Design for Electrical and Computer Engineers

Theory, Concepts, and Practice

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0.1 About the Authors

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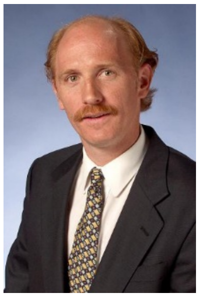

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Contents

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$^{\text{TM}}$ 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.

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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,

0.3 System Reliability

> *Quality is never an accident. It is always the result of intelligent effort.—John Ruskin*

A typical design project in your academic career may never leave the confines of a laboratory. However, in industry, engineers develop systems that are used by the public at large, and issues beyond the functionality, such as reliability, safety, and maintainability become important factors in the success of the design. Over the past 20 years, industry has made a great shift to address reliability through the adoption of processes such as Quality Functional Deployment (QFD), Six-Sigma, and Robust Design. While other chapters have addressed some elements of these processes, the objective of this chapter is to examine system reliability. Reliability attempts to answer the question of how long a system will operate without failing. Answering this question has inherent uncertainty and requires the use of probability and statistics. This chapter presents a review of basic probability theory and applies it to estimate the behavior of real-world devices. Reliability at the component and system levels is considered.

Learning Objectives

By the end of this chapter, the reader should:

- Have a familiarity with the basic principles of probability and understand how they apply to reliability theory.
- Understand the mathematical definition and meaning of failure rate, reliability, and mean time to failure.
- Understand how to determine the reliability of a component.
- Understand how to derate the power of electronic components for use under different operating temperatures.
- Understand how to determine the reliability of different system configurations.

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WHEN CAN WE START?

Figure 1: Dogbert's Six Sigma Program. (Dilbert © United Feature Syndicate. Reprinted by permission.)

0.4 Probability Theory Review

Probability theory provides a formal framework to study chance events. It is a powerful tool for modeling engineering systems and is a requisite for reliability estimation. Although this section provides a review of some important concepts from probability, it is assumed that the reader is versed in the basics of probability theory.

In order to apply probability, some general definitions are examined first. An *experiment* is the process of measuring or quantifying the state of the world. The particular outcome of an experiment is an *event* (e_i),while the *event space* (E) is the set of all possible outcomes of the experiment. For example, consider an experiment where a six-sided die is rolled. The experiment is rolling the die and observing the outcome, the event is the particular outcome observed, and the event space for the experiment is the set $E = \{1, 2, 3, 3, 4, 5, 6\}$. The outcomes do not have to be numerical values. Another example experiment is tossing a coin, in which case the event space is $E = \{Heads, Tails\}$. Both are examples of a discrete event space because there are a finite number of experimental outcomes. In a discrete event space, the union of all the possible experimental outcomes defines the event space. If e_i is the i^{th} event in a discrete event space, then the event space is given by the union

$$E = \cup e_i \tag{1}$$

The probability of an event indicates how likely it is for an event to occur. This is quantified by the probability operator, P, that assigns to each event a real number between 0 and 1. The probability is the percentage of times that an event would occur if the experiment were repeated an infinite number of times (the Law of Large Numbers). Two of the three fundamental axioms on which probability theory is built are

$$P(e_i) \geq 0 \tag{2}$$

$$P(E) = 1 \tag{3}$$

The first axiom indicates that all probabilities are non-negative, while the second is a restatement of the event space definition—the outcome of an experiment must be an element of the event space. Armed with these definitions and axioms, some important concepts from probability are now examined.

0.4.1 Probability Density Functions

Not all event spaces are discrete as in the case of rolling a die or flipping a coin. Consider an experiment where the objective is to measure temperature. Clearly, such a measurement requires a variable having a continuous range of possible values. A random variable is defined as the outcome of an experiment that has a continuum of possible values. Random variables have a mathematical function known as the *probability density function* (PDF) associated with them, which when integrated, yields the probability of a range of events. A PDF is typically denoted as $p_X(x)$, where X takes values over the event space. Standard notation identifies random variables using upper case variables as the subscript for the PDF. The variable inside the parentheses is a lowercase dummy variable that does not have to match the random variable, but typically does. A question that the PDF allows us to ask is "*What is the probability that a random variable is in some range?*" Consider the case where the objective is to determine the probability that the random variable X lies between two values a and b. Written using the probability operator, this is indicated as $P(a \leq X \leq b)$. It is determined from the PDF as follows

$$P(a \leq X \leq b) = \int_a^b p_x(s)dx \tag{4}$$

Conceptually, this probability represents the area under the PDF between the two limits of integration as shown in Figure 2.

Let's examine a few more important properties of probability density functions. The first, which is analogous to equation 3, indicates that the

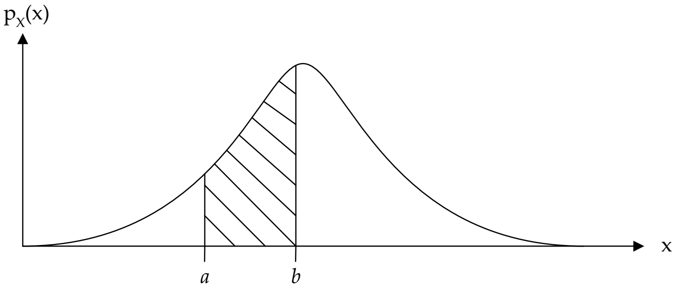


Figure 2: A probability density function. The area under the curve represents the probability that the random variable X lies in the interval $[a, b]$
.

probability of the event space occurring is equal to one. This is known as the normalization property and it is expressed as

$$\int_{-\infty}^{\infty} p_x(x)dx = 1 \tag{5}$$

Another interesting result is obtained by trying to determine the probability that a random variable takes on an exact value, for example $P(X = a)$. That is determined from the integral

$$P(X = a) = \int_a^a p_x(x)dx = 0 \tag{6}$$

This is a somewhat counterintuitive result—it indicates that the probability a random variable can take on a particular value is zero. Does this make any sense? Consider an experiment where the objective is to measure a voltage value for a random variable V. Now consider the question, "*What is the probability that the result of a voltage measurement equals π (the irrational number) volts?*" In practice, this question is impossible to answer because the precision required of the meter is infinite and contrary to its construction. So the mathematical and practical results are in harmony. There is a way around this dilemma, which is to determine the probability that the random variable is within a small range about the target value as follows

$$P(\pi < V < \pi + \Delta v) = \int_{\pi}^{\pi+\Delta v} p_V dv \approx p_V(\pi)\Delta v \tag{7}$$

This means that the probability a random variable is within a small range about a given value is approximated by the product of the PDF evaluated at the value and the size of the range.

0.4.2 Mean and Variance

Two useful and well-known statistics that are determined from the PDF are the mean (μ) and variance (σ^2). They are found from the PDF as follows

$$\mu_x = \int_{-\infty}^{\infty} x p_X(x) dx \tag{8}$$

$$\sigma_x^2 = \int_{-\infty}^{\infty} (x-\mu)^2 p_X(x) dx \tag{9}$$

The *mean* is analogous to the center of mass of the PDF; it is also known as the average value. The *variance* is the average of the squared difference between the mean and the values of the PDF, where the squared term ensures that a positive difference is taken. The square root of the variance is known as the standard deviation σ.

0.4.3 Common Probability Density Functions

There are many PDFs available for describing the seemingly random variations in the behavior of observed systems and phenomena. In this section, three common PDFs (normal, exponential, and uniform) are presented.

The Normal Density

The most common density function encountered in the physical sciences and engineering is the normal density. Many population variations can be described by a normal density. For example, the resistance values of a large batch of 2.2k ohm resistors would likely follow a normal density. The normal density is defined as

$$p_X(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{1} \frac{1}{2}\ frac(x-\mu)^2\sigma \tag{10}$$

The mean, μ, and standard deviation, σ, are part of the definition of the PDF and used to alter the shape of the density to suit the particular need. The normal PDF is plotted in Figure 3. Varying μ allows the overall function to be shifted along the x-axis, while increasing σ spreads (or flattens) the function out. Calculating probabilities from the normal density can be done (although it takes a bit of work mathematically) so they are usually

Figure 3: A normal density function with the mean (μ) and standard deviation (σ) shown.

Figure 4: The uniform density on the interval $[a, b]$.

computed from something known as the Cumulative Distribution Function that is presented shortly.

The Uniform Density

The uniform density, plotted in Figure 3, models the outcome of an experiment where all outcomes are equally likely. Mathematically, the PDF for a uniform density is given by

$$p_X(x) = \frac{1}{b-a}, a \leq x \leq b, \tag{11}$$

where a, b are selected to meet the demands of a particular problem.

The Exponential Density

Exponential densities are often utilized to model time dependent functions, such as inter-arrival times between data packets in communication systems. As shown later, the exponential density also describes the behavior of component failures as a function of time. The mathematical description of an exponential density is

$$p_X(x) = \lambda e^{-\lambda x}, x \geq 0, \lambda \geq 0. \tag{12}$$

The PDF is characterized by the parameter λ which affects the shape of the curve as demonstrated in Figure 5.

0.4.4 Cumulative Distribution Functions

An important class of questions can be phrased as, "*What is the probability that a random variable X is less than value a?*" For example, the objective might be to determine the probability that an electronic component will malfunction within two years. Returning to the first question, it is clear

Figure 5: The exponential density for two different λ values.

that the goal is to determine the probability $P(X < a)$, which is found by integrating the PDF. This result is generalized by allowing the upper limit of integration to take on an arbitrary value that spans the range of the random variable. This produces a new function, known as the *Cumulative Distribution Function* (CDF), which is the integral function of the PDF and is defined as

$$CDF(x) = \int_{-\infty}^{x} p_X(y)dy. \tag{13}$$

0.5 Reliability Prediction

Our main interest in the study of probability stems from the desire to quantify the reliability of a system. The following is a formal mathematical definition of ***reliability***.

> ***Definition***: *Reliability, $R(t)$, is the probability that a device is functioning properly (has not failed) at time t.*

In order to determine $R(t)$, it is necessary to first introduce some related mathematical entities and their meanings. The ***failure rate***, $\lambda(t)$, of a device is the expected number of failures per unit time. The failure rate is measured by operating a batch of devices for a given time interval and noting how many fail during that interval. A typical graph of failure rate versus time has the bathtub shape shown in Figure 6. The high initial failure rate is a result of manufacturing defects often referred to as infant mortality. Consequently, many manufactures will “burn-in” devices at the factory, so that if they fail, they do so before being sold. After the infant mortality phase, devices enter a phase of constant failure rate, where $\lambda(t) = \lambda$, known as the service life. Estimates for λ are determined empirically by testing a large number of components. They are usually expressed as a unit failure per a given number of hours, for example $\lambda = failure/10^6 hours$. After some period of time, devices start to wear-out and the failure rate increases. This usually happens as a result of mechanical wearing with age and use. Properly designed electronic devices will not have a wear-out region, instead continuing on at a constant failure rate. This applies only to the electronic devices themselves, not necessarily to complete systems that will likely contain mechanical devices.

In addition to failure rate, a PDF for the *failure time* of the device, $f_T(t)$ is defined, where the random variable is time T. This function allows the

Figure 6: Failure rate as a function of time, also known as the bathtub curve.

Figure 7: Example reliability and failure functions.

question to be asked "*What is the probability that a device will fail between time t_1 and t_2?*" It is important to note the difference between $\lambda(t)$ and $f_T(t)$. The failure rate tells us the average rate that a collection of identical devices will fail at a given time t, while $f_T(t)$ is a PDF used to determine the probability that a given device will fail within a specified time period. A CDF for $f_T(t)$ is determined as

$F(t)$ answers the question "*What is the probability that the device has failed by time t?*" and it is also known as the ***failure function***. Take a few seconds to go back and review the definition of $R(t)$. It is clear that $R(t)$ is directly related to $F(t)$ and is its complement. The relationship between the two is

$$R(t) = 1 - F(t) \tag{14}$$

Since $F(t)$ is a CDF, it increases monotonically from an initial value of 0 to a maximum value of 1 as time goes to ∞ as shown in Figure 8.7. Conversely, $R(t)$ starts at a value of 1 at time zero and decreases monotonically to a value of 0.

Since $\lambda(t)$ represents data that is measured empirically, it is useful to establish a relationship between $\lambda(t)$ and the ultimate goal of reliability, $R(t)$. To do so, a relationship between $\lambda(t)$, $R(t)$, and is established as follows. Consider a small period of time between t and $\Delta 4$, and determine the probability of device failure during this period. From the approximation developed in equation 14, this probability is given by

$$P(failurebetweentand\Delta t) \approx f_T(t)\Delta t \tag{15}$$

How is this probability related to $R(t)$ and $\lambda(t)$? $R(t)$ provides the probability that the device is working at time t and $\lambda(t)$ gives the probability that the device will fail at time t. The product of $R(t), \lambda(t)$, and Δt gives the same probability of failure in equation 15.

$$P(failurebetweentand\Delta t) \approx R(t)\lambda(t)\Delta t \tag{16}$$

Setting equations 15 and equ:failureBetweenUsingR provides the desired relationship between the three quantities

$$f_T(t) = R(t)\lambda(t), \tag{17}$$

that is fundamental in establishing the connection between $R(t)$ and $\lambda(t)$. However, the PDF $f_T(t)$ needs to be eliminated from equation 17. This is accomplished through its relationship to the CDF $F(t)$, and thus $R(t)$, as follows

$$f_T(t) = \frac{d}{dt}F(t) = \frac{d}{dt}\big[1 - R(t)\big] = -\frac{d}{dt}R(t) \tag{18}$$

Equating this result with equation 17 produces

$$f_T(t) = \frac{d}{dt}F(t) = \frac{d}{dt}\big[1 - R(t)\big] = -\frac{d}{dt}R(t) \tag{19}$$

Integrating both sides gives

$$\int_0^t \big[\frac{-\frac{d}{dt}}{R(\tau)}R(\tau)\big]\delta\tau = \int_0^t \lambda(\tau)\delta\tau \Rightarrow -ln(R(t)) = \int_0^t \lambda(\tau)\delta\tau \tag{20}$$

and solving for $R(t)$ produces the final result for reliability as a function of $\lambda(t)$

$$R(t) = exp\big[-\int_0^t \lambda(\tau)\delta\tau\big] \tag{21}$$

During the service lifetime phase, the failure rate is constant, which simplifies to

$$R(t) = exp(-\lambda(t)) \tag{22}$$

This important result is now applied in Example 8.1.

0.5.1 Mean Time to Failure

The ***mean time to failure*** (MTTF) is a quantity which answers the question, "*On average how long does it take for a device to fail?*" From its definition, it is apparent that the MTTF is the mean value of the random variable T (failure time). It is determined from the PDF and the definition of the mean in (8) as follows

$$MTTF = \int_0^\infty tf_T(t)dt \tag{23}$$

Example 8.1 Transistor Reliability
Problem: Consider a transistor with a constant failure rate of $\lambda = 1/10^6 hours$. What is the probability that the transistor will be operable in 5 years?
Solution: This solution is found using the reliability function for a constant failure rate in equation 22 as follows.

$$R(t) = exp(-\lambda t)$$

$$R(5years) = exp\big(-\frac{1}{10^6 hours} x \frac{24hours}{day} X \frac{365days}{year} X 5years\big) =$$

$$= exp(-0.0438)$$

$$= 0.957$$

$$= 95.6\%$$

At this point the form of the PDF for $f_T(t)$ is not known, but it can be found from equation 19 since it is the negative derivative of $R(t)$. Assuming the form of $R(t)$ found in equation 22 for a constant failure rate gives

$$f_T(t) = -\frac{d}{dt}R(t) = \lambda e^{-\lambda t} \tag{24}$$

This means that under the condition of a constant failure rate, the failure PDF follows an exponential density. The MTTF is found from $f_T(t)$ via integration by parts to be

$$MTTS = -\int_0^{\infty} te^{-\lambda t} = \frac{1}{\lambda} \tag{25}$$

This makes intuitive sense because λ is the expected number of failures per unit time for a device. Consequently, the reciprocal of λ is the expected time between failures or MTTF. Let's consider a few examples.

This is a bit counterintuitive. Although the average time between transistor failures is 114 years, an individual transistor has only a 36.8% chance of surviving to 114 years. It would seem logical that the reliability at 114 years should be 50% and that the transistor would have a 50-50 chance of failing. This would be true if $f_T(t)$ were symmetric about its mean, but that is not the case for the exponential density.

While great news for those of us seeking longevity, this calculation is clearly wrong since the upper limit on human lifespan is empirically known to be about 120 years. Why is this so? Serious problems arise if $R(t)$ is used in situations where the underlying assumption is invalid. The results in equations 22 and 25 apply only if the failure rate is constant. Although that is nearly true for people in their 20s and 30s, it is not true as people age. People do wear out and the failure rate increases with age.

0.5.2 Failure Rate Estimates

The overriding objective of this chapter is to estimate the future behavior of devices that are used in electrical and computer systems. The particular behavior of interest is the state of a device's functionality—the reliability, is it working or has it failed? Equation (23) indicates that it is fairly straightforward to determine reliability, if the failure rate (λ) is known and is constant. One question to consider is what factors influence the failure rate of a device. Many of us probably have had experiences in the laboratory where we have caused devices to fail by subjecting them to conditions outside of the normal operating bounds, notably excessive current, power, or heat. In those cases

Example 8.2 Transistor MTTF
Problem: Consider the transistor in Example 8.1. (a) Determine the MTTF, and (b) the reliability at the MTTF.
Solution:
(a) From equation 25 the

$$MTTF = \frac{1}{\lambda} = \frac{1}{1/10^6 hours} = 10^6 hours$$

$$= 114 years$$

.
(b) From equation 22 the reliability at 114 years is

$$R(t) = exp(-\lambda t)$$

$$R(114 years) = exp\big(-\frac{10^6 hours}{10^6 hours}\big) = exp(-1) = 0.368$$

$$= 36.8\%$$

.

Example 8.3 Human lifespan estimation.
Problem: Data shows that for a 30 year old population, the failure (death) rate is constant with approximately 1.1 deaths per 1000 people per year. Given this data, estimate the MTTF of humans.
Solution: In order to find MTTF, λ is needed. From the information given it is

$$\lambda = \frac{(1.1/1000) failures}{1 year} = \frac{1.1 failure}{10^3 years} = \frac{1 failure}{909 years}$$

From this MTTF is computed as

$$MTTF = \frac{1}{\lambda} = 909 years!$$

the devices probably failed, or burned up, due to the operating conditions outside of the allowed bounds for the device. However, even when operated within the allowable norms of a device's operating conditions, variations in factors such as power, operating voltages, and temperatures impact λ.

The United States Military has kept copious records of device failures in the field and the conditions under which they operated. These records are synthesized in a handbook entitled Reliability Prediction of Electronic Equipment [MIL-HDBK-217F] that provides failure rates for various analog and digital components, along with adjustment factors to account for operating conditions, the environment, and device quality. Categories of devices included in the handbook are switches, fuses, diodes, optoelectronic devices, and microelectronic devices (op amps, logic devices, microcontrollers, microprocessors). The handbook was last published in 1991 and has been discontinued, but it is still widely accepted and used. Bellcore (subsequently Telcordia) has developed newer models [Tel96] based upon MIL-HDBK-217F that were updated to better predict the reliability of components. MIL-HDBK-217F is used here since it is freely available in the public domain.

Failure rates for resistors, capacitors, transistors, and integrated circuits from MIL-HDBK-217F are included in Appendix C. For each device, a base failure rate is given, λ_b, and multiplied by a number of adjustment factors, denoted by the symbol π, to estimate the device failure rate λ. Each adjustment factor has a unique subscript and their values are found from tables or equations in the handbook.

For example, consider the low frequency field effect transistor in Appendix C. The overall failure rate is given by the equation $\lambda = \lambda_b \pi_t au \pi_A \pi_Q \pi_E failures/10^6 hours.$ λ_b is the base failure rate that is directly read from a table, π_τ is a temperature factor which is computed from an exponential equation (be careful to use the junction temperature as indicated in Appendix C), π_A is an application factor that depends upon how the device will be used, π_Q is a quality factor, and π_E is an environmental factor. The quality factor table lists some strange names and values from 0.7 to 8.0. The quality factor describes the level of burn-in and screening each device receives before leaving the factory. Joint Army/Navy (JAN, JANTX, and JANTXV) quality factors are the highest standard, and are usually required only for space vehicles. That individual attention to burn-in means that JAN parts are expensive and most JAN devices have passed their infant mortality phase before leaving the factory. When determining failure rate for a device from a table, it is common practice to always round parameters or values pessimistically so that the evaluation is a worst case analysis of its performance. That way the device should perform with a higher reliability when embedded into a system, hopefully causing only pleasant surprises in operation. Finally, the factor π_E is based upon the different operating environments that are identified in Appendix C. Example 8.4 demonstrates the application of the MIL-HDBK-217F standard for reliability estimation.

In summary, it is possible to estimate the reliability of devices if the failure rate is known and it is constant. The US Military and Telecordia handbooks provide guidance for estimating failure rates, and thus the component reliability. It must be kept in mind that they are estimates and not guaranteed to predict the exact performance. It is also apparent that this can become a rather time-consuming process if there are many components in a system, and thus the use of reliability software packages may be warranted.

0.5.3 Thermal Management and Power Derating

One of the quantities computed in Example 8.4 was the junction temperature, T_J, which was computed from the power dissipated in the device and a quantity known as thermal resistance, θ. It is important to understand this in more detail, since it impacts the reliability of microelectronic devices. Furthermore, if the junction temperature exceeds a certain value, the device will fail. Thus, thermal management issues need to be taken into account. We start with a physical model in Figure 8.8 (a), which has a junction (the integrated circuit or device), enclosed by a case (the packaging of the device), surrounded by ambient environmental conditions. In part (b) a heat sink is included which aids in thermal transfer. Each element has associated with it a quantity known as thermal resistance that measures the ability of that particular element to transfer heat to another element. A result from heat transfer for electronics is that changes in temperature (ΔT) are proportional to the product of power dissipation (P_D) and the thermal resistance. This relationship is

$$\Delta T = P_D \Theta \tag{26}$$

It is similar to Ohm's Law where the change in temperature, power, and thermal resistance (units = °C/W) are analogous to voltage, current, and electrical resistance respectively. The total thermal resistance between two elements, such as between ambient and the junction, is the sum of all thermal resistances between them. In the case with no heat sink, this produces a junction to ambient resistance of $\Theta_{JA} = \Theta_{JC} + \Theta_{CA}$, while in the case with a heat sink, $\Theta_{JA} = \Theta_{JC} + \Theta_{CA} + \Theta_{SA}$. In the case of the heat sink, Θ_{CA}

Example 8.4 Reliability estimation using the MIL-HDBK 217F.

Problem: Consider the circuit below that contains a bipolar junction transistor (BJT). This electronic circuit is a simple digital logic inverter. When the input voltage V_I is 0, the BJT is off, no current flows through any branches of the device, and the output voltage, V_O, is 5V. When the input is 5V (high) the BJT goes into saturation due to the high base current (low R_B), producing a 50mA collector current, a large voltage drop across R_C, and an output voltage close to 0V. The average collector current for the two states is 25mA, producing an average power of 125mW (25mA×5V). Assume that the circuit is used in a missile launcher, the ambient temperature is 25°C, and that JANTX quality parts are used. Determine the MTTF and reliability for the 2N3904 BJT (a low power, low frequency BJT) in 20 years.

Solution: The objective of this problem is to determine the failure rate, from which the MTTF and reliability are estimated. From the MIL-HDBK-217F data in Appendix C, the failure rate is

$$\lambda = \lambda_b \pi_t au \pi_A \pi_R \pi_S \pi_Q \pi_E \frac{failures}{10^6 hours}$$

The base failure rate is given directly as $\lambda_b = 0.00074$. π_τ is the temperature factor and its value is determined from the relationship

$$\pi_\tau = exp\big[-2114\big[\frac{1}{T_j + 273} - \frac{1}{298}\big]\big]$$

where T_j is the junction temperature. As indicated in Appendix C, it is computed as

$$T_j = T_A + \Theta_{jA} P_D =$$

$$25°C\big(200\frac{°C}{W}\big)\big(125X10^{-3}W\big) = 50°C$$

The thermal resistance, $\Theta_J A$, is read from the 2N3904 datasheet (Appendix D) and will be examined in more detail shortly. The temperature factor is

$$\pi_\tau = exp\big[-2114\big[\frac{1}{50 + 273} - \frac{1}{298}\big]\big] = 1.73$$

π_A is an application factor (switched or linear amplification), and the value for the switched logic inverter is $\pi_A = 0.70$. π_R is a power rating factor that is computed based upon the maximum rated power dissipation of the 2N3904 (625mW from the component datasheet in Appendix D) as follows:

$$\pi_R = P_R^{0.37} = 0.625^{0.37} = 0.84$$

π_S is a stress factor that is computed from the ratio of the maximum collector-emitter voltage over the maximum rated value of the device. In this circuit, the maximum value of V_{CE} is 5V (when the device is off and no current flows), while the maximum rated value of V_{CE} from the 2N3904 datasheet is 40V.
$V_S = \frac{appliedV_{CE}}{ratedV_{CE}} = \frac{5}{40} = 0.225$
π_Q is the quality factor, and based upon the fact that a JANTX part is $\pi_Q = 1.0$. π_E is the environmental factor, and for the missile launch application, $\pi_E = 32.0$.

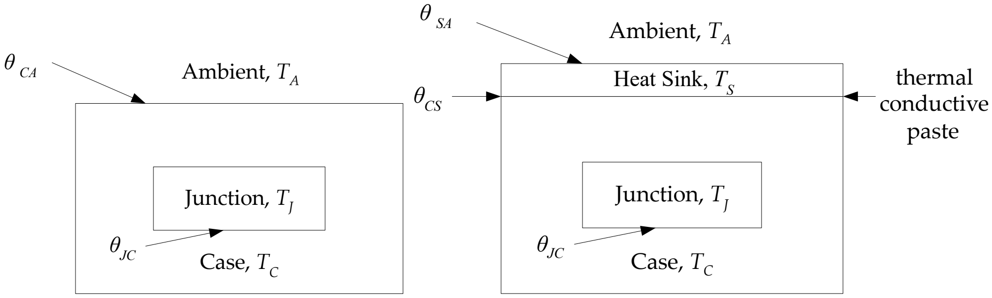


Figure 8: Physical model of microelectronic devices with thermal junctions and temperatures indicated. (a) Device inside casing. (b) Device inside casing with a heat sink added.

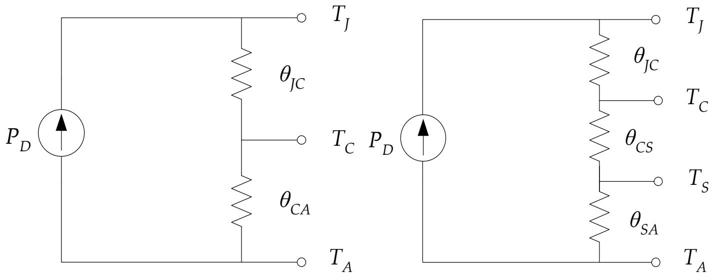


Figure 9: Resistive models for thermal transfer in microelectronic devices. (a) Device with no heat sink. (b) Device with a heat sink added.

is replaced by the sum $\Theta_{CS} + \Theta_{SA}$, which has a lower combined thermal resistance and greater ability to dissipate heat.

This Ohm's Law type of relationship means that thermal transfer can be modeled using familiar resistive circuits as shown in Figure 9. Based upon this circuit model, the temperature can be found at different points from the thermal resistance and power dissipation. Most importantly the junction temperature is found as

$$T_J = T_A + P_D\Theta_{JA} \tag{27}$$

Let's now apply these results. Manufacturer datasheets typically identify the absolute maximum power dissipation and note that the device should be derated if operated at ambient conditions above room temperature ($T_A = 25^circC$). The datasheets also supply a maximum junction temperature for the device. It is clear from the resistive model that, for a

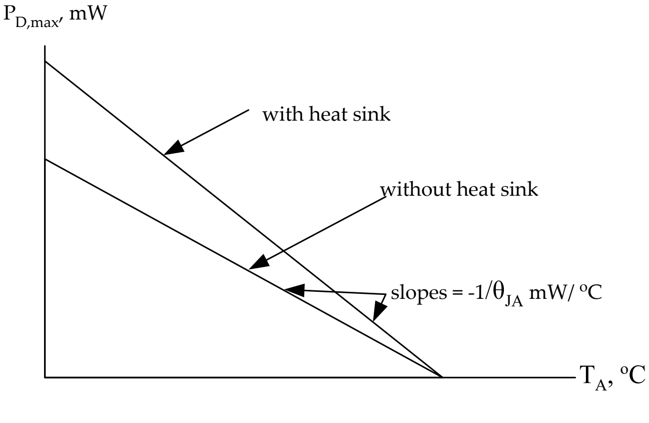


Figure 10: Typical power derating curves.

fixed power dissipation, the junction temperature increases along with ambient temperature. If the maximum junction temperature is exceeded, the device will be destroyed. Another way to look at this is that as ambient temperature increases, the maximum amount of power a device can dissipate decreases. This decrease in maximum power dissipation is known as ***derating***. From equation 27 the maximum power that can be dissipated in a device at a given ambient temperature is

$$P_{D,max} = \frac{T_{J,max} - T_A}{\Theta_{JA}} \tag{28}$$

From this relationship, a power derating curve is plotted in Figure 10 showing the maximum power versus ambient temperature. Example 8.5 demonstrates the application of this to the inverter in Example 8.4.

With this new value, the value of $\lambda = 7.00x10^{-3}/10^6 hours$, and the reliability is reduced slightly to $\underline{99.88\%}$. Note, however, the junction temperature is quite high at 145°C and further increases in temperature would likely destroy the device.

0.5.4 Limits of Reliability Estimation

It must be kept in mind that the reliability estimates are just that, estimates, and there are limitations in their use. First, realize that the failure rate data comes from accelerated stress tests, where devices are put under stress beyond normal operating conditions, and from these the failure rates are estimated. (Nobody sits around waiting 20 years for the devices to fail!) The tests are based upon mathematical models for the failure rate and the

Example 8.5 Power Derating for the Inverter Circuit.
Problem: Assume the circuit in Example 8.4 is operating at an ambient temperature $T_A = 120°C$ and that no heat sink is used. (a) Determine the derated power and if the design is within the manufacturer's limits for power dissipation at this temperature and, (b) re-compute the reliability at 20 years based upon this elevated operating temperature.
Solution: (a) From the manufacturer datasheet in Appendix D, the 2N3904 BJT has a thermal resistance of $\Theta_{JA} = 200°C/W$ and a maximum junction temperature of 150°C. From this the maximum power is computed from equation 10 as

$$P_{D,max} = \frac{(150 - 120)°C}{200°C/W} = 150mW$$

The derated, or maximum, power at this temperature is 150mW. Clearly, the 125mW of power dissipated as determined in Example 8.4 for the BJT is within this derated limit.
(b) To compute the failure rate the junction temperature and π_T are re-computed.

$$T_J = T_A + P_D\Theta_{JA} = 120°C + (125x10^{-3}W)\Big[\frac{200°C}{W}\Big] = 145 \circ C$$

$$\pi_T = exp\Big[-2114\Big[\frac{1}{145 + 273} - \frac{1}{298}\Big]\Big] = 7.66$$

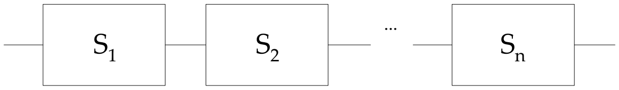


Figure 11: A series system consisting of components, or subsystems $S_1, S_2, \ldots S_n$.

device lifetime. Secondly, there are other factors that influence reliability that are not addressed by λ, such as the manufacturing processes used, the quality of manufacturing technologies, shock, and corrosion. Part of the value of reliability estimation is for comparative purposes when evaluating different design options. Applying these methods forces the designer to consider the operating conditions and factor them into the design.

0.6 System Reliability

The previous section focused on determining the reliability of a single device. It is natural to ask, "*How can the reliability of a system consisting of many devices be determined?*" In order to derive the overall reliability of a multi-component system, it is necessary to take into account the overall system structure.

0.6.1 Series Systems

Consider the inverter circuit in Example 8.4—failure of any one component in the circuit would lead to the failure of the overall system or circuit. Conceptually, a system in which the failure of a single component (or subsystem) leads to failure of the overall system is known as a ***series system***. Figure 11 shows a block diagram of a series system composed of boxes $S_1, S_2, \ldots S_n$ that represent the components, or the subsystems, of a larger system.

To compute the overall reliability of a series system, $R_s(t)$, it is assumed that the failure of subsystems or components are independent events. The system is operable only if subsystems $S_1 and S_2 \ldots S_n$ are all simultaneously operating. Therefore, the probability of the overall system operating is given by the product of reliabilities for all of the subsystems as follows

$$R_s(t) = R_1(t)R_2(t)\ldots R_n(t) = \prod_{i=1}^{n} R_i(t) \tag{29}$$

It is important to remember that failures are assumed to be independent events, just as flipping a coin twice is considered two independent events.

The overall system reliability is less than or equal to that of any single subsystem, since all reliability values are ≤ 1. Thus R_s decreases as the number of subsystems increases. Assuming a constant failure rate for all system components gives the following result for the overall system reliability

$$R_s(t) = e^{-\lambda_1 t} e^{-\lambda_2 t} \cdots e^{-\lambda_n t} = exp(-\sum_{i-1}^{n} \lambda_i t \tag{30}$$

This leads to a series system failure rate and MTTF of

$$\lambda_s = \sum_{i=1}^{n} \lambda_i MTTF = \frac{1}{\lambda_s} \tag{31}$$

Example 8.6 revisits the inverter problem where the failure rates of all components are considered for system reliability estimation.

0.6.2 Parallel Systems

From (30) it is clear that as more components are added to a series system, the reliability decreases. It is natural to ask if the reliability can be increased. The use of redundancy gives us a method to answer in the affirmative. A design has ***redundancy*** if it contains multiple modules performing the same function where a single module would suffice. By its very nature redundancy allows improperly functioning modules to be switched out of the system without affecting its behavior. With redundancy the overall system functions correctly when any one of the submodules is functioning. Figure 12 shows a simplified view of a ***parallel system*** with subsystems $S_1, S_2, \ldots S_n$.

In order to compute the reliability of a parallel system, note that a parallel system functions correctly when S_1 is functioning correctly, or S_2 is functioning correctly, $\ldots or S_n$ is functioning correctly. It would be nice if it were possible to write an equation stating that $R_s(t) = R_1(t) + R_2(t) + \ldots R_n(t)$ where + is the logical OR operator. Unfortunately, there is no direct way to realize the OR operation in probability theory. This is resolved by working with failure function, $F(t)$, instead. The probability that the system will fail by time $t, F_s(t)$, is equal to the probability that subsystem S_1 will fail and S_2 will fail and $\ldots S_n$ will fail. This probability is expressed mathematically as

$$F_s(T) = F_1(t)F_2(t) \ldots F_n(t) = \prod_{i=1}^{n} F_i(t) = \prod_{i=1}^{n} (1 - R_i(t)) \tag{32}$$

Table 1:

Example 8.6 Inverter circuit reliability.
Problem: For the system in Example 8.4 estimate (a) the overall system reliability in 20 years, and (b) the MTTF. Assume room temperature and that $\frac{1}{4}$ watt fixed composition resistors are used.
Solution:
(a) Conceptually this is a series system—if any of the individual components fail, then the overall system will fail. That means that failure rates for the two resistors are needed in addition to the value previously computed for the transistor. They depend upon the power dissipated in each resistor, which is 125mW and 0.9mW for the collector and base resistors respectively. The failure rate for a fixed composition resistor from MIL-HDBK-217F is

$$\lambda_{resistor1} = \lambda_b \pi_R \pi_Q \pi_E failures/10^6 hours$$

For the collector resistor, R_C, the base failure rate is computed as

$$\begin{aligned}\lambda_b &= 4.5x10^{-9}exp[12[\frac{T+273}{343}]]exp[\frac{S}{0.6}\ fracT+273273]]\\ &= 4.5x10^{-9}exp[12[\frac{25+273}{343}]]exp[\frac{0.125/0.25}{0.6}\ frac25+273273]]\\ &= 3.77x10^{-4}\end{aligned}$$

The S term is the ratio of power dissipated to the maximum power rating. The values $\pi_R = 1.0$, $\pi_Q = 15.0$, and $\pi_E = 27.0$ are directly read from tables. Thus the overall failure rate for the collector resistor is

$$\lambda resistor2 = (3.77x10^{-4}(1.0)(15.0)(27.0) = 1.53x10^{-1} failure/10^6 hours$$

The process for the base resistor, R_B, is similar, and results in

$$\lambda resistor2 = 6.1x10^{-2} failure/10^6 hours$$

The total failure rate is given from equation 31 as

$$\lambda_s = \lambda_{BJT} + \lambda resistor1 + \lambda resistor2 = 0.215 failures/10^6 hours$$

$$R_s(t) = exp(-\lambda_s t) = exp\big(-\frac{0.215}{10^6 hours} x \frac{24 hours}{day} x \frac{365 days}{year} x 20 years\big)$$

$$96.3\%$$

Since resistors are pretty reliable devices, the overall system reliability decreases only a small amount relative to that of the BJT itself.
(b) The MTTF is given by $1/\lambda_s$ which in this case is $\underline{\text{531 years}}$.

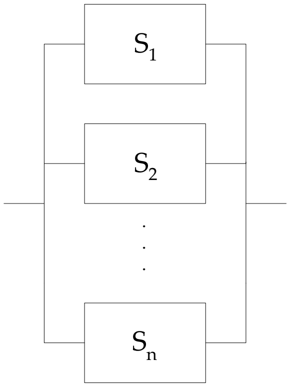


Figure 12: A parallel, or redundant, system consisting of subsystems $S_1, S_2, \ldots S_n$

The overall system reliability of the parallel system is found from this as

$$R_s(t) = 1 - F_S(t) = 1 - \prod_{i=1}^{n} \left[1 - R_i(t)\right] \tag{33}$$

As more redundant components are added to a parallel system, additional $1 - R_i(t)$ terms are introduced into the product term. This decreases the value of the product, hence the overall system reliability is increased as more redundant systems are added.

In order for a parallel system to work, a mechanism must be in place to monitor each of the subsystems to make sure that they are operating correctly. Developing circuits to detect failures and control the switching between subsystems can be complex and is not considered here. Special care must be paid to the switching circuit itself, as malfunction of this circuit could lead to an overall system failure. An example of parallel system reliability is given in Example 8.7.

In order to achieve this reliability, n=8 disks are required. The reliability of each individual disk is low at 42%, but using redundancy, the overall system reliability is quite high.

0.6.3 Combination Systems

Many real systems do not fit neatly into either parallel or series reliability models as shown in Figure 8.13. Rather, they may be a combination of the two, and such systems will be referred to as combination systems. One way

Example 8.7 Reliability of a Redundant Array of Independent Disks (RAID).
Problem: In a RAID, multiple hard drives are used to store the same data, thus achieving redundancy and increased reliability. One or more of the disks in the system can fail and the data can still be recovered. However, if all disks fail, then the data is lost. For this problem, assume that the individual disk drives have a failure rate of $\lambda = 10 failuresx/10^6 hours$. How many disks must the system have to achieve a reliability of 98% in 10 years?
Solution: The reliability of a parallel system with redundancy is given by equation 33. Since all of the disks are identical, the expression simplifies to

$$R_s(t) = 1 - [1 - R_i(t)]^n$$

$$0.98 \leq 1 - \big[1 - exp\big(- \frac{10}{10^h ours} x \frac{24 hours}{day} x \frac{365 days}{year} x 10 years\big)\big]^n$$

$$0.98 \leq 1 - [1 - 0.42]^n$$

$$0.02 \leq (0.58)^n$$

$$log(0.02) \leq nlog(0.58)$$

$$n \geq 7.2$$

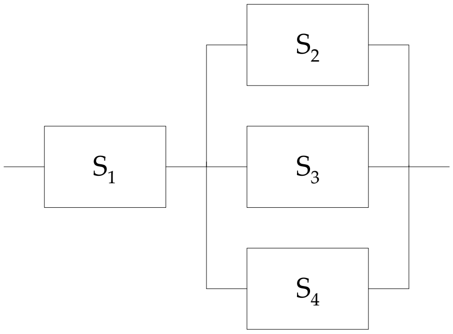


Figure 13: A combination series-parallel system. $S_2, S_3, and S_4$ are redundant parallel systems.

to determine the reliability of a combination system is to utilize the results obtained for series and parallel systems in (30) and (34). The system network is reduced by combining parallel subsystems into a single block, whose reliability is given by (34), while series subsystems are reduced to a single block whose reliability is given by (30). This is conceptually analogous to combining series and parallel resistances in electrical circuits. The network is continually reduced until only a single block remains whose reliability is known from all of the subsystem combinations.

To illustrate this, consider the system in Figure 8.13. To determine the reliability, start by combining the three parallel systems $S_2, S_3, and S_4$ whose reliability is determined by application of (34) to be $R_{s_{2-4}}(t) = 1 - (1 - R_2(t))(1 - R_3(t))(1 - R_4(t)))$. The result is then combined with S_1 in series to give the overall system reliability,

$R_s(t) = R_1(t)\,[1 - (1 - R_2(t))(1 - R_3(t))(1 - R_4(t)))]$.

The chapter concludes with Example 8.8 that addresses combination system reliability.

This example demonstrates the power of redundant systems. $S_1 and S_2$ have somewhat low reliabilities relative to the overall system goal, but the reliability of the parallel combination of S_1 and S_2 is 96%. It requires a reliability for systems 3 and 4 of $R_3 = R_4 = 90\%$, while the combined reliability of systems 3 and 4 is 99%.

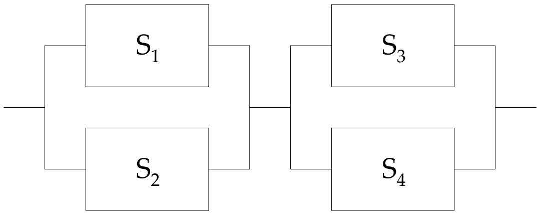
0.7 Summary and Further Reading

This chapter presented the basics of probability theory and methods for estimating the reliability of components and systems. Failure rate is an

Table 2:

Example 8.8 Combination system reliability.

Problem: Consider the system shown below with the following reliabilities at a fixed time $t, R_1 = R_2 = 80\%$. Determine the reliability that subsystems $R_3, and R_4$ must have so that the overall system reliability is greater than 95%.



Solution: The parallel systems can combined into single systems whose reliabilities are

$$R_{s_{1,2}} = 1 - (1 - R_1)(1 - R_2)$$

$$R_{s_{3,4}} = 1 - (1 - R_3)(1 - R_4)$$

They are combined in series to give the overall system reliability

$$R_s = [1 - (1 - R_1)(1 - R_2)]\, x\, [1 - (1 - R_2)(1 - R_3)]$$

Substituting values and assuming $R_3 = R_4$ gives

$$0.95 = \left[1 - 0.2^2\right] \left[1 - (1 - R_{3,4})^2\right]$$

.

Solving for the reliabilities gives the final result

$$R_3 = R_4 = 0.90$$

important quantity that is determined empirically and provides the rate of failure over the lifetime of a component or system. A mathematical definition of reliability was derived from this quantity, which takes a simple exponential form in the case of a constant failure rate. This was applied to estimate the reliability of single components, particularly using failure rates from MIL-HDBK-217F. Issues of thermal transfer and power derating were considered. Reliability estimation was extended to more realistic systems consisting of multiple components in series and parallel forms. The use of redundancy with parallel systems to increase the overall system reliability was addressed.

There are plenty of good textbooks available on the probability theory, if it is necessary to study probability theory further. The book Practical Reliability of Electronic Eq [Hna03] provides detailed coverage for electrical systems reliability. It includes factors not considered here such as thermal management on printed circuit boards, procurement practices, and electromagnetic interference. Two excellent articles that demonstrate the application of design for reliability and redundancy for an embedded system application are by George Novacek in Circuit Cellar magazine [Nov00, Nov01].

0.8 Problems

1. Consider a random variable that obeys a uniform density and varies from 2 to 5. (a) Determine the mean and variance of the random variable. (b) What is the probability that the random variable is between 2 and 3? (c) Plot the CDF.

2. In Figure 7 it was assumed that the CDF function is monotonically increasing. That is,$F(f) \leq F(t + \Delta t)$. Show why this is so using equation 13.

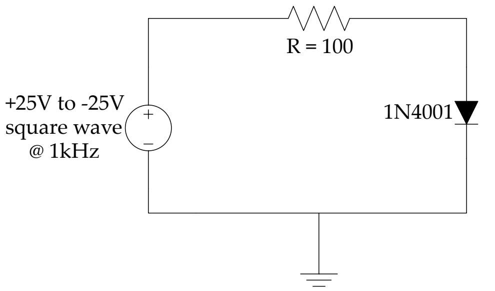
3. Describe what is meant by *failure rate*, *failure function*, and *reliability*.

4. Consider an integrated circuit that has $\lambda = 50/10^6$ hours. (a) Determine the mean time to failure. (b) Determine the reliability in 5, 10, 15, and 20 years.

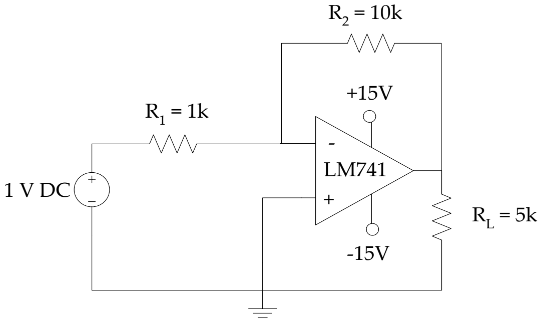
5. Consider a CD4001BC 2-Input Quad NOR gate (datasheet available in Appendix D). Also assume it is a glass-sealed dual inline package, 15 years in production, $\Theta_{JA} = 70^circC/W$, the power dissipated in the application averages 10mW, it has B-1 quality, and that it is to be operated in laboratory equipment at an ambient temperature of $25°C$. Use the MIL-HDBK-217F data in Appendix C to determine the MTTF and estimate its reliability in 25 years.

6. Use the MIL-HDBK-217F data in Appendix C to estimate the reliability of a 32 bit CMOS microprocessor. Assume that it is used in a missile launcher, the ambient temperature is $120°C$, that it has 64 pins, that it has been in production for 6 months, B-1 quality parts are used, and it is a non-hermetic DIP. Determine the MTTF and reliability for the microprocessor in 20 years. (Note: this is the same operating environment used for the BJT in Example 8.5.)

7. Consider a 1N4001 diode (datasheet in Appendix D) that is to be operated in the switching circuit shown below. Also assume that the part quality is Lower, it is metallurgically bonded, and that it is to be used in an airborne inhabited cargo environment at an ambient temperature of $50°C$. Use the MIL-HDBK-217F data in Appendix C to determine the MTTF and estimate its reliability in 25 years.



8. Use the MIL-HDBK-217F data in Appendix C to determine the reliability of the inverting op amp circuit, shown below, in 15 years. Assume that it is used in an automotive application (environmental factor $= G_M$), the ambient operating temperature is $80°C$, industrial quality parts are employed, and 1/4 watt fixed composition resistors of the lowest quality are used. The datasheet for the LM741 op amp is in Appendix D. The LM741 is considered to be a linear microcircuit, comes in a dual inline package (DIP), contains 25 bipolar transistors, has S quality, and has been in production for well over 20 years.

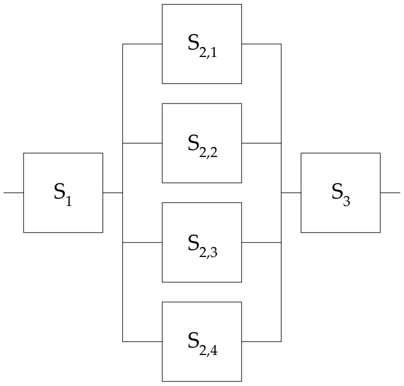


9. Consider the circuit in Example 8.4. Assume that a heat sink is attached to the 2N3904 BJT (datasheet in Appendix D) and it has the following thermal resistance values $\Theta_{CS} = 10^circC/W$ and $\Theta_{SA} = 8^circC/W$. If the device is operated at an ambient temperature of $130°C$, determine the maximum power dissipation of the BJT and its reliability in 50 years.

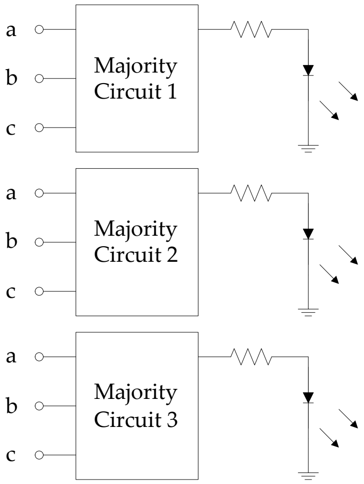
10. Your company intends to design, manufacture, and market a new RAID (Redundant Array of Independent Disks) for network servers. The system must be able to store a total of 500GB of user data and must have a reliability of at least 95% in 10 years. In order to develop the RAID system, 20GB drives will be designed and utilized.

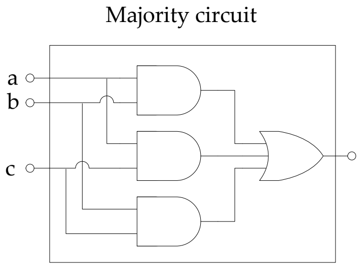
To meet the requirement, you have decided to use a bank of 25 disks (25x20GB=500GB) and utilize a system redundancy of 4 (each of the 25 disks has a redundancy of 4). What must the reliability of the 20GB drive be in 10 years in order to meet the overall system reliability requirement?

11. S_1 has a failure probability of 2% and S_3 has a failure probability of 3%. $S_{2,1}, S_{2,2}, S_{2,3}, and S_{2,4}$ are identical redundant systems. Determine the required reliability of the redundant systems necessary for the overall system to have a reliability of 94%.



12. Consider the design of a triply-redundant majority voting system, with three binary inputs a, b, and c shown below. The inputs represent data from 3 independent sources from which the objective is to determine if the majority of the input bit values are logic level 0 or 1. Each majority circuit outputs the bit value that is in the majority of the inputs. The output of each majority circuit is fed into a resistor and LED (light emitting diode) network. The LEDs are lit if the output of the majority circuit is a logic 1, otherwise the LED is off. Ideally, all three LEDs are lit if the majority of inputs is 1, else they are all off. However, if part of the system fails, the LED readings may not be reliable, so a majority rules decision is used on the LEDs. The criterion used is that if two or more LEDs are on, then the majority of inputs are considered to be high, otherwise, the majority of inputs are considered to be low. Determine the probability of a false reading based upon this criterion if each component in the system (gate, resistor, or LED) has a reliability of 90%.


a
b
c
Majority
Circuit 1
a
b
c
Majority
Circuit 2
a
b
c
Majority
Circuit 3


Majority circuit
a
b
c

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).