Design for Electrical and Computer Engineers

Theory, Concepts, and Practice

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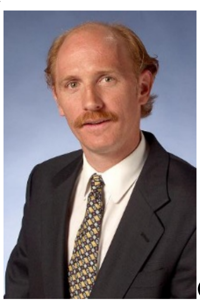
0.1 About the Authors

Ralph Ford obtained his Ph.D. and M.S. degrees in Electrical Engineering from the University of Arizona in 1994 and 1989 respectively. He obtained his B.S. in Electrical Engineering from Clarkson University in 1987. He worked for the IBM Microelectronics Division in East Fishkill, NY from 1989-1991, where he developed machine vision systems to inspect electronic packaging modules for mainframe computers. Ralph also has experience working for IBM Data Systems and the Brookhaven National Laboratory. He joined the faculty at Penn State Erie, The Behrend College in 1994. Ralph has experience teaching electronics and software design, as well as teaching the capstone design course sequence in the electrical, computer, and software engineering programs. His research interests are in engineering design, image processing, machine vision, and signal processing. Ralph is currently Director of the School of Engineering at Penn State Behrend. He also serves as a program evaluator for ABET. He was awarded a Fulbright Scholarship to study at the Brno University of Technology in the Czech Republic in 2005.



Chris Coulston obtained his Ph.D. in Computer Science and Engineering from the Pennsylvania State University in 1999. He obtained his M.S. and B.S in Computer Engineering from the Pennsylvania State University in 1994 and 1992 respectively. Chris has industry experience working for IBM in Manassas, VA and Accu-Weather in State College, PA. He joined the faculty at Penn State Erie, The Behrend College in 1999. He has experience teaching design-oriented courses in digital systems, embedded systems, computer architecture, and database management systems.

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Contents

0.2 Preface

This book is written for undergraduate students and teachers engaged in electrical and computer engineering (ECE) design projects, primarily in the senior year. The objective of the text is to provide a treatment of the design process in ECE with a sound academic basis that is integrated with practical application. This combination is necessary in design projects because students are expected to apply their theoretical knowledge to bring useful systems to reality. This topical integration is reflected in the subtitle of the book: Theory, Concepts, and Practice. Fundamental theories are developed whenever possible, such as in the chapters on functional design decomposition, system behavior, and design for reliability. Many aspects of the design process are based upon time-tested concepts that represent the generalization of successful practices and experience. These concepts are embodied in processes presented in the book, for example, in the chapters on needs identification and requirements development. Regardless of the topic, the goal is to apply the material to practical problems and design projects. Overall, we believe that this text is unique in providing a comprehensive design treatment for ECE, something that is sorely missing in the field. We hope that it will fill an important need as capstone design projects continue to grow in importance in engineering education.

We have found that there are three important pieces to completing a successful design project. The first is an understanding of the design process, the second is an understanding of how to apply technical design tools, and the third is successful application of professional skills. Design teams that effectively synthesize all three tend to be far more successful than those that don't. The book is organized into three parts that support each of these areas.

The first part of the book, the *Design Process*, embodies the steps required to take an idea from concept to successful design. At first, many students consider the design process to be obvious. Yet it is clear that failure to understand and follow a structured design process often leads to problems in development, if not outright failure. The design process is a theme that is woven throughout the text; however, its main emphasis is placed in the first four chapters. Chapter 1 is an introduction to design processes in different ECE application domains. Chapter 2 provides guidance on how to select projects and assess the needs of the customer or user. Depending upon how the design experience is structured, both students and faculty may be faced with the task of selecting the project concept. Further, one of the important issues in the engineering design is to understand that systems are developed for use by an end-user, and if not designed to properly meet that need, they will likely fail. Chapter 3 explains how to develop the Requirements Specification along with methods for developing and documenting the requirements. Practical examples are provided to illustrate these methods and techniques. Chapter 4 presents concept generation and evaluation. A hallmark of design is that there are many potential solutions to the problem. Designers need to creatively explore the space of possible solutions and apply judgment to select the best one from the competing alternatives.

The second part of the book, *Design Tools*, presents important technical tools that ECE designers often draw upon. Chapter 5 emphasizes system engineering concepts including the well known functional decomposition design technique and applications in a number of ECE problem domains. Chapter 6 provides methods for describing system behavior, such as flowcharts, state diagrams, data flow diagrams and a brief overview of the Unified Modeling Language (UML). Chapter 7 covers important issues in testing and provides different viewpoints on testing throughout the development cycle. Chapter 8 addresses reliability theory in design, and reliability at both the component and system level is considered.

The third part of the book focuses on *Professional Skills*. Designing, building, and testing a system is a process that challenges the best teams, and requires good communication and project management skills. Chapter 9 provides guidance for effective teamwork. It provides an overview of pertinent research on teaming and distills it into a set of heuristics. Chapter 10 presents traditional elements of project planning, such as the work breakdown structure, network diagrams, and critical path estimation. It also addresses how to estimate manpower needs for a design project. Chapter 11 addresses ethical considerations in both system design and professional practice. Case studies for ECE scenarios are examined and analyzed using the IEEE (Institute of Electrical and Electronics Engineers) Code of Ethics as a basis. The book concludes with Chapter 12, which contains guidance for students preparing for oral presentations, often a part of capstone design projects.

Features of the Book

This book aims to guide students and faculty through the steps necessary for the successful execution of design projects. Some of the features are listed below.

- Each chapter provides a brief motivation for the material in the chapter followed by specific learning objectives.

- There are many examples throughout the book that demonstrate the application of the material.

- Each end-of-chapter problem has a different intention. Review problems demonstrate comprehension of the material in the chapter. Application problems require the solution of problems based upon the material learned in the chapter. Design problems are directly applicable to design projects and are usually tied in with the Project Application section.

- Nearly all chapters contain a Project Application section that describes how to apply the material to a design project.

- Some chapters contain a Guidance section that represents the author's advice on application of the material to a design project.

- Checklists are provided for helping students assess their work.

- There are many terms used in design whose meaning needs to be understood. The text contains a glossary with definitions of design terminology. The terms defined in the glossary (Appendix A) are indicated by ***italicized-bold*** highlighting in the text.

- All chapters conclude with a Summary and Further Reading section. The aim of the Further Reading portion is to provide pointers for those who want to delve deeper into the material presented.

- The book is structured to help programs demonstrate that they are meeting the ABET (accreditation board for engineering programs) accreditation criteria. It provides examples of how to address constraints and standards that must be considered in design projects. Furthermore, many of the professional skills topics, such as teamwork, ethics, and oral presentation ability, are directly related to the ABET Educational Outcomes. The requirements development methods presented in Chapter 3 are valuable tools for helping students perform on cross-functional teams where they must communicate with non-engineers.

- An instructor's manual is available that contains not only solutions, but guidance from the authors on teaching the material and managing student design teams. It is particularly important to provide advice to instructors since teaching design has unique challenges that are different than teaching engineering science oriented courses that most faculty are familiar with.

- PowerPoint™ presentations are available for instructors through McGraw-Hill
- There are a number of complete case study student projects available in electronic form for download by both students and instructors and available at. These projects have been developed using the processes provided in this book.

How to Use this Book

There are several common models for teaching capstone design, and this book has the flexibility to serve different needs. Particularly, chapters from the Professional Skills section can be inserted as appropriate throughout the course. Recommended usage of the book for three different models of teaching a capstone design course is presented.

- **Model I.** This is a two-semester course sequence. In the first semester, students learn about design principles and start their capstone projects. This is the model that we follow. In the first semester the material in the book is covered in its entirety. The order of coverage is typically Chapters 1–3, 9, 4–6, 10–11, and 7–8. Chapter 9 (Teams and Teamwork) is covered immediately after the projects are identified and the teams are formed. Chapters 10 (Project Management) and 11 (Ethical and Legal Issues) are covered after the system design techniques in Chapters 5 and 6 are presented. Students are in a good position to create a project plan and address ethical issues in their designs after learning the more technical aspects of design. Chapter 12 (Oral Presentations) is assigned to students to read before their first oral presentation to the faculty. The course concludes with principles of testing and system reliability (Chapter 7 and 8). We assign a good number of end-of-chapter problems and have quizzes throughout the semester. By the end of the first semester, design teams are expected to have completed development of the requirements, the high-level or architectural design, and developed a project plan. In the second semester, student teams implement and test their designs under the guidance of a faculty advisor.
- **Model II**. This two-semester course sequence is similar to Model I with the difference being that the first semester is a lower credit course (often one credit) taught in a seminar format. In this model chapters can be selected to support the projects. Some of the core chapters for consideration are Chapters 1–5, which take the student from project

selection to functional design, and Chapters 9–11 on teamwork, project management, and ethical issues. Other chapters could be covered at the instructor's discretion. The use of end-of-chapter problems would be limited, but the project application sections and example problems in the text would be useful in guiding students through their projects.

- **Model III**. This is a one-semester design sequence. Here, the book would be used to guide students through the design process. Chapters for consideration are 1–5 and 9–10, which provide the basics of design, teamwork, and project management. The project application sections and problems could be used as guidance for the project teams.

Acknowledgements

Undertaking this work has been a challenging experience and could not have been done without the support of many others. First, we thank our families for their support and patience. They have endured many hours and late evenings that we spent researching and writing. Melanie Ford is to be thanked for her diligent proofreading efforts. Bob Simoneau, the former Director of the Penn State Behrend School of Engineering, has been a great supporter of the book and has also lent his time in reading and providing comments. Our school has a strong design culture, and this book would not have happened without that emphasis; our faculty colleagues need to be recognized for developing that culture. Jana Goodrich and Rob Weissbach are two faculty members with whom we have collaborated on other courses and projects. They have influenced our thinking in this book, particularly in regard to project selection, requirements development, cost estimation, and teamwork. We must also recognize the great collaborative working environment that exists at Penn State Behrend, which has allowed this work to flourish. Our students have been patient in allowing us to experiment with different material in the class and on the projects. Examples of their work are included in the book and are greatly appreciated. John Wallberg contributed the disk drive diagnostics case study in Chapter 11 that we have found very useful for in-class discussions. John developed this while he was a student at MIT. Thanks to Anne Maloney for her copyediting of the manuscript. The following individuals at McGraw-Hill have been very supportive and we thank them for their efforts to make this book a reality – Carlise Stembridge, Julie Kehrwald, Darlene Schueller, Craig Marty, Kris Tibbetts, and Mike Hackett.

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We hope that you find this book valuable, and that it motivates you to create great designs. We welcome your comments and input. Please feel free to email us.

Ralph M. Ford,

Chris S. Coulston,

Chapter 1

The Engineering Design Process

1.1 The Engineering Design Process

> ***en-gi-neer (n)*** *1. One versed in the design, construction, and use of machines. 2. One who employs the innovative and methodical application of scientific knowledge and technology to produce a device, system, or process, which is intended to satisfy human needs. —American College Dictionary*

Take a moment to read and analyze the key elements of the two definitions presented above. If you are an engineering student or practicing engineer, do you think that this definition applies to you? The first definition uses the terms *design* and *construction*. People like to think of themselves as designers. Why is that so? The answer may be in the combination of the term *construction,* and from the second definition, the idea of *innovation.* Applying innovation and creativity to produce something new is a wonderfully rewarding process. The great thing about being an engineer is that it allows you to be a creative designer. That is generally not the way the profession is viewed. What is the difference between engineering design and other types of design that are associated with creativity such as interior design, fashion design, or webpage design? The answer is supplied in the second definition which states *"...methodical application of scientific knowledge and technology..."* As an engineering student, you have studied a great deal of math, science, and fundamental technology, but probably have had limited exposure to creative and innovative design.

The definition also contains the somewhat contradictory terms *innovative* and *methodical*. If there is an established and methodical way of employing a scientific principle or process, it does not seem to allow much room for creativity and innovation. The truth is that the two concepts are in competition with each other, but a good engineer realizes this and utilizes both effectively. The definition also indicates that engineers design to satisfy human needs, an important, yet often overlooked point. That means that when designing systems, it is necessary to determine the user's needs and the ethical application of the technology.

This book aims to help electrical and computer engineers become effective designers, to better understand professional practices, and to provide guidance for executing design projects. This chapter presents the processes by which designs are realized, the characteristics of successful engineers, and an overview of the book.

Learning Objectives

By the end of this chapter, the reader should:

- Understand what is meant by engineering design.
- Understand the phases of the engineering design process.
- Be familiar with the attributes of successful engineers.
- Understand the objectives of this book.

1.2 The Engineering Design Process

ABET (formerly known as Accreditation Board of Engineering and Technology) provides the following definition of engineering design [ABE03].

> Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.

The definition indicates that, in engineering design, different phases of the process have to be re-visited and the deliverables for each phase updated as necessary. Realistic problems are complex with many potential solutions; the goal is not to find just any solution, but the best one given the constraints and available resources. This requires the application of sound judgment, decision-making skills, and patience in constantly evaluating progress towards a solution. The definition identifies some common elements of the design process, such as establishment of criteria, synthesis, construction, and testing.

Design processes embody the steps required to take an idea from concept to realization of the final system, and are problem-solving methodologies that aim to develop a system that best meets the customer's need within given constraints. This is not all that different from some everyday processes, such as preparing dinner. Say you are hungry and need to eat dinner before you can go to see a movie that starts in one hour. The constraints are time, money, food, your tastes, and nutritional value if you are health-conscious. You brainstorm and come up with the options of making dinner at home, going to a restaurant, or buying something to eat at the theater. Based on these options, you then select the solution based on your evaluation of the best one. This is similar in philosophy to the stages of design processes where you have a problem to solve, constraints, and a number of potential solutions to select from.

A related term is known as the *product realization process*. The product realization process is broader in scope, including aspects such as entrepreneurship, market research, financial planning, product pricing, and market strategy. Many technologies have their own particular design processes that have evolved over time and have been found by practitioners in the field to be valuable. For example, different methodologies are applied in the design of integrated circuits (VLSI), embedded systems, and software systems, yet they all have some degree of commonality, such as requirements analysis, technical design, and system test. Design processes continue to evolve. One field in which this is particularly true is in software design due to the constantly changing nature of software and the special challenges that large software projects pose.

Cross [Cro00] identified two types of design processes—prescriptive and descriptive. As the name implies, ***prescriptive design processes*** set down an exact process, or systematic recipe, for realizing a system. Prescriptive design processes are often algorithmic in nature and expressed using flow charts with decision logic. An example of a prescriptive process is shown in Figure 1.1, which describes the front end of the design process where

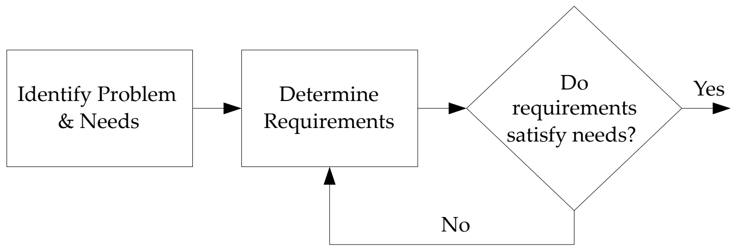

Figure 1.1: A prescriptive design process for problem identification and requirements selection.

the problem and requirements are determined. A decision block is included where the requirements are examined to determine if they satisfy the needs of the problem. ***Descriptive processes*** are less formal, describing typical activities involved in realizing designs with less emphasis on exact sequencing. The distinction between descriptive and prescriptive processes is not always clear, however, and some processes may be considered more strongly associated with one property than the other. Cross makes an important point in stating that design processes are sometimes viewed as common sense and thus ignored, resulting in failed products. Cross cites two good reasons to adhere to design processes: 1) they formalize thought processes to ensure good practices are followed, leading to better and more innovative solutions, and 2) they keep all members of the team synchronized in terms of understanding where they are in the design process.

A descriptive process that is widely applicable to design problems is shown in Figure 1.2. In a perfect world, the process starts with the identification of the problem, proceeds clockwise to research, followed the requirements phase, and so on until the system or device is delivered and goes into service (maintenance phase). This scenario is unrealistic, ignoring the iterative nature of design where the design team alternates between different phases as necessary. Consequently, links are inserted that allow transitions between all the different phases of the

design process. Of course, transitions between certain phases are unreasonable or very costly. It is virtually impossible to move directly from problem identification to system integration without developing a design concept first. It is much more likely for engineers to alternate between nearby phases in the process, such as problem identification, research, requirements specification, and concept generation. This does not mean that you can't move between phases that are not in close proximity in the model. For instance,

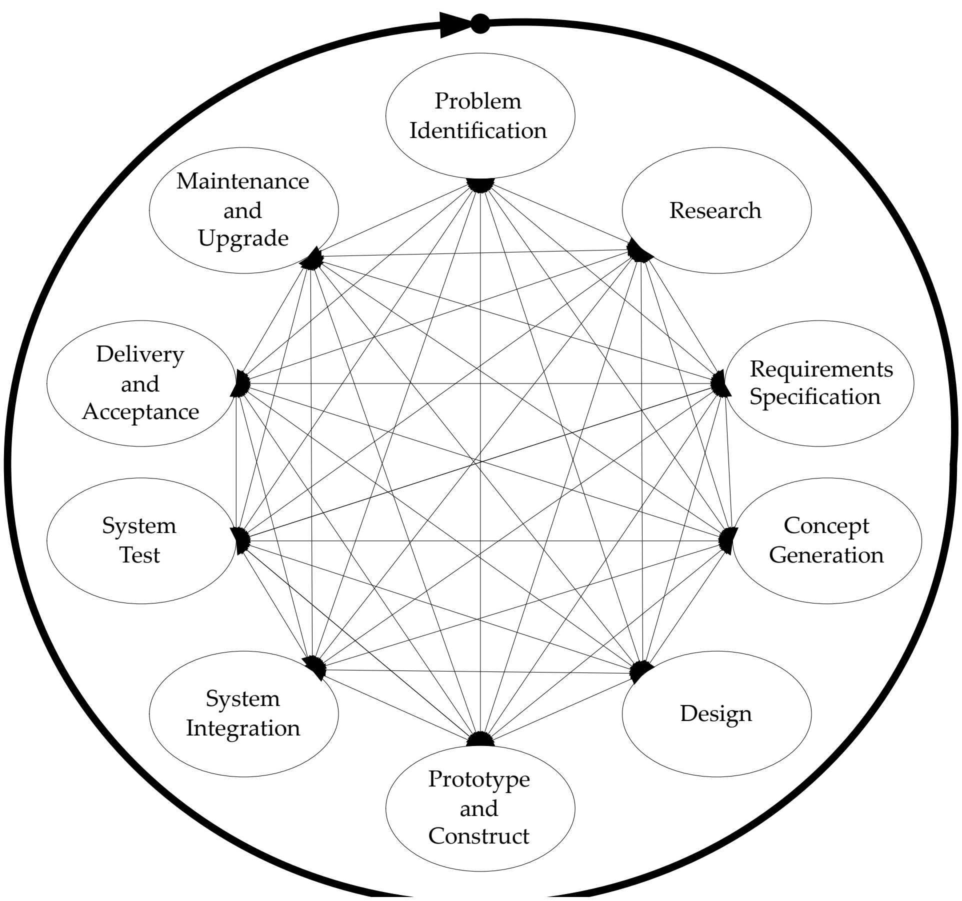

Figure 1.2: A descriptive overview of the design process.

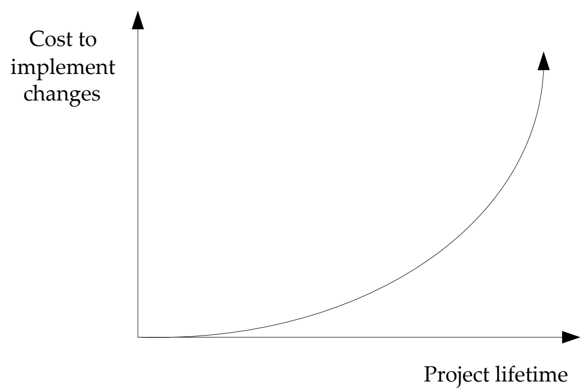

Figure 1.3: The cost to implement design changes increases exponentially with project lifetime.

the customer's needs may change while in the design phase, necessitating re-evaluation of the needs, correction of the requirements specification, and system redesign—all at a substantial cost in time and money. Studies have shown that the cost required to correct errors or make changes increases exponentially as the project lifetime increases, as presented in Figure 1.3.

1.2.1 Elements of the Design Process

Nearly all the phases of the design process in Figure 1.2 are covered in this book, with the exception of the maintenance phase. The objective of the first phase, ***problem identification***, is to identify the problem and customer needs. This occurs in a variety of ways, from someone conceiving a new idea to a client coming to you with a problem to solve. In either case, it is important to determine the true needs for the product, device, or system (terms that are used interchangeably throughout the book and often referred to as systems). Failure to correctly identify the needs has negative ramifications for the entire process, typically resulting in costly redesigns, or even worse, abandonment of the project.

In the ***research phase*** the design team conducts research on the basic engineering and scientific principles, related technologies, and existing solutions. The objective is to become experts on the problem, save time and money by not re-inventing the wheel, and be positioned to develop new and innovative solutions.

The ***Requirements Specification*** articulates what the system must do for it to be successful and to be accepted by the customer. It is important to focus on what the system must do, as opposed to how the solution will be implemented. This is challenging since engineers tend to focus on solutions and propose implementations early in the process. This is not surprising since engineering education focuses on solving problems rather than specifying them. The requirements are the mission statement that guides the entire project, and if properly developed, provide flexibility for creativity and innovation in developing solutions.

In ***concept generation,*** many possible solutions to the problem are developed. The hallmark of design is that it is open-ended, meaning that there are multiple solutions to the problem and the objective is to develop the one that best meets the requirements and satisfies the constraints. In this phase, wild creativity is encouraged, but it is ultimately tempered with critical evaluation of the competing alternatives.

In the ***design phase,*** the team iteratively develops a technical solution, ultimately producing a detailed system design. Upon its completion, all major systems and subsystems are identified and described using an appropriate model that depends upon the particular technology being employed.

In the ***prototyping and construction phase,*** different elements of the system are constructed and tested. In rapid prototyping, the objective is to model some aspect of the system, demonstrating functionality to be employed in the final realization. Many prototypes are discarded or modified as the system evolves—the idea is to experiment, demonstrate proof-of-concept principles, and improve understanding. Prototypes may be used anywhere in the process—you may present the client with prototypes after the concept generation phase, or they may be utilized in the design phase to test a design idea, or as the final system is tested and developed.

During ***system integration,*** all of the subsystems are brought together to produce a complete working system. This phase is challenging and time-consuming since many different pieces of the design must be interfaced, and the team must work closely to make it all work. Care taken in the design phase to clearly communicate the functionality and interfaces between subsystems aids in system integration. System integration is closely tied to the ***test phase***, where the overall system is tested to demonstrate that it meets the requirements.

Ultimately the system is *delivered* to the customer where it is likely that they will test it using a mutually agreed upon process. Development does not necessarily end when the system goes into service, as it will likely enter the ***maintenance phase*** where it is maintained, upgraded to add new functionality, or where design problems are corrected. Following and understanding the design process improves the probability of successful system

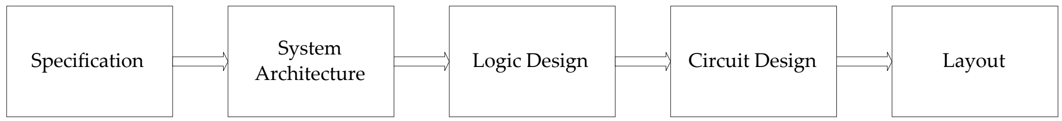

Figure 1.4: A process for integrated circuit (VLSI) design [Wol02].

development. The process is flexible, and the designer needs to transition between different phases in order to bring the system to realization. Design is an iterative process—you may not fully understand everything necessary in any given phase and have to revisit different steps as the system evolves. That is not a license for not trying to develop the best design you can on the first attempt—by all means do so—but realize that flexibility and a willingness to change the design are necessary.

1.2.2 Technology Specific Design Processes

Different application domains have developed specialized processes for technology-specific design. One such example is VLSI (Very Large Scale Integration) design. A typical VLSI design process is shown in Figure 1.4 [Wol02]. In this model the system specification is used to develop the system architecture. The system architecture is composed of the major functional units that constitute an integrated circuit. Each functional unit is then designed at the gate logic level, which is subsequently designed at the circuit (transistor) level, and finally the circuit elements are laid out on the silicon chip. This is an excellent demonstration of the divide-and-conquer approach to design, where a complex system is broken down into lower levels of abstraction and each of these is further broken down until the design objectives are met.

Next, consider the design process for embedded computer systems shown in Figure 1.5. Embedded systems are combined hardware/software systems embedded into a larger system to perform dedicated application specific operations. Embedded systems are employed in automobiles, DVD players, and digital cameras to name a few applications. Performance issues dominate embedded applications, and the designer needs to partition tasks between software and hardware to achieve optimum performance. This design process is somewhat prescriptive with phases for requirements gathering, specifications, and architectural design. The process reflects the unique nature of embedded systems with separate software and hardware design blocks, married together by the interface design.

The field of software engineering is one in which the development of

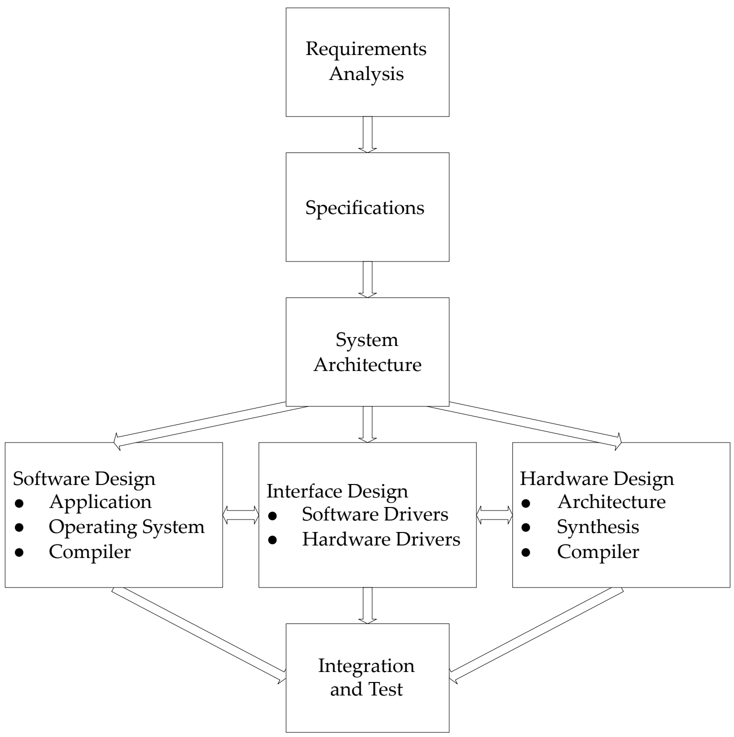

Figure 1.5: An embedded system design process [Ern97].

different design process models is still under considerable flux today. This is due to the complex nature of software and the failure of computer scientists and engineers to effectively develop high-quality software systems. There are many reasons why this is so. The sheer size of software programs may easily exceed one million lines of code written by many different software developers. One small mistake in those millions of lines of code can cause the system to fail. Another difficulty is in designing for upgrade and reuse of software. What if the needs change after the millions of lines of code are developed and one of the fundamental structures or objects needs to be upgraded?

The *waterfall model* shown in Figure 1.6 is one of the first proposed and most well-known software design processes. This is a prescriptive model since the development proceeds linearly from the first step where the user's needs are analyzed through the phases of specification development, design, test, and maintenance. This works for well-defined and moderately complex software applications, but fails as complexity grows due to the inability to move between phases. A more flexible and descriptive software design process is known as the *spiral model*, which is a cyclical process where phases are revisited as necessary [Som01]. *Extreme Programming* is a more recent and controversial software development process, where relatively small teams of software developers rapidly develop software following some strict rules. Both the spiral model and Extreme Programming are examined in more detail in the end of chapter problems.

1.3 The World-Class Engineer

The ability to effectively design is important for engineers, requiring strong technical skills and an understanding of the design process. Yet, this ability in itself is not enough to become an effective practicing engineer. The Pennsylvania State University Leonhard Center for the Advancement of Engineering Education, in consultation with a number of industries, developed a description of what is referred to as a "World-Class Engineer" [Leo95]. Shown in Table 1.1, the description identifies the characteristics of successful engineers, and contains six major elements: 1) Aware of the World, 2) Solidly Grounded, 3) Technically Broad, 4) Effective in Group Operations, 5) Versatile, and 6) Customer-Oriented. The description recognizes that engineers must be effective in group operations, since the majority of projects are carried out in teams. Not only that, many projects span multiple technical disciplines and are executed in multifunctional organizations that have

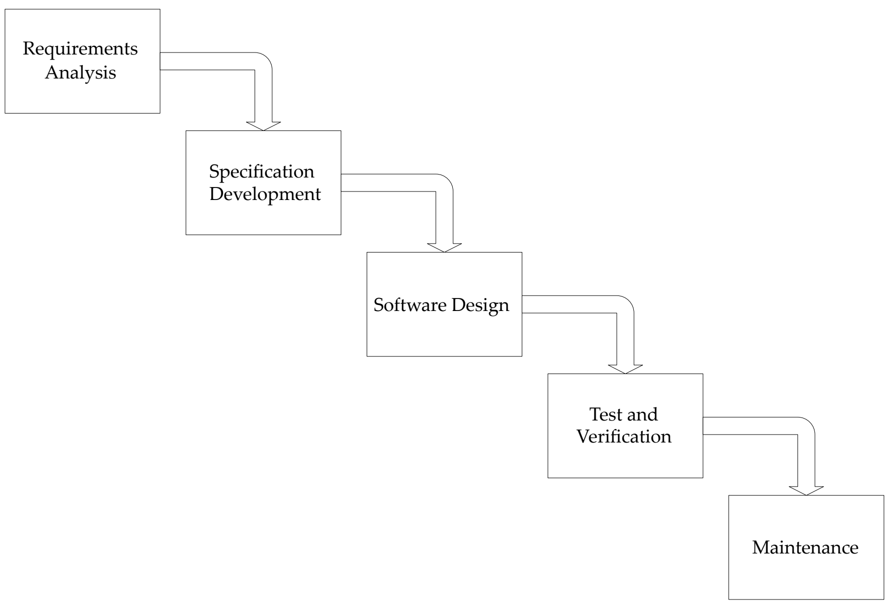

Figure 1.6: Waterfall software development process. In this model, development proceeds linearly from requirements analysis, through each subsequent phase, terminating with maintenance.

diverse groups such as marketing, finance, human resources, technical support, and service. It also recognizes that an engineer must be versatile, innovative, understand ethical principles, and be customer-oriented, important themes that are stressed throughout this book.

1.4 Book Overview

Consider the digital camera, the cellular phone, and the space shuttle, all complex systems that integrate a variety of technologies. A digital camera is the synthesis of an embedded electronics system, optics, a mechanical lens assembly, and the camera package itself. The embedded electronics contain an imaging sensor, a digital display, digital interface circuitry, flash memory storage, system control software, and the user interface. The challenges of integrating the components of such a system and having it record and transfer huge amounts of image data, within an acceptable timeframe, are immense. Cellular phones are another good example of a complex system that represents a technology that has shrunk in size, but increased tremendously in functionality at the same time. They encompass digital data communications, antenna design, encryption for secure data transmission, a user interface display, and Internet connectivity. At the other end of the spectrum are large-scale space and military systems, such as the space shuttle. Despite the two shuttle accidents, the safety and reliability requirements of the space shuttle are incredibly high. Realizing such a system is accomplished by a tremendous number of people from many disciplines working for different organizations. All three of these technologies were developed by large teams that encompass multiple disciplines. The processes and practices employed in their development represent application of the fundamentals that this book hopes to cover. While you won't be building complete space shuttles by the end of this design course, you can expect to apply design principles that allow you to design and integrate a relatively complex system, maybe even a part of the space shuttle.

Table 1.1: The World-Class Engineer (Copyright the Leonhard Center for the Advancement of Engineering Education, The Pennsylvania State University. Reprinted by permission.)

I) Aware of the World

- sensitive to cultural differences, environmental concerns, and ethical principles
- alert to market opportunities (both high- and low-tech)
- cognizant of competitive talents, work ethic, and motivation

II) Solidly Grounded

- thoroughly trained in the fundamentals of a selected engineering discipline
- has a historical perspective and remains aware of advances in science that can impact engineering
- realizes that knowledge doubles at breakneck speed and is prepared to continue learning throughout a career

III) Technically Broad

- understands that real-life problems are multidisciplinary
- thinks broadly, seeing an issue in a rich context of various alternatives, probabilities, etc., rather than a narro quest to find a single answer
- is conversant in several disciplines
- is trained in systems modeling and the identification of critical elements. Understands the need to design exper ments to verify or extend analysis, as well as meet specification requirements
- is psychologically prepared to embrace any field necessary to solve the problem at hand

IV) Effective in Group Operations

- cooperative in an organization of individuals working toward a common creative goal that is often multidisciplinar and multifunctional in nature
- effective in written and oral communication
- willing to seek and use expert advice
- cognizant of the value of time and the need to make efficient use of the time in all phases of an endeavor
- understanding and respectful of the many facets of business operation -- general management, marketing, financ law, human resources, manufacturing, service, and especially quality

V) Versatile

- innovative in the development of products and services
- sees engineering as applicable to problem solving in general
- considers applying engineering beyond the typical employment focus of engineering graduates in the manufacturin industries, to the much broader economy (financial services, health care, transportation, etc.) where engineerin skills could make a dramatic improvement in the productivity of those segments of the economy that employ 8 percent of the U.S. population

VI) Customer Oriented

- realizes that finding and satisfying customers is the only guarantee of business success
- understands that products and services must excel in the test of cost-effectiveness in the global marketplace

The intention is to teach the application of design principles to computer and electrical engineers and to help prepare students for a professional ca-

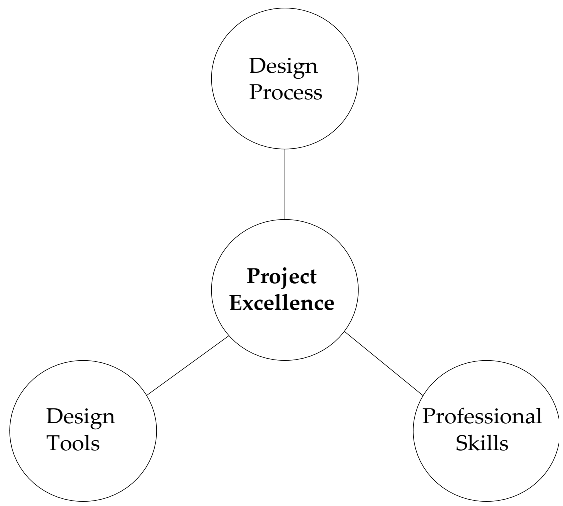

Figure 1.7: The guiding philosophy of this book. In order to achieve success in executing engineering and design projects, it takes an understanding of the design process, strong technical design tools, and professional skills.

reer. The majority of engineering education is devoted to math, science, engineering science, and problem-solving. They are important topics required to enter this highly technical field. However, it is clear that there are other aspects beyond this that are equally important for success, including an understanding of system design, innovation, ethical principles, teamwork, and strong communication skills.

The book is divided into three parts: I–Design Process, II–Design Tools, and III–Professional Skills. This is shown in Figure 1.7 as three separate, but related components that play a key role in achieving Project Excellence—the ability to complete a project, in an ethical manner that meets the customer's need, satisfies the constraints, and is clearly communicated to all involved. The chapters are decoupled as much as possible so that the reader can move between chapters as necessary. In Part I, the emphasis is on understanding and gaining experience in the different phases of the design process. The reader is guided through the steps of project identification, research, specification development, creative concept generation, and critical evaluation of competing solutions. Part II addresses topics that are often employed in design, including functional decomposition, description of system behavior, reliability, and testing. Part III addresses professional skills, including teamwork principles, project planning, ethics in design and the profession, and oral communication skills.

Here are a few thoughts to conclude the chapter and get started on the path to great designs. You are embarking on what will likely be a fun, challenging, sometimes frustrating, and ultimately rewarding journey. The systems that engineers work with continue to become increasingly complex and multi-disciplinary in nature. The example problems presented in this book come from the fields of analog electronics, digital electronics, electrical systems theory, and software systems. These four areas comprise a significant problem-domain common to the education of most electrical and computer engineers. Finally, consider the quote below by Robert Hayes on the importance of design.

Fifteen years ago, companies competed on price. Today it's quality. Tomorrow it's design.—Robert H. Hayes, Harvard Business School, 1991.

What is this saying? Well, it is clear that the world continues to move to a more knowledge-based society, where individuals and companies compete on the strength of their intellectual capital and ability to produce new and innovative products. That is what design is all about. It is not saying that price and quality are unimportant, they certainly are; in fact quality and reliability in design are part of this book. It is that quality and price are a given, and successful products will be distinguished by their design characteristics. The implication is that design will play a larger role in the development and success of products. The future Hayes predicted is now. Design is what distinguishes between products that are seen as commodities and those that are truly unique and profitable.

1.5 Summary and Further Reading

Engineering design is an iterative process in which the design team employs creativity and technical knowledge to develop a solution that best meets the end-users' needs within the constraints applied to the problem. There is no single design process that can be applied to all situations and technologies, but there are many common elements shared, regardless of the technology under consideration. In order to successfully bring designs to fruition, it takes a combination of design tools, professional skills, and a clear understanding of the process needed to complete designs. The objective of this book is to develop your proficiency in these areas so that you may become an effective engineer and achieve excellence in design projects.

Engineering Design Methods by Nigel Cross [Cro00] presents the differences between descriptive and prescriptive design processes, and covers a wide array of processes in more detail. It also discusses the cognitive characteristics of effective designers. There are many good books on software engineering process development methods. Software Engineering by Ian Sommerville [Som01] discusses the different software design process models, such as the waterfall and spiral models. This is also true of many modern software engineering texts. The original reference to the waterfall model is by Royce [Roy70]. The Art of Innovation by Michael Kelley [Kel01] describes the activities of well-known design company IDEO and is a highly readable description of their design practices. The ABC *Nightline* news program also produced an interesting segment on IDEO [ABC01] that can be purchased at the ABC website. The Circle of Innovation by Tom Peters [Pet97] is another popular book that provides his perspective on current trends in business and the importance of design.

Chapter 2

Project Selection and Needs Identification

> *For every problem there is a solution that is simple, neat, and wrong.—H.L. Mencken*

Traditionally, companies have organized resources based on functions such as accounting, engineering, finance, manufacturing, and marketing. It is often more effective to organize around projects that are of significant value and align resources to meet the needs of the project. This means that traditional departments and middle management are being de-emphasized and the role of projects is growing. Capstone design projects provide a great opportunity to gain experience in the management and execution of a project. One of the first and most important decisions encountered is selecting a project to pursue.

The objective of this chapter is to provide pragmatic guidance in the project selection phase. A description of design and engineering projects is presented, followed by advice on how projects can be selected by engineering students who wish to put design principles into practice. The chapter addresses how to identify the needs of the end-user and provides guidance for conducting background research. All of this information is brought together in a Problem Statement that identifies the needs, the goals of the project, and research on the technology.

Learning Objectives

By the end of this chapter, the reader should:

- Have an understanding of the types of projects that electrical and computer engineers undertake.
- Understand and be able to apply criteria for project selection.
- Know how to determine, document, and rank end-user needs.
- Be aware of resources available for conducting research surveys.
- Have selected a project concept and developed a Problem Statement.

2.1 Engineering Design Projects

This section provides a classification of design and describes some of the types of projects undertaken by practicing engineers and those tackled in student projects. In reality, most projects don't fit neatly into the categories presented, but are some combination of them. The objective of a design project is to create a new ***artifact*** (system, component, or process) to meet a given need. Within the design domain there are different types of designs that are classified broadly into three categories of Creative, Routine, and Variant designs [Cro00].

Creative designs represent new and innovative products. An example of a creative design is the Palm Pilot Personal Digital Assistant (PDA). While the idea for the PDA had been around for awhile, earlier attempts at developing the technology, notably the Apple Newton, were unsuccessful. This was primarily due to unreliable handwriting recognition that frustrated the user. However, Palm Computing had the creative idea to develop a simplified handwriting language, Graffiti, which eliminated the need for natural handwriting recognition. The Palm Pilot is a great example of a creative design—it is simple (four basic functions), fits in your pocket, and is easy to use. This innovation spawned a huge hand-held computing industry.

Variant designs are variations of existing designs, where the intent is to improve performance or add features to an existing system. Many engineering projects fall into this category. For example, the objective may be to increase accuracy or system throughput.

Routine designs represent the design of devices for which theory and practice are well-developed. Examples are DC power supplies, analog and digital filters, and basic digital components such as adders and comparators. Routine designs are often components of more complex creative and variant designs.

Within these three categories of design, there are many different types of projects. *Systems engineering and systems integration projects* represent the synthesis of many subsystems into a larger system. They may be creative or variant designs, but have unique challenges since they are typically large and involve many people and technologies. Adherence to good design processes is important for their success. Engineers are often engaged in *systems test*, where the objective is to ensure that a system meets stated requirements and the needs of the user. Examples include the testing of systems for use in space and military environments.

The objective in *experimental design projects* is to design experimental procedures and apparatus for determining the characteristics of a system. For example, an engineering team may test a system under a variety of operating conditions. Example 2.3 presented later in the chapter is such a project, where the objective was to design a series of experiments to test the feasibility of gigabit Ethernet technology in a military environment. The test explored the impact of environmental factors such as temperature and vibration, and further used this data to estimate the operating lifetime of the Ethernet board. Upon completion of this project, the team made recommendations as to the allowable operating ranges of the technology.

The objective in *analysis projects* is to analyze some aspect of an existing system to improve or correct it. For example, a system or process may be failing in the field and the source of the failure unknown. Tools such as the Failure Mode Effects and Analysis technique may be applied in this situation to identify the sources of failure. In t*echnology evaluation projects*, technologies are assessed to determine if they can be used in a given application. This may be to determine if the technology can improve an existing system, or to characterize its operating performance.

The objective of a *research project* is to perform research or experiments with the goal of discovering or creating a new technology. The fundamental difference between this and other types of projects is that the ultimate outcomes are unknown. Most engineering research falls under the category of *applied research*. This refers to the creation of new technology or systems based on existing technology and theory developed from fundamental research. *Fundamental research* emphasizes the discovery of new scientific principles without necessarily having an intended application. Fundamental research is very valuable, but not typically a part of design projects.

2.2 Sources of Project Ideas

Depending upon your situation, you may have the opportunity to identify and select your project. The list below provides some places to search for project ideas:

- *Industry sponsored projects.* Many companies will sponsor projects and are happy to do so, particularly if you have worked for them on an internship.
- *Engineers without Borders (www.ewb-usa.org).* This organization sponsors student projects to improve the quality of life in developing countries.
- *www.FreeRandD.com.* This is a clearinghouse for businesses and students teams to collaborate on projects. It allows businesses to post capstone project ideas for students to work on, while students can post resumes and project interests.
- *Your campus and local community.* In our school, a number of student teams have identified novel projects by asking other departments on campus for ideas. They have also been successful in approaching local community organizations for ideas, such as museums and research institutes.
- *Brainstorm.* Get together with a group of your peers and brainstorm on project ideas. You will be surprised at how many project ideas you can develop in a good brainstorming session (see Chapter 4). Do not only consider project ideas, but also brainstorm to identify problems that need solutions.

2.3 Project Feasibility and Selection Criteria

This section provides questions to consider when examining the feasibility of a project. George H. Heilmeier (an electrical engineer who has held positions as Chief Technology Officer of Texas Instruments, Director of the Defense Advanced Research Projects Agency, and CEO of Bellcore) developed a set of questions to answer when starting a new project [Sha94]. Heilmeier argued that all projects must be tied to the goals of the organization, and applied this by asking the following questions:

- What are you trying to do? Articulate your goals using absolutely no jargon.
- How is it done today, and what are the limitations of current practice?
- What is new in your approach, and why do you think it will be successful?
- Who cares? If you are successful, what difference will it make?
- What are the risks and payoffs?
- How much will it cost? How long will it take?
- What are the midterm and final exams to check for success?

Heilmeier credits successful completion of projects that he managed to answering these questions up-front and adhering to disciplined project management processes.

A second perspective is offered from an organizational project management viewpoint [Gra02] that provides the following criteria for project selection:

- *The project must be tied to the mission and vision of the organization.* Believe it or not, organizations often spend resources fruitlessly on projects that don't meet this criterion. To be fair, there is always risk associated with a project and it is sometimes hard to judge exactly how well a project meets this criterion. For engineers who are new to an organization, it is hard to judge a project's importance relative to the mission and goals, but if you find yourself in this situation, do not be afraid to ask some questions. Novices ask basic questions that are often overlooked by those who are highly experienced or intimately involved in a project.
- *Must have payback.* An economic analysis should be done to estimate if the project will make a profit. Much of this is outside the scope of this text, requiring marketing and financial analyses. Chapter 10 covers the basics of project cost estimation that will help in trying to answer this question.
- *Should have selection criteria.* Sound criteria for selecting among competing projects should be employed. The example at the end of this section demonstrates the application of criteria in project selection.

- *Objectives of the Project should be SMART: Specific, Measurable, Assignable, Realistic, Time-Related.* Chapter 3 addresses how to determine project requirements that are Specific and Measurable. Assignable, Realistic, and Time-Related all refer to project management aspects that are covered in Chapter 10. The objective is to develop tasks that are assigned to groups or individuals and realistically can be completed in the given timeframe.

The following example demonstrates how to apply a project selection model using a method known as the Analytical Hierarchy Process. AHP is a decision making method that is described in Appendix B and is utilized frequently throughout the text – **the reader should read Appendix B prior to proceeding with this example**.

Example 2.1 A project selection model for capstone design.

Assume that you are part of a capstone design team that has the opportunity to select their project from competing project ideas. The steps in making a decision using AHP are to select the criteria that drive the decision, determine relative weights of the criteria, rate the alternatives (in this case project concepts) against the criteria, to compute a weighted score for each of the alternatives, and then review the decision.

<u>Step 1: Determine the selection criteria</u>

To select the criteria, assume that the team brainstorms to determine the following criteria that interest the team members:

A – Match to team skills

B – Technical complexity

C – Creativity

D – Market potential

E – Industry sponsorship

<u>Step 2: Determine the criteria weightings</u>

Assume the team applies the method of pairwise comparison to determine the weights as shown in Appendix B. In order to do so, the team systematically compares each criterion to all others using the following scale of relative importance:

1 = equal, 3 = moderate, 5 = strong, 7 = very strong, 9 = extreme.

Again, details of pairwise comparison are outlined in Appendix B and the results are below.

Criteria	A	B	C	D	E	Weight
A	1	5	5	3	3	0.52
B	1/5	1	3	1/3	1/3	0.12
C	1/5	1/3	1	1	3	0.09
D	1/3	3	1	1	5	0.18
E	1/3	3	1/3	1/5	1	0.09

Table 2.1: Weighting for selection criteria.

Selection	Weights	Alternatives		
		Project 1	Project 2	Project 3
A (Match to skills)	0.52	0.40	0.20	0.40
B (Technical Complexity)	0.12	0.40	0.30	0.30
C (Creativity)	0.09	0.45	0.20	0.35
D (Market potential)	0.18	0.05	0.35	0.60
E (Industry sponsorship)	0.09	0.00	1.0	0.00
Score		0.31	0.31	0.38

Table 2.2: Weighted score for the selection criteria.

This is an important step and one often overlooked – the team has identified what is important to it in project selection. It is clear that match to the team skills (criterion A) is most important, by a large margin, followed by market potential.

Step 3: Identify and rate alternatives relative to the criteria

Assume that the team identifies three potential projects ideas: 1 – IEEE sponsored robot competition, 2 – Industry sponsored project to design a new test protocol, and 3 – Design of an item-finder device to help people locate lost items. Furthermore, the team goes through the process of rating each project relative to the criteria as outlined in Appendix B. These ratings are reflected in the decision matrix in the next step.

Step 4: Compute scores for the alternatives

The decision matrix below is constructed and the scores for the alternatives determined.

Step 5: Review the decision

Project 3 (item finder) is rated the highest among the three choices based upon the weights determined by the team members. It is a good match to the team skills, but also matches their desire to solve a problem with good market potential. The remaining two projects are rated about equal.

2.4 Needs Identification

Often a customer, client, or supervisor comes to you with a problem to solve and you must determine the needs or requirements for the solution to the problem. In other words, determine the *voice of the customer*. This seems like a simple statement—ask the customer what they want and you are done, right?

As an illustration, let's say a client comes to you with the following request—*The traffic at the front of campus is too congested. I would like you to design a new traffic lane for northbound traffic exiting at the intersection at the front of the college.* So you design this new lane and have it added to the intersection. However, you find out three months later that the traffic congestion has decreased a little bit, but it is still a significant problem. So what went wrong? Clearly you did what was asked of you, but the problem was not solved, meaning that you were solving the wrong problem. The real problem was to improve the flow of traffic at the entrance. In this case, the client gave both the problem and the solution all in one statement. That is fine if a careful feasibility study was done and it was known that the additional traffic lane would alleviate the problem, but that was not the case here. This hypothetical situation is not so far fetched and happens in practice via neglect to do the up-front research or because underlying assumptions change. The point is that the <u>correct</u> problem should be identified and solved.

It would be better if the client had simply asked to improve the traffic flow, providing the opportunity to analyze the situation and develop different design options. Some questions to be asked in this situation are: *How much additional traffic is there? At what times does this happen? Where is the traffic coming from? What is an acceptable waiting time at the intersection?* It may be that several new lanes are needed, or perhaps the sequencing of the traffic signals is wrong, or maybe a new entrance could be added for less cost and improved traffic flow.

The lesson is that customers often come with the problems and solution all wrapped up together. When this is done, the ***design space***, the space of all possible solutions to the problem, is unnecessarily limited. Be ready to tactfully challenge the assumptions and ask questions to get to the root of the problem. Ask clarifying questions, analyze, pick apart the request, and focus on the problem, not the solution.

Researchers and practitioners have examined the problem of eliciting needs, and it is an important pre-requisite for developing good engineering requirements specifications. Ulrich and Eppinger [Ulr03] proposed a process

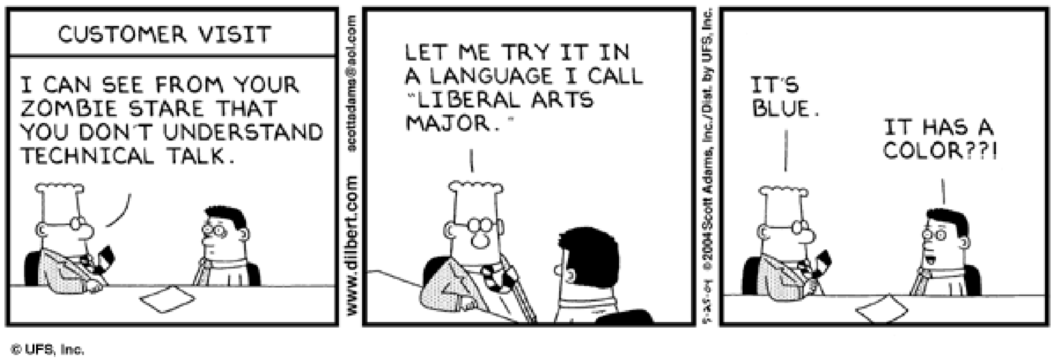

Figure 2.1: The difficulties of communicating with the customer. (Dilbert © United Feature Syndicate. Reprinted by permission.)

for obtaining the *voice of the customer* using the following five steps: 1) Gather raw data from users; 2) Interpret raw data in terms of needs; 3) Organize needs into a hierarchy; 4) Determine the relative importance of the needs; and 5) Review the outcomes and the process. Each of these steps is described in the following sections.

Step 1: Gather Raw Data from Users

DILBERT® by Scott Adams

This is often accomplished via interviews with supervisors, key users, or people from the client organization. In cases where new products are being developed, focus groups are often employed. The advantage of interviews and focus groups is that they provide the opportunity for dialogue with the user where new ideas, concepts, and needs may emerge. Another option is direct observation, where the team goes out and examines the system in use and develops concepts for improving it. IDEO Corporation is an innovative and successful company that designs new products and systems. They rely heavily on direct observation as a technique for successfully developing innovative products [Kel01]. For example, IDEO was asked by a client to develop a new medical instrument for balloon angioplasty used in hospital operating rooms. A critical requirement from the user was that only one hand could be used to operate the device because the technician's other hand had to be free during the procedure. From direct observation, the IDEO design team found that even though the current system was designed for one-hand use, it was impractical, and the technicians actually used both hands. IDEO designed and developed a two-handed pump that not only worked better than the one handed pump, but was quieter, easier to read, and had increased precision. This is another example of the customer specifying the solution as part of the problem statement.

Ulrich and Eppinger provide the following questions to ask during an interview:

- When and why do you use this type of product (system)?
- Walk us through a typical session using the product.
- What do you like about the existing products?
- What do you dislike about the existing products?
- What issues do you consider when purchasing the product?
- What improvements would you make to the product?

Step 2: Interpret the Raw Data in Terms of Needs

In this step the raw data is translated into customer needs. The needs are expressed in terms of what the system must do (a requirement) as opposed to how it is done. Statements of the customer's needs are known as ***marketing requirements*** or ***marketing specifications***. For example, "*The system should have high-quality audio*" is a need or marketing requirement from the customer regarding performance, but says nothing about how it will be achieved. Marketing requirements are short sentences that describe the need in the language of the customer. They typically do not have a numerical target and are described as a state of being for the system. Other examples of marketing requirements are, "*The system should be easy-to-use,*" and "*The system should be able survive a drop from the runner's height.*"

Step 3: Organize Needs into a Hierarchy

The marketing requirements are organized into a hierarchy of needs arranged from the most general to the most specific in successive levels of detail as required by the problem. It is organized by functional similarity, not as hierarchy of importance (that is the next step). This hierarchy is referred to as an ***objective tree***. An example objective tree for a portable audio device intended for use by runners is shown in Figure 2.2. The three high-level objectives determined were high-quality audio, portable, and easy-to-use.

	High-Quality Audio	Portable	Easy-to-Use	Weight
High-Quality Audio	1	1/3	2	0.24
Portable	3	1	4	0.62
Easy-to-Use	1/2	1/4	1	0.14

Table 2.3: Pairwise comparison matrix for ranking the highest-level needs of the portable audio device. This comparison should be carried out for all levels of the objective tree.

Each of these is further sub-divided into the characteristics that support the higher level. For example, portability is divided into the needs of lightweight, small, ergonomic, and the ability to operate in the environment. The environmental need is further expanded into needs that support it.

Step 4: Determine the Relative Importance of the Needs

The relative importance of the needs is determined based upon the user needs. As we saw in Example 2.1 and as presented in Appendix B, the pairwise comparison is a good technique for determining relative importance and weighting of needs. In pairwise comparison, all needs are systematically compared to all other needs at the same level in the hierarchy. An example pairwise comparison table for this problem is shown in Table 2.3 with the resulting weights for each need indicated. This shows that portability is the most important need, followed by audio quality and ease-of-use. The weights are also reflected in the objective tree in Figure 2.2. In addition, the needs at each sublevel in the hierarchy are compared, the results of which are reflected in Figure 2.2. The rankings are used in later chapters to compare design alternatives.

Step 5: Review the Outcomes and the Process

The design process and all of its sub-processes are methods for making good decisions, and this technique for needs identification is no different. There is a certain amount of subjectivity and judgment that goes into it; the end result should be reviewed to determine if it makes sense. The objective is to challenge assumptions, fully identify the problem, and make informed decisions.

The three outcomes of this process are the marketing requirements that identify the needs, an objective tree that provides a hierarchical representation of the needs, and a ranking of the relative importance of needs. This

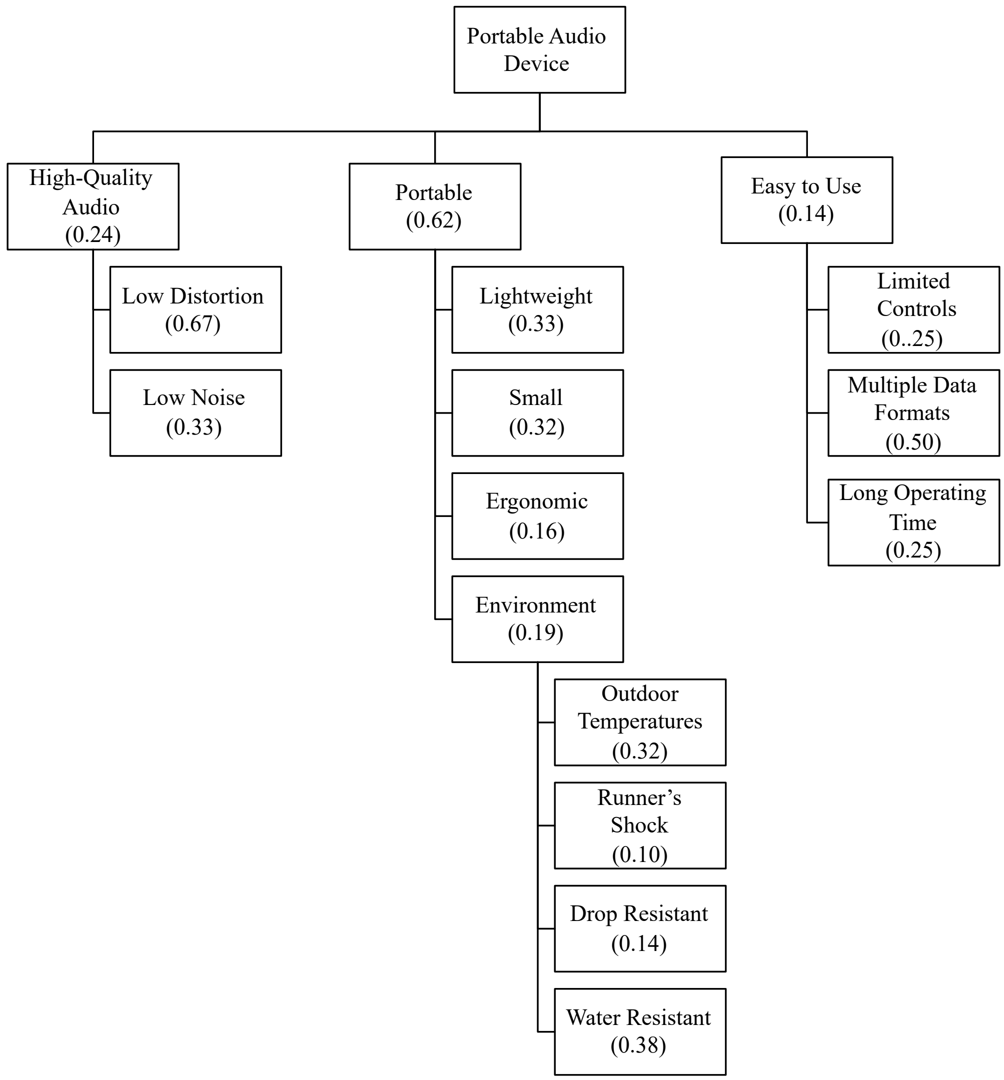

Figure 2.2: Objective tree for a portable audio device to be used by runners. The weights reflect the relative importance of needs at each level in the hierarchy as determined in Step 4 of the process.

process may seem as though it does not apply to student design projects, but in reality it does. The questions in this chapter are certainly candidates to ask when working on company-sponsored projects. If it is not a company sponsored project, the user needs should still be considered. For example, questions can be asked of friends and co-workers who are potential users of the system, focus groups can be formed, surveys administered, and Internet bulletin boards and discussion groups employed to gather this information.

2.5 The Research Survey

It is important to conduct a thorough research survey while defining the project concept. Failure to do so may translate into time and money spent reinventing the wheel, while not taking full advantage of existing components, knowledge, practices, and technology. During the research phase, competing systems and technologies are identified, and based upon them the project concept refined, or in some cases abandoned. The character and strategy of the research survey is driven by the nature of the project. In general, the objective is to develop an understanding of the underlying scientific principles and demonstrate a familiarity with the state-of-the-art in the particular field. Some questions to be answered in the research survey are:

- What is the basic theory behind the concept?
- How is it currently being done?
- What are the limitations of current designs or technology?
- What are the similarities and differences between your concept and existing technologies?
- Are there existing or patented technologies that may be relevant to the design? If so, what are they and why are they relevant?

Internet Searching

The Internet is a powerful, fast, and readily accessible source for conducting research. There are many excellent search engines for locating web resources, but understand that it is important to go beyond the well-known search engines and beyond the Internet in the survey.

One of the risks, and also one of the wonderful things, about the Internet is that virtually anybody can post information. It is important to analyze websites to ensure that they are reliable and credible. There are resources available that provide pointers on how to evaluate this credibility [Mci02, Sch98], and a little common sense goes a long way. One of the important things to look for is authorship—the author should be clearly identified and any affiliations listed. Carefully determine whether the information is subjective opinion or possibly a commercial for a product. Credible sites should provide references to original sources of material. Another step is to verify website content in print media or other reliable sources.

There are thousands of search engines available, making the task of selecting one challenging. Also, there are different types of search engines: text (search for the text or keywords; subject heading or full-page text search), indexed (information categorized into directories), meta-search (engines that search other engines), and natural language processing (allowing natural language queries). A listing of search engines to try are www.altavista.com, www.AskJeeves.com, www.google.com, www.kartoo.com, and www.yahoo.com. The Librarian's Index to the Internet, www.lii.org is a collection selected and evaluated by librarians, and according to their website, it is *a "well-organized point of access for reliable, trustworthy, librarian-selected Internet resources.*" This information may change rapidly and represents current information at the time of publication.

Electrical and Computer Engineering Resources

Realize that the major search engines will not find all information available on the Internet. There are many websites with specialized search capabilities related to electrical and computer engineering design.

- EE Product Center, www.EEProductCenter.com. A website for locating electronic components and their manufacturers. It provides links to product datasheets and application notes. It has a keyword search engine and a tree structure search for finding components. For example, you can start with Op Amps and delve into sub-categories such as Precision and High-Speed.

- Circuit Cellar, www.CircuitCellar.com. This companion website for the magazine is a great reference for designers. It emphasizes embedded systems and electronics projects with many tutorial articles and project ideas.

- Datasheet Catalog, www.DatasheetCatalog.com. A datasheet source for electronic components and semiconductors.

- Dr. Dobbs, www.ddj.com. The magazine and companion website are a resource for software developers that includes tips and tutorials.

- EE Times, www.EETimes.com. Industry newspaper for electrical engineering field with information on current technology developments.

- Electronic Design Magazine, www.EDNmag.com. This is free magazine for electrical design engineers that provides information on the latest products. The website has a number of categorized technical resources and a design ideas section.

- ON Semiconductor, www.OnSemi.com. ON Semiconductor is a supplier of semiconductors for a wide range of applications, with a particular emphasis on power management. The website has a searchable database of over 15,000 components, and provides guidelines for component selection based on different applications.

- The Thomas Register, www.ThomasRegister.com. This is a source for finding companies and products in North America. It allows searches for parts and equipment that may be used in a design project. It provides profiles of companies that meet the search criteria and describes the products they make.

  In addition, most manufacturers of electronic components have websites providing product datasheets and application notes for their products. Application notes demonstrate how to use components in real applications. Examples are Dallas Semiconductor, Fairchild Semiconductor, Motorola, and Texas Instruments.

Government Resources

- US Bureau of Labor Statistics, `http://stats.bls.gov`. This has valuable information on consumer spending information, allowing one to determine things such as how much people spend and what they spend it on. It also profiles specific industries and forecasts employment in different industry sectors.

- US Government Official WebPortal, www.FirstGov.gov. This is an entrance to all US government web resources.

- US Patent Office, www.uspto.gov. A searchable database of all patents back to 1790. Full text searches are available back to 1976 and full images back to 1790. It has information on the basics of patents, trademarks, and copyrights.

Journal and Conference Papers

The search should include journal and conference papers if technically detailed information on the latest theory or applications is needed.

- ACM (Association for Computing Machinery) Digital Library, www.acm.org. Provides abstracts (full text for subscribers) for ACM journals and conference proceedings.
- Compendex, www.engineeringvillage2.org. This provides indices to journal and conference papers in a broad scope of engineering fields, referencing material back to 1970.
- IEEE (Institute of Electrical and Electronics Engineers) Xplore Electronic Library, www.ieee.org. Provides abstracts (full text for subscribers) to all IEEE journals, transactions, magazines, and conference subscriptions published since 1988. Abstracts for all IEEE standards are publicly available.

2.6 Needs and Objectives Statements

Two parts of the Problem Statement are the needs and objectives statements. The *needs statement* identifies and motivates the need for the project and should:

- Briefly and clearly state the need being addressed.
- Not provide a solution to the problem.
- Provide supporting information collected as outlined in Section 2.4.
- Provide any supporting statistics and anecdotes that support the need.
- Describe current limitations.
- Describe supporting processes that are needed to understand the need. This is particularly important in industry-sponsored projects having specific needs that may not be clear to the average person.

The *objectives statement* typically ranges from one or two sentences to one or two paragraphs in and should:

- Summarize what is being proposed to meet the need.

- Provide some preliminary design objectives (detailed requirements are developed later).

- Provide a preliminary description of the technical solution, avoiding a detailed description of the implementation. Often the input and output behavior of the system are described. The complete solution is not usually posed until after the engineering requirements are fully determined.

Example needs and objectives statements are provided in Examples 2.2–2.4.

Example 2.2 iPod Hands-Free Device Needs and Objectives. *Abstracted from the iPod Hands-Free Device Design Report by Al-Busaidi, Bellavia, and Roseborough [Alb06].*

Need: According to AppleInsider, approximately 10.3 million people owned iPods at the end of 2004 and many of the owners used them while operating their automobiles. The National Highway Traffic Safety Administration estimates that driver distraction is a contributing cause of 20 to 30 percent of all motor vehicle crashes – or 1.2 million accidents per year. One research study has estimated that driver inattention may cause as many as 10,000 deaths each year and approximately $40 billion in damages. iPods can present a distraction to drivers that is similar to cell phones in that the driver's attention is divided between controlling the steering wheel, watching the road, and navigating controls on the iPod. A system is needed to allow users to navigate among the music selections of their iPod without distracting their attention from the road.

Objective: The objective of this project is to design and prototype a device that will make the iPod safer to use while driving an automobile, by allowing hands-free control of the iPod. The device will interact with the user using spoken English commands. The user will be able to issue simple voice commands to the device to control the operation of the iPod. In turn, the device will communicate information verbally, such as song titles that are displayed on the iPod screen, to the user.

Example 2.3 Experimental Design Problem Needs and Objectives. *Abstracted from the Intel Pro 1000XF Server Testing Design Report by Esek, Hunt, and Lewis. [Ese03].*

Need: Our industry sponsor is investigating the performance of commercial grade gigabit Ethernet fiber optic equipment for computer data communications in a military environment. The proposed system will utilize an Intel Pro1000 XF server card. This is a harsh operating environment and its effects on the performance and lifetime of the equipment are unknown. The client wishes to understand how the military environment affects the optical power margin of the Intel Pro 1000 XF card and associated connectors and cabling.

Objective: The goal of this project is to design the experimental equipment and test procedures to determine the effects of temperature variations and vibration on the optical power margin and the operating lifespan of the system.

Example 2.4 Portable Aerial Surveillance Needs and Objectives. *Abstracted from the PASS Design Report by Andre, Kolb, and Thaler [And06].*

Need: Emergencies happen all across the world, all of the time. There are nearly 2,000,000 reported fires in the United States every year, and over 90 tactical activations of Pennsylvania's Special Emergency Response Team which handles barricaded suspects and hostage situations. There have been over 100 documented riots in the United States in the past century, with the Los Angeles Riot alone causing $1 billion in damage. Having an aerial view of these situations would be a great benefit to the emergency workers on the ground. For example, police may have to monitor a large crowd or a hostage situation where aerial surveillance would allow them to observe the situation from a safe distance and use the footage as evidence in court. Firefighters could use aerial surveillance to examine fire damaged buildings and search for victims through the windows of high-rise buildings. In large cities, emergency organizations often employ helicopters for aerial surveillance. However, in smaller rural towns, helicopters either take too long to reach the scene from a nearby city or they are too expensive to afford. The least expensive two-seat helicopters cost over $400,000, while new helicopters cost well over a million dollars with average operating costs of $400-$1000 per hour. There is a need for a low cost aerial device that can provide emergency workers with overhead surveillance of emergency situations.

Objective: The objective of this project is to design a device that will provide emergency workers with a live aerial view of a situation at a cost that small municipalities can afford. The device will deploy rapidly and record and log video. The camera will also include pan and zoom functionality to make identification of victims and suspects easier.

2.7 Project Application: The Problem Statement

A format for a Problem Statement that integrates the elements of this chapter is as follows:

- *Need.* A statement that identifies the needs of the project.
- *Objective.* Describes the concept proposed to meet the needs identified.
- *Background.* A summary of the research survey on the relevant technologies and systems. The objective is to provide an introduction answer the questions posed in Section 2.4. The length and content of this section varies depending upon the project.
- *Marketing Requirements.* Short statements describe the user needs.
- *Objective Tree.* A hierarchical representation of the needs based on functional similarity with the relative weights of the needs identified.

2.8 Summary and Further Reading

This chapter addressed the types of projects that are often undertaken by engineers and provides guidance in terms of questions to ask when selecting a project. The success of design projects depends upon adequately determining the user's needs and desires for the system. A process developed by Ulrich and Eppinger for needs elicitation was presented. The three outcomes of this process are: 1) marketing requirements identifying the customer needs, 2) an objective tree that hierarchically represents the needs, and 3) a ranking of the relative importance of the needs. It is important to conduct research on the concept and related technologies, and pointers for conducting the research survey were provided. Finally, a format for a Problem Statement was presented that summarizes the needs, objectives, and research survey for a design project.

The works by Griffin and Hauser [Gri93] and Ulrich and Eppinger [Ulr03] are readable and more detailed discussions on how to obtain the voice of the customer. There are also other design books available that address how to identify needs and develop objective trees [Cro00]. Cagan and Vogel [Cag02] have proposed a process for product development known as iNPD (integrated new product development) and provide methods for navigating what they refer to as "the fuzzy front end of project definition."

2.9 Problems

1. In your own words, describe the differences between creative, variant, and routine designs.

2. List three guidelines that should be employed when selecting a project.

3. Assume a customer comes to you with the following request—*Design a mechanical arm to pick apples from a tree.* What are the assumptions in this statement? Rewrite the request to eliminate the assumptions. (This problem was originally posed by Edward DeBono [Deb70]).

4. Assume a customer comes to you with the following request—*Design an RS-232 networked personal computer measurement system to transmit voltage measurements from a remote location to a central server.* What are the assumptions this statement? Develop a list of questions that you might ask the customer to further clarify the problem statement.

5. Describe what is meant by a marketing requirement.

6. What is the purpose of an objective tree and how is it developed?

7. The needs for a garage door opener have been determined to be: safety, speed, security, reliability, and noise. Create a pairwise comparison to determine the relative weights of the needs. Apply your judgment in making the relative comparisons.

8. Consider the design of an everyday consumer device such as computer printer, digital camera, electric screwdriver, or electric toothbrush. Determine the customer needs for the device selected. The deliverables should be: 1) marketing requirements, 2) an objective tree, and 3) a ranking of the customer needs using pairwise comparison.

9. **Project Application.** Select criteria to be applied for selecting a project concept as shown in Example 2.1 then brainstorm and search to generate project concepts. Rank the top three to five concepts against the criteria as presented in Example 2.1.

10. **Project Application.** Determine the needs for the project selected. The result should be list of marketing requirements, an objective tree, and a ranking of the needs.

11. **Project Application.** Conduct a research survey for your project using the guidance presented in Section 2.4. The result should be a report summarizing the results of the survey.

12. **Project Application.** Develop a Problem Statement for your project concept as outlined in Section 2.7. Apply the processes presented in the chapter as appropriate.

Chapter 3

The Requirements Specification

Specification • (n) A detailed and exact statement of particulars, a statement fully describing something to be built.—American Heritage Dictionary

The Requirements Specification identifies those requirements that the design must satisfy in order for it to be successful. It is in effect the mission statement that drives all subsequent stages of development, and when completed should be a detailed and complete vision of the design goals. An effective Requirements Specification should identify all important requirements, yet provide enough flexibility for the design team to develop innovative solutions. It also serves as a communication tool for everyone involved in the design, such as engineering, marketing, and the client. All parties should agree to the requirements before further development proceeds. In some cases, the Requirements Specification serves as a legally binding agreement between the developers and the client.

A major challenge in developing the requirements is in many ways analogous to the proverbial "*What came first, the chicken or the egg?*" question. The final solution is analogous to the chicken and the requirements are analogous to the egg. In the beginning, the chicken is hidden inside the egg, yet the egg must be capable of describing what the chicken will become. The difficulty is that it is hard to develop the *what* for the requirement without already having solved the problem or created the chicken.

This chapter guides the reader through the process of developing a Requirements Specification and is organized as follows. First, the properties of an engineering requirement are defined and numerous examples for computer and electrical systems are provided. Then, the properties of the complete Requirements Specification (the collection of marketing and engineering requirements) are considered followed by a number of case study examples. The chapter concludes with advanced methods of analyzing and refining requirements, utilizing tools such as the House of Quality.

Learning Objectives

By the end of this chapter, the reader should:

- Understand the properties of an engineering requirement and know how to develop well-formed requirements that meet the properties.
- Be familiar with engineering requirements that are commonly specified in electrical and computer systems.
- Understand the properties of the complete Requirements Specification, as well as know the steps to developing one.
- Be able to conduct advanced requirements analysis to identify design tradeoffs.

3.1 Overview of the Requirements Setting Process

The ***Requirements Specification***, which is the focus of this chapter, is a collection of engineering and marketing requirements that a system must satisfy in order for it to meet the needs of the customer or end-user. Figure 3.1 illustrates a process for developing a Requirements Specification that is from the IEEE Guide for Developing System Requirements Specifications [IEEE Std. 1233-1998]. This process is the focus of this chapter and there are three stakeholder groups in it – the customer, the environment, and the technical community. The input from the customer includes the marketing (raw) requirements that were addressed in Chapter 2. The environment introduces requirements in the form of constraints and standards that impact or limit the design. The input from the technical community is based upon the knowledge of engineers who are primarily responsible for design, implementation, testing, manufacturing, and maintenance of the system.

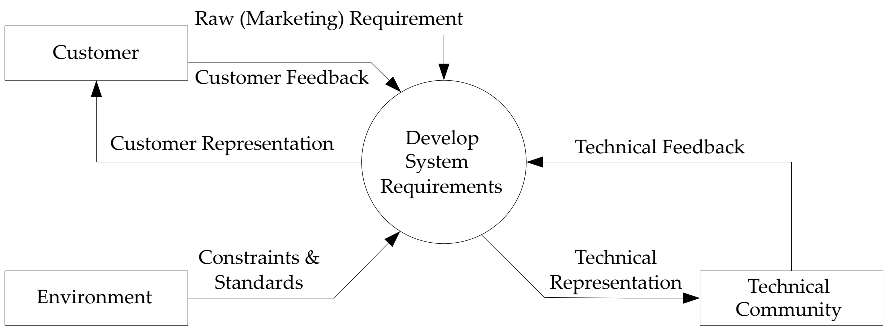

Figure 3.1: Requirements Specification development processes from IEEE Std. 1233-1998. The three input sources to the process are the customer, environment, and technical community.

3.2 Engineering Requirements

Before developing the complete Requirements Specification, designers need to first determine individual engineering requirements. ***Engineering requirements*** are short statements that address a technical need of the design. A simple example is "*The system should be able to supply 50 watts of power.*" This section identifies the desirable properties of engineering requirements, methods of identifying requirements, and provides numerous examples.

3.2.1 Properties of an Engineering Requirement

Each engineering requirement should meet the four properties below [IEEE Std. 1233-1998]:

1) *Abstract.* This means that a given requirement should specify *what* the system will do, not *how* it will be implemented. This is the chicken and egg problem described earlier. It is frequently the most difficult property to satisfy since designers often have a preconceived concept for the solution. Unless absolutely necessary, the requirements should say nothing about the implementation. For example, a requirement stating that a certain microcontroller (i.e., technology) <u>will</u> be used should be avoided. Admittedly, this is not always possible due to customer constraints or in cases where a system is being built upon pre-existing technology. A common analogy used for the "*what versus how*" problem is that of designing a bridge. The requirement is to

transport people from one side to other, without specifically stating the solution is a bridge, because another solution, like a ferry, may be a much more effective solution.

2) *Verifiable.* Verifiability means that there should be a way to measure or demonstrate that the requirement is met in the final system realization. Doing so allows the system to be tested or verified against the requirements. The idea is that if there is no way to verify that the requirement is met, then it should not be a requirement. Verifiability is used to answer the question of "*Are we building the system correctly?*"

3) *Unambiguous.* Each requirement should have a single unambiguous meaning and be stated with short complete sentences.

4) *Traceable.* Requirements should be traceable marketing requirements. If the design doesn't satisfy the customer's needs, it won't be successful.

Let's examine an example requirement for a robot whose objective is to navigate autonomously within a specified environment. Consider the following requirement

> *The robot must have an average forward speed of 0.5 feet/sec, a top speed of at least one foot/sec, and the ability to accelerate from standstill to the average speed in under one second.*

Are the four properties for an engineering requirement met? In terms of the abstractness property, the answer is yes; it states what the system must do, not how it will be implemented. In terms of the second property, can the requirement be verified? Speed and acceleration are directly testable in the final realization, and thus it is verifiable. Is it unambiguous? It gives clear bounds for speed and acceleration. Finally, traceability can't be shown without the marketing requirements and is addressed later.

Now we analyze a second example requirement for the robot to see if it meets the properties

> *The robot must employ IR sensors to sense its external environment and navigate autonomously with a battery life of one hour.*

This requirement is not abstract since it identifies part of the solution in terms of the sensor type and the fact that batteries must be used. It is somewhat ambiguous in that it should specify what is meant in terms of autonomous and the operating period. In terms of operating period, should it work for exactly one hour and stop, or is greater than an hour acceptable? Again, traceability can't be demonstrated without the marketing requirements. This requirement would be hard to verify without a good definition of what autonomous navigation in this context means. A better requirement would be

> *The robot must navigate autonomously, with the aid of only landmarks in the specified environment, for a period of least one hour.*

Realize that good requirements typically have two key elements in the statement – a description capability and condition. Capability describes what the system must do and in the above requirement, that capability is autonomous navigation. Conditions are measurable or testable attributes of the capability and are critical for verification.

3.2.2 A Fifth Property – Realism

In addition to meeting the four properties, requirements should be realistic or justified. This is not defined in the IEEE standard as a property, but it is an important aspect that is often overlooked. To be realistic, there should be a way of demonstrating that the target is technically feasible. For example, a requirement could indicate that a robot to should travel at a speed of 1,000,000 miles per hour, which could be verifiable, unambiguous, and abstract – yet, completely unachievable. Realistic targets can be determined with a little research, engineering know-how, creativity, or system modeling. One way to do this is to assume a solution for the final system – violating the abstractness property. For example, consider the design of a robot where some basic assumptions are made on the weight of the robot, the motors used, the wheel size, and the battery selected. An engineering model based upon these characteristics could be developed to predict performance and estimate realistic requirements. Alternatively, target requirements can be based upon an actual prototype, where a model or experimental system is developed to show that a particular requirement is feasible. This is how the technical community in Figure 3.1 feeds into the requirements process.

The use of benchmarking to identify similar systems and their performance provides a reference for realistic targets. It is generally hard to surpass the performance of well-developed products and systems on a first-generation design. An exception is with new and innovative approaches that allow you to surpass the competition. Competitive benchmarks may also be obtained from similar, but not necessarily identical, products. Experience working with a particular technology or previous generations of a system also provides guidance in selecting realistic targets. That being said, organizations wishing to gain or maintain a market edge often press the development team to achieve performance on new generations that were once believed to be unrealistic. Sometimes it just may not be feasible to determine the technical feasibility of requirements. In such cases, the requirements should have a certain amount of tolerance built into them and be updated as development proceeds.

3.2.3 Constraints

One of the inputs to the requirements process in Figure 3.1 is the environment, serving as the source of both constraints and standards. In reality, all engineering requirements impose some sort of constraint on a design, but in design a constraint is a special type of requirement. A ***constraint*** is a design decision imposed by the environment or a stakeholder that impacts or limits the design. Constraint requirements often violate the abstractness property. For example, a constraint requirement is

> *The system must use a PIC18F52 microcontroller to implement processing functions.*

This constraint requirement specifies how the system will be implemented. This could be because the project sponsor has developed a great deal of expertise using this particular microcontroller and does not want to spend the development time learning a new platform. Note that a number of other references define constraints to be synonymous with non-functional requirements (usually indicated as items that are not specifically functions). However, that terminology is avoided here since it is not well defined nor universally accepted.

3.2.4 Standards

Standards are exactly what the name implies, a standard or established way of doing things that ensure interoperability. Without standards, the use of technology would be severely limited, if not downright impossible. Standards ensure that products work together, from home plumbing fixtures to the modules in a modern computer. Imagine if every computer manufacturer had their own communication standard, instead of following established protocols such as RS-232, TCP/IP, and USB—computers would have a hard time printing, sending email, instant messaging, or surfing the Internet! Furthermore, standards ensure the health and safety of products that people use every day. Identifying and following standards is an expected part of good engineering practice.

The focus in this chapter is on identifying standards that impact the requirements and ultimately the design. The question becomes, what standards are relevant to your project and how do you use them? There are different levels of interaction with standards that we denote as: user, implementation, and development levels. At the *user level*, the standards are simply employed in the design, and detailed technical knowledge of the standard is typically not necessary. For example, when using a component that communicates to other devices, it is likely that a standard communication protocol is used. Other than having to configure software or hardware to communicate with the standard, detailed knowledge of the standard isn't required. Another example would be in developing software to display digital images in a standardized format such as JPEG-2000 (Joint Photo Experts Group), in which case it is likely that existing software components would be used to read and display data in this format.

At the *implementation level* details of the standard need to be understood. Standards at the implementation level are most likely to impact the design and the requirements. For example, when developing low-level drivers for computer peripherals, you need to become an expert on the underlying standard. Another example is reliability, where the requirement may be that "*the system will have a reliability of 95% in 10 years.*" In this case a reliability standard, such as Military Handbook for Reliability Prediction of Equipment [MIL-HDBK 217F] may be employed, and its usage requires an understanding of both the reliability theory and the standard itself.

New standards are constantly being developed and existing ones modified, leading to the final level of interaction at the *development level*. Depending upon the standard, engineers from different organizations, professional societies, and corporations take part in the standards setting process. Many participants in this process are trying to gain a competitive advantage for their products and services.

It can be difficult to navigate the world of standards; they tend to be highly detailed and limited parts of a standard may apply to a project. In addition, many standards are costly to obtain, while some are freely distributed. The following is advice for identifying and employing standards. First, conduct research on applicable standards. Virtually all standards organizations maintain websites that provide basic information on their particular standards. The IEEE Xplore database is a good place to start since it has a wide variety of standards and provides free searchable abstracts. Many companies and universities have subscriptions databases of complete standards. Second, determine the expected level of interaction. Based upon your analysis of the problem, do you foresee applying standards? Or will you need to develop an in-depth knowledge at the implementation level? In the latter case, you need to obtain detailed information on the applicable standards. Finally, you should consider asking your client. They may have their own internal standards and procedures to follow, and they may have experts on the applicable standards.

The list below identifies some of the types of standards that may be employed in a project and included in the requirements.

- *Safety.* Safety standards address how to design for safety and how to test products to ensure that they are safe.

- *Testing.* Testing standards are often related to safety, but are broader in scope. For example, standardized benchmark tests are used for comparing computational performance, one well-known standard being the SPEC (Standard Performance Evaluation Corporation) benchmarks.

- *Reliability.* Reliability standards address general reliability principles and design methods for different classes of systems. Another practical aspect is in the estimation of reliability of electronic systems, such as the IEEE and military reliability standards.

- *Communications.* They address how electronic systems communicate and transfer information, such as in computing, telephony, and satellite communications.

- *Data Formats.* Standard data formats ensure that systems and software can properly share information. Examples include image, video, and database standards.

- *Documentation.* There are standards for technical report documentation. In addition, there are standards for documenting processes and business practices, a well-known case being the ISO (International Standards Organization) 9000 and subsequent standards.

- *Design Methods.* Certain design techniques are standardized as well. Examples include software design methodologies, and the use of design languages such as the Hardware Description Language (HDL) and the Unified Modeling Language (UML).

- *Programming Languages.* Programming language syntax is standardized so that software maintains a level of portability between systems and compilers.

- *Connector Standards.* Standards for cable connections are common and should be followed to ensure that systems are easily interfaced and manufactured.

- *Meta-Standards.* Some standards are a combination of multiple standards known as meta-standards. For example, the RS-232 standard is really a combination of a mechanical standard describing the connector physical dimensions connector, an electrical standard describing the voltages, a functional standard describing the pins and their function, and a procedural standard describing how entities communicate.

3.2.5 Identifying Engineering Requirements

There are many techniques for identifying requirements listed below [IEEE Std. 1233-1998]:

- Structured workshops and brainstorming sessions.
- Interviews, surveys, and questionnaires.
- Observation of processes or devices in use.
- Competitive benchmarking and market analysis.
- Prototyping and simulations.
- Research and technical documentation review.

Many requirements may be specified for a design, but knowing which to include is the challenge. The remainder of this section is a guide to describe the types of engineering requirements that may be specified for electrical and computer systems. Requirements in categories of performance and functionality are presented first as they are often critical, followed by an alphabetical grouping of a potpourri of other types requirements. **This taxonomy of requirements is by no means definitive or inclusive of all possibilities, and the design team needs to carefully determine those that are applicable to the particular situation. Careful attention must be given to the verifiability of requirements for the particular application.**

Performance

These requirements reflect a critical aspect of the performance of the system or device. They often are characterized by time, accuracy, throughput, or percentage error. The following is an example requirement that might be used in a security application with camera surveillance.

> *The system should detect 90% of all human faces in an image.*

In order to verify this, a test might be constructed where the system is presented with a large database of face images that the system was not developed or trained with. The number of faces correctly detected would then be determined. Here is another example performance requirement for a system that measure part location

> *The system should be able to measure part location to within ± 1mm.*

One way to verify this would be to take independent measurements of the system's ability to measure part location and compare them to the result of the system. The following is an example that could apply to software response time.

> *The system should retrieve the user data no less than three seconds for 90% of requests and in a maximum of six seconds for all requests.*

This could be verified by constructing a test where a large number of queries for user data are presented to the software under a variety of operating conditions and the response time measured. Yet another example is:

> *The system should be able to process video data at a rate of 30 frames per second.*

This could be verified by providing an input video stream at the frame rate and testing to ensure that proper processing occurs. The test procedure would need to specify length and number of videos to test, issues that are addressed in Chapter 7. A final example of performance is one that could apply to electrical audio amplification

> *The amplifier will have total harmonic distortion of less than 1%.*

Total harmonic distortion is a measure that quantifies how closely an amplifier is able to replicate the original signal. This would likely be verified using laboratory instrumentation to measure the harmonic distortion in the output signal.

Functionality

These requirements describe the type of functions that a system should perform. Often, they provide inputs, outputs, and the transformation that the system will perform on the inputs. This is examined further in Chapter 5, which presents functional design techniques. The following is an example, where the input is ambient air temperature is converted to a digital readout. It also has a performance aspect in that the accuracy is specified.

> *The system will convert ambient temperature to a digital readout of temperature with an accuracy of 1% over the measurement range.*

The following is an example from a real capstone project to develop a wireless mouse that is worn by the user and integrated into a glove.

> *The system will implement the left and right button functions of a standard mouse.*

The following are several functional examples for software systems.

> *The user shall be able to search all five company internal databases.*

> *The system will protect the user's identity with 128-bit encryption.*

Note that in these last two cases, verification would be by inspection.

Economic

Economic requirements include the costs associated with the development (design, production, maintenance) and sale of a system. They may also include the economic impact of the final system, such as how it will to contribute to profits or save the user money. Two example economic requirements are below.

> *The costs for developing the system (labor and parts) should not exceed $50,000.*

> *The total parts and manufacturing costs cannot exceed $500 per unit.*

Energy

Virtually all systems consume and/or produce energy and thus have energy requirements. Energy consumption is the amount of power that a system consumes, and may be specified in terms of maximum, minimum, or average values. Example requirements are

> *The system will have an average power consumption of 500mW.*

> *The system will have a peak current draw of 1A.*

These requirements could be verified by measuring current and voltage draws under the different operating conditions, or by estimating the power drawn by all components in the system.

Operating lifetime addresses how long the system will operate from a given power source. For battery-powered devices, operating time is critical, and the lifetime for a given source may be an important requirement. An example of such a requirement is

> *The system will operate for a minimum of three hours without needing to be recharged.*

Source characteristics refer to the characteristics of the input and/or output sources, such as voltage, current, impedance, frequency, number of phases, and power requirements. An example requirement is

> *The system will operate from a 12V source that supplies a maximum current of 300mA.*

Environmental

These requirements address the impact of the design on the external environment and usage of the earth's resources. For example, energy usage is an important factor and example requirement is as follows

The system will use 20% less energy than the industry average for similar products and qualify for US Energy Star certification.

Recyclability is the ability to dismantle a product into its constituent materials for reuse in other products. European countries have regulations on the recyclability of consumer products. In many cases, the producer of a product is responsible for its safe disposal once its service life is over. An example requirement is as follows

50% of the modular components will be able to be repaired and re-used in similar products.

Health and Safety

The health and safety of anyone affected by the final product is an especially important consideration. For example, IEEE and ANSI standards provide guidance on safe levels for exposure to radio frequency electric fields.

The system will not expose humans to unhealthy levels of electromagnetic radiation and will meet conditions for safe operation identified in ANSI Std. C95.1.

There is a tendency to think that physical harm is not an issue in electrical and computer systems, but many electronic systems control mechanically moving parts. Consider the design of an automatic garage door system. An example constraint could be that

The door should stop moving if a person or object is detected in the door path.

This could also translate into further engineering requirements on the amount of force on the door required to trigger it to stop. There are many safety standards, and two that are widely applied for consumer products are the UL (Underwriters Laboratory) and CE (Common European) standards. Examples are

The system will use only UL approved components.

The final system will be meet UL and CE standards and be tested at an independent laboratory for approval.

Legal

Designs should not infringe upon existing patents, copyrights, and trademarks, particularly if the intention is to sell the product. Patent searches should be conducted, and search capabilities are available at the United States Patent Office website (www.uspto.gov). An example is

> *An intellectual property search will be conducted to ensure that there is no infringement on prior patents.*
>
> *This could be verified by having an external firm will conduct the patent search and evaluate the design against existing intellectual property.*

Security and privacy constraints apply to systems that handle sensitive data or personal communications. The ability of computing systems to withstand malicious attacks by hackers is another consideration, and the use of firewalls or other protective measures may be warranted. Examples are

> *The system will protect the user's identity with 128-bit encryption as required by law.*

Maintainability

The maintenance of the system being developed and compatibility with other systems are often considerations. Will the system be designed so that it can be reused in future applications? This is common in software development where the objective is to design modules that are reliable and flexible enough to be used in other applications. It is also a consideration in terms of the reusability of electronic or digital components in future system upgrades. An example reuse constraint is

> *The software should maintain downward capability and be able to use version 2 object libraries.*

After a product goes into service, it enters the maintenance phase, where it is maintained and upgraded. In software designs this is an important consideration, as software is regularly upgraded and maintained. On the hardware side, maintenance can be facilitated by the use of plug-in modules that are easily removed and replaced. Examples are

The system will initially be available to 100 users at five field locations, and within one year must be expanded to address usage by 5,000 users company-wide.

The system should have a modular design such that failed components can be replaced by a technician in under 15 minutes.

There may be internal restrictions on system development imposed by the company based on their internal expertise and ability to maintain the system, such as the following constraint requirement.

The system will use only PIC microcontrollers.

Manufacturability

A prevalent product development paradigm that used to be employed in many engineering organizations was to "*throw the design over the wall.*" What this meant is that the design and development team would create a new product and hand it off to the manufacturing team to produce (throw it over the wall and run), often without having considered the manufacturability of the product. The manufacturing team would then address how to produce the design, and in many cases could not do so without major redesign. Fortunately, this has given way to much better concurrent engineering practices where all aspects of product development are considered throughout the process. All of the examples presented here are constraints, in that that they are external decisions that limit the design.

Size is a consideration in terms of the amount of space the final design will occupy, particularly if it has to be physically integrated with other components. An example constraint requirement is

The system must be manufactured on a circuit board with dimensions of no greater than 1"x2".

The realization and portability of the system is a consideration. For example, with electronics, will it be built on a printed circuit board? Following design rules and file format guidelines is important for manufacturing printed circuit boards and integrated circuits. A chip foundry may require that integrated circuit layouts utilize certain file formats. Examples are below, which again are clear constraints on the design.

The system will be manufactured using three layer printed circuit board technology.

> *The product should be run on the Linux operating system.*

The use of readily available parts, instead of low volume or hard to find components, improves manufacturability, and an example is

> *The design shall only incorporate components that can be purchased through two of our main suppliers.*

Operational

Operational requirements address the physical environment in which the system will operate. Characteristics could be temperature, humidity, electromagnetic radiation, shock, and vibration. Note, that these can often be quite difficult to verify and may require specialized equipment to do so. An example temperature operational requirement is

> *The system should be able to operate in the temperature range of 0°C to 75°C.*

This could be tested via test in an environmental chamber which the operation of the system is tested over the complete temperature range. Alternatively, indirect verification is a possibility. For example, in the design, only components that are known to meet this operational requirement, as specified in their product datasheet, could be used.

Depending upon the customer needs, the system may be tested in an environmental chamber to verify that the requirement is met. Humidity is similar in concept to the temperature requirement, addressing the required ambient humidity range. A system may also need to be water-resistant (withstand rain and snow) or waterproof (be submersible in water). An example requirement is

> *The system must be waterproof and operate while submersed in water.*

Be careful with the differences between waterproof (submersible in water) and water-resistant, which indicates the ability to withstand outdoor elements such as rain and snow. For example, outdoor decorative lights are water-resistant, but not waterproof.

Depending upon the environment, the system may need to withstand vibrations. Bounds are typically specified in terms of frequency, magnitude, and duration of the vibration. An example requirement is

> *The system must be able to withstand vibrations of up to 60Hz with a peak magnitude of 1mm for a period of 1 minute.*

Electromagnetic Interference *(EMI)* results from any electromagnetic energy that interferes or disturbs the operation of an electronic system. Electronic systems may produce electromagnetic radiation and limits may need to be placed upon the amount of radiation emitted. EMI is typically measured with specialized testing apparatus. Conversely, a system may need to be able to operate properly given a certain level of EMI.

The system may need to withstand a specified amount of shock and still operate. This may be measured in G-force or via heuristics. An example requirement is

> *The system should withstand a drop from a height of six feet and still operate.*

Political

Political constraints address relationships to political, governmental, or union organizations. Examples include obtaining governmental approvals, resolving trade barriers, and determining the acceptance of systems for use in unionized environments. Examples are below.

> *The system will need to obtain FDA approval before it can be sold to medical users.*

> *The software will comply with the Digital Millennium Copyright Act.*

Reliability and Availability

This refers to the expected period of time that a system will operate properly. Measures of r*eliability* include failure rates and mean time to failure. Estimation of system reliability is given detailed coverage in Chapter 8. The following is an example of a reliability requirement.

> *The system will have a reliability of 95% in five years.*

This requirement means that 95% of the systems should be properly operating (have not failed) in five years. Direct measurement of reliability would not be possible, unless you are willing to wait five years to see how many systems fail, thus the use of estimation. This would require indirect verification using mathematical techniques to estimate the system reliability.

Availability is related to reliability, but addresses the amount of time that a system is available for operation. Example availability requirements are

> *The system will be operational 99% of the time.*
>
> *The system will be operational from 4AM to 10PM, 365 days a year.*

These might be hard to verify this since it is only determined for sure once the system is deployed. Verification would have to address under which conditions the system would be tested to ensure this occurs.

Social and Cultural

This addresses aspects such as benefits, risks, and acceptance of products by the intended user or by society at large. For example, robots have tremendous benefits for improving product quality, while freeing people from dangerous and repetitive tasks. Yet when used in automation, they present the risk of displacing workers and causing job losses.

Many great products have fallen by the wayside because users were unwilling to accept it. An example is the early Apple Newton Personal Digital Assistant, the first product of its kind. The fatal flaw was handwriting recognition that required a training process for accurate recognition. This was not accepted by consumers and Palm® Computing solved the problem by employing a simplified alphabet known as Graffiti. Graffiti was also seen as risky when it was being developed, but due to its simplicity it was accepted by consumers and the product became a huge success. In the mid 1980s, Phillips electronics released the Laser Disk player, which failed magnificently, but was far superior to VHS technology. Their failure was attributed to the cost of the players and disks when compared to VHS. Fifteen years later DVDs, with the help of computers, reached a price point which now makes them preferable to VHS.

Will the system be used by engineers, technicians, laborers, doctors, lawyers, or the general public? Each group has its own culture, educational background, and willingness to accept innovations. Example requirements are

> *The product shall provide help menus to the user in either English or Spanish.*

> *The software will be designed to easily be used by operators on the manufacturing floor. The software will be tested by a group of 25 operators and the average time to learn the basic functionality of the software will not exceed 8 hours.*

Usability

Usability requirements address the ease of use of a system. Although they are quite common, they are often difficult to verify. Usability can address how long it takes to learn the product and satisfaction by the end-user or a group of users. To aid in verification conditions can be placed on the number of menus in the system, an estimated learning time, and number and types of errors the user is allowed to make. An example requirement is that

> *Users of the system should be able to learn 80% of its functionality within two hours.*

The method of verification would need to be clearly specified, such as, a group of 25 test users who have never used the product will be provided two hours to learn the product. Another example of a usability requirement is

> *The system will have a maximum of 20 functions and a maximum of two menus of depth.*

3.3 Developing the Requirements Specification

The Requirements Specification is the complete set of all system requirements. The steps in developing the Requirements Specification are to:

- Identify requirements from the customer, environment, and the technical community (focus of the previous section).
- Ensure the engineering requirements are well-formed (meet the properties).
- Organize the requirements. Similar requirements should be presented together and relationships between engineering and marketing requirements identified. The collection of requirements should meet the properties identified in this section.

- Validate the Requirements Specification – which means all requirements are examined to ensure they meet the needs of the stakeholders.

3.3.1 Properties of the Requirements Specification

The desirable properties of the Requirements Specification are as follows [IEEE Std.1233-1998]:

1) *Normalized (orthogonal) set.* There should be no overlap or redundancy between engineering requirements. A mathematical analogy is that of orthogonal vectors. For example, the x and y axes of the two-dimensional Cartesian space are orthogonal vectors, meaning that the projection (dot product) of one vector onto the other is zero. Ideally, all requirements should be orthogonal with no redundancy.

2) *Complete set.* A complete Requirements Specification addresses all of the needs of the end-user and also those needs required for system implementation. Failure to define a complete set results in ***under-specificity*** where not all needs are met.

3) *Consistent.* The engineering requirements should not be self-contradictory.

4) *Bounded.* The scope of the Requirements Specification should be identified. Determine the minimum acceptable bound for target values; going beyond what is necessary limits the design space of potential solutions. Applying unnecessary bounds results in ***over-specificity***.

5) *Modifiable.* Requirements are typically considered to be evolutionary. This is because there are many unknowns at the start of a project, hence estimates for the requirements are made. The original requirements are known as ***baseline requirements***. The estimates can change as development proceeds, as long as the changes are communicated to and agreed upon by all affected parties. Versions of the requirements should be tracked and identified as modifications take place.

3.3.2 Requirements Validation

An important property of an engineering requirement that we saw earlier was verifiability. Verifiability seeks to answer the question of whether or not the system is being developed correctly, or *"Are we building the product correctly?"* A related concept is that of validation, which seeks to answer the question "*Are we building the correct product?*" More formally, ***validation*** is the process of determining whether the system meets the needs of the user—is it valid? This is more general in scope than verification and more difficult to show. Requirements validation is usually carried out by reviews of the requirements by a team of people. Validation is demonstrated by being able to answer the following questions in the affirmative [Som01]:

- For each individual engineering requirement, are the traceability and verifiability properties met? Is each requirement realistic and technically feasible?
- For the Requirements Specification, are the properties of orthogonality, completeness, and consistency met?

A complete Requirements Specification includes all the requirements, both marketing and engineering, along with the relationships between them. The relationships between the engineering and marketing requirements need to be described to ensure that all the marketing requirements are being addressed by design. The relationship between the marketing and engineering requirements is called a mapping because, like a mathematical mapping, it defines which elements of the domain (marketing requirements) are associated with which elements of the range (engineering requirements).

3.4 Requirements Case Studies

This section presents case study examples of Requirements Specification, most of which are from real capstone design projects. They are presented in a table format that presents each engineering requirement, the mapped marketing requirements (supporting the traceability property), and the justification for each requirement. The marketing requirements are summarized at the end of the table.

3.4.1 Case Study: Car Audio Amplifier

Table 3.1 presents the Requirements Specification for a car audio amplifier. This simple example was selected because of the relative ease of understanding, broad familiarity with this type of device, and it will be expanded upon later.

Audio power amplifiers are widely available devices, so the requirements were determined through competitive benchmarks and knowledge of amplifier circuit designs. The first engineering requirement directly impacts sound

Table 3.1: Requirements Specification for an audio amplifier for use in an automobile.

Marketing Requirements	**Engineering Requirements**	**Justification**
1, 2, 4	1. The *total harmonic distortion* should be <0.1%.	Based upon competitive benchmarking and existing amplifier technology. Class A, B, and AB amplifiers are able to obtain this level of THD.
1–4	2. Should be able to sustain an *output power* that averages $\geq$ 35 watts with a peak value of $\geq$ 70 watts.	This power range provides more than adequate sound throughout the automobile compartment. It is a sustainable output power for projected amplifier complexity.
2, 4	3. Should have an efficiency $\eta > 40\%$.	Achievable with several different classes of power amplifiers.
3	4. *Average installation time* for the power and audio connections should not exceed 5 minutes.	Past trials using standard audio and power jacks demonstrate that this is a reasonable installation time.
1–4	5. The *dimensions* should not exceed 6" x 8"x 3".	Fits under a typical car seat. Prior models and estimates show that all components should fit within this package size.
1–4	6. *Production cost* should not exceed \$100.	This is based upon competitive market analysis and previous system designs.

Marketing Requirements
1. The system should have excellent sound quality.
2. The system should have high output power.
3. The system should be easy to install.
4. The system should have low cost.

quality and is known as total harmonic distortion (THD). THD measures how closely the amplifier output signal follows the input signal. It is desirable for an amplifier to have a linear relation between input and output, where the output signal is identical to the input signal, except for an amplification factor. In reality, all amplifiers have some degree of nonlinearity or distortion. It is measured by applying a pure sinusoid as the input to the amplifier, which in the case of a perfectly linear amplifier produces a pure output sinusoid of the same frequency. Any nonlinearity introduces unwanted harmonic frequencies. THD represents the power of unwanted harmonics relative to the power of the fundamental sinusoid. THD is typically less than 1% for a good amplifier.

The second requirement, output power, is quantified in terms of both average and maximum values to minimize ambiguity. The third engineering requirement addresses the efficiency of the power transfer, or how much of the power consumed by the device is actually converted to audio power. The fourth engineering requirement, ease of installation, is perhaps easy to understand intuitively, and the expected installation time provides the condition for verification. The fifth requirement addresses the physical size of the device, and is important as it will need to be installed somewhere in the vehicle.

3.4.2 Case Study: iPod™ Hands-Free Device

Table 3.2 presents the Requirements Specification for a hands-free device whose intent is to allow a driver to communicate with an iPod™ audio player while driving. The Problem Statement was presented in Chapter 2 (Section 2.6).

To develop the marketing requirements, this team conducted an informal survey of students on campus, asking the target group what their desires for such a system would be. The first three engineering requirements are related to the important issues of the system functionality and performance. In order to develop justifications for some of the requirements a prototype solution had to considered, although the solution has not been formally posed. For example, in order to estimate a time for responding to a user's command, some assumptions were made on the types of components that might be used in the design. The last two requirements are operational requirements, ensuring that the device will work in its intended environment.

Table 3.2: Requirements Specification for the iPod™ Hands-Free Device.

Marketing Requirements	**Engineering Requirements**	**Justification**
4, 6	1. System will i*mplement nine voice command* functions (menu, play/pause, previous, next, up, down, left, right and select) and respond appropriately according to each command.	hese are the basic nine commands that are used to control an iPod and will provide all functionality needed.
1, 3, 4, 7	2. The *time to respond* to voice commands and provide audio feedback should not exceed 3 seconds.	The system needs to provide convenient use by responding to the user inputs within a short time period. Based on research it was determined that the response time for the iPod is less than 1 second and an average voice recognition system requires 2 seconds to recognize commands.
4, 6	3. The *accuracy* of the system in accepting voice commands will be between 95% and 98%.	Research demonstrates that this is a typical accuracy of voice recognition chips. Speaker independent systems can achieve 95% and speaker-dependent up to 98%.
5, 6	4. The system should be able to *operate* from a 12 V source and will draw a maximum of 150 mA.	The automobile provides 12V DC. A current draw budget estimate was developed with potential components and 150mA was an upper limit of current estimated.
5, 6, 7	5. The *dimensions* of the prototype should not exceed 6” x 4” x 1.5”.	This system must be able to fit in a car compartment, somewhere between the seats. Estimate is based upon a size budget calculation using typical parts.

Marketing Requirements
1. Should not minimize or slow down the functional quality of the iPod.
2. User should be able to search for songs and artists and receive feedback on selection.
3. System should provide clear understandable speech.
4. System should be able to understand voice commands from user.
5. Should be able to fit and operate in an automobile.
6. Should be easy to use.
7. Should be portable.

3.4.3 Case Study: Gigabit Ethernet Card Testing

Table 3.3 presents an example Requirements Specification developed for the design of an experimental test setup [Ese03]. The Problem Statement for this example was presented in Chapter 2, where the objective was to design a system to test a gigabit Ethernet card for use in a harsh operating environment. In particular, the effects of temperature and vibration variations on the optical power margin, both of which impact the bit-error rate and the system performance, were determined.

The marketing requirements were quite brief and direct, and not surprising due to the fact the customer in this case was group of engineers who had a good idea of what they wanted. The engineering requirements were selected based upon characteristics of the operating environment, through discussion with the engineers, and via some educated guesswork. Let's consider some of the requirements, starting with the effects of temperature variation on the optical power output. The testing requirement on the temperature range was selected based on the operating environment, while the accuracy is driven by the test equipment. The requirements also address the vibration testing requirements, including the vibration frequency range, amplitude, and resonant frequency.

3.4.4 Case Study: Portable Aerial Surveillance System

The Requirements Specification for the Portable Aerial Surveillance System (Problem Statement presented in Chapter 2) is shown in Table 3.4. This system is intended to provide police and emergency responders with a low-cost easy to deploy aerial surveillance system.

This project was developed in conjunction with Penn State Behrend and the Mercyhurst College's Institute for Intelligence Studies to meet a need that the institute identified. The student team met with a number of law enforcement officials to determine the needs. The first engineering requirement addresses the critical functionality that the system is to provide, while engineering requirements 2–5 address the performance and ability to work in the outdoor environment. Note the inclusion of a federal standard that drives the requirement on the maximum deployment height of the device. Requirement 7 addresses the cost, which can often be difficult to justify in student projects, but in this case the team has developed a clear justification.

Table 3.3: System Requirements for a Gigabit Ethernet card testing project.

Marketing Requirements	**Engineering Requirements**	**Justification**
1	Must be able to measure the *optical power output* with an *accuracy* of ± 0.5dB.	This is based upon commercially available optical power measurement instruments.
2	Must be able to measure the *optical power output* from 10°C to 55°C.	This range simulates the operating environment, and 55°C is the maximum operating temperature of the card.
2	The system must maintain *temperature accuracy* to within ± 1°C during all tests.	Based upon accuracy of commercially available test chambers.
3	Must be able to measure optical power over a *frequency range* from 4Hz to 33Hz in increments of 1Hz.	The frequencies encountered in actual operation will not exceed this range.
3	The *peak vibration amplitude* should be 0.01 inches.	The amplitude in the operating environment will not exceed this value.
3	The card should be tested at a given frequency for a *duration* of 1 minute.	This exceeds the expected duration of vibration at given frequency that the system will encounter.
3	The vibration effects should be tested in x, y, and z *directions.*	The system will encounter vibrations in multiple directions. This will provide data on differences in directional variation due to vibration.
3	The experiment should determine *resonant frequency* to an accuracy of ± 0.5Hz.	This will provide data on worst case vibration at the resonant frequency.
Marketing Requirements 1. The measurement of the optical power should be accurate. 2. It should measure the effects of temperature variations on optical power. 3. It should measure effects of vibration on the fiber optic connector and optical power output.		

Table 3.4: System Requirements for the Portable Aerial Surveillance System.

Marketing Requirements	Engineering Requirements	Justification
6	System will provide visual recognition of license plate text from a minimum distance of 150 feet during daytime and nighttime use.	Recorded images and video will be used as trial evidence. The device's maximum height is 150 feet, so the device should allow text recognition at an absolute minimum of that distance. The device must be also usable during nighttime.
4, 9	The device must be operable by a single person.	A police officer dispatched alone in his or her cruiser should be able to launch and operate the device with no assistance.
2	This device must remain airborne for a minimum of two hours.	Based upon interviews with law enforcement users. This is a time period that covers most emergency situations.
7, 8	The device will be able to be used in at least 14 mph winds.	Device will be used outdoors and in non-ideal conditions in Erie, PA, where there is a 95% chance that winds will be at or below 14 mph.
7	The device must not exceed a height of 150 feet above ground level when in use.	This device must comply with FAA regulation 101.15
3	Must fit into the trunk of a police cruiser. The Chevrolet Impala has a trunk measuring 54 inches wide by 38 inches deep by 16 inches high.	Will be transported in a police cruiser and must fit into the trunk of the vehicle.
1	The device will cost less than $3000 per year to operate.	The budget allotted to Erie county police departments was $16.7 million. 0.85% of Erie's annual budget would allow for $140,280 to be used for a helicopter. A device having less than 2% of the annual operating costs of a helicopter, and having many of the same surveillance capabilities would be considered a reasonable expense.
Marketing Requirements		

Table 3.5: Engineering-marketing tradeoff matrix for the audio amplifier. $\uparrow$=positive correlation, $\uparrow\uparrow$=strong positive correlation, $\downarrow$=negative correlation, $\downarrow\downarrow$=strong negative correlation.

		THD	Output Power	η, Efficiency	Install Time	Dimensions	Cost
		-	+	+	-	-	-
1) Sound Quality	+	$\uparrow\uparrow$	$\downarrow$			$\downarrow\downarrow$	$\downarrow\downarrow$
2) High Power	+	$\downarrow$	$\uparrow\uparrow$	$\uparrow$		$\downarrow\downarrow$	$\downarrow$
3) Install Ease	+		$\downarrow$		$\uparrow\uparrow$	$\uparrow$	$\downarrow$
4) Cost	-	$\downarrow\downarrow$	$\downarrow$	$\downarrow$		$\downarrow$	$\uparrow\uparrow$

3.5 Advanced Requirements Analysis

This section examines more advanced methods that are used to analyze and refine requirements. There are tradeoffs between the different requirements and understanding them is valuable for refining the requirements themselves and developing solution concepts. This section addresses tradeoffs between engineering and marketing requirements, tradeoffs between engineering requirements themselves, and benchmarking. At the conclusion, all of this is integrated in to the well-known House of Quality.

3.5.1 The Engineering-Marketing Tradeoff Matrix

This matrix identifies how engineering and marketing requirements impact each other. To demonstrate its construction, we continue to examine the automobile audio amplifier example from Table 3.1. The tradeoff matrix is shown in Table 3.5, where the marketing requirements constitute the row headings and the engineering requirements the column headings.

One of the first things to note is that each requirement has an associated polarity. A requirement with a positive/negative polarity, denoted with a +/- symbol, means that increasing/decreasing that requirement increases the desirability of the product, respectively. A goal is considered a requirement with its polarity. For example, cost almost universally has a negative polarity because decreasing cost almost always makes a product more desirable.

The entries in the body of the matrix can be thought of as a correlation that measures the ability to achieve the marketing and engineering goals simultaneously. A positive correlation (↑) means that both goals can be simultaneously improved, while a negative correlation (↓) means that improving one will compromise the other. Not all correlations are of equal importance, the strength of the correlation being denoted by the number of arrows. Blanks entries in the matrix mean that there is no correlation between the requirements.

To better understand the matrix, consider the entries in the top row associated with sound quality. The relationship between THD and sound quality is denoted by the double positive arrow. This relationship is interpreted as

> *The goal is to increase sound quality and decrease THD. There is a strong positive correlation between them since decreasing THD increases sound quality.*

What wasn't so clear in the 1-to-1 mapping is that there is a link between the goal of maximizing output power and the goal of maximizing sound quality (second entry in the top row). This entry is interpreted as

> *The goal is to increase sound quality, to increase output power, and there is negative correlation between them since increasing output power will decrease sound quality.*

That is because electronics can be designed to achieve larger output power at the expense of sound quality. However, it gets a little more complicated, since output power can be increased without loss in sound quality, if more amplifier stages are employed. That increases the dimensions and cost, thus the relationships between sound quality, cost, and dimensions are identified in the first row. When creating the entries in the matrix, it should be assumed that only the associated requirements can vary and that all others are held constant. When finished, the matrix allows a quick and easy reading of the tradeoffs between engineering and marketing requirements. This example demonstrates the complex nature of a seemingly simple device, and provides a much clearer picture of the design tradeoffs involved.

3.5.2 The Engineering Tradeoff Matrix

The example of output power in the previous section illustrates the need to examine the tradeoffs between the engineering requirements, which are shown in Table 3.6. In this table the engineering requirements constitute the headings for both the row and column entries. Only the entries above

Table 3.6: The engineering tradeoff matrix for the audio amplifier. ↑=positive correlation, ↓=negative correlation.

		THD	Output Power	η, Efficiency	Install Time	Dimensions	Cost
		-	+	+	-	-	-
THD	-		↓			↓	↓
Output Power	+			↑		↓	↓
η, Efficiency	+					↑	↓
Install Time	-					↓	
Dimensions	-						↓
Cost	-						

the upper diagonal elements are filled in due to the redundancy of the lower diagonal elements. Again, positive and negative correlations are indicated along with the strength of correlation.

Let's examine the tradeoffs involved with output power. High output power can be achieved at the expense of THD as shown in the first row of the table. The second row indicates that there is a positive correlation between efficiency and output power, since the more efficient an amplifier is, the more power it can deliver. There is a negative correlation between the dimensions and power, since larger parts and greater surface area aid in dissipating more power. Finally, there is a negative correlation between the output power and cost because of the greater size and number of parts needed to achieve higher power.

3.5.3 Competitive Benchmarks

Competitive benchmarking helps to select targets for the engineering requirements. By analyzing competing systems, a better understanding is gained of what is realistic and where the design may potentially outperform the competition. The benchmark table lists the requirements in the row headings and the competitors in the column headings as shown in Table 3.7.

Table 3.7: Competitive benchmarks for the audio amplifier.

	Apex Audio	**Monster Amps**	**Our Design**
THD	0.05%	0.15%	0.1%
Power	30W	50W	35W
Efficiency	70%	30%	40%
Cost	$250	$120	$100

3.5.4 The House of Quality

A well-known tool for developing requirements is the House of Quality (HOQ). The HOQ is part of a product development process known as Quality Functional Deployment (QFD) that is widely used in industry. QFD is a series of processes for product development that incorporate the needs of the customer throughout the system lifecycle. It encompasses design, manufacturing, sales, and marketing. QFD is characterized by a series of matrices that have a visual appearance similar to that of a house. The matrices relate different aspects of the development process and are effective for communicating between different units in an organization. There are houses for different phases of product development, but here the focus is on using the HOQ for the Requirements Specification. A HOQ for the audio amplifier example is shown in Figure 3.2. It contains all of the elements that we have addressed so far—marketing requirements, engineering requirements, engineering-marketing tradeoffs, engineering tradeoffs, and the target values for the engineering requirements. The HOQ is presented for completeness, but is redundant since it contains all of the information already presented in Tables 3.5–3.7. The HOQ also becomes visually overwhelming and hard to read as problem complexity grows.

3.6 Project Application: The Requirement Specification

The following is a recommended format for a Requirements document that integrates the Problem Statement from Chapter 2.

- *Needs, Objectives, and Background.* Include the elements from the Problem Statement in Chapter 2.

- *Requirements.* Identify the marketing requirements, engineering requirements, and justification in a table format (see Tables 3.1 – 3.4).

Figure 3.2: The complete House of Quality for the audio amplifier example. This integrates the information in Tables 3.5, 3.6, and 3.7.

		THD	Output Power	η, Efficiency	Install Time	Dimensions	Cost
		-	+	+	-	-	-
1) Sound Quality	+	↑↑	↓			↓↓	↓↓
2) High Power	+	↓	↑	↑↑		↓↓	↓
3) Install Ease	+		↓		↑↑	↑	↓
4) Cost	-	↓↓	↓	↓		↓	↑↑
Targets for Engineering Requirements		<0.1%	35 Watts	> 40%	≤ 5 minutes	6 x 8 x 3 inches	≤ $100

Supplement this with tradeoff matrices and competitive benchmarks as necessary.

Table 3.7 presents a self-assessment checklist for the Requirements Specification.

3.7 Summary and Further Reading

This chapter presented a process for developing the Requirements Specification, which consists of identifying the requirements from the user, environment, and input of the technical community. The desirable properties of engineering requirements and the complete Requirements Specification were presented. The verification of a requirement is particularly important, as it seeks to help in answering if the system is being built correctly. Requirements validation addresses whether the requirements meet the needs of the user, or if the correct product is being designed. Tools for benchmarking and analyzing the tradeoffs between requirements were given. Proper determination of the requirements significantly influences all subsequent phases of the design, thus the final requirements document should be agreed upon by all stakeholders.

Table 3.8: Self-assessment checklist for the Requirements Specification. 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree.

Engineering Requirements	**Score**
Each engineering requirement is abstract.	
Each engineering requirement is verifiable.	
Each engineering requirement is unambiguous and written as a concise statement.	
Each engineering requirement can be traced to a user need.	
Each engineering requirement is realistic and has a justification provided.	
Standards and constraints applicable to the project have been identified and included.	
The Requirements Specification	
The requirements are normalized, with minimal redundancy and overlap.	
The engineering requirements are organized by similarity.	
The requirements are complete, addressing all needs.	
The requirements are bounded (not over-specified).	
The requirements have been validated and agreed upon by all stakeholders.	

The processes presented here were developed from research in the field and the authors' teaching experiences. Pugh [Pug90] presents a good perspective on identifying requirements and constraints, although with more emphasis on mechanical systems. The article by Robert Abler [Abl91] is a short primer that provides good advice on how to develop specifications that overlaps with the properties presented in the IEEE Standard 1233 [IEEE Std. 1233-1998].

The HOQ technique was originally developed by Hauser and Clausing [Hau88] and has gained wide acceptance. Their original article provides a case study of the technique applied to the design of automobile door seals as implemented by Toyota Motor Corporation. Ullrich and Eppinger [Ull03] present a good perspective on developing specifications employing the QFD techniques and the HOQ with an emphasis on the voice of the customer.

3.8 Problems

1. Briefly describe the four properties of an engineering requirement.

2. Identify the three levels of standards usage and what is meant by each one.

3. For each of the engineering requirements below, determine if it meets the properties of abstractness, unambiguous, verifiable, and realistic. If a requirement does not satisfy the properties, restate it so that it does:

   (a) The TV remote control will be easy to use.

   (b) The robot will identify objects in its path using ultrasonic sensors.

   (c) The car audio amplifier will be encased in aluminum and will operate in the automobile environment.

   (d) The audio amplifier will have a total harmonic distortion that is less than 2%.

   (e) The robot will be able to move at speed of 1 foot/sec in any direction.

   (f) The system will employ smart power monitoring technology to achieve ultra-low power consumption.

   (g) The system shall be easy to use by a 12 year old.

   (h) The robot must remain operational for 50 years.

4. Provide three example engineering requirements that are technically verifiable, but not realistic.

5. Describe the difference between *verification* and *validation*.

6. Explain how *validation* is performed for a Requirements Specification.

7. Provide an example of a project (real or fictitious) where verification is successful, but validation is unsuccessful.

8. Consider the design of a common device such as an audio CD player, an electric toothbrush, or a laptop computer (or another device that you select). Identify potential marketing and engineering requirements. Consider those categories presented in Section 3.2, as well as any others that are applicable to the problem. You do not need to select the target values, but should identify the measures and units. Present the requirements in a table format as in Table 3.1.

9. Develop a marketing-engineering tradeoff matrix for the device selected in Problem 8.

10. Develop an engineering tradeoff matrix for the device selected in Problem 8.

11. Develop a list of potential standards that would apply to one of the devices proposed in Problem 8, and for each indicate how it would apply to the design.

12. **Project Application.** Develop a complete requirements document for your project as outlined in Section 3.6. Make sure that the engineering requirements meet the five properties identified in the chapter. The team should complete the self-assessment checklist in Table 3.8.

Chapter 4

Concept Generation and Evaluation

Creativity is a great motivator because it makes people interested in what they are doing. Creativity gives hope that there can be a worthwhile idea. Creativity gives the possibility of some sort of achievement to everyone. Creativity makes life more fun and more interesting.—Edward DeBono

When developing a design, it is important to explore many potential solutions and select the best one from them. Too often a single concept is generated and is the only one pursued, the unfortunate result being that potentially better solutions are not considered. When confronted with a problem, engineers must explore different concepts, critically evaluate them, and be able to defend the decisions that led to a particular solution. Two key thought processes employed are creativity and judgment. Creativity involves the generation of novel concepts, while judgment is applied to evaluate and select the best solution for the problem. Creativity and judgment appear to be inherent individual qualities that can't be taught. That is to some extent true, but with practice and application of formal techniques, they can be improved.

It is important to distinguish between innovation and creativity. Creativity refers to the ability to develop new ideas, while innovation is the ability to bring creative ideas to reality. Innovation is valued by companies since new products and services are often their lifeblood. That is why many make it a priority to hire engineers who can bring creativity to the design process. This chapter addresses creativity, concept generation, and evaluation in design. The first part describes barriers to creative thought,

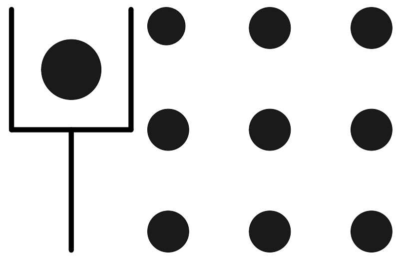

Figure 4.1: (a) The shovel problem. Think of this as a shovel with a coin on the spade. The objective is to move two lines so that the coin is no longer in the spade, but there is still a shovel. (b) The nine dot problem. Draw four connected straight lines that pass through all nine dots.

followed by strategies for overcoming them and enhancing creativity. Next, methods for concept generation are presented, followed by techniques for concept evaluation.

Learning Objectives

By the end of this chapter, the reader should:

- Understand the importance of creativity, innovation, concept generation, and concept evaluation in engineering design.
- Be familiar with the barriers that hinder creativity.
- Be able to apply strategies and formal methods for concept generation.
- Be able to apply techniques for the evaluation of design concepts.

4.1 Creativity

Is creativity something that is inherent in the individual or something that can be learned? It appears that both are true; some individuals are naturally more creative than others, yet people can enhance their creativity with conscious effort and practice. This section examines barriers to creativity, different thinking modes, and strategies for enhancing creativity. One of the ways to spark creativity is to solve puzzles. To get into the creative spirit the reader can try to solve the puzzles presented in Figure 3.

4.1.1 Barriers to Creativity

James L. Adams, an engineer and former professor at Stanford University, has researched innovation in technical domains. He examined the barriers to creativity and classified them into the following four types: 1) perceptual blocks, 2) emotional blocks, 3) cultural and environmental blocks, and 4) intellectual and expressive blocks [Ada01].

Perceptual blocks are those that prevent people from clearly seeing the problem for what it is. A common perceptual block is the tendency to delimit the problem space, or in other words, to put constraints on the problem that don't exist. Have you solved the puzzles shown in Figure 3 yet? If not, it is possible that you are placing constraints on the problems that don't exist. Knowing that this is the case, you may want to go back and try again. Another example of a perceptual block is the tendency to stereotype or see a solution to a problem that one is biased to see. This occurs because we have used similar techniques for solving the problem in the past. For example, if you have used a microcontroller to solve a certain type of problem, chances are that you are going to consider using a microcontroller in all related problems in the future. Another perceptual block is the difficulty of isolating the true problem. Three pictures that illustrate this are shown in Figure 4.2. When examining these images, people tend to form a conclusion as to what the content of each one is. Look carefully, as each picture has two equally valid interpretations.

One of the most common *emotional blocks* is the fear of failure. People often have creative ideas, but are afraid to express them since they may be criticized or may not have the "correct" answer. It is cliché to hear that you must fail often to succeed, but true. The highly successful product design company, IDEO, that was examined in Chapter 2 takes the approach in concept generation to "*fail early and often*" in order to succeed [Kel01]. Their design teams are encouraged to develop many seemingly outlandish ideas that are often discarded, but sometimes lead to innovative solutions. Another emotional block is a fear of chaos and disorganization. The creative process challenges engineers, since it is disorganized and not a neat scientific approach to which they are accustomed. Another block is the tendency to critically judge ideas, rather than generate and build upon them. Finally, it takes time for creative ideas to incubate. Most of us can relate to the experience when we could not solve a problem that nagged us for a period of time, followed by that unexpected *"Aha!"* moment when we identified the solution.

Environmental blocks refer to those things in our environment that limit

Figure 4.2: Each of the images shown above has two different interpretations. Can you determine what they are?

creative ability. This could be in the form of poor teamwork where members distrust each other and criticize each other's ideas. In the workplace, this could be due to autocratic management that resists new ideas. There are also cultural biases against creativity. There is a bias against creativity as an approach to problem solving in the engineering field. This is usually based upon the reasoning that there is a single correct solution to a problem and creativity is an excuse for poor engineering. It is true that creativity and brainstorming alone do not solve engineering problems—the concepts generated need to be scrutinized using engineering principles to become viable innovations.

The final block that Adams identified is that of *intellectual and expressive*. In an engineering context, this means that the designer needs to have an understanding of intellectual tools that are applied to solve problems. For example, mathematics is a universal language for expressing and solving scientific problems. Specific examples in ECE are languages that describe the characteristics of systems such as functional, logical, and state behaviors. Examples in digital design are truth tables (input, output behavior) and state diagrams (stimulus-response). In the domain of electronics design, a functional approach (input, output, and function) is commonly used. Chapters 5 and 6 present tools for modeling the behavior of ECE systems.

4.1.2 Vertical and Lateral Thinking

Edward DeBono is the father of a field known as ***lateral thinking***, which offers a different perspective on the barriers to creativity. Lateral thinking is contrasted to what is known as the vertical thinking process [Deb67, Deb70]. Engineers tend to be vertical (or convergent) thinkers, meaning that they are good at taking a problem and proceeding logically to the solution. This is typically a sequential linear process, where the engineer starts at the highest level and successively refines elements of the design to solve the problem. This is usually based upon experience solving similar problems and conventional tools that are employed in that particular area.

The objective of lateral (or divergent) thinking is to identify creative solutions. It is not concerned with developing the solution for the problem, or right or wrong solutions. It encourages jumping around between ideas. In the words of DeBono "*The vertical thinker says: 'I know what I am looking for.' The lateral thinker says: 'I am looking but I won't know what I am looking for until I have found it.'* " The field of lateral thinking is characterized by puzzles of the following type found at Paul Sloane's Lateral Thinking Puzzles website [`http://dspace.dial.pipex.com/sloane`]:

A body is discovered in a park in Chicago in the middle of summer. It has a fractured skull and many other broken bones, but the cause of death was hypothermia.

A hunter aimed his gun carefully and fired. Seconds later, he realized his mistake. Minutes later, he was dead.

A man is returning from Switzerland by train. If he had been in a non-smoking car he would have died.

The objective in these puzzles is to develop plausible scenarios that explain how each of the above situations could have happened. A solution for the first example is that a person stowed away in the wheel compartment of a jet airliner. While in flight he froze and died of hypothermia. When the plane prepared to land, it lowered its landing gear, causing the body to fall to the park, fracturing his skull, and breaking his bones. Can you develop plausible scenarios that describe each of them?

Vertical thinking focuses on sequential steps toward a solution and tries to determine the correctness of the solution throughout the process. This is very different from lateral thinking where there is nonlinear jumping around between steps and there is no attempt to discern between right and wrong. As such, lateral thinking is more apt to follow least likely paths to a solution, whereas vertical thinking follows the most likely paths. The goal in lateral thinking is to develop as many solutions as possible, while vertical thinking tries to narrow to a single solution.

Lateral thinking is appropriate for the concept generation phase. So should concept generation and brainstorming be done by the individual or by a team? DeBono and Osborn [Osb63] conclude that creativity is more effective by individuals than by teams. However, Osborn also points out that there is great value in applying creativity in teams, since it provides a place for the team to work together on problems and see other perspectives. Our anecdotal observations of student design teams supports this—group brainstorming is effective for developing concepts, new product ideas, new features, and different ways to combine technologies. This is because in groups, ideas are readily built upon by other team members. More mathematical, technical, and theoretical breakthroughs tend to be the work of the lone genius. Examples of this are the Theory of Relativity (Einstein), Boolean Logic (Bool), and Shannon's Sampling Theorem. We have also observed that novice designers, who do not have much experience in concept generation, can benefit greatly from group brainstorming techniques.

4.1.3 Strategies to Enhance Creativity

There are valuable strategies that can be employed to enhance the creative process. The body of research on the subject is very large and key points are summarized as follows:

- *Have a questioning attitude.* One of the keys is to have a questioning attitude and challenge assumptions. The willingness to do this generally decreases as people age. Young children are highly creative and are constantly questioning everything, with questions such as "*Why do trees have leaves?*" or "*Why is the sky blue?*" Asking basic questions stimulates creativity and is applicable to technical designs. When examining a design with a microcontroller, ask questions such as "*Is there a way to replace the microcontroller?*", "*Are there other features that I can achieve with the microcontroller?*", and "*Is there a better microcontroller that can be used?*"

- *Practice being creative.* Research shows that people can improve their creative ability through conscious effort. For example, try solving the puzzles presented in this chapter and in the end of the chapter problems. Be conscious of things that bother you ("pet peeves") in your everyday life and try to develop new solutions for them.

- *Suspend judgment.* It is easy to criticize and immediately dismiss ideas, so it is important to defer judgment and be flexible in thinking. Seemingly outlandish ideas can lead to other concepts that are valuable solutions. The opportunity for new solutions is curtailed if ideas are immediately judged and discarded. Creative concepts can be developed by taking a concept and modifying it or combining it with other seemingly unrelated concepts.

- *Allow time.* The creative process needs time for incubation. The human mind needs time to work on problems, so set aside time to reflect on the problem and to allow it to incubate so that the "*Aha!*" moment of discovery can happen.

- *Think like a beginner.* New solutions often come from novices. The reason is that novices don't have preconceived ideas as to the solution for a problem. Experience is a double-edged sword—it allows one to quickly solve problems by drawing upon pre-existing solutions, but can inhibit creativity. If confronted with a new problem that bears similarity to one encountered in the past, then it is likely that the new solution will bear similarity to the old one. If everyone else is it doing it one way, consider the opposite.

Many creative ideas arise from novel combinations and adaptations of existing technology. SCAMPER, an acronym for Substitute, Combine, Adapt, Modify, Put to other use, Eliminate, and Rearrange/Reverse, can be used as a guide to systematically generate creative concepts. The SCAMPER principles are valuable in brainstorming and are described below:

- *Substitute.* Can new elements be substituted for those that already exist in the system?

- *Combine.* Can existing entities be combined in a novel way that has not been done before?

- *Adapt.* Can parts of the whole be adapted to operate differently?

- *Modify.* Can part or all of a system be modified? For example, size, shape, or functionality.

- *Put to other use.* Are there other application domains where the product or system can be put to use?

- *Eliminate.* Can parts of the whole be eliminated? Or should the whole itself be eliminated?

- *Rearrange or Reverse.* Can elements of the system be rearranged differently to work better? This is different from substituting in that the elements of the system are not changed, but rearranged or ordered differently to create something new. In terms of reversal, are there any roles or objectives that can be reversed?

SCAMPER is a modification of a set of questions that was originally posed by Osborn [Osb63] and was modified to its form above by Michalko [Mic91].

4.2 Concept Generation

After the problem is defined, the next step is to explore concepts for the solution. It is unlikely that a design team will have reached this stage without some ideas for solving the problem, but it is important to fully explore the design space. Ullrich and Eppinger [Ull03] identify the following phases of concept generation – search internally, search externally, and systematically explore. Each is considered in turn.

External searching was covered to a great extent in Chapters 2 and 3, which addressed conducting background research and benchmarking. Methods of external searching are:

- Conduct literature search.
- Search and review existing patents.
- Benchmark similar products.
- Interview experts.

Internal searching is done by the team members via methods such as brainstorming. The team members need have to have a common problem definition for this to be effective. Understanding the tradeoffs using requirement analysis methods in Chapter 3 is also valuable, as overcoming tradeoffs leads to innovative solutions. Furthermore, the team should decompose larger problems into sub-problems and the attack the sub-problems individually. Chapter 5 addresses the process of problem decomposition.

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The most well-known method of internal searching is ***brainstorming***. Group brainstorming is effective for generating many concepts in a short period of time. Experienced design teams are known to generate hundreds of concepts in an hour. Traditional brainstorming is not highly-structured—though a facilitator helps—and employs five basic rules:

- No criticism or judgment of ideas.
- Wild ideas are encouraged.
- Quantity is stressed over quality.
- Build upon and modify the ideas of others.
- All ideas are recorded.

Figure 4.3: Wally brainstorming. (Dilbert © United Feature Syndicate. Reprinted by permission.

Many novice design teams struggle with unstructured brainstorming and more formalized approaches, such as brainwriting and the Nominal Group Technique, can be of benefit. The steps of ***brainwriting*** are:

1. The team develops a common problem statement that is read out loud.
2. Each team member writes their ideas down on a card and places it in the center of the table.
3. Other team members then take cards from the pile and use other's ideas to generate new ones or build upon them, keeping in mind the principles of SCAMPER. Alternatively, members can each generate an idea, write it on a card, and then pass it to another team member. Each member then builds upon the idea passed to them.

Brainwriting 6-3-5 is a variation where the objective is to have six people, develop three ideas in five minutes. The optimal number of people for the exercise is thought to be six, although it is not necessary. Each person generates three ideas in five minutes, and clearly describes it using sketches and written descriptions on paper. At the end of five minutes, each team member passes their ideas to another team member. The next person reviews the ideas of their teammate and adds three more by building on them, developing new ones, or ignoring as necessary. This process continues until all members have reviewed all papers.

In the ***Nominal Group Technique*** (NGT) [Del71] each team member silently generates ideas that are reported out in a round-robin fashion so that all members have an opportunity to present their ideas. Concepts are selected by a multi-voting scheme with each member casting a predetermined number of votes for the ideas presented. The ideas are then ranked, discussed further, and voted upon again if necessary. The steps of NGT are as follows:

- *Read problem statement.* It should be read out loud by a team member (the facilitator).
- *Restate the problem.* Each person restates the problem in their own words to ensure that all members understand it.
- *Silently generate ideas.* All members silently generate ideas during a set period of time, typically 5–15 minutes.
- *Collect ideas in a round-robin fashion.* Each person presents one idea in turn until all ideas are exhausted. The facilitator should clarify ideas and all should be written where the entire team can view them.
- *Summarize and rephrase ideas.* Once the ideas are collected, the facilitator leads a discussion to clarify and rephrase the ideas. This ensures that the entire group is familiar with them. Related ideas can be grouped or merged together.
- *Vote.* Each person casts a predetermined number of votes, typically three to six, for the ideas presented. The outcome is a set of prioritized ideas that the team can further discuss and pursue.

To systematically generate concepts, the problem is decomposed sub-functions and solutions are sought for the sub-functions. A ***concept table***, demonstrated in Table 4.1, is a tool for identifying different combinations, arrangements, and substitutions. The table headings identify functions to be achieved in the design, while the entries in the corresponding column represent potential solutions. Novel products or solutions are generated by combining elements from each of the columns, which are identified in the table by circled elements. The solutions can be in the form of a single element selected from each column, or as in the example shown, multiple elements selected from each column.

Based on the concepts circled in Table **??**, one can imagine a personal computing system that has the following features: 1) is wearable with different credit card size components placed on the body and in clothing to make it comfortable to use; 2) is powered by a combination of solar cells, fuel-cells, and from thermal heat generated by a person's body; 3) has a microphone

Table 4.1: A concept table for generating ideas for a personal computing system. The potential solution is identified by the combination of circled elements.

User Interface	**Display**	**Connectivit & Expansion**	**Power**	**Size**
Keyboard	CRT	Serial & Parallel	Battery	Hand-held, Fits in pocket
Touchpad	Flat Panel	USB	AC Power	Notebook size
Handwriting Recognition	Plasma	Wireless Ethernet	Solar Power	Wearable
Video	Heads-up Display	Wired Ethernet	Fuel Cell	Credit Card Size
Voice	LCD	PCMCIA	Thermal Transfer	Flexible in shape
		Modem / Telephone		

and camera integrated in the user's clothing for interface to the system, as well as a flexible foldable keyboard for typing that is stored in a pocket; 4) has a heads-up display integrated with the user's eyeglasses or baseball hat; and 5) has a miniature earpiece microphone used for communication. While the above example focused on novel combinations and substitutions, the concept table can also be used to examine the possibility of eliminating ideas. For example, the table inherently assumes that a display will be used. However, it should also be asked if it is absolutely necessary in the design.

Another example is shown in Table 4.2, where the objective is to identify design concepts for a temperature measurement and display device. There are three main elements to the proposed solution: the thermal sensing method, circuitry that converts the sensor information (temperature) to a voltage, and a display unit that converts the voltage to a displayed temperature. Note that the table implies a three-stage architecture, thus concepts are generated within that framework. There may be completely different architectures that are better.

A related tool is a ***concept fan,*** which is a graphical representation of design decisions and choices. An example concept fan for the temperature

Table 4.2: Concept table for a temperature measurement device.

Thermal Sensing	Conversion to Voltage	Display
Thermistor	Op Amp Design	Seven-Segment LEDs
RTD	Transistor Designs	LCD
Thermocouple		Analog Dial Indicator

measuring device is shown in Figure 4.5. Design decisions are identified by circles; solutions are indicated by squares. In this example, more options are shown than in Table 4.2. Concepts are generated by selecting among the different solution blocks.

4.2.1 Concept Evaluation

The concepts generated are evaluated to determine which are the most promising to pursue. The designer should exercise engineering judgment and use the customer needs and technical factors to drive the decision. This process is shown in Figure 4.5, where the user needs, concepts, and engineering consideration serve as inputs to a decision process to ranks the concepts. A point of caution—some of the methods presented generate numerical scores for comparing concepts, leading one to potentially believe that the quantitative results are infallible. Keep in mind that the inputs are based on qualitative and semi-quantitative assessments and can be geared to select a preconceived notion of the solution. It is important to maintain flexibility of thinking, to challenge assumptions, and ultimately determine the best concept.

4.2.2 Initial Evaluation

The concepts generated should be initially reviewed and those that are completely infeasible discarded. Some of the reasons a concept may be deemed infeasible are that it may be far too costly, will take too long to develop, or involve too much risk. In many cases it may be deemed that using cutting-edge technology represents an unacceptable risk. Concepts that clearly cannot meet the engineering requirements should also be discarded. Care should be taken not to completely eliminate ideas that may have merit, as conditions change and some concepts that were previously thought unrealistic may become viable in the future.

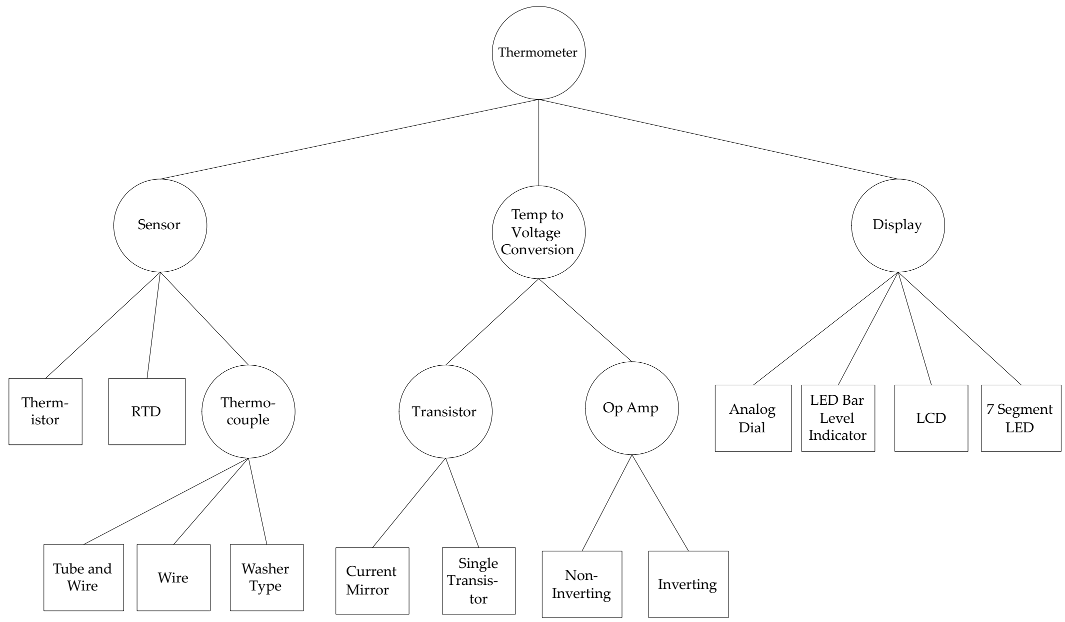


Figure 4.4: A concept fan for the temperature measuring device. The circles represent the choices to be made and the squares represent potential solutions to the choices.

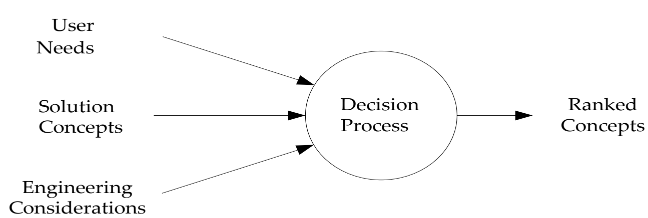


Figure 4.5: Process for concept evaluation.

Table 4.3: **Table 4.3** A strengths and weaknesses analysis of proposed methods for heating an Intel 1000XF card to be used in lifetime testing. [Ese03].

Method	Strengths	Weaknesses
Contact Heating	• Simplest design • Could be used internally to computer	• Does not create uniform temperature • Hard to control temperature
Temperature Chamber	• Uniform temperature • Greater control over temperature	• Must be external to computer • More difficult to design • Expensive

4.2.3 Strengths and Weaknesses Analysis

Another form of evaluation is to complete a ***strengths and weaknesses analysis*** of the potential solutions. Table 4.3 demonstrates the application of this analysis applied to an experimental design project for testing of the Intel 1000XF card (examined in Chapter 2 (Example 2.2) and Chapter 3 (Table 3.2)). In order to test the card under different operating temperatures, a method of heating the card and holding its temperature fixed during the experiment was needed. The two solutions compared were to use a contact heating element or to place the card in an environmental test chamber. In this particular example, the temperature chamber solution was ultimately selected due to the need for a uniform temperature distribution. The strength and weakness analysis is good for examining problems of moderate complexity. It suffers in that it does not require uniform criteria for comparison. To make the method more quantitative, relative scores for the strengths (plus factors) and weaknesses (minus factors) can be assigned and used to score the concepts.

4.2.4 Analytical Hierarchy Process and Decision Matrices

In the Analytical Hierarchy Process, design alternatives are compared against pre-selected criteria, such as the engineering or marketing requirements. AHP is covered in detail in Appendix B and was first applied in Chapter

Table 4.4: A decision matrix for the Analytical Hierarchy

		Design Option 1	**Design Option 2**		**Design Option n**
Criteria 1	ω_1	α_{11}	α_{12}	...	α_{1n}
Criteria 2	ω_2	α_{21}	α_{22}	...	α_{2n}
Criteria $\boldsymbol{m}$	ω_m	α_{m1}	α_{m2}	...	α_{mn}
Score		$S_1 = \sum_{i=1}^{m} \omega_i * \alpha_{i1}$	$S_2 = \sum_{i=1}^{m} \omega_i * \alpha_{i2}$	...	$S_n = \sum_{i=1}^{m} \omega_i * \alpha_{im}$

Table 4.5: Pairwise comparison matrix.

	Accuracy	**Cost**	**Size**	**Availability**	**Weights**
Accuracy	1	5	3	$\frac{1}{4}$	0.42
Cost	1/5	1	2	$\frac{1}{4}$	0.12
Size	1/3	$\frac{1}{2}$	1	1	0.12
Availability	4	4	1	1	0.34

2 for project selection. The reader is encouraged to review Appendix B as necessary. The end result of AHP is a decision matrix is shown in Table 4.4, where the criteria are listed in the leftmost column with the associated weighting factors (ω_i) quantifying the relative importance of the criteria. The body of the matrix contains design ratings, α_{ij}, that reflect the technical merit of each of the j^{th} design options relative to i^{th} criterion. The total score, S_j, for each design option is computed as a weighted summation of the design ratings and weighting factors.

Table 4.4 Process.

The application of AHP is demonstrated for the design of an electronic circuit for measuring temperature, by producing a voltage signal that is directly proportional to temperature.

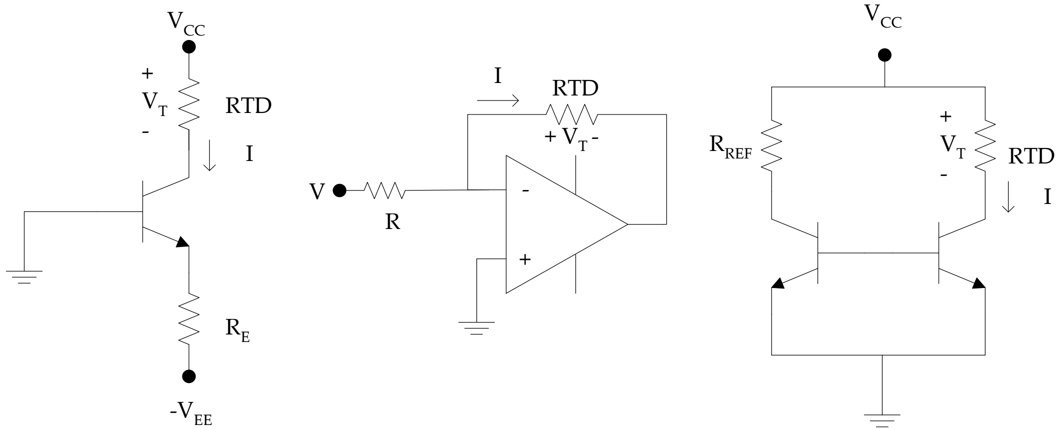
Step 1: Determine the Selection Criteria

Assume that the criteria for comparing the concepts are high accuracy, low cost, small size, and availability of parts for manufacture.

Step 2: Determine the Criteria Weightings

Assume that the criteria were ranked using pairwise comparison and weights computed (see Appendix B) as shown in Table 4.5.

Figure 4.6: Candidate solutions for temperature measurement.



1: Single Transistor 2: Inverting Op Amp 3: Current Mirror

Step 3: Identify and Rate Alternatives Relative to the Criteria

Three candidate solutions are shown in Figure 4.6. Each acts as a constant current source that drives a temperature measurement device (RTD). The resistance of an RTD varies with temperature, and when driven by a constant current, I, produces a voltage, V_T, that varies proportionally with temperature. Each circuit supplies a constant current of I=1mA.

The accuracy of each design was evaluated by a sensitivity analysis using a SPICE circuit simulation package assuming 10% resistors. The deviation of the output voltage (maximum deviation from nominal) for the three designs is 9.2%, 1.3%, and 1.9% respectively. Since the objective is to minimize the deviation, the following rating metric is used:

$$\alpha = \frac{min[deviation]}{deviation}$$

This produces the following normalize design ratings for accuracy: $\alpha 11 = 0.008$, $\alpha 12 = 0.55$, and $\alpha 13 = 0.37$.

The parts costs are the following: resistors = \$0.05, bipolar junction transistors (BJTs) = \$0.15, op amps = \$0.35, and RTDs = \$0.25. Using a measure for cost similar to (1) gives following normalized cost ratings for the three options respectively: $\alpha 21 = 0.31$, $\alpha 22 = 0.28$, and $\alpha 23 = 0.31$.

Assume that to manufacture each circuit on a printed circuit board requires the following dimensions: design 1 = 1 in^2, design 2 = 1.56 in^2, and design 3 = 2.25 in^2. The objective is to minimize size, and againusing a

Table 4.6: The decision matrix.

		Single BJT	**Op Amp**	**Current Mirror**
Accuracy	0.42	0.08	0.55	0.37
Cost	0.12	0.41	0.28	0.31
Size	0.12	0.48	0.31	0.21
Availability	0.34	0.35	0.40	0.25
Score		0.26	0.44	0.30

measure analogous to (1) for the required space to manufacture each produces the following normalized decision ratings: $\alpha 31 = 0.48$, $\alpha 32 = 0.31$, and $\alpha 33 = 0.21$.

Assume that the parts have an in-stock availability of 95%, 70%, 90%, and 80% of the time for the resistors, BJTs, RTDs, and op amps respectively. A measure for the overall availability of parts to manufacture each design is required. One way to measure this is to compute the probability that a design will be able to be manufactured based upon the past history of part availability. This is found by multiplying the availability of all individual components needed for the design:

P(design 1 can be produced) = (0.95)(0.90)(0.70) = 0.60

P(design 2 can be produced) = (0.95)(0.90)(0.80) = 0.68

P(design 3 can be produced) = (0.95)(0.90) (0.70)(0.70) = 0.42

This produces the following normalized decision ratings for availability: $\alpha 41 = 0.35$, $\alpha 42 = 0.40$, and $\alpha 43 = 0.25$.

Step 4: Compute Scores for the Alternatives

The decision matrix is built and the overall weighted scores for the alternatives are computed as shown in Table 4.6.

Step 5: Review the Decision

Remember that this is a semi-quantitative method. The final ranking indicates that design options 1 and 3 are quite similar, while both are inferior to option 2.

4.2.5 Pugh Concept Selection

Pugh Concept Selection is a method of comparing concepts against criteria, similar to what we saw with a decision matrix. It is different in that it has

Table 4.7: Pugh Concept Selection matrix.

		Option 1 (Reference)	Option 2	Option 3	Option 4
Criteria 1	4	-	0	0	+1
Criteria 2	5	-	+1	-1	0
Criteria 3	2	-	-1	0	+1
Criteria 4	1	-	+1	+1	-1
Score		-	4	-4	5
Continue?		Combine	Yes	No	Combine

a simpler scoring method and it is an iterative process. The steps of Pugh Concept Selection are:

1. Select the comparison criteria, usually the engineering or marketing requirements.
2. Determine weights for the criterion.
3. Determine the concepts.
4. Select a baseline concept that is initially believed to be the best.
5. Compare all other concepts to the baseline, using the following scoring method: +1 better than, 0 equal to, -1 worse than.
6. Compute a weighted score for each concept, not including the baseline.
7. Examine each concept to determine if it should be retained, updated, or dropped. Synthesize the best elements of others into other concepts wherever possible.
8. Update the table and iterate until a superior concept emerges.

An example of a Pugh Concept Selection matrix is shown in Table 4.7.

4.3 Project Application: Concept Generation and Evaluation

The following advice is provided for teams in the concept generation and evaluation phase:

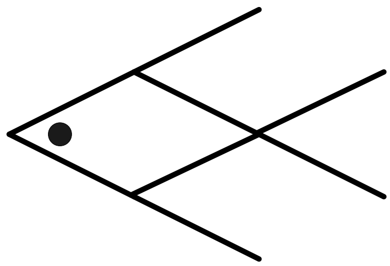
- Set aside time specifically for concept generation and evaluation and take it as a challenge to identify as many concepts as possible.

- Search externally, including literature reviews and patent searches.
- Search internally using brainstorming, brainwriting, or the Nominal Group Technique. Effective teams generate many concepts in a brainstorming session.
- Examine solutions for the entire design, for sub-functions of the design, and for individual components (such as integrated circuit selection). The techniques in this chapter can be combined with design methods presented in Chapters 5 and 6.
- Utilize SCAMPER, concept tables, and concepts fans as tools to facilitate and document concept generation.
- Critically and objectively evaluate concepts against common criteria.
- Clearly identify the concept(s) selected and the rationale for selection.

4.3.1 Summary and Further Reading

In the design process, it is important to creatively generate different concepts for a solution to a problem. This is followed by an evaluation of concepts to determine which are the most promising. This chapter identified barriers to creativity and provided strategies for enhancing creative ability. The concepts of vertical and lateral thinking were introduced, and their impact on the design process was explored. Methods of concept generation, including brainstorming, concept tables, and concepts fans were presented. Finally, methods for critically evaluating concepts (strength/weakness analysis, Analytical Hierarchy Process, and Pugh Concept selection) were presented.

There are many references that examine creativity and concept generation. Adams [Ada01] is a good reference for creativity and problem-solving with a technical bent. Alex Osborn was an advocate of creativity and developed two readable works that address the creative process, the need for creativity, and strategies for enhancing it [Osb48, Osb63]. Edward DeBono is another well-known authority in the field and has produced many works on lateral thinking and creativity [Deb67, Deb70]. Paul Sloane has published numerous books with lateral thinking puzzles [Slo91, Slo93, Slo94]. TRIZ [Alt99] is a more advanced and complex approach to concept generation, that centers around resolving tradeoffs in a problem. It is fairly complex and may be considered by more advanced teams.



4.4 Problems

1. Consider the nine dot puzzle shown in Figure 4.1 (b). Draw **three** connected straight lines that pass through all nine dots.

2. Consider the six sticks shown below. Rearrange the sticks to produce four equilateral triangles (the sticks cannot be broken).

3. Consider the fish shown below made of eight sticks and a coin for the eye. The objective is to make the fish face the other direction by moving only the coin and three sticks.

4. For each of the following lateral thinking puzzles, develop a plausible solution (from Paul Sloane's Lateral Thinking Puzzles [http://dspace.dial.pipex.com/sloane]):

   - A man walks into a bar and asks the barman for a glass of water. The barman pulls out a gun and points it at the man. The man says 'Thank you' and walks out.
   - A woman had two sons who were born on the same hour of the same day of the same year. But they were not twins. How could this be so?
   - Why is it better to have round manhole covers than square ones?
   - A man went to a party and drank some of the punch. He then left early. Everyone else at the party who drank the punch subsequently died of poisoning. Why did the man not die?

5. Legislation was passed to allow handguns in the cockpits of passenger airliners to prevent hijacking. Brainstorm to develop concepts that prevent anyone other than the pilot from using the handgun.

6. Imagine if scientists and engineers were able to develop a technology that would allow people to be transported from any place on earth

	Accuracy	Cost	Size	Availability
Accuracy	1	1/3	2	$\frac{1}{2}$
Cost	3	1	5	1
Size	1/2	1/5	1	2
Availability	2	1	$\frac{1}{2}$	1

to another instantaneously. Brainstorm to determine the potential impact this would have on society.

7. Student advising at many colleges and universities is seen as an area that can be improved. Brainstorm to develop ideas as to how student advising could be improved at your college or university.

8. In your own words, describe what a concept table and a concept fan are.

9. Consider the problem solved in Section 4.3.2. For this example assume that:

   - The following is the result of the paired comparison.
   - The parts costs are the following: resistors = \$0.05, bipolar transistors (BJTs) = \$0.10, op amps = \$0.35, and RTDs = \$0.25.
   - The parts have an in-stock availability of 99%, 90%, 85%, and 70% of the time for the resistors, BJTs, RTDs, and op amps respectively.
   - Everything else is the same as presented in Section 4.3.2.

   Compute the rankings of the design options using a weighted decision matrix of the type shown in Table 4.5.

10. **Project Application.** Utilize the methods in this chapter to generate concepts for your particular design problem. Critically evaluate the concepts generated using one or more of the techniques presented in the chapter that is appropriate for the problem. Section 4.4 provides guidance on how to conduct this process and document the results.

Appendix A Glossary

Term	Definition
acceptance test	An acceptance test verifies that the system meets the ***Requirements Specification*** and stipulates the conditions under which the customer will accept the system (Chapter 7).
activity on node	A form of a ***network diagram*** used in a project plan. In the Activity on Node (AON) form, activities are represented by nodes and the dependencies by arrows (Chapter 10).
activity	An activity is a combination of a ***task*** and its associated ***deliverables*** that is part of a project plan (Chapter 10).
activity view	The activity view is part of the ***Unified Modeling Language***. It is characterized by an activity diagram; its ***intention*** is to describe the sequencing of processes required to complete a task (Chapter 6).
Analytical Hierarchy Process (AHP)	A decision-making process that combines both quantitative and qualitative inputs. It is characterized by weighted criteria against which the decision is made, a numeric ranking of alternatives, and computation of a numerical score for each alternative (Appendix B and Chapters 2 and 4).
artifact	System, component, or process that is the end-result of a design (Chapter 2).
automated script test	An automated script test is a sequence of commands given to a unit under test. For example, a test may consist of a sequence of inputs that are provided to the unit, where the outputs for each input are then verified against pre-specified values (Chapter 7).
baseline requirements	The original set of requirements that are developed for a system (Chapter 3).
black box test	A test that is performed without any knowledge of internal workings of the unit under test (Chapter 7).

Term	Definition
bottom-up design	An approach to system design where the designer starts with basic components and synthesizes them to achieve the design objectives. This is contrasted to ***top-down*** design (Chapter 5).
Bohrbug	Bohrbugs are reliable ***bugs***, in which the error is always in the same place. This is analogous to the electrons in the Bohr atomic model which assume a definite orbit (Chapter 7).
brainstorming	A freeform approach to concept generation that is often done in groups. This process employs five basic rules: 1) no criticism of ideas, 2) wild ideas are encouraged, 3) quantity is stressed over quality, 4) build upon the ideas of others, and 5) all ideas are recorded (Chapter 4).
Brainwriting	A variation of ***brainstorming*** where a group of people systematically generate ideas and write them down. Ideas are then passed to other team members who must build upon them.
break-even point	The break-even point is the point where the number of units sold is such that there is no profit or loss. It is determined from the total costs and revenue (Chapter 10).
bug	A problem or error in a system that causes it to operate incorrectly (Chapter 7).
cardinality ratio	The cardinality ratio describes the multiplicity of the entities in a relationship. It is applied to ***entity relationship diagrams*** and Unified Modeling Language ***static view diagrams*** (Chapter 6).
class	Classes are used in object-oriented system design. A class defines the attributes and methods (functions) of an ***object*** (Chapter 6).
cohesion	Refers to how focused a module is—highly cohesive systems do one or a few things very well. Also see ***coupling*** (Chapter 5).
component design specification	See ***subsystem design specification*** (Chapter 3).
concept fan	A graphical tree representation of design decisions and potential solutions to a problem. Also see ***concept table*** (Chapters 1 and 4).
concept generation	A phase in the ***design process*** where many potential solutions to solve the problem are identified (Chapter 1).
concept table	A tool for generating concepts to solve a problem. It allows systematic examination of different combinations, arrangements, and substitutions of different elements for a system. Also see ***concept fan*** (Chapter 4).

Term	Definition
conditional rule-based ethics	An ethics system in which there are certain conditions under which an individual can break a rule. This is generally because it is believed that the moral good of the situation outweighs the rule. Also see ***rule-based ethics*** (Chapter 11).
constraint	A special type of requirement that encapsulates a design decision imposed by the environment or a stakeholder. Constraints often violate the abstractness property of engineering requirements (Chapter 3).
controllability	A principle that applies to testing. Controllability is the ability to set any node of the system to a prescribed value (Chapter 7).
copyright	Copyrights protect published works such as books, articles, music, and software. A copyright means that others cannot distribute copyrighted material without permission of the owner (Chapter 11).
coupling	Modules are coupled if they depend upon each other in some way to operate properly. Coupling is the extent to which modules or subsystems are connected. See also ***cohesion*** (Chapter 5).
creative design	A formal categorization of design projects. Creative designs represent new and innovative designs (Chapter 2).
critical path	The path with the longest duration in a project plan. It represents the minimum time required to complete the project (Chapter 10).
cross-functional team	Cross-functional teams are those that are composed of people from different organizational functions, such as engineering, marketing, and manufacturing. Also see ***multi-disciplinary team*** (Chapter 9).
data dictionary	A dictionary of data contained in a ***data flow diagram***. It contains specific information on the data flows and is defined using a formal language (Chapter 6).
data flow diagram	The ***intention*** of a data flow diagram (DFD) is to model the processing and flow of data inside a system (Chapter 6).
decision matrix	A matrix that is used to evaluate and rank concepts. It integrates both the user-needs and the technical merits of different concepts (Chapter 4).
derating	A decrease in the maximum amount of power that can be dissipated by a device. The amount of derating is based upon operating conditions, notably increases in temperature (Chapter 8).
deliverable	Deliverables are entities that are delivered to the project based upon completion of ***tasks.*** Also see ***activity*** (Chapter 10).

Term	Definition
descriptive design process	Describes typical activities involved in realizing designs with less emphasis on exact sequencing than a ***prescriptive design process*** (Chapter 1).
design architecture	The main (Level 1) organization and interconnection of modules in a system (Chapter 5).
design phase	Phase in the ***design process*** where the technical solution is developed, ultimately producing a detailed system design. Upon its completion, all major systems and subsystems are identified and described using an appropriate model (Chapter 1).
design process	The steps required to take an idea from concept to realization of the final system. It is a problem-solving methodology that aims to develop a system that best meets the customer's need within given constraints (Chapter 1).
design space	The space, or collection, of all possible solutions to a design problem (Chapter 2).
detailed design	A phase in the technical design where the problem can be decomposed no further and the identification of elements such as circuit components, logic gates, or software code takes place (Chapter 5).
engineering requirement	A requirement of the system that applies to the technical aspects of the design. An engineering requirement should be abstract, unambiguous, verifiable, traceable, and realistic (Chapter 3).
entity relationship diagram (ERD)	An ERD is used to model database systems. The ***intention*** of an ERD is to catalog a set of related objects (entities), their attributes, and the relationships between them (Chapter 6).
entity relationship matrix	A matrix that is used to identify relationships between entities in a database system (Chapter 6).
ethics	Philosophy that studies ***morality***, the nature of good and bad, and choices to be made (Chapter 11).
event	An event is an occurrence at a specific time and place that needs to be remembered and taken into consideration in the system design (Chapter 6).
event table	A table that is used to store information about ***events*** in the system. It includes information regarding the event trigger, the source of the event, and process triggered by the event (Chapter 6).
failure function	The failure function, $F(t)$, is a mathematical function that provides the probability that a device has failed at time t (Chapter 8).

Term	Definition
failure rate	The failure rate, $\lambda(t)$, for a device is the expected number of device failures that will occur per unit time (Chapter 8).
fixed costs	Fixed costs are those that are constant regardless of the number of units produced and cannot be directly charged to a process or activity (Chapter 10).
float	The amount of ***slippage*** that an activity in a project plan can experience without it becoming part of a new ***critical path*** (Chapter 10).
flowchart	A modeling diagram whose intention is to visually describe a process or algorithm, including its steps and control (Chapter 6).
functional decomposition	A design technique in which a system is designed by determining its overall functionality and then iteratively decomposing it into component subsystems, each with its own functionality (Chapter 5).
functional requirement	A ***subsystem design specification*** that describes the inputs, outputs, and functionality of a system or component (Chapters 3 and 5).
Gantt chart	Gantt charts are a bar graph representation of a project plan where the activities are shown on a timeline (Chapter 10).
Heisenbugs	Heisenbugs are ***bugs*** that are not always reproducible with the same input. This is analogous to the Heisenberg Uncertainty Principle, in which the position of an electron is uncertain (Chapter 7).
high-performance team	A team that significantly outperforms all similar teams. Part of the Katzenbach and Smith team model (Chapter 9).
integration test	An integration test is performed after the units of a system have been constructed and tested. The integration test verifies the operation of the integrated system behavior (Chapter 7).
intention	The intention of a model is the target behavior that it aims to describe (Chapter 6).
interaction view	The interaction view is part of the ***Unified Modeling Language***. Its ***intention*** is to show the interaction between objects. It is characterized by collaboration and sequence diagrams (Chapter 6).
key attribute	An attribute for an entity in a database system that uniquely identifies an instance of the entity (Chapter 6).

Term	Definition
lateral thinking	A thought process that attempts to identify creative solutions to a problem. It is not concerned with developing the solution for the problem, or right or wrong solutions. It encourages jumping around between ideas. It is contrasted to ***vertical thinking*** (Chapter 4).
liable	Required to pay monetary damages according to law (Chapter 11).
marketing requirement (specifications)	A statement that describe the needs of the customer or end-user of a system. They are typically stated in language that the customer would use (Chapters 2 and 3).
maintenance phase	Phase in the ***design process*** where the system is maintained, upgraded to add new functionality, or design problems are corrected (Chapter 1).
matrix test	A matrix test is a test that is suited to cases where the inputs submitted are structurally the same and differ only in their values (Chapter 7).
mean time to failure	The mean time to failure (MTTF) is a mathematical quantity which answers the question, "*On average how long does it take for a device to fail?*" (Chapter 8).
module	A block, or subsystem, in a design that performs a function (Chapter 5).
morals	The ***principles*** of right and wrong and the decisions that derive from those principles (Chapter 11).
multi-disciplinary team	In general, a multi-disciplinary team is one in which the members have complementary skills and the team may have representation from multiple technical disciplines. Also see ***cross-functional team*** (Chapter 9).
negligence	Failure to exercise caution, which in the case of design could be in not following reasonable standards and rules that apply to the situation (Chapter 11).
network diagram	A network diagram is a directed graph representation of the activities and dependencies between them for a project (Chapter 10).
Nominal Group Technique (NGT)	A formal approach to brainstorming and meeting facilitation. In NGT, each team member silently generates ideas that are reported out in a round-robin fashion so that all members have an opportunity to present their ideas. Concepts are selected by a multi-voting scheme with each member casting a predetermined number of votes for the ideas. The ideas are then ranked and discussed (Chapters 4 and 9).

Term	Definition
non-disclosure agreement	An agreement that prevents the signer from disseminating information about a company's products, services, and trade secrets (Chapter 11).
object	Objects represent both data (attributes) and the methods (functions) that can act upon data. An object represents a particular instance of a ***class***, which defines the attributes and methods (Chapter 6).
object type	Characteristic of a model used in design. The object type is capable of encapsulating the actual components used to construct the system (Chapter 6).
objective tree	A hierarchical tree representation of the customer's needs. The branches of the tree are organized based upon functional similarity of the needs (Chapter 2).
observability	This principle applies to testing. Observability is the ability to observe any node of a system (Chapter 7).
over-specificity	This refers to applying targets for ***engineering requirements*** that go beyond what is necessary for the system. Over-specificity limits the size of the ***design space*** (Chapter 3).
pairwise comparison	A method of systematically comparing all customer needs against each other. A comparison matrix is used for the comparison and the output is a scoring of each of the needs (Appendix B, Chapter 2, and Chapter 4).
parallel system	A system that contains multiple modules performing the same function where a single module would suffice. The overall system functions correctly when any one of the submodules is functioning (Chapter 8).
patent	A patent is a legal device for protecting a design or invention. If a patent is held for a technology, others cannot use it without permission of the owner (Chapter 11).
path-complete coverage	Path-complete coverage is where every possible ***processing path*** is tested (Chapter 7).
performance requirement	A particular type of ***engineering requirement*** that specifies performance related measures (Chapter 3).
physical view	The physical view is part of the ***Unified Modeling Language***. Its ***intention*** is to demonstrate the physical components of a system and how the logical views map to them. It is characterized by a component and deployment diagram (Chapter 6).

Term	Definition
potential team	A team where the sum effort of the team equals that of the individuals working in isolation. Part of the Katzenbach and Smith team model (Chapter 9).
prescriptive design process	An exact process, or systematic recipe, for realizing a system. Prescriptive design processes are often algorithmic in nature and expressed using flowcharts with decision logic (Chapter 1).
principle	Fundamental rules or beliefs that govern behavior, such as the Golden Rule (Chapter 11).
problem identification	The first phase in the design process where the problem is identified, the customer needs identified, and the project feasibility determined (Chapter 1).
processing path	A processing path is a sequence of consecutive instructions or states encountered while performing a computation. They are used to develop test cases (Chapter 7).
prototyping and construction phase	Phase in the ***design process*** in which different elements of the system are constructed and tested. The objective is to model some aspect of the system, demonstrating functionality to be employed in the final realization (Chapter 1).
pseudo-team	An under-performing team where the sum effort of the team is below that of the individuals working in isolation. Part of the Katzenbach and Smith team model (Chapter 9).
Pugh Concept Selection	A technique for comparing design concepts to the user needs. It is an iterative process where concepts are scored relative to the needs. Each concept is combined, improved, or removed from consideration in each iteration of the process (Chapter 4).
real team	A team where the sum effort of the team exceeds that of the individuals working in isolation. Part of the Katzenbach and Smith team model (Chapter 9).
redundancy	A design has redundancy if it contains multiple modules performing the same function where a single module would suffice. Redundancy is used to increase ***reliability*** (Chapter 8).
reliability	Reliability, $R(t)$, is the probability that a device is functioning properly (has not failed) at time t (Chapter 8).
research phase	Phase in the ***design process*** where research on the basic engineering and scientific principles, related technologies, and existing solutions for the problem are explored (Chapter 1).

Term	Definition
Requirements Specification	A collection of engineering and marketing requirements that a system must satisfy in order for it to meet the needs of the customer or end-user. Alternate terms that are used for the Requirements Specification are the *Product Design Specification* and the *Systems Requirements Specification* (Chapter 1 and 3).
reverse-engineering	Process where a device or process is taken apart to understand how it works (Chapter 11).
routine design	A formal categorization of design projects. They represent the design of artifacts for which theory and practice are well-developed (Chapter 2).
rule-based ethics	Rule-based ethics are based upon a set of rules that can be applied to make decisions. In the strictest form, they are considered to be absolute in terms of governing behavior (Chapter 11).
satisfice	Satisfice means that a solution may meet the design requirements, but not be the optimal solution (Chapter 11).
series system	A system in which the failure of a single component (or subsystem) leads to failure of the overall system (Chapter 8).
situational ethics	Situational ethics are where decisions are made based on whether they produce the highest good for the person (Chapter 11).
slippage	Refers to an activity in a project plan taking longer than its planned time to complete. See also ***critical path*** and ***float*** (Chapter 10).
standards	A standard or established way of doing things. Standards ensure that products work together, from home plumbing fixtures to the modules in a modern computer. They ensure the health and safety of products (Chapter 3).
state	The state of a system represents the net effect of all the previous inputs to the system. Since the state characterizes the history of previous inputs, it is often synonymous with the word memory (Chapter 6).
state diagram (machine)	Diagram used to describe systems with memory. It consists of states and transitions between states (Chapter 6).
static view	The static view is part of the ***Unified Modeling Language***. The ***intention*** of the static view is to show the classes in a system and their relationships. The static view is characterized by a class diagram (Chapter 6).
step-by-step test	A step-by-step test case is a prescription for generating a test and checking the results. It is most effective when the test consists of a complex sequence of steps (Chapter 7).

Term	Definition
strengths and weakness analysis	A technique for the evaluation of potential solutions to a design problem where the strengths and weaknesses are identified (Chapter 4).
structure charts	Specialized block diagrams for visualizing functional software designs. They employ input, output, transform, coordinate, and composite modules (Chapter 5).
strict liability	A form of ***liability*** that focuses only on the product itself—if the product contains a defect that caused harm, the manufacturer is liable (Chapter 11).
stub	A stub is a device that is used to simulate a subcomponent of a system during testing. Stubs simulate inputs or monitor outputs from the unit under test (Chapter 7).
subsystem design specification	Engineering requirements for subsystems that are constituents of a larger, more complex system (Chapter 3).
system integration	Phase in the ***design process*** where all of the subsystems are brought together to produce a complete working system (Chapter 1).
task	Tasks are actions that accomplish a job as part of a project plan. Also see ***activity*** and ***deliverable*** (Chapter 10).
Team Process Guidelines	Guidelines developed by a team that govern their behavior and identify expectations for performance (Chapter 9).
technical specification	A list of the technical details for a given system, such as operating voltages, processor architecture, and types of memory. The technical specification is fundamentally different from a requirement in that it indicates what was achieved in the end versus what a system needs to achieve from the outset. (Chapter 3).
test coverage	Test coverage is the extent to which the test cases cover all possible ***processing paths*** (Chapter 7).
test phase	Phase in the design process where the system is tested to demonstrate that it meets the requirements (Chapters 1 and 7).
testable	A design is testable when a failure of a component or subsystem can be quickly located. A testable design is easier to debug, manufacture, and service in the field (Chapter 7).
top-down design	An approach to design in which the designer has an overall vision of what the final system must do, and the problem is partitioned into components, or subsystems that work together to achieve the overall goal. Then each subsystem is successively refined and partitioned as necessary. This is contrasted to ***bottom-up*** design (Chapter 5).

Term	Definition
tort	The basis for which a lawsuit is brought forth (Chapter 11).
trade secret	An approach to protecting intellectual property where the information is held secretly, without ***patent*** protection, so that a competitor cannot access it (Chapter 11).
under-specificity	This refers to a state of the ***Requirements Specification***. When it is under-specified, requirements do not meet the needs of the user and/or embody all of the requirements needed to implement the system (Chapter 3).
Unified Modeling Language (UML)	A modeling language that captures the best practices of object-oriented system design. It encompasses six different system views that can be used to model electrical and computer systems (Chapter 6).
unit test	A unit test is a test of the functionality of a system module in isolation. It establishes that a subsystem performs a single unit of functionality to some specification (Chapter 7).
use-case view	The use-case view is part of the ***Unified Modeling Language***. Its ***intention*** is to capture the overall behavior of the system from the user's point of view and to describe cases in which the system will be used (Chapter 6).
utilitarian ethics	In utilitarian ethics, decisions are made based upon the decision that brings about the highest good for all, relative to all other decisions (Chapter 11).
validation	The process of determining whether the requirements meet the needs of the user (Chapter 3).
value	A value is something that a person or group believes to be valuable or worthwhile. Also see ***principles*** and ***morals*** (Chapter 11).
variable costs	Variable costs vary depending upon the process or items being produced, and fluctuate directly with the number of units produced (Chapter 10).
variant design	A formal categorization of design projects. They represent the design of existing systems, where the intent is to improve performance or add features (Chapter 2).
verifiable	Refers to a property of an engineering requirement. It means that there should be a way to measure or demonstrate that the requirement is met in the final system realization (Chapter 3).
vertical thinking	A linear, or sequential, thought process that proceeds logically towards the solution of a problem. It seeks to eliminate incorrect solutions. It is contrasted to ***lateral thinking*** (Chapter 4).

Term	Definition
whistleblower	A person who goes outside of their company or organization to report an ethical or safety problem (Chapter 11).
white box test	White box tests are those that are conducted with knowledge of the internal working of the unit under test (Chapter 7).
work breakdown structure	The work breakdown structure (WBS) is a hierarchical breakdown of the tasks and deliverables that need to be completed in order to accomplish a project (Chapter 10).
working group	A group of individuals working in isolation, who come together occasionally to share information. Part of the Katzenbach and Smith team model (Chapter 9).

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