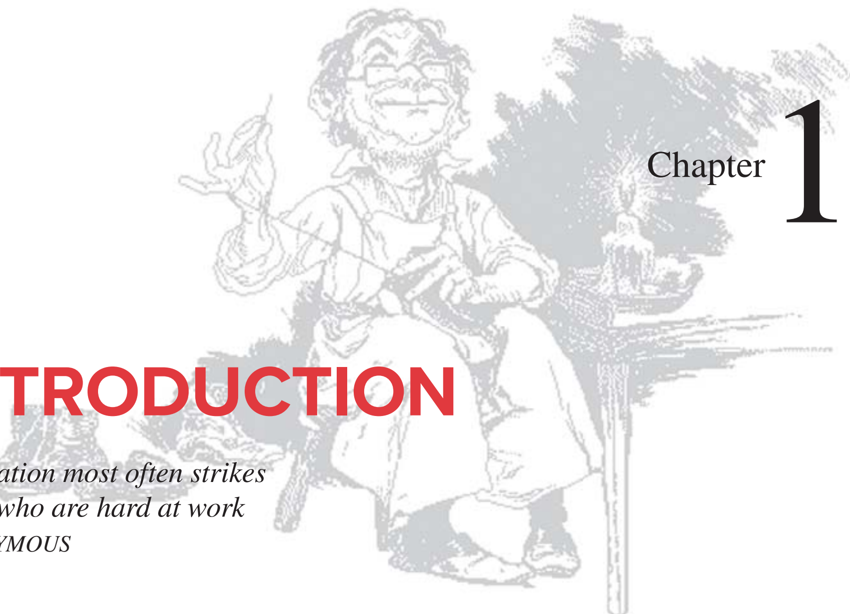


Chapter 1

INTRODUCTION

Inspiration most often strikes
those who are hard at work
ANONYMOUS

1.0 PURPOSE *Watch a lecture video (39:10)**

In this text we will explore the topics of **kinematics** and **dynamics of machinery** in respect to the **synthesis of mechanisms** in order to accomplish desired motions or tasks, and also the **analysis of mechanisms** in order to determine their rigid-body dynamic behavior. These topics are fundamental to the broader subject of **machine design**. On the premise that we cannot analyze anything until it has been synthesized into existence, we will first explore the topic of **synthesis of mechanisms**. Then we will investigate techniques of **analysis of mechanisms**. All this will be directed toward developing your ability to design viable mechanism solutions to real, unstructured engineering problems by using a **design process**. We will begin with careful definitions of the terms used in these topics.

* http://www.designofmachinery.com/DOM/Introduction.mp4

1.1 KINEMATICS AND KINETICS

KINEMATICS *The study of motion without regard to forces.*

KINETICS *The study of forces on systems in motion.*

These two concepts are really *not* physically separable. We arbitrarily separate them for instructional reasons in engineering education. It is also valid in engineering design practice to first consider the desired kinematic motions and their consequences, and then subsequently investigate the kinetic forces associated with those motions. The student should realize that the division between **kinematics** and **kinetics** is quite arbitrary and is done largely for convenience. One cannot design most dynamic mechanical systems without taking both topics into thorough consideration. It is quite logical to consider them in the order listed since, from Newton's second law, $\mathbf{F} = m\mathbf{a}$, one typically needs to know the **accelerations** ($\mathbf{a}$) in order to compute the dynamic **forces** ($\mathbf{F}$) due to the motion of the system's **mass** (m). There are also many situations in which the applied forces are known and the resultant accelerations are to be found.

One principal aim of **kinematics** is to create (design) the desired motions of the subject mechanical parts and then mathematically compute the positions, velocities, and accelerations that those motions will create on the parts. Since, for most earthbound mechanical systems, the mass remains essentially constant with time, defining the accelerations as a function of time then also defines the dynamic forces as a function of time. **Stresses**, in turn, will be a function of both applied and inertial ($m\mathbf{a}$) forces. Since engineering design is charged with creating systems that will not fail during their expected service life, the goal is to keep stresses within acceptable limits for the materials chosen and the environmental conditions encountered. This obviously requires that all system forces be defined and kept within desired limits. In machinery that moves (the only interesting kind), the largest forces encountered are often those due to the dynamics of the machine itself. These dynamic forces are proportional to acceleration, which brings us back to kinematics, the foundation of mechanical design. Very basic and early decisions in the design process involving kinematic principles can be crucial to the success of any mechanical design. A design that has poor kinematics will prove troublesome and perform badly.

1.2 MECHANISMS AND MACHINES

A **mechanism** is a device that transforms motion to some desirable pattern and typically develops very low forces and transmits little power. Hunt[1] defines a mechanism as "a means of *transmitting, controlling, or constraining relative movement*." A **machine** typically contains mechanisms that are designed to provide significant forces and transmit significant power.[1] Some examples of common mechanisms are a pencil sharpener, a camera shutter, an analog clock, a folding chair, an adjustable desk lamp, and an umbrella. Some examples of machines that possess motions similar to the mechanisms listed above are a food blender, a bank vault door, an automobile transmission, a bulldozer, a robot, and an amusement park ride. There is no clear-cut dividing line between mechanisms and machines. They differ in degree rather than in kind. If the forces or energy levels within the device are significant, it is considered a machine; if not, it is considered a mechanism. A useful working **definition of a mechanism** is *a system of elements arranged to transmit* **motion** *in a predetermined fashion.* This can be converted to a definition of a **machine** by adding the words **and energy** after **motion**.

A mechanism

Mechanisms, if lightly loaded and run at slow speeds, can sometimes be treated strictly as kinematic devices; that is, they can be analyzed kinematically without regard to forces. Machines (and mechanisms running at higher speeds), on the other hand, must first be treated as mechanisms; a kinematic analysis of their velocities and accelerations must be done, and then they must be subsequently analyzed as dynamic systems in which their static and dynamic forces due to those accelerations are analyzed using the principles of kinetics. **Part I** of this text deals with **Kinematics of Mechanisms**, and **Part II** with **Dynamics of Machinery**. The techniques of mechanism synthesis presented in Part I are applicable to the design of both mechanisms and machines, since in each case some collection of movable members must be created to provide and control the desired motions and geometry.

A machine

1.3 A BRIEF HISTORY OF KINEMATICS

Machines and mechanisms have been devised by people since the dawn of history. The ancient Egyptians devised primitive machines to accomplish the building of the pyramids and other monuments. Though the wheel and pulley (on an axle) were not known to the Old Kingdom Egyptians, they made use of the lever, the inclined plane (or wedge), and probably the log roller. The origin of the wheel and axle is not definitively known. Its first appearance seems to have been in Mesopotamia about 3000 to 4000 B.C.

A great deal of design effort was spent from early times on the problem of timekeeping as more sophisticated clockworks were devised. Much early machine design was directed toward military applications (catapults, wall scaling apparatus, etc.). The term **civil engineering** was later coined to differentiate civilian from military applications of technology. **Mechanical engineering** had its beginnings in machine design as the inventions of the industrial revolution required more complicated and sophisticated solutions to motion control problems. **James Watt** (1736-1819) probably deserves the title of first kinematician for his synthesis of a straight-line linkage (see Figure 3-29a) to guide the very long stroke pistons in the then new steam engines. Since the planer was yet to be invented (in 1817), no means then existed to machine a long, straight guide to serve as a crosshead in the steam engine. Watt was certainly the first on record to recognize the value of the motions of the coupler link in the fourbar linkage. **Oliver Evans** (1755-1819), an early American inventor, also designed a straight-line linkage for a steam engine. **Euler** (1707-1783) was a contemporary of Watt, though they apparently never met. Euler presented an analytical treatment of mechanisms in his *Mechanica Sive Motus Scienta Analytice Exposita* (1736-1742), which included the concept that planar motion is composed of two independent components, namely, translation of a point and rotation of the body about that point. Euler also suggested the separation of the problem of dynamic analysis into the "geometrical" and the "mechanical" in order to simplify the determination of the system's dynamics. Two of his contemporaries, **d'Alembert** and **Kant**, also proposed similar ideas. This is the origin of our division of the topic into kinematics and kinetics as described on a previous page.

In the early 1800s, L'Ecole Polytechnic in Paris, France, was the repository of engineering expertise. **Lagrange** and **Fourier** were among its faculty. One of its founders was **Gaspard Monge** (1746-1818), inventor of descriptive geometry (which incidentally was kept as a military secret by the French government for 30 years because of its value in planning fortifications). Monge created a course in elements of machines and set about the task of classifying all mechanisms and machines known to mankind! His colleague, **Hachette**, completed the work in 1806 and published it as what was probably the first mechanism text in 1811. **Andre Marie Ampere** (1775-1836), also a professor at L'Ecole Polytechnic, set about the formidable task of classifying "all human knowledge." In his *Essai sur la Philosophie des Sciences*, he was the first to use the term **cinematique**, from the Greek word for motion,* to describe *the study of motion without regard to forces*, and suggested that "this science ought to include all that can be said with respect to motion in its different kinds, independently of the forces by which it is produced." His term was later anglicized to *kinematics* and germanized to *kinematik*.

Robert Willis (1800-1875) wrote the text *Principles of Mechanism* in 1841 while a professor of natural philosophy at the University of Cambridge, England. He attempted to systematize the task of mechanism synthesis. He counted five ways of obtaining

* Ampere is quoted as writing "(The science of mechanisms) must therefore not define a machine, as has usually been done, as an instrument by the help of which the direction and intensity of a given *force* can be altered, but as an instrument by the help of which the direction and *velocity* of a given motion can be altered. To this science . . . I have given the name Kinematics from Κινμα—motion." in Maunder, L. (1979). "Theory and Practice." *Proc. 5th World Cong. on Theory of Mechanisms and Machines*, Montreal, p. 1.

relative motion between input and output links: rolling contact, sliding contact, linkages, wrapping connectors (belts, chains), and tackle (rope or chain hoists). **Franz Reuleaux** (1829-1905) published *Theoretische Kinematik* in 1875. Many of his ideas are still current and useful. **Alexander Kennedy** (1847-1928) translated Reuleaux into English in 1876. This text became the foundation of modern kinematics and is still in print! (See bibliography at end of chapter.) He provided us with the concept of a kinematic pair (joint), whose shape and interaction define the type of motion transmitted between elements in the mechanism. Reuleaux defined six basic mechanical components: the link, the wheel, the cam, the screw, the ratchet, and the belt. He also defined "higher" and "lower" pairs, higher having line or point contact (as in a roller or ball bearing) and lower having surface contact (as in pin joints). Reuleaux is generally considered the father of modern kinematics and is responsible for the symbolic notation of skeletal, generic linkages used in all modern kinematics texts.

In the 20th century, prior to World War II, most theoretical work in kinematics was done in Europe, especially in Germany. Few research results were available in English. In the United States, kinematics was largely ignored until the 1940s when **A. E. R. de Jonge** wrote *What Is Wrong with 'Kinematics' and 'Mechanisms'?*[2] which called upon the U.S. mechanical engineering education establishment to pay attention to the European accomplishments in this field. Since then, much new work has been done, especially in kinematic synthesis, by American and European engineers and researchers such as **J. Denavit**, **A. Erdman**, **F. Freudenstein**, **A. S. Hall**, **R. Hartenberg**, **R. Kaufman**, **B. Roth**, **G. Sandor**, and **A. Soni** (all of the United States) and **K. Hain** (of Germany). Since the fall of the "iron curtain" much original work done by Soviet Russian kinematicians has become available in the United States, such as that by **Artobolevsky.**[3] Many U.S. researchers have applied the computer to solve previously intractable problems, of both analysis and synthesis, making practical use of many of the theories of their predecessors.[4] This text will make much use of the availability of computers to allow more efficient analysis and synthesis of solutions to machine design problems. Several computer programs are included with this book for your use.

1.4 APPLICATIONS OF KINEMATICS

One of the first tasks in solving any machine design problem is to determine the kinematic configuration(s) needed to provide the desired motions. Force and stress analyses typically cannot be done until the kinematic issues have been resolved. This text addresses the design of kinematic devices such as linkages, cams, and gears. Each of these terms will be fully defined in succeeding chapters, but it may be useful to show some examples of kinematic applications in this introductory chapter. You probably have used many of these systems without giving any thought to their kinematics.

Virtually any machine or device that moves contains one or more kinematic elements such as links, cams, gears, belts, and chains. Your bicycle is a simple example of a kinematic system that contains a chain drive to provide torque multiplication and simple cable-operated linkages for braking. An automobile contains many more examples of kinematic devices. Its steering system, wheel suspensions, and piston engine all contain linkages; the engine's valves are opened by cams; and the transmission is full of gears. Even the windshield wipers are linkage-driven. Figure 1-1a shows a linkage used to control the rear wheel movement over bumps of a modern automobile.

(*a*) Auto suspension linkage

(*b*) Utility tractor with backhoe
Photo by the author

(*c*) Linkage-driven exercise mechanism
Photo by the author

FIGURE 1-1

Examples of kinematic devices in general use

Construction equipment such as tractors, cranes, and backhoes all use linkages extensively in their design. Figure 1-1b shows a small backhoe that is a linkage driven by hydraulic cylinders. Another application using linkages is that of exercise equipment as shown in Figure 1-1c. The examples in Figure 1-1 are all of consumer goods that you may encounter in your daily travels. Many other kinematic examples occur in the realm of producer goods—machines used to make the many consumer products that we use. You are less likely to encounter these outside of a factory environment. Once you become familiar with the terms and principles of kinematics, you will no longer be able to look at any machine or product without seeing its kinematic aspects.

1.5 A DESIGN PROCESS *Watch a lecture video (29:47)**

Design, Invention, Creativity

These are all familiar terms but may mean different things to different people. These terms can encompass a wide range of activities from styling the newest look in clothing, to creating impressive architecture, to engineering a machine for the manufacture of facial tissues. **Engineering design**, which we are concerned with here, embodies all three of these activities as well as many others. The word **design** is derived from the Latin **designare**, which means *"to designate, or mark out."* Design can be simply defined as creating something new. Design is a common human activity. Artwork, clothing, geometric patterns, automobile bodies, and houses are just a few examples of things that are designed. Design is a universal constituent of engineering practice. **Engineering design** typically involves the creation of a device, system, or process using engineering principles.

The complexity of engineering subjects usually requires that the beginning student be served with a collection of **structured**, **set-piece problems** designed to elucidate a

* http://www.designofmachinery.com/DOM/Design_Process.mp4

TABLE 1-1
A Design Process

1	Identification of Need
2	Background Research
3	Goal Statement
4	Performance Specifications
5	Ideation and Invention
6	Analysis
7	Selection
8	Detailed Design
9	Prototyping and Testing
10	Production

Blank paper syndrome

particular concept or concepts related to the particular topic. These textbook problems typically take the form of "*given A, B, C, and D, find E.*" Unfortunately, real-life engineering problems are almost never so structured. Real design problems more often take the form of "*What we need is a framus to stuff this widget into that hole within the time allocated to the transfer of this other gizmo*." The new engineering graduate will search in vain among his or her textbooks for much guidance to solve such a problem. This **unstructured problem** statement usually leads to what is commonly called "**blank paper syndrome**." Engineers often find themselves staring at a blank sheet of paper pondering how to begin solving such an ill-defined problem.

Much of engineering education deals with topics of **analysis**, which means *to decompose, to take apart, to resolve into its constituent parts.* This is quite necessary. The engineer must know how to analyze systems of various types, mechanical, electrical, thermal, or fluid. Analysis requires a thorough understanding of both the appropriate mathematical techniques and the fundamental physics of the system's function. But, before any system can be analyzed, it must exist, and a blank sheet of paper provides little substance for analysis. Thus the first step in any engineering design exercise is that of **synthesis**, which means *putting together.*

The design engineer, in practice, regardless of discipline, continuously faces the challenge of *structuring the unstructured problem.* Inevitably, the problem as posed to the engineer is ill-defined and incomplete. Before any attempt can be made to *analyze the situation,* he or she must first carefully define the problem, using an engineering approach, to ensure that any proposed solution will solve the right problem. Many examples exist of excellent engineering solutions that were ultimately rejected because they solved the wrong problem, i.e., a different one than the client really had.

Much research has been devoted to the definition of various "design processes" intended to provide means to structure the unstructured problem and lead to a viable solution. Some of these processes present dozens of steps, others only a few. The one presented in Table 1-1 contains 10 steps and has, in the author's experience, proved successful in over 40 years of practice in engineering design.

ITERATION Before we discuss each of these steps in detail, it is necessary to point out that this is not a process in which one proceeds from step one through ten in a linear fashion. Rather it is, by its nature, an iterative process in which progress is made haltingly, two steps forward and one step back. It is inherently *circular*. To **iterate** means *to repeat, to return to a previous state.* If, for example, your apparently great idea, upon analysis, turns out to violate the second law of thermodynamics, you can return to the ideation step and get a better idea! Or, if necessary, you can return to an earlier step in the process, perhaps the background research, and learn more about the problem. With the understanding that the actual execution of the process involves iteration, for simplicity, we will now discuss each step in the order listed in Table 1-1.

Identification of Need

This first step is often done for you by someone, boss or client, saying, "What we need is . . .." Typically this statement will be brief and lacking in detail. It will fall far short of providing you with a structured problem statement. For example, the problem statement might be "We need a better lawn mower."

Background Research

This is the most important phase in the process, and is unfortunately often the most neglected. The term **research**, used in this context, should *not* conjure up visions of white-coated scientists mixing concoctions in test tubes. Rather this is research of a more mundane sort, gathering background information on the relevant physics, chemistry, or other aspects of the problem. Also it is desirable to find out if this, or a similar problem, has been solved before. There is no point in reinventing the wheel. If you are lucky enough to find a ready-made solution on the market, it will no doubt be more economical to purchase it than to build your own. Most likely this will not be the case, but you may learn a great deal about the problem to be solved by investigating the existing "art" associated with similar technologies and products. Many companies purchase, disassemble, and analyze their competitors' products, a process sometimes referred to as "**benchmarking**."

Identifying the need

The **patent** literature and technical publications in the subject area are obvious sources of information and are accessible via the World Wide Web. The U.S. Patent and Trademark Office operates a web site at www.uspto.gov where you can search patents by keyword, inventor, title, patent number, or other data. You can print a copy of the patent from the site. A commercial site at www.delphion.com also provides copies of extant patents including those issued in European countries. The "disclosure" or "specification" section of a patent is required to describe the invention in such detail that anyone "skilled in the art" could make the invention. In return for this full disclosure, the government grants the inventor a 20-year monopoly on the claimed invention. After that term expires, anyone can use it. Clearly, if you find that the solution exists and is covered by a patent still in force, you have only a few ethical choices: buy the patentee's existing solution, design something that does not conflict with the patent, or drop the project.

Reinventing the wheel

Technical publications in engineering are numerous and varied and are provided by a large number of professional organizations. For the subject matter of this text, the *American Society of Mechanical Engineers* (ASME), which offers inexpensive student memberships, and the *International Federation for the Theory of Machines and Mechanisms* (IFToMM) both publish relevant journals, the ASME *Journal of Mechanical Design* and *Mechanism and Machine Theory*, respectively. Your school library may subscribe to these, and you can purchase copies of articles from their web sites at http://mechanicaldesign.asmedigitalcollection.asme.org/journal.aspx and http://www.journals.elsevier.com/mechanism-and-machine-theory/, respectively.

The World Wide Web provides an incredibly useful resource for the engineer or student looking for information on any subject. The many search engines available will deliver a wealth of information in response to selected keywords. The web makes it easy to find sources for purchased hardware, such as gears, bearings, and motors, for your machine designs. In addition, much machine design information is available from the web. A number of useful web sites are catalogued in the bibliography of this chapter.

Grass shorteners

It is very important that sufficient energy and time be expended on this research and preparation phase of the process in order to avoid the embarrassment of concocting a great solution to the wrong problem. Most inexperienced (and some experienced) engineers give too little attention to this phase and jump too quickly into the ideation and invention stage of the process. *This must be avoided!* You must discipline yourself to *not* try to solve the problem before thoroughly preparing yourself to do so.

Goal Statement

Once the background of the problem area as originally stated is fully understood, you will be ready to recast that problem into a more coherent goal statement. This new problem statement should have three characteristics. It should be concise, be general, and be uncolored by any terms that predict a solution. It should be couched in terms of **functional visualization**, *meaning to visualize its function*, rather than any particular embodiment. For example, if the original statement of need was *"Design a Better Lawn Mower,"* after research into the myriad of ways to cut grass that have been devised over the ages, the wise designer might restate the goal as "**Design a Means to Shorten Grass.**" The original problem statement has a built-in trap in the form of the *colored* words "lawn mower." For most people, this phrase will conjure up a vision of something with whirring blades and a noisy engine. For the **ideation** phase to be most successful, it is necessary to avoid such images and to state the problem generally, clearly, and concisely. As an exercise, list 10 ways to shorten grass. Most of them would not occur to you had you been asked for 10 better lawn mower designs. You should use **functional visualization** to avoid unnecessarily limiting your creativity!

TABLE 1-2
Performance Specifications

1 Device to have self-contained power supply.

2 Device to be corrosion resistant.

3 Device to cost less than $100.00.

4 Device to emit < 80 dB sound intensity at 10 m.

5 Device to shorten 1/4 acre of grass per hour.

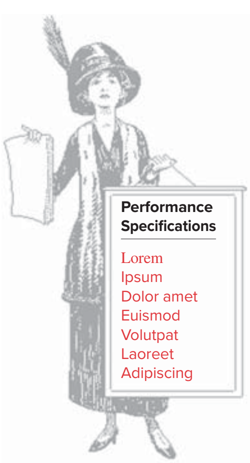
6 etc. . . . etc.

Performance Specifications [*]

When the background is understood, and the goal clearly stated, you are ready to formulate a set of *performance specifications* (also called *task specifications*). These should **not** be design specifications. The difference is that **performance specifications** define **what** *the system must do*, while **design specifications** define **how** *it must do it*. At this stage of the design process it is unwise to attempt to specify *how* the goal is to be accomplished. That is left for the **ideation** phase. The purpose of the performance specifications is to carefully define and constrain the problem so that it both *can be solved* and *can be shown to have been solved* after the fact. A sample set of performance specifications for our "grass shortener" is shown in Table 1-2.

Note that these specifications constrain the design without overly restricting the engineer's design freedom. It would be inappropriate to require a gasoline engine for specification 1, because other possibilities exist that will provide the desired mobility. Likewise, to demand stainless steel for all components in specification 2 would be unwise, since corrosion resistance can be obtained by other, less-expensive means. In short, the performance specifications serve to define the problem in as complete and as general a manner as possible, and they serve as a contractual definition of what is to be accomplished. The finished design can be tested for compliance with the specifications.

[*] Orson Welles, famous author and filmmaker, once said, "*The enemy of art is the absence of limitations*." We can paraphrase that as *The enemy of design is the absence of specifications*.



Ideation and Invention

This step is full of both fun and frustration. This phase is potentially the most satisfying to most designers, but it is also the most difficult. A great deal of research has been done to explore the phenomenon of **creativity**. It is, most agree, a common human trait. It is certainly exhibited to a very high degree by all young children. The rate and degree of development that occurs in the human from birth through the first few years of life certainly requires some innate creativity. Some have claimed that our methods of Western education tend to stifle children's natural creativity by encouraging conformity and restricting individuality. From "coloring within the lines" in kindergarten to imitating the textbook's writing patterns in later grades, individuality is suppressed in favor of a socializing conformity. This is perhaps necessary to avoid anarchy but probably does have the effect of reducing the individual's ability to think creatively. Some claim that creativity can be taught, others that it is only inherited. No hard evidence exists for either theory. It is probably true that one's lost or suppressed creativity can be rekindled. Other studies suggest that most everyone underutilizes his or her potential creative abilities. You can enhance your creativity through various techniques.

CREATIVE PROCESS Many techniques have been developed to enhance or inspire creative problem solving. In fact, just as design processes have been defined, so has the *creative process* shown in Table 1-3. This creative process can be thought of as a subset of the design process and to exist within it. The ideation and invention step can thus be broken down into these four substeps.

IDEA GENERATION is the most difficult of these steps. Even very creative people have difficulty inventing "on demand." Many techniques have been suggested to improve the yield of ideas. The most important technique is that of *deferred judgment*, which means that your criticality should be temporarily suspended. Do not try to judge the quality of your ideas at this stage. That will be taken care of later, in the **analysis** phase. The goal here is to obtain as large a *quantity* of potential designs as possible. Even superficially ridiculous suggestions should be welcomed, as they may trigger new insights and suggest other more realistic and practical solutions.

BRAINSTORMING is a technique for which some claim great success in generating creative solutions. This technique requires a group, preferably 6 to 15 people, and attempts to circumvent the largest barrier to creativity, which is *fear of ridicule.* Most people, when in a group, will not suggest their real thoughts on a subject, for fear of being laughed at. Brainstorming's rules require that no one be allowed to make fun of or criticize anyone's suggestions, no matter how ridiculous. One participant acts as "scribe" and is duty bound to record all suggestions, no matter how apparently silly. When done properly, this technique can be fun and can sometimes result in a "feeding frenzy" of ideas that build upon each other. Large quantities of ideas can be generated in a short time. Judgment on their quality is deferred to a later time.

When you are working alone, other techniques are necessary. **Analogies** and **inversion** are often useful. Attempt to draw analogies between the problem at hand and other physical contexts. If it is a mechanical problem, convert it by analogy to a fluid or electrical one. Inversion turns the problem inside out. For example, consider what you want moved to be stationary and vice versa. Insights often follow. Another useful aid to creativity is the use of **synonyms**. Define the action verb in the problem statement, and then list as many synonyms for that verb as possible. For example:

Problem statement: *Move this object from point A to point B.*

The action verb is "move." Some synonyms are push, pull, slip, slide, shove, throw, eject, jump, spill.

By whatever means, the aim in this **ideation** step is to generate a large number of ideas without particular regard to quality. But, at some point, your "mental well" will go dry. You will have then reached the step in the creative process called **frustration**. It is time to leave the problem and do something else for a time. While your conscious mind is occupied with other concerns, your subconscious mind will still be hard at work on the

TABLE 1-3
The Creative Process

5a	Idea Generation
5b	Frustration
5c	Incubation
5d	Eureka!

Brainstorming

Frustration

Eureka!

problem. This is the step called **incubation.** Suddenly, at a quite unexpected time and place, an idea will pop into your consciousness, and it will seem to be the obvious and "right" solution to the problem . . . **Eureka!** Most likely, later analysis will discover some flaw in this solution. If so, back up and **iterate!** More ideation, perhaps more research, and possibly even a redefinition of the problem may be necessary.

In "Unlocking Human Creativity,"[5] Wallen describes three requirements for creative insight:

- Fascination with a problem.
- Saturation with the facts, technical ideas, data, and the background of the problem.
- A period of reorganization.

The first of these provides the motivation to solve the problem. The second is the background research step described above. The period of reorganization refers to the frustration phase when your subconscious works on the problem. Wallen[5] reports that testimony from creative people tells us that in this period of reorganization they have no conscious concern with the particular problem and that the moment of insight frequently appears in the midst of relaxation or sleep. So to enhance your creativity, saturate yourself in the problem and related background material. Then relax and let your subconscious do the hard work!

Analysis

Once you are at this stage, you have structured the problem, at least temporarily, and can now apply more sophisticated analysis techniques to examine the performance of the design in the **analysis phase** of the design process. (Some of these analysis methods will be discussed in detail in the following chapters.) Further iteration will be required as problems are discovered from the analysis. Repetition of as many earlier steps in the design process as necessary must be done to ensure the success of the design.

	Cost	*Safety*	*Performance*	*Reliability*	*RANK*
Weighting Factor	.35	.30	.15	.20	1.0
Design 1	3 / 1.05	6 / 1.80	4 / .60	9 / 1.80	5.3
Design 2	4 / 1.40	2 / .60	7 / 1.05	2 / .40	3.5
Design 3	1 / .35	9 / 2.70	4 / .60	5 / 1.00	4.7
Design 4	9 / 3.15	1 / .30	6 / .90	7 / 1.40	5.8
Design 5	7 / 2.45	4 / 1.20	2 / .30	6 / 1.20	5.2

FIGURE 1-2

A decision matrix

Selection

When the technical analysis indicates that you have some potentially viable designs, the best one available must be **selected** for **detailed design**, **prototyping,** and **testing.** The selection process usually involves a comparative analysis of the available design solutions. A **decision matrix** sometimes helps to identify the best solution by forcing you to consider a variety of factors in a systematic way. A decision matrix for our better grass shortener is shown in Figure 1-2. Each design occupies a row in the matrix. The columns are assigned categories in which the designs are to be judged, such as cost, ease of use, efficiency, performance, reliability, and any others you deem appropriate to the particular problem. Each category is then assigned a **weighting factor**, which measures its relative importance. For example, reliability may be a more important criterion to the user than cost, or vice versa. You as the design engineer have to exercise your judgment as to the selection and weighting of these categories. The body of the matrix is then filled with numbers that rank each design on a convenient scale, such as 1 to 10, in each of the categories. Note that this is ultimately a *subjective ranking* on your part. You must examine the designs and decide on a score for each. The scores are then multiplied by the weighting factors (which are usually chosen so as to sum to a convenient number such as 1) and the products are summed for each design. The weighted scores then give a ranking of the designs. Be cautious in applying these results. Remember the source and subjectivity of your scores and the weighting factors! There is a temptation to put more faith in these results than is justified. After all, they look impressive! They can even be taken out to several decimal places! (But they shouldn't be.) The real value of a decision matrix is that it breaks the problem into more tractable pieces and forces you to think about the relative value of each design in many categories. You can then make a more informed decision as to the "best" design.

Detailed Design

This step usually includes the creation of a complete set of assembly and detail drawings or **computer-aided design** (CAD) part files for *each and every part* used in the design. Each detail drawing must specify all the dimensions and the material specifications necessary to make that part. From these drawings (or CAD files) a prototype test model (or models) must be constructed for physical testing. Most likely the tests will discover more flaws, requiring further **iteration**.

Prototyping and Testing

MODELS Ultimately, one cannot be sure of the correctness or viability of any design until it is built and tested. This usually involves the construction of a prototype physical model. A mathematical model, while very useful, can never be as complete and accurate a representation of the actual physical system as a physical model, due to the need to make simplifying assumptions. Prototypes are often very expensive but may be the most economical way to prove a design, short of building the actual, full-scale device. Prototypes can take many forms, from working scale models to full-size, but simplified, representations of the concept. Scale models introduce their own complications in regard to proper scaling of the physical parameters. For example, volume of material varies as the cube of linear dimensions, but surface area varies as the square. Heat transfer to the environment may be proportional to surface area, while heat generation may be proportional to volume. So linear scaling of a system, either up or down, may lead to behavior different from that of the full-scale system. One must exercise caution in scaling physical models. You will find as you begin to design linkage mechanisms that a **simple cardboard model** of your chosen link lengths, joined together with thumbtacks for pivots, will tell you a great deal about the quality and character of the mechanism's motions. You should get into the habit of making such simple articulated models for all your linkage designs.

TESTING of the model or prototype may range from simply actuating it and observing its function to attaching extensive instrumentation to accurately measure displacements, velocities, accelerations, forces, temperatures, and other parameters. Tests may need to be done under controlled environmental conditions such as high or low temperature or humidity. The microcomputer has made it possible to measure many phenomena more accurately and inexpensively than could be done before.

Production

Finally, with enough time, money, and perseverance, the design will be ready for production. This might consist of the manufacture of a single final version of the design, but more likely will mean making thousands or even millions of your widget. The danger, expense, and embarrassment of finding flaws in your design after making large quantities of defective devices should inspire you to use the greatest care in the earlier steps of the design process to ensure that it is properly engineered.

The **design process** is widely used in engineering. Engineering is usually defined in terms of what an engineer does, but engineering can also be defined in terms of *how* the engineer does what he or she does. **Engineering** is *as much a method, an approach, a process, a state of mind for problem solving, as it is an activity*. The engineering approach is that of thoroughness, attention to detail, and consideration of all the possibilities. While it may seem a contradiction in terms to emphasize "attention to detail" while extolling the virtues of open-minded, freewheeling, creative thinking, it is not. The two activities are not only compatible, they are also symbiotic. It ultimately does no good to have creative, original ideas if you do not, or cannot, carry out the execution of those ideas and "reduce them to practice." To do this you must discipline yourself to suffer the nitty-gritty, nettlesome, tiresome details that are so necessary to the completion of any one phase of the creative design process. For example, to do a creditable job in the design of anything, you must *completely* define the problem. If you leave out some detail of the problem definition, you will end up solving the wrong problem. Likewise, you must *thoroughly* research the background information relevant to the problem. You must *exhaustively* pursue conceptual potential solutions to your problem. You must then *extensively* analyze these concepts for validity. And, finally, you must *detail* your chosen design down to the last nut and bolt to be confident it will work. If you wish to be a good designer and engineer, you must discipline yourself to do things thoroughly and in a logical, orderly manner, even while thinking great creative thoughts and iterating to a solution. Both attributes, creativity and attention to detail, are necessary for success in engineering design.

1.6 OTHER APPROACHES TO DESIGN

In recent years, an increased effort has been directed toward a better understanding of design methodology and the design process. Design methodology is the study of the process of designing. One goal of this research is to define the design process in sufficient detail to allow it to be encoded in a form amenable to execution in a computer, using "artificial intelligence" (AI).

Dixon[6] defines a design as a *state of information* which may be in any of several forms:

> . . . words, graphics, electronic data, and/or others. It may be partial or complete. It ranges from a small amount of highly abstract information early in the design process to a very large amount of detailed information later in the process sufficient to perform manufacturing. It may include, but is not limited to, information about size and shape, function, materials, marketing, simulated performance, manufacturing processes, tolerances, and more. Indeed, any and all information relevant to the physical or economic life of a designed object is part of its design.

He goes on to describe several generalized states of information such as the *requirements* state that is analogous to our **performance specifications**. Information about the physical concept is referred to as the *conceptual* state of information and is analogous to our **ideation** phase. His *feature configuration* and *parametric* states of information are similar in concept to our **detailed design** phase. Dixon then defines a design process as

> The series of activities by which the information about the designed object is changed from one information state to another.

Axiomatic Design

N. P. Suh[7] suggests an *axiomatic approach* to design in which there are four domains: **customer** domain**, functional** domain**, physical** domain, and **process** domain. These represent a range from "what" to "how," i.e., from a state of defining what the customer wants through determining the functions required and the needed physical embodiment, to how a process will achieve the desired end. He defines two axioms that need to be satisfied to accomplish this:

1 Maintain the independence of the functional requirements.

2 Minimize the information content.

The first of these refers to the need to create a complete and nondependent set of performance specifications. The second indicates that the best design solution will have the lowest information content (i.e., the least complexity). Others have earlier referred to this second idea as *KISS,* which stands, somewhat crudely, for "*keep it simple, stupid*."

The implementation of both Dixon's and Suh's approaches to the design process is somewhat complicated. The interested reader is referred to the literature cited in the bibliography to this chapter for more complete information.

1.7 MULTIPLE SOLUTIONS

Note that by the nature of the design process, there is **not** any **one** correct answer or solution to any design problem. Unlike the structured "engineering textbook" problems, which most students are used to, there is no right answer "in the back of the book" for any real design problem.* There are as many potential solutions as there are designers willing to attempt them. Some solutions will be better than others, but many will work. Others will not! There is no "one right answer" in design engineering, which is what makes it interesting. The only way to determine the relative merits of various potential design solutions is by thorough analysis, which usually will include physical testing of constructed prototypes. Because this is a very expensive process, it is desirable to do as much analysis on paper, or in the computer, as possible before actually building the device. Where feasible, mathematical models of the design, or parts of the design, should be created. These may take many forms, depending on the type of physical system involved. In the design of mechanisms and machines, it is usually possible to write the equations for the rigid-body dynamics of the system, and solve them in "closed form" with (or without) a computer. Accounting for the elastic deformations of the members of the mechanism or machine usually requires more complicated approaches using **finite difference** techniques or the **finite element method** (FEM).

* A student once commented that "*Life is an odd-numbered problem*." This (slow) author had to ask for an explanation, which was, "*The answer is not in the back of the book*."

1.8 HUMAN FACTORS ENGINEERING

Make the machine fit the man

With few exceptions, all machines are designed to be used by humans. Even robots must be programmed by a human. **Human factors engineering** is the study of the human-machine interaction and is defined as *an applied science that coordinates the design of devices, systems, and physical working conditions with the capacities and requirements of the worker*. The machine designer must be aware of this subject and design devices to "fit the man" rather than expect the man to adapt to fit the machine. The term **ergonomics** is synonymous with *human factors engineering*. We often see reference to the good or bad ergonomics of an automobile interior or a household appliance. A machine designed with poor ergonomics will be uncomfortable and tiring to use and may even be dangerous. (Have you programmed your VCR lately, or set its clock?)

There is a wealth of human factors data available in the literature. Some references are noted in the bibliography. The type of information that might be needed for a machine design problem ranges from dimensions of the human body and their distribution among the population by age and gender, to the ability of the human body to withstand accelerations in various directions, to typical strengths and force-generating ability in various positions. Obviously, if you are designing a device that will be controlled by a human (a grass shortener, perhaps), you need to know how much force the user can exert with hands held in various positions, what the user's reach is, and how much noise the ears can stand without damage. If your device will carry the user on it, you need data on the limits of acceleration that the body can tolerate. Data on all these topics exist. Much of it was developed by the government which regularly tests the ability of military personnel to withstand extreme environmental conditions. Part of the background research of any machine design problem should include some investigation of human factors.

1.9 THE ENGINEERING REPORT *Watch a short video (15:57)**

Communication of your ideas and results is a very important aspect of engineering. Many engineering students picture themselves in professional practice spending most of their time doing calculations of a nature similar to those they have done as students. Fortunately, this is seldom the case, as it would be very boring. Actually, engineers spend the largest percentage of their time communicating with others, either orally or in writing. Engineers write proposals and technical reports, give presentations, and interact with support personnel and managers. When your design is done, it is usually necessary to present the results to your client, peers, or employer. The usual form of presentation is a formal engineering report. Thus, it is very important for the engineering student to develop his or her communication skills. *You may be the cleverest person in the world, but no one will know that if you cannot communicate your ideas clearly and concisely*. In fact, if you cannot explain what you have done, you probably don't understand it yourself. To give you some experience in this important skill, the design project assignments in later chapters are intended to be written up in formal engineering reports. Information on the writing of engineering reports can be found in the suggested readings in the bibliography at the end of this chapter.

* http://www.designofmachinery.com/DOM/Documentation.mp4

1.10 UNITS *Watch a short video (10:07)**

There are several systems of units used in engineering. The most common in the United States are the **U.S. foot-pound-second (fps) system**, the **U.S. inch-pound-second (ips) system**, and the **Systeme International (SI)**. All systems are created from the choice of three of the quantities in the general expression of Newton's second law

$$F = \frac{ml}{t^2} \tag{1.1a}$$

where F is force, m is mass, l is length, and t is time. The units for any three of these variables can be chosen, and the other is then derived in terms of the chosen units. The three chosen units are called *base units*, and the remaining one is then a *derived unit*.

Most of the confusion that surrounds the conversion of computations between either one of the U.S. systems and the SI system is due to the fact that the SI system uses a different set of base units than the U.S. systems. Both U.S. systems choose ***force***, ***length***, and ***time*** as the base units. **Mass** is then a derived unit in the U.S. systems, and they are referred to as ***gravitational systems*** because the value of mass is dependent on the local gravitational constant. The SI system chooses ***mass***, ***length***, and ***time*** as the base units and force is the derived unit. SI is then referred to as an ***absolute system*** since the mass is a base unit whose value is not dependent on local gravity.

The **U.S. foot-pound-second (fps)** system requires that all lengths be measured in feet (ft), forces in pounds (lb), and time in seconds (sec). Mass is then derived from Newton's law as

$$m = \frac{Ft^2}{l} \tag{1.1b}$$

and the units are pound seconds squared per **foot** (lb-sec^2/ft) = **slugs.**

* http://www.designofmachinery.com/DOM/Units.mp4

1

The **U.S. inch-pound-second (ips)** system requires that all lengths be measured in inches (in), forces in pounds (lb), and time in seconds (sec). Mass is still derived from Newton's law, equation 1.1b, but the units are now:

Pound-seconds squared per **inch** (lb-sec^2/in) = **blobs**

This mass unit is not slugs! It is worth twelve slugs or one blob.*

Weight is defined as the force exerted on an object by gravity. Probably the most common units error that students make is to mix up these two unit systems (**fps** and **ips**) when converting weight units (which are pounds force) to mass units. Note that the gravitational acceleration constant (g) on earth at sea level is approximately 32.2 **feet** per second squared, which is equivalent to 386 **inches** per second squared. The relationship between mass and weight is:

Mass = weight / gravitational acceleration

$$m = \frac{W}{g} \tag{1.2}$$

It should be obvious that, if you measure all your lengths in **inches** and then use g = 32.2 **feet/**sec^2 to compute mass, you will have an error of a *factor of twelve* in your results. This is a serious error, large enough to crash the airplane you designed. Even worse off is the student who neglects to convert weight to mass *at all* in his calculations. He will have an error of either 32.2 or 386 in his results. This is enough to sink the ship!†

To even further add to the student's confusion about units is the common use of the unit of **pounds mass** (lb$_m$). This unit is often used in fluid dynamics and thermodynamics and comes about through the use of a slightly different form of Newton's equation:

$$F = \frac{ma}{g_c} \tag{1.3}$$

where m = mass in lb$_m$, a = acceleration, and g_c = the gravitational constant.

The value of the **mass** of an object measured in **pounds mass** (lb$_m$) is *numerically equal* to its **weight** in **pounds force** (lb$_f$). However the student *must remember to divide* the value of m in lb$_m$ by g_c when substituting into this form of Newton's equation. Thus the lb$_m$ will be divided either by 32.2 or by 386 when calculating the dynamic force. The result will be the same as when the mass is expressed in either slugs or blobs in the $F = ma$ form of the equation. Remember that in round numbers at sea level on earth:

1 lb$_m$ = 1 lb$_f$ 1 slug = 32.2 lb$_f$ 1 blob = 386 lb$_f$

The **SI** system requires that lengths be measured in meters (m), mass in kilograms (kg), and time in seconds (sec). This is sometimes also referred to as the **mks** system. Force is derived from Newton's law, equation 1.1b, and the units are:

kilogram-meters per second^2 (kg-m/s^2) = newtons

Thus in the SI system there are distinct names for mass and force which helps alleviate confusion. When converting between SI and U.S. systems, be alert to the fact that mass converts from kilograms (kg) to either slugs (sl) or blobs (bl), and force converts from newtons (N) to pounds (lb). The gravitational constant (g) in the SI system is approximately 9.81 m/s^2.

* It is unfortunate that the mass unit in the **ips** system has never officially been given a name such as the term ***slug*** used for mass in the **fps** system. The author boldly suggests (with tongue only slightly in cheek) that this unit of mass in the **ips** system be called a *blob* (bl) to distinguish it more clearly from the ***slug*** (sl), and to help the student avoid some of the common units errors listed above.

Twelve slugs = one blob

Blob does not sound any sillier than slug, is easy to remember, implies mass, and has a convenient abbreviation (bl) which is an anagram for the abbreviation for pound (lb). Besides, if you have ever seen a garden slug, you know it looks just like a "*little blob.*"

† A 125-million-dollar space probe was lost because NASA failed to convert data that had been supplied in *ips* units by its contractor, Lockheed Aerospace, into the metric units used in the NASA computer programs that controlled the spacecraft. It was supposed to orbit the planet Mars, but instead either burned up in the Martian atmosphere or crashed into the planet because of this units error. *Source: The Boston Globe, October 1, 1999, p. 1.*

TABLE 1-4 Variables and Units
Base Units in Boldface – Abbreviations in ( )

Variable	Symbol	ips unit	fps unit	SI unit
Force	F	**pounds (lb)**	**pounds (lb)**	newtons (N)
Length	l	**inches (in)**	**feet (ft)**	**meters (m)**
Time	t	**seconds (sec)**	**seconds (sec)**	**seconds (sec)**
Mass	m	lb–sec^2/in = bl	lb–sec^2/ft = sl	**kilograms (kg)**
Weight	W	pounds (lb)	pounds (lb)	newtons (N)
Velocity	v	in/sec	ft/sec	m/sec
Acceleration	a	in/sec^2	ft/sec^2	m/sec^2
Jerk	j	in/sec^3	ft/sec^3	m/sec^3
Angle	θ	degrees (deg)	degrees (deg)	degrees (deg)
Angle	θ	radians (rad)	radians (rad)	radians (rad)
Angular velocity	ω	rad/sec	rad/sec	rad/sec
Angular acceleration	α	rad/sec^2	rad/sec^2	rad/sec^2
Angular jerk	φ	rad/sec^3	rad/sec^3	rad/sec^3
Torque	T	lb–in	lb–ft	N–m
Mass moment of inertia	I	lb–in–sec^2	lb–ft–sec^2	N–m–sec^2
Energy	E	in–lb	ft–lb	joules (J)
Power	P	in–lb/sec	ft–lb/sec	watts (W)
Volume	V	in^3	ft^3	m^3
Weight density	γ	lb/in^3	lb/ft^3	N/m^3
Mass density	ρ	bl/in^3	sl/ft^3	kg/m^3

The principal system of units used in this textbook will be the U.S. **ips** system. Most machine design in the United States is still done in this system. Table 1-4 shows some of the variables used in this text and their units. Table 1-5 provides conversion factors between the U.S. and SI systems.

The student is cautioned to always check the units in any equation written for a problem solution, whether in school or in professional practice after graduation. If properly written, an equation should cancel all units across the equal sign. If it does not, then you can be *absolutely sure it is* ***incorrect.*** Unfortunately, a unit balance in an equation does not guarantee that it is correct, as many other errors are possible. Always double-check your results. You might save a life.

TABLE 1-5 Conversion Factors

From U.S. Customary Units to Metric Units

1 Blob (bl)	=	175.127	Kilograms (kg)
1 Cubic inch (in^3)	=	16.387	Cubic centimeters (cc)
1 Foot (ft)	=	0.304 8	Meter (m)
1 Horsepower (hp)	=	745.699	Watts (W)
1 Inch (in)	=	0.025 4	Meter (m)
1 Mile, U.S. statute (mi)	=	1 609.344	Meters (m)
1 Pound force (lb)	=	4.448 2	Newtons (N)
	=	444 822.2	Dynes
1 Pound mass (lbm)	=	0.453 6	Kilogram (kg)
1 Pound-foot (lb-ft)	=	1.355 8	Newton-meter (N-m)
	=	1.355 8	Joules (J)
1 Pound-foot/second (lb-ft/sec)	=	1.355 8	Watts (W)
1 Pound-inch (lb-in)	=	0.112 8	Newton-meter (N-m)
	=	0.112 8	Joule (J)
1 Pound-inch/second (lb-in/sec)	=	0.112 8	Watt (W)
1 Pound/$foot^2$ (lb/ft^2)	=	47.880 3	Pascals (Pa)
1 Pound/$inch^2$ (lb/in^2), (psi)	=	6 894.757	Pascals (Pa)
1 Revolution/minute (rpm)	=	0.104 7	Radian/second (rad/s)
1 Slug (sl)	=	14.593 9	Kilograms (kg)
1 Ton, short (2000 lbm)	=	907.184 7	Kilograms (kg)

Between U.S. Customary Units

1 Blob (bl)	=	12	Slugs (sl)
1 Blob (bl)	=	386	Pounds mass (lbm)
1 Foot (ft)	=	12	Inches (in)
1 Horsepower (hp)	=	550	Pound-feet/second (lb-ft/sec)
1 Knot	=	1.151 5	Miles/hour (mph)
1 Mile, U.S. statute (mi)	=	5 280	Feet (ft)
1 Mile/hour	=	1.4667	Feet/second (ft/sec)
1 Pound force (lb)	=	16	Ounces (oz)
1 Pound mass (lbm)	=	0.0311	Slug (sl)
1 Pound-foot (lb-ft)	=	12	Pound-inches (lb-in)
1 Pound-foot/second (lb-ft/sec)	=	0.001 818	Horsepower (hp)
1 Pound-inch (lb-in)	=	0.083 3	Pound-foot (lb-ft)
1 Pound-inch/second (lb-in/sec)	=	0.021 8	Horsepower (hp)
1 Pound/$inch^2$ (lb/in^2), (psi)	=	144	Pounds/$foot^2$ (lb/ft^2)
1 Radian/second (rad/sec)	=	9.549	Revolutions/minute (rpm)
1 Slug (sl)	=	32.174	Pounds mass (lbm)
1 Ton, short	=	2000	Pounds mass (lbm)

1.11 A DESIGN CASE STUDY

Of all the myriad activities that the practicing engineer engages in, the one that is at once the most challenging and potentially the most satisfying is design. Doing calculations to analyze a clearly defined and structured problem, no matter how complex, may be difficult, but the exercise of creating something from scratch, to solve a problem that is often poorly defined, is *very* difficult. The sheer pleasure and joy at conceiving a viable solution to such a design problem is one of life's great satisfactions for anyone, engineer or not.

Some years ago, a very creative engineer of the author's acquaintance, George A. Wood Jr., heard a presentation by another creative engineer of the author's acquaintance, Keivan Towfigh, about one of his designs. Years later, Mr. Wood himself wrote a short paper about creative engineering design in which he reconstructed Mr. Towfigh's presumed creative process when designing the original invention. Both Mr. Wood and Mr. Towfigh have kindly consented to the reproduction of that paper here. It serves, in this author's opinion, as an excellent example and model for the student of engineering design to consider when pursuing his or her own design career.

Educating for Creativity in Engineering[9]

by George A. Wood Jr.

One facet of engineering, as it is practiced in industry, is the creative process. Let us define creativity as Rollo May does in his book, The Courage to Create.[10] It is "the process of bringing something new into being." Much of engineering has little to do with creativity in its fullest sense. Many engineers choose not to enter into creative enterprise, but prefer the realms of analysis, testing and product or process refinement. Many others find their satisfaction in management or business roles and are thus removed from engineering creativity as we shall discuss it here.

From the outset, I wish to note that the less creative endeavors are no less important or satisfying to many engineers than is the creative experience to those of us with the will to create. It would be a false goal for all engineering schools to assume that their purpose was to make all would-be engineers creative and that their success should be measured by the "creative quotient" of their graduates.

On the other hand, for the student who has a creative nature, a life of high adventure awaits if he can find himself in an academic environment which recognizes his needs, enhances his abilities and prepares him for a place in industry where his potential can be realized.

In this talk I will review the creative process as I have known it personally and witnessed it in others. Then I shall attempt to indicate those aspects of my training that seemed to prepare me best for a creative role and how this knowledge and these attitudes toward a career in engineering might be reinforced in today's schools and colleges.

During a career of almost thirty years as a machine designer, I have seen and been a part of a number of creative moments. These stand as the high points of my working life. When I have been the creator I have felt great elation and immense satisfaction. When I have been with others at their creative moments I have felt and been buoyed up by their delight. To me, the creative moment is the greatest reward that the profession of engineering gives.

Let me recount an experience of eight years ago when I heard a paper given by a creative man about an immensely creative moment. At the First Applied Mechanisms Conference in Tulsa, Oklahoma, was a paper entitled The Four-Bar Linkage as an Adjustment Mechanism.[11] It was nestled between two "how to do it" academic papers with graphs and equations of interest to engineers in the analysis of their mechanism problems. This paper contained only one very elementary equation *and five simple illustrative figures; yet, I remember it now more clearly than any other paper I have ever heard at mechanism conferences. The author was Keivan Towfigh and he described the application of the geometric characteristics of the instant center of the coupler of a four bar mechanism.*

His problem had been to provide a simple rotational adjustment for the oscillating mirror of an optical galvanometer. To accomplish this, he was required to rotate the entire galvanometer assembly about an axis through the center of the mirror and perpendicular to the pivot axis of the mirror. High rigidity of the system after adjustment was essential with very limited space available and low cost required, since up to sixteen of these galvanometer units were used in the complete instrument.

His solution was to mount the galvanometer elements on the coupler link of a one-piece, flexure hinged, plastic four bar mechanism so designed that the mirror center was at the instant center of the linkage at the midpoint of its adjustment. (See Fig 4.) It is about this particular geometric point (see Fig 1.) that pure rotation occurs and with proper selection of linkage dimensions this condition of rotation without translation could be made to hold sufficiently accurately for the adjustment angles required.*

* The theory of instant centers will be thoroughly explained in Chapter 6.

Unfortunately, this paper was not given the top prize by the judges of the conference. Yet, it was, indirectly, a description of an outstandingly creative moment in the life of a creative man.

Let us look at this paper together and build the steps through which the author probably progressed in the achievement of his goal. I have never seen Mr. Towfigh since, and I shall therefore describe a generalized creative process which may be incorrect in some details but which, I am sure, is surprisingly close to the actual story he would tell.

The galvanometer problem was presented to Mr. Towfigh by his management. It was, no doubt, phrased something like this: "In our new model, we must improve the stability of the adjustment of the equipment but keep the cost down. Space is critical and low weight is too. The overall design must be cleaned up, since customers like modern, slim-styled equipment and we'll lose sales to others if we don't keep ahead of them on all points. Our industrial designer has this sketch that all of us in sales like and within which you should be able to make the mechanism fit."

Then followed a list of specifications the mechanism must meet, a time when the new model should be in production and, of course, the request for some new feature that would result in a strong competitive edge in the marketplace.

I wish to point out that the galvanometer adjustment was probably only one hoped-for improvement among many others. The budget and time allowed were little more than enough needed for conventional redesign, since this cost must be covered by the expected sales of the resulting instrument. For every thousand dollars spent in engineering, an equivalent increase in sales or reduction in manufacturing cost must be realized at a greater level than the money will bring if invested somewhere else.

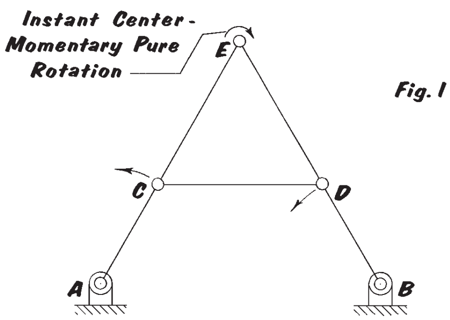
(research)

In approaching this project, Mr. Towfigh had to have a complete knowledge of the equipment he was designing. He had to have run the earlier models himself. He must have adjusted the mirrors of existing machines many times. He had to be able to visualize the function of each element in the equipment in its most basic form.

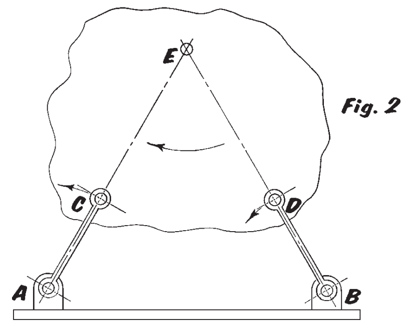
(ideation)

(frustration)

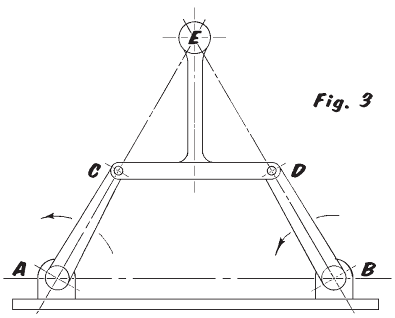
Secondly, he had to ask himself (as if he were the customer) what operational and maintenance requirements would frustrate him most. He had to determine which of these might be improved within the design time available. In this case he focused on the mirror adjustment. He considered the requirement of rotation without translation. He determined the maximum angles that would be necessary and the allowable translation that would not affect the practical accuracy of the equipment. He recognized the desirability of a one screw adjustment. He spent a few hours thinking of all the ways he had seen of rotating an assembly about an arbitrary point. He kept rejecting each solution as it came to him as he felt, in each case, that there was a better way. His ideas had too many parts, involved slides, pivots, too many screws, were too vibration sensitive or too large.



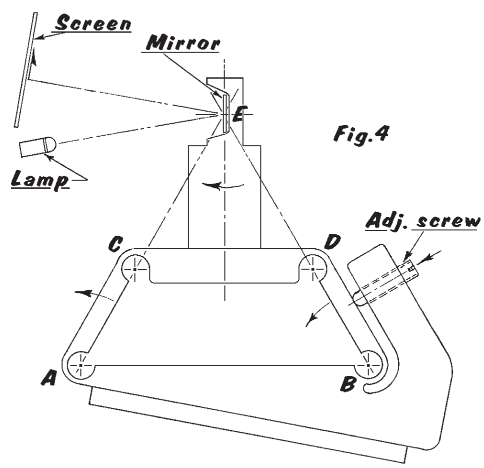
The Theory



The Development



The Mechanism



The Final Product of Keivan Towfigh

He thought about the problem that evening and at other times while he proceeded with the design of other aspects of the machine. He came back to the problem several times during the next few days. His design time was running out. He was a mechanism specialist and visualized a host of cranks and bars moving the mirrors. Then one day, probably after a period when he had turned his attention elsewhere, on rethinking of the adjustment device, an image of the system based on one of the elementary characteristics of a four bar mechanism came to him.

(incubation)

(Eureka!)

I feel certain that this was a visual image, as clear as a drawing on paper. It was probably not complete but involved two inspirations. First was the characteristics of the instant center. * *(See Figs 1, 2, 3.) Second was the use of flexure hinge joints which led to a one-piece plastic molding. (See Fig 4.) I am sure that at this moment he had a feeling that this solution was right. He knew it with certainty. The whole of his engineering background told him. He was elated. He was filled with joy. His pleasure was not because of the knowledge that his superiors would be impressed or that his security in the company would be enhanced. It was the joy of personal victory, the awareness that he had conquered.*

The creative process has been documented before by many others far more qualified to analyze the working of the human mind than I. Yet I would like to address, for the remaining minutes, how education can enhance this process and help more engineers, designers and draftsmen extend their creative potential.

* Defined in Chapter 6.

The key elements I see in creativity that have greatest bearing on the quality that results from the creative effort are visualization and basic knowledge that gives strength to the feeling that the right solution has been achieved. There is no doubt in my mind that the fundamental mechanical principles that apply in the area in which the creative effort is being made must be vivid in the mind of the creator. The words that he was given in school must describe real elements that have physical, visual significance. $F = ma$ must bring a picture to his mind vivid enough to touch.

If a person decides to be a designer, his training should instill in him a continuing curiosity to know how each machine he sees works. He must note its elements and mentally see them function together even when they are not moving. I feel that this kind of solid, basic knowledge couples with physical experience to build ever more critical levels at which one accepts a tentative solution as "right."

It should be noted that there have been times for all of us when the inspired "right" solution has proven wrong in the long run. That this happens does not detract from the process but indicates that creativity is based on learning and that failures build toward a firmer judgment base as the engineer matures. These failure periods are only negative, in the growth of a young engineer, when they result in the fear to accept a new challenge and beget excessive caution which then stifles the repetition of the creative process.

What would seem the most significant aspects of an engineering curriculum to help the potentially creative student develop into a truly creative engineer?

(analysis)

First is a solid, basic knowledge in physics, mathematics, chemistry and those subjects relating to his area of interest. These fundamentals should have physical meaning to the student and a vividness that permits him to explain his thoughts to the untrained layman. All too often technical words are used to cover cloudy concepts. They serve the ego of the user instead of the education of the listener.

Second is the growth of the student's ability to visualize. The creative designer must be able to develop a mental image of that which he is inventing. The editor of the book Seeing with the Mind's Eye,[12] by Samuels, says in the preface:

> *". . . visualization is the way we think. Before words, images were. Visualization is the heart of the bio-computer. The human brain programs and self-programs through its images. Riding a bicycle, driving a car, learning to read, baking a cake, playing golf - all skills are acquired through the image making process. Visualization is the ultimate consciousness tool."*

Obviously, the creator of new machines or products must excel in this area.

To me, a course in Descriptive Geometry is one part of an engineer's training that enhances one's ability to visualize theoretical concepts and graphically reproduce the result. This ability is essential when one sets out to design a piece of new equipment. First, he visualizes a series of complete machines with gaps where the problem or unknown areas are. During this time, a number of directions the development could take begin to form. The best of these images are recorded on paper and then are reviewed with those around him until, finally, a basic concept emerges.

The third element is the building of the student's knowledge of what can be or has been done by others with different specialized knowledge than he has. This is the area to which experience will add throughout his career as long as he maintains an enthusiastic curiosity. Creative engineering is a building process. No one can develop a new concept involving principles about which he has no knowledge. The creative engineer looks at problems in the light of what he has seen, learned and experienced and sees new ways for combining these to fill a new need.

Fourth is the development of the ability of the student to communicate his knowledge to others. This communication must involve not only skills with the techniques used by technical people but must also include the ability to share engineering concepts with untrained shop workers, business people and the general public. The engineer will seldom gain the opportunity to develop a concept *truly ingenious ideas are lost because the creator cannot transfer his vivid image to those who might finance or market it.*

Fifth is the development of a student's knowledge of the physical result of engineering. The more he can see real machines doing real work, the more creative he can be as a designer. The engineering student should be required to run tools, make products, adjust machinery and visit factories. It is through this type of experience that judgement grows as to what makes a good machine, when approximation will suffice and where optimization should halt.

It is often said that there has been so much theoretical development in engineering during the past few decades that the colleges and universities do not have time for the basics I have outlined above. It is suggested that industry should fill in the practice areas that colleges have no time for, so that the student can be exposed to the latest technology. To some degree I understand and sympathize with this approach, but I feel that there is a negative side that needs to be recognized. If a potentially creative engineer leaves college without the means to achieve some creative success as he enters his first job, his enthusiasm for creative effort is frustrated and his interest sapped long before the most enlightened company can fill in the basics. Therefore, a result of the "basics later" approach often is to remove from the gifted engineering student the means to express himself visually and physically. Machine design tasks therefore become the domain of the graduates of technical and trade schools and the creative contribution by many a brilliant university student to products that could make all our lives richer is lost.

As I said at the start, not all engineering students have the desire, drive and enthusiasm that are essential to creative effort. Yet I feel deeply the need for the enhancement of the potential of those who do. That expanding technology makes course decisions difficult for both student and professor is certainly true. The forefront of academic thought has a compelling attraction for both the teacher and the learner. Yet I feel that the development of strong basic knowledge, the abilities to visualize, to communicate, to respect what has been done, to see and feel real machinery, need not exclude or be excluded by the excitement of the new. I believe that there is a curriculum balance that can be achieved which will enhance the latent creativity in all engineering and science students. It can give a firm basis for those who look towards a career of mechanical invention and still include the excitement of new technology.

I hope that this discussion may help in generating thought and providing some constructive suggestions that may lead more engineering students to find the immense satisfaction of the creative moment in the industrial environment. In writing this paper I have spent considerable time reflecting on my years in engineering and I would close with the following thought. For those of us who have known such times during our careers, the successful culminations of creative efforts stand among our most joyous hours.

Mr. Wood's description of his creative experiences in engineering design and the educational factors which influenced them closely parallels this author's experience as well. The student is well advised to follow his prescription for a thorough grounding in the fundamentals of engineering and communication skills. A most satisfying career in the design of machinery can result.

1.12 WHAT'S TO COME

In this text we will explore the **design of machinery** in respect to the **synthesis of mechanisms** in order to accomplish desired motions or tasks, and also the **analysis of mechanisms** in order to determine their rigid-body dynamic behavior. On the premise that we cannot analyze anything until it has been synthesized into existence, we will first explore the synthesis of mechanisms. Then we will investigate the analysis of those and other mechanisms for their kinematic behavior. Finally, in Part II we will deal with the

dynamic analysis of the forces and torques generated by these moving machines. These topics cover the essence of the early stages of a design project. Once the kinematics and kinetics of a design have been determined, most of the conceptual design will have been accomplished. What then remains is **detailed design**—sizing the parts against failure. The topic of *detailed design* is discussed in other texts such as reference [8].

1.13 RESOURCES WITH THIS TEXT

The **Video Contents** contains a list of downloadable Master Lecture videos made by the author. An index of additional downloadable files is in the Appendices. These include computer programs, sample files for those programs, PDF files of all problem figures for use in solving them, two linkage atlases (the Hrones and Nelson fourbar atlas, and the Zhang, Norton, Hammond geared fivebar atlas), and digital videos with tutorial information on various topics in the book, program use, and views of actual machines in operation to show applications of the theory. There are also Powerpoints of the author's master lectures on most of the topics in the book. Clickable links to the Master Lectures, videos, and other files are also inserted in the e-book version of this text.

Programs

The commercial program Working Model (WM) is included in a "textbook edition" that has some limitations (see the Preface for more details). It will run all the WM files of book figures and examples that are included. Three programs written by the author for the design and analysis of linkages and cams are provided: DYNACAM, LINKAGES, and MATRIX. User manuals, sample files, and tutorial videos for some of these programs are provided and are accessed from within the programs.

Videos

The videos provided are in four categories: lectures, tutorials, and snippets on topics in the text, tutorials on program use, virtual laboratories, and depictions of actual mechanisms and machines.

LECTURES/TUTORIALS/SNIPPETS The lectures and tutorials on topics in the text typically provide much more information on the topic than can be presented on the page and also provide a "show and tell" advantage. These are all noted in the sections of the text where the topics are addressed. See the **Video Contents** for more information.

PROGRAM TUTORIALS The tutorials on program use give an introduction to the programs. These videos can be viewed from within the programs if the computer has an Internet connection.

VIRTUAL LABORATORIES There are two virtual laboratory videos provided, one on linkages and one on cams. These show and describe laboratory machines used by the author at WPI to introduce students to the measurement and analysis of kinematic and dynamic parameters on real machines. It is instructive to see the differences between theoretical predictions of a machine's behavior and actual measured data. All the data taken in a typical lab session from these machines is provided along with descriptions of the lab assignment so that anyone can do a virtual laboratory exercise similar to that done at WPI.

1

Machines in Action These range from commercially produced videos about a company's products or manufacturing processes to student-produced videos about their projects that involved mechanisms. Most students have not had an opportunity to visit a manufacturing plant or see the inner workings of machinery, and the hope is that these videos will give some insight into applications of the theories presented in the text.

1.14 REFERENCES

1 **Hunt, K. H**. (1978). *Kinematic Geometry of Mechanisms*. Oxford University Press, p.1.

2 **de Jonge, A. E. R.** (1942). "What Is Wrong with 'Kinematics' and 'Mechanisms'?" *Mechanical Engineering*, **64** (April), pp. 273-278.

3 **Artobolevsky, I. I.** (1975). *Mechanisms in Modern Engineering Design*. N. Weinstein, translator. Vols. 1 - 5. MIR Publishers: Moscow.

4 **Erdman, A. E.**, ed. (1993). *Modern Kinematics: Developments in the Last Forty Years*. Wiley Series in Design Engineering, John Wiley & Sons: New York.

5 **Wallen, R. W.** (1957). "Unlocking Human Creativity." *Proc. of Fourth Conference on Mechanisms*, Purdue University, pp. 2-8.

6 **Dixon, J. R.** (1995). "Knowledge Based Systems for Design." *Journal of Mechanical Design*, **117b**(2), p. 11.

7 **Suh, N. P.** (2014). "Axiomatic Design of Mechanical Systems." *Journal of Mechanical Design*, **117b**(2), p. 2.

8 **Norton, R. L.** (2006). *Machine Design: An Integrated Approach*. 5ed, Prentice-Hall: Upper Saddle River, NJ.

9 **Wood, G. A. Jr**. (1977). "Educating for Creativity in Engineering," Presented at the 85th Annual Conf. ASEE, Univ. of No. Dakota

10 **May, R**. (1976). *The Courage to Create*, Bantam Books: New York.

11 **Towfigh, K**. (1969). "The Four-Bar Linkage as an Adjustment Mechanism," 1st Applied Mechanism Conf., Oklahoma State Univ., Tulsa, OK, pp. 27-1– 27-4.

12 **Samuels. M.** (1975). *Seeing with the Mind's Eye: The History, Techniques and Uses of Visualization*, Random House: New York.

1.15 BIBLIOGRAPHY

For additional information on the ***history of kinematics****, the following are recommended:*

Artobolevsky, I. I. (1976). "Past Present and Future of the Theory of Machines and Mechanisms." *Mechanism and Machine Theory*, **11**, pp. 353-361.

Brown, H. T. (1869). *Five Hundred and Seven Mechanical Movements*. Brown, Coombs & Co.: New York, republished by USM Corporation, Beverly, MA, 1970.

de Jonge, A. E. R. (1942). "What Is Wrong with 'Kinematics' and 'Mechanisms'?" *Mechanical Engineering*, **64** (April), pp. 273-278.

de Jonge, A. (1943). "A Brief Account of Modern Kinematics." *Transactions of the ASME*, pp. 663-683.

Erdman, A. E., ed. (1993). *Modern Kinematics: Developments in the Last Forty Years*. Wiley Series in Design Engineering, John Wiley & Sons: New York.

Ferguson, E. S. (1962). "Kinematics of Mechanisms from the Time of Watt." *United States National Museum Bulletin*, **228**(27), pp. 185-230.

Freudenstein, F. (1959). "Trends in the Kinematics of Mechanisms." *Applied Mechanics Reviews*, **12**(9), September, pp. 587-590.

Hartenberg, R. S., and J. Denavit. (1964). *Kinematic Synthesis of Linkages*. McGraw-Hill: New York, pp. 1-27.

Nolle, H. (1974). "Linkage Coupler Curve Synthesis: A Historical Review - I. Developments up to 1875." *Mechanism and Machine Theory*, 9, pp. 147-168.

Nolle, H. (1974). "Linkage Coupler Curve Synthesis: A Historical Review - II. Developments after 1875." *Mechanism and Machine Theory*, 9, pp. 325-348.

Nolle, H. (1975). "Linkage Coupler Curve Synthesis: A Historical Review - III. Spatial Synthesis and Optimization." *Mechanism and Machine Theory*, 10, pp. 41-55.

Reuleaux, F. (1963). *The Kinematics of Machinery*, A. B. W. Kennedy, translator. Dover Publications: New York, pp. 29-55.

Strandh, S. (1979). *A History of the Machine*. A&W Publishers: New York.

For additional information on ***creativity and the design process****, the following are recommended:*

Alger, J., and C. V. Hays. (1964). *Creative Synthesis in Design*. Prentice-Hall: Upper Saddle River, NJ.

Allen, M. S. (1962). *Morphological Creativity*. Prentice-Hall: Upper Saddle River, NJ.

Altschuller, G. (1984). *Creativity as an Exact Science*. Gordon and Breach: New York.

Buhl, H. R. (1960). *Creative Engineering Design*. Iowa State University Press: Ames, IA.

Dixon, J. R., and C. Poli. (1995). *Engineering Design and Design for Manufacturing—A Structured Approach*. Field Stone Publishers: Conway, MA.

Fey, V., et al. (1994). "Application of the Theory of Inventive Problem Solving to Design and Manufacturing Systems." *CIRP Annals*, **43**(1), pp. 107-110.

Fuller, R. B. (1975). *Synergetics: Explorations in the Geometry of Thinking*. Macmillan, New York.

Fuller, R. B. (1979). *Synergetics 2*. Macmillan, New York.

Glegg, G. C. (1969). *The Design of Design*. Cambridge University Press: Cambridge, UK.

Glegg, G. C. (2009). *The Science of Design*. Cambridge University Press: Cambridge, UK.

Glegg, G. C. (2009). *The Selection of Design*. Cambridge University Press: Cambridge, UK.

Gordon, W. J. J. (1962). *Synectics*. Harper & Row: New York.

Grillo, P. J. (1960) *Form Function and Design*. Dover Publications: New York.

Haefele, W. J. (1962). *Creativity and Innovation*. Van Nostrand Reinhold: New York.

Harrisberger, L. (1982). *Engineersmanship*. Brooks/Cole: Monterey, CA.

Johnson, C. L. (1985). *Kelly: More than My Share of It All*. Smithsonian Inst. Press: Washington, DC.

Kim, S. (1981). *Inversions*. Byte Books, McGraw-Hill: New York.

Moore, A. D. (1969). *Invention, Discovery, and Creativity*. Doubleday Anchor Books: New York.

Norman, D. A. (1990). *The Design of Everyday Things*. Doubleday: New York.

Norman, D. A. (1992). *Turn Signals Are the Facial Expressions of Automobiles*. Addison-Wesley.

Osborn, A. F. (1963). *Applied Imagination*. Scribners: New York.

Pleuthner, W. (1956). "Brainstorming." *Machine Design*, January 12, 1956.

Suh, N. P. (1990). *The Principles of Design*. Oxford University Press: New York.

Taylor, C. W. (1964). *Widening Horizons in Creativity*. John Wiley & Sons: New York.

Unknown. (1980). *Ed Heinemann: Combat Aircraft Designer*. Naval Institute Press, 1980.

Von Fange, E. K. (1959). *Professional Creativity*. Prentice-Hall: Upper Saddle River, NJ.

For additional information on ***human factors****, the following are recommended:*

Bailey, R. W. (1982). *Human Performance Engineering: A Guide for System Designers*. Prentice-Hall: Upper Saddle River, NJ.

Burgess, W. R. (1986). *Designing for Humans: The Human Factor in Engineering*. Petrocelli Books.

Clark, T., and E. Corlett. (1984). *The Ergonomics of Workspaces and Machines*. Taylor and Francis, New York.

Huchinson, R. D. (1981). *New Horizons for Human Factors in Design*. McGraw-Hill: New York.

McCormick, D. J. (1964). *Human Factors Engineering*. McGraw-Hill: New York.

Osborne, D. J. (1987). *Ergonomics at Work*. John Wiley & Sons: New York.

Pheasant, S. (1986). *Bodyspace: Anthropometry, Ergonomics & Design*. Taylor and Francis, New York.

Salvendy, G. (1987). *Handbook of Human Factors*. John Wiley & Sons: New York.

Sanders, M. S. (1987). *Human Factors in Engineering and Design*. McGraw-Hill: New York.

Woodson, W. E. (1981). *Human Factors Design Handbook*. McGraw-Hill: New York.

For additional information on ***writing engineering reports****, the following are recommended:*

Barrass, R. (1978). *Scientists Must Write*. John Wiley & Sons: New York.

Crouch, W. G., and R. L. Zetler. (1964). *A Guide to Technical Writing*. The Ronald Press: New York.

Davis, D. S. (1963). *Elements of Engineering Reports*. Chemical Publishing Co.: New York.

Gray, D. E. (1963). *So You Have to Write a Technical Report*. Information Resources Press: Washington, DC.

Michaelson, H. B. (1982). *How to Write and Publish Engineering Papers and Reports*. ISI Press: Philadelphia, PA.

Nelson, J. R. (1952). *Writing the Technical Report*. McGraw-Hill: New York.

Some useful ***web sites*** *for design, product, and manufacturing information:*

http://www.machinedesign.com

Machine Design magazine's site with articles and reference information for design (searchable).

http://www.motionsystemdesign.com

Motion System Design magazine's site with articles and reference information for design and data on motors, bearings, etc. (searchable).

http://www.thomasregister.com

Thomas Register is essentially a national listing of companies by product or service offered (searchable).

http://www.howstuffworks.com

Much useful information on a variety of engineering devices (searchable).

http://www.manufacturing.net/dn/index.asp

Design News magazine's site with articles and information for design (searchable).

http://iel.ucdavis.edu/design/

University of California Davis Integration Engineering Laboratory site with applets that animate various mechanisms.

http://kmoddl.library.cornell.edu/

A collection of mechanical models and related resources for teaching the principles of kinematics including the Reuleaux Collection of Mechanisms and Machines, an important collection of 19th-century machine elements held by Cornell's Sibley School of Mechanical and Aerospace Engineering.

http://www.mech.uwa.edu.au/DANotes/design/home.html

A good description of the design process from Australia.

Suggested ***keywords*** *for searching the web for more information:*

machine design,

mechanism,

linkages,

linkage design,

kinematics,

cam design