ABSTRACT

BARRETT, ROLIN FARRAR, JR. Mechanical Engineering Capstone Senior Design Course Textbook. (Under the direction of Eric Klang.)

This textbook is intended to bridge the gap between mechanical engineering equations and mechanical engineering design. To that end, real-world examples are used throughout the book. Also, the material is presented in an order that follows the chronological sequence of coursework that must be performed by a student in the typical capstone senior design course in mechanical engineering. In the process of writing this book, the author surveyed the fifty largest engineering schools (as ranked by the American Society of Engineering Education, or ASEE) to determine what engineering instructors are looking for in a textbook. The survey results revealed a clear need for a textbook written expressly for the capstone senior design course as taught throughout the nation. This book is designed to meet that need.

This text was written using an organizational method that the author calls the General Topics Format. The format gives the student reader rapid access to the information contained in the text. All manufacturing methods, and some other material presented in this text, have been presented using the General Topics Format. The text uses examples to explain the importance of understanding the environment in which the product will be used and to discuss product abuse.

The safety content contained in this text is unique. The Safety chapter teaches engineering ethics and includes a step-by-step guide to resolving ethical conflicts. The chapter includes explanations of rules, recommendations, standards, consensus standards, key safety concepts, and the legal implications of product failure.

Key design principles have been listed and explained. The text provides easy-to-
follow design steps, helpful for both the student and new engineer. Prototyping is presented as consisting of three phases: organization, building, and refining.

A chapter on common manufacturing methods is included for reference.
MECHANICAL ENGINEERING
CAPSTONE SENIOR DESIGN COURSE TEXTBOOK

by
ROLIN FARRAR BARRETT, JR.

A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

MECHANICAL AND AEROSPACE ENGINEERING

Raleigh
2005

APPROVED BY:

___________________________
Chairman of Advisory Committee

___________________________
___________________________
BIOGRAPHY

Rolin Farrar Barrett, Jr., was born in Raleigh, North Carolina. He earned a Bachelor of Science in Electrical Engineering from North Carolina State University in 1986 and a Bachelor of Science in Mechanical Engineering from North Carolina State University in 1991. Mr. Barrett earned a Master of Science in Mechanical Engineering from Louisiana Tech University in 1996 and has worked to fulfill the requirements for a Ph.D. in Mechanical Engineering from North Carolina State University since 2000.

Mr. Barrett is a professional engineer and has been awarded design patents. Through his work as a consulting engineer, Mr. Barrett has analyzed more than 650 vehicle accidents, more than 175 fires and explosions, industrial accidents, ship and boat accidents, and electrical-shock accidents.
## TABLE OF CONTENTS

**LIST OF FIGURES** ................................................................................................................. vi

**Preface** ................................................................................................................................... ix

### Chapter 1 - Working as a Team

1.0 - This Book and You ................................................................. 1

1.1 - The Best Advice ................................................................. 1

1.2 - Your Project ....................................................................... 1

1.3 - Choosing the Team ............................................................ 2

1.4 - What to Expect at Your First Team Meeting ....................... 2

1.5 - Small-Group Dynamics ....................................................... 4

1.6 - Scheduling and Budgeting .................................................. 5

### Chapter 2 - Information-Gathering and Communicating Your Ideas

2.0 - Introduction ........................................................................ 7

2.1 - Literature Reviews ............................................................ 7

2.2 - Learning the Environment .................................................. 8

2.3 - Analyzing Existing Designs ............................................... 13

2.4 - Plans and Drawings ........................................................... 15

2.5 - Presentations ..................................................................... 16

2.6 - Website ............................................................................... 18

### Chapter 3 - Safety

3.0 - Ethics .................................................................................. 20

3.1 - Regulations and Standards ............................................... 23

3.2 - Concepts ............................................................................. 25
3.3 - Workplace Issues.........................................................................................................29
3.4 - Power-Tool Safety.......................................................................................................36
3.5 - Vehicle Safety Issues - Land ....................................................................................44
3.6 - Vehicle Safety Issues - Air .......................................................................................60
3.7 - Occupant Protection .................................................................................................61
3.8 - Vehicle Safety Issues - Other Vehicles .....................................................................71
3.9 - Fire Safety and Burn Injuries ....................................................................................74
3.10 - Agricultural Equipment .........................................................................................81
3.11 - Recreational Products ...........................................................................................82
3.12 - Designing for the Elderly, Handicapped and Infirm ....................................85
3.13 - Discussion Topics.................................................................................................87

Chapter 4 - Design Principles and Creativity .................................................................90

4.0 - Introduction .............................................................................................................90
4.1 - Key Principles .........................................................................................................90
4.2 - Inspiration and Creativity ......................................................................................105

Chapter 5 - Application of Theory .............................................................................110

5.0 - Introduction ...........................................................................................................110
5.1 - Hand Analysis .........................................................................................................110
5.2 - How to Gain the Most from the Steps ...............................................................117
5.3 - Key Steps ..............................................................................................................117

Chapter 6 - Preparing to Prototype ..........................................................................128

6.0 - Introduction ...........................................................................................................128
6.1 - Prototyping Steps .................................................................................................128
LIST OF FIGURES

Figure 1 - Typical muddy construction site .................................................................10
Figure 2 - Keyless electric drill chuck........................................................................12
Figure 3 - Homemade grinder guarding.....................................................................31
Figure 4 - Switch guard..............................................................................................32
Figures 5a and 5b - Integrated safety.........................................................................33
Figure 6 - Slip and fall..............................................................................................34
Figure 7 - Lawnmower guarding................................................................................40
Figure 8 - Trimmer shield..........................................................................................41
Figure 9 – Pressure-relief safety...............................................................................42
Figure 10 - Deform and absorb..................................................................................62
Figure 11 - Fire safety...............................................................................................74
Figure 12 - Hair dryer filter.......................................................................................79
Figure 13 - Coffee maker...........................................................................................80
Figure 14 - Cork retainer..........................................................................................84
Figure 15 - Belt drive................................................................................................140
Figure 16 - Gear drive..............................................................................................142
Figure 17 - Shaft drive..............................................................................................143
Figure 18 - Chain drive.............................................................................................146
Figure 19 - Lead-screw drive....................................................................................147
Figure 20 - Cable-and-pulley actuator ................................................................. 152
Figure 21 - Cam actuator ..................................................................................... 153
Figure 22 - Gravity actuator ................................................................................ 154
Figure 23 - Trip-lever actuator .......................................................................... 155
Figure 24 - Spring actuator .................................................................................. 156
Figure 25 - Blow molding ...................................................................................... 171
Figure 26 - Cold heading ....................................................................................... 173
Figure 27 - Drilling ................................................................................................. 175
Figure 28 - Extrusion .............................................................................................. 177
Figure 29 - Forging ................................................................................................ 179
Figure 30 - Grinding ............................................................................................... 181
Figure 31 - Heat treating ....................................................................................... 183
Figure 32 - Injection molding ............................................................................... 186
Figure 33 - Lathe .................................................................................................... 188
Figure 34 - Material coatings ............................................................................... 190
Figure 35 - Milling .................................................................................................. 192
Figure 36 - Roll forming ......................................................................................... 194
Figure 37 - Sawing ................................................................................................ 196
Figure 38 - Shearing ................................................................................................ 198
Figure 39 - Stamping and folding ........................................................................ 200
Figure 40 - Welding..........................................................................................................203
Preface

What This Book Offers
- Chronological presentation of material
- Real-world examples
- General Topic Format
- Rapid access to information
- Key design principles
- Easy-to-follow design steps
- Step-by-step guide to ethics
- Unique safety content

Many books have been written about mechanical engineering design. Some of these books are widely used as references by mechanical engineers in their professional work. While these books offer equations and formula for determining pertinent engineering data, they fail to convey the analytical thought that culminates in a safe and successful design. For example, current mechanical engineering design books may provide the student with the material necessary to calculate the design features of a stamped part and a machined part, but they seldom concisely explain why a stamped part might be preferred over a machined part.

Mechanical engineers do not design products that are independent of the world around them. Their designs must be competitive against other similar products while avoiding the pitfalls of cost and liability. This textbook is intended to fill the gap between mechanical engineering equations and the demands of mechanical engineering design.

The mechanical engineering undergraduate curriculum can be described as having three phases. In the first phase, the student learns the fundamentals. Courses such as math, physics, statics and dynamics are among the better-known fundamental courses. In the second phase, the student learns solve complex mechanical engineering problems. The
student learns to calculate the flow of heat, the deflection of components under load, and the output and efficiency of engines, as well as how to conduct experiments. The third phase requires the student to apply the knowledge gained over the previous three phases. If any one course represents the application of mechanical engineering knowledge, it is the final mechanical engineering design course. The students are presented with an industry problem, and they must work in concert with a group of classmates to create a product that addresses the problem. They not only calculate and make decisions; they must also justify their decisions based on accepted engineering practices.

I was surprised by the similarity among the capstone senior design courses offered by the programs ranked in the ASEE's top fifty. Even more remarkable was how course instructors told me they had little familiarity with the capstone senior design courses taught at other schools. Initially, I reasoned that the similarity was likely influenced by the guidelines of the Accreditation Board for Engineering and Technology (ABET) guidelines. However, examination of ABET guidelines revealed insufficient detail to account for the commonality. Future analysis may find a correlation between commonality of capstone senior design courses and industry feedback.

Many of the most important lessons that students should derive from the capstone senior design course are non-engineering in nature. In the workplace, an engineer assigned to a design group will seldom have the ability to choose other group members. As it was in their semester-long capstone senior design course, new engineers assigned to a design team have to quickly organize and begin the design process. One of the keys to success is the ability of a design group to act not a collection of engineers but as a cohesive design team. Perhaps no other course better represents what faces the new engineer than the capstone
senior design course.

According to ASEE, the number of mechanical engineering degrees awarded nationally has steadily increased, from 12,995 in 1999 to 13,769 in 2003. More than half of these degrees were awarded by the top fifty programs, with more than one sixth of the total number of degrees awarded by the top ten programs.

I spoke or communicated with instructors for the mechanical engineering capstone senior design courses at each of these top fifty schools. The most common answer to inquiries about textbook selection was that no textbook was in use for the capstone senior design course. The universal reason for no textbook being selected was that faculty teaching the course had judged no textbook to be worthy of adoption. Among those schools where textbooks were specified for the capstone senior design course, the books served as little more than reference material and were usually textbooks from a prerequisite course. In telephone conversations, every instructor teaching the capstone senior design course stated that it was necessary to provide additional faculty-written material to the students. This suggested that a need existed for a textbook written for the capstone senior design course taught throughout the nation. Instructors also often stated that the diverse range of topics taught in the course could not be found in any single textbook. Some schools selected multiple texts. One school selects five relevant texts for its mechanical engineering capstone senior design course every semester. Existing textbooks do not seem to satisfy instructors’ needs. All instructors expressed interest in a better textbook. The results of the survey revealed a clear need for a textbook written expressly for the capstone senior design course.

Instructors also expressed a desire that ethics and safety should be taught in the capstone senior design course and included in the designated textbook. Ethics has been
previously integrated into the programs of top fifty schools, but safety has not generally been included. Some faculty suggested that "case studies" should be included in a safety chapter.

Safety has been explored as a separate chapter in this text. A thorough discussion of safety requires an explanation of rules, recommendations, standards, and the entities that create them. A chapter on safety should include key safety concepts and the legal implications of product failure. Such a chapter should also explain to the mechanical engineer the importance of understanding the environment in which the product will be used, and the chapter should give the mechanical engineer an understanding of product abuse.

Most of the instructors expressed the opinion that ethics was an important topic in the course. Despite the overwhelming support for ethics, only one ASEE top fifty school has a dedicated ethics text.

Safety and ethics are almost always overlooked or undervalued in mechanical engineering design books. Ethical issues are presented as little more than an injunction to "Do the right thing", while offering the student an unrealistic view of the professional world. Such advice might work if the engineer's co-workers were always completely honest and impartial and the engineer wealthy enough to weather all possible legal problems. Sadly, such simplistic advice is of little use to a new engineer with dependents, debt and a mortgage, who might jeopardize a promising career by calling attention to a safety issue. At a time when the new engineer must balance conscience, legal liability, and professional career, a step-by-step analysis of ethical engineering procedures is needed.

This text was written using an organizational method that this engineer has chosen to call The General Topics Format. All manufacturing methods, and some other material described in this text, have been presented using the General Topics Format. A
manufacturing process presented in this book using the General Topics Format is illustrated below.

Process: Abrasive-flow machining, abrasive jet machining

How it is used: Polishing turbines and complex shapes

Advantages:
- Little heat is generated.
- Causes no heat damage to the workpiece.
- Suitable for finishing inaccessible surfaces.

Disadvantages:
- Equipment is expensive.
- Slow material removal.
- Poor tolerance control (10%-50% common, 25% normal).

Abrasive-flow machining is performed by transporting an abrasive-filled viscous semisolid medium across the surfaces of the workpiece. As the viscous semisolid medium is pumped across the workpiece, the abrasive particles rub on jagged edges and other sharp features, slowly removing the tiny protrusions. The finished part is analogous to a shiny, well-worn boat propeller that has been polished by sand particles suspended in the water. ...

The first paragraph always describes the basics of the process. Subsequent paragraphs elaborate on the listed advantages and disadvantages. This format allows the reader to quickly learn basic information about the process. If time permits, the student can read more detailed information about the process.
Many mechanical engineering design books have been written to show how to calculate relevant design features, but few authors have explained why engineers make the choices that they do. The purpose of these chapters is to convey some of the lessons of experience learned by mechanical engineers. Each engineering problem and each solution will differ, so there is no handy formula to cover every possibility. However, the engineer with a good understanding of engineering ethics and safety and the will and ability to incorporate these concepts in optimal designs will excel.

This engineer has observed that experience breeds creativity. Unfortunately for students in the capstone design course, they may have had insufficient life experience to conceive viable designs as quickly as established engineers. This obstacle can be mitigated if the course textbook contains accepted engineering assumptions, or "rules of thumb," as they are colloquially known. The mere presence of these condensed wisdoms conveys another lesson: Engineers do not succeed by re-discovering what was already known, but by figuratively standing on the shoulders of those engineers who came before them.
Chapter 1 - Working as a Team

1.0 - This Book and You

This book was written specifically to be a textbook for the capstone senior mechanical engineering design course that is taught in most major universities. Though the reader may be a senior in the undergraduate mechanical engineering program, he or she is referred to as the engineer throughout the book. It is the author’s hope that this book will serve you well, both in the capstone senior mechanical engineering design course and in your engineering career.

1.1 - The Best Advice

If there is any secret to achieving a high grade in this course, it is to quickly build an effective team. The capstone mechanical engineering senior design course is normally taught over one semester. The actual time available for working on the group project is about fourteen weeks. In fourteen weeks, each team will have to conceive a design, communicate that design, construct a prototype, test the prototype, and correct any deficiencies.

1.2 - Your Project

In this course, you will work as a team member to solve a real-life problem. This problem has been posed by an industry sponsor who has also provided funding to purchase supplies and pay for equipment usage. As part of a team, you will analyze the problem and create a viable solution. Your solution must be based on sound engineering principles.

As soon as you know what your project will be, begin gathering information on the topic. The sooner you perform a literature review, the sooner you can begin to design.
Because your ideas are of little use if you cannot communicate them in an easily understood manner, this course requires that you present your solution through a set of plans, as well as oral and written reports.¹

**1.3 - Choosing the Team**

Your instructor may allow the students to form their own teams. If this is allowed, certain skills should be sought, regardless of the project. It is desirable to have members with proficiency in: computer aided drafting (CAD), technical writing, welding, machining, basic hand tool usage, and other relevant areas.

Some instructors opt to assign students to their respective teams. This is far more representative of the workplace that the new engineer will likely face after graduation. Additionally, the use of instructor-selected teams removes the burden of team selection from the students.²

**1.4 - What to Expect at Your First Team Meeting**

Your team probably will consist of four to eight students. From the beginning of the first team meeting, a phenomenon called group dynamics—how people interact with one another—will be a factor influencing the work of your group. Some individuals will feel comfortable speaking, while others prefer to remain quiet.³ Your group’s goal should be to leave this meeting as an organized team.

Try to hold your first team meeting in an unoccupied room with a chalk or ink board. List your team members’ names on the board. Beneath each name, write the skill (CAD, technical writing, welding, etc.) that the team member considers his or her strong point.

During this time, determine which team member you wish to be your team’s leader. Don’t let this stage become personal. Choose as leader the member whom you believe can
best oversee the successful completion of the assigned project. Ideally, the leader should be mature, experienced in teamwork, and somewhat diplomatic in personality. The team leader will need to keep accurate data on the team’s budget and scheduling.

During the semester, the team leader may be absent due to a test or illness or may simply be overburdened by the team’s needs. For this reason, you should also choose an assistant team leader. The assistant team leader can share some of the responsibilities of contacting team members and vendors.

At this first team meeting, you should discuss the problem statement. This stage is sometimes called brainstorming. It is a method of gathering and organizing ideas. Do not berate or ridicule the ideas of any team member, since this can lead to future confrontations, a reluctance to reveal new ideas, a divided team, and almost certainly a lower grade in the course.

If you strongly disagree with an idea, use engineering facts to confront it. Remain objective and refer to the idea, not to an individual who favors the idea. For example, if your idea is to use a four-bar linkage, refer to it as “the four-bar linkage” and not as “my idea.” If you call an idea “stupid” or “bad” (or worse), those team members favoring the idea may take your remark as an insult. Speak in terms of advantages and disadvantages of a given idea.

Learn whether any of the team members have prior knowledge or work experience with a similar problem. Ask them to share a few of their observations from their knowledge or experience. Something they say may save you time during the information-gathering phase.
By the third or fourth week of the course, the team will have to submit drawings and possibly a written or oral report of their design for the project. This necessitates CAD plans, so you should choose two members who will do the actual CAD drawing. Technical writing skills will also be beneficial.

1.5 - Small-Group Dynamics

During the semester, your team may experience some of the classic interactions among members that have often been observed in small groups. (For the purposes of this section, assume that there are six to eight people in your team.)

Two individuals may vie against each other for the leader’s position or control of the group. When the group selects a leader, it becomes incumbent upon the rest to work as loyal members of the team. Should you observe a problem in this area, remind members that course grades will depend on their success as a team. If the conflict continues to grow, you may wish to consult privately with the instructor, but this is best left as a last resort.

At the other extreme is a team member who is consistently absent from team meetings or who simply refuses to contribute. In an eight-member team, seven can complete the work with little added difficulty. Even in a six-member team, five can complete the work in a timely manner. Remind disgruntled team members that the “fairness” issue created by a non-contributing team member can be resolved by consultation with the instructor or by peer grading if that is an option.

Most team members happily contribute and take satisfaction in the accomplishments of the team. It has been the observation of this engineer that most new engineers speak fondly of their former teammates and proudly tell of their team’s prototype.
1.6 - Scheduling and Budgeting

Every project will have a schedule and a budget. Your team’s ability to adhere to these will influence your grade. The schedule may specify only a presentation date, but your team will need to add intermediate steps and their corresponding dates in order to keep up with the rest of class.\(^7\)

The budget can be addressed in the design phase. As part of the design process, you should estimate the costs of the raw materials. For many products, the cost of labor is a more significant contributor to the final price than the material costs. Remember, besides adding to the final cost of the prototype, a labor-intensive design adds to your team’s time in the shop during the semester.

One way to facilitate planning is to use calendar software. Print the relevant months with entries for the appropriate date and time of important deadlines as well as for future group meetings or work sessions. Regularly update the calendar, and print copies for all of the team members. Mark the version of the updated calendar to avoid confusion with previous versions of the calendar. Your team may wish to mark the calendars with numbers or letters. For example, the fifth updated calendar might be marked “5” or “E” (the fifth letter of the alphabet).

Suppose that your team must present its solution and CAD drawings at the beginning of lecture number eight. You will probably be assigned to a team before the end of lecture number two and have your first team meeting afterwards. You will need to conduct a literature review, formulate a design, draw it with a CAD program, and prepare a report. Since you likely will have learned about the project during the first lecture, you should use this early time to conduct your own literature review. If each team member does this, there
will be an excellent chance for your team to begin evaluating designs by the end of the first meeting. This can gain your team a three- to seven-day head start over the other teams—a valuable advantage indeed!
Chapter 2 - Information-Gathering and Communicating Your Ideas

2.0 - Introduction

In engineering, as in the rest of life, each generation builds upon the achievements of the previous generation. Few innovations would result if every generation of engineers had to reinvent the wheel. This chapter shows the designing mechanical engineer how to find technical knowledge about his design project.

Before a mechanical engineering team can create a superior design, they have to learn about existing designs. In studying existing designs, the mechanical engineering team can determine specific shortcomings that their design should avoid. This chapter gives the mechanical engineering design team a guide for the evaluation of existing designs.

The best ideas in the world are of little value if they are not communicated to others. This chapter also discusses ways to present the mechanical engineering design team’s ideas in a clear and concise manner.

2.1 - Literature Reviews

The mechanical engineering design team should begin the design process by researching the problem. In the capstone mechanical engineering course, information about the problem will most likely be revealed in the first or second lecture.

After learning the basic problem, the mechanical engineering design team should perform a literature review. A literature review is a search of publications that allows the engineer to learn about previous research on a given topic. The purpose of a literature review is both to inform the engineer of the latest information about the topic and to save the engineer from needless duplication of previous work.
A helpful first step in the literature review is to use Internet search engines to find relevant websites. Websites of particular interest include manufacturers’ websites, product review websites, and articles that seek to inform the reader about the role of existing designs.

After researching Internet resources, team members should review relevant articles in journals and technical publications. These can be found in the university library. In the unlikely event that a needed journal article cannot be located, design team members should search online article repositories. These online repositories usually charge the purchaser a small fee for the article.

2.2 - Learning the Environment

No amount of reading can convey the lessons offered by visiting the work environment. Some of the more important information to be obtained by a visit by the mechanical engineering design team will include the types and quantities of debris, user skill level, and real-world product maintenance.

Example #1

A mechanical engineering team has been asked to design a conveyor-belt-mounted grasper for use at an inspection station in a poultry processing plant. None of the team members has any experience with the poultry industry. In order to learn about the environment in which their design will be employed, the entire team has arranged to visit the poultry facility.

The team gathers in the parking lot and proceeds toward the security guard at the main entrance. The security guard calls the plant official who will escort the team through the plant and explain its many features.
While the team members are waiting, the security guard recommends that they bring their coats into the plant, as the entire facility is refrigerated. The team’s escort arrives and asks if the team members are wearing slip-resistant shoes, because the floors in the work areas are always wet. Already the team has learned that the work environment is cold and wet.

The team’s escort leads the team into the work area and the surroundings are unlike anything that they have ever experienced. The work area is a sea of employees and stainless steel machinery, with literally thousands of chickens in various stages of processing rapidly passing overhead in different directions. The sound level of the machinery makes conversations strained. The most overwhelming sensation is the smell of sanitizing solutions. The team members begin to realize that space is at a premium and the work pace is more hurried than they expected.

A mixture of water and sanitizer seems to cover every surface of the work area and drip down from above. The team members all recognize that their design must be impervious to these liquids. The team also knows that their design must be operable by an employee with cold, wet hands.

Finally, the team’s escort has brought them to the inspection station. Here a specially trained inspector stands in front of a stainless steel conveyor assembly as the partially processed chickens are moved from the inspector’s right to left at eye level. To prevent contamination, the inspector wears rubber gloves. The team members all notice that their design must be compatible with easy rotation by one person wearing gloves. The team also realizes that their design must not possess any features that could tear the inspector’s gloves or harm the inspector’s hands.
The team members are now convinced that their design must be easily cleaned by the procedures they have witnessed. The team will be certain that their design does not have any recessed features that could hold contaminants. The team members have learned a lot from their brief visit.

Example 2

Fig. 1. Typical muddy construction site.

A mechanical engineering team has been asked to design a battery-powered drill to be marketed to the construction industry. Only one of the team’s five members has worked in construction, having held a brief summer job working for a residential construction company. Even that member’s experience was minimal. In order for the team to learn about the commercial building environment, the corporate sponsor has helped to arrange a team visit to a large local school that is under construction.
Upon meeting the corporate sponsor’s representative, the team members are issued safety glasses and hard hats. The team’s members who thought that the gravel parking lot looked dirty will soon realize that it was one of the cleaner areas at the site.

The team has arrived at the construction site on an unusually hot and humid day. The city has received heavy rain for several days, and the construction site looks like a sea of mud as soft as pudding, punctuated by deep water holes. Projecting from the mud are large steel I-beams forming a partially assembled structure.

As the team and their corporate sponsor’s representative weave their way around the water holes and other hazards, the team’s members begin to appreciate the potential for debris-induced failure in any power tool used at the site. As the team members strive to keep their balance in the mud, the corporate sponsor’s representative remarks that after the mud dries, even a gentle breeze will blow the soil across the site until everything is covered by a thin layer of dust. The corporate sponsor’s representative remarks that mud typically clogs the cooling air vents on power tools and that dry soil disables bearings. Already the team has learned that their drill design must be able to operate in a debris-filled environment, regardless of whether it is wet or dry.

Team members soon notice the temporary electrical power cords that have been trampled into the mud or are intertwined with the portions of the building’s structure. The corporate sponsor’s representative remarks that electrical shock injuries are an ever-present risk at construction sites. Team members begin to discuss the need for an all-plastic drill body to lessen the chance of electrical shock, especially if the user should inadvertently drill into an electrical power cord.
One of the team’s members notes that any small tool dropped into the mud or a water hole is almost certainly lost. This remark leads the team members to conclude that the drill should have a keyless chuck easily turned with a wet or muddy hand.

![Keyless electric drill chuck.](image)

Observing the construction workers, the team notices that the workers must hold the workpiece with one hand while drilling with the other hand. The team’s members decide that their design must be operable with one hand. The team’s members observe that their drill design should be easily set for forward or reverse with the same hand that operates the speed control. Some team members suggest that the battery should be easy to change regardless of the size of the user’s hands.
The construction workers themselves pique the curiosity of the team members. The team has noticed that the construction workers speak different languages. Among the languages heard are Spanish, Russian, and Polish. The corporate sponsor’s representative explains that most of the workers are foreign nationals who have obtained work permits. These workers usually cannot read or write English, and some cannot read or write in any language, so they often learn to use power tools by observing their coworkers. The team members understand that the controls on their drill design must be intuitive, possibly with tiny symbols embossed into the drill housing adjacent to each control, illustrating the control’s function.

Despite the value of good tool maintenance, none of the tools is observed being lubricated. Even those construction workers who attempt to clean their power tools simply wipe the tool down the front of their dirt-encrusted T-shirts. Power tool cooling air vents stay clogged. The team resigns itself to the fact that few tools get the care and maintenance that their manufacturers specify.

The work environment visited by the team is far removed from the pictures in tool catalogs. As a result of their trip, the team has a new outlook on power tool design.

2.3 - Analyzing Existing Designs

The fact that there is a need for a new product is evidence that existing products do not satisfy the needs of the marketplace. In order to understand the advantages and disadvantages of existing products, the mechanical engineering design team should evaluate the designs of those products.

Criteria for analyzing existing designs should include objective performance data, safe and simple function, and manufacturing cost. The team should pay particularly close
attention to how existing designs overcome known problem areas, such as debris-induced failure, fatigue failure, and maintaining the alignment of precision parts.

**Example**

The mechanical engineering team in the earlier example has gathered to analyze samples of the three best-selling currently available battery-powered drills. The team members have decided to analyze the exteriors of the drills first. After they have finished with the exteriors, the team members will open the drills and analyze the design features found inside.

The team members immediately notice that the batteries of all three drills resemble boxes or ovals, each with a vertical column that inserts into their drill’s handle. As a result, the centroid of each battery hangs directly below the user’s hand. Because the body of each drill is positioned forward of the user’s hand when properly held, each drill has a slightly uncomfortable forward balance. The team members discuss positioning their battery’s centroid to the rear to give their drill a more comfortable balance.

The team members observe that all three of the drills they are studying feature a keyless chuck. This allows the user to insert and secure drill bits and drive accessories without the use of a special tool. The team members acknowledge that their drill design needs to have this same feature.

After observing that one of the sample drills has a body that is partially cast metal, the team members recall their observation of the electrical power cords and the potential for electrical shock hazards. Because drill users frequently grasp the drill body with their other hand for better support, a metal section of the drill body might facilitate the user being
shocked by accidental contact with an active conductor. The team members agree that their drill should have an all-plastic body.

All three drills use an impellor to circulate ambient air for cooling. The impellor is located in the forward half of the body in all three drills. All three drills feature long, narrow, vertical slots positioned on both the left and right sides of the drill body. The slots expose the impellor blades to aid air flow exit. At the rear of all three drills are louvered air intake ports. The team decides to design their drill’s cooling air vents so the user may easily clear debris from the vents with a common flat-blade screwdriver.

Examining the interior of the three drills, the team notices that a device called a thermal protector has been incorporated into each drill. Researching thermal protectors, the team members learn that thermal protectors interrupt the electrical power circuit when the temperature exceeds a predetermined value. The purpose of using a thermal protector in this application is to prevent the drill from catching fire or melting the plastic components. The team reasons that their drill should have a thermal protector.

The team continues by examining the bearings, gears, and motors. They recognize that placing the gears in an integral package would allow for fast assembly and repair times. The team members discuss using a gear housing that would either be cast or formed from stamped steel.

The team debates the merits of using a brushless motor. A brushless motor would be more expensive but would not have exposed sparks that might ignite a flammable vapor.

2.4 - Plans and Drawings

As the mechanical engineering team’s design takes form, they should formalize it with technical drawings. In the past, technical drawings were made by hand in a technique
known as drafting. Now technical drawings are created by means of computer-aided design (CAD).

The purpose of the drawings is twofold: reproduction and improving the design. Technical drawings enable the product to be produced by people who have no prior knowledge of the design. For example, if an electric can opener is designed and built in Belgium, high-quality technical drawings to would allow the product to be reproduced by a company in Argentina with skilled engineers and manufacturing personnel.

Technical drawings can assist the mechanical engineering team in improving their design. The team members can study the drawings for obvious flaws, such as overlapping holes. Technical drawings also allow the team members to visually analyze the position of each part as it relates to the other parts.

Subassemblies should have their own set of drawings. The main drawings should clearly refer to the appropriate drawings for the subassemblies. The drawings should also reflect how subassemblies connect to the main portion of the product.

2.5 - Presentations

Few moments in product development are as brief, or as important, as the presentation. During the presentation, the designing mechanical engineers must convey a wealth of technical detail to non-technical people so as to win their enthusiastic support, in a few minutes, without losing their attention.

The presentation should never exceed the allotted time limit. Exceeding the time limit will insult and alienate listeners who have their own schedules to maintain. The mechanical engineering design team should rehearse their presentation to assure both time compliance and professional delivery.
Throughout the presentation, the team’s speakers should conduct themselves in a professional manner. The speakers should strive to give the appearance of competent, dependable, knowledgeable, mature engineers.

It is inappropriate for any team member to wear a shirt with offensive writing during a presentation. The purpose of a presentation is to show the audience why your team’s design has merit. Offending the audience will reduce your team’s chances of winning over the audience with your design.

The team member’s clothes should be clean, orderly, and appropriately chosen. If the audience will be wearing dress business attire, then so should the engineering team members. Ideally, the team’s members should be dressed slightly more formally than the audience. The team members’ clothes do not have to be expensive, just suitable for the presentation. Posture also sends a message to the audience. Professional appearance means always conveying that you are a capable and dependable engineer. The team member should mentally place him- or herself in the role of the audience to better understand this issue.

Suppose that two mechanical engineers give identical presentations. The only difference is that the first engineer slouches, looks down at the podium, and at times is difficult to hear. He presents the material while wearing ragged jeans and a T-shirt festooned with holes, various food stains, and the name of the engineer’s favorite bar. The second engineer stands erect, engaging the audience with eye contact. She speaks clearly and confidently about a design with which she is obviously familiar. The second engineer wears business clothes, has an orderly appearance, and displays an enthusiasm for the design.

Which of these engineers is more likely to instill confidence in the design among the audience? Which of these engineers is more likely to earn the support of superiors or
investors? Appearance, gestures, posture, and speaking voice all contribute to the overall quality of the presentation.

The mechanical engineering design team will benefit by structuring the presentation in five parts. The first part should be an introduction, beginning with a one- or two-sentence statement about the team, with the speaker naming the team members. This is a personal touch illustrating to the audience that the team members are real people who have put forth their best creativity and engineering talents. The introduction should conclude with the problem statement.

The second part of the presentation should briefly explain the approach taken by the mechanical engineering design team to solve the problem in the problem statement. The team’s speakers should use this opportunity to state the logic that led to the design.

The third part of the presentation should explain how the team transformed the design into a real prototype. This section doesn’t have to discuss every nut and bolt. However, it should be used as a way of proving to the audience that the team has transformed theory into reality.

The fourth part of the presentation should present the prototype’s test results. This section should demonstrate to the audience that the designing team has succeeded—that they achieved what they set out to accomplish.

The fifth part of the presentation should be the conclusion. It should summarize the presentation.

2.6 - Website

The development of a team website facilitates two-way communication. The team can post information about their project and their solution for others to read. Readers can also
post their questions or comments to the team. The team website also allows rapid communication from the course instructor. The instructor need only post information to the team websites to inform all students of new course material.

A website can serve as a type of continuous presentation. Unlike human engineers, the website can present the team’s design at any hour or any day. By maintaining a website about their work, a designing mechanical engineering team can reach a far larger audience than would be possible without the website.

Composing the website is not enough to realize its maximum utility. The mechanical engineering design team needs to take some simple steps that will allow the website to be found. The first step is to list the website with several popular search engines. If someone performs a web search for “mechanical engineering design” and “prototype”, the team’s website will be among the returned list of search results.

Another valuable step for making the website available to visitors is linking. In linking, the team contacts another website and arranges for that website to post an electronic link to the team’s website. Suppose that a visitor to another website wishes to read more about ongoing mechanical engineering design projects. The visitor can select a link from that website to the team’s website. In this scenario, the link on the other website has added an additional person to the team’s audience.
Chapter 3 - Safety

3.0 - Ethics

Where used: Throughout engineering

Ethics issues:

1) Ethics are the foundation of safety and the consumer’s trust in the engineer.

2) Specific laws and standards exist to maintain ethics and safety.¹

3) Well-defined ethics steps exist for engineers to follow.

There is perhaps no concept more fundamental to engineering than safety. When a consumer chooses a product, the choice implies the consumer’s confidence that safety was incorporated into the design. In order for a product to be successful, the designing engineer should balance function, safety and cost.

Consumers often address safety concerns by confirming that the product meets standards established by commercial testing facilities, government agencies, or professional organizations. The purchaser of an appliance may examine the packaging for the mark of a respected testing laboratory. The purchaser of an automobile may read government automobile crash test ratings. The purchaser of air-conditioning equipment may select a product because it meets ASHRAE standards.

Safety became a major engineering concern of the industrial age after attention was brought to well-publicized accidents and unsafe workplace conditions. As steam engines became widely used in riverboats, trains, ships and factories, boiler accidents led to a public demand for safer designs. At about the same time, journalists like Upton Sinclair began writing of dangerous workplace conditions facing many Americans, particularly in the meat industry.² Critics of these journalists called them “muckrakers” and other derogatory names,
accusing them of sensationalizing and exaggerating. In time, workplace safety emerged as an important issue to many Americans. Although few statistics on workplace injuries were recorded during the early twentieth century, conversations with people alive during that period reveal that it was common to see people missing a limb or eye due to workplace accidents. In the textile industry, many machines manufactured in the 1920’s are still in use. The absence of proper guards on these machines continues to result in workplace injuries.

Ultimately, safety begins with the engineer, and that requires ethics. Any discussion of ethics requires that it first be defined. Perhaps there is no better definition of ethics than the colloquial expression, “Ethics is doing the right thing when nobody is looking.” It seems all too easy to dismiss ethics as a utopian concept, a quaint idea that cannot survive in the real world. Ironically, it is in the real world where ethics can decide the fate of an engineer’s career. When the cold light of financial loss or personal injury litigation is cast upon the engineer, ethics will be examined. Many regrettable decisions can be avoided by striving to maintain ethical conduct and documenting that an ethical course of action was followed. In order to promote competence and ethical behavior in engineering, all fifty states in the U.S. have professional engineering licensure boards. The procedures established by these engineering boards include standards for engineering education and requirements for written testing, supervised engineering experience, and continuing professional development. Engineering licensure boards are generally empowered to reprimand, levy fines, and suspend or revoke licensure. When an engineer’s work is examined in a courtroom, the court will seek to learn if the engineer’s work was based on sound engineering practices. The court will seek to answer if the engineer was both competent and ethical.
One of the most difficult problems facing the engineer in the workplace is knowing the appropriate steps to take in order to fulfill both occupational demands and maintain ethical conduct. When an engineer raises an ethical concern that is ignored by a superior, the engineer will face what may seem like a dilemma. The first step for the engineer in these circumstances should have been taken long before the problem: The engineer should already have researched the employer’s ethics policies and the state engineering board’s published guidelines. The next step should also begin before a problem occurs: personal financial responsibility. Engineers with fewer financial obligations will likely find an ethical course of action easier to follow. Always document your efforts to communicate safety-related concerns. Keep duplicate documentation at a separate location for added security. Documentation is sometimes referred to as “leaving a paper trail”. Communicate in clear, concise and professional terms. After communicating a safety concern to a superior or co-worker, decide on a reasonable time frame for a response. If, for example, you set the response time frame at one week, resubmit your concern if the time frame passes without a response. If multiple communications receive an unsatisfactory reply or no reply, communicate your concerns to others based on your employer’s written policy and engineering board publications. If you are threatened with dismissal for maintaining your ethics, you may choose to pursue legal options. If you do pursue a legal option, the “paper trail” that you established will prove invaluable. Possibly the truest measure of ethics comes from within yourself. If you make ethical decisions as an engineer, you will feel the pride and honor they bring.
3.1 - Regulations and Standards

Where used: Throughout engineering

Regulation and standards issues:

1) Specific laws and standards exist to maintain ethics and safety.

2) Federal, state and local government agencies enforce safety regulations.

3) Professional societies and private organizations often have their own regulations and standards.

In order to protect the public, regulations and standards exist that relate to most engineering applications. Regulations have been established at federal, state and local levels to promote safety. A list of the Federal regulatory agencies that relate to engineering design would include but not be limited to NHTSA, NTSB, OSHA, FDA, and EPA.

Formed in 1970 under the Department of Transportation by the National Highway Safety Act, the NHTSA (National Highway Traffic Safety Administration) works to reduce motor vehicle economic losses, deaths and injuries. NHTSA aims to improve safety by regulating automobile design, studying traffic flow and driver behavior, and investigating safety defects in motor vehicle design. NHTSA also sets and enforces fuel economy standards as well as vehicle anti-fraud and anti-theft regulations.

The NTSB (National Transportation Safety Board) was formed in 1967. NTSB works to determine the probable cause of all U.S. civil aviation accidents, major marine accidents, hazardous materials releases, and fatal or major accidents involving railroads, pipelines, or recurring transportation issues.
OSHA (Occupational Safety and Health Administration) takes its name from the Occupational Safety and Health Act of 1970. In compliance with this legislation, OSHA was formed in 1971 to address workplace safety and illness.

The FDA (Food and Drug Administration) has relevance to engineers designing for the food, medical and pharmaceutical industries. The FDA began as a single chemist in 1862 operating under the Department of Agriculture. An example of the FDA’s relevance can be found in their Good Manufacturing Practices/Quality System Regulation guidelines, which specifically affect the design of manufacturing and processing equipment.

The EPA (Environmental Protection Agency) was formed in 1970 and regulates the design of engines, manufacturing equipment, and water treatment mechanisms, among other items.

In addition, many of the functions of federal regulatory agencies are supplemented or duplicated at the state and local levels.

Hundreds of years ago in Europe, craftsmen formed guilds to establish and maintain standards to be followed by those in a given trade. In a similar effort, many professional societies have developed what are termed consensus standards. By themselves, consensus standards have no legal authority. Designers usually adhere to them to instill confidence in the consumer that the design is sound. ASME, SAE, ANSI, ISO and ASHRAE are among the consensus standard organizations better known to the mechanical engineer. It is common for government agencies to adopt consensus standards as regulations. This is especially true in engineering, as the professional societies are able to draw on the knowledge gained from respected experts in the affected engineering fields. When a consensus standard is adopted as
a regulation, it has the power of law. Reputable designers always consult the consensus standards.

In a manner similar to consensus standards, third-party testing laboratories also let consumers know that a product meets one or more known standards of that laboratory. Perhaps the third-party testing laboratory best known to American consumers is UL, Underwriters Laboratories Inc.

It should be readily apparent that government regulations and consensus standards play a role in all aspects of engineering. The mechanical engineer designing a device will find the design process much easier if he or she takes the time to research the applicable regulations and standards.

3.2 - Concepts

Where used: Throughout engineering

Safety issues:

1) Fundamental safety concepts help ensure the safety of a design.

2) Safety concepts have been proven through trial and error.

3) Always try to incorporate safety into the basic design.

The most fundamental of all safety concepts is that if the design should fail, it should fail safe. This means that should a design fail, it is better for the system to become inoperable than for it continue operating but in a dangerous manner. Some older automobiles used a small metal piece known as a parking pawl to prevent their transmissions from inadvertently shifting from park into reverse. Unfortunately, wear in the linkage enabled these transmissions to accidentally slip into reverse, with potentially dangerous results. In 1997,
this engineer examined and tested an emblem press and an industrial paper cutter, neither of which had failed safe during an actual equipment failure. Serious personal injuries resulted.

A truck tractor’s air brake system is connected to its semitrailer’s air brake system by two air hoses. One of these hoses serves the semitrailer’s normal air brakes. The other air hose is the emergency air supply. If the emergency air hose connection is severed, the semitrailer’s emergency spring brakes will be activated. This allows the semitrailer’s brakes to fail safe.

In the Caribbean and in other clear waters, tourist submarines are a popular attraction. They are equipped with a row of windows on each side, allowing passengers to safely and conveniently enjoy the underwater beauty of the sea. These tourist submarines are all electric-powered. To ensure safety, they have a positive buoyancy. This means that the submarine must use power to remain submerged. If the submarine were to become disabled, it would gently float to the surface. With this safety feature, the tourist submarine that fails will fail safe.7

It is always desirable for the mechanical engineer to design in redundancy. The spare tire in an automobile is an example of redundancy; five tires are carried when only four are needed. Many aircraft warning lights consist of a plastic optical conduit with multiple bulbs providing light for that single warning feature. The pilot sees the illuminated conduit when the warning feature is activated. Should one bulb burn out, the other bulbs can communicate the warning when necessary.

Safety need not be inconvenient. As Henry David Thoreau concluded in Walden, human beings are prone to following the path of least resistance.8 When a safety device hinders the product’s use, the consumer may attempt to bypass or remove the safety. In 2000,
this engineer examined a wood press in which the safety had been bypassed in an effort to improve productivity, with tragic consequences. The engineer should strive to design safety features that function without conscious thought by the product operator.

Account for some degree of product abuse in safety design. The agricultural industry is an example where product abuse may be encountered. Many agricultural workers have little or no formal training in the operation of tools and machinery. This is especially true in underdeveloped nations. The long hours and hard physical labor common to agricultural work can leave the workers tired and less alert to potential hazards.

Selecting design features that minimize maintenance, or at least make maintenance more convenient, reduces the occurrence of accidents. Applications involving wire rope and hydraulics are examples of mechanisms that can benefit from this design approach. Wire rope requires frequent inspections. If those inspections can be easily made, they are more likely to be made. Hydraulic mechanisms, such as those used in lifting machinery, normally require daily maintenance. When lubrication ports are difficult to reach, consumers may neglect lubrication, leading to failure.

Simplicity is both an important design concept and a safety enhancement. In lay terms, “Fewer parts means fewer things to go wrong.” If each machine component has a given probability of failure, reducing the total number of components reduces the chance that a part of the machine will fail. Charles Lindbergh selected a single-engine airplane for his famous 1927 solo flight across the Atlantic Ocean because a twin-engine plane would not be able to complete the flight if one engine failed, and having two engines instead of one would double his chance of engine failure.\textsuperscript{9}
Commonality of operation procedures enhances safety by easing consumers’ transitions to the product. This would include such steps as positioning any controls and hand grips of a power tool in the same locations as on other similar products.

All designs should incorporate a safety factor. The safety factor is the quotient of the expected load and the load at which a component fails. The safety factor chosen depends upon the application. A larger safety factor may tolerate more abuse and better resist fatigue than a low safety factor. Conversely, a large safety factor may result in a bulky or overweight component that is unable to compete with rival designs. When a product has an unreasonably large safety factor, it may be said to be overdesigned. Safety factors for many common products are between 1.25 and 1.75, according to the application. Consensus standards often include guidelines for choosing an appropriate safety factor.

Product liability is a significant issue for the mechanical engineer. If a product fails and personal injury results, it is nearly certain that questions of civil liability will arise. During this litigation, the designing mechanical engineer can expect his competence and ethics to be examined.

Not only must the engineer address genuine product safety concerns; meritless and fraudulent claims should also be expected. Meritless litigation commonly occurs because the user operated the product in an unsafe manner or altered the product prior to the accident. Some consumers believe that they can improve the product by modifying it themselves. Unfortunately, modifications made by these consumers may inadvertently lead to product failure and personal injury. This engineer is aware of accidents in which people acted in grossly irresponsible ways that contributed to the accidents they had, yet they received compensation from the manufacturer.
For reasons of product liability, some manufacturers favor design features that hinder unsafe modification of their products. These features include tamper-resistant fastening and devices to restrict the space available for installing unsuitable components. Some manufacturers use mechanisms that indicate when someone has tampered with their product. These may include seals that display lettering when removed or threadlocking materials with proprietary compositions. Should product-liability litigation result, evidence of tampering can absolve the manufacturer of blame. A small number of well-publicized product tampering incidents during the 1970s led to the use of tamper-resistant seals on food and drug products. A popular American trailer rental company has used proprietary safety chains. To the average trailer renter, these chains would appear the same as other similar safety chains. This engineer has examined safety chains that were alleged to have failed on this company’s trailers. The claims were that the failed chains caused personal injury accidents. In each of these claims, the evidence chains were shown not to be the original safety chains.

Incorporate guarding and shielding in the design, even if no regulation or standard calls for it. Examples of places where guarding is useful include chains and sprockets, meshing gears and other mechanical pinch points. Lawn care equipment is an example of where shielding is beneficial. Rocks and other debris may be propelled at dangerous speeds from beneath mowers, trimmers and edgers.

**3.3 - Workplace Issues**

Where used: Occupational locations

Safety issues:

1) Incorporate guarding.

2) Design in redundant safeties.
3) Design for safe maintenance.

Workplace hazards that the mechanical engineer should consider include but are not limited to machine operation, vehicle operation, the potential for worker slips or falls, burns, and electrical shock. Electrical shock may seem outside of the responsibility of the mechanical engineer, but it is not. The author once examined a lighted storefront sign in which the mechanical engineer had designed an incandescent light fixture sufficiently close to electrical wiring for the heat given off by the light to degrade the wiring insulation over time. Eventually, a customer touched the sign and was electrocuted.

The traditional method of designing machinery has been to focus on the objective of the design and the anticipated forces to which the design will be subjected. The mechanical engineer can benefit greatly by taking another step first. The mechanical engineer should endeavor to learn about the environment in which the machine will be used.

Machinery is seldom operated in an environment devoid of human interaction. The workers in proximity to the machine are themselves an important part of the machine’s operational environment. What is their education level? What language do they speak? Can they read and comprehend technical and safety labels? What formal training have they had regarding operation of the machine? These are questions that the designing mechanical engineer has to ask and answer. Some of the useful methods for designing safety into a new machine are guarding, maintenance access design, and safeties.
Machine guarding

Fig. 3. Homemade grinder guarding. This guarding provides excellent protection against injury.

Machinery guarding is indispensable in the workplace. The new engineer may be lulled into a tunnel vision about guarding, viewing it as a means of keeping the curious worker from inserting a finger into the machine. The reality is that guarding also prevents clothing or hair from becoming entangled with moving parts. In the close confines of some industrial settings, loose clothing can be drawn into the machine, taking the worker with it. The author is familiar with a line-shaft accident in which static electricity caused a nearby worker’s hair to suddenly wrap around the spinning shaft, effectively scalping the worker. Proper guarding would have prevented the accident.
Inevitably, machines need maintenance, which usually requires that a worker gain access to a region of the machine that is normally guarded. The engineer can improve safety by designing the machine with human nature in mind. If maintenance requires that extensive guarding be removed, workers will likely not replace the guarding, to save time and effort in anticipation of future maintenance access. Even if maintenance personnel properly replace the guarding, inconvenient maintenance may lead to workers neglecting routine maintenance.
Worse, workers sometimes attempt maintenance while the machine is in operation. They frequently do this because they think it will save them time or to avoid lost productivity.

**Machine safeties**

Figs. 5a, 5b. Integrated safety. This wooden mockup of a manufacturing machine illustrates how safeties can be integrated to ensure that both of a worker’s hands are clear of the dangerous parts prior to operation.

Safeties can be designed into a machine to avoid many common types of accidents. A safety device may require that the operator of a machine grip sensors with both hands, thereby assuring that the worker’s hands are clear of the hazardous components. Light-beam sensors are popular for detecting the presence of a worker standing dangerously close to a machine. Multiple sensors are often necessary to ensure reliable worker ingress detection. Accidents have been known to occur during maintenance procedures when another worker, unaware that someone was working on the machine, started the machine. Safety features
should be designed into the machine to automatically disable the machine during maintenance.

Slip and fall

Fig. 6. Slip and fall. Slip-and-fall injuries highlight the importance of good design of shoe soles and walking surfaces.

Any steps, walkways, or other workplace access designed by the mechanical engineer should conform to all applicable regulations and standards. When designing any feature not directly addressed by regulations, the engineer should defer to consensus standards. The engineer should design to prevent condensation, oil or other fluids from flowing onto any surface that would cause a worker to slip or fall.
Vehicles around workers

Many work environments include vehicles operating among pedestrian workers. Safety in this type of setting has traditionally included horns, reverse-actuated alarms, rotating amber lights, strobe lights, and safety cages for vehicle operators. Safety cages protect vehicle operators from falling objects. Horns function just as they do on automobiles, enabling the driver to warn pedestrians or other drivers. Rotating lights and strobe lights are an especially valuable asset in noisy work environments. Reverse-actuated alarms require no thought by the vehicle operator to function. A more recent design approach has been the inclusion of proximity and presence detectors. The two most common methods of presence and proximity detection are sonar and radar. Reduced electronics manufacturing costs have begun to make sonar and radar economically viable options. The author once examined a sanitation truck that had killed a sanitation worker during a three-point turn. If a detection system had been available on the sanitation truck, this accident likely could have been prevented.

Hazardous chemicals

Some hazards typically remain unseen by workers. Without adequate warning and precautionary steps, hazardous chemicals can cause death or inflict serious bodily harm. Most safety measures for workers near a chemical hazard can be summarized as preventing skin contact and maintaining a supply of fresh air. From the mechanical engineer’s perspective, chemical hazard safety measures include but are not limited to selecting materials that are impervious to the chemicals they contact, designing for safe and convenient maintenance routines, and designing to avoid an unsafe discharge of a hazardous chemical in the event of an accident (fail safe).
Because many maintenance personnel may neglect or be unaware of the safety steps necessary for working around hazardous chemicals, the mechanical engineer may want to design the size and placement of human access ports to promote proper ventilation (convenient safety).

### 3.4 - Power-Tool Safety

Where used: Power tools operated by or near humans

Safety issues:

1) Address mechanical safety, electrical safety and user issues.

2) Account for operator misjudgment when possible.

3) Learn about the environment in which the tool will be used.

For the mechanical engineer designing a power tool, safety factors can be divided into three groups: mechanical safety, electrical safety, and user issues. Mechanical safety can refer to several different concepts. The obvious implication is that should a component break, no injury should result. Mechanical safety also includes design features that interrupt operation unless the tool is in the correct position. Examples of such mechanical safeties can be seen on air-driven nail guns. Air nailers usually have a feature that requires the tool be pressed against a surface to operate. This is to lessen the danger of an unintentionally discharged nail. Since construction workers may be within close distances of each other, this mechanical safety reduces the chance that a worker could be struck by an errant nail. Electrical safeties often take the form of pressure-release switches. A popular type of pressure-relief switch is the grip safety. An example of a grip safety on a power tool would be a circular saw, where the primary grip contains a grip safety. If for any reason the user’s hand releases its grip, the power supply to the saw would be interrupted.
User issues are more complicated than simple safeties. The engineer needs to learn about the debris, chemicals and weather to which the tool will be subjected, as well as how the targeted consumers use existing power tools. Some power tool users apply excessive force to tools, exceeding the recommendations of the manufacturer. Excessive force can not only accelerate wear; it can burden a tool’s electric motor, raising the risk of overheating.

Example

Let us assume that a mechanical engineer has been asked to design a portable band saw to be marketed to industrial plumbing contractors. Band saws are held by two hands and may be used to cut in different orientations, including inverted. Band saws normally use an electric motor to turn a continuous steel band blade fitted with cutting teeth along one edge. The band is wrapped around two wheels, one of which is powered by the electric motor. Operation of band saws is normally controlled by the application of index-finger pressure on a trigger-type electrical switch. Many saws are configured to allow the trigger switch to be locked in the “on” position to lessen hand fatigue. Cutting takes place along the segment of the band blade between the two wheels, moving toward the user. The other segment of the band blade is normally guarded.

If the engineer is not already familiar with the work of industrial plumbers, some research is in order. After reading about the role of these professionals, the engineer should seek permission to visit a job site and observe first-hand what the work environment is like. If this is the first time that the engineer has visited a new construction site, he or she may be surprised by a significant presence of mud, sand, snow, or even large pools of standing rainwater. These environmental conditions will influence the success of the design. The engineer should learn what criticisms consumers have about existing band saws. The
engineer may hear that existing designs become easily clogged with debris, are too heavy, or suffer frequent parts breakage. It may prove valuable for the engineer to ask consumers about the ergonomics of existing designs, common sizes of pipes to be cut, and even the number of hours a day that they spend working. This last question may provide insight to the tool’s life and the safety alertness of the consumer. A tool that stays in near-constant use may receive little care or maintenance. A consumer is likely to be less safety conscious after working for eleven hours than after six hours, increasing the chance of tool misuse. While watching consumers at work with existing band saws, the engineer should try to estimate the force with which the worker holds the blade against the pipe. This can be later duplicated in controlled tests with force gauges. Do consumers consistently wear eye protection? Do they keep their electrical cords and power sources away from pools of water? Armed with this information, the engineer is better able to design the product.

The region around the wheels should be guarded to preclude the user getting a finger caught between one of the wheels and the band blade. The trigger switch should be designed in a way that will prevent the switch accidentally sticking in the “on” position. The handles of the saw should be constructed of non-conducting materials to prevent electrical shock should an uninsulated electrical conductor contact the inside of the handle. The handles of the saw should be designed to provide purchase (grip) and avoid dangerous slippage of the user’s hands. All metal of the saw should be grounded through the power cord in case of contact with an unintended electrical source. If the saw uses external electrical power supplied to the tool through a cord, the cord should be protected from wear and unintentional separation from the tool.
Engine-powered tools

Where used: All engine-powered tools

Safety issues:

1) Prevent exposure of people to missiles or burns from tool.
2) Prevent the ingress of body parts.
3) Use integral safeties such as pressure-release switches.

Many tools and machines need to cooperate in locations that are remote from electrical power or without the limitations of long electrical power cords. These tools are normally powered by small gasoline or diesel engines. Common examples include lawnmowers, chainsaws, edgers, trimmers, augers, and blowers.

Lawnmowers, trimmers, and edgers use an engine to rotate a blade or thin wire. The mechanical hazards presented by these tools include missile injuries and injuries resulting from the ingress of body parts. Missile hazards include but are not limited to rocks, bolts, nails, and wood chips. The most popular methods of preventing these injuries are guarding, shielding, and pressure-release safeties.
Fig. 7. Lawnmower guarding. Well-designed lawnmower shielding protects against both tool-propelled missiles and the ingress of body parts.
Shielding involves designing and constructing the tool to block the path of missiles from striking the user. The deck of a mower also serves as shielding. Guarding involves designing and constructing the tool to block the ingress of the user’s body parts. An example of this can be seen in the guard positioned at the rear of a mower deck, near the user’s feet. A pressure-release safety on mowers is a thin bar parallel to the handle that must be grasped by the user for the mower engine to operate. An example of an unsafe modification by users is bypassing the pressure-release safety by means of tape or string. This may be done in an effort to reduce mowing time. It is important for mechanical engineers to address human behavior in safety design.
An auger is a tool that uses an engine to turn a large spiral screw for drilling holes in earth. The tool is usually oriented to place the screw tip against the soil. In this orientation, the engine sits atop the screw, with the X-shaped handles immediately beneath the engine. Large augers may be configured for use by two operators. The primary safety concern with augers is that the users’ feet not contact the large spiral screw.

Engine-powered blowers are popularly employed to quickly clear lawn debris. They consist of an engine, an impellor, and tubing to direct the air flow. In order to reduce operator fatigue, the engine and its attached impellor are often mounted on a frame carried on the operator’s back. Two safety concerns with blowers are burns and hearing loss. Burns can result from operator skin contact with hot engine components. This hazard can be safely
avoided by incorporating guarding and heat shielding in the blower’s design. Hearing loss is a more persistent problem. Even when the employer emphasizes the need to wear hearing protection, blower operators may not understand the importance of this safety feature. Blower operators may mistakenly reason that if the blower engine noise is not causing pain, no hearing damage is done. Another concern is the hearing loss a blower engine may cause to other people nearby. State legislation is increasingly restricting engine-driven blower operation due to objectionable noise. All of these hearing-loss concerns could be best addressed by designing noise reduction features into the blower before manufacture.

Modern chainsaws are examples of how unobtrusive safety features can be incorporated into the design of an otherwise dangerous machine. Chainsaws consist of an engine, a thin bar extending from the engine with a rounded free end and grooved edge, and a continuous engine-driven chain blade that traverses the grooved edge of the bar. The chain blade consists of a roller chain fitted with small protruding individual blades.

The chainsaw user holds the tool by purpose-built handles at the engine end. The rearmost handle is fitted with the controls and a grip safety. The grip safety must be depressed for the tool to operate. The forward, or supporting, handle is positioned above the juncture of the chain and bar with the engine. The user’s supporting hand is protected from slippage-induced contact with the chain blade by guarding placed immediately forward of the supporting hand position.

One of the deadliest types of chainsaw accidents is kickback. When the tip region of the chain blade contacts an object, the resulting force at the tip will rapidly and unexpectedly rotate the chainsaw tip toward the user’s head, neck, shoulders and face. This rotation exposes the user to being cut by the upper surface of the chain blade. Mechanical engineers
have sought to prevent kickback by adding guards to the tip region of the bar, preventing the chain blade from contacting objects. Unfortunately, guarding can become detached with use or be intentionally removed should the tip guard be viewed as reducing tool efficiency. The best solution to this safety problem has been the design and implementation of anti-kickback chain blades.

3.5 - Vehicle Safety Issues - Land

Vehicles are vital to modern economies, transporting food, fuel, products, workers, and tourists. Vehicles sharing the same roads vary in size from a 500-pound motorcycle and rider to an 80,000-pound truck. Arguably the greatest influence of safety research can be observed in the design of vehicles, and with good reason. Even the largest and most advanced interstate highways mandate that the driver of an eight-foot-wide truck tractor and semitrailer steer the vehicle within a 12-foot-wide lane while covering a distance nearly as long as an American football field in three seconds.

The task of safely maneuvering a vehicle can be divided into three parts: propulsion, steering, and braking. Propulsion is the means by which a vehicle attains motion. The selected propulsion system should provide power in a controllable, predictable manner. The propulsion system has to use a reasonably non-hazardous fuel in a manner consistent with the needs of its operator. An internal combustion engine using gasoline or diesel fuel is well suited to vehicle propulsion. If, during refueling, a small quantity of fuel were to contact the operator’s skin, he or she would suffer only an unpleasant odor. Alternatively, suppose that an engineer designed an automobile, motorcycle, or truck that used liquid rocket fuel. Despite resulting enhancements in power or efficiency, the design might well be unwise due
to safety concerns. Many rocket fuels cause burns upon contact with skin, illustrating that the mechanical engineer needs to consider more than just the technical numbers.

**Turbine engines**

Where used: Aircraft, petroleum pipeline pumps, emergency power generation

Safety issues:

1) Excellent reliability.
2) Slow throttle response.
3) Dangerous exhaust heat.

Although popular in aircraft, turbine engines have yet to gain favor in vehicles. The advantages of turbine engines include a high power-to-weight ratio, multi-fuel ability, and greater reliability than reciprocating engines. The disadvantages of turbine engines include the heat of their exhaust, their long response time to a new throttle input, and their cost. Turbines were experimentally tried in automobiles as early as the late 1950’s, but they have yet to be used in a production automobile. Even if mass production of turbines for automobiles resulted in lower costs, the heat of their exhaust and their long response times to new throttle inputs would remain unresolved. Few drivers would be willing to wait several seconds for their automobile to begin moving forward when the stoplight turns green. Imagine the difficulties associated with parking and merging into traffic with an engine response time significantly longer than that for reciprocating engines.

Suppose that a mechanical engineer were to solve the throttle response delay by means of a flywheel or other method of energy storage capable of being quickly released. The exhaust heat would still pose engineering obstacles. Turbines used in aircraft safely direct their exhaust to the rear for all of their propulsion, or for part of the propulsion in the
case of turboprop airplanes and turbine-powered helicopters. While operating on the ground, only trained personnel approach aircraft and only from certain directions known to be safe. The turbine-powered automobile would not have this luxury. Pedestrians of every stripe walk near a multitude of automobiles every day. If automobiles featured jet exhaust as used in the fictional (but fascinating) Batmobile, severe burns could result. Under the best of circumstances, damage would occur to following vehicles, the tires of the vehicle in question, or to the pavement beneath. As a result, it would be dangerous to direct raw turbine exhaust from an automobile. Manufacturers experimenting with turbine-powered vehicles have addressed the exhaust heat problem through the implementation of heat exchangers. However, this adds weight, cost, and complexity to the application. The mechanical engineer should note that turbine engines for vehicle use would have less exhaust heat than a pure jet. This is because turbine engines suitable for use in land vehicles are variations of turboprop engines. As a result, these turbine engines extract more energy from the turbines than are needed to turn the compressor. Correspondingly, this extracts additional heat from the exhaust gases. At this time, reciprocating engines are better suited than turbine engines for the driving that characterizes the needs of most automobile users.

Turbine engines may have application in some vehicles such as truck tractors, which are normally operated on highways over hundreds of miles at near-constant speed. Large trucks are almost always powered by diesel engines, which are characterized by efficiency and high torque. The turbine engine’s longer throttle response time is less of a disadvantage in these trucks. Since a truck tractor usually has a higher purchase cost than the average automobile, the turbine engine’s added cost would increase the price of the truck by a smaller percentage than it would increase the price of the average automobile. From an engineering
standpoint, trucks have another advantage over automobiles: more room to fit the engine components. With more room “under the hood”, fitting a suitable heat exchanger poses fewer technical problems.

**Turbocharging and supercharging**

Where used: Automobiles, trucks, aircraft

Safety issues: None

While the majority of vehicle engines are normally aspirated, turbocharging and supercharging are both popular means of increasing engine performance, especially turbocharging. Turbocharging uses residual energy in the exhaust gases to compress incoming air. Supercharging uses a mechanical linkage from the engine to compress incoming air. If properly designed and constructed, neither turbocharging nor supercharging poses a safety risk.

**Perception and reaction**

Where used: In safety calculations

Safety issues:

1) Unavoidable delay in driver decisions.

2) Physical fitness can reduce the delay.

3) There is no known way to eliminate the delay.

Vehicle safety problems that the mechanical engineer must consider are not confined to technical design factors. The weak link in vehicle safety is often the driver as a human being. Human data of importance to the mechanical engineer include visibility distances and perception-and-reaction time. Visibility distance is the range at which a driver can see and recognize potential hazards using the available lighting. Perception-and-reaction time is the
time from when the driver sees a hazard until that driver initiates a response. The mechanical engineer can think of this as the time from when the light reflected by a hazard first strikes the driver’s eyes until the driver begins depressing the brake pedal. Perception-and-reaction time is a function of both driver age and driver athleticism and alertness. For young or athletic drivers to begin depressing the brake pedal, the perception-and-reaction time is approximately 0.8 seconds. For the 95th percentile of drivers to begin depressing the brake pedal, the perception-and-reaction time is approximately 1.6 seconds. For the purpose of calculations, a young or athletic driver should be assigned 0.8 seconds for the perception-and-reaction time value, while an older, non-athletic driver should be assigned the perception-and-reaction time value of 1.5 seconds.10

If the driver steers to avoid a hazard, the perception-and-reaction time may be slightly less. This is due to drivers having their hands already in contact with the steering wheel, as opposed to releasing the accelerator pedal and applying the brake pedal. For a driver with a perception and reaction time of 1.5 seconds, the steering option may reduce this time to 1.25 seconds.

**Vehicle directional control**

Where used: Understanding vehicle dynamics

Safety issues:

1) Vehicles need stable steering geometry.

2) Average drivers are safer with mildly understeering vehicles.

3) Drivers can receive valuable vehicle information by tactile means.

The safe directional control of vehicles requires the mechanical engineer to resolve multiple technical issues. The vehicle’s steering, suspension geometry, and weight
distribution should cause the vehicle to favor a straight path. This tendency allows the vehicle to assist the driver in returning to a safe and stable attitude. The vehicle’s steering system should allow the driver’s hands to sense the vehicle’s lateral acceleration. An important step in achieving vehicle stability is in the careful selection of the castor, camber, and toe-in of the steerable wheels. Almost all vehicles are configured for the two frontmost wheels to steer. The exceptions are large trucks such as self-propelled cranes and a few automobiles that can also turn their rear wheels a few degrees to assist parking.

“Understeering” refers to a vehicle’s tendency to lose adhesion on its front tires before its rear tires during a turn, and “oversteering” is the term used to denote a vehicle’s tendency to lose adhesion on its rear tires before its front tires during a turn. A vehicle that neither understeers nor oversteers is said to be neutral-steering. Most automobiles are designed to understeer, as this is regarded as safer for most drivers. Some sports cars are exceptions; driving enthusiasts often prefer a neutral or slightly oversteering automobile.

With advancements in electronics, automated vehicle stability systems have appeared in some production automobiles. Yaw is the angle between the vehicle’s longitudinal axis and the line of its co-linear direction of travel. These systems sense if a vehicle is yawing and apply specific vehicle brakes to reduce the yaw.

**Compliant suspensions**

Where used: All vehicles

Safety issues:

1) Suspension compliance influences rollover.

2) Suspension compliance permits safer travel.

3) Suspension compliance affects understeering/oversteering.
Roads are not perfectly flat. To compensate for this fact, vehicles are designed with compliant suspensions. Suspensions consist of linkages, springs, and dampers. Suspension linkages keep the wheels in their proper orientation as they follow the contour of the road, retracting and extending from the vehicle body. Without the linkage, a road surface feature could cause the vehicle to follow an undesired path. The springs return the wheel to an extended position after being displaced by road surface features. Without the springs, the vehicle body would lack sufficient compliance to remain in control. Dampers eliminate oscillations of the springs and linkages. Without dampers, large oscillations could cause a loss of control. Coaxially located wheels can share loads by means of a type of torsional spring called an anti-sway bar. Functionally, the anti-sway bar reduces vehicle body roll. Anti-sway bars can affect vehicle understeer or oversteer.

By its design, a compliant suspension permits some measure of vehicle body roll. Small quantities of body roll are inconsequential, but excessive body roll of a vehicle with a high center of gravity can lead to overturning, sometimes referred to as rollover. In most automobiles the lateral acceleration limits of the tires will be exceeded before the vehicle can overturn. In trucks, however, this is not necessarily true. The lateral acceleration limits (coefficients of friction) of most truck tractor and semitrailer tires on pavement are between 0.50-0.55 g’s; 0.55 could be expected on interstates and better highways. Unfortunately, most semitrailers begin to overturn when the peak lateral acceleration exceeds 0.45 g’s. Some semitrailer configurations begin to overturn at a lower peak lateral acceleration.¹¹

There are two categories of vehicle rollover: tripped and untripped. When a vehicle overturns due to the height of its center of gravity and the lateral load on its tires, the vehicle is said to have experienced untripped rollover. Conversely, when a vehicle overturns as a
result of the height of its center of gravity and a lateral impact against its tires, the vehicle is said to have experienced a tripped rollover. When a vehicle yaws as it traverses turf, it is common for accumulations of turf against the tires to produce a tripped rollover. A truck tractor and its attached semitrailer may suffer either a tripped or untripped rollover. However, a sports car that overturns almost always does so as a result of a tripped rollover.

Another important factor in vehicle rollover is body compliance. While automobile and truck bodies generally have too much stiffness to influence rollover, this is not true of semitrailers. Van body and tanker semitrailers have bodies that are torsionally stiffer along their longitudinal axes than flatbed semitrailers. Flatbed semitrailers are particularly vulnerable to rollover accidents. Since vehicles neither stretch nor shrink to any significant degree, all parts of a vehicle have the same longitudinal speed, regardless of the maneuver. If the vehicle in question is a semitrailer, for a given longitudinal speed, only the radius of the path followed can affect the lateral acceleration. Because the rear of a semitrailer has a shorter radius in a turn than does the front, rollover will initiate at the rear of a semitrailer. As the rear of a semitrailer will overturn before the front, the tendency of a semitrailer to overturn is directly related to its body compliance.

**Braking**

Braking converts a vehicle’s kinetic energy into frictional energy. It allows the driver both a means conveniently ending travel and, when necessary, a chance to prevent an accident. In order to maximize the advantages of braking, it must be reliable and controllable.

All vehicle braking consists of forcing a frictional material against a moving part. Customarily, the frictional material is forced by the application of either hydraulic fluid or air
pressure. Accordingly, these two types of brakes are known as hydraulic brakes and air brakes.

**Hydraulic brakes**

Where used: Automobiles, light trucks, some medium trucks

Safety issues:

1) Near-instant response.

2) Poorly suited to large trucks.

3) Not fail-safe.

Hydraulic brakes are the brakes of choice for automobiles, light trucks, and some medium trucks. When the driver depresses the brake pedal with his or her foot, hydraulic fluid is placed under pressure by a piston. On most hydraulic brake-equipped vehicles, a booster system amplifies the force of the piston against the fluid. On the other end of the hydraulic brake system are the brake cylinders and their pistons. Because the hydraulic fluid is not compressible to any significant degree, the hydraulic fluid forces the brake cylinder pistons outward. As each brake cylinder piston moves outward, it forces a frictional material against a rotating part, thus reducing the speed of the vehicle. Even on automobiles, hydraulic brakes are seldom able to completely stop wheel rotation while the vehicle is operated on a dry road surface. As a measure to enhance safety, hydraulic brakes on vehicles are normally split into two separate systems. Generally, one system services the front brakes while the other services the rear brakes. Should one system fail, the vehicle will not suffer a total loss of braking.

The advantages of hydraulic brakes are simplicity, cost, and near-instant response to brake pedal application. The disadvantages of hydraulic brakes are the dangers of an air
bubble in the fluid, no fail-safe feature if the fluid leaks, and insufficient power for large-
truck use.

**Air brakes**

Where used: Large trucks, all truck tractors and semitrailers, some medium trucks

Safety issues:

1) Air brake lags.

2) Well suited to large trucks.

3) Can be configured to be fail-safe with spring brakes.

Air brakes are the universal braking system of choice for large trucks. Air brakes are also widely employed on medium trucks. On an air-brake-equipped truck, an engine-driven pump supplies air under pressure to storage tanks. When the truck’s driver depresses the brake pedal, a valve is opened, sending an air signal to mechanical air solenoids. These solenoids then open, supplying pressurized air to the brake chambers. Each brake chamber contains a piston and connecting rod that are forced outward by the pressurized air when it reaches a minimum pressure. As the piston and its connecting rod move outward, a linkage is engaged that applies the frictional material against the rotating part, usually a drum. A spring returns the brake to its “deactivated” position after the driver releases the brake pedal. Air brakes as fitted to most commercial vehicles have the capability of physically stopping the rotation of the wheels for moderate loads. Air-brake-equipped vehicles have the brakes on some axles fitted with spring brakes. Both truck tractors and semitrailers are fitted with spring brakes. These spring brakes remain in their unapplied position unless the air pressure within the vehicle’s air brake system is above a design value, usually about 60 psi. These spring brakes serve as both parking brakes and, more importantly, as emergency brakes,
allowing the air brake system to fail safe. In the unlikely event that a semitrailer should unintentionally become disconnected from its truck tractor, the evacuation of air from the trailer’s air brake system will cause the semitrailer’s spring brakes to apply, failing safe.

As an additional measure of safety, air-brake-equipped vehicles are normally fitted with dual air systems. In the case of truck tractors, one air system services the brakes on the front axle plus the rear drive axle brakes, if the truck tractor has two drive axles. The other air system services the brakes of the drive axle, or the forward drive axle on truck tractors with two drive axles. The truck tractor is also fitted with check valves so that the loss of one air system cannot compromise the other air system.

Air from each of the truck tractor’s two air systems is blended to become the air supply for the semitrailer. This allows the semitrailer to brake normally in the event of a failure of one air system. Check valves are also fitted in the connection between the truck tractor’s blended air supply and the semitrailer’s air brake system. Should the air connection between the truck tractor and semitrailer be severed, the truck tractor will not lose air pressure, again failing safe.

Unfortunately, the sequence of events during the air brake activation process takes time, normally between 0.3 and 0.5 seconds. For the purpose of calculations, 0.4 seconds is commonly used as the value for the air brake lag time. This air brake lag time is an important safety problem, because during this lag, the vehicle continues to move forward at its original speed.

Large articulated vehicles, such as a truck tractor pulling either one or two semitrailers, can introduce complex braking problems for the mechanical engineer. If during severe braking the driver loses the ability to steer, then the driver will be unable to
directionally control the vehicle. A loss of steering occurs when the steerable wheels cease to rotate while the vehicle continues to travel. In order to prevent this loss of control from occurring during braking, the brakes on the steerable wheels of an air-brake-equipped vehicle are designed to be less powerful than the other brakes on the vehicle. The steerable wheels (the frontmost wheels) are fitted with brakes that are 50 percent to 67 percent as powerful as the other brakes on the vehicle, with 50 percent being the norm. This is usually achieved by one of two means: using smaller-diameter front brake chambers, or placing a pressure reducer between the air source and the front brake chambers. Both methods work equally well, and neither has any safety advantage over the other. The disadvantage of de-powering the front brakes of a truck tractor is that it reduces the total braking ability of the vehicle. On a truck tractor pulling a fully laden semitrailer, this poses no significant loss of braking.

When truck tractor is driven without pulling a semitrailer, the weight of the vehicle is almost evenly distributed between the front and rear axles. Because the brakes on the front axle have only half of the power of the rear brakes, the truck tractor without semitrailer has only three quarters of the braking ability of the truck tractor towing a semitrailer. This usually does not present as much of a safety problem as it might appear to, because truck tractors are rarely driven without towing a semitrailer. Nonetheless, this issue should be considered in the case of a truck tractor pulling a lightly loaded semitrailer.

Example #1

A mechanical engineer has been asked to design an obstacle warning system for use on large air-brake-equipped trucks and needs to calculate the minimum stopping distance from a speed of 70 miles per hour. To calculate the minimum stopping distance, the
mechanical engineer needs to divide the problem into three parts: perception-and-reaction distance, air-brake-lag distance, and the distance traveled after the brakes have been applied.

The truck’s speed is 70 miles per hour (102.667 feet per second). It would be prudent to use 1.5 seconds for the driver’s perception and reaction time. Assuming that the truck is at zero distance when the driver begins to perceive and react, the truck travels 154 feet before the driver depresses the brake pedal.

With the brake pedal depressed and the air signal sent, 0.4 seconds will pass before braking initiates. During the 0.4 seconds, the truck will travel an additional 41 feet.

With the initial speed known, the distance traveled by the truck during brake application depends on the kinetic coefficient of friction between the truck’s tires and the road surface. The engineer can equate the truck’s kinetic energy to the force to slide the tires times the braking distance (the unknown) and thus solve for the braking distance. The term for mass is a common component and can be factored out. This leaves us with the square of the initial velocity equal to two times the product of the coefficient of friction, the acceleration of gravity, and the braking distance. The braking distance is calculated to be 298 feet.

The total distance needed to stop the truck from 70 mph is the sum of the three distances. Therefore, the total distance needed to stop the truck from 70 mph is 493 feet.

Example #2

A mechanical engineer has been asked to design an obstacle warning system for use on large air-brake-equipped trucks and needs to calculate the minimum stopping distance from a speed of 70 miles per hour. To calculate the minimum stopping distance, the
mechanical engineer divides the problem into three parts: perception-and-reaction distance, air-brake-lag distance, and the distance traveled after the brakes have been applied.

But this time the engineer realizes the importance of calculating the minimum stopping distance for the same truck but without an attached semitrailer.

The truck’s speed is again 70 miles per hour (102.667 feet per second). The driver’s perception and reaction time is 1.5 S, and the truck travels 154 feet before the driver depresses the brake pedal.

With the brake pedal depressed and the air signal sent, 0.4 seconds will pass before braking initiates. During the 0.4 seconds, the truck will travel an additional 41 feet. This, too, is the same as in the previous example.

For the truck tractor without a semitrailer, the engineer will need to include a term to account for the decreased braking. While the rear brakes are of normal strength, the front brakes are at half strength, giving three quarters of the possible braking. This time the engineer should set the truck’s kinetic energy equal to three quarters of the force to slide the tires times the braking distance (the unknown). The term for mass is a common component and can be factored out. This leaves us with the square of the initial velocity equal to two times the product of the coefficient of friction, the acceleration of gravity, and the braking distance. The braking distance for the truck tractor without a semitrailer is calculated to be 397 feet.

As before, the total distance needed to stop the truck from 70 mph is the sum of the three distances. Therefore, the total distance needed to stop the truck tractor without a semitrailer from 70 mph is 592 feet.
By accounting for the safety of driving a truck tractor without a semitrailer, the engineer learns that the obstacle avoidance device will need 99 more feet than previously calculated.

**Visibility**

Where used: Increasing driver perception of hazards

Safety issues:

1) Visibility affects safe speeds.

2) Visibility is specifically addressed by federal regulations and SAE standards.

3) Visibility distance should exceed stopping distance.

All vehicles operated in darkness require illumination in the vehicle’s path so that the driver may safely avoid hazards. Human factors data are available that predict the distance at which a driver with average or corrected vision may recognize hazards that are illuminated by the vehicle’s headlamps. High-beam headlamps allow a greater recognition distance than low-beam headlamps. Combining these data with vehicle stopping-distance calculations permits the engineer to determine safe vehicle operating speeds and braking parameters.

The illumination should not unduly affect the vision of the drivers of oncoming vehicles. Federal regulations and SAE (Society of Automotive Engineering) standards specifically address vehicle illumination. SAE standards specify headlamp intensity based on the angle from the headlamp’s longitudinal axis.\(^{12}\)

Many accidents occur when the driver of an automobile or light truck fails to see a semitrailer in time to avoid hitting the side or rear of the semitrailer. Semitrailers are usually 28, 40, or 53 feet long, about 13 feet high, and 8 to 8.5 feet wide. While a semitrailer may be easily visible in daylight, most of these accidents occur at night or in inclement weather. The
underside of most semitrailers is about the same height above ground as is the hood or base of the windshield of most automobiles and some light trucks. This type of accident is colloquially called an “underride”. When an automobile hits the side of a semitrailer, it is not uncommon for the roof of the automobile to be sheared from the body of the automobile. Sadly, this almost always results in the bifurcation of the occupants. In order to reduce the risk of these automobile-semitrailer accidents, federal regulations seek to heighten the conspicuity of the semitrailer by means of lights and conspicuity tape. Conspicuity tape is a highly reflective tape consisting of alternating red and silver segments.

Most of these accidents occur when the truck tractor and semitrailer are on a road that crosses the automobile’s path, or when the semitrailer is being backed into a driveway. The designers and owners of some semitrailers take extra steps to improve the visibility of their vehicles and further lessen the chance of an accident. These extra steps involve added lighting, additional conspicuity tape, highly reflective paint schemes, or combinations of these steps.

Because increasing the visible light output of headlamps poses a hazard to approaching drivers, efforts have been focused on integral infrared-based and light-amplification-based vision systems. Both of these systems have been paired with head-up displays.

Visibility is a factor in many motorcycle accidents, too. Some states have passed laws requiring motorcyclists to use their headlamps during operation. Headlamp use obviously increases motorcycle visibility on dark, overcast days. Interestingly, headlamps are extremely effective in enhancing motorcycle visibility on sunny days, where shadows irregularly cover the road. The author has participated in tests that demonstrated this effect. To the driver of a
vehicle under these conditions the alternating light and shadows act much like a zoopraxiscope, the forerunner of the modern cinematic camera that flashed fixed images through slits in a moving wheel. On a partially shaded road, motorcycles are remarkably more difficult to discern than cars at the same distances.

3.6 - Vehicle Safety Issues - Air

Where used: Aircraft safety

Safety issues:

1) Turbine engines are usually more reliable than reciprocating engines.

2) Icing and structural fatigue are key aircraft hazards.

3) Design for easy safety inspections and maintenance.

Despite their disadvantages in land vehicles, turbine engines are popular in aircraft. Except for some small commuter planes, virtually all passenger-carrying commercial aircraft are turbine-powered. From a safety perspective, turbine engines offer greater reliability than reciprocating engines and higher power-to-weight ratios.

Most general aviation aircraft are powered by reciprocating engines. This is largely due to cost, an area where the reciprocating engine has the advantage. In some aircraft applications, such as agricultural aircraft, the turbine engine’s slower throttle response is as much of a concern as it is in automobiles. Agricultural aircraft operate unusually close to the ground, distributing insecticides and other chemicals on cultivated fields. This risky type of flying often requires sudden power increases to avoid trees and other hazards. Some agricultural pilots prefer reciprocating engines in this role.

If proper maintenance routines are followed, most aircraft safety issues can be attributed to pilot error, fatigue, weather, and navigation. While pilot error and electronic
navigation devices are beyond the scope of the mechanical engineer, the engineer can have some influence on the effects of weather and fatigue. Among the most dangerous weather phenomena is icing. During certain conditions, ice may form on an aircraft in flight. Ice accumulation on an aircraft adds weight and disrupts the airflow. If the aircraft becomes sufficiently covered in ice, it will no longer be able to remain airborne, often with disastrous consequences. Reliable and effective de-icing equipment can greatly enhance aircraft safety. Fatigue failure of aircraft components can be partly resolved through maintenance inspections and component design, the latter of which is an area of study within mechanical engineering.

### 3.7 - Occupant Protection

Where used: All vehicles where possible

Safety issues:

1) Limit peak acceleration to less than 20 g’s.

2) Restrain the occupants.

3) Prevent passenger compartment intrusions.

Despite improvements in safety, vehicle accidents can and do happen. It is during the accident that the final safety feature, occupant protection, proves its worth. Prior to an accident, safety efforts seek to both keep the occupants from harm and prevent the loss of property. At its core, occupant protection is akin to medical triage. The mechanical engineer designs to keep the occupants from harm while sacrificing portions of the vehicle known as crush zones.
Human beings can normally survive accelerations of less than 25 g’s, although they can withstand accelerations of 25-40 g’s for a few thousandths of a second. It is desirable to design vehicles so that occupants are subjected to a peak acceleration of less than 20 g’s. The engineer should note that if the peak acceleration is limited to 20 g’s, it can remain constant over the duration of the vehicle crush.

Collisions

Where used: Understanding the nature of collisions

Safety issues:

1) Vehicle is accelerated from the collision.

2) Occupants are subsequently accelerated.

3) Peak acceleration and occupant protection can determine the outcome.
There are two separate collisions during an accident. The first collision, the exterior collision, takes place when the vehicle collides with another vehicle or an object. The second collision, the interior collision, occurs when the occupants collide with the interior of the vehicle.

The mechanical engineer should start by addressing the interior collision. Fundamental approaches consist of restraining the motion of the occupants, maintaining the integrity of the passenger compartment, and preventing intrusions of objects into the passenger compartment.

In order to better understand the valuable role fulfilled by seatbelts, it would be beneficial for the mechanical engineer to examine an automobile or light truck that has experienced a frontal impact while one or more of its occupants was not using seatbelts. The engineer will likely notice a large, oval region of fracture in the windshield. This is where an occupant hit the windshield with his or her face and upper front head. If the engineer examines the lower dashboard, he or she may observe tennis-ball-sized indentations caused by the impact of an unrestrained occupant’s knees. If it was the driver who was not belted at the time of impact, the engineer will likely observe that the steering wheel rim is uniformly deformed, not from the driver’s hands, but from an impact by the driver’s chest. It should come as no surprise to any mechanical engineer that the correct use of seatbelts enhances the chance of an occupant surviving an accident at highway speeds and lessens the chance of an occupant suffering chest, knee, or head injuries.

Restraining the motion of the occupants has been successfully achieved by the use of seatbelts and airbags. Seatbelts not only prevent the impact of the user with the interior; they can prevent a loss of vehicle control caused by the displacement of the driver from the seat.
Traditionally, seatbelts have been composed of woven textile straps with metal fasteners. Formerly, seatbelts were manually adjusted to tension by means of a frictional slide. Now seatbelts are lightly tensioned by a spring assembly. Upon sufficient acceleration, a pendulum is displaced through an arc, locking the seatbelt from further extension.

Maintaining the integrity of the passenger compartment is important to occupant protection in both collisions and vehicle overturning. It is desirable for the mechanical engineer to incorporate a safety cage in the design of a vehicle’s passenger compartment. Safety cages are, as their name suggests, cages or structures that surround the occupants of the vehicles. Safety cages are increasingly designed into construction and logging equipment. All racing vehicles and most agricultural aircraft utilize safety cages. New mechanical engineers should take time to examine forklifts, log skidders, bulldozers or racing cars to see how safety cages serve the needs of occupant protection.

If a safety cage is, for any reason, impractical for a vehicle, then the mechanical engineer should at least provide rollover protection. An inexpensive means of providing rollover protection is the roll bar. These usually are curved sections of pipe aligned generally perpendicular to the longitudinal axis of the vehicle. The purpose of the roll bar is to support the weight of an overturned vehicle and thus prevent the vehicle from crushing the occupants. When employed, roll bars are usually mounted directly behind the front seats. The may be either a single roll bar or two smaller arches, one behind each seat.

With the integrity of the passenger compartment assured and the passenger restrained from being hurled against the interior of the vehicle, the mechanical engineer should now focus on preventing dangerous intrusions to the passenger compartment. Trailer tongues are an illustrative example of passenger compartment intrusions. The author has examined
construction trailers that became unhitched while in motion. In each case, the trailer entered the oncoming lanes of travel and struck an automobile. In one instance, the trailer tongue perforated the lower front region of the driver’s door, fatally injuring the driver. Since the tongue entered at a shallow angle, design features might be incorporated to reduce the chance of this type of penetration. Sections of guardrail, fence posts, and pipe in transit all possess the ability to penetrate the passenger compartments of most vehicles. Intrusions from the engine compartment can be lessened by deflecting any collision-induced rearward movement of the engine or transmission downward. During a frontal impact, glass from the vehicle’s windshield can pose a hazard to the occupants. This has largely been solved by constructing the windshield as a laminate with a plastic layer between two layers of glass.

**Crush zones**

Where used: All vehicles where possible

Safety issues:

1) Crush zones reduce peak acceleration.

2) Realistic needs mandate that crush zones contain radiator, suspension, etc.

3) Few accidents are truly co-linear.

Crush zones are regions of a vehicle that are designed to deform during a collision, absorbing energy and spreading the force of the impact over the longest possible duration. The depth over which the vehicle deforms inward is the crush distance. The time over which the crushing occurs is sometimes called the crush duration. The author heard a NASCAR driver express the crush zone concept succinctly: “If the car is made any stronger, then in an accident the driver will take a harder lick.”
**Example**

Suppose that an automobile, initially traveling at 55 miles per hour, were to frontally collide with a smooth-faced, vertical, immovable barrier, bringing the automobile to a rest. In order for the occupants to survive, the maximum acceleration should be limited to 20 g’s. Assuming that the vehicle’s front crush zone can deform consistently, how long must the crush distance be at minimum?

The automobile’s initial speed is 55 miles per hour, or 80.67 feet per second. The crush zone serves to convert all of the automobile’s kinetic energy into the work to deform the structure of the crush zone. Setting the kinetic energy equal to the work used to deform the automobile’s front end, the mass term can be factored out from both sides. This leaves the square of the vehicle’s velocity equal to two times the product of the vehicle’s average acceleration and crush distance. The engineer will need to express the acceleration as 20 g’s times 32.17 feet per second/per g. The resulting minimum crush distance calculates out as 5 feet.

But wait: The answer is not so simple. Mechanical engineers may recognize that this calculation was based on assumptions that are not necessarily valid.

The vehicle’s metal has volume and therefore cannot be crushed into an infinitesimally small final volume. So the crush zone must be longer than the minimum in order to contain the crushed metal. Despite the best efforts of engineers, it is unlikely that the automobile’s crush zone will deform at a perfectly consistent rate of joules per foot of crush. This is made even harder to achieve by the fact that the crush zone will have to consist of widely varying structures. It will include the bumper, wheel wells, and engine compartment,
all with different stiffnesses. Since it is the peak acceleration that the engineer seeks to limit, deviation of the peak acceleration from the average necessitates additional crush distance.

This example examined a frontal impact with a smooth faced, vertical, immovable barrier. In real life, this almost never happens. What are described as frontal impacts, and are colloquially called “head-on” accidents, are usually at angles from the vehicles’ longitudinal axis. Further, the impacts frequently are offset to one side, giving different accelerations to each occupant. During an impact to a vehicle that is displaced with respect to angle, or offset, some of the energy will cause rotation of the vehicle. Rotation may lessen the accelerations felt by the occupants, thereby reducing the severity of the injuries.

Despite the image of frontal impacts as the greatest threat to a vehicle’s occupants, side impacts offer more difficult engineering challenges. This is due to the shorter distance available for a crush zone. Measurements from the outer surface of an automobile driver’s door to the left side of the driver’s chest usually reveal an available distance for crush of approximately three quarters of a foot to one and a half feet. Here again, the measurements and equations alone are insufficient to analyze the problem. The mechanical engineer will find that because the human head and neck form an articulated structure, the head can pivot closer to the window than it usually resides in normal driving. Examination by the author of vehicle side windows subsequent to side impacts, as well as post mortem examinations of those accident victims by medical personnel, confirms this safety hazard. In automobiles and many trucks, occupants’ heads are vulnerable to impact with adjacent side windows. Side-curtain airbags will certainly lessen the danger, but nothing can alter the short distance available for vehicle crush. This highlights the need for mechanical engineers to develop improved side-impact protection.
Occupants’ heads also may be vulnerable to contact with the rear window in standard cab pickup trucks during a rear impact. This type of injury is due to the close proximity of the rear windshield to pickup occupants’ heads in standard cab configurations. Seatback headrests can offer some measure of protection, but a dangerously high acceleration to the occupants’ heads may still result.

**Motorcycles**

Where used: Understanding motorcycle safety

Safety issues:

1) Rear impacts to motorcycles can result in a loss of control.

2) Frontal impacts to motorcycles can forcibly dismount riders.

3) Side impacts to motorcycles often result in the loss of a rider’s leg.

Motorcycles provide fun and economical operation, but they offer the least protection to riders of any vehicle type legal for highway use. Accidents involving motorcycles and other vehicles can be divided into three directions of impact to the motorcycle: frontal, rear, and side.

Rear impacts to motorcycles may induce yaw or deform the rear wheel of the motorcycle, either of which can result in a loss of control of the motorcycle. These types of accidents are often caused by a combination of the motorcycle’s limited visibility, as seen from the rear, and error by the driver of the other vehicle. When a vehicle impacts the rear of a motorcycle with enough force, a loss of control of the motorcycle can result.

Frontal impacts to motorcycles that are operating headlamps are more likely to be a product of driver error than limited visibility. These impacts may forcibly dismount riders when the motorcycle is literally stopped and the rider continues forward. This engineer
analyzed an accident in which a motorcycle hit the right rear door of an automobile. The rider was thrown through the right rear window, across the rear seats, and out of the car again through the left rear window of the automobile. The mechanical engineer may be able to improve the rider’s safety by incorporating a deformable front suspension. This would prolong the duration of the impact, possibly lessening injury.

Side impacts to motorcycles by vehicles often result in the motorcycle rider losing a leg.13 The addition of an enclosure protecting the rider’s legs might reduce the severity of an injury, but it might not be popular in the marketplace. Such devices are unlikely to compensate for the dangers inherent to motorcycles. If consumers refuse to purchase a product due to the presence of a safety feature, then that feature is of little value.

Package delivery trucks

Where used: Understanding package truck safety issues

Safety issues:

1) Package delivery trucks are often operated with open occupant doors.

2) They provide poor occupant protection.

3) Occupants are especially vulnerable in frontal impact.

Several of the most popular package delivery companies use two-axle van-bodied trucks equipped with a sliding door on either side of the passenger compartment. These vehicles have comparatively blunt front ends, typically weigh 5,000 to 12,000 pounds, and are commonly operated with the doors open, especially in warm weather. When one of these vehicles receives an impact to the front, directed from front to rear, the instrument panel is at risk of being forced rearward into the driver’s lower chest and abdomen.14 In severe frontal impacts, it has been my observation that these vehicles deform where the base of the
windshield meets the instrument panel. I hope this is a safety issue that mechanical engineers will address in future designs.

**Vehicle and pedestrian accidents**

Where used: Understanding vehicle-pedestrian accident issues

Safety issues:

1) Pedestrian will usually go forward or under truck.

2) Pedestrian will usually go forward or over automobile.

3) Windshields cause head injuries in automobile impact.

In a vehicle-oriented society it is perhaps inevitable that vehicle-pedestrian accidents will occur. While nineteenth-century locomotives were frequently fitted with a device known as a pilot, better known as a cow-catcher, no such device yet exists for road vehicles. Vehicle-pedestrian accidents can be broken down into two groups: automobile and truck. This differentiation between automobile and truck is valid because vehicles with high body feature heights interact differently with pedestrians than do those with low feature heights.

Truck impacts with pedestrians usually involve initial contact with the truck’s radiator grill region and the bumper beneath it. These areas contact the pedestrian’s body from the knees upwards. When a pedestrian is struck by a truck, the pedestrian is almost always propelled in the direction of the truck’s travel and then passes under the truck. Subsequent impacts against the pedestrian are made by the truck’s suspension components or tires. Some of these accidents are the result of intentional acts by the pedestrians. Most other truck-pedestrian accidents are the result of an unsecured object from the truck. Dump truck tailgates that were not properly fastened, wheels that were not tightly attached to the axle, and failed tire fragments are the causes of many others. Truck-pedestrian accidents are
almost always fatal for the pedestrian. Any innovation by a mechanical engineer that would reduce the chance or severity of these accidents would be a valuable accomplishment.

Most automobile bumpers are at the same height as, or slightly lower than, the knees of pedestrians, while fenders are at thigh height. Automobile-pedestrian accidents rarely throw the pedestrian only forward. Instead, the initial contact with either bumper or fender propels the pedestrian upward with rotation. Even contact by the pedestrian with the side fenders produce this effect. The pedestrian’s legs are pushed in the direction of the automobile’s travel, causing the pedestrian’s head to contact the front windshield. It is this contact with the hard windshield glass that yields the usually fatal injury. The incorporation of external air bags, deployed from the base of the windshield by a signal from a vehicle-mounted sensor, may reduce the likelihood of head injury in this manner.

3.8 - Vehicle Safety Issues - Other Vehicles

All-terrain vehicles and personal watercraft

Where used (all-terrain vehicles): Unpaved roads, fields, and designated paths

Safety issues:

1) Rollover.

2) The position of riders raises the center of gravity.

3) Severe consequences of operator misjudgment.

Where used (personal watercraft): Lakes, rivers, and seas

Safety issues:

1) Stability.

2) Hazard posed to riders if forcibly dismounted.

3) Potential for collision with swimmers, scuba divers and other watercraft.
All-terrain vehicles sold in the United States can be described as four-wheeled motorcycles. The rider and any passengers sit atop the vehicle, and the controls are very similar to those for motorcycles. Previously, three-wheeled all-terrain vehicles were sold in the United States, but this ceased as a result of product liability and government legislation. Three-wheeled all-terrain vehicles were involved in well-publicized overturning accidents that were attributed to the tricycle arrangement of the wheels. They also suffered torque-induced rearward overturning accidents when drivers accelerated sufficiently to overcome the moment arm of the vehicle about its rear axle. It seems logical to the author that micro-accelerometers could be incorporated into the design of all-terrain vehicles. The signals from these micro-accelerometers could be used to activate an engine fuel cutoff to prevent these torque-induced accidents.

Four-wheeled all-terrain vehicles are manufactured in both two- and four-wheel drive versions. They are usually capable of seating from one to three riders, depending on the model and size. Accidents involving all-terrain vehicles commonly result in the vehicle overturning, producing crushing injuries to riders. The severity of these injuries is a function of vehicle weight, speed, the position of the all-terrain vehicle on the rider’s body, and any objects struck during the accident. The vehicle’s speed becomes a factor in injury severity principally when an object is struck.

Personal watercraft accidents can be produced by vehicle stability and control issues. However, most personal watercraft accidents appear to result from operator error. Personal watercraft are normally propelled by an engine-driven water pump, thus eliminating the hazards associated with propellers. Injuries can result when a forcibly dismounted rider violently contacts a hard surface on the craft. Strategically placed padding can lessen the
chance of such accidents. Throttle controls on personal watercraft are normally fitted with a spring to return the engine to idle should the rider’s grip on the throttle control be released.

**Monorails**

*Where used: Within or between urban areas*

**Safety issues:**

1) Fire.

2) Structural damage to rail support.

3) Safe extraction of passengers.

As traffic flow and pollution issues have arisen, many communities have examined the use of monorails. Monorails are commonly employed to transport riders between a city and an airport, between two nearby cities, or to different locations within a city. Monorails are small trains that traverse a single elevated rail. Elevating monorail tracks eliminates the chance of striking a vehicle, animal or person on the track. Elevating monorail tracks also minimizes eminent domain intrusions. Although monorail accidents are rare, fire does pose a hazard. The most important safety issue with regard to monorails is extraction of riders during an emergency. Elderly, disabled, or infirm passengers cannot be expected to use ladders.
Understanding fire

Where used: Understanding fire concepts

Safety issues:

1) Heat transfer is a process that takes time.

2) Solids and liquids do not burn; only gases burn.

3) The heat of a fire depends upon the net energy released by combustion.

The mechanical engineer will be more effective when he or she understands the true nature of fire. Solids and liquids do not burn; only gases burn. Consider paper held in a
candle flame. If the paper is passed quickly through the flame, little will happen. However, if the paper is held in the flame, heat from the flame will raise the temperature of the paper. While the temperature of the paper rises, increasing quantities of fumes are released from the paper. As the temperature approaches 500 degrees Fahrenheit (the exact temperature depends on the quantity of clay or other admixed materials in the paper), the paper will produce enough fumes to burn. The burning paper produces sufficient heat to ignite adjacent paper mass. In this way, the fire will spread.

Some materials are self-extinguishing, meaning these materials will burn with the application of enough heat but cannot sustain their own combustion. The reason for this is that the combustion process for these materials is endothermic, i.e., the reaction requires more heat than is generated.

Smoke and fumes are usually responsible for most fire deaths. While the heat of a fire can produce burns on nearby victims, smoke and poisonous gases can cause casualties at extended distances.

Fire myths

Where used: Understanding the causes and propagation of fire

Safety issues:

1) Arcing almost never ignites paper or wood.

2) There is no such thing as a fire caused by a “high-resistance short circuit.”

3) Arcing and melting caused by an external heat source are easily discernable.

Fire safety is impeded by persistent myths about how fires start and propagate. These myths serve to direct the public’s focus away from the real causes of fires and how to prevent them.
Many fires are mistakenly blamed on arcing. Certainly it is possible to start fires with arcing. The ordinary internal combustion gasoline-fueled automobile engine ignites its fuel with an arc. However, arcing wires do not ignite wood beams, books, or even tissue paper.\(^\text{18}\) Arcing occurs when two conductors become physically close enough to complete an electrical circuit. The maximum distance over which an electrical arc can occur is called the arc distance.

When arcing occurs between a two metal conductors, a large amount of heat will affect the small region of contact. In the region where arcing occurs, the metal will be rapidly heated until it melts and then transforms to a rapidly expanding gas. On a microscopic scale, this expanding gas will propel molten metal away from the arc region. While airborne, these fragments of amorphous, molten metal assume a spherical shape under the influence of surface tension. Some of these molten spheres will strike the conductor and resolidify while retaining their spherical shape. This is called spatter.

Some spatter will impact the adjacent metal conductor with which the arcing occurred. If the two conductors are made of dissimilar metals, this transferred metal can be detected in a scanning electron microscope by means of an energy dispersive spectroscopy analysis.

Melting of a metal conductor caused by an external heat source does not produce spatter. Rather, the metal conductor acquires an appearance reminiscent of a partially burned candle that has rivulets of resolidified wax on its exterior.

The high-resistance short circuit myth is usually based on a claim that a wiring staple was pressed against the electrical conductor’s insulation hard enough to cut through and
allow the conductor’s wires to arc. Claims based on this myth then postulate that the arcing led to the fire.

A short circuit occurs when electrical current follows an unintended path, reducing the current flow in the designed path. The heat produced by a short circuit is proportional to the current flowing through it. If, in a properly wired structure, the current does not trip the applicable circuit breaker, then the heat produced will be insufficient to start a fire.

Fire safety design concepts - household appliances

Where used: Designing household appliances to lessen the chance of fire

Safety issues:

1) Design for non-combustible and self-extinguishing materials when possible.

2) Incorporate temperature-limiting features as needed.

3) Consider user inattentiveness and product abuse.

Household appliances are the focus of great concern in fire safety. This is due in part to the large number of powered appliances in the average home, the close proximity of fuel such as clothes, towels and wood cabinets, and the nature of household activities. While in their homes, particularly if they are asleep, people may not readily detect a fire unless their smoke alarm or pet alerts them.

Clothes washing machines and clothes dryers can illustrate basic fire safety design concepts for the mechanical engineer. Clothes washing machines consist of a water-bearing tub agitated by an electric-motor-driven feature. Clothes dryers consist of a tub rotated by an electric motor while the tub is subjected to forced, heated air. The dryer’s electric motor and tub are usually connected by means of a fabric-reinforced rubber V-belt. The structures of both machines are normally fabricated from non-combustible steel stampings.
Due to their designs, modern clothes washing machines pose no significant risk of fire. Neither their steel bodies nor their water-filled tubs burn. Only their V-belts can burn, and these are usually self-extinguishing and contained within the steel bodies. Clothes dryers can and sometimes do originate fires. Frequently, modern clothes dryer fires result from the failure of their operators to remove lint accumulations from the dryer lint screens.

Hair dryers are a common source of burns. A typical hair dryer may consume more than 1500 watts of electrical power while in use. The author’s unpublished tests of hair dryers manufactured in the late 1980s showed that peak temperatures were frequently more than 600 degrees Fahrenheit. Subsequent unpublished tests conducted by the author of hair dryers manufactured in the late 1990s revealed peak temperatures of approximately 300 degrees Fahrenheit. This reduction in observed peak temperature was caused by the incorporation of temperature-limiting devices. These devices interrupted electric current flow to the hair dryer heating elements upon reaching a predetermined temperature.

Examinations of hair dryers in regular use will often reveal accumulations of hair and lint in the vicinity of the air intake. Despite the presence of product warning labels and user instructions to clear such accumulations, they can often be observed. The reduction in air flow caused by these accumulations lessens cooling and promotes peak temperatures that may exceed design values. Similar observations can be made of clothes dryers in regular use. Users that do not remove lint deposits on lint collection screens risk elevated dryer temperatures and increased chance of fire.
Dishwashing machines and automatic coffee makers have also benefited from safety improvements. Electronic timers have largely supplanted mechanical timers to regulate dishwashing machines. The corresponding reduction in mechanical parts has lessened the chance for timer failure and the attendant chance of a fire.

Some early automatic coffee makers acquired reputations for causing fires. Improvements such as temperature-limiting devices and better electrical controls have overcome this problem. A separate safety issue concerning automatic coffee makers has been the temperature at which the machine holds the coffee. Litigation and out-of-court settlements have resulted from claims that burn injuries were caused by hot coffee.
Regardless of whether these claims have merit, exact coffee temperature control should be of concern to the mechanical engineer designing this product.

Even currently manufactured coffee makers may not fail safe. If the coffee maker is equipped with a mechanical switch, a failure of the switch’s spring powered detent will result in a switch that can randomly settle in either the “on” or “off” positions.19

Small kitchen-countertop cooking machines are popular products. A well-known example is the toaster oven. The safety challenge for the mechanical engineer is to provide heated surfaces suitable for cooking without presenting a fire or burn hazard.
3.10 - Agricultural Equipment

Where used: Agricultural worker protection

Safety issues:

1) Provide operator protection during rollover accidents.

2) Avoid the ingress of workers’ body parts.

3) Incorporate automatic sensor-based safeties.

Agricultural equipment is used in conjunction with soil and plants. Frequently, agricultural equipment is operated by personnel with little formal education or experience. The nature of their work may require long periods of hard work under great pressure to complete their work within a specific time. These workers may not be aware of good safety practices, nor may they understand the importance of safety practices. These workers may also believe that additional time spent ensuring safety could result in the termination of their employment. Mechanical engineers can lessen the chance of a tragedy by designing safety features into agricultural machinery that requires no conscious activation by agricultural workers.

An example of this type of safety can be found in tractors. Tractors are commonly fitted with “dead man” switches under the seat. If there is insufficient weight on the driver’s seat of the tractor, the tractor is disabled by the dead man switch. Should the tractor driver leave the tractor, it cannot accidentally begin moving under its own power.

Multiple studies independently conducted by Pennsylvania State University and National Ag Safety Database revealed that tractor accidents were the leading cause of agricultural fatalities. Most of these accidents were tractor rollovers. Integral occupant protection has been shown to reduce the frequency of these fatalities.
Other factors contributing to tractor-related injuries and fatalities are road accidents, electrical power line contact, and ingress of workers into power takeoff machinery connected to the tractor. The incorporation of guarding and heat-sensing presence detectors on power takeoff machinery may reduce these types of accidents. Increasing tractor visibility to oncoming vehicles lessens that chance of collisions.

Combines are another source of horrible accidents. Combines are large, self-propelled machines with a rotating array of tines to harvest crops. Periodically, a worker must crawl into the crop entrance to clean the tine array. An all-too-common occurrence is that a second worker, unaware of the actions of the first worker, enters the combine cab and starts the machine. As the tine array begins rotating, the first worker is struck by the tine array, with fatal results. The use of a heat-sensing presence detector in the tine array may lessen the chance of this type of accident.

Some of these accidents may be avoidable by increasing the driver’s visibility. Allowing a portion of each window in an enclosed cab to slope outward would offer the driver the opportunity to peer downward, close to the machine. This would increase the driver’s chance of avoiding injuring co-workers with the machine.

### 3.11 - Recreational Products

Where used: Carbonated beverage containers, portable grills, toys

Safety issues:

1) Prevent ballistic eye injuries.

2) Reduce the likelihood of cut, crush, burn, or choking injuries.

3) “Child-proof” toys.
Carbonated beverages contain dissolved gas within the product. If the product is agitated immediately prior to opening the container, significant gas pressure will be present. Eye injuries have occurred when highly carbonated product bottles have been opened immediately after considerable agitation or when they were warm. These accidents have usually involved bottles sealed with synthetic stoppers.

The initial resistance of the stopper was greater than the force exerted by the gas pressure within the bottle. As the stopper was being removed, the resistance of the stopper dropped below the magnitude of the force exerted by the gas in the bottle. In accidents where this happened, the stopper was forcefully ejected the remainder of the way from the bottle, traveled in a ballistic path, and struck the eye of a nearby person. The impact of the stopper was often violent enough to cause blindness in the eye that was struck.

Eye injuries caused by stoppers where the stopper material was noted suggested that stoppers made from synthetic materials posed a greater risk than stoppers made from cork. Some of the factors that may have led to this risk disparity were lower coefficients of friction of the synthetic materials, greater plastic deformation of synthetic stoppers, and the presence of a rim on many synthetic stoppers that facilitated the use of hand pressure to eject the stopper.

After being initially displaced during the opening of the bottle, the synthetic stoppers frequently were expelled from the bottles in a sudden and unpredictable manner. The velocities of the stoppers usually allowed them to strike the victims before the victims could perceive and react to avoid injury.
The danger posed by synthetic stoppers has been successfully negated by manufacturers of carbonated products. Some manufacturers have surrounded the stopper with a wire cage after it has been placed in the filled bottle. Other manufacturers have attached string tethers to synthetic stoppers, preventing propelled stoppers from traveling more than a few inches from the bottle.

Toys pose a special challenge for mechanical engineers, as they must combine an understanding of market demands, creativity, and higher-than-normal levels of safety. When an adult uses a product, there is an assumption of some responsibility and caution on the part of the user. Children by definition are immature and unaware of many common hazards.
With this understanding, toys marketed to children, especially young children, must meet a higher standard of safety.

The mechanical engineer endeavoring to design toys would be well advised to observe small children at play. Children are prone to handling toys in every possible manner, so the toy must not be capable of cutting them. If a part can be removed from a toy, children will find a way to do it. Like puppies, children may attempt to eat or taste part or all of a toy. Materials selected for the manufacture of toys should be non-toxic. Parts that are likely to be removed by a child should be designed to minimize choking hazards. The mechanical engineer must account for this product abuse.

Materials selected for toy manufacture should fail in a ductile mode. This lessens the chance that a child could be injured by a sharp edge. A ductile mode of failure also reduces the chance that a child could receive an eye injury by propelled fragments resulting from parts breakage.

3.12 - Designing for the Elderly, Handicapped and Infirm

Where used: Common household products for people with limited physical abilities

Safety issues:

1) Reduced ability to grasp and hold.

2) Diminished vision, hearing, and touch.

3) Reduced fine motor skills.

During the latter part of the twentieth century, advances in medicine, nutrition, and health maintenance increased the life span of the average human being. Unfortunately, the ability to reverse aging-induced frailties of the human body has yet to be realized.
One of the more common disabling affections is arthritis. Arthritis restricts the motion of body joints in human beings and makes joint motion painful. People with arthritis may have difficulty holding utensils, cups, toothbrushes, and other household items. Arthritis can limit the ability of those afflicted with it to turn door knobs, discharge fire extinguishers, use garden tools, write, and perform other tasks requiring a firm grip. If the common smooth, round door knob acquires a film of water, oil, or grease, it may become nearly impossible for an arthritic person to turn.

One way in which mechanical engineers have overcome arthritis-related limitations is the development of soft, elastic adaptors for utensils, writing instruments, and dental care instruments. Also, the ability to escape a fire requires that exits be designed for easy and instinctive use. Engineers have used push-bar-operated door latches in place of regular door knobs where necessary.

Automatic safety devices in household appliances are even more valuable to the disabled. In addition to a lessened ability to sense danger, some people may suffer limitations that preclude the opportunity to avert a conspicuous danger. For example, a wheelchair-bound individual may not be able to right an overturned space heater. The incorporation of a tilt-actuated cut-off switch and proper guarding features by the designing mechanical engineer may save the person from loss of property, serious injury, or loss of life.

Slip-and-fall accidents are a serious safety concern for anyone, but they pose a special threat to the elderly. Showers and bathtubs are a frequent source of such accidents. Slip-and-fall accidents that result in broken bones often require immobilization of the victim for a period of weeks or months. Immobilization of elderly individuals increases their chances of developing pneumonia, with potentially fatal consequences. Steps taken by mechanical
engineers to prevent slip-and-fall accidents among the elderly have included high-traction surfaces and load-bearing handles in danger areas.

Disabilities can take the form of a loss of vision, hearing, or touch. The loss of vision likely has the strongest effect on an individual’s life. Visually impaired people experience difficulty using many ordinary products. A flashing light on a smoke detector indicating that its battery power is low, the liquid crystal display on a microwave oven, and an overhead emergency exit sign are all useless to the blind. Mechanical engineers who have designed products to be easily used by the visually impaired have often included product-operation features that were based on auditory or tactile senses.

3.13 - Discussion Topics

1) A mechanical linkage on an aspirin production line consists of an aluminum bar with a bearing on each end. Each bearing is an exposed ball-type bearing, lubricated with a petroleum-based grease. Each night, workers clean the linkage with a solution that is known to slowly corrode aluminum.

   Instructor ideas: Substitute a smooth stainless steel rod, because aluminum will develop pits that may accumulate bacteria. The bearings could be replaced with disposable inserts made of a self-lubricating material. Refer to the U.S. Food and Drug Administration’s Good Manufacturing Practices guidelines for additional information.

2) Your company has asked you to help design an automotive fuel tank that will be mounted between the rear axle and the rear bumper of a car. Your task is to decide if the fuel tank should be made from steel or plastic. What safety concerns need to be addressed?
Instructor ideas: This fuel tank is at risk of rupture during a collision, especially a rear-end collision. A low-carbon steel fuel tank would likely offer more fracture toughness than many plastics. If a fire results from a collision, a plastic fuel tank may lose its structural properties sooner than a steel fuel tank.

3) Your company has asked your engineering group to design a new coffee maker. What problems might occur if it is fitted with a mechanical “on/off” switch?

Instructor ideas: Mechanical “on/off” switches may not fail safe. They commonly use spring-powered detents. If the detent becomes inoperative, a mechanical switch could come to rest in either the “on” or “off” positions. For this reason, many mechanical switches cannot be depended upon to fail safe.

4) Side impacts place vehicle passengers at great risk of death or serious bodily harm. How might you better protect the passengers from a side impact to the door?

Instructor ideas: Strengthen the door. Design the vehicle to have more space between the seat and the door. This gives more crush distance, thus reducing the accelerations on the passengers. At some point, these steps will become too costly for the automobile to sell.

5) Your company has assigned you to review another engineer’s plans for pressurizing a fifty-year-old boiler to increase its efficiency. The engineer’s calculations are correct, but why might this be a bad idea?

Instructor ideas: After fifty years, rust or corrosion may have reduced the boiler’s wall thickness to an unsafe dimension. Adding pressure may lead to an explosive boiler failure.

6) Elderly and infirm people often need “walkers”, devices that assist mobility. What practical design features could be incorporated to enhance safety?
Instructor ideas: It should be lightweight to allow easy lifting by weak hands when mounting curbs or steps. The grip surfaces should be large and well padded to distribute the loads and provide a comfortable feel. Consider adding small rear-view mirrors. Some users may have difficulty watching for bicycles, pedestrians, and vehicles approaching from behind. Small wide-angle mirrors might lessen the need for users to turn their heads. If the walker is to be fitted with wheels, larger-diameter wheels are less likely to be impeded by obstacles or debris than smaller wheels.

7) Engineer Blue and engineer Yellow work for a power tool manufacturer. Engineer Yellow finds a dangerous flaw in one of the company’s more popular products. Yellow speaks to Blue, but never gets a reply as promised. Yellow sends Blue an e-mail, and Blue replies that the concern is being studied. Yellow again asks Blue about the dangerous flaw, but Blue dismisses the concern. What would you do if you were engineer Yellow?

Instructor ideas: Yellow should immediately start a “paper trail.” If Blue shows so little regard for a potentially dangerous product that may harm consumers, Blue may also think nothing of turning against Yellow. Yellow should print out copies of all e-mails and other communications sent and received about this matter. Yellow might be wise to keep two sets of copies, one at work and the other at home, in case Yellow is dismissed by the company. Yellow should review all company policies pertaining to these circumstances, follow each step, and keep proof that the steps were taken. If Yellow is correct, then legal trouble for the company will likely occur in the future. If Yellow is correct and Yellow’s concerns are taken seriously, then the company will benefit by avoiding costly litigation.
Chapter 4 - Design Principles and Creativity

4.0 - Introduction

This chapter introduces some key design principles and ideas to enhance creativity. The key design principles are a way to convey the collective experience of engineers. They serve as a guide that can be applied while designing each component of the prototype.

Unlike equations and theories, creativity is something that cannot be conveyed from one person to the next. Fortunately, however, one person can help another to develop his or her own creativity. In order to inspire the creativity of the designing mechanical engineer, this chapter includes suggestions on how to conceive prototype design features.

4.1 - Key Principles

- Strive for simplicity.
- Design for symmetry when possible.
- Know the process.
- Use the least amount of material to do the job.
- Incorporate an appropriate safety factor.
- Design for interchangeable parts.
- Choose an appropriate tolerance.
- Study the environment in which the product will be used.
- Remember that technology does not exist in a vacuum.
- Design for an appropriate product life span.
Principle: Simplicity

How it is applied: Designing and refining existing designs

Why:

- “Fewer parts mean fewer things to go wrong.”
- Using fewer parts simplifies parts inventories.
- Using fewer parts can lower costs.

The designing mechanical engineer should seek to balance the desire for utility with the demands of complexity. While a ruler, a coat hanger, and a wrench may consist of only one part, many other products must consist of multiple parts to perform their intended tasks.

Famed cartoonist Rube Goldberg entertained readers with his illustrations of overly complex machines to perform simple tasks. Goldberg conveyed the virtues of simplicity in design so well that some engineering societies named contests in his honor.

An important consideration is that reducing the total number of components reduces the chance of parts breakage, all else being equal. For instance, when the exterior shells of optical instruments are manufactured from fewer parts, the result is fewer places for the ingress of moisture into the instruments, which could degrade their performance.

In 1919, French businessman Raymond Orteig offered a prize of $25,000 to the first person who could fly from Paris to New York or New York to Paris. On May 20-21, 1927, when Charles Lindbergh became the first person to fly nonstop from New York to Paris, he did so in a single-engine airplane. Most aviation experts of that period believed that an airplane attempting to cross the Atlantic Ocean should have three engines, in case of the failure of an engine. Lindbergh, however, thought that three engines made the chance of an engine failure three times as likely. He also had the opinion that if one engine failed on a
three-engine airplane, it might not be able to reach Paris with only two engines functioning.
He reasoned that the lighter, more fuel-efficient single-engine design was better for his trip, and the rest is history.¹ (More information about Charles Lindbergh, his accomplishments, and his airplane design philosophy can be found at www.charleslindbergh.com/plane/index.asp.)

There are other benefits to using fewer parts. A product that uses fewer parts may require fewer steps to manufacture. If the product is assembled from parts that are manufactured by other parties, the use of fewer parts may make possible smaller component inventories and the use of less storage space within the manufacturing facility. Having to make fewer parts means that a manufacturer can invest in fewer machines and employees, greatly reducing the cost to make the product. Having to inventory a smaller number of parts lessens the warehouse space requirement, further reducing costs to the manufacturer.

**Principle: Design for symmetry**

How it is applied: Designing both components and whole machines

Why:

- Symmetry simplifies loading.
- Symmetry can allow the use of simpler bearings and supports.
- Asymmetrical moving parts may exhibit uneven wear on bearing surfaces.

In order to appreciate some of the benefits of symmetry as it is applied to design, the reader can perform a simple experiment. Obtain two identical objects, such as water-filled buckets. Lifting one object in each hand, the reader will notice a pleasing sense of being balanced. The same thing holds true for mechanical parts. Symmetry can be seen in nature. Like humans, most animals exhibit bilateral symmetry.
When asymmetrical parts are used in a product, they normally require bearings or supports that can sustain three-dimensional loads and moments. Symmetrical design of parts often simplifies the loads and moments to two dimensions, permitting implementation that is less costly.

When an asymmetrical part is moved under load, the resulting wear patterns may be uneven. If a part’s bearing surface wears at a faster rate on one end than on the other, the part may require replacement sooner than the equivalent symmetrical part.

Although the designing mechanical engineer should attempt symmetry where possible, asymmetrical designs should not be entirely discounted. During World War II, the German aviation company of Blohm und Voss designed and produced asymmetrical aircraft. Their asymmetrical designs balanced out the aerodynamic and engine forces that normally cause aircraft to deviate from their course.

While not greatly asymmetric, the Wright brothers’ first airplane, the 1903 Flyer, had some minor asymmetries. The engine and pilot lay side by side on the lower wing, each offset to one side of the airplane’s longitudinal centerline. Also, the 1903 Flyer’s wings on the right side were four inches longer than the wings on the left side. This latter asymmetry helped to balance the airplane in flight.

**Principle: Know the process**

How it is applied: Automobile manufacture, microelectromechanical systems

Why:

- Increased reliability.
- Reduced costs.
- Eliminates complicated inspections.
With the traditional method of manufacturing, a product was inspected after manufacture, and any detected flaws were corrected. The know-the-process approach was first espoused by Dr. W. Edwards Deming when he wrote, “Cease dependence on inspection to achieve quality. Eliminate the need for inspection by building quality into the product and the service in the first place.”\(^2\)

Perhaps the most visible transition to this approach can be seen in the automotive industry. Reliability of automobiles has been greatly enhanced by assembling vehicles from parts of known quality, rather than depending on an inspection after manufacture to ensure quality. (For more information on Deming and his philosophies, visit the W. Edwards Deming Institute at www.deming.org.)

The know-the-process approach reduces the costs of manufacturing a product because it eliminates the need for disassembling the product to replace a defective part, and because no money is wasted in handling and transporting defective parts. Also, valuable storage space and accounting resources are not wasted on processing the replacement of the defective part. Possibly the greatest advantage of the product quality improvements offered by this principle is that the manufacturer’s reputation among customers is enhanced.

A new and rapidly growing type of mechanical engineering involves microelectromechanical systems (MEMS). MEMS devices are frequently composed of features that are too small to measure in a mass-production setting. As a result, MEMS is based on the idea that knowing the process allows the engineer to know the product that results from the process. For instance, an engineer may know that one minute of exposure to a certain vapor deposition process may yield a coating that is four angstroms thick.
Therefore, the engineer can use the duration of vapor deposition to predict the final part dimension.

**Principle: Use the least amount of material to do the job**

*How it is applied:* Reducing material costs and product weight

*Why:*

- Lower material costs allow lower product cost.
- Lower product weight means lower shipping costs.
- Lower part weight reduces part stresses.

Theoretically, anyone could design a part large enough to sustain a given load. What sets the designing mechanical engineer apart from the non-engineer is the ability to design safe and efficient products that satisfy market requirements. The key for the designing mechanical engineer is to remember that using the least amount of material in the design of a part can yield benefits far beyond the simple savings in the cost of manufacturing the part.

A portion of any product’s cost is the sum of the material costs needed to make that product. One of the most useful manufacturing advances in the twentieth century was the development of stamped parts as an alternative to milled parts. Previously, some steel products produced by milling resulted in the removal and waste of more than 80 percent of the metal. Because stamping does not waste metal, material costs were lowered.

Using the least amount of material to make a part for the assembly of a product brings further benefits. Suppose that the body of a truck tractor can be made using less material, thereby reducing the weight of the truck. With less body weight, the truck’s body support members can be lighter. Because a truck’s maximum weight is usually limited by law, a
lighter truck weight means the truck can carry more cargo. The ability to carry more cargo makes the truck more efficient and reduces shipping costs.

When a machine part is in motion, the part’s inertia contributes to the part’s stresses. When less material is used in the part, the part’s inertia—and, therefore, its stresses—are reduced.

**Principle: Safety Factor**

How it is applied: Reducing product failure and chance of injury

Why:

- A part that is stronger than needed is less likely to fail.
- Accounts for some product abuse.
- Accounts for some part flaws.

The safety factor of a part is the quotient of the load at which the part will fail and the maximum rated load of the part. If the part will fail at 140 pounds of force (lbf) and the maximum rated load of the part is 100 lbf, then the part’s safety factor is said to be 1.4.

The principle of a safety factor is somewhat in opposition to the principle of using the least amount of material to do the job. The role of the safety factor is to account for some measure of engineering uncertainty and product abuse. Engineering uncertainty may result from inadequate data about the loads to be placed on the product. Some products, such as shovels and wristwatches, are subjected to widely differing loads, depending on the user and the product’s use environment. Shovels used by homeowners would likely sustain smaller loads than shovels used by contractors. Wristwatches worn by office workers, nurses, or accountants would be subjected to lower inertial loads than those worn by athletes, landscapers, or tow truck operators.
The designing engineer will have to consider product abuse, and the safety factor addresses this concern. It has been this engineer’s observation that utility trailers and ropes are frequently abused by their owners. I have observed utility trailers that have received little or no maintenance and have been overloaded. These utility trailers had been so abused that their frames and axles were deformed. I have also seen a climbing rope being used to tow a truck laden with logs. The climbing rope failed. It seems unlikely that the climbing rope’s designer envisioned this application of the product.

Principle: Interchangeable Parts

How it is applied: Whenever possible in products

Why:

- Reduces manufacturing labor costs.
- Reduces repair labor costs.
- Simplifies parts replacement procedures.

Few innovations have increased productivity as much as interchangeable parts. Interchangeable parts are parts that can be replaced without the need for fitting. Without interchangeable parts, a new or replacement part has to be properly sized. The sizing process usually has to be done by human labor. As a result, the sizing process can be both time-consuming and expensive.

To design interchangeable parts, the designing mechanical engineer specifies a part size and a tolerance range. For example, the engineer might call for the width of a part to be 7.62 mm with a tolerance range of -0.003 mm to 0.001 mm. This means that the minimum part width would be 7.617 mm, and the maximum part width would be 7.621 mm. Further,
the designing mechanical engineer guarantees that any new or replacement part with a width between 7.617 mm and 7.621 mm will fit and function properly.

If all the parts used in the assembly of a product are interchangeable, the manufacturer does not have to divert valuable resources to the fitting of parts. Using the traditional approach of fitted parts, Connecticut clockmaker Eli Terry’s factory produced approximately 100 clocks a year. In 1807, Terry’s factory began assembling clocks using interchangeable parts. His factory produced 4000 clocks from 1807 to 1810.4

In the same way that interchangeable parts revolutionized the manufacture of products, they have greatly simplified parts replacement in existing products. Every day, automobile spark plugs, oil filters, water pumps, and other parts are replaced without the need for fitting. In like manner, students insert consumable and interchangeable graphite/polymer sticks into mechanical pencils without fitting them. Other common items such as lawnmowers, chainsaws, and computer printers may be repaired, if need be, by means of readily interchangeable parts. In the 19th century, broken wagon wheels were repaired by a craftsman. Beginning early in the 20th century, a non-craftsman could replace a deflated or damaged vehicle wheel and tire with a serviceable, interchangeable wheel and tire.

**Principle: Appropriate Tolerances**

**How it is applied:** Interaction between any two parts

**Why:**

- Tight tolerances promote precision.
- Loose tolerances reduce manufacturing and repair costs.
- Cumulative tolerances can impede assembly, repair, or proper operation.
Tolerances are the permissible variations in part sizes. When a designing mechanical engineer specifies a tolerance for a given part dimension, that engineer is describing the maximum and minimum permissible values for that dimension of the part. At the same time, the engineer is stating that any part no smaller than the minimum permissible value and no greater than the maximum permissible value will fit properly. Parts within the maximum and minimum dimensions may be assumed to be interchangeable.

When tolerances are small, they are sometimes said to be “tight.” Tight tolerances hold the part closer to the desired dimension. A disadvantage of tight tolerances is that it raises the manufacturing costs for the part.

When tolerances are large, they are sometimes said to be “loose.” Loose tolerances allow greater variation in part size and thus reduce manufacturing costs for the part. A disadvantage of loose tolerances is that the overall precision of the product is reduced when compared to tight tolerances.

The mechanical engineer should analyze the cumulative effects of tolerances, or cumulative tolerance, when designing a product. Cumulative tolerance occurs when multiple parts are connected and their respective tolerances combine in an additive way.

Suppose that four 120-inch-long shafts, each with a length tolerance of plus or minus 1 inch, are to be connected end to end. The combined shafts will have a length of between 476 inches and 484 inches. The effects of cumulative tolerance may cause the combined shafts to be too short or long for the application. The designing mechanical engineer should take care not to overlook the effect of cumulative tolerance with other design considerations, such as drilled holes and paint or coatings on parts.
When selecting the material for a part, consider thermal expansion. If two adjacent parts have different thermal expansion rates, one or both of them may exceed their design tolerances during operation.

**Principle: Study the environment in which the product will be used**

How it is applied: Determining product features

Why:

- Helps the designer understand the extent of debris.
- Helps the designer understand the extent of abuse.
- Helps the designer understand market needs.

When designing a product, the mechanical engineer is likely to be sitting in a dry, well-lighted, comfortable room. While a clean, pleasant setting is conducive to good design work, it may not represent the product’s future work environment. The product may be exposed to temperature extremes, loose soil, corrosive fluids, animal waste, abrasive particles, or foreign objects.

It is incumbent upon the designing mechanical engineer to learn about the product’s intended work environment, preferably including a visit to locations that are representative of the intended work environment. If the engineer is designing a power tool for construction, then the engineer should visit some building sites. If the engineer is designing an agricultural implement, then the engineer should visit some farms. The engineer should photograph key features of the product’s future work environment and make notes about potential design considerations.

The working environments of turbine and reciprocating engines have posed major obstacles for designing mechanical engineers. Turbine engines are used to power aircraft and
hovercraft, pump oil through pipelines, and provide emergency electrical power generation. When used to power aircraft, turbine engines may be exposed to airborne soil, salt spray, and bird strikes. Air ambulance helicopters are normally flown in unprepared areas, and their turbine engines may experience premature wear due to airborne soil. The turbine engines of hovercraft operated over salt water will ingest salt spray. The impact of birds on both turbine engines and reciprocating engines has caused numerous aircraft accidents. Birds pose enough of a hazard to aircraft safety that bird activity warnings are often issued at airports.

Otherwise excellent products often fail due to abuse and neglect. The designing mechanical engineer should consider the likely user of a product. Detailed instructions describing the care and maintenance of a product are of little value if the user cannot comprehend the importance of the required maintenance. Even if the user understands how to properly care for the product, demands of the work environment may obstruct maintenance. Whenever it is economically feasible, the designing mechanical engineer should incorporate features and materials into the product that minimize maintenance requirements. Examples include, but are not limited to, using stainless steel instead of carbon steel, sealed bearings instead of exposed bearings, and protective coatings over corrodible metals.

Abuse can be a difficult factor for the engineer to design around. Abuse can occur with any product. The common flat-blade screwdriver’s intended purpose is to transmit torque from the user’s hand to a screw. Nevertheless, the flat-blade screwdriver is often used in a myriad of unintended ways, such as to pry the lids off of paint cans, pry the retainer from the top of automobile brake fluid reservoirs, manually check brake strokes on air-brake-equipped vehicles, pry automobile parts into alignment, and scrape rust from steel surfaces, to name only a few. When designing a product, the mechanical engineer will benefit from
studying the ways in which existing products are abused. This will give the engineer insight in the ways that a future product might be abused by the same users.

A product’s users may not be able to avoid abusing or neglecting the product. Harsh work environments or the demands of a job may not facilitate the maintenance necessary for a product. Therefore, minimal maintenance is a market demand. Emergency room personnel have little or no time to maintain their equipment while on duty. Operators of truck tractors and semi-trailers lose money when they have to frequently check manually adjusted air-brake slack adjusters; thus, many prefer automatic air-brake slack adjusters. Most wrenches and socket sets are chrome-plated to minimize user maintenance requirements.

Principle: Technology does not exist in a vacuum.

How it is applied: Understanding the role of the product

Why:

− Most products interact with other products.

− The product should integrate smoothly with other products.

− Higher technology alone is not always the solution.

Products are often purchased for their ability to interact with other products. A trailer towing kit must reliably connect an existing trailer to an existing vehicle. A coffee cup might offer improvements over the competitors’ coffee cups, but if it doesn’t fit existing automobile cup holders, it may fail in the marketplace. Regardless of the merits of an innovation, if that innovation cannot blend with existing products, consumers may not accept it.

In the poultry industry, products normally move about the packaging lines in a standard type of plastic container, often referred to as a “tote.” All of the machines along the packaging lines are designed to interact with these totes. Any product intended for use on one
of these packaging lines must function properly with these totes. If a mechanical engineer were to design a poultry packaging product that did not function with the existing totes, the cost to replace the existing machinery and totes would likely be prohibitively expensive for poultry industry consumers.

Higher technology is not always desirable. An electric spoon would offer little advantage over the currently used utensil. The least expensive digital wristwatch is far more precise than the fine, but expensive mechanical wristwatches of Rolex and Patek Philippe. Yet many purchasers prefer either electrical or mechanical analog wristwatches, often for reasons of aesthetics or fashion. Ultimately, the advantages of higher technology must be balanced with the cost to the consumer, the convenience of the product’s use, and the consumer’s satisfaction.

**Principle: Design for an appropriate product life span**

**How it is applied: Establishing realistic product durability**

**Why:**

- Increasing product life span increases product cost.
- An unnecessarily long product life span may unnecessarily increase product weight.
- An unnecessarily long product life span may necessitate the use of materials that are unnecessarily difficult to machine.

It is natural for the mechanical engineer to strive to design the most enduring product possible. A long product life span is often viewed as a measure of quality. However, a disadvantage of designing an unnecessarily long product life span is that it increases the product’s cost.
The classic example of designing for a finite life span is the disposable or one-time-use product. Plastic or wood eating utensils, bandages and some surgical implements, chemically powered light sticks, and disposable cameras are examples of products designed for one-time use.

The designing mechanical engineer should consider that some products can be used multiple times but are designed to be non-maintainable. Many mass-produced ultrasonic measuring devices and some timepieces are examples of products designed to be non-maintainable.

The non-maintainable, electrically powered product has several design advantages over its maintainable counterpart. The non-maintainable, electrically powered product does not require battery replacement or performance adjustment accesses, which allows the product to maintain water resistance at a lower cost than if accesses were part of the product. Because access covers and any associated O-rings or other sealing devices constitute additional parts, eliminating these parts and the labor to assemble them further reduces manufacturing costs.

Like the people who design them, all machines have a finite life span. Prototypes normally have much shorter life spans than most production machines. Increasingly, engineers are being asked to design into a machine some ability to be recycled. This can take the form of designing around easily recyclable materials or components.

Machine components made from materials such as steel, glass and some plastics can be recovered at the end of a machine’s life. These components can be melted and formed or simply used again. The prototype machines constructed by students during their mechanical
Some components, such as truck diesel fuel caps, receive little wear while in use on a larger product. These components can often be cleaned and resold. Designing machines for easy recovery of recyclable parts can reduce salvage costs.

Few texts have embodied the essence of designing for a brief product life as well as E. J. Tangerman’s essay, “Drei Minuten,” in his book Horizons Regained. In the essay, Tangerman cites the example of a rocket that must last only three minutes.5

4.2 - Inspiration and Creativity

Mimicking nature.

Joints

Motion

Historically successful design updated with modern technology.

Refining an existing but flawed design.

Technique: Mimicking nature

How it is applied: Reducing design time

Why:

– The design feature has already been proven.

– Helps avoid intellectual property rights issues.

– Allows engineers to leapfrog over difficult creativity obstacles.

Many mechanical engineers have examined nature for inspiration while designing. This is especially true when designing articulated or self-propelled machines. Knee and hip
joints are among the phenomena found in nature that have been adapted to the design of machines.

Natural phenomena have already been proven. Further, there are no patents or intellectual property rights issues to be resolved. By adapting a proven design, mechanical engineers can sometimes solve difficult problems without a significant time expenditure. For example, small, autonomous, remotely piloted aircraft have been modeled after birds. These aircraft are often less than 30 centimeters in length. They are technically ornithopters, flapping like birds or bats in order to fly. Also, designers of research submarines have been developing miniature submarines that resemble fish. Not only do these submarines look like fish; they can swim like fish by wagging their tails.

Engineers do not always just mimic nature in their designs. Engineers specializing in the manufacture of microelectromechanical systems have even harvested items in nature for use in products. For instance, some corals form tubes radiating from a central structure. Mechanical engineers have harvested these tubes and machined them to serve as microshafts.

**Technique:** Historically successful design updated with modern technology

**How it is applied:** Making existing ideas marketable by introducing small changes

**Why:**

- May allow the use of existing machinery.
- Expedient way to design a marketable product.
- Previous reputation will help market acceptance.

Many successful products eventually fade from the marketplace due to increases in labor or materials costs. But just as a book that has been long out of print can be reprinted and again become popular, some designs can be revived. Designs of bicycles, furniture,
coffee grinders, sports cars, and other products that were popular in the past are often restored to the marketplace after being updated with modem technology.

One or more changes to the product’s design or its methods of manufacture will be necessary. It could be possible to use the original manufacturing machinery to manufacture those product components that remain unchanged, if that machinery is available. If this is the case, the cost of the original machinery would likely be lower than the purchase price of replacement machinery.

A design that succumbed to increasing labor costs might be made profitable by substituting computer numerical control manufacturing methods for labor-intensive practices. A design that succumbed to unacceptably high materials costs might be made profitable by substituting a modern material for an increasingly rare or expensive raw material. These approaches may be combined for added benefits. For instance, substituting a less expensive, investment-cast chrome-molybdenum steel component for the previously used forged chrome-vanadium steel component would reduce both material and labor costs.

When designing mechanical engineers can restore a previously popular product to the marketplace, the original product’s reputation will assist market acceptance of the product. Consumers’ association of the redesigned product with the original will be enhanced if the redesigned product maintains the same outward appearance, feel, and operation as the original product.
Technique: Refining an existing but flawed design 6

How it is applied: Saving development time and money, restoring popular designs to the workplace

Why:

- May save design time and cost.
- Only a small change may be needed to create a successful product.
- Some flawed designs have been corrected by simply specifying a different material.

An otherwise excellent design may suffer from a single flaw. If the designing mechanical engineers are able to correct the flaw and use the design, a successful product may result. When an otherwise excellent design possesses a single flaw so severe that it causes either consumers or manufacturers to reject the design, it is sometimes called a “fatal flaw.” By correcting the fatal flaw in an existing design, the mechanical engineers can save the time and money that would have been spent on the rest of the design.

An example of this design technique can be found in aircraft. Several famous aircraft achieved acceptance among consumers only after different engines were substituted for their originally specified engines. Similarly, invention of the pneumatic tire made high-speed automobile and truck travel feasible.

Another example of this technique was utilized by Alfred Nobel, the inventor of dynamite and the originator of the Nobel Prizes. Explosives have great value in farming, mining, construction, and other occupations. Prior to Nobel’s innovation, straight nitroglycerin was used. Unfortunately, nitroglycerin is extremely dangerous to handle, and many accidents resulted from its use. Nobel added a powdery, hardened algae known as
kieselguhr to nitroglycerin, transforming it into a stable industrial explosive. Today, stable explosives are used even in the manufacture of automobiles in a process known as hydroforming.

Sometimes an existing design can be salvaged by simply specifying a different material for one or more components of the design. A design that suffers from a corrosion problem might be made successful by substituting stainless steel or titanium components for steel or aluminum components. A design that is too heavy might be made successful by substituting aluminum, a scandium-aluminum alloy, titanium, carbon fiber, or even polymer components for steel components.
Chapter 5 - Application of Theory

5.0 - Introduction

One of the most important time-saving tools available to the designing mechanical engineer is hand analysis. This chapter gives the designing mechanical engineer an understanding of hand analysis and its importance.

Theories alone may be inadequate for the inexperienced designing mechanical engineer. The new engineer—and every engineer was new once—will likely benefit from the enumeration of specific design steps. This chapter gives the new engineer a step-by-step guide to designing a prototype machine.

5.1 - Hand Analysis

This section explains what hand analysis is, why it is important, and how it is performed. Despite the usefulness of computers and design software, so-called hand calculations allow the designing engineer to save valuable time and avoid wasted effort.

Hand analysis consists of making assumptions that allow the use of simple equations to gain valuable information about the viability of a design feature. As suggested by the name, hand analysis is usually performed with a pencil, a pad, and a hand calculator.

It is the assumptions that make hand analysis so fast and convenient. A complex shape might be approximated by a simple shape. For example, the deflection of an extended arm of the prototype might be estimated by a hand analysis using a simple beam-deflection equation. The heat conduction of a stepped shaft might be approximated using the conductive heat-transfer equation for a shaft of continuous diameter.

The initial use of hand analysis should occur when mechanical engineers are thinking of their initial designs. Hand analysis can serve as a design triage, classifying design features
as worth further analysis, possibly workable, or not worth further consideration. If the hand
analysis of a beam’s deflection does not indicate excessive displacement under a worst-case
scenario, then the time consumed by a detailed analysis may be worthwhile.

Example #1

A mechanical engineering design team has been asked to design a child’s jumping
stick toy. The team would like to design the jumping stick with a main tube, a step assembly,
a hand-grip assembly, a strut, and an inner compressive assembly. The team envisions the
strut telescoping into the main tube during compression.

The team has performed a literature review. The recommendation posted on the
website of a child-safety advocacy group specifies that for safety, jumping-type toys should
permit a 45-kilogram child to fall 0.5 meters prior to impact and sustain a maximum of 2 g’s
of acceleration during impact. The team members have met to discuss their project and to
perform a hand analysis of this recommendation as it relates to their concept.

The team members opt to neglect any friction that might occur during compression,
so as to create a worst-case scenario. The team members also agree that air friction will play
no meaningful role and thus eliminate it as a factor in their calculations. The team decides to
estimate the total mass of a 45-kilogram child plus the toy jumping stick as having a mass of
50 kilograms.

The potential energy of the child plus the toy jumping stick at a height of 0.5 meters
above the ground is 245.25 N-m. The team members have decided to assume all of this
potential energy is converted to kinetic energy, which is in turn converted into spring
potential energy.
The team members then calculate that at the instant before impact, the child and toy jumping stick will have a velocity of 3.13 meters per second. The team members then conclude that because the maximum acceleration should not exceed 2 g’s, or 19.62 meters per second squared, the duration of the impact should be at least 0.16 seconds. Further hand analysis by the team members shows that the strut must compress 0.25 meters during the impact.

The team members have apprehension about the distance the strut must compress as the result of an impact by 50 kilograms (the total weight of the child plus the toy jumping stick) from 0.5 meters. The team reasons that designing the jumping stick to compress as much as 0.25 meters would place the feet of a child user at least 0.3 meters above the ground. Team members believe that this height would make it difficult for the child to maintain his or her balance, thus actually increasing the likelihood of an injury. For this reason, the team decides to not use the child-safety advocacy group’s recommendation.

Example #2

A mechanical engineering design team has been asked to design an electrically powered, remotely controlled toy airship. The toy airship will be inflated with helium.

As the team begins to design the toy airship, it becomes apparent that the team must choose between two propulsion packages, each containing batteries, a receiver, a controller, two motors, and two propellers. While both offer the same performance, the cheaper propulsion package weighs 0.26 kg, and the more expensive propulsion package weighs 0.17 kg.
From reference books, the team has learned that air in the regions where the toy airship will be marketed has a minimum density of 1.250 kg per cubic meter. These reference books also state that helium has a density of 0.179 kg per cubic meter.

After studying the shape of the inflated gas bag, the team chooses to approximate the inflated gas bag as a cylinder 1 meter long and 0.5 meters in diameter, with two hemispherical end pieces, each 0.5 meters in diameter.

The volume of the team’s model of the filled gas bag is determined to be 0.262 cubic meters. This analysis also shows that the model gas bag would have a lift capacity of 0.280 kg.

The team’s initial hand analysis shows that the weight of the cheaper propulsion package makes it a marginal choice. The gas bag itself will add to the mass of the toy airship. Any added features such as fins will also add mass. Although the toy airship may be able to fly with the cheaper propulsion package under ideal conditions, a change in gas bag helium pressure or weather could cause the toy airship to no longer remain airborne.

The hand analysis shows that selecting the more expensive but lighter propulsion package would likely allow the toy airship to carry a small payload. Should the more expensive but lighter propulsion package be chosen, another option would be to include ballast weights so the user could tailor the toy airship’s performance to his or her wishes.

The value of hand analysis in this example is that it enabled the mechanical engineering design team to quickly assess their design options. Rather than spending more time and money at an early stage on finite element modeling, hand analysis provided reasonably accurate information in a few minutes.
Example #3

A mechanical engineering design team has been asked to design an agricultural mower that will be pulled behind a tractor. The mower will be driven by a shaft that will transmit power from the tractor. One of the team members has located a commercially available solid shaft 0.75 inches in diameter. If the shaft will work for the team’s application, using it would save the team much-needed time. Before the team purchases the mower power shaft, they have decided to perform a quick and simple hand analysis to estimate the maximum shear stress and torsional deflection that would be placed on the cylindrical shaft.

The shaft must transmit 20 horsepower while spinning at 800 rotations per minute. The shaft must be 4 feet long. Based on these requirements, the team calculates that the shaft must transmit 1576 pound-inches of torque.

The team uses 30,000,000 pounds per square inch for the shaft steel’s elastic modulus and 0.3 for the steel’s Poisson ratio. Based on these values, the team estimates the shear modulus of the shaft’s steel to be 11,500,000 pounds per square inch.

The team then uses the shear modulus to estimate the torsional deflection. The team finds that the shaft would deflect 0.2115 radians, or 12.1 degrees.

The team calculates the polar moment of inertia of the commercially available shaft to be 0.0311 inches quad. The team then calculates that using the commercially available shaft to transmit the required power to the mower would place a maximum shear stress of 18,999 pounds per square inch on the shaft.

Before beginning their hand analysis, the team members had agreed that the maximum allowable shear stress in the shaft was 50,000 pounds per square inch. Because the maximum shear stress in the shaft would be 18,999 pounds per square inch for this
application, the shaft would provide a substantial margin of safety, should the team decide to use it.

Example #4

A mechanical engineering design team has been asked to design a power-operated ramming mechanism for use in a pharmaceutical manufacturing facility. Inside of the cylinder, ahead of the ram, will be a measured quantity of a topical anti-inflammatory medication in paste form. The ram will be used to fill a packaging tube with the predetermined amount of anti-inflammatory paste.

The ram will be connected to the power-operated mechanism. Compressed air at 206 pounds per square inch, plus or minus 6 pounds per square inch, and 240-volt electrical power are available to operate the ram mechanism. The mechanical engineering design team members decide to perform a hand analysis of the feasibility of using compressed air for their ramming mechanism.

Allowing high-pressure air to push directly against the ram might force contaminants through the clearance between the ram and the inner cylinder wall, thereby contaminating the anti-inflammatory medication ahead of the ram. For this reason, the design team wants to use a piston mechanism that lies alongside of the ramming cylinder and connects to the ram.

By necessity of the application, the rod that connects the piston to the ram would have to be constructed of stainless steel. Information provided by the company states that in order to fill the packaging tube in the required time, the ram requires 120 lbf to begin moving, 93 lbf to move at mid-stroke, 108 lbf by the end of the stroke, and 32 lbf for the return stroke. The company’s information also states that the ram’s fill stroke is 2.0 inches long.
The mechanical engineering design team begins the hand analysis by assuming the worst case for each engineering parameter in the problem. The pressure of the compressed air is assumed by the team to be 200 pounds per square inch. The team then assumes the force to drive the ram is a constant 120 lbf. By assuming the force to drive the ram is a constant value, the team simplifies its calculations and thus saves time in this early analysis. The team calculates the diameter of the piston that would provide the required force to be 0.874 inches.

However, the team realizes that the ram must be returned to its starting position before it can begin the next filling cycle. The team members consider two commonly employed methods of providing power for a return stroke: a double-acting air cylinder and a coil return spring. After researching the costs of double-action cylinders and their necessary control valves, the team determines that a spring-powered return stroke would be more economical and reliable.

The team concludes that the return spring could be installed pre-compressed to maintain more than the 32 lbf needed to power the return stroke. The team also concludes that the diameter of the piston could be slightly increased to both power the fill stroke and compress the return spring.

If the return spring were to have a spring constant, k, of 50 pounds per inch, it could be pre-compressed 1.0 inch. This would mean that the piston would need to provide an additional 150 lbf at the end of the fill stroke. Combined with the 120 lbf to power the ram during the fill stroke, the piston would have to exert 270 lbf during the fill stroke. Hand analysis by the design team determines that the piston could provide this force if it were to have a diameter of 1.311 inches. (Later detailed analysis would probably result in slightly different engineering values.)
Based on the hand analysis, the mechanical engineering design team concludes that an air-operated ramming mechanism for use in the pharmaceutical manufacturing facility is feasible.

5.2 - How to Gain the Most from the Steps

The key design steps listed below have been numbered and generally should be followed sequentially. However, design is an iterative process, with embedded step “loops” throughout the process. These loops occur when engineers change the design and must return to the design objectives to determine whether the changed design is still compatible with them.

The design process can be metaphorically described as a sequential process of placing data inputs into function boxes. Key principles, an understanding of how to design for manufacturing, and safety principles are the data inputs, placed sequentially into function boxes labeled problem definition, “paper” design, prototyping, and testing.

5.3 - Key Steps

1) Define the problem with constraints.

2) Evaluate designs of existing products.

3) Set realistic design objectives.

4) Formulate initial designs; they only need to solve the problem.

5) Look for flaws in your team’s design.

6) Incorporate improvements to address your design’s flaws.

7) Look for ways to simplify the product’s design or manufacture.

8) Incorporate these simplifications.

9) Continue improving your design in an iterative fashion.
Step 1: Define the problem with constraints

How it is applied: To understand the market need

Why:

- Helps engineers understand why a new product is needed.
- Helps engineers limit the design task.
- Helps engineers avoid confusion and wasted design efforts.

The first step in designing is to define the problem with constraints. One of the better ways to define the problem is to analyze market survey data about the type of product that the engineer seeks to design. Designing mechanical engineers should note the advantages and disadvantages of existing products, as reported by consumers surveyed. The engineers should then synthesize the information learned from the market survey so as to define the problem, with constraints, in one sentence.

The opinions of consumers of existing products will tell engineers why a new product is needed. The process of defining the problem with constraints exposes the designing mechanical engineers to consumers’ ideas of the disadvantages and failings of existing products. While engineers might view the Orange brand hand tool with 10 features and 17 parts as superior to the Lime brand hand tool with only three features and eight parts, consumers may view the products very differently. Consumers may consider the Orange hand tool confusing to use or too complicated to reassemble after cleaning. For these reasons, designing mechanical engineers would be wise to define the problem, with constraints, based on the data obtained from the market survey rather than on their opinions or the opinions of other engineers.
The inclusion of constraints narrows the scope of the design work. A common constraint would be cost. In this instance, the designing engineers would be asked to design the product but with a cost not to exceed some predetermined amount.

Defining the problem with constraints also sets a design process timetable. Without a clear definition of the problem and the attendant constraints for guidance, designing mechanical engineers could spend years constantly refining a design. After some predetermined length of time has been spent on the design, economic viability becomes a factor. No investment can sustain an endless pursuit of perfection. Eventually, the design should be either moved toward production or rejected.

Step 2: Evaluate designs of existing products

How it is applied: Learning the strengths and weaknesses of existing products

Why:

- Allows engineers to determine the advantages of existing products.
- Allows engineers to determine the disadvantages of existing products.
- Helps engineers select design concepts.

Having defined the problem, the designing mechanical engineers are better able to evaluate the designs of existing products. Although this is an informative and even fun step, it may require extended thought. The engineers might not immediately recognize all of the advantages and disadvantages of an existing product. In some instances, advantages and disadvantages may only become apparent after the engineers gain experience by using the product. If economically practical, engineers should obtain samples of existing products for experimentation.
Suppose that the mechanical engineers seek to evaluate the designs of existing swim fins. The engineers should request that their employer or sponsor purchase pairs of the most popular swim fins. Having obtained the swim fins, the engineers should arrange for the testing of the fins under both controlled conditions and conditions that represent realistic use by consumers. The laboratory-type setting can best provide data related to efficiency and other measurable concerns. Realistic-use conditions can help the engineers understand what consumers have tried to express in their responses to market surveys.

The combination of objective engineering data and experience with existing products will provide designing mechanical engineers with the knowledge needed to develop fine products. With this knowledge, mechanical engineers are better able to design.

**Step 3: Set realistic design objectives**

How it is applied: Developing design objectives

**Why:**

- Open-ended design pursuits can be too lengthy.
- Avoids the “one tool does it all” syndrome.
- Helps maintain a reasonable product cost.

In a free market, the product that will succeed is the one that consumers believe better addresses their needs or wants. The product must satisfy consumers’ requirements for performance, personal appeal, and cost. This means the designing mechanical engineer must balance product features with a predetermined cost limit. Having studied the designs of existing products, the engineer should next assess the practical limits of technology and economics. This helps the mechanical engineering design team create a viable design in a reasonable time.
Many well-intentioned designs fall victim to what might be called the “one tool does it all” syndrome. This occurs when the design is tasked with meeting too many goals. Inevitably, qualities that are desirable for achieving one goal begin to conflict with those of another goal. The result is a compromised product that achieves none of the goals in a satisfactory manner. Golfers carry different sizes and shapes of clubs, including drivers, irons, wedges, and putters. Carpenters carry an assortment of tools, such as hammers, chisels, saws, and screwdrivers.

The engineers must now set realistic design objectives. Understanding the features that existing products have offered and the costs of those products allows the engineers to set the design objectives. At least one of the design objectives should establish the product’s intended cost. If someone is selling a car for ten cents and you only have nine cents, no matter how good the deal may be, you can’t afford the car.

Suppose the mechanical engineering design team has been asked to design a hand-operated can opener. The engineers have evaluated existing hand-operated can openers and found them to be uncomfortable to use, a complaint also uncovered by market research. The typical cost of existing hand-operated can openers was found to be $4.89 in grocery stores. Market research also revealed that 80 percent of customers surveyed would be willing to pay $6.46 for a hand-operated can opener that was more comfortable to use. Based on this information, the mechanical engineers might state the design objectives as: “Design a hand-operated can opener to be sold for $6.46 that consumers would purchase for its comfort and ease of use.”
Step 4: Formulate initial designs (they only need to solve the problem)

How it is applied: Giving the engineers a starting point

Why:

- Every journey begins with a single step.
- The initial designs will spur creative thinking.
- Designing products is an iterative process.

Having set realistic design objectives, the mechanical engineers can now formulate initial designs. A highly effective way to do this is for each designing engineer to formulate his or her own initial design. The engineers should not worry about whether the designs they create at this stage are flawed. These are only the first renditions of the product’s design. The final design will almost certainly incorporate features from different designs. Just as every journey begins with a single step, the first designs simply give the engineers a starting point.

The initial designs will help the designing mechanical engineers to start visualizing the future product and will spur their creative thinking about facets of the product, such as tolerances, methods of assembly, materials selection, or manufacturing methods. Soon, features from different designs, as well as new features, will meld into a single design. After the single team design has been formulated, it will be refined multiple times in an iterative process.

Some of the most successful designers have drawn their initial designs in cartoonish fashion. The immensely successful G-Shock wristwatch began this way. The drawings and initial design sketches by Mr. Nikaido, the designer of the Casio G-Shock wristwatch, were remarkably cartoon-like in appearance. Some of the sketches were drawn to assist in setting
the wristwatch’s design goals. For more information, the reader can visit http://world.casio.com/asia/wat/g_shock/his.html on the Internet.

**Step 5: Look for flaws in your team’s design**

How it is applied: Making an unbiased appraisal of the design

Why:

- Denying flaws will not correct them.
- The marketplace will find product flaws.
- It gives the engineer needed information.

In order to produce the best possible design, the designing mechanical engineers must set aside personal pride and cast an objective eye upon their design. The engineers must now look at their team’s design for the purpose of finding flaws. They should ask themselves questions such as, “Will airborne soil interfere with this component’s motion?” or “Will this component be vulnerable to fatigue failure?”

Denying flaws will not correct them. Some flaws will become evident in the prototyping phase. Later, as the product is used, consumers will discover any remaining design flaws. Denying flaws will lead to product failures and may alienate consumers, leading to rejection of the product in the marketplace.

Finding flaws early in the design of a product will give the engineers information needed to improve their design. It also gives them information they can use to make decisions about options that will arise in later design phases.
Step 6: Incorporate improvements to address flaws in your team’s design

How it is applied: Improving the design

Why:

- A product’s reputation is set early after its introduction.
- Products with bad reputations seldom recover in the marketplace.
- Manufacturers do not want to be associated with flawed designs.

By incorporating corrections to the flaws in the design, the engineers can improve the design’s likelihood of being produced and improve the resulting product’s chance of success in the marketplace. While every product has imperfections, design flaws constitute a type of imperfection that engineers should always avoid or eliminate. Design flaws often cause products to fail in a dangerous way. It is incumbent on the designing mechanical engineers to always correct known design flaws before the product reaches consumers.

A product’s reputation begins the moment that it becomes available to consumers. Historically, products that have been introduced with significant flaws that were later corrected have seldom recovered from the damage to their reputations. Electrical ballasts used to operate fluorescent lights are a case in point. Some electrical ballasts were thought to have caused fires in the 1960s. Corrective features were incorporated in the design and production of subsequent electrical ballasts, virtually eliminating the possibility that they could cause fires. Nonetheless, many people still believe that electrical ballasts frequently cause fires.

Manufacturers do not want to be associated with flawed designs. If a product develops a bad reputation, the manufacturer’s image may also suffer. Reputable manufacturers strive to build and maintain consumer trust in the products they make.
Step 7: Look for ways to simplify your product’s design or manufacture

How it is applied: Improving manufacturability

Why:

- Using fewer parts reduces manufacturing costs.
- Parts that are easier to make reduce manufacturing costs.
- Simple designs are more readily accepted.

Simplifying a design takes two forms: reducing the complexity of the parts and reducing the complexity of the manufacture of the parts. Both ways of simplifying are valuable.

Mechanical engineers should look for opportunities to simplify their design. The engineer should examine the team’s design and consider questions like, “Can we use two parts here instead of three?” or “Could we substitute a stamped part for this forging?”

Simpler designs have other advantages. When the engineers present their design to manufacturing personnel, the engineers will have an easier time explaining the details of the design. If manufacturing personnel are presented with a simple design, they will recognize the lower manufacturing cost as compared to a complex design. Thus, simple designs are more readily accepted.

Step 8: Incorporate these simplifications

How it is applied: Reducing the cost of the final product

Why:

- Having to make and assemble fewer parts reduces the product’s cost.
- Parts that are cheaper to make reduce the product’s cost.
- Manufacturing will require less of a tooling investment.
If a product can be made with fewer parts, then its manufacturing and parts inventory costs can be reduced. Parts that are easier to make reduce labor costs. In some instances, parts that are easier to make can be produced with less expensive processes.

The designing engineers can simplify the design by looking for ways to align parts quickly and efficiently during assembly. For example, the engineers might select fastening methods that are easily used with jigs or other preset alignment fixtures. This approach allows for precise assembly with little effort by manufacturing personnel. The engineers might opt to use welding instead of bolting the parts together. If the parts are precisely aligned in the fixture and will never need to be separated, welding can offer a fast and economical method of assembly. These simplifications will reduce the time to assemble the parts, provide for consistent positioning of the parts, and reduce the number of parts used by eliminating the bolts.

**Step 9: Continue improving your team’s design in an iterative fashion**

How it is applied: Increasing the likelihood of the product succeeding in the marketplace

Why:

- Allows the final design to result in a better product.
- The more refined the design, the greater the chance of manufacture.
- The more refined the design, the greater the chance of market acceptance.

Having made improvements to the design of the product, the mechanical engineers can now return to the design objectives. Ask yourself: Will the team’s design achieve the design objectives? Do any of the design team’s engineers detect design flaws? If flaws are detected, correct them. Can the design or its manufacture be further simplified? If possible, continue to simplify the design.
Maintaining your team’s schedule is important. If there are no obvious design flaws and no further simplifications, then your team can move on to the next stage, prototyping.
Chapter 6 - Preparing to Prototype

6.0 - Introduction

During the capstone senior mechanical engineering design course, the most demanding phase is the prototyping phase. Inevitably, successful completion of the prototyping phase requires an inordinate amount of time from the mechanical engineering team members. A team that has invested enough creativity and analysis in the design phase will have a much easier prototyping phase than a team that has hurriedly or carelessly thrown a design together.

The purpose of this chapter is to give mechanical engineering design teams an understanding of what to expect during the prototype construction phase and ways to maximize their results. This chapter includes information on ordering from vendors and provides insight on troubleshooting and refining your prototype. Useful tips on various prototyping topics have been placed at relevant locations throughout this chapter.

6.1 - Prototyping Steps

The prototyping phase can be divided into distinct steps. The first step is the organization step. This step is where the mechanical engineering design team conducts an inventory of the departmental supplies available for their use. Equally important in this step is for the mechanical engineering design team to designate the order in which parts are assembled and to determine which team members will assemble them. Designating the assembly sequence permits the team to make the most efficient use of its time while preventing the necessity of later disassembling the prototype to insert a part.
The second step is the procurement step. In this step, the mechanical engineering design team procures supplies and places orders with vendors. The team must plan ahead when conducting business with vendors, as this is a potential source of problems.

The third step is actually building the prototype. Many mechanical engineering design teams encounter minor problems during this step. These minor problems may include mismatched parts due to cumulative errors or fabrication work that takes more time than the team had anticipated. These problems may be frustrating, but they are usually easy to overcome.

6.2 - Vendors

The first place where mechanical engineering design teams normally seek materials for their prototypes are resources established for the capstone senior design course by the mechanical engineering department. When the team needs materials that the department cannot obtain, the team may decide to procure the needed materials from commercial sources, often simply referred to as vendors.

Before placing an order with a vendor, the team should attempt to learn about the vendor’s reputation for correctly fulfilling orders. There are two ways to learn of the vendor’s reputation: word of mouth and vendor-review websites. The easiest way to learn about a vendor is to ask departmental technicians who have ordered from the vendor in the past. Some departmental technicians place large quantities of orders and may be able to recommend specific vendors who can best address the team’s needs. Faculty members who have taught the capstone senior design course may also know of vendors to either consider or avoid, based on student feedback from previous semesters.
Another way to learn about a vendor’s reputation is to search review websites. If the team’s members have difficulty locating review websites, they can use a search engine to do a search on the vendor’s name plus the word “review.”

Whenever a mechanical engineering design team places an order with a vendor, the team should retain some form of documentation of the order. The team should obtain an order confirmation number, a guaranteed delivery date, and a tracking number for each shipment of items. Reputable vendors normally issue a confirmation number for each order. The guaranteed delivery date is extremely important. If a vendor cannot specify the latest date on which a team’s order will arrive, then the team should seek another vendor. Because the order will normally be delivered by a commercial package delivery service, the tracking number allows the order to be located in transit. Many delivery services maintain websites that allow recipients to track their order as it is being shipped. This allows the team to better predict the arrival date and time of key components. If the order does not arrive on time or if the order is damaged, contact the vendor immediately.

Vendors may not have a needed component in stock and may thus need to order it from a wholesaler or direct from the factory. However, the vendor may not be able to find the part in time for the mechanical engineering design team to use it. Even if the part is at another location owned by the vendor, it may take several days for the part to arrive. Also, the vendor’s employee who sells you the product that your design team desperately needs may not appreciate the time constraints under which your team is operating. Unless someone has taken the course you are taking, they may not be able to understand the time pressures placed on team members.
There are techniques you can use to address the problem of potentially delayed receipt of needed parts. First, you can select the fastest shipping option. Instead of three-to-five-day shipping, the team can select two-day shipping or even next-day-air shipping. Faster shipping methods cost more, but the added expense may save the team from failing to meet a deadline. But do not depend on faster shipping to save your team from poor planning; use it as a time-saving aid. If your team does need faster shipping, think of it as an investment toward the team members’ course grades.

The second approach the design team should use is to explain to the vendor’s employee about the team’s deadline. Ask the employee for his or her assistance. Employees of vendors often know of ways to hasten a delivery. Always thank the employee for his or her help.

The third option should only be used if there is no other alternative: Cancel the order and substitute another product. Suppose that the mechanical engineering design team learns that the prototype’s chain-drive system they have ordered will be delayed and cannot be delivered until after the course has ended. The design team can cancel the order and either seek a comparable product or substitute another drive system.

When scheduling the assembly sequence, try to plan for vendor delivery delays by incorporating time cushions into the schedule; that is, simply allocate extra time for a specific task. For example, suppose that a mechanical engineering design team is awaiting a Friday part delivery from a vendor. The team had decided to schedule two of the following days—Monday, Thursday, or Saturday—to assemble a section of their prototype with the part. Which days should the team allocate for the assembly?
The team should allocate all three days to assemble the section. Most delivery services do not operate to the public on Saturdays. If the Friday delivery is missed, which does happen sometimes in the real world, the next delivery attempt will likely be Monday. When the package arrives, one team member will almost certainly have to sign for it. Because the delivery service may arrive with the package late in the day, the team will need the next two available days to assemble the section with the part. By incorporating the time cushion, the team is better able to remain on schedule.

6.3 - Using Time Efficiently

A strategy for making the best use of the prototype-building process is to assign work to team members based on their strengths. The best welder on the team should weld components that are to be welded; the best machinist should mill parts that require milling, and so forth.

Some mechanical engineering design teams may choose to have all team members meet for brief periods to construct the prototype. Other teams may choose to have team members work in shifts of two to three members. Although both approaches may have merit, the semester demands of most mechanical engineering design team members will preclude many whole-team meetings. Most teams will have no choice but to meet frequently in smaller groups. This is where the assembly sequence planning performed in step one helps the team efficiently use its time. Although the design team’s leader will not be able to be present during all assembly work, the team’s assembly sequence plan will keep work moving forward while minimizing wasted efforts.
6.4 - Budget Realities

In addition to time, the major constraint on the mechanical engineering design team is budget. The budget allocated to the capstone senior mechanical engineering design course for constructing prototypes usually comprises a combination of taxpayer money, donations to the school, and corporate funding for the project.

Despite the importance of the capstone senior mechanical engineering design course, it must compete against other courses, laboratory needs, and assorted departmental expenditures. Like a family planning its household budget, the mechanical engineering design team should keep some of its budget in reserve to cover any unexpected prototyping expenses.

Team members may be surprised at how quickly the budget is spent. This is another area where a well-conceived design and prior planning can help. For example, suppose that a mechanical engineering design team discovers a design flaw in the prototype that must be corrected by building a new section of the prototype. The team cannot recover the cost of the discarded portion of their prototype. It is money that was wasted.
Chapter 7 - Building the Prototype

7.0 - Introduction

The purpose of this chapter is to give mechanical engineering design teams advice on ways to construct their prototypes. This chapter discusses fabrication and assembly methods as they relate to the prototype and provides information on the substitution of key prototype features, should substitution be necessary or desirable. Useful tips about building the prototype have also been included in this chapter.

7.1 - Fastening Methods

- Welding
- Bolting
- Riveting
- Adhesive bonding
- Magnetic bonding

The fastening methods selected by the mechanical engineering team can strongly affect the amount of time required to assemble the prototype. During the building of their prototype, the team may wish to substitute a different method of fastening to assemble their prototype.

Welding

Suppose the mechanical engineering design team finds that they have insufficient time to drill and bolt a steel assembly. In this situation, the team may find that welding would be faster. With several team members holding the assembly in its proper alignment, the team’s welder could make several small tack welds to affix the assembly and free the
assisting team members from holding it. The team’s welder could then work alone to weld
the structural beads.

Welding is a fast and versatile method of assembling steel parts. Though some other
metals can be welded, steel is the metal best suited to welding. The precision of welding can
be greatly enhanced through the use of jigs. A jig is a fixture that holds two or more
components in their proper locations for assembly. When the components are placed in the
jig, it is a simple matter to weld the junction.

If the mechanical engineering design team selects a fastening method that requires
drilling holes in steel, titanium-nitride-coated brad-point drill bits offer several advantages
that can offset their cost. The brad point is sharper and less likely to deviate from its proper
position as it starts the hole. The titanium nitride coating allows more drilling to be
performed before the bit must be replaced or re-sharpened. In this engineer’s experience,
titanium-nitride-coated brad-point drill bits save time while drilling and locate the holes more
precisely when used with a hand-operated drill.

**Bolting**

Bolting is a proven method of fastening. However, bolting requires that some
measure be taken to prevent the bolt, or nut if present, from loosening. If the bolt is screwed
into a threaded hole, a lock washer or thread-locking compound must be used and the correct
torque applied. If the bolt passes through the hole and receives a nut on the other side to
secure the bolt, then a lock washer must be placed on the bolt before the nut or thread-
locking compound is used.
Riveting

Lightweight metal or plastic components can be attached to a frame or each other with pop rivets. Like bolts, rivets require that holes be drilled to accept them. Rivets offer advantages over bolts for attaching lightweight components. These include, but are not limited to, exteriors that are more nearly flush to the surface on one side, a rigid and lightweight fastener that cannot loosen, and a faster assembly time.

Adhesive bonding

The use of an adhesive bond is another method of attaching lightweight metal or plastic components to a frame or each other. Epoxies and cyanoacrylate glues are popular adhesives.

Magnetic bonding

Access covers and other parts that may need frequent removal, and are not load-bearing, can be attached to the prototype’s framework by the use of magnets. Magnets allow quick and easy removal and replacement.

7.2 – Bearings

- Ball bearings and roller bearings
- Hydrodynamic bearings
- Plastic-insert bearings

Most bearings that are relevant to a mechanical engineering design team prototyping a machine will fall into one of three categories: anti-friction, hydrodynamic, or plastic insert.

Ball bearings and roller bearings

Anti-friction bearings are more commonly called ball bearings or roller bearings, depending on the shape of the rolling components. These are the traditional bearings used on
vehicle axles, skateboards, and garage door assemblies. At their simplest, a ball bearing or roller bearing has an inner surface and an outer surface that move relative to each other and are separated by the rolling components. The inner surface is called the inner raceway, and the outer surface is called the outer raceway.

Some ball and roller bearings can be selected will sustain an axial load in addition to their normal radial load. These variations of ball and roller bearings are known as thrust bearings.

In order to function smoothly, ball and roller type bearings are best kept sealed from soil and airborne particles. If soil or airborne particles enter ball or roller bearings, their resistance to rolling will increase, possibly causing the bearings to cease functioning.

**Hydrodynamic bearings**

Hydrodynamic bearings are the normally chosen bearing for many applications within internal combustion engines. Hydrodynamic bearings consist of two surfaces with a lubricating film between them. The lubricating film enables the two surfaces to rotate with respect to each other without damage. Hydrodynamic bearings usually require a continuous supply of lubricant flowing through them. This is typically achieved by means of a recirculating pump and a lubricant reservoir.

Due to their tight clearances, hydrodynamic bearings must be protected from the ingress of soil or debris. Under normal operation, hydrodynamic bearings sustain their greatest wear as the two surfaces begin their relative movement.

**Plastic-insert bearings**

Plastic-insert bearings are popular in applications such as toys, kitchen utensils, and sporting goods. Plastic-insert bearings are shaped plastic parts, with one or more holes, that
are usually press-fitted into their desired locations. A rotating or translating part is then inserted into the appropriate hole in the plastic insert. The friction between the chosen plastic insert and the movable part should be low enough to allow the part to move freely.

A principle cause of plastic bearing failure is heat generated by friction. The normally used parameter to evaluate the potential for plastic bearing failure due to friction-induced heat is the product of the surface velocity of the race and the pressure normal to the race surface. This parameter is often referred to as the pressure-velocity (PV) value. The maximum sustainable PV values of some plastic bearings can be increased fivefold by supplying them with continuous lubrication.

Prototype machines do not always require the same bearings as production machines. In an effort to save either time or money, the mechanical engineering design team may wish to substitute a simpler or less expensive bearing for the originally intended bearing.

In order to prevent the binding of moving parts, the team may want to substitute a bearing that is more tolerant of misalignments. Even if the misalignment causes increased bearing wear, the reliability of the prototype can be greatly enhanced. The reduction of bearing life is of less concern on a prototype, as it may only need to function several dozen times.

The mechanical engineering design team might be able to reduce the prototype’s cost by substituting a bearing that requires frequent lubrication in place of a low-maintenance bearing that would be used in production machines. Since the prototype is operated for only a few cycles at a time, the need for frequent minor maintenance poses few problems.

7.3 - Drives

- Belt drives
Drives are mechanisms that transmit power from one location to another. Projects selected for the capstone senior mechanical engineering design course usually require one or more drive mechanisms to actuate the prototype’s features. Among the more common drives available to the mechanical engineering design team are belt drive, gear drive, shaft drive, hydraulic and pneumatic drives, chain drive, and lead screw drive.

**Belt drives**

Belt drives connect two shafts by means of a fabric-reinforced rubber belt. The most common belt drive, the V-belt, makes use of at least two wheels called pulleys, each with a “V” shaped groove on its outer edge. Each wheel is mounted at the end of a shaft. The shafts are placed parallel to each other, and the pulleys are positioned so as to be co-planar. The belt is seated in the pulley grooves in tension, so as to transmit power from one shaft to the other.
Fig. 15. Belt drive. This belt drive transmits power to multiple vehicle features.

Why might a mechanical engineering design team select a belt drive to transmit power? There are several reasons, such as the fact that belt drives are simple and inexpensive. Belt drives are somewhat tolerant of pulley misalignments. Belt drives are also lightweight and require only minimal lubrication.

However, belt drives can also create design obstacles for the mechanical engineering design team. Because belt drives are mounted in tension, the use of a belt may require the incorporation of an idler pulley. An idler pulley is a pulley that simply presses against the belt to maintain a specified tension on the belt. If an idler pulley must be used, it will add
weight, cost, and complexity to the prototype. Because the belt and pulleys create dangerous pinch points, guarding is necessary to prevent accidents, even on the prototype.³

Some slippage may occur between the belt and a pulley, making the belt drive a poor choice for precisely coordinating the angular displacements of shafts. An exception to this deficiency is the toothed belt drive. However, toothed belt drives are expensive and unnecessarily complex for prototype use.

Belt drives have an unusual advantage: water resistance. Because the common belt drive uses a rubber belt, there are no chains, shafts, or gears to rust or corrode. If necessary, each pulley used in a common belt drive can be made from a water-resistant material. Thus, a water-resistant drive can be inexpensively obtained with the belt drive.

**Gear drives**

Gear drives connect two shafts by an array of two or more gears. The teeth of one gear mesh with the teeth of an adjacent gear. When one gear rotates, the adjacent gear is forced to rotate. If the shafts are mounted close to each other, a gear drive may be the easiest way to transmit power from one shaft to the other.
As the distance between the two shafts is increased, the use of a gear drive becomes less practical. Long spans between shafts mandate the use of either larger gears or more gears. Increasing the size or number of gears rapidly increases the cost and complexity of the prototype. Gears need lubrication and must be held in alignment. Where two gears begin to mesh, a pinch point is created that requires the use of guarding.4

**Shaft drives**5

Shaft drives transmit power from one shaft to another shaft that is coaxial or nearly coaxial. The use of an articulated joint on each end of the shaft drive permits the driven shaft to be slightly non-coaxial with respect to the driving shaft. Shaft drives are commonly employed in automobiles, trucks, buses, watercraft, and lawn trimmers.
Fig. 17. Shaft drive. Automobiles and trucks use shafts to transfer power to their wheels.

Despite their obvious utility, shaft drives may not be well-suited to use by a mechanical engineering design team to build a prototype machine. Even the vibration of a small AC electric motor can be enough to cause one of the shafts to no longer be coaxial with another shaft in the drive train. This misalignment eventually can lead to binding, a bearing failure, or a fatigue failure of one of the shafts. To avoid these problems, shaft drives usually need a joint with some articulation on each end to connect the driven and driving shafts. The addition of articulated joints increases the weight and cost of the shaft drive.

With the exception of fully enclosed shafts, the use of a flexible shaft cannot safely obviate the use of articulated joints. Some popular power tools use a fully enclosed flexible shaft to connect the motor shaft with the chuck shaft, but the enclosure is what makes this
practical. If the shaft is flexible enough to deform with either the driving or driven shafts, it will probably also be able to inadvertently deform in a manner called “whip.” When whip occurs, it is dangerous and leads to shaft failure.

Another hazard of shaft drives is static electricity. A spinning shaft will acquire a static charge. If human hair comes in close proximity to a rapidly spinning shaft, the static charge is often sufficient to attract the hair. When drawn to the shaft by the static charge, long hair can quickly wrap around the spinning shaft and scalp the victim.\(^6\)

Another concern for a mechanical engineering design team considering the use of a shaft drive is whether the shaft should be solid or hollow. If a hollow shaft has the same weight as a solid shaft but a larger diameter, the hollow shaft will offer less deflection. In smaller diameters, the use of a hollow shaft may increase the cost.

Hydraulic and pneumatic drives\(^7\)

Hydraulic and pneumatic drives operate on the same principle. Both drives apply a pressure to a fluid, which in turn presses against a piston. The pressure of the fluid acts on the cross-sectional area of the piston, resulting in a force that moves the piston. Hydraulic drives use a liquid as the operating fluid, almost always an oil. Pneumatic drives use a gas as the operating fluid, almost always air.

Hydraulic and pneumatic drives are both popular for actuating machine features. However, teams in the capstone mechanical engineering senior design course should remember that hydraulic and pneumatic drives can be costly and can add considerable weight to a prototype. Both drives are vulnerable to leaks, and neither will fail safe.

Aside from leaks, the greatest weakness of hydraulic and pneumatic drives is their vulnerability to debris in their enclosed systems. If debris reaches a valve, it can compromise
the valve’s function. This can result in a failure of the hydraulic or pneumatic drive system to sustain a load, possibly causing death or serious bodily harm. This is why people should never place any body part beneath a hydraulically or pneumatically suspended load.

**Chain drives**

Chain drives connect two shafts by means of a linked chain in a manner similar to belt drives. A wheel called a sprocket, with teeth on its outer edge, is mounted on each shaft. As in the belt drive, the shafts connected by a chain drive are placed parallel to each other and the sprockets are positioned so as to be co-planar. As the sprockets are rotated, each sprocket tooth protrudes into a link of the chain, transmitting power across the bearing surfaces of the sprocket teeth and chain links.
Fig. 18. Chain drive. The chain drives of ordinary bicycles provide transportation and recreation.

Chain drives can be economically employed to coordinate the angular displacements of two or more shafts. This feature makes chain drives a popular choice for connecting crankshafts to camshafts in reciprocating piston engines.

The weakest portion of a chain drive is often the chain itself. Another problem area for chain drives is misalignment of the sprockets. When the sprockets are not properly aligned, the chain may disengage from one of the sprockets.

Chain drives create safety hazards, too. Unless the drive is enclosed, the chain and sprockets create dangerous pinch points where the sprocket teeth begin to mesh with the chain links. Guarding is necessary to prevent accidents, specifically the loss of fingers.⁹
Lead-screw drives\textsuperscript{10}

Lead screws convert rotational displacement of a driving shaft into the translation of a nut, or threaded collar. Lead screws are long, threaded shafts. The threaded collar fits over the lead screw, and as the lead screw turns, the collar is moved along the lead screw by its rotation.

Fig. 19. Lead-screw drive. The lead screw drive on this lathe longitudinally traverses the tool.

Design teams might find lead-screw drives useful because they are precise, efficient, and fail-safe. The precision that can be obtained with a lead-screw drive makes it a popular drive choice for applications such as scanning electron microscopy specimen positioning and microelectromechanical systems manufacturing.
At first glance, the efficiency of a lead screw may not be apparent, but it is easy to demonstrate through an example. Suppose that a prototype features an arm that hangs near-vertically when not in use and extends outward at 90 degrees when it is in use. If the arm is extended by a hydraulic, belt, gear, or chain drive, either power must be continuously applied to extend the arm or a locking device must be used. If the arm is extended by a lead-screw drive, the geometry of the lead-screw threads will allow the arm to remain extended with zero power consumption.

The same properties of the lead-screw drive that allow it to sustain a load with zero power consumption also serve as a safety feature. If the arm in the example above is extended by a hydraulic, belt, gear, or chain drive, and a power failure occurs, the feature will fail dangerously in the absence of a locking device. Conversely, if the arm is extended by a lead-screw drive, the geometry of the lead screw threads will allow the arm to remain extended in spite of a power failure. The safety available with lead screw drives can prevent a power failure from causing death or serious bodily harm to someone attending the machine.

Lead-screw drives can be heavier and more compact than some other drive systems. Lead-screw drives require thrust bearings, and they are usually more expensive than some other drives. Nonetheless, their features can justify the extra expense.

7.4 - Substituting Drives

- substituting for belt drives
- substituting for gear drives
- substituting for shaft drives
- substituting for hydraulic and pneumatic drives
- substituting for chain drives
Sometimes a mechanical engineering design team discovers while building the prototype that the intended drive system cannot fulfill the design requirements. When this happens, the team may wish to substitute another drive system for the original drive system.

**Substitute for belt drives**

In general, chain drives can be easily substituted for belt drives. The pulleys can be exchanged for sprockets at the same location on the shafts. In fact, the chain will be simpler to install than would the belt.

It might be possible for a gear drive to be substituted for a belt drive. This is more practical if the shafts are close to each other. However, if the shafts are to rotate in the same direction, an odd number of gears will be needed. This means that for a prototype employing a two-shaft belt drive, the substitution of a gear drive would necessitate the installation of a third shaft.

**Substitute for gear drives**

Gear drives are frequently selected for their ability to accurately match the shafts’ rotational displacements and for their strength. The substitution of a gear drive with a chain drive would best replicate the role that was originally intended for the gear drive.

An option for a substitute for a gear drive would be a toothed-belt drive. Before a toothed-belt drive was substituted in place of a gear drive, the design team would need to calculate the tension necessary to eliminate any chance of slippage by the toothed belt.

**Substitute for shaft drives**

Substituting for a shaft drive may present greater obstacles. Shaft drives are often used over longer distances than other drives. Over a long span, a belt drive might not be able
to maintain enough tension to avoid slippage. Gear drives are impractical over long distances due to the weight, complexity, and cost they would incur.

Among the commonly used drive systems, the best substitution for a shaft drive would probably be a chain drive. Because the sprocket teeth protrude through the chain’s links, the chain drive can avoid slippage without undue tension. Electrically powered garage door openers use long chain drives.

Substituting for hydraulic and pneumatic drives

Among the commonly used drive systems, the best substitutes for hydraulic or pneumatic drives are probably lead-screw and chain drives. Because hydraulic and pneumatic drives are important as positioning drives, the slippage and resulting inaccuracy of belt drives makes them unsuitable as substitutes for hydraulic and pneumatic drives.

Substitute for chain drives

A classic example of substituting for chain drives can be seen on some motorcycles. Motorcycles have traditionally used chain drives to transmit power from the transmission to the rear wheel. Popular models of motorcycles have been produced that substitute either shaft drives or toothed-belt drives for chain drives.

While both shaft drives and toothed-belt drives are acceptable substitutes for chain drives, toothed-belt drives are usually more expensive than shaft drives. If some slippage is acceptable, then a standard-belt drive may be able to substitute for a chain drive. Washing machines are an example of a machine in which either chain drives or belt drives would work equally well to transmit power from the electric motor to the oscillating drum. Because common belt drives are cheaper, they are normally used in this application.
The toothed belt has replaced the traditional timing chain in many new vehicle engines. Some of the most popular vehicle manufacturers use the toothed belt. Toothed-belt drives are frequently quieter than chain drives and may be more economical.

**Substitute for lead-screw drives**

Although they do not fail safe, hydraulic or pneumatic drives would be the best choice of the commonly used drives to substitute for lead-screw drives. Both hydraulic and pneumatic drives are available with the strength of a motor-driven lead-screw drive system. Hydraulic drives can be fitted with valves that ostensibly let them fail safe, but these valves are not foolproof.

7.5 - **Actuators**

- Cables and pulleys
- Cams
- Gravity
- Trip levers
- Springs

Mechanical engineering design teams frequently must actuate a secondary prototype machine feature at a specific moment while a primary prototype machine feature is operating. A few of the commonly used actuators are cables and pulleys, cams, gravity, trip levers, and springs. Often, two or more actuators are used together to implement the feature.

**Cables and pulleys**

Cables and pulleys can be used to actuate a feature based on the motion of a component. One way to make use of the cable-and-pulley system is to mount the pulley on the moving part. One end of the cable is then affixed to the machine’s base. The cable is
passed over the pulley, and the other end of the cable is attached to the part that is to be actuated. As the pulley is moved, tension is applied to the cable, and this pulls the actuated part into the desired position.

Fig. 20. Cable-and-pulley actuator. This cable-and-pulley system powers a grandfather clock.

Two advantages of the cable-and-pulley system are that it can be economically configured and easily adjusted. By using multiple pulleys in various combinations, the strength of the actuation system its displacement can each be magnified at the expense of the other.

The disadvantages of the cable-and-pulley system include the requirements of lubrication and regular safety inspections. The pulley’s bearings, and any hinges in the actuation system, must be lubricated to prevent overloading the cable.
When a cable-and-pulley actuation system fails, it does not fail safe. The suspended component can fall like a guillotine, with potentially tragic consequences. A key point of regular safety inspections would involve the cable itself.

What is colloquially referred to as cable is, in fact, wire rope. Like the traditional manila rope, wire rope can fray and fail. The cable must be inspected to assure that it has not frayed or been crushed prior to operation.

Cams

A cam is a contoured wheel or surface that causes the variable displacement of an adjacent part called a follower. The intake and exhaust valves in reciprocating piston engines are usually actuated by cams. In archery, modern compound bows use cams to efficiently transfer energy to arrows. The air brakes used on large trucks normally feature a cam to extend the brake shoes.

Fig. 21. Cam actuator. This lever connects to the friction-lock cam, which rigidly holds the saw fence at the desired position.
Suppose that the design of a prototype machine requires that an arm be raised before extending. A cam might be fitted in the path of the arm to permit the arm to be raised the distance to the cam. Upon contact with the cam, the arm would be extended as it followed the cam’s contour.

The mechanical engineering design team considering the use of a cam should address the need for lubrication. If the cam follower is to slide along the surface, the design team will also want to determine if wear will be a factor.

**Gravity**

![Figure 22. Gravity actuator. Gravity is ever present.](image)

Perhaps the simplest method of actuation is gravity. If a feature of the prototype machine, or any item that it handles, must be either lowered or rotated, gravity may offer the
Gravity actuation is normally facilitated by assisting mechanisms. Trip levers and releases are two commonly used gravity-assisting mechanisms.

Trip Levers

Fig. 23. Trip lever. When the trip lever on this lawn sprinkler is activated, it reverses the direction of the sprinkler’s rotation.

Trip levers are protruding levers that facilitate change after the input of sufficient energy through relative motion, due to contacting another feature. A simple analogy of how trip levers work can be easily duplicated by the reader.
The reader should walk through a doorway while holding one arm straight out to the side, parallel to the ground. As the reader passes through the doorway, the reader’s arm contacts the door frame and turns the reader toward his or her arm. In like manner, the trip lever causes activation after contacting another feature that has relative motion.

Trip levers can also be used to release energy previously stored in a compressed spring or gas. The use of trip levers is limited only by the designer’s ingenuity.

**Springs**

![Spring actuator. Compressed by the user’s thumb, this spring powers the pen’s retraction.](image)

Springs are mechanical devices that store potential energy. The ability of a spring to store potential energy is a tremendous asset for mechanical engineers designing machines. A
spring can store mechanical potential energy during one operation that will be released in a later operation.

Many common products use springs to store potential energy for later motion. Mechanical wristwatches use springs to store the energy they need to operate. Wind-up toys also use springs to store the energy they need for motion. Air brakes use springs to retract the brake shoes after application. Some compressed-air-powered tools use springs to retract mechanical parts after the power stroke. Button-operated pens and mechanical pencils use springs for the return stroke after their buttons have been depressed. The most frequently encountered types of springs include but are not limited to leaf springs, coil springs, elastic (rubber, bungee) springs, and compressed-gas springs.

Leaf springs consist of a beam that stores energy through deflection perpendicular to the beam axis. Leaf springs are popular for many large-vehicle suspension applications. The diving boards present at some swimming pools are large, soft leaf springs.

Leaf springs are simple to construct, but they are limited in the deflection they allow. Traditional beam-deflection equations are based on small deflections and may not accurately predict leaf-spring behavior. The designing mechanical engineering team should confirm whether an intended leaf spring will be subjected to a large deflection. If the leaf spring will undergo a large deflection, then the engineering team should base its analysis on the large-deflection equations.

Coil springs are beams that have been wound about an axis. Coil springs can be designed to store mechanical potential energy either by compression or rarefaction. Coil springs may be further subdivided into those that store energy along their axis of winding and those that store energy perpendicular to their axis of winding. The spring used in a button-
operated pen is an example of a spring that stores energy along the axis about which it is wound. The mainspring of a mechanical watch is an example of a spring which stores energy perpendicular to the axis about which it is wound.

Elastic springs, also called rubber springs or bungee springs, are simply springs composed of materials that possess greater-than-normal elasticity. Examples of elastic springs include ordinary rubber bands, bungee cords, and solid rubber balls used by children as toys.

Compressed-gas springs consist of a gas that is enclosed by a cylinder and piston. When a force is applied to the piston (and thus against the gas), the piston is displaced and the gas is compressed, storing mechanical potential energy. Compressed-gas springs are frequently used to support automobile hoods, hatchbacks, and lift gates. Advantages of compressed-gas springs include their ability to be lightweight and the immunity of the gas to fatigue.

Springs can also be used to lessen the severity of an impact. Springs placed between two colliding parts can store energy during the impact and then release that energy, separating the two parts. This use of springs lessens the impact between the two colliding parts. Specifically, the peak accelerations are reduced as the springs extend the duration of the collision. Because the use of springs in this application reduces the peak accelerations, the likelihood of parts failure is also reduced.
Chapter 8 - Testing, Evaluating, and Refining the Prototype

8.0 - Introduction

With your prototype completed, it is only natural to feel a great sense of pride, but the mechanical engineering team members cannot rest on their laurels. Now is the time to test, evaluate, and, if necessary, improve the machine.

The purpose of this chapter is to give mechanical engineering design teams guidelines for testing, evaluating, and refining their prototypes. This chapter returns the mechanical engineering team to the original problem statement and helps the team objectively test its machine.

Tips on refining the prototype have been included to help the mechanical engineering team maximize the prototype. This chapter also provides insight into troubleshooting your prototype, focusing on how to locate the source of a problem. As in chapters 5 and 6, useful tips on various prototyping topics have been placed at relevant locations throughout this chapter.

Chapter 8 safety comments:

Designing engineers should embrace safety as more than just a design concept. When testing, evaluating, and refining their prototype, all members of the team should wear eye protection and stay clear of any moving parts.

Prototypes are experimental machines and are prone to sudden failure or propelling broken parts as missiles. If a team member rejects eye protection as too inconvenient or "stupid looking," remind him or her of the inconvenience of blindness or extensive medical treatment.

Sandals and loose clothing may be fine for many social occasions, but not for
prototype operation. Wear enclosed, protective shoes with non-skid soles. Chains and sprockets, belts and pulleys, and meshing gears create pinch points at their junctures that will grab loose clothing, pulling the hapless wearer into the machine. Every year this engineer is asked to analyze the circumstances surrounding such accidents. These accidents always cause serious bodily harm and are frequently fatal.

Keep long hair tied up. A better solution would be to maintain short hair. Machines can and do grab long hair by means of static electricity. Once the hair becomes entangled in the moving parts, the victim is quickly scalped.

If you like your fingers, hands, and arms, keep them away from moving parts. It only takes an instant of carelessness to cause a lifetime of suffering.

8.1 - Evaluating Your Prototype

- Objective testing and evaluation
  - Revisiting the problem statement
  - Design goals
  - Keeping score
  - What the numbers mean
  - Exchanging performance
- Subjective testing and evaluation
  - Refining the prototype
  - “Gut instinct”

Objective testing and evaluation

The first step is to establish an objective set of test criteria by which to evaluate the prototype. In the capstone mechanical engineering course, a problem statement was
established before the design process was even begun. The whole purpose of designing and building the machine was to answer the problem statement. Thus, the problem statement contains the first set of test criteria.

Because the capstone mechanical engineering course is competitive, with each team’s prototype judged against the other teams’ prototypes, the design goals naturally exceeded the requirements of the problem statement. Thus, the design goals constitute the next set of criteria.

At this point, the team members can separate the criteria into two groups: those that are mandatory and those that are desirable. Criteria derived from the problem statement are mandatory, and criteria derived from design goals that exceed the problem statement criteria are desirable. For example, suppose the problem statement specifies that the machine be able to lift a 130 kg garbage can to a height of 2.5 m in 20 seconds. The mandatory criteria are the ability to raise the 130 kg garbage can 2.5 m in 20 seconds. Now suppose that the team’s design goals for the machine specify that the machine be able to raise a 200 kg garbage can to a height of 2.8 m in 15 seconds. The desirable criteria are the ability to raise a 200 kg garbage can 2.8 m in 15 seconds.

An objective scoring system based on both the mandatory and desirable criteria is a helpful tool for the team to evaluate the prototype’s performance. Each criterion should be judged on a scale. For example, suppose the team wishes to use the scale of 0 to 10, with 0 being the worst performance and 10 being the best performance. In addition, a course grade of 70 percent is the minimum passing grade on a traditional academic grading scale. Therefore, the team might designate the ability of a machine to lift a 130 kg garbage can as a 7, representing the fact that this level of performance is the minimum required to pass the
course and achieve a 70 percent grade (7 is 70 percent of 10). It would also make sense for the team to designate the ability of the machine to lift a 200 kg can as a 10, representing the fact that if the team’s machine could perform at this level, it would be achieving the highest level of performance that they want it to achieve.

Alternatively, the mechanical engineering design team may want to select a number lower than 7 to represent the minimum performance required by the problem statement. By selecting a number such as 3 or 5 to represent the minimum performance required, the scoring scale may be able to provide the team’s members with more information about the prototype’s performance.

During their evaluation of the prototype, the team should designate one member to record all test scores as well as pertinent team member observations about the prototype’s performance. The observations recorded should include comments about vibration, binding, burn odors, and other phenomena that may warn of impending machine failure.

After the first series of testing has been completed, the team members should assemble to discuss the numbers and what they mean. The team may wish to categorize each score in one of three ways: unacceptable, satisfactory, and excellent.

“Exchanging performance” is a concept in which the team intentionally makes an engineering change to the machine, reducing one ability of a machine in order to increase another ability of that machine. A performance exchange frequently entails a relatively simple change such as a gear ratio or an electrical voltage or current.

Example

A mechanical engineering design team is testing the performance of its prototype pallet-handling machine. The prototype uses an electric motor coupled to a chain-and-
sprocket drive. The problem statement requires the prototype to be able to lift 400 kg to a height of 15 cm above the floor in 10 seconds.

Suppose that the team has set 4 as the minimum acceptable performance score on the 0-to-10 scale. Any score from 0 to 3 would obviously be an unsatisfactory score. The team could then designate any score from 4 to 7 as satisfactory, while any score from 8 to 10 would be designated an excellent score.

In the load-lifting capacity test, the team finds that its prototype can lift a maximum of 1000 kg. The team also finds that its prototype meets its lifting height design goal of 20 cm. Unfortunately, the prototype requires a constant 12 seconds to raise any weight 15 cm above the floor.

The team decides that its prototype has achieved a 10 score in the load capacity test, an excellent score. In the height test, the team judges that its prototype has achieved a 5 score, a satisfactory score. The team realizes that its prototype has achieved only a 3 score in the test of the time it takes to lift the load, an unsatisfactory score. At this point, the mechanical engineering design team has three options: attempt a major design revision, substitute a more powerful motor, or exchange performance.

Attempting a major redesign of the prototype is out of the question. There is too little time during the remainder of the course to make major changes. Also, because the prototype requires a constant 12 seconds to raise any load 15 cm above the floor, substituting a more powerful motor would probably not improve the time to raise the pallet. Even a time improvement did result, a more powerful motor would increase the prototype’s cost and weight, making this design change unattractive.
Exchanging performance appears to be the team’s best option at this point. The prototype’s performance in the height test was satisfactory and should be left alone, but some of its excellent load capacity can be exchanged for more speed in lifting.

The prototype utilizes a chain-and-sprocket drive. By substituting a different sprocket combination, the team’s prototype can gain the needed speed while sacrificing an acceptable amount of load-lifting capacity. Changing the sprocket combination has the same effect as changing gear ratios. If the sprocket combination is changed to permit the pallet to be raised 15 cm in 8 seconds, the prototype will still have a load capacity of 667 kg. With this simple, quick, and inexpensive change, the team will have a prototype that exceeds the minimum performance standards.

Subjective testing and evaluation

After the mechanical engineering design team has established that their prototype can satisfy the problem statement, they are ready to perform subjective testing on the machine. Whereas objective tests produce quantifiable results, subjective tests may seem nebulous to the new engineer. Nonetheless, subjective tests can help the mechanical engineering design team refine the prototype.

The first stage of subjective testing and evaluation occurred when the observations of team members were recorded during the objective tests. Comments such as “The chain is vibrating a lot” or “It sounded like the lift-arm hinge was sticking” will form a basis for refining the prototype. Chain vibration could soon lead to the chain failing under load. A small increase in the looseness of the chain could prevent such a failure and increase the prototype’s reliability. A sticking hinge might cause the galling or shearing of a part,
resulting in the failure of the machine. The implementation of increased lubrication could be all it takes to forestall this undesirable outcome.

Experienced engineers learn to listen to their gut instinct. If a team member develops a concern about the operation of the prototype, that member should share his or her concern with the other team members. The team should analyze the observations and concerns of every team member, even if only one member made the observation or voiced the concern.

8.2 - Potential Trouble Areas

- Bearings
- Hinges
- Cams
- Drive train losses
- Binding and misalignment
- Chains and belts
- Weak structural members

Bearings

Bearings can pose a potential for trouble when they become overheated or subjected to debris. In some bearings, the lubrication serves to cool the bearing. Inadequate lubrication in these bearings will lead to failure.

Debris that enters a bearing can increase the resistance of the bearing. If the debris is hard enough, it can abrade the bearing until it no longer functions properly.

Hinges

Hinges seldom suffer from heat-related failure or debris-induced failure, but they are still subject to wear and binding. Binding poses the greater risk and is best avoided through
lubrication. Binding can result in the overloading of the drive mechanism or cause a hinge failure by shearing the hinge pin.

Cams

While cams themselves do not constitute a trouble area, cam followers and drive systems often present a problem area. At high operating speeds, a cam follower may not remain in contact with the cam’s surface, and parts actuated by the cam may then collide with other parts. When this phenomenon occurs in internal combustion engines, catastrophic failure normally results.

A cam’s drive system frequently must maintain the timing of the cam’s actuation. Because the timing of cam actuation can be crucial to the reliable operation of a machine, a failure of the cam’s drive system can have dire consequences. Although a cam’s drive system is not necessarily weak, its reliable operation must be assured to protect the prototype from the potential for self-destruction.

Drive train losses

An often-overlooked trouble area is drive train friction and power losses. In powered machines, some of the motor’s power must be used to overcome the friction and inefficiencies of the mechanisms that transmit the power to the driven components. This diversion of motor power constitutes a loss of power. If the drive train losses are too great, the power delivered to the driven components may be insufficient to perform the intended task. For this reason, designing mechanical engineers should account for drive train losses in their design. If the losses present an impediment to prototype function during testing, the team should determine whether the problem can be solved with additional lubrication. If lubrication cannot adequately reduce the losses, then a part substitution may be needed.
Binding and misalignments

Binding is typically caused by misaligned components, insufficient lubrication, or a combination of the two. The first step for the engineering team that encounters binding is to check for misaligned parts. An example of a misalignment that causes binding would be when a bolt on a moving arm of the prototype inadvertently contacts a structural member.

Insufficient lubrication may cause binding associated with a hinge if the geometry of the prototype’s moving parts reaches a configuration in which the frictional forces in the hinge become very large. In this case, the problem may not be a lack of lubrication but a need for a different lubricant. For example, the team may be able to reduce the occurrence of binding in a hinge by substituting a heavy grease in place of oil.

Chains and belts

Chains and belts offer designing mechanical engineers wonderful and versatile options for transmitting power. The potential for trouble associated with chains and belts is frequently related to their operating tension.

If a chain is operated too loosely, it may separate from the sprocket teeth. If the chain is operated too tightly, it may fail. Because the integrity of the chain drive is a function of the tension of the chain, the mechanical engineering design team may want to include a chain-tension-adjusting feature, such as a spring-powered idler sprocket of the configuration found on many multiple-speed bicycles or a variable spacing between the driving and driven sprockets.

If a V-belt is operated loosely, it may inefficiently transmit power, or it may become incorrectly positioned in the pulley and suffer abrasion until failure. Yet a V-belt can also fail if it is operated too tightly. The mechanical engineering design team employing a V-belt may
want to include a belt-tension-adjusting feature. A spring-powered idler pulley of the configuration found on many automobile engines or a variable spacing between the driving and driven pulleys as commonly found in clothes-washing machines may be necessary.

Weak structural members

Weak structural members can deflect sufficiently to interfere with proper operation of the prototype. Should the mechanical engineering design team determine that a structural member of the prototype lacks sufficient strength, the team should seek a modification that will permit proper operation. The correction will most likely require the addition of a length of bar, strap, tube, or angle stock.

If possible, the team should seek to weld the corrective piece in place as opposed to drilling and bolting. Welding is one of the faster methods of fastening steel and other weldable metals. As an added benefit, the beads of weld do not protrude as much as a bolt does.
Chapter 9 - Designing for Manufacture

9.0 - Introduction

The purpose of this chapter is to give the reader an overview of some of the more commonly used manufacturing processes. Each of the processes included in this chapter is accompanied by its name (or names) and initials. A few of the ways in which the process is used have been mentioned. In order to give the reader a quick and efficient assessment of a process, three advantages and three disadvantages of the process have been placed before the paragraphs that discuss the process. The discussion paragraphs begin with a brief description of the process and elaborate on the advantages and disadvantages of the process.

9.1 - More Commonly Used Manufacturing Processes

- Blow molding
- Cold heading
- Drilling
- Extrusion (extruding)
- Forging
- Grinding
- Heat treating
- Injection molding
- Lathes
- Material coatings
- Milling
- Roll-forming
- Sawing
- Shearing
- Stamping and folding
- Welding
Process: Blow molding

Fig. 25. Blow molding.

How it is used: Widely used for plastic containers, toys.

Advantages:

- Efficient use of material, no waste.
- Inexpensive in mass production.
Blow molding is a widely used manufacturing technique to make plastic containers and toys. Blow molding begins with an extrusion. A plastic tube called a parison is extruded and cut to the appropriate length. The parison is similar in appearance to a plastic drinking straw.

The parison is then placed inside the mold, and a metal nozzle called a blow pin is inserted into one end of the hollow parison. The parison is heated, and air is injected through the blow pin. The air pressure forces the heated parison to assume the shape of the mold, thus creating the plastic product. The molded plastic product is allowed to cool, and then it is extracted from the mold.

Blow molding can be highly automated and is therefore well suited to mass production. The combination of mass production and blow molding’s efficient use of material can result in a low cost per product.

Plastics are the only materials that can be blow-molded. Mechanical engineers designing blow-molded products should specify a uniform wall thickness throughout the product. Blow molding is not a good choice for forming sharp corners, and the process is best used with thin wall designs.
Process: Cold heading\(^2\)

Fig. 26. Cold heading.

How it is used: Bolts, screws, nails.

Advantages:

- Improved grain structure.
- Well suited to continuous feed.
- Smooth surfaces.

Disadvantages:

- Complex shapes are best avoided.
- Best for high volume.
Limited to easily formed metals.

Cold heading involves holding a part in a die while one end of the part is exposed to impact from a header. The impact from the header causes the part’s exposed end to upset. During the impact, the upset end is shaped by the contours of the header, the die, or both.

As the material of the part is upset, its grain structure becomes aligned with the contours of the part. This improves the material properties, adding strength. The resulting surface of the part is smooth and without tool marks.

Cold heading is limited to easily upset metals. Even then, complex shapes should be avoided. Cold heading is usually too expensive for small production runs, but it is well suited to large volume production. The suitability of cold heading to high-volume production is further enhanced by its compatibility with continuously fed materials, such as wound heavy-gauge wire.
Process: Drilling

Fig. 27. Drilling.

How it is used: Making holes in material.

Advantages:

- Readily available empirical equations.
- Improvements from coatings.
- Readily adaptable to computer numerically controlled production.

Disadvantages:

- Bit heat.
- Bit wear.
Different bit materials for different drilled materials.

Drilling consists of rotating a metal shape known as a bit against a part so as to remove material from the part and form a hole in it. In recent publications, some authorities have claimed that drilling is the most common machining practice.

Drilling generates heat where the bit rubs against the part. This heat is mostly dissipated by conduction into the bit, conduction into the part, and convection by a cooling fluid, if such fluid is present. Heat conducted by the part may be detrimental to material properties if the part was previously heat treated.

Heat conducted by the bit will accelerate bit wear, a detriment that is often counteracted by the use of a cooling fluid. Bits have also been improved by the addition of coatings. The primary purpose of these coatings is to reduce wear on the bit during drilling. Titanium nitride is sometimes used as a drill bit coating. It increases the hardness of the bit and adds self-lubricating properties. For some part materials, drill bits composed of special materials such as high-speed steel or carbide are needed.

Empirical equations have been developed that allow engineers to accurately predict material removal, generated heat, tool wear, and economic considerations related to drilling. The ability to quantify these data makes drilling readily adaptable to computer numerically controlled (CNC) production.
Process: Extrusion (extruding)\textsuperscript{4}

Fig. 28. Extrusion.

How it is used: Wire, small aluminum stock.

Advantages:

- Well suited to long sections, wire.
- Suitable with Al, Cu, Mg, Pb, Sn, steel, Zn.
- Smooth surface finish.

Disadvantages:

- Not good for sharp corners.
- Part may require straightening afterward.
- Produces stress concentrations.

In extrusion, the metal to be extruded is first heated to assist plastic deformation. Next, a ram pushes the metal from within a container through a die. The ram and container push the metal though a die in the same way that a syringe pushes a liquid through its opening. The ram is analogous to the plunger of a syringe, and the container is analogous to the body of the syringe. The die serves to both size and shape the extruded metal. As the metal passes through the die, the metal assumes its shape and dimensions.

Extruded parts normally exit the die with smooth surface finishes. Many aluminum alignment rails on table saws are extruded. Shower stalls with sliding doors or assembled from rigid panels frequently use extruded aluminum structural components. Extrusion is suitable for use with aluminum, copper, magnesium, lead, tin, steel, and zinc. Long sections are easily and economically produced by means of extrusion. Several shapes of extruded stock three feet (0.9 meters), four feet (1.3 meters), and six feet (1.8 meters) long are readily available in American hardware stores.

There are a few disadvantages to extruding. Extrusion is not a good choice for producing sharp corners on parts. Parts often require straightening after they have been extruded. Extruded parts may suffer from stress concentrations that can reduce their strength.
Process: Forging

Fig. 29. Forging.

How it is used: High-performance connecting rods, crankshafts, hand tools.

Advantages:

- Best feature is controlled grain structure.
- Adds strength, ductility, and impact resistance.
- Reduces internal porosities and other flaws.

Disadvantages:

- Machinery can be expensive.
- Often labor-intensive.
The forged part usually has to be machined afterward.

Forging is performed by hammering the metal blank until it assumes a shape based on two dies. First, a metal blank is placed atop one die. A second die then strikes the blank until the shape is formed as the two dies close together.

Forging adds strength, ductility, and impact resistance. Forging provides a controlled grain structure as it hammers the blank into the desired shape. An added benefit of forging is that it reduces internal porosities and other flaws within the metal part.

However, machinery used in forging can be expensive, and the forging process is usually labor-intensive. Both of these factors increase the cost of forging. Adding to the cost is the fact that parts usually require machining after they have been forged. For example, most parts are shot-peened after being forged. Shot-peening hardens the part’s surface and adds compressive stresses that impede crack growth.
Process: Grinding

Fig. 30. Grinding.

How it is used: Material removal.

Advantages:

- Simple and inexpensive.
- Works with most materials.
- Quick setup time.

Disadvantages:

- Large rake angles produce considerable heat.
- Must consider grindability and grinding wheel wear.
May require a skilled operator or CNC for some procedures.

In grinding, material is removed from the workpiece by placing it in contact with a rotating abrasive wheel. Individual abrasive particles on the wheel strip material away from the workpiece as they rub against it. The stripping of material by successive abrasive particles reduces the dimensions of the workpiece. The grinding process is halted by the human or computer operator when the desired part dimension is achieved.

Grinding is an attractive way to manufacturing parts economically. It is simple and inexpensive. Grinding works with most materials. Unlike many other manufacturing processes, grinding operations require little setup time. Along with drilling, grinding is one of the most popular manufacturing methods.

The individual abrasive particles strip away the material with undesirably large rake angles, producing considerable heat. If enough of the heat generated by grinding is allowed to flow into the workpiece, the workpiece may become warped or may lose the value of any previous heat treating.

When selecting grinding as a method of manufacturing a part, the designing mechanical engineers must consider the grindability of the workpiece and grinding wheel wear. CNC grinding operations can be programmed to account for grinding wheel wear. Additionally, the designing mechanical engineers should be aware that some grinding procedures require either a skilled operator or a CNC approach to obtain satisfactory results.
Process: Heat treating

Fig. 31. Heat treating.

How it is used: To improve material characteristics.

Advantages:

- Can improve part strength and wear resistance without reducing toughness.
- Annealing can relieve part stresses.
- Allows a cheaper material to be used in place of an expensive material.

Disadvantages:

- Increases cost and can distort the part or change its size.
- Rapid quenching can increase part stresses and cause cracks.
Best for uniform, round, or rounded cross-sections.

In general, heat treating consists of raising the temperature of a part and subsequently cooling it at a specified rate. In metals, heat treatment affects the grain size, determining whether the metal will be harder or softer than prior to the heat treatment. Heat-treating metals can also provide metal characteristics on the surface that are different from those in the core. This allows a heat-treated metal to exhibit the hardness needed to resist wear while maintaining toughness.

Glass used in buildings and vehicles is commonly heat treated (tempered) to reduce the propagation of cracks. During its manufacture, the glass is annealed to remove internal stresses. The annealed glass is then heated to near its softening point and rapidly cooled.

To understand the tempering mechanism, imagine a cross-section of the glass divided into three layers: an inner layer surrounded by two outer layers. The rapidity of the quench cools the two outer layers, leaving the inner layer still hot and soft. The two outer layers will have cooled to the point of rigidity while the inner layer remains hot and soft. As the inner layer later cools, it contracts, placing the two outer layers in compression. In order for a crack to propagate, it must first overcome the compressive preload on the corresponding outer layer. Case-hardened metal parts resist crack propagation in the same manner as tempered glass.

Heat treating adds cost, but the benefits may be worthwhile. Heat treating can be used to increase a part’s strength or wear resistance without reducing the part’s toughness. In this way, heat treating may allow the use of less material for the part, thus reducing material cost, part size, and part weight. The cost of heat treating may be an investment that results in savings by allowing the part to be fabricated from a cheaper metal.
Rapidly quenching a part can increase its internal stresses and may lead to cracking. To reduce the likelihood of cracking, a type of heat treating known as annealing can be used to relieve the internal stresses in a part.

The choice of metal and the part’s cross-section can influence the value of heat treating. Designing mechanical engineers should note that uniform, rounded, or oval-shaped cross-sections are best suited to heat treating.
Process: Injection molding

Fig. 32. Injection molding.

How it is used: Thermoplastic parts, toys, plastic clothes hangers, cores for rolled paper.

Advantages:

- Great for intricate parts in large quantities.
- Great for manufacturing that requires inserting a part into plastic.
- Allows a product to be made from a single part rather than an assembly of parts.

Disadvantages:

- Best for thin-walled parts.
- Shrinkage.
Better for large volumes due to high mold cost.

The raw material for injection molding is plastic in pelletized form. These plastic pellets are fed into a hopper that normally leads to an Archimedes screw, which is a spiral screw positioned coaxially inside a cylinder. For injection molding, the cylinder is heated to melt the plastic pellets. As the spiral screw is turned, the molten plastic is forced into the mold that shapes the part. The molten plastic in the mold is then allowed to cool and resolidify. After the part has cooled sufficiently, the mold is opened and the part extracted. The surface finish of injection-molded parts is normally smooth.

Injection molding is an economical method of producing plastic parts with complex shapes. This process is frequently used to mold intricate plastic parts in large quantities, and it is well suited to manufacturing parts in which a component is inserted into the molded part. A common example of this capability can be observed with plastic clothes hangers molded around permanently attached metal hooks. This results in a single part, rather than an assembly of parts.

Injection molding works better with thin-walled parts, so thick wall sections should be avoided. Injection-molded parts shrink upon cooling, typically by 2 to 3 percent and rarely by more than 5 percent. However, the shrinkage common to injection molding can cause shape distortions. An issue of special concern to designing mechanical engineers is the fact that shrinkage may result in shape distortions. Shrink-induced distortions should by analyzed for their impact on inter-changeability.

The economics of injection molding favor large-volume production. Small production quantities may not be cost-effective due to the initial cost of the mold.
Process: Lathes

Fig. 33. Lathe.

How it is used: Engine parts, valve parts, some bearing parts.

Advantages:

- High precision.
- Readily adaptable to CNC.
- Excellent dimensional control.

Disadvantages:

- Tool heat.
- Tool wear.
Best for low quantities.

Lathes work by rotating a workpiece about a constant axis while a tool scrapes material from the workpiece. Despite the seeming simplicity of lathes, they require careful application of tool angles and depth of cut. Fortunately for designing mechanical engineers, lathes have been the object of extensive research, so equations exist that accurately predict the relevant parameters of lathe machining.

Normally, mechanical engineers and machinists associate lathes with precision. This is because lathes offer excellent dimensional control. Lathes are readily adaptable to computer numerical control.

Lathe machining may require longer times to produce a part because the rate of material removal is partly dictated by workpiece material properties. Because lathe machining is sometimes a slow or labor-intensive process, it is best for low-volume applications.

Two unfortunate byproducts of lathe machining are heat and tool wear. The nature of material removal by a lathe generates considerable heat, which is mostly dissipated by air convection, cutting fluid convection, workpiece conduction, or lathe tool conduction. If no cutting fluid is used, most of the heat from lathe machining will be dissipated by conduction into the workpiece or the lathe tool. If too much heat conducts into the workpiece, its material properties may be affected. Specifically, a metal workpiece may lose any benefits from heat treatment performed prior to the lathe machining operation.

If the workpiece has a low thermal conductivity or if the lathe machining process generates too much heat, the lathe tool may be damaged. Heat that is caused by machining and that enters the lathe tool is initially conducted through the cutting surface. When too
much heat is conducted through the cutting surface, it loses its temper, softens, and wears faster. After the lathe tool has worn enough, it must either be re-sharpened or replaced.

Process: Material coatings

Fig. 34. Material coatings.

How it is used: Prevent rust/corrosion, increase wear resistance, aesthetics.

Advantages:

- Can improve material properties (hardness, corrosion resistance, etc.).
- Can increase or decrease electrical conductivity.
- Most coatings do not significantly alter the part’s dimensions.
Disadvantages:

- Not good for sharp corners or deeply recessed contours.
- Not good for deep holes and tubes.
- Plating solutions are often expensive.

Material coatings can improve or give new properties to the material on which they are applied. Chrome or nickel plating, galvanizing, Parkerizing, titanium nitride, paint, epoxies, and gold are examples of popular material coatings. Material coatings are frequently used to improve a metal’s resistance to rust or corrosion. Material coatings can also be used to reduce wear or to improve or diminish electrical conductivity.

Fortunately, most coatings do not significantly alter the dimensions of the part to which they are applied. Regardless, designing mechanical engineers should determine the increases in part dimensions that would be caused by the intended coatings.

In general, material coatings are not good for sharp corners or deeply recessed part contours. Nor are material coatings good for deep holes and tubes, as the coatings may not thoroughly extend into the passage.

Cost may be the deciding factor for the designing mechanical engineers considering the use of a coating. For example, engineers may want to substitute a hard-chromed carbon steel part for a stainless steel part. Carbon steels are usually cheaper and easier to machine than stainless steels, but the chroming process will add to the manufacturing cost of using carbon steel.
Process: Milling

Fig. 35. Milling.

How it is used: Precise flat surfaces, reciprocating engine parts, brake parts.

Advantages:

- Fast, large-scale material removal.
- Offers high precision, small tolerances.
- Low tooling costs.

Disadvantages:

- Typically more expensive than casting or extruding.
- Surfaces to be machined must be easily accessible.
Extensive milling wastes material.

Milling is a process whereby an engine-turned cutter that resembles a gear or drill bit strips material away from the workpiece. Milling can be performed on most materials. The surfaces to be milled must be easily accessible.

Milling is usually more expensive than casting, extruding, or stamping, but it is fast and can maintain a high degree of precision. Milling is a proven way to produce parts of an exact size and shape. Unfortunately, milling can cause a great wastage of material. However, the chips produced by milling can be recycled, offsetting some of the material wastage cost.

Beginning in the mid-twentieth century, milling was increasingly replaced by stamping and extruding. This has been especially true in high-volume production. Nonetheless, engineers in need of a small number of parts in a hurry would do well to consider milling.
Process: Roll-forming

Fig. 36. Roll forming.

How it is used: Metal structural members, gutters.

Advantages:
- Well suited to long lengths, complex cross-sections, and high-volume production.
- Low labor cost.
- Efficient use of material, gentle on finish, and suitable for coated materials.

Disadvantages:
- High tooling costs.
- Long setup times.
Larger, thicker parts are formed less precisely.

Roll-forming is a method of transforming spools of sheet metal into complex shapes such as gutters and corrugated metal siding. The workpiece begins as a long section of sheet metal. The sheet metal passes through a successive series of shaped rollers until it acquires the desired cross-sectional shape.

Roll-forming is well suited to long lengths, complex cross-sections, and high-volume production. Roll-forming is efficient in its use of the material, causing no waste. Also, roll-forming is gentle enough on the existing material finish to make it suitable for coated materials. Low production labor cost is an added benefit of roll-forming.

Although roll-forming is economically suited to mass production, it requires a considerable setup investment. Roll-forming suffers from high tooling costs and long setup times. Roll-forming is better suited to forming thin sheet metal; in practice, thicker parts are roll-formed less precisely than thin parts.
Process: Sawing\textsuperscript{13}

Fig. 37. Sawing.

How it is used: Sizing lumber and metal stock.

Advantages:

- Fast procedure.
- Can be highly automated; well suited to mass production.
- Simple process.

Disadvantages:

- Must account for reduction in dimension due to saw kerf.
- Must select proper blade and speed.
Cut ends should be dressed.

Sawing is one of the most frequently used manufacturing operations. I-beams, lumber, steel angle stock, and even the aluminum stock used to assemble glass shower stalls is saw-cut to the correct length.

Sawing is a fast procedure and is well suited to mass production. The advent of power saws greatly advanced manufacturing. The lumber industry was transformed from large hand saws, or at best water-wheel-powered saws, to high-speed electric saws.

There are different types of saws, including power-hack saws, circular saws, band saws, and abrasive-cutoff saws. Power-hack saws resemble hand saws operated by machines. Circular saws use blades in the shape of discs with teeth on their periphery. Band saws use blades that form large metal loops with teeth along one edge. Band-saw blades are driven much like a belt and pulley. Some hard materials, such as tile and brick, cannot be efficiently cut by normal saw blades. These materials are best cut with abrasive-cutoff saws, which use a disc-shaped blade that contains abrasive particles in place of traditional teeth.

From an engineering perspective, sawing is a simple process. The mechanical engineer selecting sawing as a manufacturing process need only consider the blade type, the blade’s cutting speed, the effect of the saw kerf, and how to dress the cut surface.

The saw kerf is the cut or channel made by the saw. Another way to conceptualize the saw kerf is to think of it as the material that is directly in the path of the blade and that is lost in the cutting process. As the blade teeth sweep across the progressing cut, each tooth strips away a small amount of material that becomes metal shavings or, in the case of wood, saw dust. The saw kerf has a width equal to the thickness of the saw blade.
The speed of the blade teeth and the rate at which the cut progresses influence the quality of the cut and the usable life of the blade. The mechanical engineer specifying sawing as a manufacturing process should consult reference materials to determine the proper blade type and speed to use.

**Process: Shearing**

Fig. 38. Shearing.

How it is used: Sheet metal.

Advantages:

- Well suited to high volume production.
- Well suited to low-carbon steels, copper, brass.
- Very economical.

Disadvantages:

- Poor choice for brittle materials.
- May require de-burring, or even machining, after shearing.
- Plastic deformation and dimensional change.

As its name implies, shearing is a cutting of the metal. The workpiece consists of a thin piece of metal that is subjected to a pressure that exceeds its elastic strength. At first the workpiece deforms plastically, then it tears, and finally it breaks along the regions of high stress concentration.

Shearing is very economical and is an excellent choice for high-volume production. From a materials standpoint, shearing operations are well suited to low-carbon steels, copper, and brass.

A disadvantage of shearing operations is that they are not suitable for brittle materials. Shearing operations typically leave sharp or irregular edges on the part. It may be necessary to de-burr the part after having sheared it. In applications that require greater precision, some machining of the part may be necessary.
Process: Stamping and folding

Fig. 39. Stamping and folding.

How it is used: Constructing metal box shapes.

Advantages:

- Economical for high volumes.
- Increase of material strength.
- Stampings are usually lighter than milled parts.

Disadvantages:

- Best suited to cold-rolled, low-carbon steels.
- Holes and edges may require de-burring.
- Not suitable for sharp corners.

Stamping-and-folding operations either plastically deform or shear a steel workpiece. Stamping-and-folding operations are analogous to folding and sharply creasing a sheet of paper. In this example, the crease in the paper remains after it is released. Shearing, punching, and blanking operations are the same as hole-punching devices found in most offices.

During the 1940’s, stamping-and-folding operations rapidly replaced many conventional mass production machining processes, especially milling. Stamping-and-folding operations were preferable to milling because they were faster and did not waste as much material.

These advantages of stamping-and-folding operations can be easily recognized in the manufacture of a small steel box. If the steel box were milled from a solid block, more than 95 percent of the workpiece steel might be wasted. The various milling steps and their setup times might take a single worker most of a work day to complete. However, if the steel box were to be produced by a single worker using stamping-and-folding operations, the box might be completed within an hour. Additionally, making the steel box with stamping-and-folding operations would likely waste less than 5 percent of the workpiece steel.

If the workpiece’s grain structure is properly aligned, stamping and folding can have a positive effect on the strength of the resulting part. Stamping and folding is very economical for high-volume production. In practice, stamped and folded parts are usually lighter than milled parts.

Stamping and folding is best suited to cold-rolled, low-carbon steels. Holes and edges on stamped or folded parts may require de-burring. Stamping and folding is not a good
choice where sharp corners are needed. In fact, sharp corners should be avoided in stamping-and-folding operations.

There are times when designing mechanical engineers can benefit from the combination of stamped or folded parts and milled parts. Stamped or folded parts can be used for the bulk of a product’s structure, where precision requirements are lower. Milling can be used to make the smaller parts of the product where precision is paramount. The various parts can then be welded or pinned together using alignment fixtures.
Process: Welding

Fig. 40. Welding.

How it is used: Connecting metal parts.

Advantages:
- Fast and inexpensive.
- Makes rigid, permanent connection.
- Low profile.

Disadvantages:
- Not suitable for removable parts.
- Requires skilled worker or computer control.
Welding is one of the fastest and least expensive means by which two pieces of steel can be connected. At its simplest, arc welding uses electric current to melt a steel rod onto the juncture of two pieces of steel. As the molten metal cools, the two pieces of steel become bonded. The bond between the metal pieces will be rigid and permanent.

An advantage of welding is that the weld seams, or beads, do not protrude from the surface nearly as much as nuts and bolts used as connectors. Weld beads can be ground flush with the surface if desired.

Sometimes a permanent bond between two parts is not wanted. For example, welding should not be used to attach access covers. Welding is also a poor choice for joining two metal parts if one or both of them is heat-treated because the high temperatures generated by welding will negate the benefits of the heat treatment.

While welding can be simplified by the use of jigs to hold the parts in alignment when forming the beads, the operation still requires a skilled worker or computer control. The quality of the weld is very dependent on the skill of the welder. To insure consistent quality control, many industries have acquired computer-controlled welding machines.

9.2 - Less Commonly Used Manufacturing Processes

- Abrasive-flow machining, abrasive-jet machining
- Adhesive bonding
- Broaching
- Chemical machining (blanking, machining)
- Electrical-discharge machining
- Electron-beam machining
– Explosive forming (contact, standoff [a.k.a. hydroforming])
– Impact extrusion (cold extrusion)
– Investment casting, lost-wax process
– Laser machining
– Metal injection-molding
– Sand casting

Process: Abrasive-flow machining, abrasive-jet machining

How it is used: Polishing turbines and complex shapes.

Advantages:
– Little heat is generated.
– Causes no heat damage to the workpiece.
– Suitable for finishing inaccessible surfaces.

Disadvantages:
– Equipment is expensive.
– Slow material removal.
– Poor tolerance control (10%-50% common, with 25% normal).

Abrasive-flow machining is performed by transporting an abrasive-filled, viscous, semisolid medium across the surfaces of the workpiece. As the medium is pumped across the workpiece, the abrasive particles rub on jagged edges and other sharp features, slowly removing the tiny protrusions. The finished part is analogous to a shiny, well-worn boat propeller that has been polished by sand particles suspended in water.
Abrasive-flow machining produces little heat, meaning this process cannot ruin the workpiece through excessive heat. Because abrasive-flow machining is accomplished by pumping the medium across the workpiece, inaccessible surfaces are easily finished.

Abrasive-flow machining equipment is expensive and requires a high initial investment. Although abrasive-flow machining can polish otherwise inaccessible surfaces, the material removal rate is quite slow. Abrasive flow machining also suffers from poor tolerance control, so it is usually employed in polishing roles.

Abrasive-jet machining is basically the same procedure as abrasive-flow machining, except that it uses a gas medium containing fine, suspended abrasive particles. Sandblasting is an example of abrasive jet machining.

Process: Adhesive bonding

How it is used: Assembling parts.

Advantages:

- Low weight.
- Good for easily damaged parts.
- Low equipment cost.

Disadvantages:

- Needs joint overlap.
- Possibly messy cleanup.
- Materials to be joined must have matching expansion coefficients.

Adhesive bonding simply involves placing an adhesive, or glue, between two overlapping surfaces to fasten them. Children commonly assemble models, artwork, and Popsicle-stick structures by adhesively bonding the pieces.
Adhesive bonding places no mechanical stresses on the components during the bonding process, so it is suitable for joining easily damaged parts. Using adhesive bonding in place of more traditional fastening methods helps keep the weight of the assembled part to a minimum. Other advantages of adhesive bonding include low equipment cost and the ability to create smooth joints.

After applying the adhesive and joining two parts, some cleaning of excess adhesive may be necessary.

Mechanical engineers who wish to use adhesive bonding successfully will need to account for a few design considerations. Adhesive joints should be designed to transmit loads in tension, compression, or shear; adhesive joints are not as strong against bending moments and cleavage. Engineers will also need to specify that materials to be joined adhesively have compatible thermal expansion coefficients.

Process: Broaching⁹

How it is used: Keyways, splines.

Advantages:

- Works with most materials.
- Great for inside tubes.
- Excellent surface finish.

Disadvantages:

- Usually best for high-volume products.
- Not good for blind holes.
- Not good for tapered splines.
Broaching involves passing a cutting tool, the broach, axially along the part while contacting the surface of the part. As the broach traverses along its path, one or more cutting teeth remove material from the part.

Broaching works on most materials and leaves a smooth surface finish on the cut feature. Broaching is well suited to use inside tubes where other tools cannot be used. Economically, broaching is best used in high-volume production.

Broaching is popular for cutting keyways, splines, and features inside tubes. Broaching is not a good choice for blind holes or tapers. The exception to this would be blind holes with a larger cavity on the closed end of the hole.

Process: Chemical machining (blanking, machining)

How it is used: Photo-lithography, aircraft parts manufacture.

Advantages:
- Complex surfaces okay.
- No mechanical cutting pressures or stresses.
- Large parts okay.

Disadvantages:
- Not good for sharp corners.
- Hazardous materials safety concerns.
- Hazardous materials handling and disposal costs.

One of the most commonly used forms of chemical machining is photo-lithography. There are other forms of chemical machining, and they are used in widely varying applications. One form of chemical machining is used to apply lettering to clothes, such as T-shirts and sweatshirts. In photo-lithography, the workpiece to be machined is coated with the
chemical that performs the machining. A mask is then placed so as to protect the portions of
the surface that are not to be machined.

Next, light is projected onto the mask. Light that passes through the openings of the
mask strikes the chemical coating on the surface to be machined. When the light enters the
coating, it causes a chemical change to take place that allows the coating to be removed from
the unmasked regions of the workpiece. At this point, the regions of the workpiece surface
are protected in the areas not to be machined and exposed in the areas that are to be
machined. A chemical is then applied to the workpiece surface that erodes material from the
unprotected regions.

Chemical machining is used to fabricate semiconductor chips. Multiple etchings and
deposits are performed. This allows complex semiconducting structures to be formed. As it is
used in semiconductor manufacture, X-ray-stimulated chemical machining can achieve a
precision unavailable with other manufacturing methods.

Chemical machining offers the designing mechanical engineering team an easy way
to machine large or complex surfaces. Chemical machining can undercut masked areas,
should that be desired. Another benefit of chemical machining is that it places no mechanical
cutting pressures or stresses on the part.

An interesting aspect of chemical machining is the ease with which the mask can be
constructed. This engineer has successfully performed chemical machining with masks
constructed by photocopying a picture of the desired pattern onto a transparent sheet.

Unfortunately, chemical machining is not suitable for shapes with sharp corners.
Chemical machining also poses hazardous material safety concerns. Special handling and
disposal procedures mandated by the components of chemical machining affect the cost.
Process: Electrical-discharge machining (EDM)\textsuperscript{21}

How it is used: Gas nozzles, various small precision parts.

Advantages:

- Burr-free parts.
- Great for intricate shapes and one-of-a-kind items.
- Excellent precision.

Disadvantages:

- Workpiece must be electrically conductive.
- Slow material removal, best for small quantities.
- Expensive equipment.

In electrical-discharge machining (EDM), an electrode is placed near the workpiece and a pulsed electrical arcing is established between the electrode and the workpiece. Localized heating at the arc region on the workpiece causes small amounts of workpiece material to be vaporized. Cooling fluid is circulated around the workpiece during the process. As the vaporized material leaves the workpiece, it is cooled by the fluid until it re-solidifies. These re-solidified particles are then transported away by the cooling fluid.

Two types of electrical discharge machining are commonly used: sinker EDM (also called die EDM, die sinking EDM, probe EDM, and sinking EDM) and wire EDM. In sinker EDM, a shaped electrode, or die, is placed near the workpiece, and the arcing forms a shape in the workpiece that corresponds to the die. As material is ablated, the die is slowly moved into the machined area, maintaining material removal until the desired workpiece shape is achieved.
In wire EDM, a continuously scrolled conductive wire serves as the electrode. A small hole is drilled through the workpiece, and the wire is fed through the hole. The wire is then traversed to cut the desired pattern into the workpiece.

EDM is capable of excellent precision and leaves the workpiece free of burrs. EDM is also well suited to cutting intricate and custom shapes.

Because the workpiece must be conductive, EDM is not applicable to nonmetals. EDM is slower than many other manufacturing methods. The material removal rate is usually expressed in units of cubic inches per hour or cubic centimeters per hour. Designing mechanical engineering teams should also consider the high cost of EDM equipment.

**Process: Electron beam machining**

*How it is used:* Fuel-injector nozzles, wire-drawing dies.

**Advantages:**
- Most often used for drilling fine holes.
- Can drill or cut closely spaced patterns.
- Works with any material.

**Disadvantages:**
- Slow material removal; best for fine cuts in thin workpieces.
- High equipment costs.
- Must be operated in a vacuum.
- Process generates X-ray radiation.

Electron-beam machining is performed by focusing an electron beam on a small spot on the workpiece. The beam heats the workpiece at the desired location. The workpiece material becomes heated to the point that it melts and vaporizes.
Electron-beam machining works on any material and is popular for drilling fine holes and closely spaced patterns. Electron-beam machining has a slow material removal rate, so it is best suited for fine cuts in thin workpieces.

Electron-beam machining has some similarities to a scanning electron microscope. Electron-beam machining must operate in a vacuum, because the electrons will be scattered if they contact the molecules present in atmosphere. Like scanning electron microscopy, electron-beam machining has a high equipment cost. Another similarity is a safety concern. When an electron in the beam hits the workpiece, the energy of that electron is transferred to the atoms of the workpiece. This raises the energy level of the electrons in the workpiece’s electrons, which causes the atoms’ electrons to jump to higher shells within the atoms. As those electrons settle back down to their normal state, they release the excess energy in the form of X-rays. These are the same types of X-rays used for medical examinations, and shielding is required for operator safety. Unshielded exposure to X-rays has been shown to cause cancer.

Process: Explosive forming

How it is used: Forming frame rails of cars and light trucks, aircraft parts, housings.

Advantages:
- Can form complex shapes and very large parts.
- Fast setup time.
- Low tooling costs.

Disadvantages:
- Requires special safety precautions.
- Labor-intensive.
Explosive forming is an innovative process that can form complex or unusually large shapes. In explosive forming, an explosive charge is detonated, forcing the workpiece to conform to a die by means of plastic deformation. There are two basic types of explosive forming: contact and standoff. Contact explosive forming typically generates pressures of five or more times the magnitude of the pressures generated by standoff explosive forming.

In contact explosive forming, the charge is placed directly against the workpiece. When the explosive charge is detonated, the resulting pressure pushes the workpiece into the mold. The pressure from the detonated explosive charge is high enough to plastically deform the workpiece, causing the workpiece to assume the desired shape.

Standoff explosive forming differs from contact explosive forming in that the explosive charge is placed some distance from the workpiece. Upon detonation, the pressure wave is transmitted to the workpiece by a medium, usually water. The form used in standoff explosive forming locates a pocket between the form and the workpiece that is filled with air or another suitable gas. Upon detonation, a pressure wave moves outward from the explosive charge. When the pressure wave reaches the workpiece, it plastically deforms it into the mold cavity, causing the workpiece to assume the desired shape.

Water is a popular choice for the standoff explosive forming medium because it is inexpensive and essentially incompressible. When water is used as the medium for stand-off explosive forming, the process is popularly called hydroforming. The reader can learn more about standoff explosive forming with water as the medium at this Internet address: www.hydroforming.net/hydro/home/html/index.php.
Obviously, explosive forming mandates special safety precautions. Both forms of explosive forming are labor-intensive but are quick to set up. While explosive forming offers a lower tooling cost than most traditional forming methods, the production rate is slow. The greatest asset of explosive forming is its ability to make parts that cannot be made by other means.

Process: Impact extrusion (cold extrusion)

How it is used: Air tanks, fire extinguisher bottles.

Advantages:

- Good for long, thin objects, especially closed cylinders.
- Good for high-volume production.
- Smooth surfaces.

Disadvantages:

- Not good for asymmetrical shapes.
- Best for high volume.
- Not good for sharp contours.

Impact extrusion, also called cold extrusion, is a process whereby the workpiece is compressively loaded so as to cause material flow. The workpiece begins as a disc or cylinder called a “slug” or “blank” contained within a die. The slug is struck by the punch so as to exceed the yield strength of the slug and cause it to flow plastically. When the slug’s yield strength is exceeded, it flows to fill the space provided by the die and the punch. Because the slug has been deformed plastically, it maintains its new shape after the punch has retracted.
Impact extrusion is appropriate for long, thin objects. Because the process can be easily automated, impact extrusion is a good choice for high-volume production. Impact extrusion is well suited to the manufacture of closed-end cylinders. This makes impact extrusion popular as a manufacturing method for metal tanks and bottles. Most metal fire extinguisher bodies are impact-extruded.

Designing mechanical engineers should select impact extrusion to produce asymmetrical shapes. Impact-extruded parts should be designed with radiused corners, as impact extrusion cannot accurately produce sharp contours.

**Process: Investment casting, lost-wax process**

How it is used: Sporting equipment manufacture, aircraft parts.

**Advantages:**
- Suitable for most metals.
- Economically makes complex shapes.
- Gives the engineer enormous design freedom.

**Disadvantages:**
- Not good for blind holes.
- Not good for small holes (<1.5 mm).
- Must account for shrinkage as metal solidifies.

Investment casting is one of the oldest known metalworking techniques. Investment casting is also called the lost-wax process. It can be used to shape most metals.

In the primitive version of this process, a lump of wax was carved into the desired shape, complete with sprues and vents. The wax figure was then covered in successive layers consisting of a mixture of cow dung and straw. The dung-and-straw-covered wax was
carefully baked, melting the wax, which ran out of the now-firm dung-and-straw mold. Because the wax left the mold when it was melted, this method of casting was called the lost-wax process. Molten metal was then poured into the dung-and-straw mold and allowed to re-solidify. The mold was removed, usually by hammering, and the cast metal part was ready for any final finishing.

The modern version of this simple yet effective method of casting emerged as a highly respected manufacturing tool in the late twentieth century. One of the reasons that investment casting has surged in popularity is the enormous design freedom it gives mechanical engineers. This is due to the ability of investment casting to form complex shapes.

As useful as investment casting is, it does have a few shortcomings. Investment casting is not a good choice for blind holes or small holes. These holes are best drilled after casting. Metal that is investment-cast suffers from shrinkage as it re-solidifies and cools. Engineers must account for this shrinkage in order to attain the desired cast dimensions.

When careful control is maintained throughout the investment casting process, internal porosities and other flaws can be minimized. As a result, investment-cast products can compete against products that have been traditionally forged and machined.

Process: Laser machining

How it is used: Aerosol spray nozzles, holes in electronics, spot welding.

Advantages:

- High precision with consistent quality.
- Minimal tool wear.
- Works with any known material.
Disadvantages:

- High initial tooling cost.
- Best for thin parts.
- Holes are slightly tapered.

Laser machining uses a laser to focus a large amount of energy onto a small area of the workpiece, producing intense heat that vaporizes material from the lased spot.

Laser machining is popular for applications that include but are not limited to drilling aerosol spray nozzles, drilling holes in electronics, and cutting steel. Laser machining works with any known material.

Laser machining offers high precision with consistent quality. Because the laser beam does not dull or decay with usage, there is minimal tool wear. The American cutlery industry has been increasingly using laser machining for cutting blanks—steel workpieces that eventually become blades. Because the cutlery relies upon mass production, the near absence of tool wear in laser machining helps reduce manufacturing costs.

Before selecting laser machining, designing mechanical engineers need to consider that laser machining has a high initial tooling cost. Mechanically, laser machining works best with thin workpieces. Designing engineers should also be aware that holes drilled by laser beam machining are slightly tapered.

Process: Metal injection-molding

How it is used: Various small machine parts.

Advantages:

- Well suited to complex shapes.
- Suitable for high-volume production.
- Low labor cost.

Disadvantages:

- Best for small parts—walnut-sized, less than 1/4 inch thick.
- High shrinkage (20%).
- High tooling costs.

Metal injection-molding is a process whereby a mold is filled with a fine powder mixture consisting mostly of metal with polymer binders and small amounts of flow-control agents. The mold bonds the powder into the initial molded part shape, frequently called a “green” part. The process and tooling have much in common with plastic injection-molding.

The green part is then heated to remove the polymer binders and sinter the part. Considerable shrinkage occurs during this stage, typically about 20 percent. This large dimensional change needs to be considered during the design phase. Sintering results in a solid metal part.

From the perspective of designing mechanical engineers, metal injection-molding offers the ability to rapidly produce small, complex shapes of great precision with low labor cost. Metal injection-molding is a good choice for mass-producing small metal parts that would otherwise require multiple machining steps.

Metal injection-molding is limited in its applications to small parts (walnut-sized) less than 1/4 inch thick. Although metal injection-molding is well suited to mass production, the tooling costs are high.
Process: Sand casting

How it is used: Engine blocks, cylinder heads, most connecting rods.

Advantages:

- Great for intricate shapes.
- Great for large sizes.
- Usable with most metals.

Disadvantages:

- Rough finish; shrinkage (typically 1-2%).
- Needs some taper (draft) to remove pattern from mold.
- Bad for sharp corners.

Casting and molding methods offer designing mechanical engineers versatile and cost-effective manufacturing methods. Chief among casting and molding methods is sand casting.

Sand casting features a mold formed from by means of a pattern. The pattern is inserted into the medium, usually green sand, forming a cavity in the sand. The sand is pressed to conform to the pattern, and the pattern is then removed. The sand sustains the cavity left by the pattern. The cavity is filled with molten metal that is allowed to solidify. After the metal has sufficiently cooled, the sand is removed and the metal part is machined.

Sand casting can make intricate shapes cost-effectively and is well suited to the manufacture of large objects. Sand casting leaves a rough finish that may require further finishing. The part should also have a tapered shape to facilitate easy removal from the mold. Sharp corners are not advisable. Sand casting is usable with most metals.
The automotive industry makes extensive use of sand casting. The engine blocks of most reciprocating engines begin as sand castings. Cylinder heads, intake manifolds, and most connecting rods begin as sand castings.
LITERATURE CITATIONS

Chapter 1 - Working as a Team

1 - Interviews by the author of faculty members at the fifty universities with the largest mechanical engineering programs, as ranked by the American Society for Engineering Education as of 2003.

2 - Interviews by the author.


7 - Interviews by the author.

Chapter 2 - Information-Gathering and Communicating Your Ideas

Chapter 3 - Safety


7 - Interviews by the author with personnel of Atlantis Submarines, International, Vancouver, British Columbia, Canada.


13 - Personal observations by the author resulting from engineering analyses.

14 - Personal observations by the author resulting from engineering analyses.

15 - Personal observations by the author resulting from engineering analyses.

16 - Personal observations by the author resulting from engineering analyses.

17 - Unpublished measurements made by the author for analyses of vehicle-pedestrian accidents.

18 - Unpublished tests performed by the author.
19 - Personal observations by the author resulting from engineering analyses.


**Chapter 4 - Design Principles and Creativity**


**Chapter 5 - Application of Theory**


**Chapter 6 - Preparing to Prototype**

**Chapter 7 - Building the Prototype**


3. Personal observations by the author resulting from engineering analyses.

4. Personal observations by the author resulting from engineering analyses.


6. Unpublished tests observed by the author. The author participated in tests in which a person wearing a human-hair wig was positioned a short distance from a spinning shaft. Static electricity attracted strands of hair from the wig, causing them to wrap around the shaft. That action resulted in the nearly instantaneous removal of the wig.

   In the actual accident, the victim was scalped.


9. Personal observations by the author resulting from engineering analyses.


11. Personal observations by the author resulting from engineering analyses.

**Chapter 8 - Testing, Evaluating, and Refining the Prototype**

**Chapter 9 - Designing for Manufacture**


2. Ibid. pp. 3.104-3.105.


5. Ibid. pp. 3.177-3.196.


22 - Ibid. pp. 4.247-4.249.


24 - Ibid. pp. 3.119-3.124.

25 - Ibid. pp. 5.45-5.56.

27 - Ibid. pp. 3.159-3.176.