering:

- Step 1—Design the physical system—*form*.
- Step 2—Figure out how to get the pieces to *fit* together.
- Step 3—Decide what the system must do—*function*.

Evidence of this paradigm is illustrated in Figure 2.3. PURGE the *form, fit, and function* paradigm from your mind-set! The phrase simply identifies three key attributes of a system, product, or service that must be considered, nothing more!

Simply stated, a *function* represents an *action* to be performed such as Perform Navigation. A function is a *unitless* term that does not express a level of performance to be achieved. In general, it is easy to "identify functions" via *functional analysis*—sounds impressive to uninformed customers. The challenge is specifying and bounding the level of performance a function must achieve. Although *functions* and *functional analysis* are certainly valid within their own context, from a current SE perspective, the concept of functional analysis as a primary driving SE activity is outdated. The reality is functional analysis is still valid but only as a supporting SE activity. So, *how do we solve this dilemma*?

The solution resides in the term *capability*. A capability is defined as follows:

- **Capability**—An explicit, inherent feature *activated* by an external stimulus, cue, or excitation to perform an action (function) at a specified level of performance until terminated by external commands, timed completion, or resource depletion.

From an Engineering perspective, think of a capability using a vector analogy. A *capability* (vector) is characterized by a *function* (direction) and a *level of performance* (magnitude).

In summary, this text replaces *functions* and *functional analysis* with more appropriate terms *capability* and *capability analysis*.

1.3.3 System Definition: "… Configured in Various Combinations That Enable Specific Behaviors to Emerge …"

Configuration of various combinations of System Element and entity capabilities to produce system responses for a given set of system inputs—stimuli, cues, and excitations—represents a system architecture. However, system responses vary based on the User's operational needs at different times during a mission. Consider the following example of an aircraft.

Example 1.2

Aircraft Configurations and Behaviors

For an aircraft to perform a mission, it must be capable of loading passengers and cargo; taxiing; performing phases of flight (taking off, climbing, cruising, holding, and landing); and unloading passengers to accommodate various Use Cases and Scenarios (Chapter 5). Each of these activities requires unique sets of capabilities—*architectural configurations*—provided by the (Enterprise System) Elements and (Engineered System) entities to accomplish the performance-based mission outcomes and objectives.

Observe the phrase "… *enable specific behaviors to emerge* …." Emergent behavior is a key attribute of systems that enables them to accomplish a higher-level purpose that cannot be achieved by the individual elements or entities. In general, *emergent behavior* means that the system exhibits behaviors that are not readily apparent from analysis of its individual elements or entities. Consider the following example.

Example 1.3

Emergent Behavior

As humans, we have the capability to walk, run, etc. However, there is a need to travel more efficiently in a shorter period of time. To achieve this higher-level purpose, humans created bicycles expressly for enabling a human to travel great distances more efficiently. But *how would you know that (1) a set of physical components could be assembled into a Bicycle System as a prime mover capable of rolling and steering (emergent behaviors) and (2) a human could simultaneously C2—balance, pedal, and steer (emergent behaviors)—the Bicycle System*? If we analyzed the human or the bicycle, do they exhibit or reveal the capabilities—emergent

behaviors—that enable them as an integrated system to accomplish the higher-level mission (travel more efficiently in a shorter period of time)? Similar emergent behavior examples include jet engines or aircraft that can counter the effects of gravity and fly.

Chapter 3 provides additional discussion on *emergent* behavior.

1.3.4 System Definition: "… For Command & Control (C2) by Users to Achieve Performance-Based Mission Outcomes …"

Observe that the thrust of this phrase is an expectation to accomplish something—an outcome with a level of performance. More specifically, accomplish performance-based mission outcomes. Those who work in non-Aerospace and Defense (A&D) sectors often associate the term *mission* as unique to military systems. That is factually incorrect! Enterprises, projects, and individuals—medical doctors, educators, and so on—all perform missions.

A *mission* represents an Enterprise or Engineered System outcome and supporting performance-based objectives to be achieved. Consider the following mission examples.

Example 1.4

- **Medical Mission**—Improve the health conditions of …, find a cure for …, administer intravenous drugs to a patient in accordance with a doctor's orders, and so on.
- **Transportation Mission**—Safely transport passengers via air, train, or bus from one city to another, deliver parcel packages, and so on.
- **Services Mission**—Provide cable and Internet services to customer's businesses or homes, respond to fire and medical emergencies, and so on.
- **Educational Mission**—Offer an accredited (EE, ME, SwE, ChemE, IE, etc.) Engineering degree program.

The concept of missions, however, is not limited to Enterprise Systems. Interestingly, Enterprises for decades have developed *vision* and *mission statements*. Yet, often fail to recognize that the Engineered Systems they produce for the marketplace are designed to perform *missions* to support their customers'—Users and End Users—Enterprise System missions. When a system, product, or service ceases to perform a *mission*, it has no value to its Users in terms of outcomes to be accomplished—End User satisfaction and shareholder value and revenue generation—and will likely be retired or disposed.

Chapters 4 and 5 address *missions* and *mission analysis* in more detail.

1.3.5 System Definition: "… In a Prescribed Operating Environment …"

Humans and equipment often have performance limitations in terms of what types of operating environments they can operate to accomplish a mission. This requires knowledge and understanding of (1) *where* missions will be conducted—land, sea, air, space, or combinations of these—and (2) under *what* types of conditions. Once the external operating environment is understood, it must be *specified* and *bounded* in terms of performance requirements such as temperature, humidity, shock and vibration, and salt/fog.

1.3.6 System Definition: "… With a Probability of Success"

Finally, to support a User's missions, the system must be available *on demand* to reliably conduct missions and deliver performance-based outcomes with a *probability of success*. If a system, product, or service is unable to fulfill the minimum requirements for mission success prior to its mission, then mission failure may be the consequence and other alternative systems must be considered.

1.3.7 Other Definitions of a System

As a final note, national and international standards and professional organizations as well as different authors present various definitions of a *system*. If you analyze these, you will find a diversity of viewpoints, all influenced and tempered by their personal knowledge and experiences. Moreover, achievement of a "one size fits all" *convergence* and *consensus* by standards organizations often results in weak wording that many believe it to be *insufficient* and *inadequate*. For additional definitions of a system, refer to the following standards:

- INCOSE (2015). *Systems Engineering Handbook: A Guide for System Life Cycle Process and Activities* (4th ed.).
- IEEE Std 1220™-2005 (2005)—Institute of Electrical and Electronic Engineers (IEEE)
- ISO/IEC 15288:2015 (2015)—International Organization of Standards (ISO)
- DAU (2011)—Defense Acquisition University (DAU)
- NASA SP 2007-6105 (2007)—US National Aeronautics and Space Administration (NASA)
- FAA SEM (2006)—US Federal Aviation Administration (FAA)

You are encouraged to broaden your knowledge and explore definitions by these organizations. Depending on your personal viewpoints and needs, the definition stated in this text should provide a more definitive characterization.

1.4 LEARNING TO RECOGNIZE TYPES OF SYSTEMS

Systems occur in a number of forms. High-level examples include:

Example 1.5

System Examples

- Economic systems
- Communications systems
- Educational systems
- Entertainment systems
- Financial systems
- Government systems
- Environmental systems
- Legislative systems
- Medical systems
- Judicial systems
- Corporate systems
- Revenue systems
- Insurance systems
- Taxation systems
- Religious systems
- Licensing systems
- Social systems
- Military systems
- Psychological systems
- Welfare systems
- Cultural systems
- Public safety systems
- Food distribution systems
- Parks and recreation systems
- Transportation systems
- Environmental systems

Observe that many of the example systems are subsets of others and may be interconnected at various levels to form Systems of Systems (SoS). If we analyze these systems or SoS, we find that they produce combinations of performance-based outcomes such as products, behaviors, by-products, or services. As systems, they exemplify the definition of a system introduced earlier.

1.4.1 Precedented Versus Unprecedented Systems

Enterprise and Engineered Systems, in general, are either *precedented* or *unprecedented*:

- **Precedented Systems**—Systems for which earlier versions exist and provide the basis for upgrades such as technology and performance improvements
- **Unprecedented Systems**—Systems that represent innovations and radical new designs that depart from traditional designs, for example, the introduction of hybrid vehicles

To illustrate these terms, consider the following automobile example.

Example 1.6

Automobile Application: Precedented and Unprecedented Systems

Gasoline-powered automobiles are an example of *precedented* systems. Over many decades, they consisted of a frame, body, doors, engine, inflatable ties, steering, and so on.

Then, as newer automotive technologies evolved over the past 100+ years, manufacturers added new features and capabilities that were *unprecedented*. Examples included heaters, air-conditioning, power steering, electronic ignition, electrical doors and windows, compression bumpers, air bags, entertainment systems, satellite radio and phone data communications, and hybrid engines.

1.4.2 Products as Systems

Our discussions to this point have focused on the generic term *system*. *Where do consumer products and services fit into the context of a system*? A *product* consisting of two or more entities integrated together to provide a performance-based capability, by definition, is an instance of a system. Observe that a product provides a "capability" but does not address outcome. Why? Unless preprogrammed to run autonomously, products as inanimate objects are dependent on humans to apply them to a specific situation and subsequently achieve an outcome. For example:

- A pencil is a *product*—an instance of a system—comprised of a lead, a wooden or composite holder, an attached eraser that provides a capability but no outcome on its own.
- A computer monitor is a *product*—an instance of a system—comprised of an chassis, touch screen display, motherboard, processor, sound board, and interface ports—power, video, audio, and communication ports such as USB:
  - The computer processor transmits commands and data to the monitor to display formatted information to its User.
  - In response to the display data, the User has the option to provide a stimulus via the touch screen display to select an action to be performed—command

and audio volume—that results in an outcome as verification feedback of acceptance and subsequent completion of the action.

1.4.3 Tool Context

Some systems or products are employed as tools by HIGHER ORDER SYSTEMS such as an Enterprise. Let's define what we mean by a tool:

- **Tool**—A physical product or software application employed by a User to enable them to leverage their own capabilities to more *efficiently* and *effectively* perform a task and accomplish a performance-based outcome that exceeds their own strengths—capabilities—and limitations.

Consider the following example:

Example 1.7

Software Application as a Tool

A statistical software application, as a support tool, enables a statistician to efficiently sort and analyze large amounts of data and variances in a short period of time.

Now, is a wooden log, as an entity, a system? No, however, the log is considered a tool that has the capability to deliver a performance-based outcome when applied by a human operator under specific conditions.

1.4.4 Service Systems

The preceding discussion illustrates that the outcomes produced by a system may be (1) physical such as products and by-products or (2) behavioral responses—services. *What is a service*?

- *A service* is an activity provided and performed by an Organizational or Engineered System to produce an outcome that benefits its User.

Consider the following example.

Example 1.8

Consumer Product Services

- Weight scales are a consumer *product*—an instance of a system with multiple parts integrated together as a system—that respond to a User stimulus to provide weight measurement information in pounds or kilograms as a *service* response. Observe that the service delivers an outcome–displayed weight, however, no physical products are-produced.
- A digital alarm clock as a consumer product provides a service by displaying current time and an alarm when activated and set for a specific time.

Now that we have established what a system is brings us to the next question: *what is SE*?

1.5 WHAT IS SE?

Definition of SE requires an understanding of its two constituent terms: *system* and *Engineering*. Since the preceding discussions defined a *system*, the next step is to define *Engineering* to enable us to define SE.

1.5.1 Definition of Engineering

Engineering students often graduate without being introduced to the root term that provides the basis for their formal education. To illustrate this point, consider a conversational example.

Example 1.9

The Engineer's Dilemma

- *What is your profession*?
- I'm an Engineer—SE, ME, EE, SwE, ChemE, Test, and so on.
- *What do Engineers do?*
- We Engineer things.
- *So, what is Engineering?*
- (Silence) I don't know. Our instructors and courses didn't cover that topic!
- *So, even though you have received an Engineering degree, you are unaware of how "Engineering" is defined by your profession?*

The term *engineering* originates from the Latin word *ingenerare*, which means "to create" (Britannica, 2014). Its first known use is traceable to 1720 (Merriam-Webster, 2014). Let's introduce a couple of example definitions of Engineering:

- **Engineering**—"The profession in which knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize economically the materials and forces of nature for the benefit of mankind" (Prados, 2007, p. 108).
- **Engineering**—"The application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to people" (Merriam-Webster, 2014).

The Prados (2007) definition of Engineering above originates from earlier definitions by the Accreditation Board for Engineering and Technology (ABET), which accredits Engineering programs in the United States. ABET evolved the definition from its founding in 1932 until 1964. It continued to appear in ABET publications from 1964 through 2002 (Cryer, 2014).

Two key points emerge from the introduction of these definitions:

- First, you need to understand the definition and scope of your profession.
- Secondly, on inspection, these definitions might appear to be a mundane, academic discussion. The reality is that these definitions characterize the traditional view of Engineering. That is, Engineering the "Box (Equipment Hardware & Software)" Paradigm or "Box" Engineering that contributes to systems, products, or services failures attributed to "human error" (Chapter 24) or are considered by the User to be failures due to a lack of *usability*. This is a critical staging point in differentiating the scope of the SE – "Engineering the (User-EQUIPMENT) System, which includes the (Equipment) Box," versus traditional "Box" Engineering. In that context, SE exemplifies the cliché "Learning to think outside the (Engineering) box" to develop systems, products, and services that Users actually need, can use, and lead to a reduction in human errors that contribute to system failures. As a result, this impacts Enterprise System reputation, profitability, customer satisfaction, marketplace perceptions, and subsequently shareholder value.

Now that we have established definitions for a *system* and *Engineering*, let's proceed with defining SE.

1.5.2 Definition of System Engineering (SE)

Content–Grammar Principle

Principle 1.2 *Substantive content* must always precede *grammar* to achieve successful results. Avoid negotiating content for the sake of achieving grammatical elegance and eloquence unless it precludes misinterpretation.

There are a number of ways to define SE, each dependent on an individual's, project's, or Enterprise's business domain, perspectives, and experiences. SE means different things to different people. You will discover that even your own views of SE will evolve over time. So, if you have a diversity of perspectives and definitions, *what should you do*? What is important is that you, project teams, or your enterprise should:

- Establish a consensus definition for SE.
- Document or reference the SE definition in enterprise command media to serve as a guide for all.

For those who prefer a brief, high-level definition that encompasses the key holistic aspects of SE – "Engineering the System" - consider the following definition:

- **System Engineering**—The multi-disciplined application of analytical, mathematical, and scientific principles for formulating, selecting, developing, and maturing an *optimal* solution from a set of *viable* candidates that has *acceptable* risk, *satisfies* User operational need(s), and *minimizes* development and life cycle costs while *balancing* Stakeholder interests

To better understand the key elements of the SE definition, let's address each of the phrases separately.

1.5.2.1 SE Definition: "The Multi-disciplined Application of …"

System, product, and service development typically require multiple Engineering disciplines of expertise to translate a User's *operational need* and *vision* into a deliverable system, product, or service that produces performance-based outcomes required by the User. Accomplishment of that translation process requires *multi-disciplined* integration of hardware, software, test, materials, human factors, reliability, maintainability, and logistics Engineering.

1.5.2.2 SE Definition: "… Analytical, Mathematical, and Scientific Principles …"

Constructive Assessment

Author's Note 1.1 The following discussion is intended to be a constructive assessment concerning the state of traditional Engineering and its views of SE today versus what twenty-first-century Engineering and SE demand. The time has come to shift the educational paradigm!

Although not explicitly stated, the ABET (Prados, 2007, p. 108) definition of Engineering infers that the work scope of Engineering focuses on the innovation and development of devices, mechanisms, and structures to produce one or more performance-based outcomes for the benefit of mankind. In fact, we analytically represent the boundaries a system, product, or service as a "box" such as Figures 3.1 and 3.2. Psychologically, the simple act of establishing these boundaries automatically fosters an "Engineering within the walls of the box and connections between the boxes" paradigm. As a result, discipline-based Engineering courses and instruction focus on: