ENGINEERING BY DESIGN

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I dedicate this work to my mother and father,
Eleanor and Norman Voland,
and to all those who have made the world a better place.

PREFACE

Rationale for the Text

Engineering by Design is intended to serve a multiplicity of functions while conveying the excitement and sheer fun of solving technical problems in creative yet practical ways. It provides an introduction to the engineering profession through numerous case histories that illustrate various aspects of the design process. This is important because students can come to appreciate the interdisciplinary aspects of engineering problem solving as they work with case problems or review case histories in design which demonstrate (sometimes in a very startling but effective manner) valuable lessons in engineering practice.

Many engineering colleges are revising their curricula in response to the new ABET 2000 accreditation requirements. Various design and manufacturing topics are being integrated more into undergraduate engineering programs, and new mechanisms for delivering this course material are being developed with a general focus upon experiential learning by undergraduates. *Engineering by Design* has been developed as an aid for these important efforts. It is written in a way that I hope will be both engaging and accessible to students while maintaining the accuracy and rigor that one would expect of an engineering textbook.

Freshmen and sophomores often have little substantive knowledge of professional engineering practice; indeed, these students may have many misconceptions about the actual work that engineers perform and the types of problems with which they wrestle. The initial chapters and case histories of this book will give students a limited but informed understanding of the engineering profession. Later material (including case problems through which students can apply their newly acquired knowledge of design) then broadens and deepens this understanding.

Through this approach, students discover the need to

- formulate problems correctly
- work successfully in interdisciplinary teams
- develop their creativity, imagination, and analytical skills
- make informed ethical decisions
- hone their written and oral communication skills

Most important, they learn that engineering is a service profession, dedicated to satisfying humanity's needs through responsible, methodical, and creative problem solving.

Structure

Case Histories, Case Problems, and a Design Template

Engineering By Design introduces students to such critical design topics as needs assessment, problem formulation, modeling, patents, abstraction and synthesis, economic analysis, product liability, ergonomics, engineering ethics, hazards analysis, design for X, materials selection, and manufacturing processes. The engineering design process provides the skeletal structure for the text, around which are wrapped numerous case histories that illustrate both successes and failures in engineering design.

According to Larry Richards, Director of the Center for Computer Aided Engineering at the University of Virginia, engineering cases generally fall into one of three categories. They are case studies, case histories, and case problems.[1] A *case study* presents an ideal or benchmark solution that may serve as a model for future work. In contrast, a *case history* describes how a problem was solved, and points out the consequences of the decisions that were made. This text contains numerous case histories; the more extensive ones have been collected at the end of each chapter so that they will not interrupt the flow of material in the chapters. Each case history has been selected to illustrate a particular principle, procedure, or lesson in the text. Students and faculty can use these case histories as important resources for study, reflection, and discussion.

Finally, a *case problem* sets forth an open-ended (perhaps unsolved) situation that leaves the solution up to the reader. It can be a learning module designed to put students to work in teams to define the problem and solve it through research, discussion, and/or lab work. Four case problems have been prepared for use as active learning modules; they follow Chapter 11. Each of these case problems contains a substantial amount of background information, as well as proposed or existing solutions, so that students will be able to "hit the ground running" if any of these problems is chosen for a design project.

Moreover, these case problem modules serve as examples of the depth, breadth, and type of information that one should acquire about a technical problem before embarking upon the development of a design solution. The

1. Fitzgerald (1995).

A Sample Section of the Design Template

DESIGN PHASE 3 Abstraction and Synthesis

You have, by now, formulated a problem statement, identified general and specific design goals, and acquired background technical knowledge. At this point you need to generate alternative design solutions. Initial concepts of a solution may fall into only a few categories or types. It is a good idea to expand the number of solution types, through the method of **abstraction**, in order to ensure that a better approach or view has not been overlooked. Next, **models** will help you to organize data that is important to your problem, structure your thoughts, describe relationships, and analyze the proposed design solutions.

Assignment	Section
3.1 To initiate **abstraction,** break up your problem into as many meaningful subproblems as is reasonable. Classify these subproblems under more general categories, for which the distinctive characteristic of the subproblem is a special case. In other words, broaden the definition of the subproblem to give yourself more latitude in thinking (even if it violates some constraints of the original problem statement). Consider the principles or approaches that could be used to achieve the objective of each subproblem. Join elements of the different partial solution categories in some advantageous manner, staying within the range in each category that would still satisfy the given problem.	6.1

background material in each problem provides sufficient information to understand the general parameters and factors that must be considered during a design effort; however, students should seek additional information beyond that contained in the case problems.

Immediately following the four case problems is a list of 50 *case problem topics,* which describe some situations that call for engineering design solutions. Since these descriptions are very brief, students will need to research the background and current status of each situation. Again, the four case problem modules described above can serve as examples of the type of background data that should be collected via such research.

The text begins with a unique *Design Project Assignment Template* (immediately following this preface) that the instructor can use to select and assign tasks to students who are working on a design project. With this template, instructors can directly correlate their students' efforts on a project with appropriate material from each chapter of this text. Of course, not all assignments need to be performed; the template provides a "menu" from which instructors can select tasks and topics that they wish to emphasize.

This template also provides an abbreviated summary of the text with key concepts highlighted in **bold** font. Students can use this template to review and correlate the critical elements of the design process as they develop an overall perspective of the material presented throughout the text. If a term or concept in the template is not understood completely, the student should recognize that lack of understanding or comfort with the concept as a warning flag. The student should then return to the (referenced) section in the text in which the concept is discussed and study further. Through such efforts, the template can serve as an important learning aid.

Flexibility

The text is designed to be used in a number of different course structures and environments. We recommend either of two general coverage options—Full Path or Fast Track—depending upon the time that is available in a particular course (see Figure P.1).

Among the courses for which this text has been prepared are the following:

Introduction to Engineering Design The entire text can be covered in a full-semester (15-week) introductory course on design. Such a schedule allows the instructor to incorporate many of the exercises and activities contained in the Topic Keys (described below) into the course.

Design courses offered on a quarter-system (10-week) schedule may need to abbreviate coverage of certain topics. In such cases, a variation of the Fast Track may be best, with inclusion of some material from Chapters 5, 8, 9, and 11 in accordance with the instructor's preferences.

Introduction to Engineering The text can be used in a general introductory course to the engineering profession by focusing upon an appropriate subset of the numerous case histories integrated throughout the book. (Of course, each instructor will decide which cases are appropriate for his or her class.) These cases provide a flexible framework for in-class discussions of engineering practice, and the students will become familiar with the major phases of the design process as they work their way through the text.

An alternative approach is to follow the Fast Track with Chapter 9 (Failure Analysis and Hazards Analysis) included in the mix. The material in Chapter 9 may be particularly instructive to students in a broad sense.

Engineering Graphics and Design This text can be integrated easily into the traditional engineering graphics and design courses, particularly in two-course sequences in which there is sufficient time to cover the multitude of topics (e.g., design, graphics, and CAD) often assigned to such classes. For one-semester or one-quarter courses, we recommend the Fast Track.

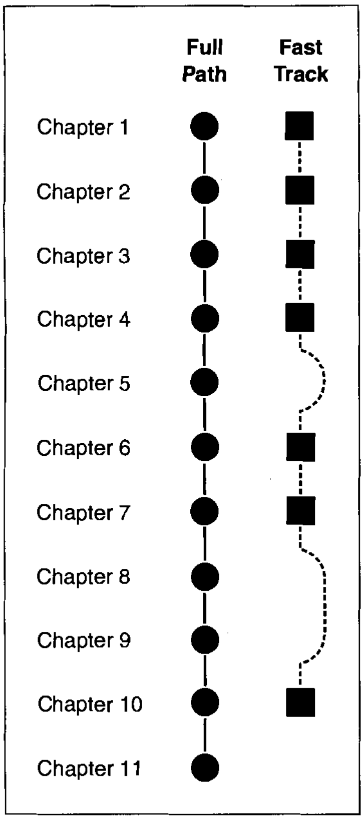

FIGURE P.1 Two of the possible routes through the material in this text.

Advanced Design Courses Many students are not formally introduced to design (in the form of a designated course) until their junior or senior years. In such cases, the entire text should be covered if time allows. Some instructors may want to devote more time to the advanced topics in later chapters, particularly Chapters 9 (Hazards Analysis and Failure Analysis) and 11 (implementation, especially the various design for X topics, fabrication processes, and materials selection).

Table P.1 summarizes these recommendations.

Annotated Overview

Chapter 1 This introductory chapter is critical because it provides an overview of all subsequent material. The design process in its entirety is reviewed, together with certain modern engineering practices. Students

TABLE P.1 Use of this text according to the course offered.

Course	Schedule	Recommended Coverage
Introduction to Engineering Design	Semester	Full Path (Chapters 1–11)
	Quarter	Fast Track + abbreviated coverage of Chapters 5, 8, 9, 11
Introduction to Engineering	Semester or Quarter	Case histories and readings selected by the instructor or Fast Track with Chapter 9 included
Engineering Graphics and Design	Two-course sequence	Full Path
	One-course (semester or quarter)	Fast Track
Advanced Design	Semester	Full Path with more time devoted to advanced topics (e.g., DFX, failure analysis, materials selection, fabrication processes)
	Quarter	Full Path

should be encouraged to focus upon Section 1.5 "Writing Technical Reports" as they prepare technical papers, design proposals, progress reports, and other documents.

Chapter 2 Again, this chapter should be incorporated into any version of the course because it is devoted to phase 1 of the design process, needs assessment.

Chapter 3 Students must become aware of how important it is, and how difficult it can be, to formulate the real problem that must be solved. Chapter 3 describes several techniques for problem formulation, phase 2 of the design process.

Chapter 4 This chapter continues the discussion of problem formulation by stressing the need for thoughtful, methodical problem solving. Its introduction of the concepts of design goals and design constraints (i.e., specs), including ergonomic considerations, is of particular importance.

Chapter 5 Section 5.1 "Science: The Foundation of Technical Knowledge" can be used to link introductory courses in physics, chemistry, and mathematics with the engineering profession. Other sections in this chapter focus on the legal protection of intellectual property and on patents as a rich source of technical knowledge.

Chapter 6 This chapter's topics of abstraction (the first segment of phase 3 of the design process) and modeling formats are critical in engineering problem solving and should be included in any basic course.

Chapter 7 Synthesis (the second segment of phase 3 of the design process) and a set of creativity stimulation techniques are included in this core chapter.

Chapter 8 The presentation of ethical issues and product liability laws in this chapter can provide students with a deeper appreciation of the need to perform rigorous analysis in engineering design. As a result, it serves as an optional but quite valuable prelude to Chapters 9 and 10.

Chapter 9 Preventive techniques for hazards analysis and diagnostic techniques for failure analysis are included in this chapter, including HAZOP, HAZAN, fault tree analysis, and failure modes effects and analysis (FMEA).

Chapter 10 This chapter focuses upon various techniques for evaluating and comparing alternative solutions as part of design analysis (phase 4 of the process). In addition, it reviews elements of economic analysis (in particular, cost estimation and the time value of money).

Chapter 11 This final chapter focuses upon implementation, phase 5 of the design process, with particular emphasis given to design for X (where X can represent manufacturability, assembly, quality, reliability, packaging, maintainability, disassembly, and recyclability), materials selection, and fabrication processes.

Please note that both metric and English units appear in the text. We chose to not limit ourselves or the readers to one particular set of units since both sets are commonly used throughout the United States and elsewhere.

In most introductory design courses, instructors must achieve a balance between a qualitative presentation of engineering practices that can be understood by students with little technical knowledge and a more quantitative approach in which substantive analytical techniques are used to develop and evaluate proposed engineering solutions. Such a balance, difficult to achieve when one is dealing with a relatively narrow and specialized topic, becomes even more challenging in a broad introductory course. *Engineering by Design* has been developed and tested to assist instructors in maintaining this balance. More quantitative techniques and examples are included in Chapters 1, 5, 9, 10, and 11, whereas Chapters 2, 3, 4, 6, 7, and 8 are more qualitative.

Instructor's Topic Keys

In order to assist instructors with the delivery of text material, there is a set of topic keys (one key for each chapter in the text). For instructors who are using *Engineering by Design,* these topic keys are available on the official World Wide Web site dedicated to this book:

http://www.awl.com/cseng/Voland

This site also provides links to other design-oriented websites; examples of the work that can be performed by students who are using this text; additional helpful hints for instruction, classroom exercises, and exams; and a chat room for instructors who wish to share their experiences in teaching engineering design.

Classroom meetings cannot be totally unconnected to the textbook, yet they should never be simple oral recitations of the text. The challenge to the instructor is to reinforce the text's presentation by helping students gain new perspectives and a deeper understanding of the material. The topic keys for this book provide a flexible structure through which instructors can meet this challenge.

Each topic key contains the following sections:

- Objectives
- Estimated Class Time
- Overview
- Materials
- Suggested Class Activities
- Reflection
- Preparation Assignment

The purpose of these sections is as follows:

Objectives Each key begins with a list of the learning objectives.

Estimated Class Time The number of one-hour meetings needed to cover a given topic is estimated. Since multiple classroom activities are suggested for each topic, the instructor may choose to devote more or less time to a particular topic as he or she deems appropriate.

Overview A brief overview of the topic, together with some comments about possible issues in its treatment in the classroom, help to focus the coverage of topics.

Materials This is a list of materials that should be provided to (or by) students during a class meeting.

Suggested Class Activities This section suggests classroom activities that can be very effective in conveying the course material to the students. These activities range from the traditional lecture approach to various active learning sessions in which students can begin to master the material by applying it to different problems. Some of the categories of activities that may be suggested in a topic key include:

- Debate, in which student teams must prepare for in-class debates
- Exercises, in which students perform design exercises in (or out of) class
- Journal, in which students share their journal (or diary) entries with the class
- Lecture, in which the instructor conveys information directly to the class
- Questions and answers (Q/A), in which students are asked questions to which they must respond in class
- Reports, in which students prepare brief reports on design topics, case histories, and other issues
- Role-play, in which students play roles in case histories or other scenarios
- Roundtable, in which the class is arranged in a circular pattern for discussion

Reflection At the end of each session, it is useful to review the lesson(s) covered during the meeting, and allow the students to reflect upon what they have experienced.

Preparation Assignment Of course, students should prepare for each class by reading the appropriate text material, reviewing their lecture notes, and so forth. However, in an interactive learning environment focusing upon complex engineering design issues, students also should perform some preparatory work through various design exercises and other activities. This section gives suggestions for such preparatory exercises and activities.

Contact with the Author

I can be contacted directly via e-mail at gvoland@lynx.neu.edu. I welcome all comments, corrections, and questions.

ensure that our freshman engineering design course is serving the needs of both the students and the faculty.

I also thank my many generous colleagues at Northeastern University who used the manuscript as their course notes. They provided valuable feedback, corrections, and suggestions for improving the text and ancillary materials. Among those deserving special mention are Professors Clayton Dillon, Charles Finn, Susan Freeman, George Kent, and Ronald Willey.

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I also would like to recognize my mentor in engineering design, Dr. William J. Crochetiere, former Chairperson of the Department of Engineering Design at Tufts University. Bill not only taught me a great deal about design, but also about the supportive and encouraging ways in which we can help one another to learn.

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I also thank the many anonymous reviewers who provided absolutely critical and thoughtful feedback on the numerous drafts of this text, and who raised the quality of the final version.

I thank my mother Eleanor Voland for her continued love and encouragement.

Above all, I thank the Lord for His support and many blessings in my life.

Gerard Voland
Bridgewater, Massachusetts

Assignment	Section
1.2 List the **needs** that you perceive in this design problem. Which needs have been addressed by engineers and which needs still require a solution? (These two lists may overlap.)	2.1, 2.2
1.3 From your list of needs, write an **initial problem statement** for your design project. Identify your problem as one of **prediction, explanation, invention**, or a combination of these types, and explain your reasoning.	2.3
1.4 Is your chosen problem related to an existing engineered product(s)? In what way? Has this product failed to perform its function(s) in any way? If so, try to identify any **physical flaws, process errors**, or **errors in perspective and attitude.**	2.4
1.5 Write an initial **design proposal** in which you justify why the design work should be performed, specify whom it will serve, and state where it will be used. State how you would approach the project, working as an individual or on a team, and what your expected schedule is. Itemize your "deliverables" such as a report, visual models, or a working model. Finally, estimate the cost of the entire project.	2.5

DESIGN PHASE 2 Problem formulation

It is important to recognize that a specific problem must be formulated if one is to develop a specific solution. **However, in order to avoid being so specific that the problem is stated in terms of a particular set of solutions, the problem statement should focus on the functions to be performed by any viable solution.** (An exception to this rule is the Revision Method, in which factors other than function become important.) The following assignments will give you experience in using several **heuristics for accurate problem formulation,** which will enable you to refine your initial problem statement.

Assignment	Section
2.1 Produce three **restatements** of your initial problem from Assignment 1.3 (e.g., changing positive terms to negative terms and vice versa; relaxing constraints or boundaries, retaining only critical goals; and specifying desired outputs, required inputs, and how the inputs are to be transformed into the outputs). Have the restatements changed the focus of the problem? Now write an improved problem statement, focusing on the function to be performed by the design solution.	2.2
2.2 Describe the **primary source** of the problem statement (corporate engineers, data acquired through private or funded research, consumers, etc.). Can you determine the **cause** of the problem (not merely its symptoms) from the problem statement or the problem source (see Assignment 1.4)?	2.3

Assignment	Section
2.13 (continued) brief descriptions for some of these patents in the *Official Gazette of the United States Patent and Trademark Office.* Finally, review the full patent disclosure (usually archived on microfilm) of the most promising patents.	5.3–5.5

DESIGN PHASE 3 Abstraction and synthesis

You have, by now, formulated a problem statement, identified general and specific design goals, and acquired background technical knowledge. At this point you need to generate alternative design solutions. Initial concepts of a solution may all fall into only a few categories or types. It is good to expand the number of solution types, through the method of **abstraction**, in order to ensure that you have not overlooked another, better approach or view. Next, **models** will help you to organize data that is important to your problem, structure your thoughts, describe relationships, and analyze the proposed design solutions.

Assignment	Section
3.1 To initiate **abstraction,** break up your problem into as many meaningful subproblems as is reasonable. Classify these subproblems under more general categories, for which the distinctive characteristic of the subproblem is a special case. In other words, broaden the definition of the subproblem to give yourself more latitude in thinking (even if it violates some constraints of the original problem statement). Consider the principles or approaches that could be used to achieve the objective of each subproblem. Join elements of the different partial solution categories in some advantageous manner, staying within the range of each category that would still satisfy the given problem.	6.1
3.2 **Models** are more or less accurate and complete representations of proposed design solutions. They may look like and/or function like the engineered design being modelled. Although models have limited accuracy, they often demonstrated interrelationships of system components, and test proposed design changes, relatively quickly and cheaply. Create models of your product design solution incorporating at least two of the following types: ■ **symbolic models** (e.g., equations) ■ **analogic models** (e.g., functional equivalents) ■ **iconic models** (e.g., scaled visual resemblances)	6.2–6.5
3.3 A system model is **deterministic** if the model allows a person to know with certainty the behavior of the system under given conditions. It is **stochastic** if the system response can be known only probabilistically (with less than 100% certainty). Does your design project include a deterministic or stochastic system model, or both? Explain. A process model is **prescriptive** if it provides general guidelines on how a process should be performed in order to achieve a certain goal. It is **descriptive** if it states exactly what process was followed in a design. Does your	6.6, 6.7

Assignment	Section
3.3 (continued) design project contain a prescriptive or descriptive process model, or both? Explain.	6.6, 6.7

Assignment	Section
3.4 Apply **Occam's razor** to your model as needed. Ask what specific contributions or insights are to be provided by the model, and eliminate unnecessary detail that would obscure its purpose or unnecessarily raise its cost.	6.8

Synthesis is the formation of a whole from a set of building blocks or constituent parts. **Creative thinking** involves the ability to synthesize, or combine, ideas and things into new and meaningful forms. Although a new synthesis may come as a flash of insight, it generally follows a period of careful, and perhaps laborious, preparation. Engineers use a number of proven techniques for stimulating creative thinking. Before studying these techniques, it is helpful to become aware of some common **conceptual blocks** to creative thinking.

3.5 Consider the models of your design solution. Do you think that one or more of the following **blockages to creativity** may be impeding you from designing the best solution? If so, what specific steps can you take to reduce or eliminate the blockage? Some common blockages are — 7.2

- **knowledge blocks:** inadequate scientific knowledge base;
- **perceptual blocks:** stereotyping elements or not recognizing other interpretations of these elements; improperly delimiting the problem or creating imaginary constraints; information overload or not distinguishing what is significant or insignificant in the data;
- **emotional blocks:** fear of failure and need for approval; unwillingness to build upon prescribed paths and methodologies; impatience or attempting to arrive at a solution too quickly;
- **cultural blocks and expectations:** inhibitions as a result of cultural predilections within the corporate environment; limitations as a result of design expectations or preconceptions held by clients;
- **expressive blocks:** misdirection as a result of inappropriate terminology having been used to define the problem or describe the solutions.

Having eliminated various blockages to creativity, you can now turn to **strategies for generating creative solutions** to an engineering problem. Since no single technique will be effective for everyone, you should experiment with different strategies to find out which ones work better for you.

3.6 With one or more other people, conduct a **brainstorming session**. Since quantity, not quality, of concepts is sought, freely suggest design concepts and associations, without evaluation or concern for practicality. Make a list of the ideas resulting from your brainstorming session. — 7.5.1

3.7 In the world of animals and plants, you can observe many important, and often difficult, tasks being performed in elegant and effective ways. Can you adapt (or gain insight from) a solution already existing in nature to solve the engineering problem under consideration? This is the creativity technique of **bionics**. — 7.5.2

3.8 For making improvements in an existing product or concept, **checklisting** may be helpful. In checklisting one uses trigger words and questions to spark creative thought. Examples are 7.5.3

- **trigger questions:** What doesn't it do? What is similar to it? What is wrong with it?
- **trigger words:** cheapen, rotate, thin
- **trigger categories:** change order (reverse, stratify); change relative position (repel, lower)

Can you apply this technique to your design problem? Explain or give the results.

3.9 At times an engineer is confronted with a problem that is so familiar that it is difficult to conceive of anything but conventional solutions. Alternatively, a problem may be so unusual that it is difficult to relate it to his or her experiences. The creativity technique of **synectics** includes the tasks of 7.5.4

- making the familiar strange, and
- making the strange familiar.

Creatively transfer your familiar problem into a strange context, or your strange problem to a familiar context, and then devise design solutions. You may apply brainstorming, checklisitng, and so on to the new problem context.

3.10 The **method of analogies** recommends progress toward a creative design solution for a given problem by linking it to another problem that resembles it in some way, and that is easier to solve, closer to being solved, or actually solved. An engineer might 7.5.5

- make a **direct analogy** between the given problem and a solved, or an almost solved, problem. Bionics, usually involves direct analogy.
- make a **fantasy analogy** to imagine the problem in an analogous but more convenient form for the purpose of advancing the design process. Synectics involves fantasy analogy.
- make a **symbolic analogy** by using a poetic metaphor, or a literary cliche, to view a given problem in a new way.
- make a **personal analogy** by imagining himself or herself as part of the system, especially under adverse circumstances, in order to gain a new perspective.

Engineers may, in addition, **adapt** a solution for an unrelated problem, or an earlier (and rejected) engineering design for a similar problem, to the current problem, and mold it into a feasible solution.

Make use of one or more of these methods of analogy or adaptation to generate design ideas, or enhance a promising solution under development.

3.11 It is often possible to obtain new insights into your design problem by simply **explaining the problem** to people who not involved in the design effort. Do this and take notes on their comments. 7.5.6

3.12 Your design problem may involve a task that many people find difficult to do (e.g., conserving a particular resource). The **inversion strategy** states that you may be more productive in solving the inverse problem, (e.g. finding many ways of wasting the resource). Then negate (or invert) your ideas in order to solve the original problem. 7.5.7

Assignment **Section**

3.12 (continued) 7.5.7

Inversion also may include changing people's perception of an object or situation. In Case History 7.9 *Jokes for Trash?*, street litter was seen no longer as articles a person was obliged to dispose of properly, but rather the means of amusement for the use of a trash receptacle.

Use inversion to stimulate creative thinking for your design effort.

3.13 An idea diagram follows a line of reasoning opposite to that of abstraction. In abstraction (Section 6.1), from the problem statement one generates broader categories that contain the initial solution concepts as particular cases. In an **idea diagram**, the problem statement itself is considered the broadest category, then subcategories showing increasing detail are generated in a tree structure in order to generate multiple solutions (see Figure 7.2). Create an idea diagram for your design problem. 7.5.8

Having used abstraction and creativity techniques to develop a set of partial solutions, or components, of the system, and modeling to define and clarify these partial solutions, there remains the task of combining the partial solutions into a whole in order to solve the given problem. The process of combining the partial solutions, or components, is synthesis. Synthesis may also be described as reasoning from principles (for example, design goals) to their applications (for example, concrete means for achieving each goal).

3.14 A **morphological chart** allows a person to systematically form different engineering designs, each of which is a solution to the same design problem (expressed by a fixed set of design goals). The rows of the morphological chart correspond to different functions, or design goals, which should be achieved by every solution. The columns correspond to different means by which these goals may be achieved (a result, perhaps, of creativity techniques). By selecting one element from each row, while avoiding impossible combinations, a designer may generate a set of alternative solutions to a given problem. Create a morphological chart for your design problem, and from it a set of design solutions. 7.6

DESIGN PHASE 4 Analysis

Ethical behavior in engineering can be the difference between success and failure in professional practice, triumph and tragedy concerning a problem, or life and death for a user. Therefore the Accreditation Board for Engineering and Technology (ABET) has called ethical, social, economic, and safety considerations in engineering practice "essential for a successful engineering career" (see Section 8.1).

An engineer needs to be familiar with, and consciously work to comply with, his or her professional society's code of ethics, as well as applicable federal, state, and local regulations, contract law, and torts law. An engineer who does this effectively guards against the loss of his or her professional reputation, and the need to defend oneself in civil or criminal lawsuits (see Section 8.2). He or she will also reap the many benefits associated with honor and appreciation.

Assignment	Section
4.1 Consider and report what specific **ethical, social, economic, or safety factors** (cited by ABET as necessary professional concepts) have been, or could be, incorporated into your design solution. What difficulties have been, or might be, encountered in incorporating these factors? Can these difficulties be overcome? (Your considerations should cover at least two of the four areas listed.)	8.1
4.2 In the case history of the *Challenger*, consider the directive given to the vice president of engineering, to "take off your engineering hat and put on your management hat" in terms of the **NSPE Code of Ethics for Engineers** (See Appendix). Is this directive in conflict with reporting all relevant information (Section II.3.a of the NSPE Code), disclosing potential conflicts of interest (Section II.4.a), or advising a client that a project is believed to be unlikely to succeed (Section III.1.b)? Explain. Apply the five **fundamental canons** of the NSPE Code of Ethics (see Part I of the code) to your design solutions, and the methods by which they came into being. Have there been infractions?	8.3.1, App.
4.3 Three BART engineers (Max Blankenzee, Robert Bruger, and Holger Hjortsvang) were commended for "courageously adhering to the letter and the spirit of theIEEE code of ethics." Explain the distinction between adhering to the **letter of a code of ethics**, and adhering to **its spirit.** These engineers contacted their supervisors, a private engineering consultant, and some members of the BART board of directors concerning their assessment of inherent dangers of the system. Have you experienced disagreements with team members or supervisors? What principles helped you resolve the difficulties?	Case History 8.4
4.4 In Case History 8.5 *A Helicopter Crash*, the company's primary defense was that the system's requirement that autorotation be activated within 1 second of power failure adhered to FAA standards. Analyze this design feature in terms the NSPE's Code of Ethics and inadequate **floor standards** for safety.	8.6.1, Case History 8.5
4.5 Engineers must **anticipate uses and misuses** of their products, and take precautions against possible injury that may result. Consider the anecdote of "The Dangerous Door." What corrective action would you order for future door shipments? What injuries might occur from use or misuse of your product, and what steps will you take to prevent them?	8.7

Engineering case histories describe how problems were solved, and point out the consequences of the decisions that were made. Case histories that chronicle disasters or engineering failures allow engineers to develop skills in **post-failure diagnostic analysis.** These skills in turn help them to become more adept at **preventive hazards analysis**, or recognizing and avoiding conditions in the design that could lead to disaster (see Section 9.1).

Once failure has occurred, specific sources of failure should be identified as accurately as possible (see Section 9.2). Known hazards in a design solution may be identified through familiarity with industrial and governmental standards, codes, and requirements (see Section 9.3.2). Unknown hazards may be discovered through application of techniques such as HAZOP, HAZAN, fault tree analysis, failure modes and effects analysis, and Ishikawa diagnostic diagrams (see Section 9.4).

Design engineers should try to reduce or prevent the known and unknown hazards through the use of safety features (shields, interlocks, sensors, etc.), a sufficiently large safety factor (strength-to-load ratio), quality assurance programs, redundancy, and appropriate warning labels and instructions (see Section 9.5).

.6 Consider the railroad warning system at Hixon Level Crossing in England, described in Section 9.1. A 24-second interval from the onset of flashing warning lights to the arrival of a train at the intersection proved to be an insufficient time for a 148-foot road-transporter to cross the tracks. (The carrier needed one full minute to clear the tracks.) Moreover, the transporter crew and its police escort were unaware of the emergency telephone installed near the intersection, and so failed to communicate their need to the railway operators. — 9.1, 9.2

Perform a **failure analysis** on this railroad disaster. Were there **physical flaws, errors in process**, or **errors in attitude**? Explain.

If you have tested a working prototype of your design solution, identify specific sources of failure, which you may have encountered, according to the outline in Section 9.2.4.

4.7 Consider the coal mine waste tips that were built up along the side of Merthyr Mountain near Aberfan in South Wales. In the context of this mine-related disaster, describe the **hazard, danger, damage,** and **risk**. Was the hazard associated with tip 7 primarily **inherent** or **contingent**? Explain. — 9.1, 9.3

Perform research to see what **standards** or requirements apply to the product or system you are developing (e.g., product performance standards, packaging standards, personal exposure standards). Report on your compliance.

In **hazards analysis (HAZAN)** (see Section 9.4.2), an engineer attempts to quantitatively estimate the **frequency** and **severity** of each hazard, and develop an appropriate **response** to each one. Consider the following case histories.

Case History 9.2 recounts the repeated incidence of corroded airplane engine fuse pins over a 14-year span. Corroded fuse pins eventually resulted in the aircraft wing engine tearing loose. There was the further complication that one broken-away wing engine could dislodge the other wing engine. The corrosion continued even after the hollow cylindrical steel pins were no longer machined on the internal surface, but an insert was used instead. This later corrosion problem was due to removal of bits of anticorrosive primer coating when the inserts were attached.

Case History 9.3 deals with another type of corrosion problem—the failure of the chain-link Point Pleasant Bridge, after 41 years of use. The design of the eyebars in this bridge made them particularly difficult to inspect. When one eyebar did crack, due to stress corrosion, a twisting motion pried loose the cap plate, which was bolted over the pin joining pairs of steel eyebars that made up the links of the bridge chain. Once one link gave way, a chain reaction followed in which other links broke loose, resulting in the bridge's collapse.

Although there was a high concentration of stresses at the point of failure (between the critical eyebar and a pin), this applied stress was still well below the limit that theoretically could be supported by the steel eyebars. Why then did it crack? Investigation showed that the inner core of the forged steel eyebar had not regained its ductility (i.e., elasticity), because the final cooling of the eyebar was performed too rapidly. This flaw in the manufacturing process gave the eyebars a brittle inner region, which made them susceptible to stress corrosion.

Assignment	Section
4.8 Consider the hazards associated with the systems described in Case Histories 9.2 and 9.3. Comment on the **frequency** and **severity** of each hazard.	Case Histories 9.2, 9.3

4.9 Assess the hazards associated with your design solution by performing a hazards analysis. Summarize your data by answering the questions, How often? How big? So what? 9.4.2

In **fault tree analysis (FTA)** (see Section 9.4.3) and **hazard and operability studies (HAZOP)** (see Section 9.4.1) one envisions possible causes of undesirable performance by a system.

In FTA, a tree diagram is created by means of top-down reasoning from system failure to the component basic faults that could have led to it. From test data, or historical records, probability or frequency of occurrence may be incorporated into the tree. A designer then may use FTA to make modifications to a system in order to eliminate faults that are most severe in their consequences and/or most frequent in their occurrence.

In HAZOP also, from descriptions of deviations from acceptable behavior of a system, first the consequences of each deviation are considered; second, possible causes that contributed to each deviation are studied; and third, the HAZOP team develops a set of specific actions that could be taken to minimize or eliminate the deviations. HAZOP is often used for identifying flaws within a process; (Case History 9.4 may be considered an example of a flawed process).

4.10 Design a fault tree diagram or perform a hazard and operability study on one of the following case histories: 9.4

Case History 9.7 *DC-10 Cargo Door Design*
Case History 9.6 *The* Titanic *Disaster*
Case History 9.4 *Disasters on the Railroads*

4.11 Postulate an undesirable event for your design solution, and create a fault tree diagram that would lead to this event. Use the symbols in Figure 9.1. 9.4

4.12 When using **failure modes and effects analysis (FMEA)** to troubleshoot a design, an engineer studies each basic component of the design, one at a time, and tries to determine every way in which that component might fail, and the possible consequences of such failures. He or she then tries to take appropriate preventive or corrective action. The engineer advances from analysis of the failure of single components, to combinations of these components, to a failure of the system itself, in a bottom-upward approach to redesigning the product. 9.4.4

Read Case History 9.10 *The MGM Grand Hotel Fire.* Construct a portion of a **FMEA sheet**, that contains at least four parts or subsystems and five columns (see Table 9.1 as an example), as part of an analysis of the hotel's fire detection, containment, and escape system.

Create a FMEA sheet for your design solution. Note the way in which a component of the system may fail, and the effect of its failure on the system.

4.13 An **Ishakawa diagnostic diagram** is a graphical display of the components or subsystems of a design, drawn as ribs extending outward from a central spine. It also shows a number of the potential flaws, weaknesses, or hazards associated with each subsystem, drawn as offshoots of each rib. 9.4.5

Construct an Ishakawa diagram, that has at least three ribs, as a diagnostic tool for studying the hazards associated with your design solution. "Invert" at least three of the weaknesses (the offshoots) to create a set of specific goals for an improved design of the system (see Section 9.4.5, footnote 24).

Assignment	Section
4.14 State how you will seek to reduce or eliminate the known and unknown hazards you have identified in your design solution. Some means to achieve this are ■ **safety features** (shields, interlocks, sensors, etc.), ■ a sufficiently large **safety factor** (strength/load), ■ **quality assurance program** (testing), ■ **redundancy** (back-up systems), and ■ appropriate **warning labels and instructions.**	9.5

You now are reaching the final stages of the design process. You used creativity techniques to generate design concepts, and synthesized your knowledge by means of a morphological chart, to arrive at complete design solutions. You have critiqued your solutions with respect to compliance with professional codes of ethics; federal, state and local regulations; contract law and torts law. Further, you have critiqued your designs in terms of preventive hazards analysis. You are ready at this point to select among the design alternatives the **best overall solution.** The outcome of a product is determined largely by the **selection and weighting of the design goals** specified in the engineering design process. In order to evaluate the competing designs, reflect upon the relative importance of each design goal, and the ability of each design to achieve these goals.

4.15 **Rank-order your design goals** as shown in Table 10.1 by assigning to each "row" goal a value 1, 1/2, or 0 to show its relative importance with respect to each "column" goal.	10.2
4.16 Assign **weighting factors** in the range 1 to 100 to your rank-ordered list of design goals, as shown in Tables 10.3 and 10.4.	10.3
4.17 Assign a **rating factor** in the range 0 to 10 to each design solution to show the degree to which that design satisfies each design goal. Refer to Table 10.5.	10.4
4.18 Using the weighting factors and the ratings factors calculated above, create a **decision matrix** to evaluate each alternative design solution. Refer to Table 10.6. Remember that decision factors within 10 percent of each other are a tie. If certain design goals absolutely must be satisfied to a certain threshold level, you may choose to create a **Kepner–Tregoe decision matrix** (see Table 10.7). The design goals are divided into "musts" and "wants." Only design solutions that satisfy all the "musts" are viable. Decision factors are calculated for viable solutions with respect to the "wants."	10.5, 10.6
4.19 The highest decision factor is only one indicator of a best solution. You should also consider the threat associated with this best solution. Create a **Kepner–Tregoe evaluation matrix of adverse consequences** (see Table 10.8). Identify the risks of each viable design solution. Calculate the threat associated with each risk as the product of the probability of its occurring (scale: 0–1.0) times its relative severity (scale: 1–10). Compute the total threat as the sum of the threats associated with each risk. If the threat for the candidate best solution seems too high, you may consider developing the second-best solution, or redesign the best solution to reduce its inherent risks. (Comment: If an inherent risk in a particular design is of truly disastrous proportions, you may indicate this by choosing a severity scale 1–10,000, for example, where all risks but one are in the 1–10 range of the scale.)	10.6, 10.7

Economic viability is another type of analysis that is necessary in order to design a successful product. An engineer may compare different methods of producing and marketing a product in order to find the method of operation that would optimize profit, efficiency, use of facilities, and aspects of the production process.

Assignment	Section
4.20 Using the **Rule of Thumb method,** estimate the expected retail price of your product. What is the anticipated sales volume? Is it expected to be economically viable? Do you recommend any design changes to improve its competitive status?	10.8

DESIGN PHASE 5 Implementation

You are now in the final phase of the design process. Implementation has to do with the physical realization of a design. However, the requirements of implementation should not be left to the end of the design process. Since materials, manufacturing, assembly, disassembly, recycling, and economic requirements can affect early decisions of the design process, these considerations should be brought to bear on decisions throughout the design effort. The method for doing this is called concurrent engineering. In order to implement a design properly, an engineer needs to be knowledgeable about fabrication materials, materials properties, and fabrication processes. Materials chosen for an engineering design should match the availability, performance (functional), economic, environmental, and processing (manufacturing) requirements of the product or system.

Assignment **Section**

5.1 **Concurrent engineering** is simultaneous development of all aspects of a design, by means of teamwork, from the initial concept to its manufacture, maintenance, and disposal, in order to optimize the performance and quality of a product and minimize its cost and production time, while achieving other design goals for its fabrication, maintenance, disassembly, recycling, or disposal, and so on. 11.2

Concurrent engineering employs the following "design for X" (DFX) considerations. Review each of the eight DFX major categories (i.e., manufacturing, assembly, reliability, quality, packaging, maintainability, disassemly, and recycling) listed below.

Design for manufacturing and **design for assembly**
–Employ division of labor.
–Use interchangeable parts.
–Use assembly line operations.
–Use machines where appropriate.
–Use modular design and subassemblies (group technology).
–Use rapid prototyping.
–Minimize number of parts.

5.1 (continued) 11.2

- –Minimize variations of parts.
- –Design multifunctional parts.
- –Avoid separate fasteners.
- –Minimize number of assembly operations.
- –Maximize tolerances for easy assembly.
- –Provide sufficient access for easy assembly.

- **Design for reliability**
  - –Select proven components.
  - –Incorporate intentional design redundancies.
  - –Perform preventive maintenance.
  - –Perform corrective maintenance.
- **Design for quality**
  - –Perform reactive (or diagnostic) operations.
  - –Use proactive (or preventive) strategies (e.g., Taguchi engineering method, benchmarking, Quality Function Deployment/"House of Quality").
- **Design for packaging**
  - –Provide aesthetic appeal and brand-name recognition.
  - –Protect the product from spoilage and damage.
  - –Provide a range of product sizes and formats.
  - –Establish product standards and measures of quality.
  - –Prevent misuse of the product.
  - –Provide inexpensive and easy-to-open closures.
  - –Reduce, reuse, and recycle packaging.
- **Design for maintainability, disassembly, and recyclability**

How have they been implemented in your design? Can more be done with these methods to enhance the viability of your design? Give at least one concrete example of application of DFX methods to your design for each of the eight major categories.

5.2 Materials are selected for a given design because they have properties that satisfy functional, environmental, manufacturing, and economic requirements imposed on the product. Some **material properties** of importance are 11.3

- mechanical properties (e.g., strength, stiffness, ductility, toughness)
- electrical properties (e.g., resistance, conductance, dielectric strength)
- thermal properties (e.g., thermal conductivity, specific heat capacity, melting point)
- availability
- cost
- toxicity
- corrosion
- biodegradability
- flammability
- permeability
- texture
- density
- appearance

What are significant material properties of (or parameters for) your finished product, and of the raw materials you will use? (You may name properties not included in the list above.) Explain why these properties are important for your design.

5.3 It is useful to know some basic properties and applications of common **fabrication materials**. An engineer should be acquainted with the following common fabrication materials: 11.4

- metals
  –ferrous (iron, steel)
  –nonferrous (aluminum, copper, magnesium, nickel, titanium, zinc)
- polymers
  –thermoplastics (acrylics, nylons, polyethylene, PVC, vinyl, etc.)
  –thermosets (phenal formaldehyde, melamine formaldehyde, urea formaldehyde)
  –elastomers (natural rubber, synthetic rubber)
- ceramics
  –brickware
  –whiteware
  –glassware
  –enamels
  –cements
- composites
  –fiberglass
  –reinforced concrete
  –wood

List the materials that will be used to implement your design and note their advantages and disadvantages.

5.4 Appropriately selected and properly executed **fabrication processes** are essential for manufacturing successful products. Fabrication processes can be identified as one of the following eight types: 11.6

- solidification processes (i.e., material is cast into a desirable form while in a molten state)
- deformation processes (e.g., rolling, forging, extruding)
- material removal processes (e.g., grinding, shaving, milling)
- polymer processes (e.g., injection molding, thermoforming)
- particulate processes (e.g., pressing, sintering, hot compaction)
- joining processes (e.g., soldering, riveting, bolting)
- heat and surface treatment processes (e.g., heating, electroplating, coating)
- assembly processes

Identify and evaluate three or more fabrication processes that could be used to produce your design. Present your analysis in tabular format.

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