Perceptions of Practitioners and Engineering Educators and Students Regarding Requisite Skills for Effective Design of Complex Systems

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PERCEPTIONS OF PRACTITIONERS AND ENGINEERING EDUCATORS AND STUDENTS REGARDING REQUISITE SKILLS FOR EFFECTIVE DESIGN OF COMPLEX SYSTEMS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Melanie A. Thom

In Partial Fulfillment of the Requirements for the Degree

of

Master of Science

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ABSTRACT


Both popular press and academic journals have reported increasing trends in design failures attributed to engineering errors, poor planning and inadequate design decisions as demonstrated by mission failures, product failures and increasing manufacturing and support costs ((McMasters & Matsch, 1996; Oberg, 2000; Lowery, 1998; Hayes & Wheelwright, 1984; Schlager, 1994; Scott, 1999, 1999a, 1999b). The authors of the articles agree that graduating engineers are competent at formulaic analysis, but they suggest a perceived lack of fundamental skills necessary for design activities. This lack of skills is described in broad terms but the descriptions lack specific metrics for assessing the possession of these abilities by matriculating engineering students. This study identified the primary skills perceived as necessary for effective design of complex systems by industry practitioners and compared them to the abilities academic researchers perceive are required by practitioners. The skills and abilities were then compared to observed behaviors of engineering students in multiple sessions of a senior aerospace engineering design course at Purdue University. The study did not consider topics such as educational theory and did not consider soft skills such as human resources or communications. The skills were defined based on an analysis and of content and meaning from the three sources, practitioners, educators, and students, and validated using a triangulation methodology. The study investigated the evolution of engineering education as it impacted current academic exposure and its relationship to the specific skills industrial representatives suggest have been lost. It was concluded there were differences in the perceptions of each cohort group.
CHAPTER ONE: INTRODUCTION

It is suggested by technical professionals involved in complex design activities that an increasing trend in design flaws is being experienced. The greatest concern expressed by these professionals is that the flaws are repetitions of problems previously encountered and solved, as opposed to challenges related to new or unexplored technologies. The repetition of avoidable design flaws has a direct and deleterious effect on cost, delivery schedule, and aftermarket support in the industrial sector.

“During the last decade there has been substantial criticism from industry and academia itself concerning several ‘competency gaps’ that newly hired engineering graduates seem to exhibit relevant to the ability to actually practice creative engineering to meet real-world needs” (Tricamo et al., 2003). The engineering community has criticisms regarding the robustness and success of contemporary engineering designs, and concerns over perceived deficiencies in engineering graduates. The lack of robustness can be characterized by the inability of a process or product to perform the defined task, by mission failures, by premature part failure, and by increased manufacturing, production and support costs. The criticisms of the graduates are expressed in general terms, such as “lack of holistic design skills,” “inability to perform system integration,” and “inability to internalize the entire design.” Individuals working in industry indicate a need to build upon and improve “system solutions” and to utilize “synergies of an integrated approach” (NASA Aeronautics Program, 2001). These general criticisms indicate a perception of a lack of application skills in matriculating engineers rather than a lack of formulaic or theoretical skills.

It is suggested that the evolution of engineering science research strongly biased the emphasis of engineering education towards engineering science versus application technology (Hayes & Wheelwright, 1984, Keating et al., 2003; McMasters & Matsch, 1996). This shift in emphasis resulted in a reduction in engineering curricula that exposed students to application-related design activities. It is hypothesized that during the educational transition, some
unidentified skills required for successful design were lost. This shift in emphasis may contribute to the perceived lack of design ability expressed by engineering practitioners.

This study explored what industry practitioners described as necessary skills for design activities and what skills and abilities academic researchers perceived industry was requesting. The knowledge and skills that students exhibited in a representative design course were observed and these observations were compared to the perceptions of the industry and academic cohorts. The comparisons were performed to discover the agreements and differences among the perceptions of the cohort groups. The conceptual convergences and divergences were reported.

The rationale and motivation for the research are discussed in the literature review. Also in the literature review is a discussion on the diversity of terms employed when discussing design. Because of the importance educators and academic researchers place on the engineering curricula surveys, a review of the content and curricula evolution is presented. This review begins with an early survey performed by Charles Mann in 1918 and extends through the Grinter Report published in 1955. This review presents the evolution of curricula content including removal of application content.

The study employed qualitative methods to determine what academic researchers and educators, and industry practitioners suggested were required of engineering graduates and contrasted those suggestions with the behaviors students exhibited during design coursework. Information on the perceptions of the academic and industry cohorts was collected through a survey of academic literature and oral interviews of industry practitioners. The student behaviors were obtained by observations of a senior design course over multiple semesters. The academic views were obtained from a literature survey because the topic had already been extensively researched. This document contains two literature activities, a literature review and a literature survey. The literature review was done to prepare for the research and was referenced in the reference list. The literature survey was a directed research activity with its own reference list in the appendix section.

To obtain specific, measurable skills that industrial representatives opined were important, it was necessary to interact directly with individuals. This information had not been researched previously and oral interviews permitted more thorough exploration of thoughts than would
have been available by other means. The sensitive nature of the conditions which illuminate a lack of ability also precluded sufficient information being available through other avenues.

Student observations were collected in a senior design course because it most closely replicated the situations and activities in which the presence or lack of the desired skills would be exhibited. The course observations also facilitated avoiding confounding factors found in industrial settings, i.e. economics, schedules, and company philosophies. Furthermore, the students were near graduation and therefore were expected to exhibit the typical knowledge and skills of an Aeronautical and Astronautical Engineering graduate of Purdue University.

**Background**

It has been observed by industry practitioners involved in aerospace systems that there is an increasing trend of multiple redesigns in the final stages of design, during manufacturing, and even after the product has been sent to the customer (Oberg, 2000). Furthermore, complex engineering systems often fail, “not because of exotic, poorly understood problems, but because of simple flaws that could not be identified in isolation from the operation of the full system” (National Research Council, 2000, p9). In many modifications of design concepts, the changes are conceived and made without thinking much beyond how it improves the one aspect observed to be lacking in the original design (Petroski, 1994, p54). In an evaluation of a series of bridge failures, it was concluded these failures may have been due to a lack of imagination or foresight in the design (Petroski, p58). McMasters and Matsch say that “Too few of our engineering graduates have an adequate understanding of ... how to manufacture anything. Fewer still seem to understand the process of large-scale, complex system integration which characterizes so much of what we do in our industry” (1996, p 2). “It has become increasingly clear to us in industry that the curricula in most of the major universities in this country overemphasize engineering science at the expense of engineering practice” [italics in original] (McMasters and Matsch, 1996).

Engineering managers also complain new graduates “tend to rush into building detailed finite element models without first attempting to understand the problem or apply basic engineering principles” (Education needs..., 1996, p54). Other complaints indicate a concern that so much time is spent presenting the students with theory that it can take as long as five years to “get up to snuff once out in the real world of work” (Ivanovich, 2001, p7) and “too
much on-the-job training was required before they (sic companies) could use the new hires” (Bell, 2000). In other cases, failures “have been attributed to design errors in overlooking or underestimating the effect of size in scaling successful designs” (Petroski, 1994, p31). During his evaluation of design failures, Petroski found that the designs were fundamentally sound concepts but were weakened by poor component choices, inferior detailing, or by seemingly simple but poorly considered design changes (1994, p9).

Because of a sense that the concerns being expressed lie in new engineers’ ability to perform in design activities, efforts to identify the design shortcoming have been made. The results of a survey performed by the National Research Council (1991) indicated that there was a feeling by industry that current engineering curricula did not focus on the entire product realization process. Where curricula introduced structured engineering design concepts, it was only a few steps of the process and used more conventional, technical procedures. This resulted in few graduating engineers understanding the multiple goals motivating design activities (p12). Garris noted, “While engineering students are generally well grounded in the fundamentals, design courses rarely provide an historical perspective on how designs have advanced in the particular discipline of interest. As a result students tend to design in a vacuum, basing their concepts on their own limited experience” (2001, p5). Hissey points out that contemporary engineers can no longer afford to be an isolated innovator in their specialty, but need to consider the “big picture” (2000).

William Scott, editor for *Aviation Week and Space Technology*, indicated part of the challenge of transitioning from academia to industry might be in expectations. He suggested that educators might expect on-the-job training to fill the applications gap while industry is expecting to hire engineers already educated in both practice and science. This challenge is further complicated by the student’s expectations. Scott quoted an engineer with whom he had spoken as saying “I got into this (engineering) to change the world, not to iterate out cost” (personal communication, July 25, 2001). Widnall echoed this concern in a presentation to the AIAA. Widnall said, “I do sense a mismatch between the expectations of (graduating) aerospace engineers and the realities faced by the industries and the atmosphere that young engineers may find upon entering the industry” (2001, p B5). McMasters and Matsch (1996) further describe the problem as new hires lacking a grasp of engineering practice and often
having erroneous, preconceived notions of what engineering practice is, particularly in the currently evolving industry environment.

If misconceptions are part of the problem, then a better understanding of the expectations of an engineering education is needed. Bordogna of the National Science Foundation (1997a) described the issues of appropriately educating engineering students, indicating that with the constraints of a four-year curriculum, it is important to fully define and understand what the outcomes and objectives of the program are. Swain echoed this observation, noting the dilemma universities face in determining what courses need to be dropped and what courses to add to an already packed curriculum (as cited in Bokulich, Gehm, & Hessler, 2001). Until you know what the content of the final product (the student) should be, it is difficult to develop the content of the curriculum (Bordogna, personal communication, August 15, 2001). Matsch of Honeywell, Inc. suggests that the process begins by defining the attributes necessary for successful career maturity. With the end attribute goals established, the supporting attributes necessary at career entry are defined. These entry-level attributes set the goals for the undergraduate program (McMasters & Matsch, 1996). These comments support the need for defining the concepts engineering students need to learn before they graduate.

Industry personnel are aware they also have a role in filling the perceived lack of skills in new employees. Traditionally, industry has used avenues such as training and mentoring programs to facilitate gaining specific skills and experience. These programs range from formal, long-term activities to ad hoc, random relationships. As in academia, the content of these programs is not well defined. Industry recognizes the need to garner knowledge of possible routes to improvement (National Research Council, 1991, p16).

The target attributes are expected to be more encompassing than “system engineering”, which is popularly used to describe the design of an entire system, and may be expected to encompass all of the characteristics leading to a good design. Systems engineering “is not meant to describe engineering in a systematic way so much as the engineering of systems” (Gardiner, 1996, p166). For this study, systems engineering only considers how to put components together to perform a specific function. The components and the function, both part of designing, are already supplied to the systems engineer. Therefore, the popularly accepted systems engineering does not deal with the industry criticisms.
The Need for Identifying the Necessary Skills

The skills identified in this study and the methodology used to develop them provides potential assistance to engineering design educators in creating assessment tools. The information is expected to also be useful to individuals responsible for the preparation and execution of industrial training and mentoring programs.

There is noted activity to improve curricula at universities and colleges (MIT, 2002; Drexel, 2002), and by accrediting bodies (Accreditation policy..., 2001) in response to industry criticisms. While these criticisms have been publicized, they are vague and lack specificity, making them difficult to resolve. Without specific, measurable definitions to characterize these criticisms, both research and education reforms are at a disadvantage. Furthermore, to be accredited by ABET, Inc., program outcomes must be measurable, published and assessed. This study supports answering “design as a part of the curriculum and how”.

The Uniqueness of the Aerospace Culture

This research was delimited to the aerospace industry, which has a distinct culture. Stinton (2001, p30) describes this culture as a juxtaposition of seat-of-the-pants, push-the-envelope risk-taking and ultra-conservative, risk avoidance. It is a “mixture of precise science, disciplined methods, consummate accuracy and telling it as it is after a flight test, gut feelings and artistry”.

The culture is comprised of individuals innovating, pushing technology to its limits and beyond, attempting “to go where no one has gone before” (Gene Roddenberry’s Star Trek, © Paramount Studios) and “slipping the surly bonds of Earth” (High Flight, written by John Gillespie Magee, Jr., September 1941). But the same individuals work under the immutable laws of "gravity always works", and "mother nature is an unforgiving mistress". The culture is permeated by a fixation on safety and reliability. The reliability is taken as a measure of airworthiness (Stinton, 2001) and "safe = airworthy = meeting requirements" (David P. Davies as quoted by Stinton, p3). Therefore, the culture is driven to meet or exceed requirements.

This fixation with safety and reliability is presumably, to some degree, a result of the industry being a litigious one. If safe is measured by airworthiness, how does the manufacturer or designer prove airworthiness? “The product is airworthy. Think for a moment of the legal questions that might follow such a ... statement after a subsequent accident” (Stinton, 2001, p3). Consider the statement reportedly made in 1976 by the American aviation lawyer Harry A.
Wilson that [aviation] manufacturers have a duty to ensure their customers are competent to handle their products (Stinton). What other industry is charged with such a suggested level of responsibility? This suggests a culture that on a daily basis deals with an “inherently dangerous activity”, where “failure equals death”, and any mistake can lead to litigation.

Not only does the culture consider the concerns of those using the products, but also the impacts to the general public who may care very little about airplanes or spacecraft until they come into contact with them. Designs created by the aerospace industry require a “minimum level of risk to the innocent public… That level of risk has an order of magnitude which must be less than one chance in one million of the public being involved” (Stinton, 2001, p4).

The juxtaposition of these two disparate attributes (risk-taking and risk avoidance) results in a culture with definitive convictions on a required level of safety and reliability, an adherence to regulations, and a commitment to surety, while at the same time fostering an atmosphere of innovation and artistry. The industry is quick to innovate but slow to change.

The environment of calculated risk leads to a cultural characteristic of asking “why” and maintaining data and part histories at a level higher than other industries. Because of the drive to be reliable and safe, the aerospace industry maintains detailed information and data down to the component level. In some instances it is possible to track a part history down to a single o-ring and even down to the batch of rubber used to manufacture it. Members of the aerospace culture expect to be able to tell where an aircraft component is at any given moment, where it has been, and what usable life remains.

Furthermore the relatively small size of the aerospace industry results in a sense of community. Competitors are aggressive with each other at the marketing table and are supportive of each other in times of industry trouble. Professionals will exchange lessons learned on risks while protecting technical advantages. When there are safety concerns, members of this community respond to requests for data or assistance both within a company and across companies. Members adhere to high levels of commitment and integrity as reflected in the codes of conduct of the aerospace companies and in their professional organizations.

The fourth major characteristic of the aerospace culture is a personal investment by the individuals into the eventual flight of the aerospace vehicle, even when they never see the final vehicle. From the component designer to the manufacturing technician to the line mechanic,
the members of the community personally feel that they have a part in the final vehicle success. This level of commitment, pride and sense of ownership; the feeling of community; the drive to know why, to document everything and to maintain part histories down to the single component; and a cautious performance in a high risk, highly litigious industry; while continuing to foster innovation and experimentation all result in a unique culture.

The Problem and Purpose

The concerns expressed by industrial representatives regarding perceived deficiencies in the skills new engineering graduates exhibited are broad and lack defined characteristics or goals. Based on the researcher’s experience and popular literature, newly graduating engineers seem to lack some skills that graduates from previous decades possessed. Academia is attempting to respond to the concerns of industry representatives. The problem is that the skills described as missing are not well defined. As a result, educators have not been able to make changes to engineering education that satisfies the concerns of industry representatives.

The purpose of this qualitative study was to begin to identify the missing skills. In particular, the goal of this study was to identify the specific, measurable skills design practitioners perceived as requisite to demonstrating the ability to participate in successful design activities.

The guiding research questions for this study were: 1) What are the perceptions of practitioners regarding the requisite skills for effective design of complex systems? 2) What are the perceptions of educators regarding what industrial practitioners perceive as requisite skills? 3) What are the perceptions of matriculating engineering students regarding the requisite skills for effective design? and 4) What are the similarities and differences in the perceived requirements for design activities exhibited by the cohort groups?

These questions were explored by determining the characteristics (skills and abilities) that industry representatives suggested were required and then comparing those characteristics to what educators perceived as the requisite skills of practitioners. The results of this comparison were also contrasted to student design behaviors in the classroom.

For the purpose of this study, successful or effective design was defined as a product or process capable of achieving expected performance and robustness, being able to be economically and efficiently produced and supported, and requiring minimal rework.
perceived requisite skills were identified as those occurring most frequently in the data generated from texts and practitioner interviews. The characteristics were separate from soft skills, such as communication, teamwork, and other human factors. Design was defined as a separate endeavor as compared to other recognized engineering endeavors, such as systems engineering, engineering science, or engineering research.

The literature discussing efforts to improve design engineering education used language lacking precision or consistency, making assessment of these efforts difficult. For the purpose of this study, the skills and abilities being investigated were required to be measurable in the sense that they could be clearly assessed with respect to their presence or absence. This was considered necessary in order for the results of the study to be useful. Because the study dealt with people and with language at its root, the study explored the perceptions of individuals and posed them in terms that were as precise and concise as possible within the scope of the study.

Significance of the Problem

Both documented and anecdotal evidence indicate that engineers skilled in engineering science periodically make design decisions that have a negative impact on the entire system (Lowery, 1998; McMasters & Matsch, 1996; Oberg, 2000; Schlager, 1994). In a series of articles prepared from research and interviews of engineers, and published by *Aviation Week & Space Technology* (Scott, 1999, 1999a, 1999b), it is noted that the mistakes consistently being made in contemporary aerospace system designs have not occurred in years and are not expected to occur now. Scott indicates that there is a problem with the basic design knowledge held by new engineers, leading to component failures, loss of profit, and safety issues.

The researcher has been personally involved in design activities in which incorrect material selections made during the initial design phase contributed to multiple prototyping iterations. In one case an engineer repeatedly redesigned the physical shape of the component which was not the root cause. In another case, design shortcomings in a control unit resulted in the grounding of a fleet of aircraft for emergency service to replace the o-rings. The selection of the o-rings was determined to be the root cause, and it was discovered that the selection decision had been made despite indications that the selection might cause a problem. These examples suggest a pattern of engineering behaviors which are described as unsuccessful.
The book, *When Technology Fails* (Schlager, 1994), reports multiple engineering design oversights or lack of foresight resulting in catastrophic failures. Problems described indicate a lack of field use considerations (Schlager, p 52), a lack of testing in real world scenarios (Schlager, p 94), and a lack of maintenance considerations (Schlager, p 101).

One of the descriptions of the broad concerns is a lack of a global or holistic view of the design. It is suggested that new engineers do not consider the ‘whole’, whether it is a design, a process or a product, when they participate in design activities. This directly impacts product cost. In the text *System Engineering Management*, Blanchard says,

> In addressing system requirements, the normal tendency is to deal primarily with those elements of the system directly relating to the performance of the mission. To meet the overall objectives of system engineering, it is essential that all aspects of the system be considered on an integrated basis. This includes not only the prime mission-oriented segments of the system, but the support capability as well (1991, p27).

The magnitude of higher development costs and high maintenance costs are not visible early in the design phase (Grouse, 1994). A system may demonstrate behavior that is explicable, but not always obvious due to interactions among the parts making up the system, interactions which may not have been projected (Gardiner, 1996, p168).

For a company to remain competitive and maintain resources for research, development, and support, the company must minimize engineering costs. This is particularly true in the aerospace industry, where single components can be costly, the component materials are expensive, product lead times are long and the number of units across which to amortize cost is small. It is estimated that 85% of the problems encountered with new products are the result of poor design processes. Much of the final product cost is committed early in the design process. The expenditure of resources on the actual design process is a small percentage of the total product cost, as little as 5% on average. The effect of a good design process on reducing the subsequent product cost is generally more than 5%. Depending on the product, the reduction in the final product cost has been reported to be routinely 50% and as high as 75% (Ullman, 1992). Blanchard (1991) indicates that over 75% of the cost of ownership of a system is in the operational and support activities. Furthermore, this 75% of the cost is determined and fixed during the first 10% of design phase activities. Operational and support activities are
traditionally areas with which design engineers have limited experience or expertise, yet the
design engineers have the greatest potential to impact the life cycle costs of a system.

By identifying measurable characteristics that define deficiencies perceived in engineers,
this study supports the improvement of academic curricula, and industry training and
mentoring programs. Better education and training programs provide more skilled engineers
who are able to provide more effective design solutions. This in turn facilitates more successful
design activities, contributing to the improvement of contemporary design activities and
quality initiatives. These improvements can ultimately be seen in the bottom line of aerospace
companies.

Definitions
For this project the following terms are specifically defined.

**Design** – Everything that contributes to the final product outcome, not just data. It
includes not only the instructions for making the item, but also considerations
for its manufacture, assembly, use, maintenance, repair, and retirement.

**Designer** – The individual responsible for the first outline or preliminary plan of a product
as opposed to the individual responsible for the entire product or process (see
design engineer). A designer may or may not be an engineer.

**Designing** – The actions involved in developing and completing the product or process
including economic, production, human factors, and warranty issues.

**Design Engineer** – The individual with the knowledge and skills from design methodologies,
application technology and engineering science/theory disciplines as
demonstrated in Figure 4. The design engineer considers all aspects of the
design, including engineering science related activities. Individual responsible
for considering and managing the entire design activity, including issues related
to concept development, quality, customer satisfaction, manufacturing,
assembly, economics, environmental considerations, maintenance, legal
implications and product retirement.

**Design Engineering Skills** – The skills with enough specificity to provide a means for
assessing or measuring their presence or absence.

**Effective Design** – A product or process capable of achieving expected performance and
robustness, being able to be economically and efficiently produced and
supported, and requiring minimal rework.
**Engineering Analysis** – The specific technological activities providing quantifiable data. Analysis includes mathematic based analysis, use of computer programs, and other formulaic analyses. Analyses evaluate a specific, technical aspect of the design, not the overall considerations of the final product. The analysis activity provides the data utilized in the validation of the scientific basis of a design. Theoretical model development and use is also located within analysis.

**Engineering Science / Theory** – The constructs that provide the basis for formulaic analyses. The theoretical tools used to analyze data, perform computational simulations, evaluate the validity of a design and used as scientific principles.

**Manufacturability** – A demonstration that the processes meet established performance objectives in terms of yield, throughput, equipment maintainability, etc. (O’Hara, Evans, & Hayden, 1993, p.300).

**Reliability** – A demonstration that the process will support the product’s ability to perform its functions for the duration of its specified lifetime (O’Hara, Evans, & Hayden, 1993, p.300).

**Success Factors** – Skills that result in achieving successful design that meet all of the application considerations based on provided requirements of “Design Engineering Skills”.

**Soft Skills** – Skills accepted as necessary for successful design such as teaming, communication, project management, and human relations. These skills may contain technical requirements, but they involve the “human factor”.

**System Engineering** – Developing the necessary formulaic and technical data required to integrate several pieces into a single product.

**Technical Institute** – An institution which is more than a trade school, more technical than traditional four year colleges and more application-oriented than the purely technical engineering schools. It includes substantial treatment of the underlying science, drawing, English and economics (Study of Technical Institutes, 1933, p31).

**Technician** – Recipient of a two year degree in a specialized area of technology. Expected to know how and why things work and applying it to real problems (American Society of Engineering Education, 2004).

**Technologist** – Recipient of a four year degree in a specialized area of technology. Expected to know how and why things work and applying it to real problems (American Society of Engineering Education, 2004).
Assumptions

1. It is assumed engineers are well educated in traditional engineering science skills. Engineers understand engineering theory and can perform traditional formulaic analyses when they graduate. Widespread lack of this knowledge is not the primary cause for the referenced design failures.

2. It is assumed other disciplines are fully considering the “soft” skills that impact successful design activities. The pedagogy of presenting these soft skills in engineering curricula is being dealt with by other disciplines. The lack of soft skills is not the sole reason for the observed increase in design failures.

3. It is assumed the industry participants selected for the study were able to provide valid insight into the characteristics needed by an engineer to be a successful designer.

4. It is assumed the interviewees responded truthfully and accurately to questions in the data collection process.

5. It is assumed the diagrams showing the relative probability of a graduating engineer having engineering science/theory skills, technology/application skills and design methodology skills realistically reflects the actual background of engineers when they graduate. This perspective is the basis for the proposed disconnect between industry expectations and academic preparation.

6. It is assumed the researcher’s participation has no more effect on the behavior of students during a senior design course than the presence of the teaching assistants. By being considered similar to the teaching assistants, the students should interact with each other, the instructor and the teaching assistants in the same manner whether they are being observed or not.

Delimitations

1. For the purposes of the study, the investigations were delimited to the aerospace industry.

2. The study did not consider traditional engineering skills such as use of computers for analyzing data, testing components, simulating performance and evaluation of designs, computer programming, mathematical computations, or formulaic evaluations.

3. The impact of soft skills such as communications, team building and project management on the design process will not be considered, even where those skills involve technical information.
Limitations

1. The study is qualitative and thereby may have limited generalizability. Limits of generalizability are considered acceptable due to the exploratory nature of the study and the role of the data as foundational.

2. Aerospace design has legal and safety considerations specific to the aerospace industry. The characteristics considered important by aerospace engineers performing design may be affected by these considerations. This may limit the applicability of the findings to other industries.

3. The use of convenience sampling is dependant on the quality of the criteria for selection and the effectiveness of the application of the criteria in selecting appropriate subjects.
CHAPTER TWO: REVIEW OF LITERATURE

Methodology of the Literature Search

The literature review used a methodology that included books, periodicals and interviews. Concepts of engineering, engineering education, management, and technology, as well as the accreditation requirements of ABET, Inc were included. The literature search identified relevant periodicals and texts using databases such as Compendex, Educational Information Resource Center (ERIC), Aerospace Index, American Institute of Aeronautical and Astronautical (AIAA) Index, National Technical Information Services (NTIS), LexisNexis and Purdue University’s library database, THOR. Multiple searches were performed in order to capture the breadth and depth of the topic. Keyword searches were performed using multiple phrases (Table 1). The initial list of key words was developed using professional experience, keywords from texts identified during the initial search, and from suggestions from advisors. As the successful keywords evolved, databases were searched again using new terms, resulting in multiple iterations. Core literature sources included both popular press and reviewed sources from the aerospace discipline, engineering education, management, and design. The range of literature was considered saturated when the same authors and texts appeared repeatedly in different searches.

In a similar manner, database searches were performed for texts and articles by authors identified as pertinent to the problem and process, and who appeared repeatedly within and across the literature (Table 2). Other publications of authors were investigated when initial texts proved to be relevant and useful.
Table 1 - Search Terms

<table>
<thead>
<tr>
<th>“Engineering Design”</th>
<th>“Applied Technology”</th>
<th>“Successful Designs”</th>
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<tbody>
<tr>
<td>“Successful Design” AND Aerospace</td>
<td>Engineering education AND Design</td>
<td>“Design methodologies”</td>
</tr>
<tr>
<td>“brain drain”</td>
<td>“Engineering Design Methodology”</td>
<td>“Design philosophy”</td>
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<tr>
<td>Engineering design education</td>
<td>System engineering</td>
<td>System engineering AND Design</td>
</tr>
<tr>
<td>System Engineering AND Design AND Education</td>
<td>“Design Flaw”</td>
<td>System Engineering Training</td>
</tr>
<tr>
<td>Industrial Engineering</td>
<td>“System Integration”</td>
<td>“Holistic Design”</td>
</tr>
<tr>
<td>“Development Training”</td>
<td>Training AND Education</td>
<td>Experiential learning</td>
</tr>
<tr>
<td>Product AND Development</td>
<td>Design</td>
<td>Engineering AND Design</td>
</tr>
<tr>
<td>“Engineering Education”</td>
<td>Engineering AND Education</td>
<td>“Engineering Applications”</td>
</tr>
<tr>
<td>“Design Education”</td>
<td>“Aviation Failures”</td>
<td>“Design Failures”</td>
</tr>
<tr>
<td>Aviation AND Design AND Failures</td>
<td>Design AND Failures</td>
<td>Aviation incidents AND Design</td>
</tr>
<tr>
<td>Necessary Design skills</td>
<td>“Design Skills”</td>
<td>Aerospace AND “design skills”</td>
</tr>
<tr>
<td>Industrial Technology</td>
<td>Industrial Engineering</td>
<td>Applied Engineering</td>
</tr>
<tr>
<td>ABET Criteria</td>
<td>“Grinter Report”</td>
<td></td>
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Table 2 - Keyword authors

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell, Trudy E.</td>
<td>Author, IEEE editor</td>
</tr>
<tr>
<td>Bordogna, Joseph</td>
<td>National Science Foundation</td>
</tr>
<tr>
<td>Clark, Kim</td>
<td>Author</td>
</tr>
<tr>
<td>Kuntz, Robert</td>
<td>California Engineering Foundation</td>
</tr>
<tr>
<td>McMasters, John H</td>
<td>The Boeing Company</td>
</tr>
<tr>
<td>Prados, John</td>
<td>University of Tennessee, past ABET president</td>
</tr>
<tr>
<td>Ramo, Simon</td>
<td>Past president of TRW</td>
</tr>
<tr>
<td>Wheelwright, Steven</td>
<td>Author</td>
</tr>
</tbody>
</table>

Texts were also recommended by the faculty committee members and were found during the course of the research. Several of the interviewees also provided bibliographies and suggested texts directly related to the topic. Additional texts were identified from the bibliographies and reference lists of reviewed books. Searches of directed projects and theses at Purdue University and of U.S. dissertations were also performed.
Initially, the literature search focused on aspects of the problem as perceived by industry. A preliminary evaluation of perceptions evident in the literature indicated that representatives of industry felt there were deficiencies in the educational backgrounds of newly hired engineers not related to the traditional engineering science skills (McMasters & Matsch, 1996). This suggested that industry representatives thought there was something lacking in contemporary engineering education curricula.

Additionally a search of the literature examining the contemporary issues of engineering education both in the past and present was conducted. The literature indicated that the accreditation requirements of ABET have influenced engineering undergraduate curricula. Using ABET accreditation requirements as the keystone of the evaluation of engineering education and how ABET responds to industry pressures is reasonable due to the nature and structure of ABET. ABET utilizes a structure designed to minimize bias through the inclusion of representatives from industry, academia and government. ABET is designed to serve as an impartial focal point for the development of standards for engineering education commonly accepted by both academia and industry.

To develop a background and understanding of what research had been done, a chain of informal interviews of accepted leaders in engineering education research occurred. These interviews were an exploratory step in order to understand the points of views, concerns and current research related to the problem statement. A chain of informal interviews was initiated by contacting William Scott, the author of the *Aviation Week and Space Technology* articles that were the focal point of popular press statements of criticism (Scott 1999, 1999a, 1999b). During the interview Scott (personal communication, July 25, 2001), suggested contacting Robert Kuntz, past president of the California Engineering Foundation and a leader in engineering education research.

Kuntz provided an introduction to Joseph Bordogna, currently of the National Science Foundation (NSF) and past NSF board member (personal communication, July 26, 2001). Kuntz suggested Bordogna might have useful input as a key participant during the recent redesign of the ABET accreditation requirements.

Bordogna provided an introduction to John Prados of the University of Tennessee and past president of the ABET, Inc. board (personal communication, August 15, 2001).
These informal, conversational interviews were performed as part of the literature review. The benefit of informal, conversational interviews is the gathering of information that is less likely to be obtained in literature or during formal interviews. In this case, the basic questions introducing the researcher, the purpose of the contact, and topic of the research, were provided to the interviewees prior to contacting them. This maximized the time actually spent in conversation without directing the responses of the interviewees, but allowed them to determine what was important to share on the topic. While the initial interviewee selection was due to an interest in the research performed for a specific series of articles, subsequent interviewees were identified and selected based on suggestions provided in previous interviews.

Due to the nature of the proposed study, it was also necessary to perform text searches related to the development of survey tools, the best practices for administering the tool to industrial representatives, and how to perform observational studies in academic settings.

Findings from the Review of the Literature

Background of the Problem

Industrial Perspective

According to Hayes, Wheelwright, & Clark, (1988) industrial and engineering workers relied on the technical skills they acquired during apprenticeships to resolve problems with quality or in making improvements to designs and processes through the 1960s. This reliance on experience, constant practice and an understanding of the realities of the shop floor carried over to the work of management. There was a sense of understanding a product and its use throughout any given company. If the decision makers did not have a holistic perspective, rooted in experience, they might not foresee how a decision might play out over time.

A shortage of traditionally trained general managers grew in the twenty years following World War II. This shortage necessitated companies reducing the service time required to earn general management responsibilities. Previously, the traditional path to the position of general manager was to have manufacturing and production experience. The concept of the "fast track" eventually became the norm, and young, ambitious managers came to feel that if they
had not moved in three years, they should look for jobs elsewhere. These new managers not only had less applied engineering experience than their predecessors, but they often moved to new jobs before they could observe the results of their decisions (Hayes and Wheelwright, 1984). When Wheelwright and Clark (1995) considered companies that were good at product development (design), they found that the senior managers “were acutely aware where they had come from and where they were going” (pp 14-15).

Numerous factors have been described as contributing to the evolution of criticisms of a growing lack of design success and robustness. In the text, Dynamic Manufacturing, Hayes, Wheelwright, & Clark (1988) described conditions indicating a growing problem in the manufacturing industries of the United States. The problem was evidenced as a loss of global position in industries classified as “high tech” by the Department of Commerce, and as a reduction in companies entering “high tech” industries.

In the 1980s and 1990s, companies responded to short-term profit pressures, reducing employment in order to deal with productivity and profitability issues. Between 1981 and 1986, at least 10% of the middle management in the U.S. manufacturing sector was eliminated. Hayes et.al, 1988 went on to describe the situation:

American industry entered the 1960s with an enormous capital base, a skilled and inherently enthusiastic workforce, an experienced and aggressive management group and acknowledged leadership in most of the world’s important processes and product technologies. Yet many companies began to treat these resources as if they were constraints. … They began to look upon their factories … and all those people as though they were impediments, obstacles to their flexibility and creativity. (p15)

This reduction of applications experience in the workforce may be one of the factors impacting the increasing numbers of design failures reported in the last twenty to thirty years.

In the early 1980s, engineers who aspired to management positions were often encouraged to obtain a Masters in Business Administration (MBA). Concurrently, new and different management theories were replacing conventional wisdom as accepted management philosophies. This conventional wisdom was the foundation of the management attitudes and practices that prevailed pre-1980 (Hayes and Wheelwright). The observation is made that engineers were sent to get MBAs to learn how to manage people and processes, at schools permeated with modern management approaches. Company leaders were then surprised when
the new engineering managers used these newer philosophies rather than the conventional wisdom with which the leaders were familiar.

Concerns about job experience continue into the 2000s. Logson, Manager of Space Operations at the Aerospace Industries Association of America notes, “When … talent leaves the aerospace ranks through either retirement or layoffs, the knowledge base is lost. The industry has not been able to balance that loss with the hiring of quantities of quality new talent” (Dykewicz, 2002, p1).

In a series of articles prepared from research and interviews and published in *Aviation Week and Space Technology* (Scott, 1999, 1999a, 1999b), industry’s concerns and their impacts of the perceived lack of skills were considered. In the late 1990s, the U.S. aerospace industry was in the middle of what was described as “The New Golden Age of Aviation” with expectations of increased opportunities for new design activities (AlliedSignal Aerospace, internal corporate communication, 1998). At the same time, there were serious concerns regarding the quality and robustness of the newest designs. Scott (1999), said “Systemic problems within large aerospace companies in the U.S. and Europe are unseen cancers that could spread quickly, triggering a loss of profitability and a decrease in quality of air transports, rockets, satellites and myriad defense systems” (p63). Oberg echoed this concern six months later (2000). Oberg reported not only concerns regarding the types of errors, citing as examples the measurement unit conflicts on the Mars Polar Lander and the grounding of the entire space shuttle fleet due to mishandled wire bundles, but also concerns related to the apparent increase in the number of the occurrences. Furthermore, Scott (1999) follows up that the “string of high profile failures in the military and civil space launch sector have raised questions about reliability and fundamental policies in what was considered a fairly mature aerospace arena (AW&ST May 3, p31)” (p65). Ultimately, quality cannot be built into a product unless it is designed into it (Ullman, 1992).

Hayes, Wheelwright and Clark point out that companies were able to survive on the prewar legacy of manufacturing and technology, and that “the challenge was not to strike off in an entirely new direction, but rather to recapture something that had been lost” (1988, p59).
Academic Perspective

Industry was not alone in its evolution from an aposterioristic approach to design and manufacturing to a more cerebral approach. During the same period in history, the engineering colleges and universities were evaluating their curricula against the evolving perceptions of the appropriate role for institutions of higher learning. In the written contributions to the EHR Advisory Committee Public Hearing on Employers’ views convened November 1, 1995, Israel Joseph Galvan, President of GHG Corporation noted:

Arguably, the last serious debate on the role of the university occurred in the 1930’s between the camps of Robert Maynard Hutchins, the traditionalist, and John Dewey, the progressive. These two giants proposed ideas that were fundamentally different, but their views were clear and unambiguous. Hutchins believed that the university should be a community of scholars, a place to train the intellect and to transmit a Great Tradition of culture. Dewey saw education as an experience and a process for coming to grips with and solving real world problems, a bridge between school and society. Hutchins opposed professional schools; Dewey embraced them.

By the 1930’s and 40’s, an evolution had taken place where colleges and universities decided to be primarily bastions of scientific research, leaving the application education and the filling of traditional application and design positions for technical institutes (Report of the Investigation of Engineering Education 1923-1929, 1930). It was agreed this role was better filled by the technical institutes which were often co-located with major employers and which could be more responsive to their respective industries.

But, over time, these technical institutes also evolved to having curricula more like the universities, to the point that many left their technical roots entirely, i.e. Massachusetts Institute of Technology, Rensselaer Polytechnic, and many of the College of Mines, such as University of Missouri at Rolla. These institutes became engineering colleges and universities in their own rights. Other organizations did not evolve at all, eventually closing.

Causal Factors of the Academic and Industry Evolution

Universities are not solely responsible for the changes made to engineering curricula content. The increasing complexity of technology, past availability of government funding, changing economics of maintaining high quality (largely graduate student focused) academic and research programs, and lack of industry attention are also responsible for the higher
education system we have today (McMasters and Matsch, 1996). Traditionally aircraft
companies have been functionally oriented. Having a functional orientation means the
company is vertically organized around functional responsibilities (technology, manufacturing,
support). Universities generally supply graduates meeting the staffing structure of the industry
they serve; in this case, a functional-oriented structure (Grouse, 1994).

It is hypothesized that a gradual shift away from applications content in engineering
curricula (drafting, shop courses, manufacturing laboratories) and the loss of the technical
institutes as a part of an evolving engineering education philosophy resulted partially from
responding to perceived industry desires. “From its beginnings in the early 19th century until
World War II, engineering education in this country focused strongly on engineering
practice… Then the government began investing heavily in engineering research and
development, and the resulting government–academe alliance stressed engineering science and
mathematics over engineering practice” (Lang, et al., 1999). Engineering practice as used by
Lang et al. describes application technology.

The researcher informally interviewed two experts because of their age, educational
background, professional experiences and involvement in the evolution of engineering
education. Dr. Kuntz of the California Engineering Foundation (personal communication, July
26, 2001), and Dr. Prados of the University of Tennessee and past president of ABET
(personal communication, February 6, 2002), were interviewed regarding a historical
perspective on the evolution of engineering education, and the theory versus application shift.

Kuntz obtained his degree in mechanical engineering in 1957 from Purdue University.
When he earned his degree, the curriculum was very application-based and was 178 credits. At
that time, Kuntz suggested, the U.S. “desperately needed” aerospace designers. Graduates of
any technical major were being hired by the aerospace industry at full professional grade (a
government pay scale ranking). Acceptable majors included chemistry, basic science, and
physics, in addition to engineering. Engineering degree programs took five or more years,
while other degree programs were traditional four-year programs. A decline in enrollment in
engineering was experienced. “After all, why go to school for five years when classmates with
four years were getting jobs of equal position?” Kuntz suggested that engineering schools had
to get their programs down to a competitive four years. To reduce the curriculum by 50 credit
hours, the first courses dropped were the five-credit, application-based laboratory classes.
The application courses dropped from the engineering program at Purdue University’s main campus were moved into technology curricula, creating a new degree. Kuntz suggested this split of engineering science from application technology led to a point of resentment for the engineers. The creation of the technology program created another technical major with which the engineering graduates had to compete for aerospace positions. He suggested that this led to active lobbying that these technical graduates were technicians as opposed to professionals on the government G-scale (hierarchical pay scale). The engineers suggested that the technologist was less prepared for engineering-based employment.

If Kuntz’ view is accurate, we currently have an engineering curriculum structured by engineers who did not receive an application-based education and who were educated in a paradigm of a distinction between theory and application. This view is echoed by Wolverton regarding the faculty’s resistance to change observed at Arizona State University. He suggests, “At a deeper level lies a philosophical desire to perpetrate the theory versus application dichotomy” (1996, p 69). This condition is one explanation for the trends we see today.

Even in schools that were supportive of the application-based education, the old-school traditionalists found it more and more difficult to compete with the more radical professors. Meehan (1982) tells the following story regarding his educational experience in Civil Engineering (CE) at MIT in the 1950’s:

Civil Engineering Projects I was supposed to stimulate our creativity and illustrate practical application of the other subjects we were studying in our sophomore year at MIT, moments of inertia and water-cement ratios and D’Arcy’s law. The course was intended to give us the feel of a big civil engineering project. Gordon Williams taught the course. Williams was a traditionalist who believed engineers should be designers and builders, men of action. This WWII view was falling out of fashion in the CE department at MIT in the 1950’s. Theory and analysis were back in style. In this Williams sniffed the first whiffs of decay. He soon left MIT, or perhaps was driven into exile. MIT was turning out theorists who did not know how to do anything practical, he later complained when I saw him in 1963.

Our other civil course that fall was Surveying I, taught by Miller, a rising star of the radical camp. Miller did not much care about traditional surveying matters, the arts of chaining distances and tapping reticule screws. He used Surveying I as a front for the doctrines of numerical analysis. Once I asked him why he even still called the course surveying and he said he had to keep the name for the image or the alumni would complain. Miller taught us a kind of scientific archeology: how to sift through the middens of observational data, separating pottery shards from pebbles, applying principles as Newton’s backward-
difference interpolation formula to recreate the ethereal form of the original artifact.

William’s and Miller’s classes were our introduction to CE. It made us aware that engineering like any art or profession was a divided house; the split along traditional lines; William’s romanticist promoted design synthesis practice, Miller’s classicist, reduction theory analysis. At other times these different styles could co-exist peacefully, even collaboratively. But by the late 1950’s MIT’s once proud CE department was on the skids. Only 15 of the 650 sophomores in the class of 61 chose CE as their major. In accordance with the laws that govern institutions, the threat of extinction had stimulated some revolutionary thinking.

It took Miller’s whiz-kid analysis only two or three years to win dominance of MIT’s CE department. By the time I graduated in 1961, the traditional design oriented group had been all but obliterated and most of us had been converted to the analytical creed (pp. 193-195).

The interview with Prados addressed a similar time frame but provided a slightly different perspective from Kuntz. Prados pointed to World War II as being a watershed event for engineering. At this point, the major contributors to the war effort were scientists as opposed to engineers (H-bomb, rocket fuel, synthetic rubber). He also pointed out that the primary locations for research up to that time were in government research laboratories funded by the War Department (later the Department of Defense), the Atomic Energy Commission (later the National Laboratories which would eventually come under the Department of Energy), and NACA (predecessor to NASA). The primary goals of the government laboratories were mission oriented. The motivation was basic research, so the laboratories required trained researchers, i.e. the PhD. When the government closed or privatized the majority of its research facilities, much of the research moved to the university sector. However, the government continued to be the primary source of funding. This observation was echoed by Hayes, Wheelwright, and Clark, (1988) who noted that the success of American technology during W.W.II brought focus to large-scale, complex projects rather than small improvements. The dramatic nature of these efforts and the prestige accorded those who worked on them was attractive to companies. To follow the model, separate research and development laboratories were utilized. Only later was it realized this structure separated research from practice. Hayes, et al (p54) went on to note that a similar distancing occurred in the engineering schools at about the same time. “Influenced by the highly publicized achievements of “big science” they
became more and more theoretical in the orientation.” Lang, Cruse, McVey, & McMasters observed that in the post WWII era:

Newly minted engineering PhD’s joined the ranks of academia without industry experience and perpetuated the research emphasis on campuses for the last 40 years. While this research has contributed immeasurably to our technical advancements, the widening separation of faculty and curriculum from industry needs and expectations has resulted in a real threat to our competitiveness in the global market place (1999, p43.)

Prados noted that when he joined the chemical engineering department at the University of Tennessee in 1956, there were very few PhD's on the staff. The staff was not particularly strong in mathematics and science skills because the instructors were primarily from industry and were applications (experiential) based. As the department evolved, the university required its faculty to have a doctorate and to be professional researchers. This was deemed necessary to obtain research funding. Today the department has almost no one with industry related, application-based experience instead it is comprised of nearly all PhDs (Prados, personal communication, February 6, 2002). McMasters and Matsch point out that “Design education generates little research revenue and leads to few publications in the ‘right’ journals. Manufacturing has been held in even lower esteem until quite recently since, in academic terms, it is perceived to lack ‘intellectual content’” (1996, p5). This perceived lack of intellectual content means that universities in general do not value engineering design as an intellectual activity, either in research or in teaching (National Research Council, 1991, pg.12). Furthermore, it has been suggested that engineering graduate education has “neglected the fullest professional graduate development of a strong engineering workforce in industry because of the flawed belief originating in 1945 U.S. Science Policy that the majority of technology developments flow primarily from basic research” (Keating et al., 2003).

Hayes, Wheelwright and Clark report a similar phenomenon in industry. “With focused, large-scale research projects as their model and with government funding as an inducement, many firms established central R&D labs during the war and in the decades following. These labs came to be staffed with scientists whose allegiance was to the (sic scientific) discipline, not the application needs” (1988, p 55). Hayes, et al gave an example of this shift by describing the progression of heads at the research and development laboratory of General Motors. When the laboratory first opened in the early 1920s, Charles Kettering, an accepted brilliant inventor and hands-on researcher with close ties to the automotive business, was its head. In 1947,
Charles McCuen, also an engineer with strong ties to automobiles, replaced Kettering. In 1955, Laurence Hafstad, a nuclear scientist with no automotive experience but noted scientific recognition, replaced McCuen. The progression was from research laboratories staffed with individuals who understood the technology from the ground up and who could provide a source of ideas and assistance linked to market needs, to individuals without close ties to the product, the customer or the business, but who had good credentials in the scientific community and an inclination toward “big science” (p55). As has been noted, the academic sector tends to mimic its industry sector partner in both its structure and its goals.

The esteem with which these well-known researchers were held was not without warrant. In what was to become a case study in success, Hughes (1998, pp 97-111) describes how a group of academic researchers lead by Simon Ramo and Dean Wooldridge designed and developed the Atlas missile. One of the arguments made for bringing the research under the auspices of an academic research group was the feeling that airframe companies could not provide the working environment, salaries, status and organizational structure that would attract the best trained and qualified scientists and engineers. Ramo argued that airplane manufacturers could not attract outstanding professionals as long as the manufacturers continued to handle the engineers like factory workers by utilizing time clocks, whistles, rigid lunch hours and the like. By recommending that Ramo-Wooldridge act as the systems engineer, the committee was displacing engineers familiar with traditional aeronautical engineering practice with scientists and engineers grounded in the sciences and especially experienced in electronics and computers. The committee members assumed that an organization headed by two Caltech graduates with doctoral degrees could attract engineers and scientists from Caltech, MIT, Bell Laboratories and similar institutions that stressed the need for professionals trained in the physical sciences (as opposed to engineering practice).

The Influence of Accreditation on Engineering Curricula

In order to respond to the perceived demands of industry, the curricula of engineering schools were being further directed by accreditation requirements. In order to understand the impact of this dynamic, Bordogna of the National Science Foundation and past ABET participant was interviewed. Bordogna pointed out that after W.W.II, engineering went from being a craft to a cookbook process. However, at this time engineers had the necessary experience background to look at the constraints of the systems, and the “big picture”. They
were able to see the whole and connect the pieces. Contemporary engineers no longer had the
time nor the skills to see the whole picture and they could no longer connect the pieces, due to
both their background and the complexity of contemporary advanced products (Bordogna,
personal communications, August 15, 2001). Accreditation also followed a cookbook process
and the engineers who made up ABET were trained in the engineering sciences as opposed to
engineering practices. The first accreditation processes made use of a checklist of classes. It
was held that, “If you had this many math credits, this many physics credits and this many
engineering credits, you would graduate a competent engineer” (Bordogna, personal
communication, August 15, 2001).

Over 30-40 years, the accreditation process evolved to meet evolving requirements. This
resulted in an increasingly more prescriptive process. It was realized that if engineering
education was going to change, the accreditation requirement philosophy also had to change.
Based on comments and complaints from industry and academia, a new accreditation process
was created in the 1990’s that allowed each school to develop its own strategy within modest
guidelines. Then accreditation teams “evaluated you to see if you were doing what you said you
were doing” (Bordogna, personal communication, August 15, 2001).

Prados suggests that one of the greatest obstacles to change is in an unexpected location;
industry keeps hiring graduates without making any distinction regarding how they were
educated. Another obstacle is less unexpected; academic culture from the last 50 years
discourages educational innovation (Prados, personal communication, February 6, 2002).
McMasters and Matsch commented on the large number of documents that have been
prepared recommending a wide range of reforms. “The university system has proved
remarkably resistant to many of these assaults. This resistance might be largely explained by
the fact that until quite recently the demand for products and the demand for entry-level
engineers has generally exceeded supply. These overpowering conditions were often
conveniently interpreted by academia as justification to reinforce the post W.W.II academic
agendas and paradigms, and dismiss critical feedback regarding real world (commercial)
engineering realities from our (sic aerospace) industry” (McMasters, et al, 1996, p2).
Contemporary Motivations for Curricula Reviews

Not only is academia under pressure from industry and accrediting requirements to review curriculum content, but declining engineering enrollments have caused internal pressures for review. The number of engineering degrees awarded in the U.S. declined from a peak of nearly 77,600 in 1985 to 60,900 in 1998 (Begley, 2002). American institutions are performing their own curriculum reviews to determine why students are no longer becoming engineers. The concern comes full circle as industry raises concerns over the availability and quality of the engineers when they graduate. Not only are there fewer graduates, the skills the students possess when they graduate appear less able to meet the needs of industry. At the same time, the number of engineers needed in technically advancing industries continues to grow (Begley).

The limited scope of this study prevents considering all of the experiential inputs an engineer could encounter during their career. Furthermore, it is not expected that a newly graduated engineer would be placed in a position of such responsibility as to be the sole cause of the design failures being identified in both popular and academic press. It is acknowledged that the increasing complexity and pervasiveness of technology in all aspects of life make it unlikely for a single individual to “know it all”. Furthermore it is recognized that no four-year program is going to produce a fully and permanently qualified engineer, thus efforts to cram everything a student must know into the curriculum is futile (McMasters & Matsch, 1996). Note how this is different than the view “up until W.W.II where it was expected that when a student completed a college engineering program …he was well prepared for his entire professional career” (Lopardo & Wu, 1994, pg 2939). Now it is widely accepted that the engineer largely acquires the elements of experience and judgment by working in industry after graduating. However, the university must lay the foundation for this process and prepare the individual for life-long learning (Young, 2000, p211). Yet there is a need to better understand what the skills industry expects upon graduation and how to measure a student's possession of these skills.

It is not enough to claim the increasing complexities of today’s technology precludes a breadth and depth of knowledge of the same scale as previous generations. While the complexity has increased, so have the tools used to analyze and evaluate designs, processes, and products. The author hypothesizes that the perceived shortcomings are from more than just the volume of information involved. The presence of an increasing trend in the number of
failures, as well as the types of failures being identified, would suggest that there is a difference in how contemporary engineers are designing. It is also hypothesized that whatever paradigms and basic skill sets engineers possess when they graduate, to some extent, form the context for the types of experiential learning which takes place over time.

The Use of Structured Design Tools

This study distinguishes between “engineering analysis” and “designing”. McMasters and Matsch acknowledge that, “while engineering and engineering science are related, they are not the same thing” (1996, p2). McMasters and Matsch use the term “engineering science” to mean analysis and “engineering” to describe the design synthesis process. For the purposes of this study, analysis is defined as those specific analytical activities providing data. Engineering science is the theoretical constructs used to perform the analysis. Designing is all the actions involved in the synthesis of the data. The act of designing includes not only the utilization of formulaic engineering data, but also consideration of economics, logistics, and other technical activities. Structured design methodologies are tools that can be used to support the design activity. It is believed that the final design is not determined by the methodologies, but rather the methodologies facilitate developing the design. Based upon this premise, learning how to use design methodologies is only part of learning how to design.

Impact of Lack of Precision and Conciseness in Language

During the literature review and conversations with experts it was observed there were multiple meanings to terms and concepts being used to discussed engineering design and engineering education. This lack of precision and lack of conciseness may also be a contributor to the perceived lack of skills.

The definitions of the terms used in this research are specific to disciplines, industries, and organizations. For example words such as “engineering” or “design” have multiple meanings. This diversity in terminology directly impacts this study because the terms central to the research have meanings that differ by participant. In order to identify the target characteristics practitioners and educators perceived as requisite for effective design of complex systems, a common set of definitions is required.
The Term “Design”

Designing has different meanings in different groups and organizations. There are authors who make a distinction between analyses and design (McMasters & Matsch, 1996; Vanderplaats, 1984; Thom, 2001a). Vanderplaats defines the basic purpose of design to be the “allocation of scarce resources” (1984, p2). Vanderplaats goes on that “it is important to distinguish between analysis and design. Analysis is the process of determining the response of a specified system to its environment. Design on the other hand is used to mean the actual process of defining the system” (Vanderplaats, p2). Optimal design has been defined as “the best feasible design according to a pre-selected, quantitative measure of effectiveness” (Haftka, Gurdal, & Kamat, 1990, p1). Taylor indicates the “design process is about understanding the intended environment (context) and synthesizing an artifact (form) to fit that environment; it is the process of defining the problem and generating and selecting concepts that solve the problem” (2000, p52). Young quotes Burt Rutan as saying “much of what people do, called design, is really better called analysis” (2000, p208). Taylor defines analysis as “the process of evaluating a concept. Analysis is vital to the design process, but is NOT design in its entirety. While design is an inherently creative task, analysis enables technical feasibility. Analysis must support the design process by providing information to make decisions, and leveraging the designer’s creativity” (2000, p52). It is suggested that “the idea of design and development is what most distinguishes engineering from science, which concerns itself principally with understanding the world as it is” (Petroski, 1996, p2).

In other cases, the design is considered the result of the analyses. It is suggested that a design can be developed only by performing iterative analyses. The test and simulation results become the framework of the design. These points of view illustrate the blurring of the definitions of designing and analysis. Design, as the term is used here, “is the process of defining the requirements of a system, finding a conceptual solution, modeling and analyzing, evaluating the results and as necessary, revising either the solution or the requirements” (Crawley, et al., 1993, p.9).

The Term “Engineering”

Engineering also has multiple definitions. Engineering means analysis, design and creative synthesis, or the integration of data depending on the source and interpretation. In the
Webster’s New World Dictionary, engineering is defined as “the planning, designing, construction, or management of machinery, roads, bridges, buildings, fortifications, waterways, etc.” (1957, p481). In Merriam-Webster’s online dictionary, engineering is currently defined as “a : the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to people b : the design and manufacture of complex products” (2004). The shift from doing an activity to applying theory is noteworthy.

McMasters and Matsch made a basic distinction between engineering science (analysis) and engineering (design/creative synthesis) in the education and employment of engineers. “‘Design’ and ‘engineering’ are fundamentally synonymous …” (1996, p4). Similarly, William A. Wulf, the president of the National Academy of Engineering defines engineering as “design under constraint” (Lang, Cruse, McVey & McMasters, 1999, p43). In some cases engineering is defined as being a creative process such as references to the “art of engineering”. Tricamo, et al.(2003), noted that “as a creative profession, engineering is concerned with combining of human, material, and economic resources to meet the needs of society for the advancement and betterment of human welfare. This is related to the assertion that engineering is design as opposed to analysis or even science. Tricamo, et al. continue, “Engineering is not science or even just ‘applied science.” Whereas science is analytic in that it strives to understand nature, or what is, engineering is synthetic in that it strives to create.”

*The Terms “Systems” and “Concurrent” Engineering*

The term engineering is also coupled with broader concepts, further diluting the meaning of engineering in the context of designing. In the book *Systems Engineering, Coping with Complexity*, Stevens et al. note the role of capturing and managing requirements – sometimes called requirements engineering – helps us define what the product must do (1998, p3). Systems engineering and concurrent engineering have become common terms used in conjunction with designing. Yet even these two terms have a range of interpretations.

In 1968, system engineering was defined as “a systematic approach to help a decision maker choose a course of action by investigation of the full problem, searching out objectives and alternatives, and comparing them in light of their consequences, using an appropriate framework – in so far as possible analytic – to bring expert judgment and intuition to bear on the problem” (Hicks, 1977. p46). In 1996, Christensen defined systems engineering as “a
structured design and system development process.” In other cases, system engineering concentrated on the whole as distinct from its parts, i.e. looking at a problem in its entirety (Jackson, 1997). The International Council on Systems Engineering (INCOSE) defines a “system” as an interacting combination of elements, viewed in relation to function. Further, systems engineering is “the interdisciplinary approach and means to enable the realization of successful systems” (Jackson). Hughes echoes this definition quoting Simon Ramo “Systems engineering is the design of the whole as distinct from the design of the parts. Systems engineering is inherently interdisciplinary because its function is to integrate the specialized separate pieces of a complex of apparatus and people -the system- into harmonious ensemble that optimally achieves the desired end” (1998, p69).

Stevens, Brook, Jackson & Arnold discuss the goal of systems engineering as bridging the abstract early stages and the grimy detail of implementation. System engineering first establishes what is feasible, then creates the architecture for the system to be produced. It defines the requirements for components, but does not itself produce or manufacture the components (1998, p6). Systems engineering is about creating effective solutions to problems and managing the technical complexity of the resulting developments. At the outset it is a creative activity, defining the requirements and the product to be built. The emphasis switches again to integration and verification, before delivering the system to the customer. It must handle the whole life cycle in a balanced way. According to Stevens, et al., systems engineering provides the technical coordination and communicates across disciplines independent of discipline and product type (p6). Ramo echoes this description, indicating “we’ve got to have a peculiar form of generalist that I thought of as a systems engineer who have the faculty of understanding enough of each of the pieces and are good at communications” (Collins, n.d.).

Widnall defined systems engineering as developing and using design principles to integrate the roles of subsystems across a complex design (2001). With the emergence of industrial engineering, there was discussion under whose purview system engineering belonged. Says Hicks (1977), “It is not apparent yet whether industrial engineering should claim responsibility for developing a science of systems within engineering or whether systems theory is so general that it should be developed across all engineering disciplines and not identified with any one discipline” (p52).
Concurrent engineering (also known as simultaneous engineering (Gardiner, 1996, p165)) is defined as “a systematic approach to the integrated concurrent design of products and their related processes, including manufacture and support” (Simms, 1993, p19), or as “an optimized design and development process” (Christensen, 1996). Concurrent engineering is expected to pull together expertise from many disciplines and incorporate it early in the product development process. Christensen made a distinction between the processes of system and concurrent engineering and the philosophies which use the processes (1996).

Because of the blurring in the definitions, Gardiner (1996) studied the inception and use of the two terms. He found that both concurrent engineering and systems engineering had come to have a ubiquitous contemporary connection with the development of new products. Furthermore, concurrent engineering was hailed as the essential method, approach, set of tools, or philosophy for product development. Systems engineering had only recently come to be considered an approach applicable to engineering projects of all types. The greatest difference between concurrent engineering and systems engineering was the difference in emphasis. Concurrent engineering emphasized a reduction in time to market, while systems engineering had its emphasis on quality. While the definition of systems engineering had begun to evolve through common use, it was still primarily targeted at the design of an engineering system, not a systematic way to design. Concurrent engineering was clearly more process focused.

Gardiner’s analysis of concurrent engineering and systems engineering found the contemporary definitions accepted by the profession to be:

Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product lifecycle from concept through disposal, including quality, cost, schedule, and user requirements. Institute for Defense Analysis (IDA) report R-338, 1996.

Systems engineering – The fundamental systems engineering objective is to develop a lifecycle balanced product and process data package [that] describes an integrated set of products… and processes… acceptable to customers and meets established enterprise and external constraints…. The SE process provides a focused approach for product development which attempts to balance all factors associated with product lifecycle viability and competitiveness in a global marketplace. IEEE P1220 Standard for Systems Engineering, Draft 2.3.1, 1993.
The Terms “Science”, “Research” and “Applied Technology”

Other concepts that arise during the discussion of engineering education include scientific and scientific research, applied science, and applied technology. Unlike the term engineering, science and scientific research have an almost universal agreement on definition. In general and for this research, science is the discovery or development of and experimentation on new phenomenon. It does not include considerations of value or application. This does not preclude science being a part of the design process, but it is generally not the primary reason for the design. Tricamo, et al. say, “while directed scientific research is often necessary to gain a better understanding of physical phenomena during a systematic technology development process; scientific research is not the primary driver (2003).

The concepts of applied technology, applied science and applied engineering are all used to describe the activity involved in taking a scientific construct and using it for an actual purpose. These terms encompass the use of a phenomenon as opposed to the development of the concept itself. Tricamo et al. continue, “In its broadest sense, technology is the process by which humans modify nature to meet their needs and wants” (2003). Along with the concept of applying a phenomenon or technology is the development of the scientific construct into an applicable technology. “Development is an attempt to construct, assemble, or prepare for the first time, a device, material, technique or procedure, meeting a prescribed set of specifications or desired characteristics and intended to solve a specific problem (Tricamo, et al., 2003).

Visualization of the Evolution of Engineering Education

In order to visualize the evolution of the academic preparation of an engineer, it is useful to consider the areas of expertise involved. In the beginning of the 20th century, an engineer was a craftsman or tradesman whose knowledge was completely applications-based. What science he or she knew came more from experiential learning than from formalized education. An illustration of this relationship is shown in Figure 1. (This and the following graphics are not based on statistical data and the areas of the regions are only to show relative ratios.)
Dramatic growth in all of the sciences led to efforts to create the “professional engineer”. This was evidenced by reports such as the Mann Report written in 1918 (Mann), sponsored by the Society for the Promotion of Engineering Education (SPEE) (forerunner to American Society of Engineering Education (ASEE)). Research into the content and methodologies in the engineering curricula continued with the publication of the Wickenden Reports (Report of the investigation…), volume one in 1930, and volume 2 in 1934. At this point concerns regarding the necessary curricula content for a “well rounded” engineer led to studies regarding the diversification of the curricula. This included parallel technical and humanities stems recommended in the first Hammond Report in 1939, and the second Hammond Report in 1944. The second Hammond Report, “promoted expanding technician programs to fill industrial needs then being met, non-optimally, by engineers, and teaching the “art” of engineering as distinct from scientific method” (U.S. Congress, Office of Technology Assessment, Higher Education for Science and Engineering… 1989, pp 262-3.)

By the 1940s there were essentially two categories of skills an engineer might possess, engineering science/theory primarily directed at research endeavors, and application technology used primarily for engineering practice. The probability of an engineer having skills from both categories was high. Figure 2 shows that the overlap of science and application is large enough that an engineer involved in design was likely to have skills from both categories.
In 1955, the American Society for Engineering Education (ASEE) released the Report on the Evaluation of Engineering Education, generally known as the Grinter Report (Grinter). This report included comments from 122 engineering colleges and made recommendations regarding five curricula stems, multiple degree track programs, and recommendations on a multitude of challenges. The recommendations included having a base curriculum of engineering science, not contemporary engineering practices. The report also made references to suggestions for a bifurcated engineering program. This would mean having two separate engineering curriculum paths, a science-based curriculum geared towards individuals wanting to pursue advanced degrees and research, and a technical or applications-based curriculum for those desiring to enter the workforce directly from their baccalaureate degree.

One hypothesis regarding the purported decline in strategic design skills is a shift from both a theory and hands-on applications-based engineering curriculum to a theory-based curriculum with reduced applications exposure. In a 1956 article by Davis in the Journal of Engineering Education this move can be seen. “If we are to keep ahead of the world, there must be fewer engineering vocational schools and more engineering academies…. That will mean that more of our colleges will have to weed out more and more of their ‘how-to-do-it’ courses and I for one say, ‘good riddance.’”

In order to both reduce the number of credit hours in an engineering curriculum and to fill the perceived need for a more theoretical base, the application laboratory elements of the program were predominately dropped from the curriculum. This meant that while an engineering student was getting as much or more engineering science and theory exposure, they were receiving less hands-on applications exposure. Not only were the categories more
clearly separated in a curriculum, the relative amount of application exposure available was reduced. This shift in the content resulted in a reduced probability that an engineer would graduate with the same balance of science and application exposure that was characteristic of their predecessors. An illustration of this hypothesized shift is shown in Figure 3.

Figure 3- The relative probabilities of a graduating engineer having science knowledge, application knowledge, or a balance of both (area of overlap) in the 1960’s - 1970s

As the engineering curriculum evolved, a new concern began to emerge. In 1975 the Massachusetts Institute of Technology Center for Policy Alternatives Report, Future Directions for Engineering Education (U.S. Congress, Office of Technology Assessment, Higher Education for Science and Engineering,… 1989, p 264) reported that engineering education was “too responsive to “transient” changes” and among others, recommended that the art of engineering be restored, and that industry be used more as a resource and sponsor. Studies regarding the content and goals of the engineering curriculum in the United States continued with no fewer than nine reports released in the 1980’s (U.S. Congress, 1989).

Engineering departments have attempted to respond to the criticisms of industry regarding design failures by introducing design methodologies into the engineering curriculum. This introduces a third construct illustrated in Figure 4. The probability of a graduating engineer having a balance of engineering science skills and technology application skills still remains lower than in previous decades and is indicated by the overlap of science and application. The probability of a graduating engineer having significant engineering science knowledge, technical application skills, as well as design skills, is necessarily even lower, while the probability of having both science and design skills is greater because it is now greater than zero. This is indicated by the intersection of all three circles.
This separation of science and application is further exacerbated by the reduction in opportunities for outside or extra curricular exposure to experiences applying the concepts that the theories presented in engineering programs explain and a concurrent shift of basic science courses such as physics from tangible concrete concepts to scientific theory.

Figure 4 - Relative probabilities of a graduating engineer having science knowledge, application knowledge, design knowledge, or a balance (areas of overlap) in the 2000s

This separation of skills is not necessarily negative. There are situations in which experience from a specific region is appropriate and sufficient. An engineering researcher would be expected to understand theory and science but not require significant design experience. This was the original driver for the separation. An applications technologist would have experience in practical applications, but would not be expected to have depth in engineering science. However, it is believed that the deficiencies prompting the concerns are illustrated by the low probability of an engineering graduate having substantial backgrounds in all three areas of preparation shown in Figure 4 versus the expectations of knowledge.

It is recognized that individuals from categories outside of the three-fold overlap in Figure 4 are important contributors to design activities. Teamwork can leverage the specialized knowledge skills of a variety of individuals to create robust and successful designs. However this study focuses on benefits of a balance of engineering science and application technology concepts, and a better understanding of the role design knowledge has in the design process.

Under the 1940s concept, a single person could essentially design and oversee the manufacture of an entire product. Even for a large product such as the design of a ship or bridge, one person had sufficient knowledge of the physics, materials and manufacturing
process to manage all aspects of the design and construction. The complexity of contemporary products and manufacturing processes results in the inability of a single person having sufficient knowledge or time to focus on all aspects of an evolving product. Different groups of people become responsible for design, manufacturing and overall management (Ullman, 1992, p7.) If an engineering company utilizes the concept of teamwork, then logically, a design should benefit from the breadth and depth of a team. However, in this team-based philosophy, the engineer may be expected to perform all of the technical functions for the design team, based on expectations from a 1940s perception of skills.

Evidence of a Problem

The response to Scott’s articles in AWST indicates that people in the industry are concerned with the state of the industry and the qualifications of graduating engineers. In the July 5 AWST issue (North, 1999) there are one and a half pages of letters to the editor in response to Scott’s articles, as well as an editorial. The opening lines of the editorial read, “Our recent stories on “Aerospace in Crisis” clearly struck a nerve. We have received dozens of letters, e-mails and telephone calls so far. Almost all of them reinforce the broad frustration and concern that we found in the interviews that led to the stories” (p66).

Although difficult, examples of system failures resulting from poor design decisions can be found. One example is that of design decisions in the gas turbine engine industry where seal material selection was made without appropriate materials review, resulting in the grounding of a fleet of commercial aircraft. Another example was the placement of a sensor device in a gas path of a turbine engine which provided a source of nitric acid that attacked the sensors.

The crash of an Alaskan Air aircraft on January 31, 2000 has as a possible cause premature wear and failure of a jackscrew caused by an incompatibility between the greases used to lubricate it (Miletich, 2001; Baird, 2000). While the final report cleared the grease as a cause, this incident and the subsequent concerns over the grease selection highlights a design decision that may not have fully considered the entire system.

The repeated failures of the Titan IV rockets built by Lockheed Martin, the loss of the Mars Polar Lander, and a variety of space shuttle problems were all attributed to poor design decisions (Oberg, 2000). Within the space industry, the failures and major anomalies are believed to “reflect the need for contractor program management to provide more disciplined
systems engineering [italics added] in both design and processes. Both engineering processes and workmanship have been prominent in mishaps since 1985. More specifically, the lack of disciplined systems engineering in design and processing of launch vehicles has contributed significantly to launch failures” (Sturges, Crocket, & Kuehl, 2001, p45).

The text “When Technology Fails” edited by Neil Schlager (1994) is a collection of examples of design failures and problems, from aerospace, civil, mechanical and industrial engineering. The following are selected examples of engineering design failures in aerospace.

− (p 52) 1974 DC-10 crashed following decompression and loss of flight control.

It was determined that the cargo doors could be incompletely latched resulting in the door opening in flight. This caused an explosive decompression, buckling of the fuselage structure and cutting of the hydraulic lines through the area near the tail. The loss of hydraulics caused a loss of control in addition to the hole in the fuselage and the buckled structure.

To address the potential for unlatching, a peephole was placed in the cargo door for the baggage handlers to check the latches. However, the handlers could not look through the peepholes from the ground and no one told them the peepholes’ purpose.

− (p 53) 1979 DC-10 crashed following the loss of an engine.

American Airlines requested using a fork truck instead of a crane to hold the engine during the engine pylon bearings change. McDonnell Douglas Aircraft was ‘uneasy’ with the request but gave tacit approval by providing recommendations on how to best do it with a fork truck. The large engines, complex connections, and difficulty in alignment made the engine change difficult, resulting in numerous cases of incorrect installation. Further, it was found that a failure of the No. 1 engine caused the generator to go offline, eliminating the stall warning. A No. 1 engine failure also disabled the wing hydraulics so there was a loss of control of the wing control surfaces, including leading edge. At the time there were no Federal Aviation Administration (FAA) certification requirements regarding leading edge failures.

Results – The design problems of the DC-10 were so extensive that the airworthiness certificate was revoked until repairs and upgrades could be made. This was an unprecedented action on the part of the FAA.
− (p 87) 1989 DC-10 crashed following explosion of tail engine and complete loss of hydraulic fluid.

The number 2 engine in the tail had a complete disk failure resulting in the engine exploding. This cut all of the hydraulic lines to the tail. The system was a single reservoir, resulting in a total and complete loss of hydraulic fluid for the entire aircraft. While the nature of the accident precluded any form of redundancy being effective, the fact that the aircraft was designed with no manual backups was an issue. The designers felt that there was no reason for manual backups because it was thought a single person would be unable to physically manhandle the controls. In addition, such a complete hydraulic failure could theoretically never happen (italics added).

− (p 94) 1991 Boeing 767-300 In-flight deployment of thrust reversers caused an immediate roll and crash.

In the 1980s, Boeing started using electronic instead of manual thrust reverser locks. Boeing asserted there was “no way” (italics added) a thrust reverser could deploy in-flight”. The FAA approved the design based on a low speed, low altitude deployment test. The thrust reverser design also included an auto-store feature with an indicator on the flight deck. Pilots “learned” from experience that a flickering light in the cockpit was just the auto store feature and was not a concern. In reality, the indicator had a multi-feature indication based on the color of the light.

The auto restore design was overly complex and had inadequate testing on incomplete parameters. Worn seals and debris in the system would cause the thrust reverser to auto-deploy. Worn and chaffed wires caused errant signals to the flight deck indicator, teaching the pilots to ignore the indicator.

Large aircraft are not alone in experiencing failures due to poor engineering design decisions, nor does the design activity end when drawings are produced. The Piper Tomahawk, a small general aviation aircraft, was designed to be a high speed, high performance training aircraft. Design changes made between development and manufacture resulted in an aircraft with unpredictable flight characteristics and a tendency to enter flat spins. As reported by Lowery (1998), the aircraft leaving the manufacturing plant was not the same as the original design. Engineers involved in the design process allowed the production aircraft to have fewer wing spars, lighter materials in the spars, thinner gauge skin and the wing root gloves eliminated. The changes were made to facilitate production. However, these items had been specifically designed into the aircraft to solve potential problems identified in the flight characteristics due to potential flexing of the wings. This example demonstrated why the
design process does not end until retirement of the product and how changes in one area of a product design can impact performance in other areas of the design.

It can be argued that in these examples, no one knew that the design choices would have negative impacts. Nor could they foresee all of the permutations of potential design issues. Nevertheless, such examples show the importance of considering the entire system and its application. This is not to suggest engineering design is without risk, however, the types of failures being discussed are not caused by risk taking, but rather from simple mistakes, lack of data, not recognizing problems, and not considering the impact of an action on the entire design. It is not expected that the engineers of the 1950s knew how everything in the design worked. Nor is it sufficient to explain the concerns by saying contemporary designs are more complex than previous designs. Correcting for the level of technology available, previous designs had complex considerations that are being assumed to be correspondent with today’s design issues. The increasing trend of atypical design flaws may indicate they knew something about design that contemporary engineers do not.

Examples of application experience having a positive impact on design and profitability are not restricted to aerospace products. Lorentz Iversen was an immigrant to the U.S. in 1900. Before coming to the U.S., Iversen had been apprenticed as a machinist and then earned an engineering degree. From 1900 to 1960, the company he started was one of the premier engineering companies in the U.S. When Iversen left the company in 1960, it lost its technological drive and its long established competitive advantage in engineering (design) eroded. By 1983, the company no longer existed (Hayes, Wheelwright, Clark, 1988). What skills were missing in the engineers working for the company in the 1980s that were present in those working for the company in 1950?

**Contributing Factors Beyond the Scope of This Research**

A review of the literature indicates there are multiple potential factors contributing to the current concerns regarding engineering education. One factor presented is the shift from a balance of applied engineering and engineering theory and science. Other equally important considerations are reductions in the number of talented individuals entering the field, lack of process management and communication skills, reduced employee motivation, short-term profit horizons, and rapidly changing management philosophies.
While these considerations were beyond the scope of this research, it was important to briefly review the concepts.

Communication

Poor communication skills are a contributor to the criticisms regarding the robustness of designs. Industry has complained that in general engineers cannot communicate or work in teams (Education needs…, 1996). Hessler, editor for SAE International Update noted, “While college education may provide young engineers with many of the technical skills required for career success, non-technical skills such as teamwork and communications are sometimes lacking in the engineering lecture halls” (2002, p 2).

A review of the engineering curricula at multiple colleges and universities indicated the recognition of a need for, and the implementation of, communication components into their programs. For example, Massachusetts Institute of Technology (MIT) specifically includes a communication requirement as part of their undergraduate curriculum. According to MIT’s web site, the faculty recognized “a changing demand on their graduates and initiated a multi-year process of collaboration and curricular pilots involving communication education. The result of this process was the development of an instructionally based Communication Requirement that is sequenced throughout the four undergraduate years” (MIT, 2002).

Economic and Management Issues

Management incentives that are tied to investor satisfaction on a short-term basis are barriers to taking long-term risks. In the aerospace industry, the turn-around time for an innovative aircraft is 10 to 20 years. Most management will not be in place for the time it takes for the return on investment to be realized. The typical CEO is in place for five years and his or her primary driver is to keep stock prices high (Scott, 1999a).

Similarly, considering people as commodities, rapidly changing the process tools, and “management philosophies of the week” are all examples of problems related to human resources and management. The impact of frequently changing philosophies and the feelings of unimportance by employees have been reported to impact quality and productivity, and therefore play a role in the problems reported by industry.
**Productivity**

“Speed is god, Time is the devil.” – Hitachi company slogan (Thackara, 1997, p14)

“Do more with less.”

“Work smarter, not harder.”

When driven by faster, better, cheaper, one of the goals will be sacrificed. The old adage of “I can do anything you want (better), as soon as you want it (faster). Just add money” sums this up succinctly. One of the three must be sacrificed. A review of a series of Titan rocket failures by an independent review team concluded “the company focused too heavily on cutting costs and not enough on supervising the quality of its work” (Oberg, 2000, p16).

Scott (personal communication, July 25, 2001) identified several contributing factors to the increase in design mistakes resulting in system failures during his research. Among them was a lack of time to think. The pace led to an inability to complete an entire problem-solving matrix.

Kriegel & Brandt note quality can suffer due to rushing. “The reason we’re racing along at this dangerous clip is to increase our productivity and profits. Yet, exactly the opposite happens. What happens to quality when you’re in a hurry? You make more mistakes… dumb ones, careless ones… It’s not that these tasks take any brainpower. It’s just that when you’re rushing you get sloppy. And there’s no time to double check your work” (1996, p27).

**Loss of Talent**

Industry and academia have expressed concerns regarding the loss of talent in the field of engineering (Begley, 2002; Birch, 2001; Adelman, 1998). Birch says, “There is a growing concern in some areas of aerospace about a shortage of engineers with appropriate skills and knowledge” (2001, p11). Bokulich, Gehm, and Hessler (2001) point out that while industry consolidation has reduced the overall employment numbers, there is still an increase in the employment needs in the engineering disciplines. Begley (2002) points out that there is a growing concern in industry that students are not pursuing degrees in engineering because they become disillusioned early in their educational career. In a report of the Commission on the Future of the United States Aerospace Industry …, the panel suggests the aerospace industry is losing qualified engineers at “an alarming rate” (Dykewicz, 2002, p1).
Sheila Widnall, former Secretary of the Air Force and past president of the American Institute of Aeronautics and Astronautics (AIAA) read a letter from an aerospace engineer who had left the industry in frustration and summed up the issue; “The passion is clearly there. Because of this passion, at least in the near term, we will benefit disproportionately in our effort to attract the best and brightest... But we must be realistic about the way they are educated and insure that their education builds skills, the expectations and the motivation to attack the central critical challenges facing the industry” (Widnall, 2001).

In a monograph prepared for the National Science Foundation, Adelman (1998, p xi) attempts to better understand what caused students to change their field of study while in college. Migration out of engineering was specifically chosen by Adelman for his research. Adelman noted that students who migrated from engineering predominately changed to other disciplines requiring strong quantitative skills, not to “easier” disciplines.

David Logsdon of Aerospace Industries Association of America noted a “loss of talent in the aerospace industry due to early retirements and lay offs, and the inability to balance the loss with the hiring of quantities of quality new talent” (Dykewicz, 2002, p1).

It is also suggested by organizations such as the NSF and ABET that students no longer enter engineering because it is no longer perceived as “fun” or “interesting” (Begley, 2002). Bordogna asserts that the engineering student must also experience (in addition to technical competencies) the functional core of engineering, “the excitement of facing an open-ended challenge and creating something that has never been” (Bordogna, 1997).

**Education and Training Pedagogy**

While this study does not directly consider educational or training pedagogies, the identification of measurable skills deemed necessary for successful design participation should provide tools for improvements in engineering education. Noticeable activities have taken place to make changes to the content of engineering curricula and to improve the methods used for teaching. It is necessary to understand current efforts to avoid duplication of efforts.

**Education and Training**

Education and training are similar in that they provide information to individuals. Education primarily provides general knowledge in a formal environment, while training
provides a more specific knowledge in either a formal or informal environment (Webster, 1976). Generally, education is what is expected from colleges and universities and training is provided by organizations separate from the formal college environment.

When Scott was performing the research for his articles, he observed individuals asking, “How do we complete the education process? What should be in it?” Scott found an assumption by educators that on-the-job training completes the engineering education. Industry, on the other hand, tended to expect a finished product, nearly ready to be a productive contributor to the process. There was a general feeling expressed by engineering managers that they are paying the new engineers a lot of money to engineer for them, and expect results now (i.e. immediate return on investment) (Scott, personal communication, July 25, 2001). In cases where industry had made the effort to teach engineering design, intended to compensate to some degree for perceived educational shortcomings, the efforts were often too fragmented and not institutionalized as natural components of the way business was performed (National Research Council, 1991, p12). Note that these expectations of readiness are separate from the awareness of the need for lifetime learning.

According to a review by Gehm (2002), most aerospace companies currently provide on-the-job training for their newly hired engineers. Goodrich places new hires directly into a one-year job rotation program. Lockheed Martin has a technical mentoring program to provide structured, technical training to increase the skills of all new hires and uses the Engineering Leadership Development Program to further develop select new hires.

There has been discussion in the popular and academic press with respect to the quality of the education system. A report from a government panel, The Commission on the Future of the United States Aerospace Industry, charged that “the aerospace sector has been hurt by an educational system that needs to be “dramatically improved”, especially in the subjects of science, math, and engineering” (Dykewicz, 2002, p1). Others point out that most students lack sufficient understanding of statistics, materials, manufacturing processes, cost accounting, and product life cycle considerations. Industrial training courses try to fill these gaps at considerable cost and with varying degrees of success (National Research Council, 1991, p12).

Conversely, Swain reports that the education and training universities offer is 90% adequate to needs at Boeing. “We encourage universities to give students hands-on, cross-functional experiences and many are responding” (Bokulich, Gehm, & Hessler, 2001, p20).
By working together, academia and industry are attempting to improve the educational experience for students. Lockheed Martin sends engineers to universities to teach ‘real-life’ aircraft design case studies to students in an attempt to improve the skill sets of graduating engineers (Bokulich, Gehm, & Hessler, 2001). Purdue University has an engineer in residence program in which General Motors (GM) engineers teach two undergraduate mechanical engineering courses and oversee a collaborative vehicle dynamics research project between Purdue and GM. John Zinser, chief engineer says, “The engineering in residence program has provided an excellent opportunity to enhance the partnership… The students get a strong role model who can demonstrate the practical application of what they are learning and we gain a stronger insight regarding the synergies that can be enhanced between the University and our company in all areas, particularly research” (GM Engineer…, 2002, p3).

The lack of measurable characteristics for use in developing programs may be demonstrated in the condition of the relationships between industry and academia. In a survey of industries performed by the National Research Council, it was noted that partnerships among industry, research and education were so limited that the relevant needs of each were poorly serviced by the others. Design education and research were divorced from industry. Industry did not articulate its requirements, support changes to the design component of curricula or consider education as an incubator of future design talent (1991, p12).

**Challenges of Integrating Education and Training Needs**

As the complexity of contemporary technology increases, the distinction between education and training may continue to blur. The key to preserving intellectual capital may be having engineers who are constantly learning and upgrading their skills. Some firms are already trying to foster this new engineering culture by recognizing that the expense, the time, and the expenditure of resources for an engineer to be a “perpetual student” will be paid back many times in productivity and quality (Smerdon, 1997). For example, The Boeing Company offers in-house graduate programs and Motorola maintains the Motorola University (Smerdon). Lockheed Martin has created a Technical Fellows Program, in which fellows are required to provide learning and development opportunities to less experienced engineers (Gehm, 2002).

Conversely, there are authors suggesting this is an era in which the responsibility for career development is no longer the duty of the organization but rather that of the individual
engineer (Hissey, 2000). This would indicate that the individual engineer needs to recognize insufficiencies in their skills and find the means to improve their skills on their own, rather than expecting their employer to point out areas for improvement and make suggestions for remedying them. One method suggested is the use of continuing education at local universities, bringing the education and training cycle full circle.

**Academic Reforms**

In response to industry requirements, changes in technology, concerns over the loss of talent, and accreditation requirements, schools are initiating academic reforms. The NSF in particular has assumed a major leadership role in academic reform, dedicating many millions of dollars to activities such as the Engineering Coalitions whereby experiments in new, innovative approaches to engineering pedagogy have been encouraged (Garris, 2001, p4). At the University of Massachusetts Dartmouth, engineering curriculum developers have developed an integrated first year modeled after the NSF Coalition at Rensselaer. The program has integrated the introductory sequences in physics, calculus, chemistry, English, and engineering so that concepts taught in one course support the concepts in others. A specially designed, technology oriented classroom is used. Courses are taught using teamwork among students and faculty, and active, cooperative learning methods are employed (Pendergrass et al., 1998).

In 1991 Purdue University’s School of Mechanical Engineering “embarked on a major initiative to improve its undergraduate curriculum, with an emphasis on enhancing elements pertinent to engineering practice” (Incropera, 1994).

ABET has provided engineering schools with the basic guidance that the schools provide students with the “ability to function in multi-disciplinary teams” and the “ability to identify, formulate and solve engineering problems” (Bernold, 2000). At Arizona State University, engineering faculty convinced the college to participate in a study to ascertain the future needs of engineering education. “As one faculty member stated, ‘The idea was not to let industry or anyone else tell us what courses and topics to teach. It was to let them define the characteristics of the students as they graduate from our program and then assess and measure (italics added) whether or not our process produces the desired product’” (Wolverton, 1996, p65).

It is in execution of these general, high-level recommendations where issues arise. Universities must determine how to teach them. “We need to know what the schools do, why
they do it, and with what consequences before we prescribe what the school should do differently” (Mary Haywood Metz as quoted by Peshkin, 1993). Bernold points out that it is just as unrealistic to try and teach multidisciplinary team work and creative problem-solving in a course based on tests and homework as it is to expect students to be good communicators from a single forced communication course (2000). Furthermore, faculty at North Carolina State University have observed that traditional engineering education has favored two types of learners, those who excel at regurgitating facts and those who like working in isolation on theoretical analyses (Education needs..., 1996). It was further noted in the National Research Council Review, that individuals who enjoy design and excel at it take a fundamentally different approach to their work than engineers and scientists whose forte is analysis (1991, p31). There is concern that this traditional teaching philosophy may present challenges when attempting to incorporate the multidisciplinary, team structure into the classroom.

Design Education Methodologies

Structured Design Methodology Tools

Because design problems lack specificity, the tendency and tradition of a design organization is to follow an ad hoc process. Despite being ill defined, they can be examined scientifically and solved with a scientific approach (Taylor, 2000). In an effort to respond to industry criticisms regarding the robustness of contemporary engineering designs, both academic education and industrial training have been developed that use structured design methodology tools. These methodologies are tools that are used to facilitate the design process and improve design robustness. The tools help formalize and manage the information flow throughout the team and provide a baseline for understanding and improving the design process. They also provide insight into the structure of the design process itself (Taylor). They are tools to aid in the synthesis process rather than the means to a robust design. Examples of these tools include total quality management (TQM) initiatives, Taguchi, Voice of the Customer (VoC), Quality Function Deployment (QFD), 6σ and Pugh’s Method. These tools are designed to assist in identifying customers, their requirements, the relative importance of the requirements and the degree with which a design parameter meets the requirement. They are tools to aid in the synthesis process and assist in the identification of data needs and the
evaluation of that data. Structured design methods can improve the effectiveness of team processes through higher quality communication and team processes (Taylor, 2000). By using these tools, engineers are able to make educated decisions, identify missing data, and document the design process. Furthermore, the tools are expected to facilitate communication between individuals of diverse discipline and experience backgrounds. This is necessary because design is both an organizational and technical activity (Taylor).

Total quality management provides instruction in effective team structure and use of a variety of structured tools. “Taguchi addresses quality in two main areas: off-line and on-line quality control” (Ross, 1988) and includes a systematic use of design of experiment. Voice of the Customer and the related quality function deployment is a conceptual map providing the means for inter-functional planning and communication (Hauser & Clausing, 1996). VoC provides a means of assuring that the customer desires and requirements are considered early in the design process. VoC and QFD are means of getting a better concept and then guiding the development of that concept (Clausing, 1994). Six Sigma is a philosophy of reducing variability in a process. “Six Sigma refers to a mere 3.4 defects per million opportunities, or 99.9997% error-free operation in any given process” (McCoy, 1999). The discipline and insight Pugh’s method provides results in a selection process that iteratively improves design concepts (Clausing). The tools are designed to facilitate leveraging the variety of expertise and backgrounds of team members who have the requisite technical expertise and knowledge. Using such tools cannot remedy a lack of experience or skills in team members.

The addition of these design methodologies to engineering curricula has been noted in the literature. Arizona State University (ASU) engineering instructors learned about teaching TQM philosophies by going to The Boeing Company and other organizations using TQM to learn about the philosophies, and how to use them and teach them. The TQM experiences helped reshape the previous ASU sophomore curriculum into a new, integrated curriculum. For the engineering faculty to create a TQM environment with the students, the instructors had to examine how they defined engineering excellence (Wolverton, 1996). By 2002 the effort had been abandoned due to difficulties in assessment and implementation.
Course Structure Utilizing Design Projects, Team Teaching and Cross-functional Exposure

Industry has also expressed criticism with the exposure students receive regarding how to bring a project in on time and under budget, managing client relationships, coping with difficult personalities on a team or relating well with management (Buckley, 2000). In response academia has restructured courses to create environments characteristic of those encountered in industry. Methods include the use of open-ended engineering design projects, team teaching of courses, and the integration of multiple courses of different disciplines with a common design project. Schaffer (2000) points out recent studies suggest that real world experiential, or collaborative approaches to teaching are good compliments to traditional methods used in undergraduate education and that partnering with actual practitioners can further enhance the effectiveness of the approach. The following examples illustrate the range of challenges to success of such attempts in college settings.

At Oregon Institute of Technology, faculty with industrial experience participated in a cross-functional class activity in which a sophomore accounting course was taught with a sophomore fluid mechanics course (Rogers & Stemkoski, 1995). The class was divided into teams and challenged with preparing a business case and a design for a waterslide park. The project had mixed results. Students expressed frustration with understanding the goals, there was an observed tendency for ‘accounting versus engineering’ in group efforts, and there was a lack of utilization of the industry participants made available to the class.

Similarly, Pennsylvania State University at Altoona introduced a team-based collaborative problem-solving model into a three-credit-hour electrical engineering technology course using structured design methodology tools (Anwar & Rothwell, 1997). Initially the report work was performed more serially, each student waiting for the results other students. By the end of the semester, time constraints forced the students to work in parallel. The authors observed that by the end of the semester the students had come to the realization they did not have to solve the entire problem on their own, but began to leverage the expertise of multiple participants.

Bernold of North Carolina State also participated in a team teaching activity (Bernold, 2000, p67). According to Bernold, the first thing the instructors had to do was teach the students how to learn in the team teaching environment while weaning the students off traditional study habits. “Students applied principles of math and physics to solve engineering problems, discovering how torque feels and how it can be measured. The students didn’t know
if they were in Physics 208, Math 102 or Engineering 100”. While the activity was an educational success, the program was not continued. “It did not fit the traditional “divide & conquer” (sic teaching in compartmentalized bits) organization of our university. Squabbling while ignoring the good of the students, the department involved couldn’t agree on who was going to be responsible (and paid) for what” (Bernold, p67).

At Vanderbilt University, seniors in the mechanical engineering program are required to take a sequence of two courses in mechanical engineering design (Garris, 2001). These courses are intended to expose the students both to the formalism of design methodology and to actual problems in design similar to those encountered by practicing engineers (Vanderbilt…, 1994). Changes to course content at George Washington University include a project-oriented design course in which the role of patents in design is heavily integrated. Students are required to utilize the United States Patent system to research ideas and product evolution prior to designing their own product. The environment simulates a competitive industry environment in which teams of students compete against each other for a marketable design. During the course of the semester, two separate design projects are required.

**Studio Methods**

Studio is meant to describe a general approach to interaction with students that is instructor-facilitated, student-centered and very hands-on. The focus in a studio is to be on the work done by the student. The goal of a studio environment is to provide open-ended, complex projects, requiring multiple, rapid iterations of solutions. Peers, industrial partners, and professors critique the work in progress. Students are encouraged to study previous works and use them in the development of a “big picture” solution. The role of the faculty is that of guidance and facilitator as opposed to instructor and lecturer.

“Introduction to engineering design” has been offered for more than 35 years at Harvey Mudd University (Little & Cardenas, 2001). In 1992, the course was re-structured to incorporate formal design methods. A variety of studio permutations were tried to determine how to best structure the physical space, the pedagogy, and the assessment process. The studio method was a departure from the previously used traditional classroom structure for the class and student responses ranged from highly positive to highly negative. Students liked that each activity built on previous exercises and the practical application of course material. The
students were uncomfortable with the vagueness of the requirements, the difficulty of open-ended problems, and the lack of structure.

Courses taught as studio range from self-taught, computer-based learning through open-ended design projects (Little & Cardenas, 2001). In attempts to teach design-oriented courses, it is assumed the students possess the necessary skills to be successful. They are provided with an open-ended problem and a design environment in which to “put it all together”. Problems observed in execution of the studio method may be due to erroneous assumptions of student ability or an inability of educators to measure success. This inability may be due to a lack of defined characteristics with which to measure success and provide feedback.

**Concurrent Engineering**

The academic reforms described above used concepts and methods similar to those of concurrent engineering used in industry. Concurrent engineering evolved due to designs becoming too complex for a single individual to accomplish. This complexity, coupled with the need for faster design development and increased quality, resulted in a need to bring together expertise from multiple disciplines. Concurrent engineering became the means to orchestrate and integrate this diverse input. Concurrent engineering was developed to facilitate input and feedback loops as opposed to focusing on quality. Improved quality could be expected to result from the improved communications.

Prior to the 1980s, designers were often the focal point for defining aerospace hardware. Everyone would gather around the engineer's desk (often a drafting table) to discuss and develop a new product. With the increasing use of computer-aided design equipment, which needed to be in environmentally controlled rooms with limited access, the design activity was fragmented, and the role of the lead designer changed. “The design process grew longer, encompassing many serial activities. Re-design and rework were required to incorporate manufacturing and user requirements that had not been incorporated earlier in the cycle. Additional systems engineers became necessary to integrate the various development activities” (Simms, 1993, p21).

In order to reduce the serial nature and the loss of connection of each individual participant, industry developed the concept of “concurrent engineering”. The concept utilized
structured design methodology tools, redesigned facilities to bring participants together, and redefined team structures to increase probability of design success.

In academia these attempts may be observed but are logistically restricted to engineering students in single courses. This may mean that the isolation mentality of engineering is reinforced rather than dispelled.

**Emphasis on Computer Simulation**

The use of computer simulation to provide experiential exposure to concepts is being increasingly used by academia. Students participate in laboratories or perform homework calculations using computer simulations of a variety of complex concepts. These tools permit more rapid changes in input and output observations than traditional laboratory experiments. Furthermore after the initial expenditure for computer equipment and simulation code, the laboratories are less expensive to run and maintain and require less floor space than their traditional laboratory counterparts. All of these benefits are attractive to universities.

The drawbacks to the dependence on simulations include a lack of opportunity for students to internalize the basic, tangible concepts, leading to an inability to recognize “garbage in – garbage out” or deal with permutations outside of the specific simulations to which they have been exposed. Because students have no intuitive sense of appropriate response from a given simulation, students must assume and accept the validity and accuracy of the code used in the simulation. Students can only run simulations for which code has been written; however, because most aerospace systems are so complex, only isolated and simplified simulations are routinely performed at an academic level. This may have the unintended result of reinforcing a segmented view of complex designs as opposed to an integrated system perspective.

**Relationship between the Study Purpose and Educational Pedagogy**

While educational theory is beyond the scope of this project, it is within the framework of education where the resources of a major university play the greatest role. Before concentrating on “how” to educate students, however, it is important to first identify “what” to educate. As summed up by Bordogna (personal communication, 8/15/2001), “the answer is not to keep adding more courses to a curriculum. The courses are the tools to provide the fundamentals. First, you must define the fundamentals.”
In order to define these fundamentals, industry needs to articulate a coherent, consistent position to academe on industries needs and expectations. “A major stumbling block, however, remains the lack of a relentless, strategic commitment to shared objectives by academe and industry” (McMasters & Matsch, 1996, p2).

Adelman (1998, p7) points out in his monograph that engineering has a significant social aspect and requires that a curriculum provide greater exposure to the “client” considerations, such as negotiations and communications. Research into providing “soft skills” such as communication skills, technical writing, quality management tools, and team activities is being done and progress in incorporating these skills into college curricula has been made. However, application skills requested by industry typically are expressed in very global terms such as critical thinking, systems engineering, and problem solving skills. These general terms do not define the specific skills that demonstrate the traits, the desired outcome of presenting the skills, or how to incorporate the education of these skills into current curricula. Adelman (1998) points out that his research, directed at recruitment and retention, does not deal with whether students have mastered the technical engineering portions of their curriculum, or to what degree they are able to handle theoretical constructs because it is beyond the scope of the available data. In Taylor’s doctoral dissertation, he comments, “research into the integration and interaction of technology and organization tools to improve the [design] process is generally absent from the literature” (2000, p2).

Process Review

Background – The Need to Identify the Skills

Although educational theory is not the purpose of this study, it is important to consider the basic constructs of college education and the requirements of students. Educators are coming to the understanding that education has changed from rote memorization to something else (Bordogna, 2001). It is by understanding the underlying concepts and principles, that knowledge can be applied to new contexts (Bordogna, 2000a).

One thing that has been suggested as missing from the engineering curriculum is the concept of viewing a design or process as a whole, rather than in pieces. By being able to
consider the whole, the engineer can begin to look at the issues of system integration. This is not a simple concept to understand much less to teach. As Bordogna (2001) suggests:

Something new happens in the integration process. A singular or separate dynamic emerges from the interaction. That’s probably why when economists are analyzing productivity inputs they refer to the residual, what’s left after you factor in capital, labor, land, etc. as the “black box”. They can’t explain the dynamism or interaction of the leftovers such as R&D, education, workplace interaction and the like. They can only recognize that something better, more enhanced comes out on the other side (page 7 of 8, ¶ 2 under Holism).

It is suggested that during the move from teaching a balance of engineering application and engineering science to treating the concepts in separate programs, graduates have lost the ability to see the system as a whole and consider its use and its integration. According to Bordogna, Prados, Kuntz, and other engineering professionals, engineers do not always focus on the big picture. Bordogna suggests that most curricula require students to learn in unconnected pieces in separate courses. The relationships among the pieces and to the engineering process are not explained until late in the bachelor’s degree. Engineering education is usually described in terms of a set of topics engineers “need to know”, leading to the conclusion that an engineering education is a collection of courses. The content may be valuable but this view seems to ignore the need for connections and for integration that should be at the core of engineering education (Bordogna, 1997). The question is how to teach the integration of seemingly disparate things into a greater whole (Bordogna, 2000).

Bordogna quotes Peter Drucker, “Knowledge applied to tasks we already know how to do is productivity. Knowledge applied to new and different enterprises and delivering new products and services is innovation” (Bordogna, 2000). Bordogna suggests that students can learn the process of innovation and risk taking from models and collective experience long before they themselves enter the workforce. Bordogna goes on to quote Kash & Rycroft who write, “Economic well-being in the future will likely go to those who are successful in innovating complex technologies” (Bordogna, 1997, paragraph 19). To be successful, contemporary engineers need more than first-rate technology and science skills. It requires a broad, holistic background. Since engineering itself is an integrative process, engineering education must focus on this end. Scientific inquiry is an analytical, reductionist process, involving discovery of new knowledge. Engineering is the process of integrating all knowledge
to some purpose (Bordogna, 1997a). While Bordogna stresses the need for the education process to teach engineering as a holistic activity and to include system integration concepts, as well as the need to define desired outcomes, he does not provide any metrics for success nor define the skills required.

The National Research Council estimated that 70% or more of the costs of product development, manufacture and use are determined during the initial design stages (Bordogna, 1997). Similarly, Blanchard indicates that over 75% of the cost of ownership of a system is in the operational and support activities. This 75% of the cost is determined and locked in during the first 10% of design phase activities, the initial design engineering (1991, p 6-7). Yet, the skills necessary for success in the engineering design process are not well defined.

In the text *Introduction to Industrial Engineering and Management*, Hicks points out that in the early 1900s engineers had an innate sense of size, proportion, stresses and system requirements. They could almost “see” all of the concepts that engineers were later to be taught empirically (1977). Contemporary industrial perspective suggests this skill has been lost, resulting in an inability of the engineer to “see” their part of a system design or its impact on other parts of the product. It is hypothesized that this inability to consider the whole is one of the reasons there is a need for more rework and design in current aerospace systems.

Deskin presented a paper on the successful design of the propulsion system for the F-22 and the overall robustness of the design at the 2002 Joint Propulsion Conference (Deskin & Yankel, 2002). The success was attributed to the use of structured design tools and that the “key to successful execution was comprehensive planning that applied system engineering principles as the driving focus” (p1). But in neither the presentation nor the accompanying paper did the authors define what skills or characteristics were present in the engineers that achieved this success. The results of The Presidential Space Launch Vehicles Broad Area Review of Spacelift Failures reported, “The government must ensure that industry acts to correct causes of recent failures and improve systems engineering and process disciplines” (Sturges, Crocket, & Kuehl, 2001). The report implies that the task of defining the deficiencies in system engineering and process disciplines is up to industry.

If this need for innovation and integration and the requirement for holistic understanding are so critical to successful design and profitability of the final product, then it should be
equally as important to provide engineers involved in design with more than traditional engineering science skills. Identifying what those skills are is by necessity, the first step.

*Project Process Methodology Review – How were the skills identified?*

In addition to literature reviews to identify educational and industrial skill characteristics, a survey of engineers involved in design was done. The use of survey methods was one of the few methods allowing individuals familiar with the issues, problems, and actual design failures to provide candid data. The ability to obtain this data solely through literature was limited by the lack of publicly available data, the reticence of industry participants to discuss internal problems, and that only catastrophic or unusual failures were publicized beyond internal design teams. This data could not be developed in a contrived setting due to the nature of the target data and the time required for the problems to manifest.

The goal of this analysis was to identify the primary technical characteristics perceived by practitioners to be requisite for successful design activities. The data was developed using a methodology of literature surveys, structured interviews of industrial practitioners and observations of senior engineering design classes at Purdue University. These characteristics were determined by their frequency of appearance within each cohort group. The observations of representative aerospace engineering design classes were collected and the observations compared to concepts identified in the literature. The results were used as a basis for developing an interview frame.

The interview can be a very powerful data gathering mechanism when correctly prepared. To assure useful results, literature reviews of the best practices in preparing and administering interviews was performed.

*The Interview Tool*

Based on an evaluation of literature and textbooks, an oral interview was selected as appropriate. The development of the scenarios and introductory questions was anticipated to be the most difficult step of the process. It was acknowledged that content, wording, and delivery had important implications on the entire study (Trochim, n.d., McNamara, n.d., Moore & McCabe, 1999). To deal with this challenge, questions from other researchers’ studies were examined and where appropriate modified, for this research. Other questions
were generated based on the observations made during the academic observation sessions. The goal was not to replicate the results of previous research but to use the results as the foundation for preparing an interview frame for identifying characteristics that describe the requirements for successful design participation.

Following the structure of similar surveys, a series of interview questions and probes were prepared. The interview guide was used to obtain participants opinions regarding the design activity. The interview guide is included in Appendix E.

**Sample Selection**

For this study, convenience (a.k.a. purposive) sampling was the best choice. Using the purposive sampling method for selecting participants traded the ability of performing rigorous statistical analyses and a reduction of generalizability, for the ability to target participants with the specific knowledge of interest (Levin & Rubin, 1998, Moore & McCabe, 1999). This study was interested in a specific type of information; a simple random sample of the population was pointless (Sekaran, 2000). This reduction in generalizability was acceptable due to the exploratory nature of the study, providing foundational data for future studies. Participants were selected from technically complex industries based on criteria described in the methods section. The results of this study were contextual to the aerospace engineering industry, but were expected to be predictive of other highly technical engineering fields.

**Summary of the literature review**

The amount of literature, the level of activity and the extent of expressed concerns all suggest that the aerospace engineering design industry has a problem. It costs companies money, academic engineering departments student base, and industries their reputations. Based on the literature review, numerous factors are identified which could be contributing to the problem. Several of these factors are well defined and have active research being done into the education and training methodologies best suited to deal with them. However, while reports, articles and presentations describe a problem with “lost” skills, and while researchers are trying to fix the engineering education process, little has been done to define what characteristics are actually missing. The result is noticeable activity to try to cure symptoms rather than
determining the root cause. A potential reason for the lack of activity in defining the characteristics may be the vague terms used by industry to express their concerns.

Literature reviews indicate that the use of a well-defined interview tool is useful in collecting nebulous comments and drawing definitions of concepts from them. This is the type of information expected to contain the desired data, making it best suited for this study.
CHAPTER THREE: PROCEDURES AND METHODOLOGY

The guiding research questions for this study were: 1) What are the perceptions of practitioners of the requisite skills for effective design of complex systems? 2) What are the perceptions of educators regarding what industrial practitioners perceive are requisite skills? 3) What are the perceptions of matriculating engineering students of requisite skills for effective design? and 4) What are the similarities and differences in the perceptions among the cohort groups? These questions were answered by determining what characteristics industry practitioners believed were required and comparing those to what educators perceived to be practitioners expectations for such skills. Additional evidence was established by contrasting observation data of student behaviors in design classes to the identified perceptions of the industry and academic cohort groups.

In order to identify skills perceived as requisite to design effectively, three investigative activities were performed. The activities were: 1) interviews of industry practitioners on perceived success factors; 2) a review of the educational and industrial literature for similar research or identification of success factors; and 3) an analysis of observations performed in an educational environment. The academic perceptions were developed by conversations with local instructors and through an analysis of the most frequently expressed concepts in published literature. The results of the literature search and observational study were used to develop and refine scenarios and questions for the interviews of industry representatives. The results of the interviews, literature survey and observations were separately categorized and analyzed for patterns and trends. Frequency distributions were developed to identify any significant differences between the three data sources. Analyses were also performed to ascertain if there was convergence between the results from each of the three data sources.

The processes used to develop the research questions, sample type and size, and the investigation procedures were developed with extensive use of Patton’s *Qualitative Research and Evaluation Methods* (2002), Strauss and Corbin’s *Basics of Qualitative Research, Grounded Theory*

Qualitative Inquiry Methodology

Introduction

Research regarding the perceptions of individuals regarding skills that are needed to participate effectively in complex design activities is exploratory in nature. The nature of qualitative inquiry allows understanding the world as seen by the respondent and does not predetermine the point of view through prior selections of questions (Patton, 2002, p 21).

"Quality is the watchword of our times. People in ‘knowledge intensive’ societies prefer ‘better’ to ‘more’ (Cleveland, 1989, p 157 as quoted in Patton, p146). ‘More’ requires quantitative dimensions; ‘better’ evokes qualitative criteria.” For this analysis, the ultimate goal is provide data to contribute to making the education of engineers involved in design better. Furthermore, this study is a connoisseurship study in that the evaluator’s perceptions, not the stakeholders’ are at the center of the evaluation process (Patton, p. 172). The researcher is the expert, and draws heavily on her own judgments of excellence. The results of the study are expected to be used to facilitate improvements in education and industry training activities making the study a utilization-focused evaluation.

Due to the exploratory nature and the lack of existing concepts the most applicable methodology for this research is qualitative inquiry.

Bias

Because of the nature of qualitative inquiry, the researcher is the research tool, using all their senses, not just cognition. This researcher reflected on, managed and reported potential sources of bias and error. Systematic data collection procedures, multiple data sources, triangulation, and external reviews were all utilized to reduce researcher bias.

Sample selection was done using a purposive methodology which could introduce bias. To facilitate reducing this bias, an exercise was performed to determine why a certain informant type was important (Miles & Huberman, 1994, p33). Who else should be interviewed was
considered. In this case the initial sample population was “engineers”. Engineers were considered because they were intimately involved in dealing with the technical development and fundamentals of a new design. Others who might have significant input or be acting in an analytic or synthesis support role in design were also considered legitimate participants and included technicians and engineering technologists. These individuals have different backgrounds and experiences as well as different foci within the design activity. When the extent of the design activity was considered, other technical professionals such as chemists, scientists and computer hardware and software professionals were also determined to have a potential role in the core design activity. At this point the potential participants included technical professionals working on a design project and the sample population was deemed to be acceptably inclusive.

Because the researcher acted as a participant observer, a similar exercise to evaluate researcher bias was performed. It was realized that there are rules governing social interactions, involving implicit understandings and expectations, or background assumptions. These background assumptions are generally so taken for granted that they are rarely even noticed (Simpson, n.d.). It is in these background assumptions that the research must look for potential bias. By using Miles & Huberman’s techniques, potential sources of researcher bias were evaluated and found to include:

1. Sensitivity to gender and a potential to perceive data differently based upon gender of the respondent
2. The preconceived perceptions of the researcher that the reasons for the problem include a tendency for engineers to be myopic in design activities.
3. The personal belief of the researcher that applications-based exposure during the education process is beneficial.

Theoretical Framework

Due to the exploratory nature of the study, the theoretical framework best suited for this research was determined to be grounded theory (Patton, 2002). Grounded theory was a framework which permitted the development of conclusions from observations and interviews, and which utilized comparative analysis. The framework also allowed the utilization of tools from different frameworks as the study evolved. The research questions guided the
selection of tools more strongly than a particular theoretical construct (Patton, 2002). Other frameworks were deemed inappropriate for this study because of the lack of the foundational questions on which the more specific theoretical questions contained in other frameworks would be based. While the guiding research questions indicated a weak link to systems theory, i.e. why does the system work the way it does, this theory was too broad to be useful in this study.

Academic Environment Observations and Literature Reviews

Prior to the preparation of scenarios and conducting interviews, similar research on concerns of practitioners regarding graduating engineers was identified. A review of the literature was expected to identify items considered to be soft skills such as teamwork and communications. References to design tools, such as formalized methodologies, (Hauser and Clausing, 1996; Dixon, 1988), and educational needs expressed in general terms (Bordogna 2000a, 2000, 1997, 1997a; McMasters and Matsch, 1996) were expected to be readily available. This research covered the aerospace industry, and other industries involving complex design activities.

For this research, a complex design activity results from a process where the ultimate goal is the result of trades between conflicting needs and desires from diverse disciplines and information sources and which exceeds the ability of three to five individuals or disciplines to accomplish. The characteristics of this process are defined by inter-related outcomes between decisions made by people, among disciplines, and among components, where the reliability of the final product is critical.

By comparing the information from the literature sources, general impressions of the concepts required were formulated even if not defined in specific. The primary technical characteristics selected were those concepts appearing with the greatest frequency. Developing names and definitions of these concepts was the goal of this project.

Concurrently, design activities in a controlled educational environment were observed (Thom, 2004, 2003, 2002, 2001). Observations were made of students’ behaviors in a senior aerospace engineering design class. The students were informed on the first day of class the purpose of the observations, how the data would be used, and that the results had no impact
on their grades. The researcher also informed the students that she would be available to them as a technical resource during the design activities.

Sekaran (2000) indicates observational data can be gathered in an unstructured manner with observer participation. This data has the advantage of being more likely to be indicative of normal behavior and permits consideration of the environment on outcomes, i.e. time pressures and ambiguous responses to questions. It is also useful when the information can be difficult to obtain with a more structured collection methodology. The researcher has no input into the sample selection, reducing researcher bias due to sampling.

To observe and explore the design thought process of the engineering students, the researcher acted as a technical resource for the students. This allowed the researcher to ask specific questions and aided the students in fully articulating their thought process during the design activity. This articulation facilitated making observations that were more complete than passive observation. The participation of the researcher was presented to the students by the instructor as similar to the participation of the teaching assistant. It was assumed this would minimize any bias in the student behavior due to the researcher’s participation. Each class was a separate sample; there was no control group, and there were limited means to evaluate the sample for bias due to researcher participation. Instructors were requested to comment on their perceptions of any differences in general behavior between classes that were observed and previous sessions that were not observed. Based on the instructors’ responses, it was concluded that the researcher’s presence in the class did not noticeably change the students’ behaviors. This indicated it was reasonable to attribute the observations to the students’ perceptions of the design activity as opposed to the presence of the researcher.

Use of data from an educational environment simplified controlling such variables as profitability concerns, managerial inputs, and normal industrial timeline considerations. Students were also less likely to have biases imposed by company philosophies, and were more likely to have fresh perspectives than individuals in the workforce because they did not have a corporate history on which to base their decisions and had not previously seen similar problems. The environment was also one in which it should have been easier to take design risks. Although the students were limited by their practical design experience, the results should have been directly applicable to the condition of engineers when they graduate.

The class observations were compared to the constructs identified from the literature.
Participant Observation Data Collection

In order to systematically observe multiple iterations of the senior design class it was necessary to prepare a means of training the observer. The major research questions were used to guide the inquiry and the likely data collection procedures (Erickson, 1986, p142). Utilizing the methodology described by Miles & Huberman (1994), a list of words and concepts (triggers) for which to specifically listen was prepared. The researcher was to make observations involving terminology, group dynamics, occurrences of phrases which described design activities, specific complaints expressed by students regarding the process, and general observations regarding things which did and did not go well. Key concepts which specifically triggered records were statements of difficulties, mentions of activities that would occur after the computational activities, statements of where and how design decisions were made, instances of needing or obtaining outside assistance and inputs from the instructors. Responses to instructor inputs were also specifically noted. Triggers included the following concepts as opposed to specific words:

- If I had _____, We didn’t have _____
- We (I) assumed _____
- We (I) couldn’t _____
- We (just) picked _____
- We (I) considered _____ [noting what was not considered where practical]
- The computer code said _____
- We (I) thought that _____
- It didn’t make sense.
- No one told us _____
- It was obvious that _____
- We used _____ to get _____

- When the instructor or other professionals provided specific guidance or input, did the students follow up on it or follow up on it later?
- Was the customer satisfied? Why or why not?
- In classes where the product was a remote control aircraft, did it fly?
- In classes with a paper design, did it meet the requirements?
- Were items presented as trade studies actually trades or were they the answer to an analysis?
- Did students recognize or acknowledge inputs and inter-relationships between components, requirements or disciplines?
- Did students ask for help/inputs from other sources besides the internet?
- Did students utilize historical data, previous designs or accepted technical concepts, or did they start from scratch?
The observations expected included: activities employed by the engineering students; resources utilized; questions asked, especially as compared to problems encountered in the design; and success of the designs as measured by the customer of the class exercise. The observations were collected as key phrases and concepts expressed by the students during the design activity as well as problems that were left without solution. Records were kept of successes and demonstrations of positive design behaviors as indicated by the literature analysis and professional experience. An example form is included as Appendix A. Success or failure of the design was based only on observed performance and not on student grades.

**Literature Reviews**

In a similar manner, specific considerations were prepared before going to the literature and analyzing the interview data to look for success factors. Because it was expected that much of the literature would focus on soft skills, it was necessary to be aware that some of the suggested success factors might actually be soft skills, such as team work and communication skills, presentation skills, and interpersonal relationship skills. It was necessary to recognize that the possession of technical skills might be demonstrated or described by what appeared to be soft skills. When looking at the descriptions of soft skills, the researcher considered,

- Are they constructions considered to be the domain of liberal arts or of business departments?
- Are concepts of economics and business related to designing a product (technical) or to running a business (soft)?
- Are concepts of writing and presentations related to maintaining and transmitting technical information (technical) or to business communications and personal interactions (soft)?

Furthermore, it was important to be aware that some of the presented technical factors might actually describe activities being defined in this study as formulaic analysis. When looking at descriptions of technical skills, the researcher considered,

- Are they specific learn-to-do formulaic activities, for example “Calculate with the formula ...” Or “Use computer simulations to ...”
- Are they descriptions of knowing why to do something?

The key difference is to compare the concept for analyses versus synthesis.
Literature Data Collection

The data were collected from the literature by reading selected texts and identifying single words or phrases describing successful design activities or activities negatively affecting success. Each concept was entered on a color-coded card, green for support and red for complaint or statements that no problem exists. The cards were then subjected to open coding to identify categories. After categories were generated, the concepts were subjected to axial coding to identify defined measurable characteristics responding to the expressed concerns. Frequency distributions were then prepared of the number of occurrences of each characteristic.

It was also noted that there were two distinct types of authors writing the majority of the articles reviewed. These authors were either primarily professional academics or they were industrial academics. Professional academics were defined to be those individuals who did the majority of their work and research within an academic environment. Industrial academics were individuals who were employed by companies but who were primarily involved in academic and theoretical activities as opposed to production activities.

Interviews of Industry Representatives

Preparation of scenarios and introductory questions

The results of the literature review and the observational study were used to develop descriptive scenarios and a guide for the interviews. The desire was not to replicate the results from the literature survey through leading questions, but to determine what engineers who are involved in design believe were the key concepts necessary for successful participation in design. There was an opportunity to provide answers to open-ended questions and the responses were categorized based on similarities in key concepts and phrases. The advantage of the oral survey was the ability to discuss, explain, and request clarifying information to further elucidate the answers which was important in identifying skills (Sekaran, 2000). The scenarios, a description of the types of information the interview would cover, and demographic questions were supplied to the participant prior to the interview, see Appendix D. The interview guide questions were not supplied a priori so that the responses would be
more extemporaneous and the participant would be less likely to script answers or put positive
spin on the answers due to the presence of questions regarding negative experiences.

The interview guide is included in Appendix E.

The objective was to obtain responses specific to the technical skills practitioners involved
in design believed were necessary to achieve successful designs. These technical skills were
independent of soft skills, such as teamwork or communication skills, and independent of
traditional formulaic activities, defined as analysis in this study. The respondents were also
requested to describe an example from their experience in which the lack of possession or use
of these skills resulted in some form of problem with the design, i.e. required excessive rework,
product did not perform to the desired level, or a program was lost.

Utilizing the methodology described by Miles & Huberman (1994), the following research
questions for the industry group were developed:

1. Do individuals engaged in design activities and educated in different academic
disciplines have different perceptions of what factors lead to successful designs and
being successful designers?
   a. Did their education emphasize hands-on/application/laboratory learning or
      was it theoretical/conceptual/analytic learning? (This was to evaluate the
      relationship to and support of the separation model.)
   b. When was the degree received? How long did it take to obtain?
      (This was to evaluate the relationship/support of the separation model.)

2. Do engineers who have more analytical/conceptual education experiences have
different perspectives of success than technicians or other technical disciplines? (This
is for comparison of industry perspectives to the perspectives of the academic
literature.)

3. Does the person express the same success factors when talking about themselves as
when discussing the behaviors of others?

4. Are there similarities in the success factors across:
   a. Experiences?
   b. Education?
   c. Disciplines?
5. How does the person recognize the need for input during analysis and design activities?
   a. How do they get the information?
   b. How easy is it for them to obtain it, both from within the company and from outside of the company

Preparation of an Interview Frame

The above questions were used to develop the interview frame. Interview questions dealing with the research questions and supporting probes were then prepared. The questions were used in the same order each time. In some cases a question was related to or dependant on the answers of the previous questions. There was a risk that the later answers received less discussion than the first questions due to fatigue, boredom, impatience, or insufficient available time. The goal was to provide the participant the ability to answer as fully as they desired without rushing them through any particular question. It was expected that variations in the questions on which a participant desired to spend the greatest amount of time would balance out over the entire sample set.

Interview Tool Validity

Committee members, engineering and engineering technology professors, and the researcher’s own peers were solicited to serve as panelists for the purpose of establishing the validity of the survey instrument. The panelists reviewed the content of the questions to establish both face validity and content validity. Criterion-related validity was assessed through reviews by experts at Purdue University familiar with use of this type of tool. University experts in this type of qualitative research were requested to review the guide in terms of mechanics and clarity.

Due to the qualitative nature of the interview activity, the statistical analysis of validity is limited. As stated in Miles and Huberman in their text *Qualitative Data Analysis* (1994):

> In qualitative research, issues of instrument validity and reliability reside largely on the skills of the researcher. Essentially a person –more or less fallibly- is observing, interviewing and recording, while modifying the observation, interviewing, and recording devices from one field trip to the next.
Interview Tool Reliability

The reliability of a test is a measure of how error-free the tool is (Sekaran, 2000). There are two types of reliability: stability and consistency. Stability is the ability to obtain the same results from a tool over time. Consistency is a measure of how well the results from a tool agree across the sample population and if the results of questions measuring the same concept within a tool agree. For this test, tool stability analysis will not be performed because the tool will only be used once and no temporal data will be available for analysis. A review of consistency will only be performed to the extent the results of question topics converge on similar concepts. In addition, two of the questions are related to look for consistency in the response. This is sufficient due to the exploratory nature of the study and its purpose of generating foundational data for subsequent scientific studies.

Interview Sample Selection

Sample Selection Methodology (Sample Frame)

The logic of the qualitative approach versus the quantitative approach is distinct because the purpose of each strategy is different (Patton, 2002, p45). In quantitative research a large number of samples are used to generalize the findings to a population. In qualitative research a small number of samples are purposively collected to permit an in-depth understanding of the phenomenon of interest. Using purposively selected participants leads to insights and in-depth understanding as opposed to empirical generalizations.

Due to the nature of the data desired for this research, the sample selection method was a purposive sample. While this reduced the statistical generalizability of the sample, this was the only practical means of obtaining individuals with the desired information and was acceptable for this study (Sekaran, 2000). The participants were professionals involved in design at companies with technically complex products or systems. The participants were not required to be traditionally educated engineers but were required to have been out of school and in career a minimum of five years. They were to be involved in design activities currently, managers who have performed engineering design activities in the past or individuals who now lead design teams. Participants were selected based on input from academic and professional experts, chain sampling during the interviews and personal experience. Participants were
selected based on availability, positive reputation, and subjective measures of success. Because the purpose of this research was to explore practitioners’ perceptions regarding successful behaviors, the participants could not be chosen based on defined success criteria. Examples of subjective measures included, people “suggested” that these individuals were successful, they “looked good” on first inspection, they had been involved on “successful” programs or they were “award winning” in areas suggested to be related to success.

Samples were selected using the explicit sampling frame cited above. This research utilized multiple case sampling and chain sampling (recommendations from current interviewees for other potential interviewees). Names which appeared frequently were particularly important. This facilitated adding confidence in the data, and strengthened the precision and validity (Miles & Huberman, 1994).

Sample Size

Due to the qualitative nature of the study and the lack of a population frame, the sample size could not be determined statistically. Literature references (Miles & Huberman, 1994, p30) suggested that the sample size should be no more than 30, and in most cases a sample size of 10 to 20 would be sufficient for this type of inquiry. For this research, the sample size was to be at least 10 and no more than 30.

Interview Data Collection

A copy of the scenarios and specific topics, were provided to the participants prior to the interview. Demographic information was requested ex ante so that interview time would not be spent obtaining this information unless it had not already been received from the interviewee. A teleconference or meeting was arranged with each participant. Questions were asked of the participants using the interview guide. The data was transcribed from notes and prepared for analysis after completion of the interview.

Ethics

Ethics in research such as this study are more complex than not lying, or falsifying data. According to Bodner (1991, p274) "Charles Babbage proposed a classification system for
scientific fraud." Bodner goes on to classify unethical activities into three categories: fraud, embellishment, and self-deception. Both fraud and embellishment are conscious acts of dishonesty, and "outright scientific fraud is rare..." (Miles & Huberman, 1994, p294). Self-deception results from finding in the data what you hoped or expected to find. The researcher needs to be aware of, and deal with the more subtle ethical considerations in both the analysis of data and the handling of subjects.

In this study a utilitarian or traditional scientific stance (Miles & Huberman, 1994) was employed. The stance stressed recruitment of respondents by informed consent, conducting fieldwork in a manner to avoid harm to others, and protection of confidentiality in the reports. The primary ethical concerns were avoiding careless data gathering, using the data with integrity, i.e., not forcing a point of view, and the use of people as a data source. By utilizing well-defined data gathering techniques and specific training, the researcher was aware of good data handling techniques which helped minimize flawed data. The honest evaluation of bias and considering means of controlling the biases helped minimize misusing the data or skewing the conclusions to advance the personal agendas of the researcher or committee members.

Regarding the ethics of using human subjects in the gathering of data, it was important to consider the confidentiality and anonymity of the participants. The first step in this process was the procurement of human subject approval. From an ethical perspective, this was only the first step. First the participants in the research must have been able to give informed consent and felt able to say no to participating. This was most difficult for the observation activity in the classroom. While the students could request they not be included in the observation data, the continued presence of the researcher may have made the students uncomfortable to the extent of having their educational experience altered. To deal with this concern, the consulting and resource activities of the researcher were emphasized and the observation activities downplayed. Further, while the students were not required to participate in the closing survey, they may have felt pressured by the encouragement from the professors who were seen as ultimate authorities due to their control over the students’ grades. An attempt to minimize this impact was made by assuring the students that the professors never saw the surveys and by insisting the students not identify themselves on the actual survey. Additionally there was the potential dilemma where the target data was demonstrated by someone requesting not to participate, thus making the data unavailable for analysis. It was
determined if this situation arose that the data would not be included in the analysis, but what was learned from the observation would be used to direct other observations.

The interviews of industry representatives were also performed with an assurance of confidentiality. Unlike the student interviews in which there were few identifiers except the semester of participation, the researcher knew exactly which industry participants provided which data. The onus of protecting the confidentiality of the participants was on the researcher. This was done by avoiding reporting any identifying information such as participant name, department identifiers, product identifiers, or company names. In the aerospace industry such confidentiality is standard to the culture, so participants were already familiar with such assurances.

Human Subject Approval

Prior to the classroom observations and interviews, approval was obtained from the Purdue University Committee on the Use of Human Research Subjects.

Copies of the introductions, observation forms being used, and target concepts being observed during the classroom observations were provided to the committee along with the required documentation. Approval for exemption was received February 4, 2002. A revision was obtained to add the industrial target population and approval was obtained on December 17, 2003.

The observation form is included as Appendix A, the student questionnaire as Appendix B, and the Human Subjects approval form as Appendix C. A copy of the demographic questions, scenarios, and interview frame are included in Appendix D and E.

Study Analysis

Once the raw data were collected, inductive analysis was performed. This involved taking specific observations and identifying patterns. It did not presuppose what the important dimensions would be. Categories emerged from patterns in the data. The observational, literature, and interview data were analyzed by grouping the results into distinct categories of traits and skills, and coding them. Coding was of three types: open coding, axial coding and selective coding (Strauss & Corbin, 1990, p58). Frequency distributions of the categories were
prepared. No statistical significance tests such as F-tests, T-tests or chi-squared analyses were performed.

The frequency distributions, the key words, phrases & concepts, and the categories from each data source were compared for frequently occurring concepts and categories, as well as for convergence or divergence. The data were reviewed for consistency among the literature, the observations of engineering students, and the surveys using the triangulation method. It was possible, for example, that the concepts identified in the literature and the observational study would not match those identified in the interviews. This would indicate either a disconnect between what the literature was purporting as important and industry needs, or a problem with one of the methods utilized in the study.

This information would be valuable as the basis for subsequent research into what specific topics should be taught in an engineering curriculum.

**Data Triangulation**

Multiple means of triangulation were used. There were a variety of data sources; multiple interviewees, texts, and academic class sessions; and multiple methods of observations, literature review, and interviews. Using triangulation among data sets allowed for dealing with rival contributing factors. Each method revealed different aspects of empirical reality. The point was to test for consistency by generating triangulated data and methodologies (Patton, 2002, p248). Finding variation did not weaken the credibility of the results but offered opportunity for greater insights. A form of theory triangulation, i.e., was the same theory generated through multiple analyses of the same data, was used during multiple reviews of the raw data during the coding procedures. This provided different perspectives during the interpretation of the data set. This resulted in strengthening the accuracy of the conclusions drawn from the data.

**Validity and Reliability of the Study**

The validity and reliability of the study was improved through the use of recognized qualitative methodologies suggested by the grounded theory framework.

The list of sensitizing triggers presented above was prepared with direct links to the research questions before attending the academic class sessions. The reliability of the academic
observations was improved by observing the same course over multiple semesters, with multiple instructors and multiple design project outcomes. The researcher had no control over the participants, the instructor or the course project, helping to reduce researcher bias. The validity of the conclusions relative to the results from the classroom observations were facilitated by using a naturalistic setting where the participants were working on their own projects and would have done them even in the absence of the study. The final assertions were drawn from comparing groups rather than individuals.

For the interviews, sampling bias inherent to purposive sampling was minimized by utilizing a sampling plan generated prior to beginning interviewing and actual participant identification.

The validity and the reliability of the results were strengthened by the use of data triangulation among data sets.
CHAPTER FOUR: FINDINGS AND DISCUSSION

Researcher Experience and Qualifications

*Academic and Industrial Training*

Ms. Thom received a Bachelor’s of Science in Chemistry from Purdue University, West Lafayette, Indiana in 1988. Upon graduation she accepted a position of engineer with Bridgestone/Firestone in Akron, Ohio. In this position, she worked in a group which integrated the various components of a tire into a finished design. Ms. Thom was specifically responsible for the choice, testing, and integration of the sidewall material.

In 1990, Ms. Thom became a chemist in the materials laboratory of AlliedSignal Aerospace. In this position she performed material certification, failure analysis, receiving and inspection, material selection, unknown identification, and organic analysis for local and remote production facilities and engineering departments. She also prepared and gave technical presentations, and managed and researched several projects. She chose to be responsible for liaison activities between engineering, manufacturing, customer support and final customers, including incident investigations, product development and manufacturing support. Ms. Thom facilitated communications between remote overhaul facilities and in-house investigative support activities, and provided technical expertise on multiple U.S. military engineering programs. She instructed several in-house education courses. She participated as a trained facilitator on two award winning TQM teams, as well as a number of short-term teams.

In 1998, Ms. Thom became president and chief scientist of an aerospace consulting firm. The company is a small business with less than five employees. In this role, she manages a company answering technical questions for high-tech companies. This work includes the day-to-day management activities, as well as providing document review of new designs, manufacturing processes and other engineering documents, providing design inputs, and
facilitating program management. As a scientist, she continues to provide analytical testing and chemical analyses. She works with academic researchers as a technical advisor on a number of research projects and provides professional facilitation between academia and industry. She has also taught a university aviation course and several recurrency training courses involving aerospace materials.

As the reporter and evaluator of the results of this research, it was necessary to accurately collect and present the settings, and the opinions and perceptions of the participants. This carried the same responsibilities as the scientific research activities undertaken in Ms. Thom’s professional career. Like the neutral entries in a laboratory notebook for an investigation or an analytical project, it was necessary to capture the participants’ voices without personal overtones. Fourteen years of scientific practice made this less difficult.

Ms. Thom has spent most of her career working as an engineer or with engineers involved in the design process. This further facilitates her ability to observe and listen to engineers with a reasonable certainty of understanding the topic specific language. During any situational conversation there is an accepted ‘short-hand’ which requires the listener to fill in the unspoken gaps with knowledge of the shared language. There is an intricate web of situational variables which interact to determine what meanings are derived during the conversation. This shared set of rules is often referred to as the etcetera principle (Meskill, 1996, Simpson, n.d.). Because of Ms. Thom’s long term exposure to engineers in design situations, it is reasonable to expect her understanding of the short-hand is sufficient to permit her to accurately gather and interpret data on design activities.

*Education for this research*

To prepare herself for this research Ms. Thom attended a basic aeronautical engineering aerodynamics course and an aviation technology aerodynamics course. She also attended two statistics courses, a general research methodology course, and a qualitative research methods course. She read four qualitative research texts and a number of academic articles on qualitative research. Ms. Thom followed common methodologies for setting up interview frames, question formats, and interview skills. She obtained inputs from individuals experienced in observation and interviews on my questions and methodologies.
Findings

While executing the research to identify the technical skills required of successful design engineers, several related observations were made. While these findings do not define the skills, they are deemed important findings with respect to the environment in which these skills are learned and used.

Lack of Consensus on Definitions

During the course of the research, one of the first observations was that there was no unified understanding of the basic concepts of engineering, design or technology. There was no consensus regarding the role of engineering in design or of design in engineering. While organizations such as the American Society of Engineering Education (ASEE) have attempted to develop unified definitions, a common understanding was not seen during this research.

Some of the most striking differences lie between what expectations of “a day in the life of an engineer” were for the graduating engineer as compared to university professors and industrial representatives involved in academics, and to the people actually working in the area of design and engineering. Not surprisingly, there was also a difference observed in the responses of older individuals toward the ends of their careers and individuals just entering or recently entering the career.

A related concept that seemed to lack unified understanding was engineering science versus research versus application. Depending on educational background, work experience, and age, the expressed definitions overlapped, reversed, or were completely different. There was no consensus regarding the responsibility for different activities, where in the design process the concepts should be applied, or on their overall level of perceived importance.

Lack of Consensus on Roles

Similarly, a review of the historical reports on engineering education indicated that while the field has continued to evolve and respond to inputs, at the very core of the debate was the perceived role of the engineer. As early as 1918, engineers and engineering educators expressed an inability to reconcile their role as ‘do-er’s’ with their desire to be accepted as professionals akin to doctors and lawyers. These difficulties in reconciliation were further exacerbated by the difficulties which science-based education faced during its formative years. The centers of
classical education questioned the value and appropriateness of science as an academic endeavor as compared to the more philosophical and humanistic topics. This basic conflict and duality of personality can be seen in all of the subsequent major engineering education reports over the next one hundred years.

Lack of Requirements Identification

The bulk of the academic literature and discourse centered on the educational methodologies and mechanisms, as opposed to identifying the requirements or skills required of an engineering graduate. Recommendations with respect to curriculum content were performed in very general terms, such as whether to include liberal arts or not, whether there should be more than one mathematics course, or whether foreign languages should be required. The observed activities in education reform centered on “how” to teach engineering as opposed to “what” to teach. By concentrating on “how” at the exclusion of “what” or only dealing with “what” in very general terms, three things were observed.

First there were no defined metrics against which to measure success, failure or improvement. Articles on “how” to teach focused on the tools and resources needed, what project was selected to mimic the real world, and how much the students liked the formats. They did not consider what the metrics of success were or what the specific goals or expectations of success were. The scopes of the activities tended to be large, and all-encompassing with poorly defined focus. With less than three exceptions, the articles reviewed reported on “how to teach”, “how we used a process” or the “results from the class”, but did not provide the success criteria used to assess the work, or any metrics used to measure success either for the students or for the activity. More than half the reports of positive results were written after one or two sessions and in one specific instance, further researching the activity showed that it had been scrapped after less than five years.

The second observation was that the activities appeared disconnected, frenetic, or in conflict with each other. Throughout the history of engineering education, courses were moved into or out of the engineering department, course contents were changed without consideration of the impact on the rest of the curricula of which they were an integral part, and cultural and industrial goals would align and conflict as U.S. culture changed. More recently, activities to meet the requirement of demonstrating proficiency at open-ended problem solving
has resulted in the addition of capstone engineering design courses that are placed into the curricula without documented connection to previous courses, without observed attempts to coordinate efforts between instructors and with expectations of performance which are different from the expectations with which the students are familiar. In more than half of the reports, the changes in teaching methodologies were done in isolation from the rest of the university curricula and education norms. Notable exceptions were the total restructuring of the engineering program at Massachusetts Institute of Technology and the use of cohort groups through entire academic programs.

Third, in more than half of the surveyed activities, the changes resulted in what appeared to be excessive frustration to both the instructors and students. In at least four of the accounts the activities were not pursued primarily due to the frustration and a lack of means for tracking improvement. The students expressed a frustration in not knowing what was expected of them with respect to performance. Instructors expressed frustration with an inability to objectively assess student performance, or with the onus of being subjective in a fair manner.

Ironically, recent articles on assessment, for example papers from session F1B and F4B of the Proceedings of the 32nd ASEE/IEEE Frontiers in Education conference, November, 2002, go into great detail on the importance of having well communicated goals and expectations, and clearly laid out metrics and grading requirements. These same articles do not provide insight into what the metrics should be, even through the generally expressed goals and objectives are reasonably consistent across authors and researchers. The authors stress the use of the ABET criteria in developing the goals but the goals leave development of performance standards and metrics to the discretion of an institution. Specific requirements should be those whose execution can be measured (did the student give all four examples, yes or no? Could the student provide and defend a prediction based on the input using generally accepted principles, yes or no?) and which demonstrate meeting the specified goal. To have clear measurable metrics, it is also necessary to be clear on what specific behaviors demonstrate the goal. From these metrics, educators can also assess shortcomings and improvements in the classroom which were not possible with the broad, non-specific metrics. Specific requirements facilitate reducing student frustration with educational inconsistencies, and it facilitates grading by the educators.
Knowledge, Skills and Abilities

During the analysis of the data, it was determined that the data from each cohort group clustered around the rubric of knowledge, skills and abilities (KSA). This method uses the concept that there is knowledge which is learned, skills which are practiced, and abilities which are inherent traits (Gatewood & Feild, 1987). The knowledge is made up of information, factual or procedural in nature, which is necessary for successful performance of a task. Skill is the level of proficiency or competency of an individual in performing a specific task. Ability is a more general enduring trait or capability an individual possesses at the time when he or she first begins to perform a task (Gatewood & Feild, p251). It has been suggested that “abilities are a collection of competencies”, “that are typically defined as the application of specific behaviors and motivations to knowledge, skills and understanding” (Emshousen, 2002).

In the case of the student observations, it was concluded that the instructors were looking to rate the ability of the students to perform a variety of engineering design goals by demonstrating their skill at applying the knowledge learned during their college career. The students, on the other hand, were still functioning in the mode of garnering knowledge. They saw the content of the class as a set of knowledge to be learned. It was further concluded that the majority of their coursework experience had been presented as a series of discrete pieces of knowledge to be learned but without having the knowledge connected to a higher level skill to be practiced. In essence they had read a lot of facts and were assessed on their success at regurgitating the facts. The repeated practice at performing a task reinforced the knowledge but it did not connect it to a skill.

The literature survey indicated a concentration on the abilities that a successful engineer should possess. There was no acknowledgement given to the knowledge or skills which demonstrate the existence of the abilities. Instead, the articles focused on the abilities as a goal to be taught rather than demonstrated.

During the interviews, the skills considered requisite for successful design activities were explored. Although some of the responses were still abilities, they were less general with more obvious demonstrators available for assessing them than the abilities expressed in the literature.

While having the skills is not a predictor of success, a lack of the skills is a determinator of failure. Because abilities are complex combinations of a number of attributes and traits, their
assessment requires an understanding of the contributing factors. Noticeable efforts are being made by ABET personnel and engineering educators to better understand the contributing factors.

It is in the lack of assessment of the skills, not in the grading of knowledge, which has led to the dissatisfaction in the product (new engineers). This dissatisfaction is expressed not only by industry representatives, but also by those in research organizations. Because the skills which must be applied have not been well addressed, assessment of abilities is at a disadvantage. If the skills have not been taught, the means of demonstrating abilities are negatively impacted.

Skills Identified From Industry Representative Interviews

Based on personal interviews of individuals from a variety of technical organizations and of a variety of ages, the following four skills were identified as being important to success in engineering and engineering design activities.

1. Willingness to sketch, by hand, including rendering AND understanding three dimensional visualizations.
2. Collaboration and networking
3. Recognizing the need for input, data and feedback, and the willingness to obtain such inputs.
4. Having a broad enough background to understand impacts into and out of different parts of the design.
5. Recognizing reasonable and unreasonable results from data and analyses.

These five skills together provide measurable characteristics demonstrating “global”, “holistic” and “system” thinking.

The researcher was surprised to observe that the “-ilities”, i.e. manufacturability, reliability, maintainability, etc., were actually measures of successfully employing the technical skills listed above as opposed to being the skills themselves.

Additionally the abilities expressed by the participants were observed to be achievable through the application of the four major skills. For example:

- The internalization of mechanical concepts, such that formulas and theories represent an actual visualization of an action as opposed to a manipulation of symbols.
• Taking educated and appropriate risks
• Committed to a quality product and able to make a product that works
• Recognition of business impact
• Responsive to, knows what are and understands customer needs and requirements
• Able to perform effective and appropriate trade studies

Another grouping of skills also appeared in both the literature and during the personal interviews. These skills are more intrinsic to the individual than the previous skills and are measured more by their conspicuous presence or absence. They are all subjective qualities which resist quantitative measure and thus make them difficult to teach in traditional pedagogy. They are not taught by rote exercises but by example and expectation.

• Character (moral)
• Ethical
• Leader as opposed to manager
• Curious
• Innovative
• Creative
• Decisive
• Goal-oriented
• Ingenious and clever

Another observation that appeared in the data was the pervasive description of engineering and design as “art” and as “creative endeavors”, while engineering education is more a practice of discrete facts and fundamentals, logic, and calculations. The conclusion made is that education teaches the facts as the goal and purpose of engineering, while industry expects creative application of the facts. Knowledge of the facts and formulas is expected but almost ancillary to the act of designing.

Skills Identified From Academic and Professional Literature

The survey of the literature and the analysis of the data indicated that much of what is presented in literature describes abilities that were perceived as necessary to be successful in system design activities. The analysis found the abilities could be grouped as basic abilities and
general abilities. The most frequently described general ability was performing design, followed by the ability to take something from theory to design, and a variety of intrinsic traits (i.e. ethics, curiosity, common sense, etc.).

Further analyses of the data revealed, depending on the breadth of ability, for example design, the presence of a variety of sub and sub-sub-concepts. When only the specific concepts were considered, the most frequently occurring ability was the ability to deal with the –ilities (i.e., supportability, manufacturability, reliability, etc.), followed by the ability to recognize systems and system impacts, and third the ability to apply a breadth and depth of knowledge to the activity.

Because the goal of this research was to identify specific technical skills, the data were analyzed again to attempt to identify skills as opposed to abilities. Following this analysis, thirty-three concepts were identified as abilities eighteen as skills, eleven as knowledge, and four as traits. If just the categories are considered, 60% of the categories were identified as abilities, 27% as skills, 17% as knowledge, and 6% as traits. However, if the actual number of responses was considered, then 60% of the responses were still classified as abilities, but the percentage of skills dropped to 19%, knowledge dropped to 16%, and traits dropped to 5%. This suggested that the responses were almost three times as likely to be an ability as opposed to a skill. The most frequently presented skills were: 1) identification of requirements, 2) results orientation, 3) data maintenance and presentation (not personal communications), and 4) problem recognition and identification.

**Senior Engineering Design Course Observations**

The observations of the senior design class indicated that the behaviors regarding methodologies and processes employed appeared to be consistent with the basic manner in which engineers perform after entering the workforce. The tools chosen for an activity, the interactions and technical dynamics, the recognition of problems, the level of fidelity employed, the attempts to obtain input and data, and the obtaining and processing of feedback observed from the students was similar to observations made by the researcher during her professional career. This supports the hypothesis that the basic technical skills with which students graduate form the basis of their behavior throughout their career, regardless of whether these behaviors are positive or negative.
The behaviors noted across all classroom observations included no demonstration of any integration skills. Even in the semester when the students were required to build a remote controlled aircraft, integration took place at the workbench in an ad hoc manner. Students expressed an awareness of concepts such as supportability, maintainability, and manufacturability, but they were parroting words without any comprehension. Because there was no real understanding of the concepts, they were not included in the designs and were generally not mentioned as the semester progressed. Students, in general, did not demonstrate synthesis in their designs. They were in general able to perform analysis activities and were able to respond to provided syntheses, but could not initiate the process. Students did not in general know the limitations and assumptions intrinsic to the analysis tools. They accepted computer output without consideration of validity or appropriateness.

Discussion
The discussion is presented in three sections; a historical review, an analysis and discussion of literature observations and an analysis and discussion of the results of the study.

Observations Based on Historical Reviews
While in-depth reports regarding the historical underpinnings and the evolution of engineering education are available, it is useful to trace this evolution here briefly. This historical review demonstrates that the concerns, goals and desires of the profession and of education have changed very little from its beginning in the 1860’s. By reviewing the primary surveys done by the engineering societies, the root issues and values have begun to emerge. The primary literature resources used in the review include the Mann Report, 1918 included as Appendix G, the Wickenden Report, 1930, the Report on Technical Institutes, 1930, the Hammond Report, 1945, the Grinter Report, 1955, and the ASEE/FIE proceedings of the last ten years. In addition, two engineering educators who were familiar with engineering education at Purdue University during the 1950’s, William LeBold (personal interview, January 23, 2004) and William Dalton (personal interview, January 28, 2004), were interviewed.
The Mann Report

In 1918 Charles Riborg Mann offered the first formal survey of engineering education, *A study of engineering education*. This bulletin covers many of the same concerns still being dealt with today. In this document, the seeds for many of the contemporary challenges can be observed, as well as explanations for why some things in engineering education are the way they are. The content of the report is so fundamental to understanding the state of engineering education today it is included as Appendix G.

At the time of the report, engineering as a discipline was about 50 years old. Mann explained that “...significant characteristics of the report are found in the discussions of the general failure to recognize such factors as ‘the values and cost’, the importance of teaching technical subjects so as to develop character, the necessity for laboratory and industrial training throughout the Courses and the use of good English” (p.x). These are some of the same challenges facing contemporary educators. Mann also points out the difficulties in “establishing standards by which to measure successes and failures of their efforts to provide proper training for engineers” (p.xi).

Under these conditions numerous fundamental questions concerning engineering education have of necessity emerged. Do we need fewer or more schools? Is the curriculum too long or too short? Should the engineering school be made a graduate professional school? What are the present demands of science, of industry, and of education? How well are schools meeting these demands? What changes, if any, seem desirable?

The answers to questions like these are at present both vague and unconvincing. This study endeavors to define a number of the more important problems of engineering education, and to suggest policies and methods that promise to be fruitful in working towards more satisfactory solutions.

Mann’s report was the first salvo in the battle regarding the humanistic content of the engineering curriculum. At the time of this report, there was a feeling at the colleges that science and engineering were not appropriate pursuits for institutions of higher learning. The engineering educators responded that the conventional forms of instruction at literary colleges were not suitable for industrial training. Mann quotes J.B. Turner “Book learning alone does not suffice but must be supplemented with the study of things. The former produces laborious thinkers the latter thinking laborers.”
In 1918 the country was recently out of the Civil War, there was still much expansion, building and laboring to do, and the industrial segment of the nation was still in its infancy. “From the beginning the engineering schools have had a clear conception of their functions. They themselves understood that their ultimate aim was increased industrial production, and that their special contribution to this end was systematic instruction in applied science. In addition they believed that if this instruction were given with the proper spirit, engineering would become a learned profession and scientific research a recognized necessity.” It was observed that over the next 100 years scientific research rose to the top in importance and the application aims of engineering education were diluted and lost.

The concerns over the level of subdivision and specialization were already being noted in 1918. Mann pointed out that the profession had grown from one engineering degree, civil, at engineering’s inception to two degrees, civil and mechanical in 1820, to fifteen degrees plus specialties in 1918. At Harvard and the University of Missouri it was attempted to expand the program to six years to relieve congestion and raise the discipline to a professional rank like that of law and medicine. The attempt was abandoned. It was realized that “this pressure to keep up-to-date, combined with the natural reluctance of every teacher to abandon material he has once worked up for presentation to the class, is fairly certain to produce congestion even after it has been temporarily relieved” (p55).

It was suggested that “the conception underlying this and all later curricula is that engineering was an applied science; and therefore, to teach engineering, it was necessary first to teach science and then apply it” (p58). This angered the students who found the coursework structure too abstract and boring. This is the same discussion being held now with respect to retention and recruitment. Mann reported that the University of Washington switched to teaching the applications first and providing the science as needed and found that it worked quite well. This was the same conclusion reached by contemporary academic researchers.

But like today, there was a bias against shop work. It was not considered as being university grade coursework. Teachers of mechanical arts were rarely granted the title professor. Yet no one denied it was an essential element in the education of every engineer. Much the same as contemporary criticisms, Mann stated “the neglect of the possibilities of shop work was responsible in large measure for the professional criticisms that graduates cannot apply theory to practice... On the other hand, the neglect of shop work was not a result
of carelessness or of chance. It was due to a consistent effort to meet the professional demand that emphasis in school be placed on the fundamentals of engineering science” (p81).

Mann also provides a list of traits deemed necessary for success: common sense, integrity, resourcefulness, initiative, thoroughness, accuracy, an understanding of men, technological knowledge and skill. This list is similar to the intrinsic traits identified in this study.

“The spirit of investigation accomplishes valuable results only when the investigator is resourceful, accurate and efficient in mastering the facts and when he has judgment, common sense, and perspective. These qualities depend on the ability to put things in their proper relationships.” This is as true today as it was 100 years ago.

The Wickenden Report

The next major survey of engineering education occurred between 1923 and 1929. The Report of the investigation of engineering education was authored by Wickenden for the Society for the Promotion of Engineering Education (SPEE). The report was published as two volumes, volume I in 1930 and II in 1934. This survey was prepared during the ‘roaring 20’s’ and was published during the Depression. The first thing noted was that the Mann report was approximately 100 pages long. The Wickenden report had over 1000 pages in just volume I. The table of contents alone was 41 pages.

Like the Mann report, many of the concerns expressed were the same as contemporary concerns: Students are not prepared either in extent or quality as a foundation for engineering, they do not know what engineering is or requires. Jobs do not live up to graduates expectations, because the bulk of the beginning of the curriculum is to make up for inadequacies in the secondary schools and, with a four-year time limit, it makes a heavy load of subjects and subject matter.

The Wickenden report also found that, except in mechanical engineering, the amount of shop work was decreasing, and that there were a lot of minor subjects of good content which were destructive to the whole and should not be included. It was asked and determined that schools should teach fundamentals as opposed to specialized degrees. The instructors indicated only chemical engineering and mining needed foreign languages. Treatment of economics was deemed as necessary but lacking. Teachers felt shop classes were only relevant for manufacturing engineering, mechanical and electrical engineering in particular. Here we see
the beginning of the shift in value and importance placed on applications in favor of science. Over 80% of the teachers replied that mathematics and physical science should not be taught as an end unto themselves but rather as tools.

As the report progressed, the beginnings of the ‘cerebral’ versus ‘laborer’ dichotomy could be observed. This observation should be tempered with the understanding that at this point in history to be a laborer versus a professional had significantly different meaning than it did in 1918 or it does today. The laborer was truly an uneducated individual with few prospects. Even though Wickenden bemoaned “our difficulty is not that we have too much technical education but that we have yielded to the temptation to make a fetish of the standard college degree,” the indications of academic snobbery were observed.

This perceived snobbery was observed in the belief that colleges were the realm of great thought as opposed to institutions of rote learning. In the small steps of evolution and the historical frame of the report, this belief in elevation of thought over labor appeared to be positive. It was with the hindsight of time that the danger to the knowledge and skills provided to the students could be seen. Wickenden’s report suggested the role of education should be to open the mind not train it.

The report observed that the program should be “coherent and integral structures, directed to the grounding of the student in the principles and methods of engineering and to those elements of liberal culture which serve to fit the engineer for a worthy place in society and enrich his personal life” (p84). Statements such as these suggest a shift in the philosophy of teaching engineers how to do something to a philosophy of teaching how to be something.

With respect to the argument that engineering should be a professional pursuit on par with the law and medicine, the report observed that engineering was different from these professions because these professions had defined activities and distinctive social and legal responsibilities. “These considerations tended to fix the forms of professional education into a series of standard patterns. In contrast, engineering – concerned with the economic use materials and energy – was one of the very general functions in social economy, and not the exclusive function of a well-defined professional group. It had many levels of responsibility and no clear distinction between the professional and auxiliary levels” (p127).

In Vol. II, the report went on to note, “We have characterized the college curriculum in engineering as functional rather than professional. That is not to minimize its value to the
professional engineer, but to emphasize its broader utility. The majority of engineering graduates do not enter a profession unless we use that term in the loosest sense. Instead they enter upon business and industrial careers in which technical knowledge is known to be useful if not indispensable to those expecting to advance to executive positions.”

With regards to shop work, the report found that it was considered to be important. It was concluded that the purpose of the shop work was to give students exposure to principles of shop management and operations, not to result in shop proficiency. What should be noted is that it was this lack of proficiency which was eventually used to defend the elimination of shop work in the 1950s and ’60s.

Other observations made from the report included a feeling that engineering colleges focused on disciplines, --mechanical engineering, chemical engineering, electrical engineering etc.--, while industry was more interested in functions, i.e. research, design, operations (p248). It was noted that this report showed more references to moral aspects of the student and the students’ education than had been seen in the Mann report. It is believed this is due in part to the reports place in history, when the belief was that the university was responsible for instilling students with morals and ethics.

The report also shows the first step in the evolution of the aims of engineering education. The Wickenden report now suggested the aims should be to provide: 1) a scientific technique for the control of the forces, materials and energy of nature, 2) technique for organizing human effort, and 3) technique for appraising the resulting benefits to mankind. Note that these goals were more complicated than Mann's, his being to make manufacturing more productive and efficient.

The Report on Technical Institutes

Concurrent to the educational surveys overseen by Wickenden was a report on the Technical Institutes, which were institutions whose primary role was to prepare individuals for positions in manufacturing. It should be noted that this document was prepared at the same time in history as the other Wickenden reports and as such was subject to the same caveats regarding the perceptions of professionals and laborers.

The Study of Technical Institutes was published in 1931 as its own document and in 1934 in Vol. II of the Wickenden report. The purpose of this study was to answer the question: Should
there be more engineering schools or more kinds of schools in order to meet the shortage of technical graduates? The principal conclusion presented in the report included the assessment that a need existed in the postsecondary scheme of education for large number of technical schools giving more intensive and practical training than provided by the engineering colleges. The role for the schools was to train individuals principally for supervisory and technical positions in industry and for engineering work of general character. Simply speaking, if the goal was to learn science, then attend an engineering college, if the goal was to work in industry at a level of responsibility, attend a Technical Institute.

In general, with the exception of land grant colleges, the Technical Institutes grew out of specialized needs from local industries as opposed to a formal, comprehensive plan. Wickenden compared the U.S. system to the national system of technical education in Europe and found it more ad hoc. One of the observations made during this comparison was that in Europe higher, middle, and lower were distinctions of type, whereas in the U.S. the terms conveyed a level of excellence. This difference in meaning may have been one reason for the negative response seen to repeated recommendations for distinctions between education institutions. While the authors may have been recommending delineation of type, the audience interpreted them as distinctions in excellence.

Another observation was that the automation being increasingly incorporated into manufacturing facilities reduced the overall workforce needs but increased the need for professional and staff employees. Furthermore, organizations were finding that young people were going to school and staying in school longer, further reducing the pool of skilled labor from which to promote. This resulted in organizations having to educate to fill their needs as opposed to home growing them.

The other aspect of Technical Institutes as compared to colleges and universities, was their ability to “cater more effectively to people with work experience, to men with a career plan, passed out of book-mindedness and to people who want to do as opposed to study” (p8). The colleges were not effective in educating this group of people due to their different needs. Attempts to provide more intensive and practical forms of postsecondary education in auxiliary departments largely failed. These practical courses became “salvage courses for failures in the larger (sic engineering) courses. Their positive appeal to a distinct group of genuine promise had been low” (p9). The classes became stigmatized as courses for people
who could not succeed in the standard engineering courses. Even at Purdue University, one of the universities that has maintained a technical program, a stigma was attached to the technical courses as being inferior to the engineering courses.

The survey found there were “innumerable positions in industry for which men of engineering training are sought which do not utilize a wide range of scientific …knowledge. …The technical requirements of these (sic high responsibility) posts can be fairly met by intensive type of engineering training which avoids the most advanced science features” (p23). It was this lack of a science requirement that typified technology.

… Innumerable technical pursuits have each an underpinning of scientific knowledge and a content of rational practices from which results can be predicted with a considerable degree of accuracy. Each draws selectively on many sciences but one need not master each of these sciences a whole to gain proficiency in the art. …Since the bounds of needful knowledge can be more accurately predetermined and subject matters introduced selectively, in unit form, and without the elaborate concatenation which marks the engineering course, industrial technology can be taught in much more intensive form than engineering (p24).

This was different from engineering courses which “represented the minimum degree of specialization. Within certain broad, almost generic divisions – civil, mechanical, electrical, etc. – the aim was to teach, as fully as a fixed time would permit, the whole science of the field, with only incidental regard to any particular industry or function. Such specific practices as were taught were largely the tools of analysis and representation, and only incidental ends in themselves. Implicit in the whole process was the aim of preparing the student to choose, on scientific and economical grounds, among the whole range of resources which may be employed to solve a problem (p23).

In 1931, no sharp boundaries could be drawn in the realm between vocational, industrial and professional education. “From the viewpoint of industry, a thoroughly trained technician or operating supervisor ought to be more acceptable than a half-baked or ill-adjusted engineer” (p27). The report concluded that technical education had a real and valuable role to play in the support of America’s burgeoning manufacturing industries. The document reported a repeatedly observed ratio of 2.3:1 technically trained employees to classically trained engineer.

From the report it was also noted that the Technical Institutes were more than vocational education schools. While the curricula were more directly technical than those of the four year schools, there was still a substantial treatment of the underlying and related sciences. The
programs also included English communications and economics. Additionally, the Technical Institutes admitted students based on interest, unlike the engineering schools which usually admitted based on scholastics.

It was interesting to note that the predominance of individuals involved in production were Technical Institute graduates as opposed to engineers. Because the engineers were typically educated to perform extended analyses, data gathering and fact finding, they generally did not function well in the production area where there was not the luxury of time. Furthermore the engineering graduates generally did not want to go to production, though there was need for them. The hours were longer, the pay not as good, the working conditions less appealing, and there were fewer opportunities for advancement as compared to their more theoretical counterparts. Here was seen another source of the division between white collar workers and blue collar workers that would plague American industry for the next 60 years.

The Hammond Report

The Aims and Scope of the Engineering Curriculum (1939) and the Committee on Engineering Education after the War (1944) reports were authored by H.P. Hammond. The reports were not read by the researcher; however the content of the documents was summarized in *Higher education for science and engineering* as follows:

Aims and Scope of the Engineering Curriculum Recommended: diversification of curricula; parallel technical and humanities/social sciences “stems” reconsideration of 4-year curriculum and move to 5- or even 6-year program.

Committee on Engineering Education after the War: Reaffirmed 1939 report; promoted expanding technician programs to fill industrial needs then being met, non-optimally, by engineer; and teaching the “art” of engineering as distinct from scientific method (1989).

The Grinter Report

The Grinter Report is one of the most frequently referenced surveys in the area of engineering education. Originally published in 1955 as the *Report on evaluation of engineering education*, the Grinter report’s purpose was to develop educational standards to aid in accreditation efforts. The goal was to provide differentiation in the engineering education curricula which lie between pure science and technology.
The report presented nine recommendations. Four of the recommendations specifically referred to aims involving pure science and basic engineering science content. One of the nine was specifically concerned with the curricula supporting research activities. Of the remaining recommendations related to curricula, one was regarding appropriate humanities and social content and one considered oral and written communication. The last two recommendations dealt with graduate study concerns and the recruitment and retention of excellent faculty.

Like the Mann and Wickenden reports, Grinter had a clear aim presented for the engineering profession. Unlike Mann and Wickenden, the primary function of engineering was not the control of materials and energy in nature, but rather to serve society by making labor-saving devices and assuring society’s welfare and safety. While the connection to society and supporting its welfare are both true and laudable, the report demonstrates a shift in engineering’s role. Grinter specifically compares engineering to physicians; Mann and Wickenden suggested a desire to be seen as professionals like physicians.

Even more striking was the overt reference to technology as sub-professional. The document repeatedly placed emphasis on the learning of, and further development of, engineering science as a primary end to engineering education.

Over one-third of the report was used in the description of humanities courses and the expansion of the literary awareness of the engineer. Noticeable emphasis was placed on the importance of a liberal education in preparing an engineer to serve society. This emphasis on humanities was further treated in a report published in 1956 titled *General Education in Engineering, Report of the committee for humanistic social research project.* While this report is not discussed here, its content coupled with that of the Grinter report emphasized a re-emergence of the science versus philosophy dichotomy which troubled engineering education during its formative years. It was concluded from the reports that engineering education was responding to societal pressures “to do no harm” and the role of education as a socialistic endeavor. It was also interesting to note that this emphasis on humanistic and societal involvement occurred at a period in history where engineers were gaining a reputation for being not being social. This observation was based on the perceptions of the researcher from the tone of the literature.

Because the responsibility of an engineer to society, according to Grinter, was in expanding theory, the recommended emphasis of education shifted from that presented in previous reports. This cultural pressure was further multiplied by industry’s need for more and
greater technological discoveries. As has been discussed in this document, the historical time frame was such that researchers and scientists were held in higher regard than the individuals applying the knowledge. This emphasis on research necessitated an emphasis on including the scientific method, analysis and synthesis as major components of the engineering curricula.

The report also considered the needs and requirements of the engineering faculty. It was suggested that notoriety and position in one’s field would attract better students. This would seem to imply the students would be familiar with noted individuals in the various engineering disciplines and desire to learn from them. This may have been relevant for attracting graduate students, but it was not clear how this would attract undergraduates, who, in the researcher’s experience, were less likely to be familiar with noted personages.

The support for the elimination of the technical application courses was much stronger than was observed in previous reports. It was directly suggested that application education was the role of industry while universities taught the science which underlie the practice. It is suggested that “practicing engineers achieve results by use of a kind of intuitive sense which, no matter how successful in practice, cannot be transformed into organized knowledge that can be taught to engineering students.” Yet later in the same paper, Grinter suggests that the best use of laboratory time was in letting students explore ideas, generate data and perform analyses, all of them of the students’ own designs. Given no other input, this suggested a requirement for intuitiveness on the student’s part.

It was suggested that the pursuit of analysis and design could include projects, competition between groups, and open-ended problem solving. It was noted that Grinter suggested “synthesizing a new device rather than analyzing an old one.” This demonstrated a further separation of the students from applications, presented by the researcher as an underlying cause for the loss of technical skills. Grinter suggested that courses of descriptive (hands-on) nature were essentially sub-professional because they lacked science theory content.

As already mentioned, Grinter expressed an opinion that the role of laboratory courses, if used, should be of a more open nature. The students should observe phenomenon and seek explanations, a definition of fundamental research. With regards to standard laboratory exercises, Grinter questioned their value. This raised the question of how the students were to obtain the basic knowledge of engineering if not by prepared exercises. This was similar to the
philosophy that given abstract concepts, the students would be able to synthesize the disparate concepts into the final theory on their own without guidance.

Because of the pressures to include science theory classes, basic science courses and humanistic exposure, Grinter acknowledged that in most curricula, something must be removed. His recommendation was the elimination of courses emphasizing practical work, skills, or the art of engineering. Grinter suggested that practices changed too rapidly to be valid course content for engineering. As a historical review showed, this elimination of practical courses took place in the majority of accredited engineering programs. This was a further shift from the recommendation of Hammond that the art of engineering be taught separate from the scientific method.

While Grinter placed a value on graphical expression and spatial visualization for both communications and analysis activities, he suggested that “its value as a skill alone did not justify its inclusion in the curriculum.” His suggestion was its inclusion should be as a natural part of the design analysis courses. Based on this research, it was likely that a student’s exposure to learning and practicing the skill to a level that was useful as an analysis tool was eliminated by the removal of practical courses which contained a graphical content.

To his credit, Grinter asked industry representatives if they would “be pleased with graduates of such programs or would they prefer men able to earn their salary immediately upon graduation without special job training?” At this point in time, most of the industries had sufficient applications knowledge but were lacking in science experts, so their responses indicated they would like the graduates to have more theory. It was likely the industry representatives assumed the students would continue to receive exposure to applications and that science theory would be an addition.

There are several factors influencing the impact of embracing Grinter’s recommendations regarding practical content and science theory. First, research indicates that industry needs are generally five to ten years out of synch with academia’s response. The second impact is more long term; the state of the industries changed radically over the next thirty years while engineering education did not change radically. By comparing Purdue University’s 1990 engineering curricula to that presented in the report, the influence of and response to the recommendations is seen.
The remainder of the Grinter report went into great detail regarding graduate studies. The reference to a bifurcated engineering program as preparation for graduate work remained in this section of the document. The emphasis on the needs and requirements of a graduate program suggested a philosophical belief that engineering education should be performed primarily as support for further formal education.

While the Grinter report was not the last survey of engineering education, it remains the most often used report during contemporary curriculum reviews and educational research. As referenced in Appendix D of *Higher education for science and engineering* (1989), there were at least 14 reports on engineering education between 1959 and 1987, five of them in 1986 alone.

*Summary of engineering education reports from 1918 through 1956*

In comparing the results from the Mann report, the three Wickenden reports, and the Grinter report, the feeling of inferiority of engineering to other professional fields can be seen. In 1918 it was accepted that the role of engineering included both the science and the application activities. The engineer designed AND built the bridges, the mines, and the ships. But the labor role was at odds with the perception of professionalism as compared to physicians, lawyers and clergy. Engineering professionals began asking ‘how do we get taken seriously?’.

By 1930 the labor role of the engineer had been down-graded to a more vocational perception, the role of a blue collar worker, while the role of science was considered the realm of the professional, the white collar worker. The gap between the blue collar worker and the science theorist was filled by the engineering technology professional who was more experienced in applications and who held supervisory and management roles.

It is in the inability to reconcile the need of fulfilling an applications function with the desire to be seen as professional that the resultant loss of technical skills occurred. This evolution is demonstrated by tracing the aims and goals of engineers and the recommended educational content presented in the reports from the first in 1918 to the Grinter Report in 1956.
Interprets of Historical Experts

Because the bifurcated engineering program recommended by the Grinter Report was essentially in use at Purdue University in the 1940s-1950s, two professors who were familiar with Purdue at this time were interviewed for their remembrances and views of engineering education. Concurrently, this period in history has been put forth as the time when engineering education underwent its most radical changes from an application-based curriculum to one based more on science theory. The professors were requested to opine on this premise.

Dr. William LeBold was hired by Purdue University in 1954 and retired in 2002. Dr. LeBold began the interview by indicating that in 1932 at Purdue, an engineering degree had some mathematics and chemistry during the freshman year and physics in the sophomore year, but it also had shop courses, surveying, and drafting. Chemical engineering was the first school to push for accreditation, but they were unique in nature from the start due to the highly scientific nature of the topic.

After W.W.II, advanced graduate work became more important at Purdue. At the same time, the Grinter Report was released. Dr. LeBold noted that in the pre-release of the report, it was recommended that schools use a bifurcated program, one which had a science-based B.S. degree as preparation for graduate school and an application-based B.S. for those individuals who wanted to enter the workforce. The report also suggested that exceptional schools be designated as gold schools. “As you can imagine, all hell broke loose. No school wanted to be perceived as second class so they all wanted to be ranked gold. As a result the bifurcated program was ultimately rejected.” It was clarified that the bifurcation was coupled to the ranking in the reviews, and as such was rejected when the ranking was.

Originally the Schools of Engineering at Purdue had a requirement that the educators have a B.S. followed by industry experience before becoming university professors. The exceptions were chemical engineering, which had doctorate chemists, and electrical engineering, which had doctorate physicists on their staffs. Then there was a push that the entire engineering faculty should be licensed engineers. This resulted in some schools at Purdue having instructors who were PhD’s, while others like mechanical and civil engineering continuing to have a strong applications-orientation. This nation-wide push for licensure was followed by a Ford-funded research investigation on what an engineering faculty should be. The result of the
report was that all faculty members should have a PhD, giving an impetus to graduate programs; “you had to generate all these new PhD’s to fill the faculty positions.”

In the meantime the Technical Institutes were growing, including those at private institutions. At Purdue, Dr. Andrey A. Potter, acting university president, decided to have both the Schools of Engineering and a Technical Institute on the main campus. Most technical institutes at the time were located in industrial centers as a response to local needs. The technical institute at Purdue was a two-year associate degree offered at both the main campus and the regional campuses around Indiana. Over time on the main campus, it could be seen that in the engineering program, the application emphasis was being given up; it was the engineering science that was required to get an accredited engineering degree.

In the 1960's it was decided another report on engineering similar to the Wickenden Report was needed. The preliminary (Walker Goals of Engineering) report was released, recommending that the master’s degree be the first engineering degree and that the bachelor’s degree be an undesignated degree. “Again all hell broke loose. The engineers out there with a B.S. degree said no way they were having their degree devalued.”

At Purdue the Schools of Engineering were told they could have practical components in their degrees if they desired, but it was not the driver for the degree. Purdue administrators discussed having both a technical and an engineering degree. Dean John Hancock looked at the financial commitment to have both and saw that the laboratories of the technical degree would require much of his budget to maintain. He decided he did not want to diminish the engineering science program at the expense of expanding the technical program.

Purdue hired Dr. Charles Lawshe to be the dean of extension, continuing education and the regional campuses. His responsibilities included the technical institutes at the regional campuses and on the main campus. The first thing he did was look at the general education requirements in the three groups. At that point there were general education courses for the liberal arts majors and there were technical general education courses for the technical programs. He made them all the same and gave the technical program and the regional degrees legitimacy, and the School of Technology was formed. Lawshe was responsible for coordinating the move of any application-based content into the Technology program. This included an agreement that any course of a practical (application) nature that Engineering decided to drop could be picked up by Technology.
Dr. LeBold was asked to clarify if that was the point at which Purdue’s bifurcated engineering program was eliminated and he responded that “It didn't go away. There are still those who believe Purdue has a bifurcated program because of the School of Technology. Rather it was an evolution.”

In a second interview, William Dalton in the School of Technology (SoT) was questioned regarding SoT’s evolution. Dalton came to Purdue University in 1978 as a visiting professor. In order to become a full professor, it was necessary to obtain a master’s degree, which he worked on at Purdue, studying the educational gaps in engineering education. During his master’s work, Dalton interviewed Dr. Lawshe about forming SoT. Dalton provided a CD copy of that interview which corroborated what Dr. LeBold had said in the earlier interview.

Dalton provided insight into the shift of engineering education from that of an applications-based program to that of a science-based program from his perspective. “There were two defining moments for me. The first was when my son, who was studying at Miami of Ohio, wanted to change to chemical engineering. The plan of study my son showed me for ChemE didn’t look anything like the one my roommate at Cornell had had. I started looking and discovered the courses my roommate had had to take were in the MET (mechanical engineering technology) department.

“The second defining moment was when a young engineer with whom I worked at Alcoa came to me with an idea for production. He did not know any of the basic engineering concepts and he couldn’t sketch.”

The hypothesized shift in educational content depicted in Figures 1-3 on pages 35 to 38 were found to be descriptors of the situation described by both professors LeBold and Dalton.

Observations from the Literature

During the literature survey done to identify skill concepts put forth in the literature as requisite and considered the perceptions of engineering educators, a number of other observations were made. While not all of the concepts directly answered the question of requisite technical skills, the observations provided insight into what the concepts presented meant to the academic and industrial communities.
What Does It Mean to Design?

Based on the research, what it meant to design became one of the most complex concepts. Depending on the source or the person, the description of design varied greatly. Some people described it as “the methodological process of applying the various formal techniques along with proven scientific principles for the purpose of defining a device, a processor, or a system in sufficient detail to permit its realization” (Rowan University website, 2001). Other sources considered the results of the engineering analysis to be the design. This observation continued the trend of lack of precision in the literature discussed during the literature review section of this document.

During the course of the interviews the request to describe what is design resulted in answers ranging from “the graphical representation of the item” to “a tangible thing” to “a phase of the engineering process” to “interpretation of requirements”. Some people said it was a part of engineering. Others said it contained engineering. For some it involved lots of different kinds of disciplines, for others it contained lots of different kinds of engineers.

In a conversation regarding the literature findings with two non-engineering science doctoral students, another perspective was provided. The two women described their perceptions of design the following way,

Design is the whole thing; engineering is what makes it work. I can design an aircraft that looks pretty, but it may not fly. You can have engineering and not have the ability to see it (the thing being designed). Look at a car, it has to look good – it’s artistic. Look at an ATM. It’s engineered to certain specifications, but it looks good too. So it isn’t the same, but it overlaps. Look at it this way. This is a functional church. You can go in and worship, but it is just a block building.

Now look at this church, it is functional, but it is also designed.
So engineering gets at what is functional while design is all of the other things that make it look good too.

This description captured the concept that engineering and design is a creative endeavor and an art.

The research indicated there was no universal understanding of what design was, where or when it was to be used, or what was its purpose. This identification was deemed to be beyond the scope of this research, but was identified as one of the core difficulties for academia in trying to meet the requirement to provide “design experience” in the curriculum.

What Does It Mean to be an Engineer?

“Like it or not, the future is in the hands of engineers: people whom Plato saw as ‘doers’, who got on and did things, providing what was needed for protection and survival” (Stinton, 2001, p xvii).

If one of the contributors to graduating engineers’ ultimate performance is their perception of what it is to be an engineer, then it is useful to consider what those perceptions are. “‘Everyone knows’ what an engineer is because numerous studies published over the years tell us and ABET set the standards for the acceptable education thereof” (McMasters, 1991). But if the average person on the street is asked, “what does an engineer do?”, the answers range from “designs things” to “analyzes things” to “figures out how things work.”

Meehan suggested that “engineers are thought to be practical people” (1982, p170). But he goes on to suggest that the core of engineering contains idealism. “I mean idealism in the platonic sense, the belief that somewhere is the perfect design. We'll never see it, and we'll certainly never build it, but we know enough about it to be forever seeking it” (p170). “Engineering is the art of compromise, and there is always room for improvement in the real world. But engineering is also the art of the practical; engineers realize that they must at some point curtail design and begin to manufacture or build” (Petroski, 1996, p3).

But what does an engineer do? The answer Meehan came up with was “we fiddle with the problems until we piece together the simplest solution” (1982, p168). Ultimately, says Meehan, the big questions are what is moving what and where is it moving to.

This description still does not seem to get to the root of the question. What is the essence of engineering? Duderstadt suggests that “the essence of engineering practice is the process of
integrating knowledge to some purpose. Unlike the specialized analysis characterizing scientific
inquiry, engineers are expected to be society’s master integrators, working across many
different disciplines and fields” (2001, p3). This would imply that engineers are people of
action, like Plato’s ‘doers’. They put pieces together into new, innovative ‘things’. But being an
engineer is also knowing what needs to be designed from scratch and what can be taken and
integrated in new ways. “Sometimes being the best engineer means knowing what to buy and
how to integrate it into the total system rather than the more traditional task of designing from
scratch” (Widnall, 2001).

On the American Society of Mechanical Engineering’s (ASME) website, the following
definitions and descriptions were presented. ASME defines engineering as “the art of applying
scientific and mathematical principles, experience, judgment, and common sense to make
things that benefit people.” It describes engineers as “problem solvers, people who search for
quicker, less expensive ways to use the forces and materials of nature to meet tough
challenges.” Where engineers plan and design, ASME suggests engineering technicians and
technologists translate the engineering documents and actually build and support the product.
Engineering technology is hands-on as opposed to conceptual and research-oriented (2004).

Another perspective on engineering is more theoretical. It is a perception that engineering
is a cross-disciplinary research endeavor. “…Such cross-disciplinary research is common to
much of the work of the engineer and is what makes the pursuit of solutions to problems
always fresh and challenging” (Petroski, 1996, p54). An engineer possesses an inquisitive mind
which when presented with patterns or trends, begins to look for the engineering or scientific
explanation for the patterns. It is suggested that “an engineering program is constructed to
provide students with the skills to understand physical systems and to mathematically model
those systems” (Taylor, et al, 1997, p2). Similarly, Young quotes Koen, “It is the engineering
methods or design processes, rather than the artifacts designed, that binds all engineering
disciplines together and defines the engineer” (2000, p212).

Based on the results of the exit survey given to the graduating aerospace engineers
following their senior design course, there is a perception that upon graduation a new engineer
will be involved in research and discovery. His or her role will be to model abstractions and
generate data on concepts and new technologies. But reality suggests that more activity is spent
in the “doing” as opposed to the “theorizing” types of activities.
This is not to say that the theory is not important or integral to engineering activities. On the contrary, engineering activities are indeed cerebral. But the theories describe actual behaviors of actual things. Meehan notes that in his physics course “we began by playing with toy cars that ran on tracks, bumping in to each other and running down ramps. After a while we learned that the cars and tracks could be replaced with symbols, m’s and x’s and y’s. And soon we could play with those abstract symbols instead of the cars themselves” (1982, p39). The symbols don’t replace the things, they represent them. In observing academic activities, researching engineering education, and from personal experience with professional engineers, it appears this distinction is often lost. In the end engineering design leads to a “thing” that must “do” something. This suggests that theory must eventually be applied. “The success of applied science and engineering is measured not so much by published papers, as by working devices that do useful things” (Hughes, 1998, p184). So being an engineer means recognizing technology opportunities, analyzing the data and synthesizing the results and impacts.

This level of responsibility can lead to a certain level of technical arrogance and rightly so. The problem occurs when the level of arrogance becomes unwarranted, outstrips the level of responsibility, or prevents a person from learning or garnering input. Says Hughes, quoting Baran, “if you’re not careful, you can con yourself into believing that you did the most important part. But the reality is that each contribution has to follow onto previous work. Everything is tied to everything else [italics in original work]” (1998, p274).

So being an engineer means being a professional who can get his or her hands dirty. It means analyzing and synthesizing. It means being sure of the work but willing to take input and learn from others. It means being able to design from scratch, or integrate with what is available, and the ability to tell the difference.

What Are the Expectations and Misconceptions of Graduating Engineers?

Students may be graduating with unrealistic expectations or even misconceptions of what they will be doing when they graduate. The current academic pedagogy educates engineers as though they will all go into preliminary and or concept design, the idea of a clean sheet of paper and a problem that has never been done before. But in reality, very few engineers are involved in those initial design activities.
Based on the literature, less than 25% of the graduating engineers will work in these initial, more creative design phases (Nicolai, 1993). Another 5% will be involved in strictly analysis activities such as failure mechanics or stress analyses. Of the remaining 70% over 2/3 will be involved in iterative design activities; fixing previous problems, tweaking a little more “x” out of a current design, or looking for cost saving items. The remaining 1/3 will be involved in document review, sales, or other synthesizing activities. When students were asked what they thought they would be doing when they graduated, this perception of working on something new and analyzing data to create new designs was observed.

Another misconception is the level of excitement that an engineer enjoys. Says McMasters “the sort of ‘good engineer’ we (sic Boeing) want tends to rapidly become bored or frustrated with routine job assignments” (1991). McMasters goes on “engineering as practiced in industry is sometimes boring. While much lip service is paid to the need to be creative and innovative, the majority of entry level jobs basically involve analysis and testing that follow routine practice.” This research indicates this is partially because of the students’ misconceptions of what they will be doing in their jobs. They expect to be involved in fast paced problem solving or creative, new design opportunities and are disillusioned by the mundane tasks that make up more than 90% of the job.

In other cases students have a misconception of the level of responsibility they will have as a newly hired engineer. They expect an office and a project as opposed to “doing time in the trenches.” While industry expresses dissatisfaction in the amount of time it takes for a new hire to be able to contribute to the bottom line, the disconnect is in the content of the knowledge and skills. The new hires do not expect the expectations of basic engineering principles and internalization of mechanical things. They believe they have been hired for their ability to run analyses and create things on their own or as part of teams.

Students do not expect to have to spend time on a shop floor learning how things work, or how they are made. They do not expect to have to be concerned with how the “thing” for which they are making drawings will be disposed of at the end of its life. They have a misconception that they will set up their own tests and run analyses on their own data. Based on the observations from the study, this is because that is how they have been educated.

It was observed that many of these misconceptions and expectations were mitigated by participation in co-op programs and summer internships where the students were able to see
first hand what was expected of an engineer in the workplace, giving them an opportunity to correct their misconceptions while still in school.

Misconceptions were not only the purview of students. Educators also had misconceptions regarding the goals and content of engineering education as it pertains to industry. Like the students, many educators suggested they did not really know what was expected of an engineer in the workforce because they had not worked in industry. They did not know about the boring and mundane tasks, as their role in recent years had been one of research and science, not application and manufacture.

There were also expectations and misconceptions regarding the students’ emotional investment in the educational topics. In Nicolai’s discourse on engineering education (1993), he commented that “the beauty of open-ended problems is that the students become very emotionally involved in the problem as the available information is insufficient to solve the problem and the student must generate the missing information which makes the answer unique to him or her”. Nicolai was assuming that the students did become emotionally involved. Based on the classroom observations what actually happened was the students became frustrated and fell into a “give me the problem I’ll give you the answer” frame of mind, or they did not do the activity, or they did just enough to get by the assignment.

There is also an expectation by educators that students could make the leap from being shown a theory or concept (knowledge) to using and applying the concept (skill). Based on observations, students did not have the experience or background to make the intuitive leap between the two levels. Some of this misconception came from the expectations that students had received the necessary exposure to the various concepts in previous classes. In some cases they may have, in some cases they had but did not recognize them when presented with the concepts in new contexts, and some cases the course content or life experience that an instructor assumed was there to draw on was not.

Risk Taking and Avoidance

“Engineering is intellectually dangerous. One works beyond the edge of reliable information: one never has resources to make all of the tests one would like; a deadline exists; a budget must be met; and prudent risk-taking is the setting for every decision” (Hughes, 1998, p184). The fact is that no matter how hard a designer tries, the risk can never be mitigated to
zero. But as was described in the section “aerospace culture”, aerospace designers are extremely risk adverse. This leads to a conundrum. The effort to reduce risk is subject to the law of diminishing returns. After a certain point more time and money can be applied to the reduction of risk with little to no observable improvements (Stinton, 2001, p8).

On the other hand, "designers are prone to extrapolate beyond existing knowledge basis" (Petroski, 1994, p.43). Petroski also says, "many products fail to reach their promised potential because they seem not to have been sufficiently criticized or successfully scrutinized before being launched as full-scale structures…" (p28). These two statements indicate inappropriate risk-taking due to inadequate or insufficient design analysis. This analysis is linked to the ability to do appropriate trade studies, "the analysis conducted to determine the preferred option among two or more options. It is the key step which allows the designer to find the best solution for both the aircraft and its subsystems" (Jackson, 1997, p81).

Because failure and risk were so interlinked, and because the driving need was to avoid failures, designers and engineers appeared unwilling to take risks of any degree. There was a feeling that if a mistake was made or had a failure the design engineer would be fired. In other cases the designer engineers become so convinced of their own skills that risk analyses were neglected or deemed unnecessary. The resulting failures could be spectacular and could ruin a career, i.e. the Challenger mishap.

The key was to take informed risks, to minimize what could be minimized and to not take unnecessary risks in the pursuit of advancing technology. Avoiding unnecessary risks meant performing appropriate analyses and trade studies during design, and being critical of the resulting analyses. It also required learning to deal with acceptable failure.

**Dealing With and Learning From Failure**

During the identification of the problem for this research, complaints regarding the occurrence of unexpected or inappropriate failures were observed throughout the literature. Industry representatives intimated that the design engineers were making mistakes in employing the first engineering principles and were repeating mistakes identified and solved in previous decades. There was also a sense that the design engineers did not understand basic failure mechanisms of materials much less of systems. The literature expressed a sense that there was no learning from mistakes which in turn resulted in repeated failures.
While surveying the literature, four concepts began to appear. First, the engineering profession as an entity appeared to spend so much time focusing on successes that there was little time spent on failures, despite the fact more is learned from failure that from success. Furthermore, “… increasing dramatic successes of engineers drove from the literature and apparently the mind of the engineering profession the failures and mistakes they seem doomed to repeat. Judging from the paucity of professional literature on failure in the first three-quarters of this century, it was unfashionable at best and unprofessional at worst to deal too explicitly with errors of engineering” (Petroski, 1994, p98).

The second observation was that one of the expected parts of the design process was a serious critique of all aspects of the design. “It should be seen as a professional responsibility of the engineer to recognize an obligation to the engineering method to look critically at every aspect of the design and manufacturing process that went into creating the failed artifact, including the basic assumptions of design and analysis. Should those assumptions be flawed but not identified as such, all design “corrections” or refinements could be for naught” (Petroski, 1994, p80). The designer should thoroughly assess the design, asking "what if X?" Based on the literature readings, the answers were too often, "that can't happen" and the design engineer moved on to the next activity. When X did happen, the engineer was surprised and embarrassed. At the same time there was a sense that the “environment placed the onus for success squarely on the procedures and practices used to turn innovative concepts into manufacturing processes and products” (O'Hara, Evans, & Hayden, 1993). It was concluded that the authors were suggesting that the perfect process would yield the perfect product, negating the need for human analyses. During the classroom observations, students actively resisted requests to evaluate failure modes or to seriously critique each others designs, much less critiquing their own.

The third observation made from the literature and from observations was a noticeable lack of educating engineers knowing how to do this critical review. When the analysis became difficult or required information outside of the engineering students’ experience, the analysis was terminated. The education process was geared towards teaching to success as opposed to teaching to failure. "Design studies that concentrate only on how successful designs are produced can thus miss some fundamental aspects of the design process, which is difficult enough to articulate as it is" (Petroski, 1994, p1). While the student should not be taught that
every test should be run to failure in the workplace, it was noted they were not generally allowed to do it in the educational environment either. Discussions with students and parents, as well as the literature, suggested children do not experiment to failure recreationally either.

During the classroom observations of the semesters with an remote controlled (R.C.) aircraft as the product, it was noted that there was no requirement or opportunity to test components to failure. In a special session of the course, the students did have the opportunity to perform a wing loading test to failure. The academic results were noticeable. The students demonstrated both learning and internalization of mechanical concepts as well as a better understanding of their design as indicated by their questions and discussions with the faculty, support staff and each other.

The fourth observation made was that throughout the literature even when discussions on failures and failure modes were made, they were made with effacing and apologies, and with a sense of not wanting to appear as though the author was throwing stones. This was observed even in the scientific research papers where failures would be expected.

All of these observations suggested there were few opportunities to personally learn from failure, that there were limited opportunities to learn from others’ failures and that the occurrence of a failure was presented in educational and professional environments as being intrinsically bad. Because failures were ignored in comparison with the emphasis placed on learning from success, there was a lack of internalization of failure mechanics, there was a lack of awareness in performing critical analyses of designs with respect to potential failure modes, and there was a learned fear of failure that prevented appropriate risk-taking. This lack of understanding negatively impacted design success through a lack of recognition of the cues that precede impending failure.

“If there were a more heightened awareness among designers (sic design engineers) that in case after case throughout history there have been surprises in exploratory design, then designers engaged in such design situations might pay more attention to the warning signs that seem invariably to prefigure failures. They are ignored when the design environment rests on successes rather than awareness of failures” (Petroski, 1994, p97).
Problem Solving

One of the repeated themes throughout the literature expressed by both academics and technical professionals was the ability to perform problem-solving. The concept seemed to be that the introduction of open-ended problems would force students to employ all the educational concepts learned in their previous classes to solve the problem. This would allow them to practice the skills necessary to design once in the workplace.

One of the first challenges was to understand what industry practitioners meant by problem-solving skills and why it was important. Accepting that the engineer solves problems then “great engineering is measured by proper gauging of people’s needs and the delivery of affordable, high-grade products and services” (Tricamo, et al., 2003). “Relying on the discoveries and creation of science, engineering seeks to delineate answers to client-posed problems within constraints of time and resources, then select the optimum response from the range of possibilities” (Adelman, 1998, p38). This suggested that in industry problem-solving meant recognizing a challenge or opportunity and finding a way to answer it.

In order to teach the problem-solving skills necessary in the workplace, industry representatives, accrediting bodies and educational researchers repeatedly touted the open-ended problem as the educator’s panacea. But throughout the same literature, the authors neglected the instructor’s need for a set of criteria on which to grade the students’ performances on the problems. The concept as presented also ignored the experience, or lack thereof, of the students. Finally the open-ended problem-solving methodology was generally presented so broadly in class and literature, that executing it within an academic environment was problematic.

The first challenge, the problem of the success criteria, has already been discussed earlier in this document under the lack of defined metrics. Until both specific goals of executing the open-ended problem, and goals related to the specific supplied problem are defined, it is difficult to create the clear success metrics necessary for grading the endeavor.

Regarding the experience of the students, no less than five articles comment on the disconnect and discomfort for the students in radically moving from a system of rote learning with well defined problems and answers, to an environment where there was no clear questions and many possible answers. This shift and its discomfort were accepted because it was deemed part of the learning process. “The solution of a problem which clearly has no
unique answer is at first shocking and uncomfortable for many young students who have
grown to expect right and wrong answers to questions, but it is probably the first steps they
take in developing engineering judgment” (Young, 2000, p210).

While the authors acknowledged that engineering problems can have many solutions
unlike mathematics or science problems, educators spent 3 – 3 ½ years having students do
mathematics and science problems with right answers but without connecting the concepts to
what the formulas represented. Formulas did not precede an observation, they explained it. In
more than 75% of the traditional engineering courses observed by this researcher, the formula
was taught in isolation from the observation. But when the students were given an open-ended
problem, the students were expected to recognize the observation and then apply the theory.
This lack of connection was further exacerbated by encouraging the use of high-level tools
which had the connections built into the code, setting the student to learn that the tool, as
opposed to the tool user, solved the problems.

Not only were the students ill-prepared to set up and run the analyses required in an open-
ended problem-solving environment, for possibly the first time in their academic career they
were faced with generating the problem itself from a set of inputs. Based on the literature and
personal observations, there was little in the engineering curriculum that prepared them to do
this. Furthermore, the first course in which a student encountered open-ended problem-
solving did not teach the skill as a specific goal of the course, but rather the expectation was
that the student to be able to do it intuitively.

The final observation made from the literature survey and supported by classroom
observations, was that the projects given to the students in open-ended problem-solving
environments were so broad, that in more than 50% of the cases, they lacked any useful focus
for learning. The tasks for the students grew so large they did not have sufficient opportunities
to practice iteration in analyses, a key step in the design process. The problems generated so
much breadth that students had no real opportunity to learn any particular concept with
sufficient depth as to be academically useful. Based on the classroom observations, it may have
been that negative problem-solving behaviors were re-enforced, such as single iteration
analyses, lack of adequate trade studies, lack of internalization of concepts or their connection
to formulas, and lack of obtaining adequate background and feedback. An ancillary
observation was that while literature did provide examples of real-world challenges to be used
for open-ended problems, they did not provide the success criteria for the educator, they were allowed to expand beyond focused academic efforts, or they were not used at all in favor of locally important problems.

Analysis vs. Synthesis

Analysis as a part of design has been given much attention in academic reviews. Its relationship to synthesis was less noticeable. Analysis was defined as the separation of a whole into its component parts and as making a detailed examination of a complex item (Webster’s, 1976, p77). Synthesis was putting a collection of pieces together into a useful whole (Webster’s, p2321).

Engineering education included instruction regarding the analysis of complex problems, and recognizing and solving formulas describing the parts. Based on the literature, it did not place equal attention on the synthesis of an overall answer from the results of one or more analyses. This research suggested one of the areas lacking in graduating engineers was the ability to synthesize a solution to a complex problem from the disparate data obtained from the analysis process. An industrial professional stated “I can hire an analyst to crunch numbers all day, what I need is someone to tell me what the results mean to my system”. In the classroom observations so much time was spent in the analysis activities, little or no time remained for the students to have an adequate opportunity to attempt a synthesis of their data.

Computer Tools

The increase in power and speed of computers has allowed engineers to perform more calculations, more complex calculations, and to perform them more rapidly than in the past. While this was positive in terms of design productivity and fidelity, the literature indicated a concern existed with respect to the appropriate use of computers during design. These concerns were related not only to the use of the tools during the education process but also after the student enters the workforce.

The first observation was a concern that there was a lack of understanding of the fundamental principles and physical understanding on which the codes were based. Without a complete understanding of these principles, the user could not be clear on the assumptions and limitations inherent to the tool. “The advent of supercomputers has facilitated complex
computations, but their results are only as complete as the theories on which those programs are based” (Petroski, 1994, p93). Without this basic understanding, “engineers would be unthinkingly operating computers that were for all practical purposes black boxes into which an input was inserted and out from which an output was taken” (Petroski, 1996, p153).

This led to the second, related concern. The literature also indicated that there was a concern regarding the lack of checking and validating the results. “As long as one does not question the validity or recognize the restrictiveness of basic assumptions, one can overlook the fact that they are limiting one’s interpretation of the results” (Petroski, 1996, p62). It has been said that ‘garbage in – garbage out’ with respect to analyses, but the concern was that students had insufficient experience to recognize valid inputs or outputs in classroom exercises, and as such enter the workplace ignorant of the concept of tool limitations.

Similarly, there was a concern that the output from the computer analyses were not being questioned in terms of the outputs’ relationship to the entire system beyond the specific analysis being done. This myopic view of the data resulted in a loss of holistic perspective and resulted in localized optimization at the expense of the entire system’s performance.

A third observation was a concern regarding the over reliance on computers especially during the academic period. While it was agreed that computers were tools of the industry and that educators would be remiss in not teaching the tools, it may be done too early in the academic process. The students may be taught to use the tools before they understand the fundamentals, resulting in the students being overly reliant on the tools and overly trusting of the output (Crawley, et al., 1993).

Authors and industry personnel also expressed a concern regarding the correct use of the tools. The computer could only answer the questions it was asked. To date the computer is unable to look at what has been asked and recognize what else should be asked (Taylor, 2000). Without adequate experience, students did not know what else they should be asking or whether they were asking the correct things. Authors expressed the concern that designer engineers did not develop the discipline to confirm the correct question or all the questions were being asked.

The fifth observation was the existence of a concern regarding the level of fidelity appropriate for a given analysis and thus the appropriate use of the tools. It was suggested that computer time may be being used when the level of fidelity of the analysis only warrants a
hand-calculation. Furthermore, interviews of technical professionals indicated that the use of code was the only tool with which the new engineers were familiar, precluding the use of hand-calculations regardless of the level of fidelity required. Similarly the new engineers were described as being unable to recognize output behavior in the data that related to specific input behavior, resorting immediately to computer analyses. It was suggested they lacked the recognition of patterns that comes from repeated hand-calculations. They had not learned that when the output looks like ‘x’ the input probably looks like ‘y’ or vice versa.

To summarize the observations, there were concerns regarding an over-reliance on the computer, over-confidence in the results, a lack of review of the validity of the assumptions and limitations of the tool and of the results, an inability to recognize legitimate input and output, and an inappropriate fidelity level with respect to the desired analysis.

**Obtaining Information**

During the course of the research, one of the success skills described but not specifically named was the concept of obtaining information, both recognizing the need for the information and expending the effort to obtain it. A literature search for the topic located a single report, *An investigation of factors affecting how engineers and scientists seek information* by C.J. Anderson, et al., in 2001. This report coupled with the information provided by technical professionals and personal observations led to the following evaluations.

Contrary to a common perception that engineers and scientists do not ask for information, experience suggests they can and will talk to people. What is at issue is what actually triggers the process of expending the effort to obtain information.

Anderson, et al. suggested that the process was triggered when a given level of uncertainty was reached (this level was not defined). The authors defined uncertainty as the difference between the amount of information necessary to do a task and the amount of information already possessed. It was noted that it was the amount of information the individual believed they possessed and made no assessment of the validity of their information in solving the problem. Furthermore, the individual had to recognize that information necessary to doing the task was missing. If the engineer did not realize there was information missing, they did not reach the level of uncertainty that triggered looking for more information. This awareness was partially a function of experience and partially a function of breadth of education.
The authors suggested that people follow a principle of least effort; people solve problems in such a way as to minimize the total work that must be expended. This observation should not be construed as a value judgment regarding motivation or quality. Professionals tended to rely on their own personal knowledge first. Unless some feedback indicated a lack of accuracy in the knowledge, the individual returned to that knowledge repeatedly. Further, if the knowledge proved correct the first time it was applied, the individual was more likely to use that knowledge in similar situations regardless of the knowledge’s appropriateness.

The next level of personal knowledge accessed was those items immediately accessible, for example personal texts, files and other physically accessible sources. Personal observations, especially of students, indicated this also included reliance on the internet without regard to the reliability of the sources or an assessment of the validity of the information. With the students, further effort to find information after a web search was limited.

The report authors noted that information seekers choose oral communications over written carriers. They asked someone as opposed to reading about it. These sources of information were most likely to be individuals who were immediately accessible, i.e. in the same office, and individuals who had proven helpful in the past. It was noted by the technical professionals that these helpful individuals may or may not have been familiar with the topic, only that they were accessible or had been helpful.

To summarize obtaining information once a need has been recognized, engineers tended to source their own minds first, followed by their own bookshelf and the internet, then by speaking to accessible or helpful people who are around them most frequently, and only then by moving on to a larger circle of data.

Even after expanding the circle, information seekers were more likely to call or speak with someone than to move to other forms of information. One exception presented by Anderson, et al. was that the more important a written carrier was perceived to be in solving the problem at hand, the more likely it was to be used. This was noted by the researcher during the student observations in that when presented with a specific article or text as key to the project, the students would rely on the text to the exclusion of other sources of data, including the internet.

Similarly Anderson, et al., noted that when an individual did not use or was not familiar with a particular carrier, they were likely to underestimate the existence of useful information and overestimate the difficulty of obtaining the information. This was also demonstrated by
the students. In one instance, a specific industry database located in a remote campus library was recommended to help solve their problem. The students responded that the data would probably not be of help and that it would be too hard for them to access the data.

However, Anderson, et al., concluded that as the complexity of a project increased, the more likely the individual was to use multiple information carriers. Furthermore, as the complexity of the project increased, the ease of accessibility was no longer a factor; it did not have to be easy to get. With regards to the individual, the more uncertain the technical person saw the world, the greater the contact they sought outside of their firms.

The conclusions presented in the report were supported by the information gained by the researcher from the interviews of practitioners. The responses on the topics of getting input and feedback indicated that engineers are willing to take the information and feedback once they recognize they need it. This willingness, however, is tempered by a reticence of appearing unknowledgeable to their peers. In over 90% of the interviews, participants indicated that people are willing to provide input when asked unless the business structure actively hinders or prevents it. With regards to feedback, over 90% of the participants said the information was available but also indicated that it was incumbent on the engineer to take the initiative to locate and obtain it. In none of the interviews did the participant mention any other form of carrier for receiving input. The most typical source of feedback was reported to be warranty and service records.

Language

During the course of the research and particularly with respect to obtaining information, the researcher noted that understanding the language of a group was an important consideration. It was generally accepted that each industry and even each major discipline had its own language and shorthand. While this was a well documented concern, it was beyond the scope of this research to deal with this area of language. But it was important to this research to consider how it impacted obtaining information within an industry or discipline. “Oral communication may become dysfunctional if the actors who exchange communication do not share a common language” (Anderson et al., 2001, p148).

Within a discipline there are a variety of languages used. For example Ullman suggested that in mechanical engineering there were four languages used to describe a mechanical object.
These are semantic: a verbal or technical representation; graphical: drawings of an object; analytical: equations or formulas; and physical: the actual hardware (1992, p30). What surprised the researcher was that the meanings contained in the semantic and analytical languages were not consistent between related disciplines such as aeronautical engineering and aviation technology, or even within a single discipline such as aeronautical engineering. This resulted in a particular challenge when attempting to obtain input and feedback.

This disconnect within a discipline’s language was seen by the researcher during classroom observations and during interviews with technical professionals. In one particular case it was noted that the analytical representation of the same physical concept was represented differently by the same aeronautical engineering students depending on what analysis was being performed. Further it was noted that the students were not troubled by this disconnect as they saw two concepts expressed by two formulas for two different analyses. Similarly, one of the interview participants commented that he recalled a case where he had asked a second aeronautical engineer for wing loading data. Both individuals were aerospace engineers, but they worked in different areas of the air vehicle design. The data he received was not what he wanted because the term wing loading had a different meaning for the second engineer. The second engineer had provided data meeting this second definition of wing loading.

In another example from the classroom observations, it was observed that the formulaic symbol for the aeronautical engineering concept thrust was $T$. This was in conflict with the formulaic symbol $F_a$ used for thrust by the aviation technology students participating in the class. For the technology students $T$ meant temperature. For the engineering students temperature was either $t$ or temp. Until this disconnect was identified and dealt with, the sharing of data between the two related groups was hindered.

“‘When I use a word’, Humpty Dumpty said in a rather scornful tone, ‘it means just what I choose it to mean – neither more not less.’”, Lewis Carroll’s *Through the looking glass*, as quoted by Stinton (2001, p30). Personal observations have been that there could be a level of scorn when a disconnect was observed, a feeling that the other person should have known what was meant. This arrogance and assumption of a right or common language provides a potential for affecting the exchange of data. While this awareness was becoming more common between disparate disciplines, it was important to note the potential for language differences existed between related disciplines as well as within a single discipline.
Another related observation made during the classroom study and the interviews was a perception that graduating students did not have a working grasp of the basic language of their disciplines. In at least three literature sources and two interviews, it was commented that students had not learned the common terms and representations intrinsic to their discipline.

“Seeing it”

One of the abilities prevalent in the literature was the ability to view the design ‘holistically’ and to have a ‘global awareness’ of the product. After researching what was meant by a holistic view of the design, the conclusion drawn was that the ability contains an ability to ‘see’ the finished artifact in the mind’s eye. The design engineer could see in his or her mind what the artifact was, and how a change one place impacted the behavior of the entire system. This ability was demonstrated several ways.

Visualization was demonstrated through the concept of transference which was the skill of applying a familiar concept to an unfamiliar but similar application. Based on this research it appears that newly graduated engineers were less likely than their predecessors to be able to perform basic concept transference. In an aviation technology course at Purdue University the instructor found he had to make changes to his lectures on aerodynamic principles. When he tried to provide familiar examples to explain the technical principles (transference) he had students who had not ridden bicycles (gears, cranks, rotary motion), students who had not put their hand out of a moving car window (air resistance, lift), or who had not seen seesaws (levers, weights and balance). Yet when these same students entered the work force, they would be working with older individuals who had internalized these mechanical concepts and would be at best puzzled and at worst disappointed by the younger employees’ inability to ‘see’ the concepts.

In Schumacher’s 1999 article, he discussed developing a hands-on feel by having his students perform wire modeling. The students actually made motion out of static wire so they could see the concepts. The idea was that once the student had seen how mechanical motion behaved, they would begin to develop the ability to ‘see’ the behavior of the artifact without actually having to build it.

This was related to ‘seeing’ what a formulaic representation described. One student commented that they believed the person who developed the formulas got it right. It was more
important that he, the student, could see what the formula described, could understand what the formula was and then apply it than to derive it mathematically. It should be noted that this is different than the generally accepted view that educators use the activity of derivations in an attempt to provide conceptual connection of the formula to the resultant. One professor commented that there were two goals to having students work derivations. First by working the derivations, the goal was to connect the complex formula back to the fundamental formulas, for example Newton’s laws. The second reason was to provide students with the knowledge of how to manipulate the fundamental formulas to facilitate the task at hand even when a standard formula was not available. Based on student comments, students view the derivation exercises abstractly without connecting the complex formulas to a physical reality.

In talking with students, the researcher observed there was a lack of visualization taking place when presented with formulaic expressions. For example, when presented with $F=ma$, the student did not ‘see’ a mass being pushed and then ‘see’ that something heavy had to be pushed harder than something light to move it the same speed. In the students’ minds, they saw a quantity multiplied by another quantity that gave a result that could then be used in another formula.

When industry representatives complained that newly graduated engineers did not see the whole project, that they had no internalization of the artifact which they were creating, it was easy to assume this meant they could not see the wing or the aircraft or the computer code they were creating. Based on this research, however, it was concluded that the complaint was the new engineers could not ‘see’ basic mechanical concepts and were therefore unable to make the transference of a concept to a new design or to ‘see’ intuitively what each change meant to the system.

**Academic Pedagogy**

While the concepts related to engineering education pedagogy were beyond the scope of this research, several educational concepts related to the desired technical skills were observed during the literature analysis. These concepts are presented briefly with respect to their impact on the measurable criteria defining the technical skills, as well as providing insight into the success metrics that would assist educators in teaching the identified skills.
It appeared to be noteworthy that “traditional engineering education has favored two types of learners – those who excel at regurgitating facts and those who like working in isolation… Creative and risk taking types…often switch to other majors…” (Education needs, 1996). This suggested that traditional engineering curricula screen out the very type of individual that industrial sources said they want. This type of education also retained students who were most likely to have difficulties in the types of capstone design courses being incorporated into the senior year. They were also more likely to have difficulties with open-ended problems and with team structure. The researcher observed this phenomenon during the classroom observations as demonstrated by a dependence on rote application of formulas, difficulty in forming effective team structures, and as a lack of passion for the field. It should be noted that this observation did not consider students who exhibited extraordinary involvement or interest. These extraordinary students appeared to locate additional educational venues and challenges through participation in clubs and engineering design competitions.

*Science vs. Application*

In figures 1-4 of this document (page 35 to 38), it was suggested that the separation of theory from application provided one explanation for the complaints expressed by individuals in industry. When researching how engineering education evolution reached this state, it was determined the trend was due to more than just overcrowding of the curricula with new technology. At some level, institutions of higher learning imbued the two concepts with intrinsic and separate educational value. Furthermore, science theory came to be considered to be intrinsically better than application.

In a commentary on the role of engineering education in 1956, Davis expounded, “Eventually industry will teach a major portion of science, leaving it to the engineering colleges to concentrate on improving the undergraduate’s understanding of the theoretical concepts on which the applications are based.” There were two subtle shifts in perspective demonstrated in this article. The first was the assumption that erudite pursuits were the ultimate goal for all students. The second was a shift from observation, often from applications, preceding theory to theory being upon what applications were built. This perception of order persisted through contemporary reports as was evidenced by Adelman in his 1998 report to the NSF, “Science
seeks to uncover the laws of nature, expand and deepen our knowledge of basic science…,
thus establishing foundations for applications” (p38).

Davis goes on to opine “That will mean that more of our colleges will have to weed out
more and more of their ‘how-to-do-it’ courses and I for one say, ‘good riddance.’” (p792). But
in reality, “experience had to come before theory. Engineering is not simply applied science;
know-how often precedes know-why” (Hughes, 1998, p127).

This dichotomy also fed the feelings of inferiority regarding engineering’s professional role
discussed earlier. As recently as 1996, articles noted that there were naysayers countering that
project-based learning would actually impede the professionalism of engineering (Education
needs, 1996).

This perspective regarding educational value and industrial value resulted in a “very
limiting model of higher education and the academic perspective that that the nation’s
engineers and technologists are used primarily in industry as simply the “appliers” and transfer
agents of new scientific “discoveries” and research findings (originating at the nation’s research
universities) into products and processes for industrial innovation” (Tricamo et al., 2003).

The belief that theory and ‘thought’ were fundamentally better than application and
‘action’ was observed throughout education, not just in engineering education. It was observed
in basic pedagogical research. In 1991, Lave and Wenger noted that “verbal instruction has
been assumed to have special and especially effective properties with respect to generality and
scope of understanding that learners come away with, while instruction by demonstration –
learning by ‘observation and imitation’ – is supposed to produce the opposite, a literal and
narrow effect” (p105). This suggested that learning how to do something resulted in only being
able to do that one specific concept and that no transference took place from experience.
Furthermore it suggested that learning the theory resulted in knowledge that was not only
broader and more easily transferred, but the knowledge alone was sufficient for use in real
situations. Lave and Wenger went on to observe that “the historical significance of
apprenticeship as a form for producing knowledgably skilled persons has been overlooked, we
believe, for it does not conform to either functionalist or Marxist views of educational
“progress”. It was used as an example to emphasize its anachronistic irrelevance” (1991, p62).

Within the engineering workplace a similar division between theory and application was
observed. Theorists were needed and given different roles than those providing application
efforts. At first “these early engineers solved their problems with empirical solutions born of hard earned experience and precious little theory” (Gresham, 2003, p6). Because observation preceded theory, the early theorists were application-based. “In solving problems, controlling quality or making improvement, workers relied primarily on the technical skill they acquired through long apprenticeships” (Hayes, Wheelwright & Clark, 1988, p36). But then the need for new knowledge became so great in the newly emerging areas that industry needed additional sources of information. “In WWII we brought in physicists because engineers with their bachelor’s degrees didn’t know enough about science to do the things that needed doing [sic transistors, generators, electronics]” (Collins, n.d., p11).

Not only were there requirements for more technical advances, but the rate of new technology development quickly exceeded the experience base available. This meant that engineers had to do research to obtain information with which to solve problems (Lopardo & Wu, 1994). It was also believed that adding more fundamental learning of physical and mathematical science would shorten discovery to application time and still produce good engineers (Lopardo & Wu, p2939). As a result many universities initiated new engineering curricula which stressed fundamentals over practice.

When these new resources were brought in to assist technology development, these new resources actually appeared to be that which solved the problem, resulting in a culture shift that the theorists and scientists had ‘saved the day’ and that the applications groups were subordinate rather than cooperative. In reality science and application should be peers in both education and in the design process.

It was into this educational culture of a dichotomy between science theory and application technology that educators were being asked to reintroduce application concepts. The researcher herself has seen academic debate in which application-based courses were described as ‘vocational’ and having less educational value than the more theoretical courses at the university. McMasters & Ford quote CR Chaplin, 1985, that “this better balance [of science and application] does not involve a return to the vocational orientation that characterized engineering in the 1950s, but does reflect this hope: “In time the … public and possibly even the ‘educated classes’ will come to appreciate that engineering is no more applied (and therefore second rate) science, than science is theoretical engineering” (1999).
Tricamo et al (2003) observed that success in science was much easier to measure. When science research was successful there was an observable, concrete outcome; funding was received, a theory was proven, a new formula was created. Design success in undergraduate activities was much harder to assess. Because science tended to be easier to assess and thereby more likely to receive funds, it was not be surprising science research received more attention than application research.

For individuals interested in a foundational discussion, chapter 12 of the Mann Report is recommended. The report is included in Appendix G.

Engineering vs. Engineering Technology

The premise of a separation of theory and application has already been discussed in this paper as has the elevation of science over application. Nicolai noted that “our universities are turning out great scientists but mediocre engineers” (1993). He went on “the engineering graduates’ knowledge of engineering science, mathematics and analytical techniques was very good, but they were poorly equipped to use the knowledge.” Furthermore “the new theoretical engineering curriculum was fine preparation for graduate school. However, the missing practical background delayed their ability to contribute to laboratory settings in industry” (Taylor et al., 1997, p2). The need for the application of this knowledge did not go away as technology advanced.

The need for application education also still remained and attempts at bifurcated engineering programs were generally unsuccessful. This left the responsibility to those technical institutes which had not evolved into engineering science programs and to technology departments at universities. In general the technology programs consisted of 2-year associate degrees and 4-year bachelor’s degrees. Graduates of the 2-year program were designated technicians and graduates of the 4-year program were designated technologists. At the time the technical institutes were prevalent, the biggest difference noted between the technical institute graduates and engineering graduates was that the subjects were treated in a non-mathematical manner; practical concepts preceded the theoretical explanations; and subjects were more hands-on (Study of Technical Institutes, 1931).

In general the technologist title did not catch on. “The reason was that these graduates matriculated from a curriculum similar to that used by engineering programs prior to Sputnik.
They did engineering design and testing and were readily accepted by industry as engineers (Taylor et al., 1997). But this view of similarity faded as graduates of the pre-Sputnik engineering programs retired.

As the acceptance of technical graduates in engineering positions faded, the gulf between engineering and engineering technology grew. The contemporary view of a technical graduate was that of technician as opposed to engineer or even technologist. There was an assessment that the distinction between engineers and technicians was the engineer's ability to formulate and carry out the detailed calculations that were required to test a proposed design on paper (Petroski, 1996, p89). Engineers suggested that engineering technology graduates did not want to know why things work like they do, that they were hands-on and applied standard practice and routine methods rather than having skill in modeling systems (Taylor et al., 1997). There was arrogance that the more rigorous mathematics and science demands placed on engineers made them superior to those majors lacking similar demands. By default engineering technology with its greater emphasis on application and lesser emphasis on calculus, came to be viewed by many as inferior.

These findings supported the depiction of the evolution of the skill content of a graduating engineer presented in Figure 1 through Figure 4. Nicolai observed, “In the 1940s and 50s American engineering programs were very applications oriented and design received a great deal of attention in the curriculum. … Almost overnight (following Grinter and Sputnik) the engineering programs went from an application and design emphasis to research and analysis. …In the 60’s design disappeared from most engineering curriculum as the faculties became predominately analytical oriented and preoccupied with research. …They (the researched trained faculty) were more attuned to the needs of university research programs rather than to developing engineering that met the needs of American business” (1993).

The inescapable fact was that the applications facet was as important to a successful design as the mathematical modeling. “The design shortfall required changes…in how we viewed the relationship between engineering and engineering science technology” (McMasters, 1991).

*Breadth vs. Depth in Education*

One of the concerns observed in the literature and which appeared again in the industrial interviews was the concept of the breadth versus the depth of education content. The
fundamental question was whether a student should be educated very broadly across their discipline or should be provided with enough specialization to have a depth of knowledge.

From a curricula standpoint, the concepts appeared mutually exclusive; either the curricula contained courses primarily in an area of specialty or the curricula exposed the student to a variety of concepts across a discipline. Some schools attempted to provide both through such programs as a multi-disciplinary freshman year which exposed the students to a variety of engineering disciplines. The debate on liberal and humanistic course content also related to the breadth of exposure an engineering student received.

In 1956, Davis asserted that education needed to quit specializing so far. There was a need for more cross-disciplinary, broad learning in core concepts. “The century ahead in science and in engineering belongs not the specialist, but rather to the synthesist who can fit together many disparate truths and create a new truth” (p791). During the industrial interviews, discussion occurred in at least 30% of the interviews with respect to students having enough depth to do their jobs, but enough breadth to know how to do multiple activities and to recognize missing information or needed input.

In opposition to this view, Nicolai’s paper suggested in his 1990 Arizona State University evaluation that being able to define problems, evaluate solutions and affect design was significantly more important than having a breadth and depth of knowledge. This may, however, belie the fact that an individual needed to have a breadth and depth of knowledge to be able to successfully perform definition and evaluation.

Similarly there was a confusion of cross-disciplinary, interdisciplinary and multi-disciplinary concepts within the educational environment. Multi-disciplinary concepts were presented as being different types of activities a single engineer may have to employ to achieve a solution to a problem. Courses touted as cross-disciplinary contained multiple engineering disciplines, but ignored disciplines not directly engineering. Engineering students were weakly introduced to other disciplines or not at all.

This lack of exposure to disciplines outside of a student’s own specialty, or even a lack of exposure to different aspects of their own discipline results in a lack of breadth with the potential for a negative impact on success. Design problems are rarely, if ever, solely within a specialty or a single discipline. “Engineers will find themselves presiding over technological projects from concept and preliminary design through research, development and deployment.
In order to preside over projects, systems builders need to cross the disciplinary and functionary boundaries…” (Hughes, 1998). To be successful, engineers need to employ whatever resources necessary to solve the problem. “In an advanced electrical engineering course, he (sic Ramo) also learned that problems from the field of practice could not be solved if one observed the disciplinary boundaries, the kind of thing that is, even today, usually not taught in universities” (Hughes, p111).

Processes, Methodologies and Management as a Solution

The literature discussing concerns over design repeatedly referred to the use structured design tools and methodologies. More than half of the papers read discussed the use of the tools as the means to successful design as opposed to a resource to facilitate design.

In the articles that presented the process as the means to success, the processes were presented as the magic bullet. As an example, O’Hara, Evans, and Hayden propose “this environment (fast-paced, competitive) places the onus for success squarely on the procedures and practices used to turn innovative concepts into manufacturing processes and products” (p 286). This implied with a good process a good outcome must happen. This further suggested that the process was the key success factor as opposed to a tool to be used to facilitate success. O’Hara, et al., continued, “the model promotes a disciplined yet flexible, team oriented concurrent approach to new product/process development” (p 286). Throughout the article, very little emphasis was placed on the people and teams because, the authors said, “it’s beyond the scope of the article.” However it was the correct team that made a tool work, it was not the tool that obtained the right team.

“Implementation of the model automatically results in the ‘rugby team’ approach with all pertinent skills joining together as a team throughout the length of the project” (p290). This statement seemed to suggest that the perfect teams were obtained through the model and the process made the participants great. The article suggested that the process assured the correct skills were brought to bear on the design problem.

Related to the processes, management was also looked to as the solution to design problems. “Successful programs of change typically feature strong top management leadership in setting corporate goals for improved design…” (National Research Council, 2000). While it was true that top management must believe in the goals and philosophies, and communicate
them unequivocally, it was not a matter of telling the employee what to do and they would do it. Management did not create success, it facilitated it.

This distinction of processes as tools facilitating success as opposed to the cause of success was not meant to suggest a lack of value or importance to these tools. The use of the tools did facilitate getting the correct resources, getting the right people, overcoming conventional wisdom, and identifying goals. The processes helped identify what knowledge, skills, and abilities were needed. It did not replace them.

Because the processes were tools, it was important that they be allowed to evolve to the needs of the design problem. “As successful as engineering design processes have been in the past, it is unlikely that unchanged, the same procedures the same processes will be able to meet the breakthrough system characteristics required for NASA’s future missions at affordable costs” (Malone et al., 1991). There was no process, methodology, or management philosophy which can be pointed to as the key for design success.

Related to the belief in processes and structured design methodologies being the solution to the design problems being reported by industry representatives, were the tools’ use in capstone design courses. The introduction of “design methodologies” into an engineering curriculum may be a limited or incomplete strategy for dealing with industry criticisms. Often the traditional courses in engineering design were collections of how to design a specific artifact type. The design education project experiences may have lacked critical and comparative feedback based on generally accepted engineering principles (Dixon, 1988).

**Accreditation**

While discussions regarding the goals and content of the ABET criteria EC2000 was beyond the scope of this research, the criteria were used as a keystone and starting point for this research. A great deal has been written about how the new criteria have eliminated the ‘laundry lists’ of courses and credit hour requirements, instead using a list of abilities to be demonstrated by graduating engineers. The criteria left the curriculum goal setting and curriculum assessment to the academic institution (Bernold, 2000). This shift in philosophy did not come without challenge. Because the goal setting and assessment was left “to lecture oriented faculty and its constituents, it gave very little leverage to ABET evaluators” (Bernold).
As was discussed in this document in the section on metrics, the lack of well-defined goals and clear metrics with which to assess the students, put the ‘say it, do it, prove it’ philosophy of the criterion at a disadvantage. It was much easier to check curriculum courses off a list than to assess a school’s success in demonstrating meeting the desired abilities of the criteria. The challenge of assessment was a topic of interest to engineering educators as indicated by the number of papers published. In the 2003 Proceedings of the ASEE Frontiers in Education conference 327 of the 1302 papers (25%) contained ‘assessment’ as a topic. In more than 75% of those papers the emphasis was on how to set up and perform assessments and on the importance of having a means of assessment, as opposed to what the assessments should be measuring.

Because the desired outcomes were listed in EC2000, the desired outcomes for educational institutions were fixed. This was not the same thing as having the course content or individual course goals fixed. The destination was fixed, but how to reach the destination was open to the individual instructors and schools. However, because the desired abilities were the same, it seemed reasonable that a set of skills for assisting in the assessment of ability could have been identified. This would have provided a guide to the faculty in determining how they wanted to teach their respective students. It would be easier to develop curricula when given specific knowledge and skills which facilitate students demonstrating abilities.

Peters (2003) discussed the interpretation of EC2000 from the students’ perspective. Peters noted that the purpose and importance of the criteria were not well understood by the students. The students felt that the education of the “hard ed” was most important, the “soft skills” were of medium importance and global considerations and lifetime learning was least important. Not only were global considerations and lifetime learning viewed as least important, the students felt that teaching them was not a school role. Knowing the perspective of students on the criteria was important to avoid creating curricula as though the students did not exist and mitigating misconceptions.

After researching the impacts and challenges of implementing the new criteria, it was noted that there appeared to be a disconnect in the meaning of the terms. For example, “understanding engineering science fundamentals and application of the fundamentals to solve problems” was presented in the ABET EC2000 criteria. It was not clear whether “understand” was meant to refer to the internalization of the concepts or whether “understand” was meant
to refer to a student’s ability to recognize variables in an equation describing the fundamental concept and then was able to solve the formula.

It is suggested by this researcher that ABET means an internalization of the concept, which becomes an assessment of the ability to “see” the fundamentals. Observations by this researcher of engineering courses suggest that current classroom assessments for the purpose of grading evaluate the ability of students to recognize and solve equations. When this is the execution of the goal at the course level, demonstration of a given concept at the program level is hampered.

Results of Literature Survey

Collection and Preparation of Data

To identify what skills were being offered by academic participants, a survey of the literature was performed. Literature for this survey began with the literature search performed during the problem definition stage of this research and described in the literature review section of this document. Additional literature was obtained from the proceedings of the ASEE Frontiers in Education conferences for the last ten years and from interviews with individuals involved in both engineering education reforms and ABET accreditation activities. National surveys on the topic were also reviewed. A bibliography of the resources used to develop the data is provided in Appendix F. It was expected that the articles might not specifically list skills by name, but instead describe the skills textually, from which the skill could be extracted.

The sources were varied in purpose and in authorship. Some of the papers expressed desired traits in or of a person, some discussed concepts and traits which made a process or product successful. For this study, these were considered part of the same goal: an individual with the necessary skills to produce a successful design whether the concepts were considered inputs (the person) or outcomes (demonstrated in a product). The sources were categorized as being from academia, academic-industrial and industrial. Academic sources were authored by an individual or organization whose primary role was to provide classical education. Academic-industrial sources were from individuals who are employed by the industrial sector but whose
role was directed at academic concerns. Industrial sources were written by individuals or organizations whose primary role was to produce profitable products.

One article specifically referenced a survey given to industry representatives to identify the knowledge and skills that were deemed critical in graduating engineers (Lang, et al, 1999). The formal survey instrument was prepared by the Science Team of the Industry-University-Government Roundtable for Enhancing Engineering Education (IUGREEE) and a summary of the results was provided in the article. The survey listed 172 skills, knowledge, descriptions and experiences and had a participation rank of 1 to 5 for new hires and those who had been out 3-5 years. The survey produced 420 voluntary responses from engineers and engineering managers representing 15 of 24 aerospace and defense related companies. Readers were encouraged to request the actual database for use in curriculum development. The researcher attempted to obtain the database and the original survey questions from the provided website without success. Attempts to obtain the database from the original authors were also unsuccessful. McMasters indicated both the database and the original research had been lost.

While reviewing the literature for the target technical skills, notations were made regarding the existence of soft skills. This was done to confirm that the concepts defined as soft skills for this research and expected to be in the literature, did appear and were expressed as important. No attempt was made to collect, categorize or count these observations. The presence of these concepts did support the expectation they would be present and confirmed that the technical skills could be identified separate from the soft skills. The overlap of soft skills with the target technical skills was determined to not be a barrier to obtaining data.

To prepare the data for analysis, statements of a needed attribute, as well as statements of lack, were entered on 3x5 cards. The concepts were selected based on the following schema. If the source made a statement indicating importance, i.e. “it is important that engineers are able to ___”, or of frustration “too few engineers are familiar with ____”, the concept was recorded as written on the card. Other authors provided lists, “the following traits are deemed necessary....” which were each entered on a separate card. In some cases it was necessary to infer importance based on the context of a discussion, “had I known that I would some day be required to ‘X’, I would have worked harder to learn how to ‘Y’”. In other cases the author would express a concept as prose that may have consisted of two or three sentences or even a
paragraph. All of the text was transcribed on the card to minimize loss of meaning and context during the data analysis. The goal was for each card to contain a single concept.

Each card was also coded for the source; academic, industrial academic or industry. This was done to allow separation of the literature-based data by source. During the analysis this separation was deemed to be non-value added for two reasons. The first was the overwhelming number of cards was attributable to academic and industrial academic sources which made comparisons non-meaningful. The second reason was that in the few sources that were industry, the responses were not appreciably different from the academic and industrial academic sources, primarily due to their general nature.

The resulting data cards were then subjected to a manual sort to place cards listing or describing the same concept together. During this initial sort, no concepts or categories were prepared *a priori*. The cards were read and sorted. The resulting groups of cards were reviewed and sorted a second time. In some cases the groups were broken into smaller concept groups, in other cases the piles were re-categorized into different, already existing groups. In some cases the sort was very straight-forward, as a number of cards contained the same words; “solve open-ended problems”, or the text very explicitly described the concept, “in the course of the design process the engineer is faced with challenges that do not have a single, right answer, but which must be solved.” In other cases the description did not overtly state a specific concept and it had to be determined by the researcher based on experience and on similarity of context.

Once these two sorts were completed, the segregated data were reviewed and the concepts identified by a single terms. During this activity, it was discovered that a number of the concepts fit into the general areas described in the literature, and were subsequently grouped under these broad areas. The review was intentionally suspended for a period of three weeks.

After three weeks, the researcher reviewed the cards with a fresh perspective to determine if any of the cards would fit better in other or new categories. With the exception of three cards, the sort remained unchanged. At this point the coding process and triangulation were considered complete.

There were 635 individual data points generated which were sorted into 49 specific characteristics and 9 broad categories.
Bias and Error

The preparation of the data from literature was subject to the researcher’s bias regarding what was presented as important. While in some cases the literature author was very overt in saying a particular concept was important, in other cases the researcher had to infer importance based on the text. This inference could have been impacted by the researcher’s personal bias of what was important. This bias was mitigated by being aware of this bias and making sure that items listed as important, or presented as important by virtue of being written about were included in the data, even if they were not items personally deemed important.

The greatest potential source of error in obtaining the data was in the selection of literature for review. Choices had to be made regarding key words, literature sources, and time frames. The methodology utilized to pick the literature may have permitted the introduction of error in the data by being an insufficient or incorrect selection methodology. The repeated references to various papers or authors suggest that the literature survey did reach saturation.

Analysis of the Data

The first observation made from the analyzed data was that the majority of the concepts described abilities as opposed to skills. At this point it was determined that the schema of knowledge, skills and abilities (KSA) would be useful.

As the concept is being used in this research, knowledge is facts that can be learned, often separate from the activity. The person may not have seen nor done the topic presented. Skills are those actions that are a part of the activity that allow the task to be done successfully. The more skill possessed the more likely the person is to be able to do the task. Ability is an inherent concept that is possessed at the onset of developing the skills. The skills provide the tools for the demonstration of the ability, but they do not create the ability. The greater the ability, the more successfully the knowledge and skills can be applied.

As applied to this research, the data described abilities as opposed to the skills. It was concluded that this high-level data was part of the reason that there was a lack of defined goals and metrics and why there was not a clear answer to the question what needs to be taught.

The second observation was that some of the broad categories contained more sub-concepts than others. The ability to design contained 12 sub-categories of which three contained sub-concepts of their own resulting in a total of 19 sub-categories. The ability to
deal with the –ilities, on the other hand, was comprised of only the single concept, dealing with the –ilities (i.e. maintainability). Because of this, care had to be taken when considering the most important skills or abilities based on frequency.

Based on the frequency distribution of the broad categories, the most important ability expressed in the literature was the ability to design, 168 responses, followed by the ability to take something from theory to a product (build something), 119 responses. The third category was possession of a variety of intrinsic skills with 91 responses. The ability to deal with the –ilities was sixth with only 58 responses.

The results of all nine broad categories are provided in Table 3 and graphed in Figure 5.

Table 3 - Major Categories from Literature Survey

<table>
<thead>
<tr>
<th>Major Category of Skills</th>
<th>No. Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design skills</td>
<td>168</td>
</tr>
<tr>
<td>Take from theory to product (build something)</td>
<td>119</td>
</tr>
<tr>
<td>Intrinsic skills</td>
<td>91</td>
</tr>
<tr>
<td>Technical skills</td>
<td>78</td>
</tr>
<tr>
<td>Societal/environmental/business</td>
<td>58</td>
</tr>
<tr>
<td>Address &quot;-ilities&quot;</td>
<td>51</td>
</tr>
<tr>
<td>Technical Interactions (people)</td>
<td>41</td>
</tr>
<tr>
<td>Risk and Safety</td>
<td>22</td>
</tr>
<tr>
<td>Profession familiarity</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 5 - Graph of Major Categories from Literature Survey
What is noteworthy was that while the –ilities could be further divided into specific topics, i.e. maintainability, supportability, etc., the concepts were all topic specific applications of the same basic ability. Under design, however, the sub-categories were related but were quite diverse; the customer, the tools, the activities, the process. Each of the sub-categories was not a different specific topic of the same concept, but rather entirely different concepts only related by their support of the ability to design.

As a result, if only the frequency distributions of the broad categories were considered, important data was obscured. In order to minimize this obfuscation, the results from all of the individual concepts were evaluated. The individual concepts and their relationships to the broad categories are presented in Table 4 and Figure 6.
Table 4 - All skills/abilities by category identified from the literature survey

<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td>169</td>
</tr>
<tr>
<td>Design</td>
<td>5</td>
</tr>
<tr>
<td>Customer</td>
<td></td>
</tr>
<tr>
<td>- Needs</td>
<td>6</td>
</tr>
<tr>
<td>- How they use it</td>
<td>6</td>
</tr>
<tr>
<td>- What are the requirements</td>
<td>11</td>
</tr>
<tr>
<td>Problem Solving</td>
<td></td>
</tr>
<tr>
<td>- Problem solving</td>
<td>14</td>
</tr>
<tr>
<td>- Recognize / identify problems</td>
<td>9</td>
</tr>
<tr>
<td>- Formulate problems</td>
<td>8</td>
</tr>
<tr>
<td>Research Activities</td>
<td>8</td>
</tr>
<tr>
<td>Setup tests and experiments</td>
<td></td>
</tr>
<tr>
<td>- Setup</td>
<td>1</td>
</tr>
<tr>
<td>- Conduct experiment</td>
<td>12</td>
</tr>
<tr>
<td>- Conduct testing</td>
<td>6</td>
</tr>
<tr>
<td>- Determine specific experiment/test requirements</td>
<td>6</td>
</tr>
<tr>
<td>Analysis</td>
<td>15</td>
</tr>
<tr>
<td>Interpretation</td>
<td>9</td>
</tr>
<tr>
<td>Synthesis</td>
<td>8</td>
</tr>
<tr>
<td>Critical thinking</td>
<td>5</td>
</tr>
<tr>
<td>Data maintenance / presentations (not comm)</td>
<td>10</td>
</tr>
<tr>
<td>Know tools capabilities / limitations</td>
<td>23</td>
</tr>
<tr>
<td>Know assumptions</td>
<td>7</td>
</tr>
<tr>
<td><strong>Take from theory to product (build something)</strong></td>
<td>119</td>
</tr>
<tr>
<td>Recognition of system</td>
<td>45</td>
</tr>
<tr>
<td>Apply knowledge (breadth &amp; depth)</td>
<td>33</td>
</tr>
<tr>
<td>Integration</td>
<td>13</td>
</tr>
<tr>
<td>Hardware consideration</td>
<td>9</td>
</tr>
<tr>
<td>Transference</td>
<td>6</td>
</tr>
<tr>
<td>Life cycle analysis</td>
<td>6</td>
</tr>
<tr>
<td>Quality process</td>
<td>3</td>
</tr>
<tr>
<td>Build something</td>
<td>2</td>
</tr>
<tr>
<td>Optimization</td>
<td>2</td>
</tr>
<tr>
<td><strong>Intrinsic abilities</strong></td>
<td>91</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>20</td>
</tr>
<tr>
<td>Deal with failures/ mistakes</td>
<td>14</td>
</tr>
<tr>
<td>Results oriented</td>
<td>11</td>
</tr>
<tr>
<td>Ethics</td>
<td>6</td>
</tr>
<tr>
<td>Decisive</td>
<td>6</td>
</tr>
<tr>
<td>------------------</td>
<td>----</td>
</tr>
<tr>
<td>Creative</td>
<td>6</td>
</tr>
<tr>
<td>Fleicle</td>
<td>5</td>
</tr>
<tr>
<td>Management</td>
<td>4</td>
</tr>
<tr>
<td>Professionalism</td>
<td>4</td>
</tr>
<tr>
<td>Curiosity</td>
<td>3</td>
</tr>
<tr>
<td>Leadership</td>
<td>3</td>
</tr>
<tr>
<td>Visualization</td>
<td>3</td>
</tr>
<tr>
<td>Common sense / practical</td>
<td>3</td>
</tr>
<tr>
<td>Pragmatic</td>
<td>2</td>
</tr>
<tr>
<td>Innovative</td>
<td>1</td>
</tr>
</tbody>
</table>

**Technical Abilities** 55

| Do trades / multiple solutions | 19 |
| Technical engineering skills  |    |
| Math and Physics fundamentals | 20 |
| Engineering skills            | 14 |
| IT/computer                   | 9  |
| Miscellaneous                 | 8  |
| Sketch                        | 4  |
| Deal with complex objectives  | 4  |

**Societal/environmental/business** 58

| Societal/environmental        | 21 |
| Economic/Business             |    |
| Costing                       | 13 |
| Business skills               | 9  |
| Economics                     | 7  |
| Schedule                      | 4  |
| Market sense                  | 3  |
| Entrepreneurial               | 1  |

**Address "-ilities"** 51

**Technical Interactions (people)** 41

| Gathering information         | 12 |
| Multidisciplinary             | 11 |
| Collaboration                 | 10 |
| Interdisciplinary             | 8  |

**Risk and Safety** 22

| Risk assessment / judgment   | 14 |
| Safety                       | 4  |
| Critical review / design scrutiny | 4  |

**Profession familiarity (Know your profession)** 7
All Identified Technical Characteristics from Literature Survey

- **Knowledge**: Knowledge of the technical aspects of the field.
- **Skill**: Technical skills necessary for the job.
- **Ability**: Technical ability required for the role.
- **Trait**: Technical traits that contribute to success.

**Fig. 6** - Graph of all Technical Characteristics

- **Recognition of systems / impacts**
- **Apply knowledge**
- **Know your tools capabilities/ limitations**
- **Societal/environmental**
- **Math and Physics fundamentals**
- **Miscellaneous intrinsic traits**
- **Do trades / have multiple solutions**
- **Analysis**
- **Problem solving**
- **Risk assessment/judgment**
- **Engineering skills (formulaic)**
- **Deal with failures / mistakes**
- **Costing**
- **Integration**
- **Conduct experiments**
- **Gather information**
- **What are the requirements**
- **Multidisciplinary**
- **Results oriented**
- **Data maintenance/presentation (not communication)**
- **Collaboration**
- **Recognize/identify problems**
- **Interpret results**
- **Business skills**
- **Hardware considerations**
- **Formulate problems**
- **Economics**
- **Know your profession / Industry awareness**
- **Know your assumptions**
- **Customer needs**
- **How the customer uses it**
- **Conduct tests**
- **Determine what are the specific test & experiment issues**
- **Transference**
- **Life cycle analysis**
- **Ethics**
- **Decisive**
- **Creative**
- **Critical thinking**
- **Flexible**
- **Schedules**
- **Safety**
- **Critical evaluation / design scrutiny**
- **Deal with complex objectives**
- **Sketch**
- **IT/Computer**
- **Management skills**
- **Professionalism**
- **Market sense**
- **Quality process**
- **Curiosity**
- **Leadership**
- **Visualization**
- **Common sense / practical**
- **Take from theory to product**
- **Optimization**
- **Pragmatic**
- **Set up tests**
- **Entrepreneurial**
- **Innovative**

Figure 6 - Graph of all Technical Characteristics
In this case the frequency distribution was dominated by the ability to deal with the –ilities, the ability to recognize systems and impacts, and the ability to apply knowledge. Furthermore, none of these characteristics were a part of the general ability of design. The –ilities were their own category, as has been discussed. Both systems and knowledge were a part of the general category, the ability to take from theory to product. The first occurrence of a characteristic that was related to the ability to design was analysis which was ninth in the frequency distribution. This implies that while the general topic of design had the greatest number of separate skills which supported it, the ability to design did not contain the most important skills as indicated by frequency.

An evaluation was also performed of each of the broad categories. This was done because it was deemed potentially useful for those educators attempting to deal with the more general categories in an educational reform. For example, the ability to design received a high relative frequency of attention in academic discussion. For educators attempting to develop assessment metrics for design activities, the concepts which were identified as being the most important to design based on frequency were knowing the assumptions and limitations inherent to the tools being used, the ability to perform an analysis, and the ability to solve problems. The graph of the entire design distribution is provided in Figure 7.

Based on this information, identifying the skills which demonstrate the ability of “knowing the assumptions and limitations of a tool” could be developed, an activity which is less difficult than trying to assess “the ability to design”. Similar exercises could be done to identify assessment skills for the ability to perform an analysis and the ability to solve problems. Using the results from the literature, these skills could not be identified.

Each of the remaining eight categories is graphed in Figure 8 through Figure 13. Based on the frequency distributions, a summary of the results follows:

<table>
<thead>
<tr>
<th>Category</th>
<th>Top characteristics</th>
<th>K, S, or A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>▪ Know assumptions/limitations of tools</td>
<td>K</td>
</tr>
<tr>
<td></td>
<td>▪ Ability to perform an analysis</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>▪ Ability to solve problems</td>
<td>A</td>
</tr>
<tr>
<td>Build something</td>
<td>▪ Recognition of systems/impacts</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>▪ Apply knowledge (breadth &amp; depth)</td>
<td>A</td>
</tr>
<tr>
<td>Intrinsic traits</td>
<td>▪ (Miscellaneous single responses)</td>
<td>T</td>
</tr>
<tr>
<td></td>
<td>▪ Deal with failure and mistakes</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>▪ Results – oriented</td>
<td>S</td>
</tr>
<tr>
<td>Category</td>
<td>Requirements</td>
<td>Level</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>Technical</td>
<td>Technical engineering knowledge</td>
<td>K</td>
</tr>
<tr>
<td></td>
<td>Do trades / multiple solutions</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Math and physics fundamentals</td>
<td>K</td>
</tr>
<tr>
<td>Societal/ environmental/ business</td>
<td>Ability to address societal and environmental concerns</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Ability to perform costing</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Basic business skills</td>
<td>S</td>
</tr>
<tr>
<td>Technical Interactions (people)</td>
<td>Ability to gather needed information</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Ability to interact multi-disciplinarily</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Ability to interact inter-disciplinarily</td>
<td>A</td>
</tr>
<tr>
<td>Risk and Safety</td>
<td>Ability to perform risk assessment /show judgment</td>
<td>A</td>
</tr>
<tr>
<td>Profession familiarity</td>
<td>Know about your profession</td>
<td>K</td>
</tr>
</tbody>
</table>
Figure 7 - Graph of responses in the literature survey general category "Design"
Figure 8 - Graph of general category from the literature survey "From Theory to Product"
Figure 9 - Graph of general category from the literature survey "Intrinsic Abilities"
Figure 10 - Graph of general category from the literature survey "Technical Abilities"
Figure 11 - Graph of general category from the literature survey

- Societal/environmental/business

- Number of responses: 20

- Abilities:
  - Societal/environmental: 20
  - Coding: 13
  - Business skills: 9
  - Economics: 7
  - Schedule: 4
  - Market sense: 3
  - Entrepreneurial: 1
Figure 12 - Graph of general category from the literature survey "Technical Interactions"

Figure 13 - Graph of general category from the literature survey "Risk and Safety"
Summary of Literature Survey

Based on the literature survey, the majority of the identified characteristics were abilities as opposed to skills. Based on frequency the most important ability was dealing with “-ilities”, followed by recognition of systems and the ability to apply knowledge. The first concept specifically identified as a skill was identifying requirements, eighteenth in the distribution.

The different concepts describing the characteristics could be collected into a series of broad abilities. The most frequently cited requisite ability was “design” followed by the ability to take something from theory to design. The third most cited category was a collection of intrinsic traits.

The data was coded to permit evaluation of differences in responses based on the role of the author, (academic, industry academic, industry) but no differences were observed, so in depth analyses were performed.

Results of Practitioner Interviews

Collection and preparation of the data

The sample selection and execution of the interviews were performed per the Procedures and Methodologies section of this document. A total of thirty-two requests to participate in the interview were sent out via email. Three were returned undeliverable and sixteen received no response. Six requests were declined. Thirteen requests were accepted but two were eliminated when repeated attempts to schedule the interviews failed. The final sample size was eleven, composed of ten males and one female.

There was one change made to the interview guide following the first interview. Originally the guide included a question regarding getting input at various levels of the respondent’s organization and outside of the organization, as well as probes regarding the layout and access available to different groups, see question 3 in Appendix E. After the first interview, it was determined the question was too unwieldy and difficult to answer. Although subsequent respondents were asked about the ease and ability to obtain input, the multi-level probes and question on facility layout were dropped from the interview guide.

Based on observations made during the classroom research, an additional question regarding sketching as a success skill was included. This question was asked of all eleven
interviewees. The participant was asked if, in their opinion, sketching was a success skill. One person answered no, and a second a qualified yes. Because it was demonstrated that respondents could and would say no to the question, it was concluded that the wording of the question did not result in overt leading.

Extensive notes were taken throughout the interview using personal shorthand and including as many direct quotes as possible. The notes were transcribed immediately following the interview to maintain as complete a transcript as possible. The transcriptions were prepared as Microsoft® text files and imported into Atlas TI © hermeneutic software. The demographic information supplied by the participants was incorporated into each transcript.

Using the coding function in Atlas TI®, each file was coded for demographic information: age, profession, gender, max degree, what degree(s), time in career, etc. This permitted confirming adequate representation in the sample set. The sample set was found to include at least one representative in each age bracket and representatives from B.S., M.S., and PhD. It included engineering and non-engineering majors, individuals who had attended school straight through their advanced degrees and those who had returned later. Job responsibilities included concept and preliminary design engineering functions, design and product support functions, researchers, and a “wise old elder”. Represented industries included electronics manufacturers, aerospace propulsion manufacturers, aerospace component manufacturers, airframe manufacturers, and space vehicle manufacturers. Both military and civilian products were represented. Respondents were responsible for writing code, for design components for manufacture, for supporting products and for providing research data.

Of the respondents, one did not meet the time-in-career selection criteria. The data was retained because the individual had come highly recommended by authorities in the field and because the responses were well articulated and appeared to be thoughtful and mature. In addition the respondent had participated in co-op employment during school which was not indicated by his career service time but which did increase his work experience.

A table of the participants versus demographic code is presented in Table 5.
After coding the transcripts using the prepared demographic codes, the transcripts were read and open-coded based on the text. Some codes were direct, for example the definitions and descriptions of design and of engineering. In other cases, particular success indicators were identified in a similar manner to that used during the literature survey and fully discussed in the literature survey section. Whenever a statement was made suggesting the presence or lack of a
success trait, it was coded such. In order to maintain the statement context, entire sentences as necessary were captured in the coding process. A list of all open codes is provided in Table 6.

Table 6 - All open codes used on the transcriptions

<table>
<thead>
<tr>
<th>CODES</th>
<th>PRIMARY DOCS</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<td>Conceptualizing</td>
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<td></td>
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<td>Design has changed</td>
<td>1 2 1 1 0 0 2 0 0 8 8</td>
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<td></td>
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<td>Educational success</td>
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<tr>
<td>Feedback mechanism</td>
<td>2 9 3 0 1 3 3 3 2 3 32</td>
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<td>Fidelity</td>
<td>1 0 0 0 0 0 0 0 1 0 0 2</td>
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<td></td>
<td></td>
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<tr>
<td>How design has chang</td>
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<tr>
<td>Input issues and mec</td>
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<td>Negative success trait</td>
<td>0 4 0 2 1 2 0 1 0 1 0 11</td>
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<tr>
<td>Simulation</td>
<td>1 1 0 0 0 0 0 0 0 0 2</td>
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<td>Sketching</td>
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<td></td>
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<tr>
<td>What is design</td>
<td>3 1 2 4 1 1 2 3 4 2 3 26</td>
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<td></td>
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<tr>
<td>What is engineering</td>
<td>2 4 1 0 2 1 2 2 5 1 3 23</td>
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<td></td>
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<td>Why - camaraderie</td>
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<tr>
<td>Why - enjoyment</td>
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<tr>
<td>Why - excitement of</td>
<td>0 1 0 0 1 0 0 1 1 0 0 4</td>
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<td>Why - Family and fri</td>
<td>1 0 0 0 0 0 0 0 0 0 0 1</td>
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<tr>
<td>Why - making a diffe</td>
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<tr>
<td>Why - new, not done</td>
<td>0 0 0 0 0 0 0 0 0 1 0 1</td>
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<tr>
<td>Why - Pride</td>
<td>1 1 0 2 0 0 1 1 1 1 1 9</td>
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<td></td>
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<tr>
<td>Why - Rarity</td>
<td>2 0 0 1 0 0 0 1 0 1 0 5</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Why - satisfaction</td>
<td>0 0 1 0 0 1 1 2 0 0 1 6</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Why - sense of owner</td>
<td>0 1 0 0 1 0 0 1 0 1 0 4</td>
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</tr>
</tbody>
</table>

After all of the data was coded, printouts of the coded data were prepared. To generate the data for frequency analysis, reports were prepared using the codes “success traits”, “negative success traits” and “sketching”. From these reports the data was entered onto 3x5 cards similar to the process used in the literature survey. Once the data was prepared, the resulting dataset contained 171 individual data points. This supports the premise that a sample size of ten was sufficient to obtain valid and reliable data on success skills. It is suggested that a larger sample size would have provided similar results, with larger frequency values.

As was done with the results of the literature survey, the individual data points were sorted to develop and identify success skills, abilities and traits. Unlike the data from the literature
survey, the individual data did not cluster around clear, single characteristics. Instead the sort
was resulting in many piles of one to three cards.

In order to create meaningful frequency distributions, it was recognized that a different
sorting procedure was required. Assistance was requested from the research faculty advisor
who had both experience in sorting data of this type and in the area of knowledge, skills, and
abilities (KSA). With his assistance, a different classification structure emerged.

Unlike the literature survey data, the interview data was more clearly related to specific
skills. This was not surprising as the interview guide was prepared expressly to focus responses
on specific technical skills as opposed to general abilities or soft skills. Because the respondents
were not permitted general, vague answers but required to explore their answers to obtain
specific responses, the results themselves were also more specific. This meant there were no
repeated general responses like those found in the literature survey.

To handle the data, the individual cards were grouped more generally resulting in
identifying the general abilities the skills supported. The structure for the data had a major
concept placed in the center of a row and designated column one. Any related supporting
concepts were grouped to the left and right of the central theme, the items on the left being
related to traits and items on the right related to behaviors. Not all rows had columns on one
or both sides. Each row was later identified as a major construct.

Once the initial sort was complete, evaluation was suspended for four weeks. Then the
cards were analyzed again and the sort reviewed. Approximately ten cards were reassigned and
one new side column created. It was concluded the sort was complete.

Descriptions for each group of data were then prepared as well as identifying the top level
construct for each row. Seven major constructs were identified: a) know your discipline
(depth), b) broad background (breadth), c) cross-functional abilities, d) visualization, c)
knowing roles and responsibilities, and f) design. An additional category emerged from the left
side of e and f and was identified as TQM© (Total Quality Management) skills. TQM is a
philosophy which includes tools and processes which facilitate quality improvements.
Examples of TQM skills include leadership (as opposed to management), planning, creativity,
innovation and dependability. These skills supported both e (knowing roles) and f (design) and
rather than trying to force them to one row or the other, they were grouped into a single
category. The classification of traits was added when it was realized a number of the data
points did not fit the KSA rubric as it was being used for this research. Those items designated as intrinsic characteristics in the literature survey analysis were considered traits in most cases.

Once the data sort was complete, the data points in each group were then classified as being knowledge, skill, ability or trait. These data were coded to facilitate later analysis.

**Bias and error**

The validity and reliability of the interview tool was discussed in the Procedures and Methodology section. The tool included an internal validity check. By including a question regarding success traits in other individuals and then later asking what they themselves did to be successful, an internal check could be made of the respondents. No divergence was observed in the responses in any of the interviews. The tool was also deemed reliable in that it provided the desired results; identification of specific skills as opposed to general abilities.

The data extracted for identification of success skills was subject to the same potential biases and errors as the literature survey as the same methodology for accepting statements as data was used.

There was a potential bias and error intrinsic to purposive sampling but which was mitigated by achieving a diverse and representative sample. Further validity of the sample set could be determined by comparing the ages, professional responsibilities to the target job field. This was not done as it was deemed unnecessary for an exploratory study. However a review of the face-validity of the sample compared to personal experience suggests the sample set is representative of the aerospace industry at a first level approximation.

Because the transcriptions were from direct quotes, notes taken in personal shorthand and complete quotes, errors due to incorrect transcriptions and bias from selective notes were minimized. Effort was made to capture all statements verbatim as opposed to summaries.

Any errors or biases in the data sorting were also mitigated by having a second researcher participate in the sorting procedure.

**Analysis of interview data**

Based on the sorting scheme used for the interviews data, the data was separated into seven major categories; a) know your discipline (depth), b) broad educational background (breadth), c) ability to work cross disciplinarily (work with others), d) visualization (sketching),
e) understanding roles and responsibilities, f) design, and a general “TQM” skills category. The category with the greatest frequency of responses was the ability to work cross disciplinarily (69) followed distantly by “TQM” skills (21) and design (18) (Figure 14).

As was already described, the data were organized around the central themes with supporting concepts placed on either side of the central theme. Within each major and support category, the data was separated into concepts. The frequency distribution of all these individual concepts is shown in Figure 15. The most frequently occurring concept was sketching (16). This may be a result of specifically asking whether sketching was a success trait. The next most frequently occurring concepts were collaboration and networking (12), getting input (11), a broad educational background (9), and knowing the discipline-depth (7). It was noted that subsequent concepts grouped into six clusters. All the concepts are listed in Table 7.
Figure 14 - Major Categories from Surveys

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>FREQUENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability to work cross-disciplinary</td>
<td>70</td>
</tr>
<tr>
<td>TQM</td>
<td>20</td>
</tr>
<tr>
<td>Design</td>
<td>15</td>
</tr>
<tr>
<td>Visualization</td>
<td>12</td>
</tr>
<tr>
<td>Roles &amp; Responsibilities</td>
<td>10</td>
</tr>
<tr>
<td>Broad educational background</td>
<td>5</td>
</tr>
<tr>
<td>Know your discipline (Depth)</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure 15 - All KSA's from interviews

All skills and Abilities

Skills and Abilities

Frequency
Table 7 - All responses from Interviews

<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
<th>Example</th>
</tr>
</thead>
<tbody>
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<td>A</td>
<td>7</td>
<td>Know your discipline (Depth)</td>
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<tr>
<td></td>
<td></td>
<td>1 Knowledge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 Skills</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Ability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Trait</td>
</tr>
<tr>
<td>B</td>
<td>9</td>
<td>Broad educational background</td>
</tr>
<tr>
<td>B1</td>
<td>8</td>
<td>Breadth</td>
</tr>
<tr>
<td>B2</td>
<td>1</td>
<td>Use tools correctly</td>
</tr>
<tr>
<td>C</td>
<td>69</td>
<td>Ability to work cross-disciplinary</td>
</tr>
<tr>
<td>C1</td>
<td>47</td>
<td>Behaviors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collaboration &amp; Networking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GIGO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ability to integrate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curious &amp; Open-minded</td>
</tr>
<tr>
<td></td>
<td></td>
<td>See beyond your part</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Understand impact on whole –s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Understand impact on whole-a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All knowledge is important-s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Set priorities/KISS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All knowledge is important-a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Recognize needs</td>
</tr>
<tr>
<td>C2</td>
<td>19</td>
<td>Professional Communications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Get input</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Be able to say I don't know/wrong</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Be open /communicate promptly</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Get feedback</td>
</tr>
<tr>
<td>C3</td>
<td>3</td>
<td>Learn</td>
</tr>
<tr>
<td>D</td>
<td>16</td>
<td>Visualization</td>
</tr>
<tr>
<td>D1</td>
<td>16</td>
<td>Sketch</td>
</tr>
<tr>
<td>E</td>
<td>16</td>
<td>Roles &amp; Responsibilities</td>
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<tr>
<td>E1</td>
<td>6</td>
<td>Understanding yours and others</td>
</tr>
<tr>
<td>E5</td>
<td>6</td>
<td>Correct decisiveness</td>
</tr>
<tr>
<td>E6</td>
<td>4</td>
<td>Perfection &amp; tenacity</td>
</tr>
<tr>
<td>F</td>
<td>18</td>
<td>Design</td>
</tr>
<tr>
<td>F1</td>
<td>8</td>
<td>Informed solutions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trades</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Informed/appropriate risk taking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accurate root cause analysis</td>
</tr>
</tbody>
</table>
Recognize the right answer 5  Skill  
Know how the world works 3  Knowledge  
Proactive doing/not reactive 2  Skill

TQM  21
Innovative/willing to stretch 6  Skill
Have a vision/goals 5  Ability
Do your job, right, without fanfare 3  Skill
Trusted 2  Trait
Deal with pressure/critiques 2  Trait
Creative 2  Trait
Able to plan 1  Ability

The major category with greatest number of responses was the ability to work cross disciplinarily. The central theme was determined to be the behaviors which demonstrate the ability. The supporting concepts were professional communication skills and learning skills (Figure 16). Within the three concepts, behavior skills had the greatest number of responses (47). These responses were categorized into specific knowledge, skills, and abilities (Figure 17). The greatest frequency was networking and collaboration (12). The second category, professional communication was also separated into knowledge, skills and abilities (Figure 18). The greatest frequency was obtaining input (11).

Figure 16 - Major components of cross-disciplinary performance from the interviews
Figure 17 - Skills and abilities from interviews demonstrating cross-disciplinary behaviors
Figure 18 - Skills from the interviews demonstrating cross functional professional communications
Figure 19 - TQM Traits and abilities from the interviews

TQM Skills

Frequency

Innovative/willing to stretch
Have a vision/goals
Do your job, right, without fanfare
Trusted
Deal with pressure/critiques
Creative
Able to plan
Of the major categories, the second most frequent was possession of what were described as TQM© skills. The category supported both knowing individual roles and responsibilities and design activities. The category was also separated into knowledge, skills, and abilities (Figure 19). The greatest frequency was the ability to be innovative and willingness to stretch (6) followed by having visions and goals (5).

The remaining category, design, was also separated into knowledge, skills and abilities (Figure 20). The most frequently appearing skill was to make informed solutions (8). This supporting category contained three skills; performing trade studies (4), risk taking (3) and root cause analysis (1) (Figure 21).

![Design skills and abilities](image)

Figure 20 - Traits and abilities from the interviews demonstrating design
The category of making informed solutions further divided into the skills of being able to perform trade studies (4), taking appropriate risks (3), and being able to perform accurate root cause analyses (1) (Figure 21).

The seventh major category was concerned with knowing the personal roles and responsibilities and roles and responsibilities of others on the design activity (Figure 22). From the frequency distribution both knowing roles and responsibilities and having appropriate decisiveness had equal responses (6) followed by having traits of tenacity and perfectionism (4) (Figure 22).
Discussion on Most Frequently Identified Skills Perceived as Requisite

Sketching

Sketching was specifically investigated during the interview; however the presence of both negative and conditional positive responses indicated the respondents were not unduly influenced by the question. One respondent indicated that in his experience there was not much need to be able to sketch as part of designing, “CFD is a visualization of flows and that is something you might sketch, but other than that we don’t really have a reason to sketch.” Another respondent indicated that it was a tool that needed to be used appropriately, “as you move up in position you have to be careful not to overdue it. If someone asks you what time it is you don’t build him a watch. It is easy to spend too much time sketching and talking when answering a question.” Another respondent indicated that “newer engineers are more
comfortable using the tools instead of sketching by hand.” “It is a success factor, not the success factor.”

The remainder of the respondents felt that it was a required skill. “Most definitely.”, “It is a primary success factor and it really comes down to good design being artistic.” The concept of design being artistic was further clarified, “In general the better it looks, the better it acts. If it looks clugy it probably works clugy.” The respondent went on, “Designs that look good also analyze better the load paths line up. This helps do trades.”

Other respondents commented on sketching with respect to its impact on communications. “There are people who are more visual. You need to use tools which help you communicate your ideas to them.” “It gets your idea out where people can see it and discuss it.” “I have this idea and I have to have someone help me get it out.”

This skill was observed to be more than just a communications tool, but actually impacted the bottom line of a company. “When we did the “product Q” it was decided to use “software C”. Now software C is a powerful toy. It allows people to very quickly draw things and dimension things and let a lot of people work on a design at the same time. But it is just a powerful tool. We had 5500 people to be trained on software C. We didn't think that this was going to be a big undertaking. As it turned out none of the people had had any mechanical drawing so they couldn't see things in 3-D and they couldn’t make the leap into software C. I won’t even tell you how much extra money we had to spend and the percentage it added to the bottom line of the project to get these people up to a basic level of 3-D.”

Based on the frequency of response and the intensity of response, it was determined that sketching was perceived by practitioners to be a requisite skill.

**Collaboration and Networking**

Both collaboration and networking, and the next most frequent response, obtaining input were closely related. Both concepts centered on interacting with other experts and individuals. With respect to collaboration and networking, practitioners felt that the skills involved were incorporating all available lessons learned, from multiple individuals. But it was incumbent on the design engineer to make the effort. “If you want to include things from the old project into the new project you have to go get it.” By collaborating, successful engineers go out and learn
from other experts, leveraging a wider circle of expertise. Furthermore, it was considered an important skill to collaborate with individuals at all levels, not just one’s engineering peers.

Obtaining Input

While collaboration and networking generally involved two-way communications and the sharing of ideas between individuals, obtaining input involved more listening. The first step was the recognition that input was needed. “Successful people recognize where they need input and go and get it.” The central skill to the ability was asking questions which required another implied skill, listening. “They boil it down to very simple terms and ask the right questions to get on the right path whatever the issues might be.” “And you are going to get a better design by soliciting input.” “Ask LOTS of questions. Have an insatiable desire to know more and more about the nature of the project. The less successful have an encapsulated view of the project. Tell me what you want and I’ll do it.” But before going out and asking questions, one respondent pointed out a successful engineer does their homework first. The experts are busy people too so, “you need to do your homework before you go to someone for input to maximize the time spent with them.”

Broad Educational Background

Having a breadth of experience was the next concept the participants most frequently described. This ability was demonstrated by having knowledge and skills in more than just one specialty. This was described by one participant this way. “It is like building a house. You can have a very broad foundation like building a ranch house. It is very wide footprint but very shallow foundation. You know a lot about everything and can spread it out but not a lot of depth. And there is nothing wrong with that. You can become a good integrator. However, if you want to build a sky scraper, for that you have a very deep foundation. So establish a technical expertise. Something I can rest on. So I can grow taller and bigger. The third thing you can do is sink piers to get depth, like I became very competent as a stress engineer. Then you branch out laterally to expand your horizon and experience. So now I have a breadth that I build off of, but a depth that I can always come back to rely on.”

Related to the ability to collaborate, it was suggested that successful individuals have enough experience beyond a personal specialty to understand the impact and requirements of
others’ specialties on the design. “There is a need for a breadth of skills. It is not enough to be
the absolute expert in an area. If you are the best hydraulics person in the world and
understand everything there is to know about hydraulics but don’t have any knowledge or
understanding of the other parts of the system that your component will impact, you may not
be the right person for the team. The person needs to have enough familiarity about the rest
of the system to understand why their design must be subordinate to other parts of the design,
why the single component may not be able to be optimized because of the degree of impact in
other parts.” This skill also supported recognizing needs for input because the familiarity
provided insight into where knowledge gaps might lie.

Other Findings from Practitioner Interviews

The following concepts were not specifically identified during the analysis of success skills,
but were found to be related to the literature survey and observations from the student design
class. These concepts as viewed by the industry practitioners were considered.

Internalization of Formulas

Interviewees also expressed their perceptions regarding the internalization of theoretical
concepts. It was suggested that the ability to sketch was directly related to an understanding of
what the theoretical formulas represented. “The people who can put the formula down and
everyone can see the meaning it embodies, like F=MA, is very powerful.” This skill was also
found in interviewee’s discussions on design activities. “I wanted to know what drove the
formula as opposed to just when it applied. I would take the formula and derive it myself.
Then I really understood where the formula came from and then I could apply the formula to
more than just the situation that had been presented to me. I could see how they really apply
not just how they apply to X and Y.”

One interviewee commented that he found he had a gap in his knowledge because he did
not have a good grasp on the connections between things. “I would have experienced it to see
the cause and effect.” He indicated that he now goes out to see how the things he analyzed
worked on the product.
Input Issues and Mechanisms

Interviewees were specifically questioned regarding their opinions and perspectives on obtaining input (Appendix E, question 3). Responses indicated that in most cases informational input was available but it was incumbent on the engineer to obtain it. The challenge as expressed by the interviewees was in leaving the domain of the individual’s specialty. “They are very happy to stretch and look at different things within their domain. The problem is not inside each of these domains, but where these cross functional entities come together.” “They are not comfortable at the boundary (sic of their knowledge).” “Engineers tend to talk to each other but not outside of their area as well. Then it can fall off quite rapidly.”

Another barrier to requesting input was a reluctance to appear unknowledgeable on a topic. “Having to go outside your comfort zone, to open up and have that communication, it makes you vulnerable. You have to open up and show that you aren’t knowledgeable in the area they are.” It was suggested that the reluctance to admit not knowing is partially cultural. “Asking for input is not necessarily a culture trait”, “we don’t teach people that it is okay to talk to other people.”

Companies are working to create environments that foster cross-disciplinary communications by the introduction of processes and physical layouts which force the communications to take place. “Those at location x, folks out of location y, and we folks here at location z try to get together at least once a year to talk about problems. What problems are you having? No holding back.” “The company has a rigorous process to go through for a new design or a design change. The process requires a presentation to an integrated product team that is made up of representation from every discipline.” “I think that people in general have to be brought together. People do get comfortable in their area and silo walls do come up. So you have to do things in an organization to facilitate communication.”

On the other hand, one interviewee reported that the company structure actually hindered interaction. “A typical response is I don’t have a charge number to work on that. I want to help but it is going to take longer than the maximum amount where there is no charge so I have to charge you to help you.”

Most of the interviewees indicated that the best tool was to develop a network of individuals to go to for help. Part of developing the network required “leaving your cubicle
and going out and meeting people.” “Having a network and having a list of people to call is critical.” “Trust and camaraderie come from me going to them. I do it.”

It was concluded that design engineers will attempt to gain input, although they must overcome a reluctance to admit they do not know something, especially outside of their area of specialty. Businesses have attempted to facilitate cross-functional communications by co-locating individuals on a design project and by having processes which require cross-functional communication and multi-disciplinary reviews. It was noted that the best tool design engineers can cultivate to facilitate obtaining input was the generation of a network of diverse experts.

Feedback
Interviewees were asked to discuss their experiences regarding obtaining feedback once a product or process moved on to manufacturing and the customer. It was reported that the typical form of feedback was “no news is good news”. “After it goes to the customer if they don’t complain it must be ok.” If you were not receiving complaints, then the product probably met requirements. This form of feedback did not provide insight into minor dissatisfaction or problems which were fixed later in the design process by other individuals.

All of the respondents indicated that information was available if an individual was motivated to obtain it, “yes, the information does exist and he can get it if he or she wants to. It is a matter of knowing the right person to ask for it.” “Yes, you can get it. Personally, I have been here long enough to have a network to get data from people who have in the industry long enough to know.” But unless there was sufficient motivation or a requirement to do so, it generally did not occur. The motivation can be personal, “just from your own curiosity will drive you to look for the feedback on something you haven’t heard from in a while.”

Use of Computer Tools
During the interviews, the topic of computer tools appeared in 50% of the interviews. Respondents commented on the possible over-reliance on computers. “Now there is a lot of reliance on the computer, ‘the code said, the computer said’, without understanding how to get there by hand.” “In some instances it takes longer to do it with the magic tools (sic computers).” “From a couple of pieces of paper with curves we were able to calculate some stresses and figure out what the problem had been. They went through months of analysis and
gobs of CFD analysis to show what I had figured out in 20 minutes. We recognized the problem and the solution.” Furthermore this dependence on the computer was thought to have a negative impact on the fundamental corporate and material knowledge of the newer engineers. “There is a loss of understanding of the underlying mechanics; why do we have the bond length we do and why do we wrap the phenolics like we do? Some of the reasons why things were done are getting lost.”

Not only was there a perception that the younger engineers went to the computer when hand calculations might have been more appropriate, there was a perception that the amount of analysis expanded to the available capability even when it was not clear more data was value-added. “Now instead of analyzing one or two critical load cases in a design, now with the computer we are analyzing 1000.” But at the same time participants were commenting on developing too much data, they were also expressing concern on generating the correct data. “A computer can’t tell you that you forgot to ask a question.” “The computer answers the question you asked, but can’t tell you that you didn’t ask the right question.” “They can be powerful in the hands of someone who really understands them and they can be dangerous in the hands of someone that doesn’t.”

There were also respondents who suggested that the use of computers was adequate and appropriate. (Interviewer) “Do you think there is a downside to the familiarity with the programs?” (Respondent) “No, I really don’t. I know where you are coming from with the question; I think people legitimately had a concern. I think the schools are doing a good job of fundamentals and professors are doing a good job of teaching how to use the tools.” This same individual also commented that the familiarity with the software gave the newer engineers a head start in the design process at company B because they were already comfortable with using software, it was not intimidating to them.

The conclusion form the interviews regarding the use of computers was that when the tools were used appropriately, they were a very powerful tool. But it was important that they were used as a tool to supplement the fundamentals, not replace them and that the tools were used to the appropriate level of fidelity.
Summary of Interview Results

The interview guide appeared to have performed reliably, facilitating obtaining specific skills as opposed to general abilities. During the analysis data indicated that the use of the knowledge, skills and abilities rubric would best facilitate the data analysis. The most frequently noted requisite skill was that of sketching. This was determined to have been affected by having the specific question asked. The presence of negative response indicated the question was not overly leading. The top three skills found in the data were collaboration and networking, obtaining input and having a broad educational background.

In addition to the primary goal of identifying requisite skills, support and explanation for other topics observed during the literature survey were identified.

Results of Observation of Senior Design Course

Collection and Preparation of Data

Observations were made of the senior aerospace engineering design course at Purdue University from spring 2001 through spring 2004. The course was observed during the fall 2004 semester but specific observations were not included in the data analysis. The fall 2001 session had insufficient data collected for a meaningful analysis. Each semester was considered a separate group for the purpose of analysis. Observations were collected each semester per the Procedures and Methodology section.

The course was taught by different instructors, had a variety of projects, different class sizes and a variety of instructional methodologies. The expressed goals of the course were to proceed through a design activity, including preliminary design, conceptual design, and system integration. In fall semesters the goal was to result in a flying aircraft, requiring students to also consider manufacturing and flight test inputs. The course required students to utilize knowledge from all of their courses and including knowledge and skills outside the scope of this study. Course identifiers, class size, and other descriptions are listed in Table 8.
Table 8 - Senior Design Course Descriptors

<table>
<thead>
<tr>
<th>Course ID</th>
<th>Number of Students</th>
<th>Number of Teams</th>
<th>Paper/Hardware</th>
<th>Product</th>
<th>Instructor</th>
<th>Lecture / Lab Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>14</td>
<td>2</td>
<td>Paper</td>
<td>Morphing UAV</td>
<td>TAW</td>
<td>G166 / G274</td>
</tr>
<tr>
<td>S02</td>
<td>16</td>
<td>2</td>
<td>Paper</td>
<td>UAV with Morphing Wing</td>
<td>TAW</td>
<td>G166 / G274</td>
</tr>
<tr>
<td>F02</td>
<td>22</td>
<td>3</td>
<td>Hardware</td>
<td>Remote Control</td>
<td>DA</td>
<td>G166 / G274 / ASL</td>
</tr>
<tr>
<td>S03</td>
<td>34</td>
<td>5</td>
<td>Paper</td>
<td>Wireless Power Transfer UAV</td>
<td>WAC</td>
<td>S109 / G274</td>
</tr>
<tr>
<td>F03</td>
<td>32</td>
<td>5</td>
<td>Design for next semester</td>
<td>Giant Remote Control</td>
<td>DA</td>
<td>G166 / G274</td>
</tr>
<tr>
<td>S04</td>
<td>31</td>
<td>5</td>
<td>Paper</td>
<td>Transatlantic Point to Point Commercial A/C using Morphing</td>
<td>WAC</td>
<td>P180 / G166</td>
</tr>
</tbody>
</table>

- G166 was a classroom on the first floor with windows on the right side, armchair desks, and access to a computer projector. There was a chalkboard across the front of the room and an overhead projector. Lighting was either all on or all off. The room dimensions were 25’ 10” by 24’ 5”.

- G274 was a classroom on the second floor with windows on the right side, tables and chairs with a center aisle, and access to a computer projector. Each end of the table rows was up against the walls preventing movement between the walls and the tables. There was a chalkboard along the front wall. There was no computer projector in the room unless a mobile unit was brought in. The lights were in either on or off. The room dimensions were 25’ 10” by 24’ 5”.

- S109 was a classroom on the first floor with windows on the right side, arm chair desks, and no computer projector available. There was also a chalkboard across the front of the room and two overhead projectors on either side of the room. The lights were controlled in two banks, one across the front of the room and one across the red
of the room. While the room was large enough for the number of students, seeing the board from most seats was difficult. The room was in a building where meat processing was taught, and an old meat smell permeated the room. The rumbling of the air handler in the room combined with the professor’s soft voice made hearing from the back of the room difficult. The room dimensions were 28’ 4” by 37’ 9”.

- P180 was a classroom on the first floor with two windows on the left side of the room, arm chair desks and both a computer and overhead projector. The windows were supplied with roman blinds. There was a chalkboard across the front of the room. The lights were overhead fluorescents (three rows of two each) and the room lighting could be modulated between bright, medium and dim. The room dimensions were 25’ 6” by 26’ 6”.

- ASL was a series of build areas. The groups had separate areas where they could work on their aircraft. The areas were a) along one hallway for approximately 50’ and approximately 8’ 8” wide, b) a cage area adjoining the machine shop and 28’ 8” by 22’ 8”, and c) a mezzanine area approximately 16’ by 48’.

**Bias and Error**

A potential source of error was in only observing classroom activities. More than half of the design activities were expected to take place outside of scheduled classroom sessions. The researcher took advantage of opportunities to observe students at group meetings, before and after class, and during aircraft building activities. It was observed that the students were more candid and more willing to discuss specific difficulties in the less formal environments. This indicated the classroom behaviors had the potential to be skewed towards positive behaviors. Nothing could be done to mitigate this as a source of error with the available resources.

Because the student data was observational, one of the most likely sources of error was observer bias. This was an error introduced when the observer over-emphasized behaviors expected and failed to notice behaviors not expected. This was reduced as much as possible through the use of triggers generated before entering the classroom, by recording observations with extensive contextual description, and by having another observer use the same list of triggers and comparing the observational content. This source of error could not be eliminated but by being aware of the potential could be reduced.
Related to observer bias, another potential error was inference. This occurred if the meaning of the observations was inferred as opposed to being directly reported. By drawing inference while collecting the data, a risk existed to miss observations. During the analysis of the data, inferences were required, but during the data collection the researcher minimized inference by careful contextual descriptions. By being aware of the risk of inferring during the data collection and using the structured data collection format, the researcher minimized the presence of the error.

Another potential source of error was that resulting from the presence of the researcher. This was reduced as much as possible by emphasizing the researcher's resource role, through the instructors treating the researcher in a similar manner to the class teaching assistants (also students) and by being as unobtrusive as possible while collecting data. The involved instructors were asked to consider what, if any, impact the researcher’s presence and participation had on the course. The instructors indicated the impact was from equivalent to a teaching assistant, no observed difference, to positive impact on student design behaviors because of access to a technical resource.

It was concluded that the sources of bias and error were mitigated to the greatest extent possible and that two of the three sources were more likely to skew the results to appear more positive or fewer negative behavior observations. Because the results did identify areas of behaviors that corresponded to the concerns expressed in the literature and during the interviews, the errors were deemed acceptable.

Changes in Data Analysis Methodology from those Planned

Originally the methodology to be used for collecting and analyzing the data was to capture the number of occurrences of behaviors using a prepared list of trigger concepts and then preparing frequency distributions. These frequency distributions were to be compared to the distributions from the other two cohort groups. The observations were collected using the triggers and collection form as discussed in the Procedures and Methodology section as well as contextual observations. However, when the attempt was made to analyze the data using the frequency distributions, it was determined that the frequency distributions were inappropriate for handling the data. First the data did not congregate around single concepts as was seen in
the two previous cohort groups. While a specific effort was made to identify behaviors related to the expected skills, the resulting frequency distributions generally would have been zero.

Second, the student behaviors changed over the course of a semester as they moved through the design process. Furthermore, the team structures resulted in diametrically different structures and behaviors which would have not been demonstrated by the frequency distributions. It was determined that it was more useful to display overall class behavior with respect to time. While in any class there were individual students who displayed different behavior than the majority of the students, these individuals were considered outliers and not included in the graphical representations. Teams displaying radically different behaviors are included in the graphs, particularly those receiving different instructor input (i.e. the engine teams in the spring semesters).

The third observation was that the class sizes grew and course structure responded over time, further reducing the value of simple frequency distributions.

This method of analysis was considered acceptable and still permitted comparisons to the data from the interviews and literature survey. The difference in the data could be attribution to the interviews and literature survey following a very structured format with questions developed \textit{a priori} and to the observational data being spontaneously collected as events transpired. Additionally, the first two cohort groups were more likely to have greater experience and maturity than students in a classroom environment, resulting in more coherent data results.

\textit{Analysis of Observational Data}

In preparing the data for analysis, each course was treated as a separate entity. It was noted that the clarity and descriptiveness of the observation notes improved over time. The validity of the tool was tested by providing the methodology and trigger list to a second graduate student and requesting she take observations. While the contextual observations were less complete, the desired core observations were obtained by the second observer. This supports the validity of the tool for collecting data.

The analysis of each class includes a listing of key observations, graphical representations of several key behaviors identified in the literature survey and the practitioner interviews as being important, and an assessment of the design success. The groups will be identified by
their semester and year as described in Table 8. Observations are major points and do not include all of the observations of behaviors that were made. All of the observations were used in the analysis. The graphical representations were generated by rating the observed presence of the behavior 1 with weaker demonstration being a relative value less than 1. No observed demonstration was rated 0 and in cases where students actively demonstrated negative behaviors, a rating up to -1 was assigned. The rating was strictly subjective and based on observed statements, presentations and lack of expected behaviors. The representations should not be considered quantitative.

It should also be noted that while the discussions presented focus on areas of challenge, the analysis should not be interpreted to imply only negative behaviors were observed. In areas of traditional engineering science, soft skills, manipulation of computer code and professionalism, the observations were all very positive. These areas are not discussed as they are not the focus of this study and are already experiencing positive results.

S01

- Students indicated they had been exposed to many of the design concepts but their behaviors did not indicate they had learned to use them.
- Structured design tools were taught during the first two weeks of the course and the students were required to use them for the initial design phase activities. Once this requirement was satisfied, the students stopped using the tools.
- The preliminary design activities were observed to be equivalent in tool use and design behaviors to those observed in the workplace.
- During presentations students repeatedly indicated that they had “guessed” and “assumed” data and requirements despite having generated supporting information during the preliminary design phase.
- There was no use of provided professional network contacts, even when questions arose that these individuals could have answered.
- Critiques and inputs from the professor and support staff were unilaterally ignored. This included requests for clarification on aerodynamic concepts, design issues, and data presentation.
- During the last half of the course input and critiques were met with excuses and active defiance. “We don’t have to worry about civilian air traffic at 35,000 feet, we’re designing a military aircraft.” Students also actively dismissed any design contributors which were not “easy” to solve.
- Students refused to use lessons learned, design completely from scratch and ignored any inputs with which they were unfamiliar.
• One design looked like a contemporary design but it did not reference or use any lessons learned from that design.

• One design referred to “archaic” data, but ignored any contemporary information. They also used the data incorrectly, resulting in flight control surfaces in the wrong places, i.e. the leading edge of the wing as opposed to the trailing edge. When this was pointed out, the critique was dismissed.

• The course also had a sub team of students working on propulsion. These students were initially more receptive to inputs, but this fell off as the workloads increased and the design requirements grew.

• The design teams never reached the state of component integration, even at major structural levels; wings to fuselage, engine to fuselage, empennage to fuselage.

• Students relied on code without understanding inputs and outputs, code assumptions or design requirements. They did not compare the output with other available analyses.

• Students depended on course textbooks almost exclusively, even when other resources were suggested.

• Students were unable to answer the question “why” to any design selection question through to the final presentations.

• Students did not ask “what if” to any of their design decisions versus requirements.

• Students were uncomfortable having to come up with requirements on their own. The activity of answering a mock request for proposal met with resistance from the students.

The students presented their final designs to a military customer. The customer expressed concerns regarding the students’ lack of familiarity with contemporary design concepts. The overall success was considered low based on the customers’ lack of being impressed, frustration with obtaining answers to technical questions, and lack of general knowledge of the design decisions’ impacts on performance.

It should be noted that students demonstrated positive knowledge and skills in areas outside the delimitations of this study and the observations should not be considered an indication of general unsuccessful course performance.
Figure 23 - S01 Relative Demonstration of Behaviors
Students were not provided with any type of specific downstream “-ilities” requirements and were not required to address them even at a superficial level. Students actually did not appear to be aware of the difference between the concepts, much less how to address them. In some cases the students expressed a customer requirement in terms of an “-ilities” concept, but the requirements were not pursued or were lost in the press of other requirements.

Students demonstrated few attempts to obtain any information on the “-ilities”. In the final presentation one presenter said with respect to placing an access panel, “I thought the maintenance person would rather be suspended over the area then have to lay on the ground under it.” Even with two licensed mechanics in the class, no efforts were made to ask anyone who would be impacted downstream.

Students selected materials solely on perceived performance requirements and no trades were performed.

In one case, a group of students recognized that the historical data and code output did not make sense for the application and wrote their own code. They then validated the code with known data points.

Students would ask specific questions as long as academic resources were present and pointed out problems.

Students showed little willingness to use existing resources beyond the Web.

Students would not define what data was needed but waited for someone to tell them what they needed. In one case a student actually said, “Just tell me what I need to calculate and I will.”

Even within the groups, students continually waited for someone else in the group to provide needed data, even though they often did not ask for specific inputs.

In one case, the students noted suspect data output, but instead of addressing the concern, they just changed the design point used in the analysis.

Dependence on historical data was exhibited at the exclusion or expense of actual engineering output.

Students did not recognize when designs were contra to conventional wisdom or could not defend design decisions.

Students often would not address wrong answers and assumptions, even after they were pointed out.

Students were uncomfortable with low fidelity values and incomplete requirements. They did not want to “guess” at a starting point, but would not use currently available technology as a starting point either.

Students would use unreasonable levels of accuracy, as demonstrated by using 4-8 decimal places at the point of a rough order of magnitude guess.
• Students could provide and defend explanations of design using basic linear physics. This was strictly a mathematical defense as opposed to a conceptual understanding. Students were less comfortable with angular and rotational physics.

• Students were very comfortable with “engineering” pieces. They appeared less able to visualize their design beyond outer mold lines.

• Comments were made such as “If we couldn’t measure it, we dropped it.”

• Students complained they could not do analyses for off design flight profiles because “no one told us what they had to be.”

• Students were unable or unwilling to leverage current and new technology in fields other than aerospace into their design.

• Students demonstrated design ownership in being able to defend the parts they most understood. They were less able to defend or explain choices arrived at using code or historical data. In some cases, the defense boiled down to “Raymer said so”, or “I guessed.”

The students presented their final designs to a military customer. The customer expressed concerns regarding the students’ lack of trade analyses. The overall success was considered average based on the customers’ satisfaction with the results, the completeness of the designs and the innovations developed with the Aviation Technology professor.

It should be noted that students demonstrated positive knowledge and skills in areas outside the delimitations of this study and the observations should not be considered an indication of general unsuccessful course performance.
Figure 24 - S02 Relative Demonstration of Behaviors
During the initial brainstorming there were suggestions to use structured design tools during the project. They did not follow through on the suggestion.

Group activity to do initial sizing resulted in one or two students from each group doing the research and the remainder of class talking or leaving.

All requests for trade studies were ignored.

Engineering design tools were not used well or at all. The students had trouble using the tools and had difficulty drawing meaning from the resulting output.

Students repeatedly made assumptions, even on items where resources were available to answer the question with data.

Groups made plans for testing which time precluded them from being able to execute.

Students became aware of the impacts of the “-illities” once they began to build their remote controlled aircraft. But they did not understand them and were not able to incorporate their consideration during the design process.

During final presentations which were to be a design review, students did not acknowledge any failures took place. When questioned on the design inadequacies, they argued there were none.

One team was specifically questioned early in the design process regarding radio transmissions and carbon fiber aircraft. They ignored the question, stated “It won’t be a problem”. When there were problems, they blamed them on the pilot being too conservative.

Groups asked the flight test pilot for input on the aircraft performance, and then ignored them, making no changes to their aircraft and not addressing them in the final presentation.

During the build activity, when the integration problems were encountered, design changes were made without any pre or post engineering analyses. During the final presentations, the presented analyses were for the aircraft that went into build, not the one that was actually built.

None of the team prepared flight test plans, despite being told they needed them.

Design choices did not support use requirements (i.e., balsa for a slip fit wing joint).

Based on the performance of the aircraft during demonstration flights, two of the designs were assessed as unsuccessful. One aircraft would not fly; and one aircraft would fly only with post build additions to the control surfaces and antenna. The classic design that received weak engineering analyses flew very well, but the students did not really know why as was demonstrated in their final presentations.
It should be noted that students demonstrated positive knowledge and skills in areas outside the delimitations of this study and the observations should not be considered an indication of general unsuccessful course performance.

Figure 25 - F02 Relative Demonstration of Behavior (Building began at week 10)
• First assignment was a business plan; students were not able to boil it down to the fundamental question of how many and how much.

• Students were unable to come up with ideas without being given all the issues AND their solutions.

• Students wanted to be given the components to use as opposed to designing them.

• One of the teams understood marketing very thoroughly.

• One team used a customer needs survey.

• One team emailed questions to potential customers regarding the project.

• There were efforts at benchmarking during the preliminary design phase.

• Comments from the teams after their preliminary design review were defensive and expressed that some of the customer comments were “unrealistic or unreasonable”.

• There were high expectations of the customer’s abilities to use the product without investigating the expectations, (i.e. what were the FAA requirements; did an aircraft carrier really have excess power to provide to the product; could the customer fly it).

• The students demonstrated typical lecture and note taking behaviors during the first eight weeks of class. This demonstrated employing a standard knowledge gathering methodology as opposed to demonstrating skill.

• Students did sketch during brainstorming as a requirement of the exercise.

• During the preliminary design phase, students used the structured engineering design methodologies as a fulfillment of a task requirement. They did not return to the results as the design progressed.

• Instructor presented lessons connecting concepts to fundamental principles. The students’ responses indicated there was no engagement of the students into the lesson.

• Students did not recognize poor output behavior from their analyses.

• Students spent so much time working on the wireless power transfer problem, they did not adequately design the aircraft. This was only partially their fault as the class organization encouraged this behavior.

• This semester’s groups did a better job of being aware of the impact of manufacturing and support on life costs.

• The students did not answer most of the questions or critiques as the designs proceeded, and the customer did not require it as was indicated by the lack of follow up in subsequent presentations.
The designs from this semester could not be adequately evaluated for success as the students never moved beyond outer mold lines in their design. The students spent as much time trying to learn how to use a piece of specialty software as they did working on designs. The students’ response to the instructor left the impression they did not fully understand specific fundamental engineering principles necessary for designing an aircraft as is indicated by the first graph. As the semester progressed the students appeared less able to understand the output from their analyses, less able to defend solutions and less involved in the project. Students demonstrated no understanding of non-linear physics and rotary motion.

It should be noted that students demonstrated positive knowledge and skills in areas outside the delimitations of this study and the observations should not be considered an indication of general unsuccessful course performance.
Figure 26 - S03 Relative Demonstration of Behaviors
This semester was different from other fall semesters in that it had a resource team from Aviation Technology, and it was designing a giant scale aircraft to be built the following semester. Each of the five teams was observably different. One team was strong at formulaic analysis but they could not initiate the analysis themselves. One used reverse engineering but could not defend the choices made with an engineering analysis. One focused on non-traditional propulsion but became mired in the analysis. This was done at the expense of the rest of the design. One team started out with strong use of structured tools, but team dynamics degraded, impacting design success. One demonstrated average tool use and design analysis.

- Students were told to keep design notebooks; they may have but did not turn in copies. This became a disadvantage during the second semester build.
- Students designed to what they could manage not to what they needed.
- Students did not trust their work and routinely added safety margins of up to 100%.
- Students would respond to input from the resource team, but the resource team had to initiate the interaction.
- As the semester proceeded, there was an increasing trend in the presentations of “But this is probably going to change.” There was never a design freeze.
- Students did not understand how to perform trade studies. One student did a trade study that resulted in a wing that was aluminum weighing 400 pounds versus the same wing in composite material weighing 16 pounds. This did not make sense, but the student did not recognize the oddness of the answer.
- Students used information without understanding it. “We’re using 15% MAC like the Petersen report.” “Why?” “I don’t know, I didn’t read the report.”
- Made design changes because the new choices were easier to analyze.
- Students could not explain results from their analyses, made unwarranted assumptions and extrapolation.
- As the semester proceeded, the number of technical errors in the presentations increased.
- Students were unable to respond to the professor’s numerous requests for considerations of integration. The professor wanted to know how the pieces were going to go together. Students attempted to provide answers but limited themselves to the capabilities of computer graphics programs.
- Students did ask to have an opportunity to see an example of a giant scale remote control aircraft, but scheduling and weather prevented the demonstration from occurring.
• Students do not do a good job of analyzing and presenting what the design can do as opposed to what it will do. They present that a design will meet a specific requirement, but not how far beyond the requirement.

• One team wanted to prepare drawings for the following semester to build from, but was unable to complete the goal.

• Direct connections between current design activities to knowledge learned in other classes were made on a number of occasions. Students demonstrated using text and code from other classes.

• Visually and structurally the students did not have a feel for the “rightness” of a design or the physical impacts of those decisions, i.e. unusually large tail surfaces, long cantilevered structures, long wingspans on small attach points.

• Throughout the semester students referred to iterating their analyses. The impact of iteration in one part of the design was not evaluated in other parts of the design.

• Students used general data for analyses as opposed to calculating design specific data.

• A student expressed a concern in the results of the mathematical analyses versus the reported actual results. The student requested help in reconciling this disconnect.

The success of the design activities was rated as low. The professor did not like any of the designs presented to him and resorted to choosing the design with the most engineering analyses. The content of the final presentations had insufficient detail to be considered completed designs.

It should be noted that students demonstrated positive knowledge and skills in areas outside the delimitations of this study and the observations should not be considered an indication of general unsuccessful course performance.
Figure 27 - F03 Relative Demonstration of Behaviors
Students were unable to deal with the low fidelity expectations of the design. They seemed unable or uncomfortable providing answers which were “close enough” and appeared unable or unwilling to define what “close enough” meant with respect to the point in the design process and course expectations.

It was observed that the students had difficulty in dealing with having to do an analysis to make a decision that in turn became a requirement. This was as opposed to just being given requirements to which they had to design. This is an example of difficulty dealing with open-ended problems.

Once given the specialized software, the students focused on the software and would not or could not dual focus. They would not use simpler tools from previous courses which they had, understood and could quickly manipulate. This persisted even when the students knew they had difficulties with the output from the software and even when the resource team suggested, requested, or asked for such other analyses.

Students actively refused to sketch their designs even after repeated requests.

After six weeks the students in general had no concept of what their aircraft looked like. There was no internalizing of their concepts as a system or as a general outline.

When asked specific questions on design activities, in the majority of cases the students were unable to answer even generally. “What does the center of gravity of your aircraft do?” “I don’t know, it is in my notebook somewhere.” “What was the aerodynamic reason for this design decision?” “…????”. “What is the engineering reason for the eight wheel truck?” “Because it will fit in the wing and Raymer says that is how much we need.” “Can you get that size wheel and tire?” “I don’t know.” “Does it have enough brake to stop your aircraft?” “I don’t know.”

Students utilized added safety margins on all design decisions, even when the level of available fidelity did not merit the margin. This appeared to be a case of “add it” because the students did not understand the output from the tools enough to know what a legitimate safety margin was. “Why did you pick this point?” “I wanted to be a little safer.” “But this level of fidelity doesn’t warrant such considerations”

Students did not keep track of the basic engineering design considerations as they proceeded through the design process. “Someone is watching the weight and balance, right?” No. “What is your stability doing?” The group laughed because everyone knew they hadn’t considered stability.

Students had difficulty in making the assessment of “does this make engineering sense” as they proceeded through the design process.

Observations indicated that the students could not connect the observations from their constraint diagrams to their carpet plots. The data remained isolated and was not used to drive decisions. It was done more like an exercise to be completed as opposed to a tool to be used.
The success of the design activities was rated as average. The students accomplished three low fidelity designs as three separate designs. The goal was to do three iterations of a single design. The students could use their analysis to defend half of the design decisions. The commercial customers also expressed assessments of average performance from the students. They expressed concerns the designs did not deal with integration issues well.

It should be noted that students demonstrated positive knowledge and skills in areas outside the delimitations of this study and the observations should not be considered an indication of general unsuccessful course performance.
Figure 28 - S04 Relative Demonstration of Behaviors
Summary of the Student Observations

It should be noted that students demonstrated positive knowledge and skills in areas outside the delimitations of this study and the observations should not be considered an indication of general unsuccessful course performance. Students demonstrated positive abilities in analysis activities and professionalism.

While the students, projects, instructors, and size of the senior design class were all different each semester, there were several consistent observations. This demonstrates that the consistent observations of behaviors were present despite differences in the class populations. This supports the conclusion that the observations are indicative of fundamental characteristics that are not the result of artifacts due to a specific population. It is suggested these observations would also be present in any senior aerospace design course which was a part of a similarly styled engineering curriculum and not specific to Purdue University.

First, while the students were able to perform analysis using computer tools, they did not consistently demonstrate an understanding of the limitations of the tools being used. Depending on the complexity of the tool and individual student familiarity with the tool, the students were not always able to identify unusual output. In more than half of the cases the students did not understand industry standard software sufficiently enough to understand what input was expected or how to convert design changes into corresponding input changes.

The students were generally aware of the concepts of basic “-ilities” but did not have the knowledge of how they differed, how they impacted the design process or where to obtain input on their consideration. In particular they recognized the importance of manufacturability but did not have sufficient knowledge to know how to incorporate it into their designs. They recognized the existence of reliability, but had no knowledge of the term’s meaning and therefore did not know how to evaluate the reliability of their designs. Other –ilities were expressed with less frequency and less understanding. Students were specifically required to consider cost and economics but universally did not have sufficient knowledge to apply the concepts to individual designs.

Students universally did not have the knowledge or skills with which to address design integration. They were unable to determine, present or defend integration of major components and were unaware of integration concerns for minor components. During the semesters when students were required to build the aircraft, they recognized the presence of
integration issues but solved them in an ad hoc manner as opposed to by engineering analysis. Attempts to develop integration plans were only to the extent that available computer programs provided suggestions. This difficulty was noted especially with respect to wing and landing gear placement and attachment during the semesters where the aircraft was built.

Regarding the obtaining of and responding to input, the classes had equal numbers of individuals who did seek input and who did not, and equal level of response versus lack of response. It was observed that in most cases the requests for inputs dropped off as the semester progressed and work load increased. With the exception of the two semesters with active AT resource participation, the response to inputs also tended trend downward. Similarly student response to criticism, even when requested, was defensive about two-thirds of the time. In some cases the students displayed active listening and openness to the critiques but were heard to be defensive and dismissive as they returned to their seats. Instructor requests for the students to critique and perform trade studies on their own designs were ignored over three quarters of the time.

Students demonstrated a good grasp of calculations based on linear physics. They were less able to demonstrate calculations involving rotational physics. Analyses were done in isolation and the results not well carried through the design. Attempts to have students explain what the output meant physically were observed to have low levels of success. The students could not relate the numerical output of a calculation to a physical result on the design.

Comparison of Results

The most noticeable observation was the concentration of the three cohort groups around the concepts of knowledge, skills, and abilities. This method of analysis was not chosen prior to the data analysis but was indicated by the data. Using these concepts to evaluate the data it was determined that the industry practitioners had been successfully guided to provide specific, definable skills. The observations taken from the literature survey found the responses to center on broad abilities but lacked specific skills. The student behaviors were observed to focus on garnering knowledge to do a specific task as opposed to using the knowledge in an active way, i.e. demonstrating skills. Thus it was concluded all three cohort groups had similar
goals, i.e. to be successful in the workplace, but were all operating to different perceived expectations.

This disconnect in expectations was demonstrated by the data obtained from the three cohort groups. The industry practitioners indicated that they assumed the graduating engineers would have the basic engineering fundamental knowledge. They also indicated this was not always a reasonable assumption as they found the students had an understanding of the formulas and their solutions but not necessarily an understanding of the physical reality the formulas represented. This concern was demonstrated during the student observations as well. When the students were questioned regarding the impact of the answer from a calculation on the design, they could not explain it. Discussions involving equations of motions were not observed to be coupled with the physical construct of motion. This lack of a specific skill perceived by the practitioners is one demonstrator of a lack of ability to “internalize the whole design” or a lack of “global visualization”.

The ability most frequently expressed by practitioners was the ability to work cross-disciplinarily, followed distantly by the abilities embodied by TQM© principles and the ability to design. The academic perception of importance was different. To the educators the most important ability was the ability to design followed by taking a concept to product and the possession of what have been defined as intrinsic traits, i.e. creativity, honesty, etc. This difference in the perceived importance between practitioners and educators regarding the ability to design was key to the realization that engineering education was giving industry practitioners what engineering educators thought the practitioners wanted, as opposed to giving the practitioners what they actually wanted. It was the perception of the industry practitioners that the abilities of cross-disciplinary work and abilities embodied by TQM© skills would result in the ability to design successfully. It was further expected that possessing these cross-disciplinary abilities and TQM© skills would support the other business endeavors required in successful system design. Academic researchers and educators perceived that the ability to design was itself the most important ability and had focused their efforts on design as the ultimate goal.

The specific skills that industry perceived as requisite for effective design were sketching, collaborating and networking, getting input and a broad education background. Collaboration and networking and getting input are both skills demonstrating the ability to work cross-
disciplinarily, further demonstrating the overall importance placed on cross-disciplinary activities.

Although specifically discussed, the skill sketching was nearly universally identified during the interviews as a skill used to assess the ability to visualize and internalize a design. When the literature was surveyed, it was observed that sketching and three dimensional rendering did appear, but with a very low frequency. It was even found to be considered vocational or to have been superseded by computer-based tools. Practitioners saw sketching as a tool that brought together a variety of knowledge in a clear, succinct manner that facilitated the ability to design and to work collaboratively. The students were not observed to be comfortable with sketching, preferring to use computer graphics tools if any drawing was done. “While having had specific instruction on drawing and modeling, (students) were still very hesitant to use these skills to explore their designs” (Schumacher, 1999).

Industry practitioners suggested two concerns regarding the use of computer graphic tools. First the output of computer graphic tools was not immediate. Someone had to go to a computer and spend time programming a representation. Second the computer graphic output imbued the sketch with an inappropriate level of fidelity. One practitioner commented that drawings on the computer are often lost as iterations proceed making it difficult to return to a previous drawing or to show the iterations at a later time.
CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The first observation made was that the resulting conclusions were not what were expected. The outcomes from the data were related and similar to the expectations, but what was concluded differed from the expectations. This was deemed a positive result, demonstrating the validity of the research.

Based on the investigation and evaluation of the data from the three cohort groups a number of conclusions can be made. Early during the literature search it became apparent to the researcher that the lack of precision in describing the perceived requisite engineering skills resulted in a lack of quantitative or subjective criteria suitable for evaluating whether the engineering graduate actually had the requisite engineering skills. This lack of criteria has made it difficult for engineering educators to address the perceived problems in engineering and engineering technology education.

Supporting data were identified for the initial belief that the removal of applications exposure measurably reduced the opportunities for students to learn and practice skills.

Based on the observations of the students, and through discussion with industry practitioners, it was concluded that theory-based curricula did not appear to appropriately connect knowledge with skills. Furthermore, conventional courses appear to teach knowledge expecting abilities as the outcomes.

In an attempt to provide more applications exposure, the greater use of computer-based simulations has been observed in the literature. Laboratory courses based on computer simulations may not be adequate in providing applications that connect knowledge to developing skills. The disassociation from the physical reality does not provide opportunities for seeing results and connecting cause and effect.

The most import skills expressed by industry representatives were: 1) sketching, rendering and understanding three dimensional visualizations, 2) collaboration and networking, 3) recognizing the need for input, data and feedback, and the willingness to obtain such inputs, 4)
having a broad enough background to understand impacts into and out of different parts of
the design, and 5) recognizing reasonable and unreasonable results from data and analyses.

The results of the literature survey showed that the majority of the items expressed by
engineering educators as “skills” were instead broadly and vaguely defined “abilities”. The
most frequently suggested ability expressed in the academic literature was for “designing”.

The majority of the students in the study did not demonstrate the skills expressed as
important by industry practitioners. The students demonstrated a knowledge garnering
philosophy during the senior design class, as opposed to an application of skills. The students
were adept at analysis activities but did not demonstrate noticeable levels of synthesis.

The study shows that there was a greater difference between how the three cohorts
pursued demonstration of the requisite skills than in identifying what the skills were. The
principle difference was not in what should be shown in terms of requisite skills but rather the
difference lay in how to show that the desired skills were accomplished.

The most significant disconnect was the emphasis placed on design. Industry practitioners
found sketching, networking and collaboration and obtaining input the most important skills
based on frequency, the educators placed the greatest emphasis on the ability to design.
Industry practitioners believed that good design would come out of demonstrating the desired
skills while educators placed their emphasis on design tools and activities as opposed to more
basic and universal skills.

The conclusion regarding the importance of developing specific metrics for use in
assessing classroom performance was extensively supported in the 1998 ASEE Publication,
*How Do You Measure Success?*

**Recommendations**

Further research regarding the relationship between the specific skills suggested as requisite
by industry practitioners and the assessment of desired abilities from graduating engineering
students is recommended. This research is necessary in order to identify the specific goals for
characterizing the desired abilities of graduates and for generating a list of skills precise enough
to permit assessment in an academic environment. These skills should be described with
sufficient precision that they can be measured with a yes or no for demonstration during the
assessment.
Specifically, it is recommended that subsequent researchers utilize the interview guide developed in this research to interview a larger population of industry practitioners (n>100) who meet the selection criteria. The interviews must lead to answers with sufficient specificity and clarity that the resulting data can be used to develop academic performance goals the presence or absence of which can be directly measured.

During the course of this research, a link between the quality of the engineering science research and application of the engineering knowledge was observed. Indications existed that engineering research was also negatively impacted by the loss of experiential learning. Related research is recommended to identify the link between the perceived requisite skills for success in the workplace and the requisite skills for success in engineering science research.

It is recommended that educators involved in technology and engineering technology programs take advantage of the lessons learned by engineering educators. Early engineering education programs were negatively impacted by their inability to reconcile their desire to be accepted as professionals with their responsibility to apply their knowledge. In the author’s opinion, this inability to reconcile these desires and acceptance resulted in the current difficulties in curriculum assessment and practitioners’ concerns regarding graduating engineers’ ability to participate in design activities. Technology and engineering technology educators are currently at the same decision point. It is recommended that technology educators evaluating their curriculum contents not make the same mistakes of trading application skills for the perceived value of professional stature. This current study demonstrates the risk of regarding applications knowledge as sub-professional and eliminating experiential learning from the curriculum. Further, the historical review shows that the skills which caused the technologist to be viewed as a professional equivalent to the engineers are the same experiential skills which are often defamed as sub-professional during contemporary reviews. It follows that the skills in question are not sub-professional and the loss of the skills results in risking the ability to progress to the desired level of perceived professionalism in the future.
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World Publishing Company.


Press.


Written Contributions to the EHR Advisory Committee Public Hearing on Employers’ Views Convened

Appendix A

Example Observation Form

CLASS OBSERVATION FORM

EXAMPLE

Class Date: 19-Sep-02

<table>
<thead>
<tr>
<th>Key Phrase</th>
<th>Times Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>I contacted an engineer at company X about the issues.</td>
<td>//</td>
</tr>
<tr>
<td>I looked in the library and found these references on the topic.</td>
<td>///</td>
</tr>
<tr>
<td>Does anyone know someone who can do this?</td>
<td>///</td>
</tr>
<tr>
<td>I tried to get an answer but it didn’t make sense.</td>
<td>///</td>
</tr>
</tbody>
</table>

Other Comments:

A lot of discussion observed.
Appendix B

Student Exit Questionnaire

1. What do you expect to do for your first job?
   a. Design some type of system
   b. Perform stress analysis, propulsion analysis, structural analysis or other specific engineering analysis
   c. Perform reliability and maintainability
   d. Attend graduate school
   e. I don’t know
   f. None of the above, I expect to ________________________

2. Have you learned or used any engineering software? I.E. Catia, ON-X, FEMA, etc
   a. Yes (List here) ______________________________________________
   b. No

3. In your opinion, do you think professionals from other disciplines have trouble relating to engineering designs due to (circle all that apply):
   a. a lack of engineering background,
   b. a lack of engineering language skills
   c. a lack of effort?
   d. Yes there is a problem, but because of _________________________
   e. No, there isn’t a problem understanding
   f. I don’t know why others don’t understand

4. For each of the following, rate how often you think you will be expected to interact or consult with each of the following individuals using the following rating scale:
   1 – Never
   2 – Sometimes
   3 – Whenever they need help
   4 – Whenever I need help
   5 – On a regular basis

Other Design Engineers on my project
Other Design Engineers in my department
Other Design Engineers in my company
Marketing Engineers for my company
Design Engineers at other companies
Materials/Chemical professionals
Reliability engineers in my company
Reliability engineers at my customer’s company
Technical support and technical writers in my company
The technicians at the customer
The head, i.e. the CEO, the General, the President.

5. On a scale of 1 (not at all) to 5 (very, just need company specific introductions), how prepared do you expect to be to go to work as an engineer upon graduation.              _____

6. Describe the actual activities you expect to do on a daily basis. In other words, describe your primary job duties as an engineer on a project. What do you think you will be required to do on a daily basis. For example, run stress calculations on a design, draw the blueprints for a test piece, write a report on test data, make telephone calls, go to meetings, etc. Be as descriptive as you can and describe what you think a day in the life of an aero engineer looks like. You may type this up in Word or handwrite it. If you use word, please print it on this page.
Appendix C

Human Subject Approvals and Consent form

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
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<tbody>
<tr>
<td>1.</td>
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</tr>
<tr>
<td>2.</td>
<td>Anticipated Funding Agency: None</td>
</tr>
<tr>
<td>3.</td>
<td>Principal Investigator(s) [Must be faculty member]: Aviation Technology, Hangar 1, ph. 494-9757, fax 494-2305, <a href="mailto:jmthom@tech.purdue.edu">jmthom@tech.purdue.edu</a>, Department, Building, Phone, FAX, E-mail address</td>
</tr>
<tr>
<td></td>
<td>Associate Professor</td>
</tr>
<tr>
<td></td>
<td>Name and Title</td>
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<td></td>
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<tr>
<td></td>
<td>J. M. Thom</td>
</tr>
<tr>
<td></td>
<td>Name and Title</td>
</tr>
<tr>
<td></td>
<td>Department, Building, Phone, FAX, E-mail address</td>
</tr>
<tr>
<td>4.</td>
<td>Other Personnel [Such as consultants or graduate students]: Technology, Hangar 1, ph. 746-3542, fax 743-9812, Department, Building, Phone, FAX, E-mail address</td>
</tr>
<tr>
<td></td>
<td>Melanie Thom</td>
</tr>
<tr>
<td></td>
<td>Grad student</td>
</tr>
<tr>
<td></td>
<td>Name and Title</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><a href="mailto:MelanieThom@compuserve.com">MelanieThom@compuserve.com</a></td>
</tr>
<tr>
<td>5.</td>
<td>Specific procedures to be followed. Include a copy of questionnaires or consent forms, if applicable. (Please note that interviews can be taped if the tapes will be erased within two weeks of the interview's completion.) Specific procedures, survey form, observation form, and explanation forms attached.</td>
</tr>
<tr>
<td>6.</td>
<td>Will subject's data be gathered anonymously? YES X NO</td>
</tr>
<tr>
<td>7.</td>
<td>Type of subjects to be employed and recruitment procedures: University students in classroom environment with permission of instructor. University professors by invitation. Instructors will be selected randomly from department lists. I have read the Human Subjects &quot;Instructions&quot; and, in particular, pages 4 and 5 concerning exempt research. (Signature) Principal Investigator Signature 1-11-2002 Date</td>
</tr>
<tr>
<td></td>
<td>Institutional Approval by: Exempt X Submit Regular Application</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rebecca D. Armstrong, D.V.M., Ph.D. Assistant Vice President for Research Compliance</td>
</tr>
<tr>
<td></td>
<td>Howard N. Zelaznik, Ph.D., Chair</td>
</tr>
<tr>
<td></td>
<td>Richard D. Mattes, Ph.D., Assoc. Chair</td>
</tr>
<tr>
<td></td>
<td>Committee on the Use of Human Research Subjects</td>
</tr>
<tr>
<td></td>
<td>Submit to: Human Subjects Office, 1071 Hovde Hall, Room 307</td>
</tr>
</tbody>
</table>
Purdue University
COMMITTEE ON THE USE OF HUMAN RESEARCH SUBJECTS
Revision of Protocol Form

1. Project Title: Evaluation of Engineering Design Decision Process
2. Principal Investigator: James M. Thom/M. Thom
3. Department/Head: AT/AT-- T. Q. Carney
4. Protocol Approval Date: 1/30/2002
5. Revision of Protocol Review Date: Date 12-10-03

Richard D. Mattes, Ph.D., Chair
Darlene A. Sedlock, Ph.D., Associate Chair
Bruce A. Craig, Ph.D., Associate Chair

Rebecca D. Armstrong, D.V.M., Ph.D.
Assistant Vice President for Research Compliance

1. In the original approval Human subjects in the above-titled project are in the following classes:

<table>
<thead>
<tr>
<th>Minors</th>
<th>Pregnant Women</th>
<th>Fetuses</th>
<th>Other Vulnerable Populations</th>
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<td></td>
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</tbody>
</table>

2. The Institution Review Board (IRB) has determined in the original approval that:

- [X] Human subjects will be at no higher than MINIMAL risk.

3. Original application approved through:

- [ ] Full Review Board  [ ] Expedited Review  [X] Research Exemption

Evaluation of revision was done by:

- [ ] Full Review Board  [ ] Expedited Review  [X] Exempt Review

All activities in this application have been reviewed by Purdue University's IRB in accordance with the requirements of the Code of Federal Regulations on Protection of Human Subjects (45 CFR 46) and our Federal-Wide Assurance with HHS (Number 00001548)

cc: T. Q. Carney
N/A
NOV 21 2003

Purdue University
COMMITTEE ON THE USE OF HUMAN RESEARCH SUBJECTS
Revision Of Protocol Form

Principal Investigator: J.M. Thom Protocol Title: Evaluation of Engineering Design Decision Process
Protocol Reference No.: 02-082E Phone/Fax 494-9757
Department/Building: Technology, Hansen 1 Email: jmthom@tech.purdue.edu

1. Describe the purpose of the revision:
   Add a second target population

2. Describe changes to the procedure:
   None

3. Describe changes to recruitment:
   None

4. Submit copies of all instruments and consent forms affected by this revision.
   Attached

INSTRUCTIONS: Submit the original Revision of Protocol Form PLUS one copy of any additional materials. If the revision is for a protocol approved via full Committee review, submit the original and additional materials PLUS nineteen (19) copies to our office.

Principal Investigators Signature: [Signature] Date: 11-21-03
Appendix D

Interview Scenarios, Introduction and Demographics

Dear Participant:

Thank you for participating in this research survey. Your input is an essential component of my research. I am attempting to identify those skills which professionals involved in design engineering think are important to success, both in terms of the individuals and in terms of the product being developed. Your responses will be kept confidential and all data will be destroyed after this dissertation is completed.

This research has been approved by the Human Subjects board of Purdue University. Please read through the remainder of the description, and if you are willing to participate, please respond to the demographic questions below. Once data has been collected, the analyzed results will be provided.

Consider the following scenarios. A chemist and her friend, an engineer involved in designing a complex control, are talking casually. During the conversation, the engineer tells her about a problem he is currently having in designing the control. Every time he tested the control, it would work for a while and then begin to leak. He had discussed the problem with other engineers in his group and as a result he had repeatedly redesigned the physical shape of the unit. Each time he redesigned the unit, the drawings had to be changed, and the unit had to be re-manufactured. He had been working on the problem for nearly a year and they were in danger of losing the program. The chemist asked the engineer a few questions and rapidly discovered the problem was with the choice of rubber for the o-ring. The material was incompatible with the system and no matter how many times the engineer redesigned the o-ring glands, it was going to leak. There was no crash and the program was not lost.

In another scenario, an engineer was designing a component made out of an expensive material that was difficult to machine. Initial testing and the engineer’s feelings indicated there was a potential problem with the design’s robustness. If the design could not be made both robust and be able to be machined cost-effectively, the company was going to lose the program. The design engineer worked with people from several different disciplines, including the manufacturing technicians to get a wide range of information, asked a lot of questions from people outside his immediate circle of peers, and incorporated machining considerations into the design while he was still doing computational analyses. The engineer used his knowledge and the information others gave him to complete several different
engineering analyses. The new design was found to be less costly to produce than had been forecasted, resulting in increased profits and it was more robust than previous designs increasing the marketability for the company and resulting in more business. This was all accomplished in less time than had been forecasted and with fewer resources in materials and manpower.

Now that you have read the two scenarios, I would like you to think about your career experiences, both good and bad. Think about what you think made them successful or not within the following limitations. Don’t think about success in terms of soft skills like teamwork or communication skills, and don’t focus on things like access to good computer simulations or analysis programs. Think about those unique skills that engineers have that make them good at designing a product. I would like to explore with you these special skills, what experiences have made you and others able to participate in design, and how you and they went about getting what you needed. Think about specific stories where something small or unexpected resulted in a problem. The problem might have been a cost overrun, or a bad customer review. It might be something more dramatic like the loss of the program, or a failure in the field. Remember, all stories will have company specific information removed so that the company, product, you and customer are all confidential.

If you agree to participate, answer the following demographic questions. Return them to me in the next five days along with two or three suggested time to talk. The interview will take approximately an hour. I realize your time is valuable, but without your input, I can not successfully complete this research characterizing the successful engineering skills and provide you with the analyzed data.

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Suggested contact dates and times: ______________________________________
Contact Phone Number: _______________________________________________

PERSONAL EDUCATION AND TRAINING EXPERIENCE

Name: _______________________
Age: _______________________
Title of first college or university degree: _______________________________
College or university of first degree: _________________________________
Time it took to achieve first degree: _________________________________
Date first college or university degree received: _____________________________
Date and location of any subsequent degrees: ____________________________
(Use as much space as necessary)

• During your educational experience, did you have any application based laboratories, internships, co-ops or other experiential learning?
  ○ What were they?
• At any time during your professional career did you have or were you yourself a mentor?
  ○ Was this relationship formal or informal?
• Have you received any other organized education outside of traditional coursework? Excluding things like equipment training, one-day seminars, or other soft skill courses.

PRODUCT DESIGN EXPERIENCES

• How long have you been involved in design activities in some capacity?
• During your career, have you been able to work on a single project start to finish? That is, were you involved from the first design considerations until a prototype or product was finished?
  ○ Are most of your experiences of this type, or are they more “fighting fires”.

METHODS FOR OBTAINING DATA

• In the course of your job responsibilities do you have an opportunity to go to where manufacturing or physical testing takes place?
  ○ Why or why not?
• In obtaining necessary data for analysis of the design, has it been more computer based simulations or actual testing of components?
  ○ In either case are you generally directly involved in the generation of the data or is the data provided to you?
  ○ When testing is required, do you generally prepare the test plan or is it a provided standard?
Appendix E

Interview Guide

The respondents will have already received the preparatory scenarios and demographics. Reiterate the confidentiality of the responses and the handling of the data. Confirm that the respondent will allow the discussion to be recorded.

“Considering the scenarios I gave you describing successful and unsuccessful design activities, I would like to explore your experiences and perceptions of skills necessary for a design and an engineer involved in design to be successful. I do not want to discuss soft skills like teamwork and communications, and I do not want to discuss the ability to run engineering software and perform analyses. I want to explore those unique technical skills that set what you think of as exceptional design participants apart from average or incapable participants. Do you have any questions before we get started?”

“In my introductory email, I asked you to think about both positive and negative situations, along with the projects and the people that were involved. With those experiences providing the basic framework, I’d like to discuss your perspective of those engineering design activities.

1) First I would like to explore your thoughts regarding “designing”.
   Probe: Is there a difference between “designing” and “engineering?”
   Probe: If yes — “How do they differ?”
   If no — “Why are they the same?”

2) Think about your perception of design and the design projects and people you considered for this interview. Give an example of what made those individuals, who in your opinion are successful, successful? Feel free to do this by sharing a story.

3) [You mentioned getting input] [Consider how you and your co-workers obtain necessary data and input to design]. Describe your observations or experiences regarding the ease of asking for assistance from other individuals?
   Probe: In your area?
Probe: In other departments in your company?
Probe: In locations outside of your company?
Probe: In your opinion why do these individuals provide useful or helpful information?
Probe: Why don’t they provide useful or helpful information?
Probe: Get a description of their work area and how easy it is to get around.

Are they co-located with other disciplines like scientist or other types of professionals?
Can they move around the facility? Are there restrictions to their movements like managerial or secrecy related issues?

4) How do you get technical feedback regarding the project you are working on?

Probe: What types of feedback do you receive?

Probe: How do you know when something goes right or wrong?

5) Looking back on your career experiences, remember a time when you felt most fulfilled or most excited about your involvement on a design project. What about it excited you? A story is fine.

5a) Think about that time, and think about your observations of what design projects are like now. Do you think it is different? Has it changed for you?

Probe: How do individual differences in co-workers make designing different?

6) Overall, when you think about your career experiences and successes, what things have you done to be successful?

Probe: What skills, abilities, characteristics, and knowledge have helped you to be successful and to make the design successful?

Probe: Do you believe the ability to pencil sketch is important?

If yes – Do you believe that newer engineers are able to sketch?

7) Last question: give a specific example of a time when some seemingly unrelated design changes resulted in a design failure.

Consider things like

- Someone said “that can’t happen” and it did.
- Someone in another part of the system changed a parameter without considering its impact on your part of the design.
- Something simple and obvious was overlooked.
- Examples of a design failure could be:
  - repeated, unnecessary redesigning to solve the wrong problem,
  - missing a schedule date, a cost over-run,
  - a program was lost.
Appendix F

Bibliography of Literature Sources Used to Generate Concepts and Frequency Distributions


*Center for naval analysis report (CRM 91-258)* (1992, January).


MEmo Annual Newsletter to Alumni & Friends of Mechanical Engineering. (1994). Purdue University, West Lafayette, IN.


Appendix G

Reproduction of the Mann Report, 1918

Report prepared by scanning document with Microsoft Image Scanner and performing optical character recognition using Microsoft OCR. The resulting conversion was imported into MS Word. The layout and spelling of the original document have been maintained although some shifting of words on the page may have occurred during the process. The text is complete through the appendix section of the original document which has not been included here.
A STUDY OF ENGINEERING EDUCATION
PREPARED FOR THE JOINT COMMITTEE ON ENGINEERING
EDUCATION OF THE NATIONAL ENGINEERING SOCIETIES
BY
CHARLES RIBORG MANN

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BULLETIN NUMBER ELEVEN

NEW YORK CITY
576 FIFTH AVENUE
THE CARNEGIE FOUNDATION
FOR THE ADVANCEMENT OF TEACHING

A STUDY OF
ENGINEERING EDUCATION

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570 FIFTH AVENUE
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By the President of the Carnegie Foundation

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By the Joint Committee on Engineering Education of the National Engineering Societies

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PREFACE

THE present bulletin has been prepared under conditions somewhat different from other publications and bulletins of the Carnegie Foundation. This study of Engineering Education arose out of the action of a joint committee on engineering education, representing the principal engineering societies. More than three years ago the Committee had gathered a considerable amount of material bearing on the subject, and had come to the opinion that the work could be best carried out by the employment of some one trained in applied science, who should devote his entire attention to the study, working under the general direction of the Committee and in touch with it. The Carnegie Foundation agreed to appoint such a man and to bear the expense of the study. Professor Charles R. Mann, of the University of Chicago, undertook the work under these conditions, and the report which follows is the outcome of his studies under the general supervision of the Committee. The discussion of Professor Mann’s report by the Committee forms the introductory chapter.

It will be understood that the report did not contemplate a study or examination of the engineering schools of the United States, although a limited number of typical schools were visited and studied by Professor Mann. The point of view from which the study was undertaken was the following: Fifty years ago, when the engineering schools of the United States were inaugurated, they began their work upon a definite teaching plan and one that had at least pedagogic consistency. The course was four years. The first two were spent mainly in the fundamental sciences—chemistry, physics, mathematics, and mechanics; the last two years mainly in the applications of these sciences to theoretical and practical problems.

In the half century that has passed this course of study has been overlaid with a great number of special studies intended to enable the student to deal with the constantly growing applications of science to the industries. While the original teaching plan remains as the basis of the four-year engineering curriculum, the courses given in most schools have been greatly modified in the effort to teach special subjects. As a result, the load upon the student has become continually heavier and bears unequally in different places and in different parts of the course. In addition there is a widespread feeling that under this pressure the great body of students fail to gain, on the one hand, a satisfactory grounding in the fundamental sciences; and on the other hand, do not fulfill the expectations of engineers and manufacturers in dealing with the practical problems with which they are confronted on leaving the engineering schools.

It is out of this situation that the Committee of the Engineering Societies began its study, whose purpose is not so much to record the details of engineering teaching in the various schools as to examine the fundamental question of the right methods of teaching and of the preparation of young men for the engineering professions: in other words, to question anew the pedagogic solution of fifty years ago, to examine
the curriculum of to-day and the methods of teaching now employed, and to suggest in the light of fifty years of experience the pedagogic basis of the course of study intended to prepare young men for the work demanded of the engineer of to-day. In the effort to do this, the point of view of the teacher, of the engineer, and of the manufacturer and employer has been kept in view.

While the report and the introduction of the Committee deal with many matters of detail in the formation and development of a suitable curriculum, and suggest various methods for simplifying the present courses of study, three questions of importance are raised which are closely related to the primary purpose for which the engineering school exists.

Professor Mann argues that the present arrangement, under which the fundamental sciences are taught in advance of their applications, is the wrong method of teaching, and that the engineering education will never be satisfactory until theory and practice are taught simultaneously.

For example, mathematics is the most important tool of the engineer. It is taught for two years in the engineering school in separate courses—higher algebra, coordinate geometry, the calculus, and mechanics. The splitting up of mathematics into separate courses is itself a source of weakness from the standpoint of the student’s needs. He needs not studies nor recitations in these artificial divisions of mathematics, but a single course in mathematics illuminated and made alive at every step by applications in the solutions of actual problems. Algebra, coordinate geometry, and the calculus are not separate and unrelated studies, but merely parts of the one subject of mathematics.

As a consequence of this method of teaching Professor Mann urges that the engineering courses, as taught in the preliminary years, do not form sound criteria for judging as to the ability of the student to do successful engineering work, and that many students are sent away from the technical school without having had any fair test as to their capacity for engineering practice or study.

In the third place he gives the results of certain objective tests designed to throw light upon the fitness of the applicant to undertake engineering studies and practice. It is quite clear that the trial of these tests made hitherto is not sufficient to demonstrate their trustworthiness, but the question raised is an exceedingly interesting one. There are few devices connected with teaching more unsatisfactory than our present day examinations, whether used as tests for admission or as criteria of performance on the part of the student.

In general these suggestions of Professor Mann, if carried out, would affect present day teaching of engineering in much the same way that Langdell’s case method revolutionized the teaching of law.

Langdell built the teaching of law exclusively and directly upon the study of cases. His notion was that the principles upon which the law rests are few in number, and that these could be best apprehended and mastered by the student in the direct
examination of typical cases. The number of such cases necessary to illustrate these principles he held to be very small in comparison with the overwhelming mass of law reports to which the student had formerly been directed as the basis of the study of the law in conjunction with textbooks. Langdell’s method involved the working out by the student of the principles of the law from actual cases tried and decided in the courts. Law he conceived of as an Applied Science.

Langdell’s method is not infrequently referred to as the laboratory method of teaching law, conveying the impression that the case method of teaching law consists in transferring to the teaching of law the methods employed in the teaching of applied science. This statement has been the cause of no little confusion. The teaching of law by the case method presents only a remote analogy with the methods hitherto employed in teaching applied science. Applied science is not taught ordinarily in the engineering school by the case method. On the contrary, the methods actually employed in teaching the so-called laboratory subjects do not differ appreciably from the methods of teaching literature or Latin. At present the student undertakes to learn a vast body of theory under the name of physics, mechanics, or chemistry, illustrated in some measure in the laboratory, and then seeks later to select from this mass of knowledge the principles to be applied, for example in electrical engineering. The case method would proceed in directly the opposite manner. Taking up, for example, the dynamo as a “case,”—that is, as an illustration of physical laws in their actual concrete working,—it would proceed to analyze the machine for the purpose of discovering the fundamental physical or mechanical principles involved in its operation. It would lead the student from practical applications by analysis to a comprehension of theory, instead of from theory to applications as under present methods of teaching.

It is an interesting fact that while much is said about the teaching of science in the modern school, the methods of teaching science are actually but little changed from those employed in teaching the subjects that filled the curriculum before the teaching of science began in the school. The practical suggestion of this report is that the case method of teaching is truly scientific and that the present methods of teaching applied science are unscientific. Furthermore, as an essential feature of the new method of teaching science, Professor Mann would combine theory with practice much more intimately than occurs in the law schools of the present day, by requiring the student to learn to operate the “case” under study. The student must not merely observe and analyze the operation of the dynamo: he must also actually run it and repair it when out of order. The method of teaching he advocates for engineering students, while based on the same conceptions as Langdell’s pedagogic innovation, is designed to meet some of the objections commonly raised to-day against even case method law schools.

Whatever may be thought of this contention, the subject is one of great significance, and worthy of the attention of teachers and engineers. Engineering schools,
like all institutions of learning, are slow to undertake educational experiments. It is sometimes easier to start a new school than to try an educational experiment in an old one. But obviously an actual experiment thoroughly carried out would be the only satisfactory demonstration of the soundness of the case method of teaching science.

The report is published by the Carnegie Foundation as a work of cooperation with the great engineering societies, and with the hope that the formulation of these important enquiries and their discussion may lead to a serious effort on the part of those having to do with engineering education to reexamine the curricula of the schools, and to approach the problem of their improvement not only from the stand point of the teacher, but also from that of the practising engineer and of the employer.

HENRY S. PRITCHETT,
President of the Carnegie Foundation.
INTRODUCTION

THE Society for the Promotion of Engineering Education, at its Cleveland meeting in 1907, invited the American Society of Civil Engineers, the American Society of Mechanical Engineers, the American Institute of Electrical Engineers, and the American Chemical Society, to join the Society for the Promotion of Engineering Education in appointing delegates to a “Joint Committee on Engineering Education’ to examine into all branches of engineering education, including engineering research, graduate professional courses, undergraduate engineering instruction, and the proper relations of engineering schools to secondary industrial schools, or foremen’s schools, and to formulate a report or reports upon the appropriate scope of engineering education and the degree of cooperation and unity that may be advantageously arranged between the various engineering schools.”

At the Detroit meeting in 1908, a resolution was passed authorizing this Committee to invite the Carnegie Foundation for the Advancement of Teaching and the General Education Board to appoint delegates.

Notwithstanding the appropriation by the American Society of Civil Engineers of a sum to assist in the investigation, it was found to be utterly impracticable to carry on the work without larger funds, and the Carnegie Foundation was thereupon urged to undertake the work on a comprehensive scale. After proper examination, the Foundation generously acceded to this request, and finally selected Professor Charles R. Mann to make a careful investigation and report.

In presenting Professor Mann’s report, the Committee desire to state that they have been closely associated with Professor Mann during his investigations, and have frequently conferred with him in the progress of the work and in the different plans adopted for securing information. Many of the conclusions reached have been discussed at public meetings of educational experts and have had the advantage of mature judgment and long experience. The views of the whole engineering profession, widely scattered throughout the country and representing every phase of professional activity and practice, were ascertained. The results of some of these special enquiries were published and considered by the engineering societies; they were both interesting and surprising, and are set forth in Chapter XVI of the report.

Notwithstanding this varied experience, it was not until the Committee had the advantage of examining advance copies of Professor Mann’s report that they realized the coordination existing between all of the different portions of the investigation, and their bearing upon the value of the whole study.

We believe that this report possesses particular significance on account of the simple and clear treatment of the complicated problems involved. The history of the origin and development of the schools is concisely told, and the connection between the curriculum and the changing demands of industrial activities and growth is clearly narrated. If the study went no farther — and this is but the threshold of the report — we
believe the value of this result alone would go far toward repaying the expense of the enquiry, liberal as that has been.

Other significant characteristics of the report are found in the discussions of the general failure to recognize such factors as "values and cost," the importance of teaching technical subjects so as to develop character, the necessity for laboratory and industrial training throughout the Courses, and the use of good English. Valuable suggestions are offered for avoiding or reducing present difficulties found in many other directions, and all of the problems have been treated in a broad and comprehensive spirit. No hard and fast rules are laid down for the government of engineering education. Such a course would inevitably increase the difficulties of future advances. Changes must be made from time to time to meet conditions as they arise, and any attempts to solve the problems of engineering education must be of so flexible a nature as to admit of improvements.

We now turn to a few of the principal points emphasized in the report. Professor Mann has called attention to the waste occurring in educational efforts arising from lack of coordination shown in the histories and aims of the technical schools as set forth in the first chapter of this study.

Another point is the perplexing one of the regulation of admissions. At present sixty per cent of those who enter the schools fail to graduate. The importance of limiting admissions more strictly to those students who possess some aptitude for engineering is demonstrated, and a substitution of objective tests in place of those of a subjective character is recommended.

Another point emphasized, and one of deep importance, is that of the reorganization of curricula which are commonly acknowledged to be much congested, and which it is stated will continue, "as long as departments are allowed to act as sole arbiters of the content of the courses." Plans are offered for developing particular types of curricula suited to the environment of each school.

Emphasis is also given to the necessity for a broader training in the fundamentals of science as an equipment for all engineers and forming a sort of "common core" to every curriculum. With this broad training in the first and second years the student is expected to develop some natural leaning toward a specialty, and then will follow vocational guidance in the later stages of his education.

Among the questions that will perhaps occur to many interested in the status and progress of engineering education, in connection with this report, are—How far will the recommendations in the report be applicable to present conditions? and what will be the possible influence of this study upon education and practice? These questions are of course difficult to answer with precision. We can only form an estimate, based upon experience and knowledge of the present chaotic condition of the schools, arising from world-wide events over which they are called to exercise a powerful influence. There probably never was a time when the minds of teachers were so intently alive and receptive to rapid changes, as at the present moment. This report, made
INTRODUCTION

under the auspices of the Carnegie Foundation and with the direct assistance of this Committee, will be read and studied all over the country, as soon as it becomes available. Engineering educators are already partially familiar with the trend of the report. They, better than others, know from long experience something of the difficulties in establishing standards by which to measure the successes or failures of their efforts to provide proper training for engineers. It may take time to convince all that a measure, or scale, has been created by the practising engineers of the country by which an estimate may be formed of the amount of success in engineering teaching, irrespective of the special courses involved. That scale is the improvement of character, resourcefulness, judgment, efficiency, understanding of men, and last of all, technique, as shown by students. These facts have already been published and widely circulated, and since they became known there are probably few intelligent educators who have not asked themselves the question—Am I so teaching as to produce these results in my pupils and in the order of value specified by the engineering profession? It may perhaps be considered not unreasonable for this Committee to believe that if portions of this study have already proved of value and interest to the schools, there is some secure foundation for thinking that the whole report will awaken wide interest because of the applicability of its results, and that its influence on engineering education will be beneficial.

In addition to its possible effects on professional educators, we entertain the hope that it will also have a wider significance as an important contribution to the general cause of education. The publication of the study in the present emergency, when the Government is so deeply concerned with so many vital questions connected with educational processes, may assist also in the solution of some of the many problems arising in connection with vocational training in the different branches of military science.

American Society of Civil Engineers
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American Society of Mechanical Engineers
F. H. CLARK, FRED J. MILLER
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Society for the Promotion of Engineering Education
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Joint Committee on Engineering Education of the National Engineering Societies.
CHAPTER I
THE DEVELOPMENT OF ENGINEERING SCHOOLS IN THE UNITED STATES

DURING the Colonial period industrial production in America was almost wholly confined to agriculture. All forms of manufacture were systematically discouraged by acts of Parliament. Iron mining was encouraged, provided the product was shipped to England as pig iron; but all tools, implements, gulls, gunpowder, and machinery used in the colonies had to be purchased in the mother country. This effort to limit American production to agriculture and raw materials was one of the chief causes of the War of Independence.

When the supply of goods from British factories had been cut off by the non-importation agreement between the colonies (1774), clothing, gunpowder, tools, and equipment soon became scarce. An immediate need arose for skilled workers in all the mechanic arts. Congress sought to meet this need by urging the establishment in every colony of a Society for the Improvement of Agriculture, Arts, Manufactures, and Commerce, and by offering premiums for the best achievement in every essential line of industry. Enough was accomplished by these means to carry the war, with the help of France, to a successful termination.

After the war England sought to crush the incipient American industries by selling her goods here at lower prices than were charged at home. The Confederation was threatened by an industrial domination that seemed no less oppressive than political domination. This crisis was met, first, by the formation of numerous societies for the promotion of the useful arts, to encourage a spirit of enquiry, industry, and experiment among the members; second, by offering premiums from state treasuries for such improvements in the useful arts as might seem beneficial to the country; and third, by inviting trained artisans from abroad to settle here and give America the benefit of their training. It was on this basis that Samuel Slater, a skilled English worker from the Arkwright factory, established at Pawtucket in 1790 the first successful textile mill driven by water power.

The real beginnings of American engineering were made at this time under the spur of a patriotic spirit of industrial independence. In 1793 Eli Whitney invented the cotton gin, which determined the industrial future of the South. Oliver Evans made the first machinery for flour mills in 1787, and in 1801 constructed the first high-pressure steam engine. Philadelphia equipped its water works with a double steam pump that had a capacity of 3,000,000 gallons a day, built by Nicholas I. Rooseveltt in 1801. Six years later Robert Fulton made his famous trip up the Hudson in the Clermont. The Santee canal in South Carolina was begun in 1786. Work was started on the Middlesex canal in Massachusetts and on the canal joining the Schuylkill and the Susquehanna rivers in Pennsylvania in 1793. The mechanical inventions were made
by Americans who had no formal engineering training; the canals were built by foreign trained civil engineers.

The effect of the War of 1812 was similar to that of the War of Independence. For three years American production was stimulated by being thrown on its own resources. This was followed by a period of stimulation due to foreign competition. By 181 the exhaustion of the soil because of unscientific methods of agriculture was already driving the population to seek new laud in the West. There arose a loud cry both for instruction in better methods of farming in order that the farms might not be deserted, and for better means of transportation to the West. To meet the latter, the Erie Canal (1817— was built. This was the first great achievement of American engineering, because the work was done by three self-trained Americans, James Geddes, Benjamin Wright, and Charles Brodhead.

The demand for scientific information to increase production in agriculture and domestic manufactures is voiced in an enormous number of memorials, petitions, and committee reports to the various state legislatures. Of these the Report of the Committee on Agriculture presented by Jesse Buel to the New York State legislature on March p29, 18 is perhaps the most complete and expressive. This report urges the establishment of a tax-supported school of agriculture along the lines that had proved so successful at the Fellenberg School at Hofwyl, Switzerland. Full details of the plan, the methods, and the results to be expected are given. It was stated, finally, that if the state would undertake the support of the school, the Hon. Stephen van Rensselaer would donate the necessary land. The proposal was rejected by the legislature.

The following year Mr. van Rensselaer established at Troy the pioneer school of its kind in the United States, the Rensselaer Polytechnic Institute. At the beginning a new type of instruction was used, but it proved too expensive. In 18 the curriculum was revised, a course in civil engineering added, and for a quarter of a century this school divided with the West Point Military Academy the honor of supplying men with scientific training to meet the country's need for engineers. Many of the early graduates of both schools won renown in designing and building the pioneer high ways, bridges, canals, and railroads that led to the conquest of the West.

For engineering education the striking features of this period from 1770 to 1830 are the gradual and persistent growth of the demand for scientific information for the purpose of increasing production, and the scanty attention given to devising ways and means of satisfying it. After twenty-three years of keen discussion, the Rensselaer Polytechnic Institute, which soon specialized in civil engineering, and the West Point Military Academy, which was intended for a totally different purpose, were the only two scientific schools in the country.

In the fifty years from 1820 to 1870 the industrial conditions in the United States were completely reorganized. During this period the percentage of the working population in agriculture dropped from 83 to 47.6; while in manufacturing, trade, and
transportation it increased from 17 to 31.4. In addition a new class called personal
dervention was added and the professional group
expanded from a negligible per cent in 1820 to 3 per cent in 1870. Thus the advent of
the steam engine, the railroad, and the reaper reduced the number of farmers by 354
out of every 1000 workers, increased the number in manufacturing, trade, and trans-
portation by 144, and created the new trade of personal service, giving occupation to
180 per thousand. The professional group also expanded to include 30 per thousand.
The number of patents increased in this same period from about two hundred to over
thirteen thousand per year.

A high degree of engineering ability was required to accomplish this industrial rev-
olution. Among the civil engineers who took part were a number who had the ad-
vantage of scientific training either at Rensselaer or at West Point But in the long list
of mechanical engineers who built the locomotives, the steam engines, the machine
tools, and the farm machinery, it is difficult to find a single one who had any special
school training for the work. As science developed and machinery became more and
more complex, the need of special training for the mechanical engineer became more
pressing. Hence the period from 1820 to 1870 may be said to have indicated the val-
ue of special training for the civil engineer, and to have defined the need for trained
mechanical engineers for industrial production.

Scattered here and there in the vast mass of pamphlets, petitions, memorials, and
reports, addressed to various legislative bodies during these years, urging the estab-
ishment of state schools for training in mechanic arts, there appears another concep-
tion that added inspiration to the industrial demand for schools of science. It is to the
effect that thorough training in science must not only increase production, it must
also raise agriculture and mechanic arts to the rank of the learned professions like
theology, medicine, and law. In the Buel report just mentioned it is urged that be-
cause agriculture is the basis of all industry, it should be elevated to the rank of a lib-
eral and fashionable study. The well-known phrase in the Morrill Act—''to promote
the liberal and practical education of the industrial classes in their several pursuits
and professions in life “—implies the same conception. Some of the earliest engi-
neering schools were called Industrial Universities.

It thus appears that the clearly defined practical demand for training in science as
an aid to industrial production was blended with a vaguely defined ideal of liberal
training thru science. These were the forces that gave scope to engineering in Ameri-
can and compelled the development of the schools.

At first this development was very slow. In spite of the widespread recognition of
the need, the Rensselaer Polytechnic Institute remained for twenty-three years the
only school of its kind. At length in 1847, thru private benefactions, the Lawrence
Scientific School was established at Harvard and the Sheffield Scientific School at
Yale. The University of Michigan also voted that same year to offer a course in civil
engineering. These were the only additional engineering schools opened before the
Civil War, and they had a hard struggle for existence because their aims seemed dangerous to academic traditions.

During the Civil War Congress passed the Morrill Act (1862) granting federal aid to the several states for founding colleges of agriculture and mechanic arts. State legislatures that had for years been deaf to all appeals now quickly accepted the federal grants and voted to create the new type of school. Established colleges caught the spirit and added departments of engineering. The four schools of 1860 increased to seventeen by 1870, to forty-one by 1871, to seventy by 1872 and to eighty-five by 1880. Now there are one hundred and twenty-six engineering schools of college grade, of which forty-six are land grant colleges operating under the Morrill Act, forty-four are professional schools in universities, twenty are attached to colleges, and sixteen are independent. The number of students has increased from fourteen hundred in 1870 to thirty-three thousand in 1917, and the annual number of graduates in engineering from one hundred in 1870 to forty-three hundred. Then there were less than three graduates per million population, now there are about forty-three per million.

The rate of growth of the schools has not been constant. In the decade 1870—80 the number of graduates per million population increased from three to four. The figures for the successive decades are:

<table>
<thead>
<tr>
<th>Decade ending</th>
<th>Increase per million</th>
<th>Graduates per million per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1860</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1870</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>1880</td>
<td>4</td>
<td>0.1</td>
</tr>
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<td>1890</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>1900</td>
<td>17</td>
<td>0.7</td>
</tr>
<tr>
<td>1910</td>
<td>36</td>
<td>1.9</td>
</tr>
<tr>
<td>1916</td>
<td>43</td>
<td>1.1 (6 years)</td>
</tr>
</tbody>
</table>

It is to be noted that growth was rapidly accelerated from 1870 to 1910, especially during the last decade. Since 1910 the growth has been less phenomenal.

This increase in the number of graduates indicates another important change in school conditions. In 1870 the ratio of graduates to the total number of students was one hundred to fourteen hundred, or one to fourteen. In 1915 this ratio was forty-three hundred to thirty-three thousand, or one to seven and seven-tenths. This indicates that a much larger proportion of the students now take the full course; that is, there are relatively fewer stragglers. Back in the ‘70’s the mortality was in many cases as high as 90 per cent, that is, only ten out of every hundred freshmen continued thru the whole course. Now the highest mortality among the schools visited is 75 per cent, and the average for the twenty schools is 60 per cent. Hence the schools have not only increased in size, but their work has been better systematized and standardized.

From figures published by Mr. A. M. Wellington in the Engineering News for 1893

1 See page 32.
and from data presented in the Reports of the United States Commissioner of Education it appears that the total number of engineers graduated in the succeeding decades was approximately

<table>
<thead>
<tr>
<th>Decade</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to 1870</td>
<td>866</td>
</tr>
<tr>
<td>1871—1880</td>
<td>2,259</td>
</tr>
<tr>
<td>1881—1890</td>
<td>3,837</td>
</tr>
<tr>
<td>1891—1900</td>
<td>10,430</td>
</tr>
<tr>
<td>1901—1910</td>
<td>21,000</td>
</tr>
<tr>
<td>1911—1915</td>
<td>17,000</td>
</tr>
</tbody>
</table>

The total number of engineering degrees granted in the United States up to 1915 has therefore been about 55,000. In 1911 the eleven technical high schools of Germany were graduating engineers at the rate of 1800 per year, and the total number of graduates up to that date was 14,215.

In addition to the hundred and twenty-six engineering colleges just discussed there are forty-three degree-giving institutions that pay some attention to engineering work.

Of these, eighteen are arts colleges that claim to give “two years of engineering;” sixteen advertise engineering courses, but have neither the faculty nor the equipment to give them well; four are military schools which occasionally graduate a civil engineer; and five are privately owned institutions which endeavor to teach engineering to all who apply, without regard to previous academic training, and grant a considerable number of degrees on this basis. There are also many excellent schools, like the Wentworth Institute, the Lowell Institute, and the Franklin Union in Boston; the Baltimore Polytechnic Institute, Pratt Institute, the Bliss Electrical School in Washington, the Casino Night School in Pittsburgh, the Dunwoodie Institute in Minneapolis, the Cogswell Polytechnic in San Francisco, and the numerous technical classes of the Young Men’s Christian Association in various places, that teach engineering but make no pretense of granting college degrees. These schools are meeting a real need in a genuinely effective way without departing from their vocational purpose or confusing the educational situation by granting degrees.

The first schools offered only one course—civil engineering. The Massachusetts Institute of Technology opened in 1865 with six curricula leading to degrees in civil, mechanical, and mining engineering, practical chemistry, architecture, and general science. Now the specialized courses at the Institute have increased to fifteen and numerous other specialties are offered at other schools. The additions include all phases of engineering, such as chemical, sanitary, metallurgical, marine, cement, electro chemical, textile, automobile, aeronautical, ceramic, highway, agricultural, and engineering administration. The work of the schools has thus increased in scope and become more complex.

Unfortunately it is not possible to give any even reasonably trustworthy figures as to the resources and the equipment of all the engineering schools, because so many of them are inextricably bound up with colleges and universities. The United States
Bureau of Education still treats engineering under the general heading “Universities, Colleges, and Technological Schools.” In a university with several schools it is a very perplexing problem to determine how much of the total equipment and expense should be charged against any one division such as engineering. In order to secure some estimate of the cost and resources of engineering education, as distinguished from college education, the following summary of the conditions at the sixteen independent schools that devote all their resources to engineering alone is presented. The figures are from the Report of the United States Commissioner of Education for 1916.

In the sixteen independent schools there were, during the year 1914-15, 762 instructors and 6807 students; or on the average one instructor to nine students. The total expenditure for the year was $2,348,000, or an average of $345 per student. The plants were valued at $14,047,000, the equipment at $3,022,000, and they had endowments amounting to $12,985,000.

These sixteen schools are widely distributed over the country, the number of instructors varies from 5 to 290, the number of students from 26 to 1816, the value of the plant from $98,000 to $6,800,000, the endowment from nothing (at state schools) to $3,236,000, the value of equipment from $51,000 to $478,000, and the cost per student year from $204 to $1333. Seven are state institutions and nine are on private foundations. It is therefore not unreasonable to assume that the conditions that maintain for the 6807 students of these schools are typical of conditions for the 33,000 students in all schools. On this assumption, the total annual expenditure for the engineering instruction of 33,000 students at $345 per year is $11,385,000. On the same assumption the total value of the plants used for this purpose is about $68,000,000, the equipment is worth about $15,000,000, and the endowment is about $63,000,000. Altho these figures are merely estimated, they are as trustworthy as any that are available under present conditions.

Since the engineering schools entered upon their remarkable development fifty years ago the conditions of industrial production have changed, new fields of engineering have been developed, the professional ideals of the engineer have grown more definite, laboratory work has won recognition as an essential element of all instruction in science, and educational theory and practice have been brought within the range of scientific test. Under these conditions numerous fundamental questions concerning engineering education have of necessity emerged. Do we need fewer or more schools? Is the curriculum too long or too short? Should the engineering school be made a graduate professional school? What are the present demands of science, of industry, and of education? How well are the schools meeting these demands? What changes, if any, seem desirable?

The answers to questions like these are at present both vague and unconvincing. This study endeavors to define a number of the more important problems of engineering education, and to suggest policies and methods that promise to be fruitful in working toward more satisfactory solutions.
CHAPTER II
THE AIMS AND CURRICULA OF THE EARLY SCHOOLS

ENGINEERING schools are so obviously a result of the needs of industrial production that the conceptions on which they are founded are necessarily much the same for all. Hence three schools—the Rensselaer Polytechnic Institute (1824), the University of Illinois (1867), and the Massachusetts Institute of Technology (1865)—are here selected as typical expressions of the general movement, because the documents relative to the founding of these institutions state their ultimate aims with striking clearness.1

From the evidence presented in the History of the Rensselaer Polytechnic Institute it appears that in planning his school Mr. van Rensselaer was strongly influenced by two foreign institutions: namely, the Royal Institution of Great Britain, which was established by Count Rumford in 1799 as an offshoot of the Society for Increasing the Comforts of the Poor, and was intended to facilitate the general introduction of useful mechanical inventions; and the Fellenberg School at Hofwyl, Switzerland, which sought to educate the children of the poor thru manual work in accordance with methods devised by Pestalozzi. As stated in the official notice of the establishment of the school, its aim was to furnish instruction “in the application of science to the common purposes of life,” in order to train men to teach “the sons and daughters of farmers and mechanics...and who will be highly useful to the community in the diffusion of a very useful kind of knowledge, with its application to the business of living.” Prior to 18 no mention of professional engineers is made beyond the remark in the Buel report (page 5), that because agriculture is the basis of all industry, the state should elevate it “to the rank of a liberal and fashionable study.”

The educational conceptions of the land grant colleges developed gradually during the quarter century from 18 to 1850. They are expressed in numerous memorials to the Federal Congress, petitions to state legislatures, and resolutions of societies for the promotion of agriculture and the mechanic arts. An analysis of the more important of these documents and of the debates in Congress on the several Morrill acts has just been published by the Carnegie Foundation for the Advancement of Teaching in Dr. I. L. Kandel’s Bulletin on Federal Aid for Vocational Education. These conceptions reached their fullest expression in the meetings of the Illinois Industrial League in 1851—53. A very complete statement of the aims of the new schools is made in a memorial sent by the league to the state legislature in 1852.2


2 Ricketts, loc. cit., pages 6-80.

3 E. J. James, loc. cit., pages 90-95.
In this document the memorialists state that as members of the industrial classes personally engaged in agricultural and mechanical pursuits they have forced on their attention constantly the fact that from one-third to one-half of the products of the state are annually sacrificed because of the worker’s ignorance of scientific laws and methods of work. This appalling loss might be prevented if there were established a suitable industrial university to teach what is already known and to carry on investigations of new problems. To secure these ends, it is necessary to establish industrial universities which shall give the industrial classes a thorough scientific and practical training equivalent in all respects to the literary training already given so successfully and abundantly as preparation for the so-called learned professions.

The educational aims and methods required for this purpose were stated forcefully by Professor J. B. Turner in two addresses which are reprinted in President James’s pamphlet. In these Professor Turner makes clear that the conventional forms of instruction in literary colleges are not suitable for industrial training. Book learning alone does not suffice, but must be supplemented by a study of things. The former produces “laborious thinkers,” while industry needs “thinking laborers.” Nor are schools that teach the application of science to the art of killing men fitted to teach scientific methods of feeding, clothing, and housing men. A special type of instruction is needed, — one that analyzes practical problems and sets the student “to earnest and constant thought about the things he daily does, sees, and handles, and all their connected relations and interests.” Men secure true discipline best by “continued habits of reading, thought, and reflection in connection with their several professional pursuits in after life.” In this way schools can “teach men to derive their mental and moral strength from their own pursuits.” There are “more recondite and profound principles of pure mathematics immediately connected with the sailing of a ship, or the moulding and driving of a plow, or an axe, or a jack-plane than with all three of the so-called learned professions together,” and these should be made objects of study in order to “extend the boundaries of our present knowledge in all possible practical directions.”

It is to be noted that the aim of the founders of the “Illinois Industrial University” was increased production and professional recognition. The conception of the need and the methods of training farmers and artisans for increased production in such a way as to elevate their callings to the rank of professions is, however, much more definitely expressed than in the case of Rensselaer. The need for expanding the bounds of knowledge by scientific investigation has also been perceived.

At the Massachusetts Institute of Technology the aims and methods were defined by its first president, William B. Rogers. The seeds of the conception of a polytechnic school were planted in him during his first experience in teaching apprentices at the Mechanics Institute in Baltimore in 1827. The growth of the plan was fostered by his share in the preparation, in 1837, of a petition for the Franklin Institute to the Pennsylvania State Legislature praying for the establishment of a state school of
applied science, and by his formulation for his brother in 1846 of a “Plan for a Poly-
technic School in Boston.”

The final statement of his conceptions was printed in his *Objects and Plan of an*
*Institute of Technology, Boston, 1861*. In this pamphlet, which was issued to attract
support for the enterprise, the argument is this: “Material prosperity and intellectual
advancement are felt to be inseparably associated” (page 1). But material prosperity
requires intelligence in industrial production, and this in turn demands “that systemat-
ic training in the applied sciences, which can alone give to the industrial classes a
sure mastery over the materials and processes with which they are concerned. Such a
training, forming what might be called the intellectual element in production, has, we
believe, become indispensable to fit us for successful competition with other nations
in the race of industrial activity, in which we are so deeply interested” (page 20).
Such a training should not only impart knowledge and develop habits of exact
thought; it should also “help to extend more widely the elevating influences of a gen-
erous scientific culture.” There should also be included “a department of investiga-
tion and publication, intended to promote research in connection with industrial sci-
ence” (page 6).

It appears from the foregoing pages that from the beginning the engineering
schools have, had a clear conception of their functions. They themselves understood
that their ultimate aim was increased industrial production, and that their special con-
tribution to this end was systematic instruction in applied science. In addition they
believed that if this instruction were given with the proper spirit, engineering would
become a learned profession and scientific research a recognized necessity.

The means employed at Rensselaer in 1824 to secure these ends were novel and
unique. The first curriculum required one year for its completion, and was divided
into three terms. School opened the last week in July with an “experimental term,”
during which the students gathered botanical, mineralogical, and zoological speci-
mens, visited shops and factories near the school, and discussed with the class the
significance of what they had collected and observed. In addition each student gave a
number of lectures on chemistry and natural philosophy, fully illustrated by exper-
iments performed with his own hands.

During the second term, from the end of November to the first of March, the stu-
dents reviewed in class the sciences taught in the fall, and in addition studied rheto-
ric, logic, geography, and mathematics. The spring term lasted from the first week in
March to the end of June. For six weeks the work consisted of lectures by the stu-
dents on experimental philosophy, chemical powers, substances non-metallic, metal-
bids, metals, soils, and mineral waters. For the remaining nine weeks the students
were exercised in the application of the sciences to practical projects and in the study
of engineering works in the neighborhood of the school.

In the catalogue published in 1828 the term “civil engineering” occurs for the first time, as one of the topics on which the senior professor would lecture. The catalogue for 1831—32 states that the second sub-term would be devoted to “Trigonometry, Navigation, and the Elements of Civil Engineering.” In 1835 the legislature was petitioned to amend the charter of the school so as to permit the addition of a “department of mathematical arts, for the purpose of giving instruction in engineering and technology.” Graduates of this department were to receive the degree of Civil Engineer. This degree was awarded for the first time in the United States to four members of the class of 1835.

It will be noted that during the first ten years the Rensselaer Institute evolved from a school of natural science designed to train teachers able to spread among farmers and artisans scientific information that would assist them in production, into a school of engineering and technology. The changes in curriculum that accompanied this evolution are striking. The full program for 1835 is printed in President Rickett’s History. A comparison of this curriculum with the first one shows that the “experimental term” at the beginning has disappeared. The school year begins in November with class work in “practical Mathematics, Arithmetical and Geometrical,” combined with “extemporaneous speaking on the subjects of Logic, Rhetoric, Geology, Geography, and History,” and “Lectures on National and Municipal Law” by the senior professor. The second term of twenty-four weeks devotes eight weeks to practice in the use of instruments; eight weeks to study of the theory of mechanical powers, bridges, arches, canals, etc.; four weeks to calculations of the quantity of water per second supplied by streams with reference to their use for various practical purposes; and four weeks to inspection of “mills, factories, and other machinery or works which come within the province of mathematical arts.”

This evolution of the curriculum was carried one step farther in 1849, when the director, Professor B. Franklin Greene, went abroad and made a careful study of French technical schools. On his return the course at Rensselaer was lengthened to three years and a new curriculum adopted. This curriculum is a combination of the curricula of L’Ecole Centrale des Arts et Manufactures, which plans to train civil engineers, directors of works, superintendents of factories, and the like; and L’Ecole Polytechnique, which prepares for certain government technical institutions. The first half of the curriculum was intended to lay the general scientific basis of all engineering, and the second half to develop proficiency in some special line. This curriculum is given here in full along with the first three years of the first curricula of the Massachusetts Institute of Technology (1865) and the University of Illinois (1867).
## First Year

<table>
<thead>
<tr>
<th>Rensselaer</th>
<th>Massachusetts Institute</th>
<th>University of Illinois</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algebra, geometry,</td>
<td>Algebra, solid geometry,</td>
<td>Algebra, geometry, trigonometry</td>
</tr>
<tr>
<td>trigonometry</td>
<td>trigonometry</td>
<td>trigonometry</td>
</tr>
<tr>
<td>General physics</td>
<td>Elementary mechanics</td>
<td></td>
</tr>
<tr>
<td>Geometrical drawing</td>
<td>Drawing — mechanical and freehand</td>
<td>Descriptive geometry and drawing</td>
</tr>
<tr>
<td>English</td>
<td>English</td>
<td>English or</td>
</tr>
<tr>
<td>Foreign language</td>
<td>Foreign language</td>
<td>Foreign language</td>
</tr>
<tr>
<td>Surveying</td>
<td>Chemistry — inorganic</td>
<td>History</td>
</tr>
<tr>
<td>Botany</td>
<td></td>
<td>Botany</td>
</tr>
</tbody>
</table>

## Second Year

<table>
<thead>
<tr>
<th>Rensselaer</th>
<th>Massachusetts Institute</th>
<th>University of Illinois</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytics calculus</td>
<td>Analytics calculus</td>
<td>Analytics calculus</td>
</tr>
<tr>
<td>General physics</td>
<td>Physics</td>
<td></td>
</tr>
<tr>
<td>Chemistry</td>
<td>Chemistry</td>
<td></td>
</tr>
<tr>
<td>Descriptive geometry,</td>
<td>Descriptive geometry, machine</td>
<td>Descriptive geometry, drawing</td>
</tr>
<tr>
<td>machine drawing</td>
<td>and freehand drawing</td>
<td></td>
</tr>
<tr>
<td>Topographical and hydro-</td>
<td>Surveying—plane</td>
<td>Surveying</td>
</tr>
<tr>
<td>graphical surveying</td>
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<td></td>
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<tr>
<td>English</td>
<td>English</td>
<td></td>
</tr>
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<td>Foreign language</td>
<td>Foreign language</td>
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<td>Mineralogy</td>
<td>Astronomy, navigation</td>
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<td>Zoology</td>
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<tr>
<td>Geology</td>
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</tr>
</tbody>
</table>

## Third Year

<table>
<thead>
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<th>Massachusetts Institute</th>
<th>University of Illinois</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanics</td>
<td>Calculus, analytic and applied</td>
<td>Calculus, analytic mechanics</td>
</tr>
<tr>
<td>Practical astronomy</td>
<td>Spherical astronomy</td>
<td>Descriptive astronomy</td>
</tr>
<tr>
<td>Geodesy—trigonometrical,</td>
<td>Surveying — roads,</td>
<td>Railroad surveying</td>
</tr>
<tr>
<td>railroad and mine surveying</td>
<td>railroads and canals</td>
<td></td>
</tr>
<tr>
<td>Descriptive geometry —</td>
<td>Descriptive geometry —</td>
<td>Shades, shadows, perspective</td>
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<tr>
<td>perspective, topographical</td>
<td>masonry and carpentry</td>
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<tr>
<td>drawing, stereotomy</td>
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<td></td>
</tr>
<tr>
<td>Industrial physics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>English</td>
<td>Physics</td>
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</tr>
<tr>
<td>Practical geology</td>
<td>English</td>
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</tr>
<tr>
<td>Physical geography</td>
<td>Drawings, plans, etc.</td>
<td></td>
</tr>
<tr>
<td>Machines</td>
<td>Foreign languages</td>
<td>Chemistry</td>
</tr>
<tr>
<td>Constructions —theory of</td>
<td>Computation of earth</td>
<td></td>
</tr>
<tr>
<td>structures, bridges,</td>
<td>work and masonry</td>
<td></td>
</tr>
<tr>
<td>hydraulic works, railways</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mining</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metallurgy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Philosophy of mind</td>
<td>Hydrographical surveying</td>
<td></td>
</tr>
</tbody>
</table>

The curricula at the Massachusetts Institute and the University of Illinois did not evolve thru a period of years. They were simply adopted in the form given. How much influence the Rensselaer curriculum had in shaping the others it is impossible to say. Internal evidence suggests that this influence was large.
A comparison of these three curricula indicates that the general plan is very much the same in all. The third year at Rensselaer contains some of the technical courses that appear in the fourth year of the other two schools. But they all agree in placing mathematics, drawing, descriptive geometry, physics, and chemistry before the work in applied science. In other words, they all sought to meet the demand for increased production by first teaching the necessary theoretical science and then showing how to apply it. This was the plan in the French schools, and it was transplanted without change to America. It remained and still is the prevailing conception underlying the curricula of our engineering colleges.

But tho these three curricula agree in general plan, the methods of handling the work in the three schools were quite different. The system of instruction by the students, which has already been described, had by 1865 given place at Rensselaer to the system now used there of interrogations and blackboard demonstrations. Field trips and the observation of industrial processes in action in neighboring shops had been discontinued. These changes were made necessary by the increased attendance at the school.

At the University of Illinois the instruction in theory was given by lectures and recitations from textbooks combined with the use of plates and models. This was in a way coordinated with shopwork, in that machinery planned in the drafting room was actually constructed in the shops. Much of the early equipment, including an eight horse power steam engine, was constructed by the students in this way. Opportunities for manual labor for pay were offered the students, and many of them earned enough to meet their expenses by making furniture and apparatus in extra hours of shopwork. A chemical laboratory was part of the earliest equipment.

At the Massachusetts Institute there was no shopwork until 1877. The lecture-recitation method of instruction was used in all class work, but this was supplemented by laboratory work in physics and mechanical engineering. The first laboratory for undergraduate instruction in physics was opened here by Professor E. C. Pickering in 1869. The organization and many of the experiments he devised are still used in physics laboratories. The teaching was necessarily very like that in other colleges because all the professors had been trained in existing schools devoted mainly to literary studies.
CHAPTER III
THE STRUGGLE FOR RESOURCES AND RECOGNITION

THE Rensselaer Institute began work in 1824 in a rented house with several hundred dollars worth of equipment, all of which was supplied by the Hon. Stephen van Rensselaer. There were 25 students the first year, each of whom paid $36 tuition, and these fees were paid to the two professors as their remuneration. During the first eight years the founder paid about half the cost of maintenance—a total of $22,000. By that time the value of the equipment had increased to $4000. For twenty years work was conducted in rented quarters. Finally, in 1844, a house and lot were given the school by the city of Troy on condition that a fund equal to the value of the property be raised for maintenance. For this purpose Mr. William P. van Rensselaer gave $6500, and $1150 was raised by subscription to build a chemical laboratory. That year there were 75 students, the tuition was $40 a year, and the total value of the plant was appraised at $15,850.

In 1850 the course was lengthened to three years and the tuition raised to $60 a year. Tuition was increased to $100 in 1857, to $150 in 1864, and to $200 in 1866, at which figure it still remains. In 1851 the state gave the institution $3000 and ten years later $3750, for general purposes. After the fire that destroyed the buildings in 1862, the state gave $10,000 to help rebuild, and this was increased by a further grant of $15,000 in 1868. From 1846 to 1854 the school was classed as an academy by the state Board of Regents and as such received $744 in all as its share of the literature moneys distributed to the academies of the state. These figures represent the entire support granted by the state, a total of $32,494.

From these facts it appears that prior to the beginning of the Civil War this institution owed its existence almost wholly to private benefactions and to the devoted services of its staff, whose enthusiasm and self-sacrifice made the continuance of the work possible with meagre equipment and slender resources. The experience of other schools of this period was similar. At Yale the scientific school was started in 1847, when Professors Silliman and Norton opened a laboratory for practical instruction in the application of science to the arts of agriculture. Professor Norton was permitted to hold the chair of agricultural chemistry on condition that he should draw no salary; this entire enterprise was housed mainly in the chapel attic until 1860, when Joseph E. Sheffield supplied the funds needed to place it on a permanent footing. The Lawrence Scientific School at Harvard was more fortunate in that its early financial support was assured by the gift of Mr. Abbott Lawrence in 1847. The engineering department at the University of Michigan was the one state-supported school of engineering before 1860, but no engineering degrees were granted there until 1861.

Science and engineering in America owe a great deal to the Rensselaer Polytechnic Institute. Founded at a time when the great masses of the people knew little about
science and cared less, it quietly and persistently trained teachers and engineers who
diffused scientific information and built many of the railways, roads, and bridges that
were essential to the success of the industrial evolution. By 1860 it had graduated 318
men, while from the West Point Military Academy, for many years the only other
school for scientific training, but 200 of the graduates entered engineering before
1860. The Lawrence School at Harvard graduated 49 men before the Civil War, in
the face of an unconcealed disdain on the part of the regular faculty.

It is a very striking fact that before the Civil War so little progress was made in the
establishment of schools of science. Altho there were many far-seeing men who
urged the need of them in memorials, addresses, and petitions to legislatures, there
was little action before 1860. But a great change occurred during the strife and tur-
moil of battle. Congress passed the Morrill Act in 1862, thereby creating in each state
a fund for the establishment of a college “for the liberal and practical education of the
industrial classes in their several pursuits and professions in life.” In 1861 the Massa-
chusetts State Legislature granted a charter and a tract of land to the Massachusetts
Institute of Technology, and in four years over $100,000 had been raised by subscrip-
tion for a building, and the school had opened for work. The School of Mines at Co-
lumbia (1864), the Thayer School at Dartmouth (1867), Cornell University (1867),
the Worcester Polytechnic Institute (1868), were established at this time. In addition
the states of Illinois, California, Iowa, New York, New Jersey, Maine, Michigan,
New Hampshire, Pennsylvania, Tennessee, Vermont, and Wisconsin accepted the
terms of the Federal land grant of 1862 before 1870.

But altho after the Civil War money began to flow toward the support of technical
education, the financial struggles of the schools were by no means ended. At the
Massachusetts Institute in 1868, in spite of stringent economy, the total income of the
school was $34,230 and the total expense $42,650. The deficit had to be made up by
subscription among the friends of the project. At this time the tuition was $100 for
the first year, $125 for the second, and $150 each for the third and fourth. But the
total cost per student per year was $250. At Harvard it was then $180, at Yale $126,
at Columbia $115, at Brown $178, at Amherst $80, and at the University of Pennsyl-
vania $42. At the new Illinois Industrial University, with a total income in 1869 of
$35,000 and 156 students, it was $224, and there were no tuition fees. In other words,
the schools soon found that instruction in science was not only new, but more expen-
sive than regular college teaching, because of the relatively high cost of laboratory
work and the small number of students.

In the thirty years from 1870 to 1900 the schools slowly grew stronger and more
secure. The plant at Illinois increased in value from $186,000 in 1870 to $1,300,000
in 1900, or at the average of $37,000 a year. At the same time the annual income in-
creased from $35,000 to $483,000, or at the average rate of about $15,000 a year.
The student increase during this period was from 156 to 1756, the average rate being
53 per year.
The complete figures for the typical schools, compiled from the early records and the Reports of the United States Bureau of Education for 1900 and 1916, are given in the following table:

<table>
<thead>
<tr>
<th></th>
<th>1870</th>
<th>1900</th>
<th>1916</th>
<th>Increase 1870-1900</th>
<th>Increase 1900-1916</th>
<th>Ratio II/I</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VALUE OF PLANT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILLINOIS</td>
<td>$186,000</td>
<td>$1,300,000</td>
<td>$5,152,000</td>
<td>$1,114,000</td>
<td>$3,852,000</td>
<td>$37,000</td>
</tr>
<tr>
<td>MASS. INST.</td>
<td>400,000</td>
<td>911,000</td>
<td>6,778,000</td>
<td>511,000</td>
<td>5,867,000</td>
<td>17,000</td>
</tr>
<tr>
<td>RENSSELAER</td>
<td>50,000</td>
<td>240,000</td>
<td>1,521,000</td>
<td>190,000</td>
<td>1,281,000</td>
<td>6,300</td>
</tr>
</tbody>
</table>

| **ANNUAL INCOME** |      |      |      |                   |                   |            |
| ILLINOIS   | $35,000 | $483,000 | $2,209,000 | $448,000 | $1,726,000 | $15,000 | $108,000 | 7 |
| MASS. INST. | 45,000 | 348,000 | 817,000 | 303,000 | 469,000 | 10,100 | 29,300 | 3 |
| RENSSELAER | 19,000 | 49,632 | 225,000 | 30,000 | 175,000 | 1,000 | 11,000 | 11 |

| **NUMBER OF STUDENTS** |      |      |      |      |      |      |      |      |
| ILLINOIS   | 156 | 1,756 | 5,523 | 1,600 | 3,767 | 53 | 235 | 4 |
| MASS. INST. | 167 | 1,178 | 1,816 | 1,011 | 638 | 34 | 40 | 1.2 |
| RENSSELAER | 125 | 250 | 545 | 125 | 295 | 4 | 18 | 4.5 |

From these figures it appears that the resources and attendance increased steadily but moderately during the period from 1870 to 1900. Since 1900 the development has not only been rapid; but the buildings, equipment, and expenditures have increased much more rapidly than the number of students. Because of this the total expenditure per student per year has practically doubled since 1900, and every institution in the country is finding it yearly more difficult to live within its income.

The above figures, while as trustworthy as any that can be obtained, are not accurate to within 5 per cent or so. They, however, indicate the general drift clearly enough. In the decade from 1871 to 1880 private benefactions to education averaged $6,000,000 a year. In the past decade they have averaged $26,000,000 a year. In like manner total expenditures for education in the United States have increased from about $75,000,000 a year in 1870 to $240,000,000 in 1900 and to nearly a billion in 1916. The yearly increase up to 1900 was about $5,500,000; since then it has been $48,000,000, or nine times as great.

This growth of the engineering schools in size and resources has been closely par-
alleged by the development of the engineering profession and of the manufacturing activities of the country. As has been pointed out (page 5), the elevation of the mechanic arts to the rank of a learned profession has always been one of the conscious aims of instruction in applied science. This aim was very vague indeed when the Rensselaer Polytechnic Institute was founded, for at that time there was no engineering profession to define professional standards as a guide to the schools.

The first effort toward a more specific definition of the profession was made in 1839 by Benjamin Latrobe, John F. Houston, Benjamin White, and others, when they tried to establish a national society of civil engineers. This effort was not successful. The present American Society of Civil Engineers was established in 1852 and held its first national convention in 1869. The mining engineers attained this same degree of professional consciousness in 1872, when the American Institute of Mining Engineers was founded. The American Society of Mechanical Engineers was established in 1883, and the American Institute of Electrical Engineers in 1884.

The Census Reports are no more satisfactory concerning engineering than are the Reports of the United States Bureau of Education (page 17). The Report for 1850 lists 512 civil engineers. In 1860 the corresponding entry is 27,437 civil and mechanical engineers, with a footnote stating that this includes stationary engine and locomotive engineers. In 1870 the heading is “electricians, engineers (civil, etc.), and surveyors 7,374.” Under the heading the number in 1880 is given as 8261; in 1890 it is 43,239, and in 1900 it has increased to 93,956. The several branches of the profession are recognized for the first time in the 1910 report, which enumerates 14,514 engineers (mechanical), 6930 mining engineers, 52,033 civil engineers and surveyors, and 135,519 electricians and electrical engineers—a total of 208,996. Probably not more than 80,000 of these engineers enumerated by the census could qualify for membership in any of the professional societies mentioned, which now have about 80,000 members. Recently a number of new engineering societies have been organized, representing cement, automobiles, electric light, electric traction, etc. The total membership in all the societies having headquarters in the Engineering Societies Building in New York is about 53,000.

The rate of growth of the engineering societies is shown in the following table:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Civil Engineers</td>
<td>1852</td>
<td>2227</td>
<td>7909</td>
<td>1984 (since 1870)</td>
<td>5682</td>
<td>66</td>
</tr>
<tr>
<td>Mining Engineers</td>
<td>1872</td>
<td>2661</td>
<td>5234</td>
<td>2661</td>
<td>2573</td>
<td>95</td>
</tr>
<tr>
<td>Mechanical Engineers</td>
<td>1883</td>
<td>1951</td>
<td>6931</td>
<td>1951</td>
<td>4980</td>
<td>114</td>
</tr>
<tr>
<td>Electrical Engineers</td>
<td>1884</td>
<td>1273</td>
<td>8212</td>
<td>1273</td>
<td>6939</td>
<td>80</td>
</tr>
</tbody>
</table>
These figures indicate that the professional societies, like the schools, have grown much more rapidly since 1900. This probably does not result so much from mere increase in the total number of engineers in the country, as from an awakening and expansion of professional consciousness. The establishment of the Engineering Foundation in 1915, the cooperation of the engineering societies with the National Academy of Science in the National Research Council, the bill to charter an American Academy of Engineers introduced into Congress in 1917, and the recent discussion of the status of the engineer also indicate that the engineers have only just reached that state of professional consciousness where they are able to define their status among the professions. This definition is now in process of formulation; and until it is announced, it is unreasonable to expect the statisticians at the Census Bureau or the Bureau of Education to distinguish clearly between the professional civil engineer and the surveyor or between the electrician and the electrical engineer.

The part played by the colleges in this development of professional spirit may be estimated from the fact that the various schools had graduated 866 engineers up to 1870, or less than one-ninth of the 7374 practising engineers in the country at the time. As indicated on page 7, the total number of engineering degrees granted in the United States has been approximately 55,000. Since a number of these graduates have died and perhaps a fifth of them have gone into other lines of work, it is safe to say that there are not more than 40,000 graduates of American engineering colleges in engineering practice to-day. If the number of professional engineers is approximately 80,000, it follows that now possibly about one out of every two is a college graduate. Since this ratio was only one in eight or nine in 1870, the magnitude of the contribution of the schools to the development of the profession is obvious.

The growth of the second powerful influence on the development of the engineering schools—the manufacturing industries—is indicated by the following facts: The total value of manufactured products in the United States in 1870 was 3400 million dollars. In 1900 the value was 13,000 million dollars, and in 1916 it was 32,200 million dollars. The increase in value of manufactured products for the period 1870—1900 was therefore 9600 million dollars, or at the average rate of 320 million a year. In the sixteen years from 1900 to 1916 this increase was 18,200 million dollars, or at the average rate of 1138 million a year. Hence, like the schools and the professional societies, the manufacturing industries have developed much more rapidly in the twentieth century than in the nineteenth.

The attitude of these industries toward the college-trained man is indicated by the fact that of the 4622 technically trained men now employed by 98 representative manufacturing establishments 1992, or 43 per cent, have engineering degrees. The highest ratio is in the field of metal refining, where 87 per cent of the technical men are college graduates. The lowest ratio is in the automobile trade, where only 49 out of 186, or 24 per cent, are college-trained men. In shipbuilding the ratio is 48 per cent, 359 out of 735, and in machinery and machine tools it is 41 per cent, 836 out
of 2043. In response to the question “Do you employ men graduated from engineering colleges in preference to men trained mainly thru practical experience?” 60 out of 120 firms answered “yes;” 40, or one-third of the number, answered “no;” and 20, or one-sixth of the whole number, expressed no preference.

It is difficult to interpret the interplay that has been going on among industry, science, and engineering. At the close of the Civil War science had but scant recognition either in educational institutions or among the masses of the people. Now it has assumed a commanding position because of the transformations it has wrought in the daily life of every one thru its varied and fruitful inventions. In this development there has been no regular procedure, no well-defined organization. It has been a matter of independent action and individual effort. Sometimes it was the college professor of science, pure or applied, sometimes it was the inventor or the professional engineer, and sometimes it was the manufacturing industry that took the initiative, conceived the new idea, or made the new discovery, and sought the assistance of the others in realizing it in practice. Now evidences are multiplying to show that the time has come for a clearer definition of the relations among research, instruction, engineering practice, and industrial production. How to coordinate these elements most effectively is a large and pressing problem. Further consideration of the meaning of this problem to the engineering schools is given in Chapter XII.
CHAPTER IV

THE DEVELOPMENT OF THE ENGINEERING CURRICULUM INTO ITS PRESENT FORM

IN the fifty years that have elapsed since the curricula described in the second chapter were established a number of striking changes have taken place. The general nature of these changes is indicated in the following tables, which give the data for two of the schools selected as typical. The Rensselaer Polytechnic Institute has been omitted because its early programs do not give the number of hours per week assigned to the various subjects.

ENTRANCE REQUIREMENTS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

<table>
<thead>
<tr>
<th>1870</th>
<th>1914</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic</td>
<td>Algebra A</td>
</tr>
<tr>
<td>Geography</td>
<td>Algebra B</td>
</tr>
<tr>
<td>Algebra to quadratics</td>
<td>Plane geometry</td>
</tr>
<tr>
<td>Plane geometry</td>
<td>Solid geometry</td>
</tr>
<tr>
<td>English grammar</td>
<td>English composition</td>
</tr>
<tr>
<td></td>
<td>English literature</td>
</tr>
<tr>
<td></td>
<td>Physics</td>
</tr>
<tr>
<td></td>
<td>French</td>
</tr>
<tr>
<td></td>
<td>German</td>
</tr>
<tr>
<td></td>
<td>Electives</td>
</tr>
</tbody>
</table>

UNIVERSITY OF ILLINOIS

<table>
<thead>
<tr>
<th>1867</th>
<th>1915</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic</td>
<td>Algebra A</td>
</tr>
<tr>
<td>Geography</td>
<td>Algebra B</td>
</tr>
<tr>
<td>Algebra to quadratics</td>
<td>Plane geometry</td>
</tr>
<tr>
<td>Plane geometry</td>
<td>Solid and spherical geometry</td>
</tr>
<tr>
<td>English grammar</td>
<td>English composition</td>
</tr>
<tr>
<td></td>
<td>English literature</td>
</tr>
<tr>
<td>United States history</td>
<td>Physics</td>
</tr>
<tr>
<td></td>
<td>Electives</td>
</tr>
</tbody>
</table>

In 1867 admission was by examination. Graduation from high school was not mentioned, the sole requirement being ability to meet the tests and an age limit of 16 years. Admission is still by examination at the Massachusetts Institute of Technology, while at the University of Illinois it is now mainly by certificate from accredited high schools.

It will be noted that arithmetic and geography are no longer required, probably because it is assumed that they have been satisfactorily completed in the grammar school.

* The unit is generally defined as one-quarter of a year's work in a secondary school.
STUDY OF ENGINEERING EDUCATION

The number of examinations (or subjects required) has increased from 5 or 6 to 8 or 10. The amount of algebra, geometry, and English required has been increased by from 50 to 300 per cent. The content and methods of instruction in the various high school units have also been carefully defined and standardized by the College Entrance Examination Board, the National Educational Association, and several other associations in which colleges and secondary schools are represented.

These changes are the direct result of the development of the public high schools. Altho the average age of entrance to college has remained constant at about 19 years, the present freshman has had more instruction and more highly systematized instruction in more subjects than was possible before the recent striking development of secondary education.

At present all but 4 of the 126 engineering colleges require at least 14 units for admission without condition. These four are tax-supported institutions in states where the public school systems have not developed to the point where the requirement of four years of preparatory work would be justified. They are raising their requirements as fast as local conditions permit. Forty of the schools still advertise that they accept students with two or three units of conditions. All admit either by certificate from accredited high schools or by examination excepting the Massachusetts Institute and the Sheffield Scientific School, which admit by examination only. West of the Alleghenies entrance examinations are rare.

The number of units specifically prescribed for admission varies from 5 at the North Carolina College of Agriculture and Mechanic Arts, to 13 at Yale and George Washington University, or even to 14 at Notre Dame University. Half specify 10 or less, and half specify more than 10. All agree in demanding English and mathematics, the amounts varying from 2 to 4 units. In English nine-tenths of the schools regard 3 units as standard, while in mathematics six-tenths have settled upon 3 as standard, half of the remainder requiring more and half less. History is specifically required by 71 per cent of the schools and one science (physics or chemistry) by 73 per cent. One-third, mostly land grant colleges and state universities, require no foreign languages for admission.

The nature of the changes in the distribution of time in the curriculum itself is indicated by the following typical cases. The unit is the semester-hour.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

<table>
<thead>
<tr>
<th>Mechanical Engineering</th>
<th>Per cent of Total Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1867</td>
</tr>
<tr>
<td>Foreign languages</td>
<td>81</td>
</tr>
<tr>
<td>English</td>
<td>14</td>
</tr>
<tr>
<td>History</td>
<td>3</td>
</tr>
<tr>
<td>General studies</td>
<td>0</td>
</tr>
</tbody>
</table>

Total: 48 31 31 18
DEVELOPMENT OF THE ENGINEERING CURRICULUM

<table>
<thead>
<tr>
<th>Subject</th>
<th>1867</th>
<th>1914</th>
<th>1867</th>
<th>1914</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mathematics</td>
<td>16</td>
<td>17</td>
<td>1867</td>
<td>1914</td>
</tr>
<tr>
<td>Chemistry</td>
<td>8</td>
<td>17</td>
<td>1867</td>
<td>1914</td>
</tr>
<tr>
<td>Physics</td>
<td>12</td>
<td>14</td>
<td>1867</td>
<td>1914</td>
</tr>
<tr>
<td>Geology</td>
<td>2</td>
<td>0</td>
<td>1867</td>
<td>1914</td>
</tr>
<tr>
<td>Mechanics</td>
<td>4</td>
<td>13</td>
<td>1867</td>
<td>1914</td>
</tr>
<tr>
<td>Drawing and descriptive geometry</td>
<td>49</td>
<td>17</td>
<td>1867</td>
<td>1914</td>
</tr>
<tr>
<td>Mechanical engineering</td>
<td>10</td>
<td>0</td>
<td>1867</td>
<td>1914</td>
</tr>
<tr>
<td>Machinery and motors</td>
<td>4</td>
<td>0</td>
<td>1867</td>
<td>1914</td>
</tr>
<tr>
<td>16 specialized courses in M. E.</td>
<td>0</td>
<td>63</td>
<td>1867</td>
<td>1914</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>80</td>
<td>1867</td>
<td>1914</td>
</tr>
</tbody>
</table>

The most notable changes in the mechanical engineering curriculum of the Massachusetts Institute of Technology, as noted above, are:

- The reduction of the foreign language requirement from 31 to 7 credit hours. This is partly a result of better language work in preparatory schools.
- The apparent reduction of the English requirement from 14 to 8 credit hours. In interpreting this fact it must be noted that in 1867 the study of political economy, the United States Constitution, and some history of civilization were included under the head of English. Subjects like these are now provided for in the 12 credit hours of general studies. On the whole, however, the time given to these “humanities” has been reduced from 31 per cent to 18 per cent of the total.
- In the science group, chemistry has increased from 8 to 17 credit hours, and mechanics now gets 13 instead of 4. This latter increase is noteworthy because the fundamental principles of mechanics have not changed materially in the past fifty years. Some of the additional time is devoted to laboratory work in applied mechanics, strength of materials, etc. Mathematics and physics retain practically the same time allowance. The time given to science has in general increased from 27 per cent to 36 per cent.
- The technical subjects have been given more time (from 63 to 80 credit hours), although their percentage has increased but little (42 to 46). They have, however, been specialized to a high degree. The only technical subjects mentioned in the program for 1867 were drawing (47 hours), mechanical engineering (10), machinery and motors (4), and stereotomy (2). Today the mechanical engineer must take drawing (17 hours), heat engineering (7), mechanism (6), boiler design (8), engineering laboratory (3), electrical engineering (7), machine design (8), dynamics of machinery (2), hydraulics (5), factory construction (3), power plant design (4), foundations (1), refrigeration (1), heating and ventilating (1), and shopwork (10).
- This increasing specialization has not been confined to the subject-matter of each curriculum. In 1886 the civil engineering curriculum was divided into three sub-specialties, civil engineering, railroad engineering, and topographical engineering.
Following year mechanical engineering was divided into marine engineering, locomotive engineering, and mill engineering. As a result, the six different curricula of 1867 have now expanded into more than twenty. Fifty years ago the work of the first two years was the same in all six curricula; now specialization begins in the middle of the first year. Then a student carried only four or five courses at one time; now he carries from eight to thirteen.

The following table gives the distribution of time among the three main divisions of the materials of instruction for two curricula in the two typical schools together with the average for all 126 schools. The figures are per cents.

<table>
<thead>
<tr>
<th>1867</th>
<th>Languages</th>
<th>Mathematics</th>
<th>Drawing</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILLINOIS C. E.</td>
<td>25</td>
<td>33</td>
<td>42</td>
</tr>
<tr>
<td>ILLINOIS M. E.</td>
<td>24</td>
<td>40</td>
<td>36</td>
</tr>
<tr>
<td>MASSACHUSETTS INSTITUTE OF TECHNOLOGY C. E.</td>
<td>29</td>
<td>29</td>
<td>42</td>
</tr>
<tr>
<td>MASSACHUSETTS INSTITUTE OF TECHNOLOGY M. E.</td>
<td>31</td>
<td>27</td>
<td>42</td>
</tr>
<tr>
<td>Average</td>
<td>27</td>
<td>32</td>
<td>41</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1914</th>
<th>Languages</th>
<th>Mathematics</th>
<th>Drawing</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILLINOIS C. E.</td>
<td>12</td>
<td>30</td>
<td>58</td>
</tr>
<tr>
<td>ILLINOIS M. E.</td>
<td>14</td>
<td>33</td>
<td>53</td>
</tr>
<tr>
<td>MASSACHUSETTS INSTITUTE OF TECHNOLOGY C. E.</td>
<td>17</td>
<td>35</td>
<td>48</td>
</tr>
<tr>
<td>MASSACHUSETTS INSTITUTE OF TECHNOLOGY M. E.</td>
<td>18</td>
<td>36</td>
<td>46</td>
</tr>
<tr>
<td>Average</td>
<td>15</td>
<td>34</td>
<td>51</td>
</tr>
<tr>
<td>Average (all schools)</td>
<td>19</td>
<td>29</td>
<td>52</td>
</tr>
</tbody>
</table>

There is no agreement as to what percentage of time should be devoted to each of these main groups of subjects. The percentage devoted to professional work varies from 25 at Northwestern, or 30 at Johns Hopkins University, to 70 at Cornell, or even to 85 at the Michigan College of Mines. Similarly there is no accepted proportion for individual subjects like calculus, which varies from 52 hours at Rensselaer to 216 hours at the University of Florida. The requirement in languages in college varies from zero at Leland Stanford, the University of Virginia, and Cornell, to 408 hours (18 per cent) at the Sheffield Scientific School at Yale, or to 594 hours (18 per cent) at the Virginia Polytechnic Institute. The total number of hours of assigned work required for graduation varies from 2000 to 3800, and the number of required credit hours per week varies from 16 to 28.

At several of the schools visited efforts are being made to adjust the requirements of the several courses in such a way that a student will be able to accomplish the work in 50 hours a week, including class work, laboratory work, and outside preparation. As a matter of fact few students succeed in keeping up to grade without spending much more than this on their work. If a student is able to keep within the limit, he has, when he is carrying thirteen courses, on the average 3 hours, 50 min-
utes, and 46.15 seconds per week for each. Rensselaer is the only school among those visited that limits the students to three subjects at any one time. There each subject is pursued intensively for a stated period that varies from one to fourteen weeks. Thus the freshman begins work with chemistry, drawing, and French. At the end of eight weeks his three subjects are algebra, drawing, and French. In the second term he begins with trigonometry, French, and steam engineering, which is changed at the end of five weeks to gas analysis, French, and physics. By this means, altho he carries but three studies at one time, he actually completes from ten to eighteen different subjects each year.

There is almost unanimous agreement among schools, parents, and practising engineers that at present the engineering curriculum whatever its organization, is congested beyond endurance. It is obviously absurd to require from the student more hours of intense mental labor than would be permitted him by law at the simplest manual labor. Yet on all sides the pressure of topics and subjects that have become important because of the extraordinary growth of science and industry is constantly increasing. In 1870 a student might choose his specialty at the end of his second year; now he must decide in many cases in the middle of his first year. Formerly the choice lay among civil, mechanical, and mining engineering; now the selection must be made from aeronautical, agricultural, architectural, automobile, bridge, cement, ceramic, chemical, civil, construction, electrical, heating, highway, hydraulic, industrial, lighting, marine, mechanical, metallurgical, mill, mining, railway, sanitary, steam, textile, telephone, topographical engineering, and engineering administration. No one school offers curricula in all of these specialties. But all are offered somewhere, and enough are given at every school to render the selection during the freshman year of his life’s specialty a peculiarly difficult matter for the student.

From the wide variations in the amount of time required for completing the course and the great diversity of ways in which the schools have met the demands of increasing specialization in industry it is clear that they have reached no general agreement as to how to deal with the problem. Each has sought to adjust itself as best it could to the immediate demands in its locality, and has added specialized courses as the need for them appeared. But tho there are many variations in the details of curricula at the several schools, all have remained true to the original conception of the early curriculum; namely, that instruction in the general principles of science and in the humanities should precede instruction in the various technical specialties. In nearly all curricula the work of the freshman year consists of chemistry, mathematics, English, foreign languages, and drawing. The work of the sophomore year, while not so well standardized, very generally contains calculus, physics, some language study, and drawing, with here and there a few of the engineering courses. The junior and senior years are filled to overflowing with specialized technical courses.

The present curricula are thus the natural result of two well-defined influences; namely, the original curriculum that was imported from France in 1849 by Professor
B. F. Greene of Rensselaer, and the phenomenal expansion of science and industry. Meanwhile, two other influences have been gradually developing—the engineering profession and the science of education. The bearing of these on present practices is discussed in the later chapters.

Since the plan on which this study was carried out did not contemplate a complete survey of engineering schools or a grading of them into classes as good, bad, or indifferent, only twenty typical schools were visited. The examples in the following chapters are therefore drawn in the main from these schools, selected not because of their geographical location, but because they seemed representative of all types of engineering college. The author wishes here to express his appreciation of the cordial manner in which all college presidents and teachers cooperated in securing all the information sought and in frankly discussing mooted points. The twenty schools visited were the following:

The United States Military Academy, West Point, N. Y.
Rensselaer Polytechnic Institute, Troy, N. Y.
Massachusetts Institute of Technology, Cambridge, Mass.
Stevens Institute, Hoboken, N. J.
Carnegie Institute of Technology, Pittsburgh, Pa.
Columbia University, New York, N. Y.
Tufts College, Tufts College, Mass.
Virginia Polytechnic Institute, Blacksburg, Va.
Purdue University, Lafayette, Ind.
Cornell University, Ithaca, N. Y.
Sheffield Scientific School, Yale University, New Haven, Conn.
University of Virginia, Charlottesville, Va.
University of Pittsburgh, Pittsburgh, Pa.
University of Illinois, Urbana, Ill.
University of Wisconsin, Madison, Wis.
Ohio State University, Columbus, Ohio.
University of Cincinnati, Cincinnati, Ohio.
CHAPTER V

METHODS OF ADMINISTRATION IN ENGINEERING SCHOOLS

The final control of American Engineering Schools, as of the colleges and universities, is vested in a board of trustees or regents. In the case of state institutions the members of the governing board are usually appointed by the state governors, while in independent institutions they are self-elected for long terms. Generally the regents or trustees are citizens who have won distinction in either professional or industrial life. In a few cases a limited number of members of the faculty are also members of the board; but as a rule all communication between the faculty and the board is thru the president.

The regents or trustees are charged with the financial management of the schools. They elect the president on their own initiative and appoint or promote members of the faculty on his recommendation. All appropriations, to be legal, must have their sanction, and educational policies framed by the president or the faculty are nominally subject to their veto. This organization places large responsibilities on the president and makes it possible for him to be the dominant influence in the development of a school.

In the early schools the problem of framing and administering the requirements for admission and graduation was relatively simple. At Rensselaer the first faculty had but two members, both chosen because of their sympathy with the educational aims of the institution. Similarly at the Massachusetts Institute, President Rogers surrounded himself with a faculty of nine men who were enthusiastically devoted to him and to the new venture. Prior to 1870 no school had as many as 200 students, curricula were few, and the faculties were so small that a close and intimate cooperation among the members and with the president was everywhere the rule. But with a teaching staff of 260 and 2000 students, the present numbers at the Massachusetts Institute, this direct personal contact among the members of the faculty and between instructor and student is no longer possible. It was easy for Professor Pickering to exert a strong personal influence over every one of the 25 students in his pioneer physics laboratory; but it is impossible for any one to do the same when there are 450 students who need apparatus, attention, and guidance. The increase in number of students from 1 in 1870 to 3 now, in value of plants from about one million dollars to sixty-eight millions, in annual expenditures from about $250,000 to over eleven millions, and in number of professional specialties from four to perhaps forty, has compelled the devotion of a large amount of attention to the organization and administration of the daily routine on which the effectiveness of the school so largely depends.

The regulations and the administrative systems that have been developed at the various schools under the pressure of increasing size and complexity differ widely from
one another. All bear evidence of having been shaped to meet local needs under the
guidance of individuals of strong convictions. But while it is not possible to classify
these systems in well-defined categories, they may be arranged in a series that ex-
tends from what may be called the marked military type, on the one hand, thru the
autonomous-department type, to the well-defined cooperative type on the other.

The leading characteristics of the military type are exhibited best in the administra-
tion of the United States Military Academy at West Point. Since this school is sup-
ported from the federal purse, its financial control is vested in Congress, which
makes its appropriations for this purpose on the recommendation of the War Depart-
ment and the Board of Visitors, composed of five senators and seven members of the
House of Representatives. The administration of the school is entrusted to the supe-
rintendent and the academic board, consisting of the superintendent, the commandant
of cadets, and the eleven heads of the departments of instruction. The curriculum
framed by this board, the methods of instruction, and the textbooks selected for use
are subject to approval by the War Department. The time schedule and the order of
instruction in the several courses are determined by the academic board, which also
conducts examinations, passes on the merits and proficiency of the cadets, grants di-
plomas, and makes recommendations for commissions in the army. When consider-
ing questions concerning relative standing and promotion, the senior assistant in each
department sits with the academic board.

The officers of instruction are detailed to this duty by the War Department. Their
number varies from 110 to 120 for 580 cadets. Only the thirteen members of the aca-
demic board have any voice in selecting sub and determining methods of instruction.
The classes are divided into small sections, usually of twelve each. The ground to be
covered each day and even the questions to be asked during each lesson are as a rule
determined by the head of the department, who is also required to visit each section
frequently in order to ascertain the proficiency and qualifications of the cadets and
the manner in which the instructors perform their duty. The assistants seldom serve
more than four years, but new appointees are usually required to attend classes and
study the methods of instruction for a few months before being placed in charge of
sections.

The daily routine of each cadet is rigidly prescribed. He is responsible for some
duty every hour, is sure to be called to recite at every class meeting, and is given a
numerical grade for every recitation. These grades are reported by every instructor
every week, and the roll of the class is arranged each month in the order of the ra-
tings. The division of the class into sections is made according to the relative stand-
ings; the twelve cadets with highest standings being assigned to the first section, the
next highest twelve to the second section, and so on. The instruction is to a certain
extent adjusted to the ability of the several sections, the more difficult investigations
and subjects being given only to the higher sections. Assignments after graduation
and relative rank when commissioned follow the order of merit at graduation. The
maximum number of grade points attainable by a cadet in the four years is 2525; and since these are assigned by a large number of different instructors, the number secured is a pretty accurate measure of the cadet’s ability to meet the requirements of the academy. Because of this fact, the grading system is a very real incentive to good work and to the maintenance of the ideals of soldierly honor and obedience to orders which are such effective features of this school.

While military drill and military instruction are required of male students at all the land grant colleges, military methods of administration are little used in engineering schools. Here and there maybe found a single department that is administered in a military manner. At the University of Pennsylvania several departments divide their classes into small sections, outline the work for each “section hand,” as the instructors have been called, and rotate the instructors among the sections each week. Johns Hopkins University has recently introduced a curriculum called military engineering very similar to that given at West Point, but the methods of administering it do not differ from those used for the rest of the school. The West Point honor and grading systems and West Point discipline, either for instructors or for students, were not found at any of the other schools.

In the great majority of engineering schools the control of the curricula, the regulations for admission and graduation, the time schedule, and the discipline are vested in the faculty, which is composed of all officers of instruction above a specified rank, differently defined at the various schools. All general educational policies, requirements, and rules for students are determined by a majority vote of the faculty and administered by executive officers, deans, and boards or standing committees, usually appointed by the president, tho at several institutions they are elected by the faculty. The number of these committees varies from six to twenty-six. Every voting member of a faculty is subject to service on committees, many of which have to meet weekly and devote much time to their work.

Faculty control generally ends with the adoption of the curriculum and the time schedule. Having determined by majority vote the requirement in hours for each subject, the choice of subject-matter, texts, and methods of instruction in each subject is left entirely to the department concerned. For example, if three hours a week is assigned by the faculty to English, the department of English may use that time in any way it likes. Each department is treated as an expert in its own line, and this departmental autonomy is carefully preserved by common consent. Departments vary in size from three or four members to thirty or forty, and a serious effort is always made to assign each man to work for which he is particularly fitted by temperament, ability, and training. Hence the various phases of the work within a department are usually well coordinated, but the policies and methods of instruction in the different departments of the same school often differ widely from one another. While faculty control is more democratic than military control in that every member of a faculty has a vote on questions of general requirements and policies, it does not produce
the unity of aim and effort exhibited at West Point because its jurisdiction ends at departmental boundaries. For this reason, this form of administration is called the autonomous-department type.

When an engineering school is part of a large university, — like Cornell, Ohio State, or Illinois, — which also contains a school of liberal arts, a law school, a medical school, and an agricultural school, it is customary to vest the control of each school in an independent faculty of its own. The departments of English, foreign languages, mathematics, physics, and chemistry are usually organized under the faculty of liberal arts, frequently without representation on the engineering faculty. In such cases engineering students are under the jurisdiction of the faculty of liberal arts for most of their work during their first two years, and the engineering faculty has limited control of the instruction of its students in these fundamental subjects. Under these conditions the four-year course in engineering has no coordinating centre.

The cooperative type of administration has reached its fullest development at the engineering school of the University of Cincinnati, tho both the Sheffield Scientific School at Yale and Stevens Institute are experimenting along analogous lines. At Cincinnati the engineering school has its own departments of English, mathematics, and foreign languages; and the departments of physics and chemistry, tho organized under the faculty of liberal arts, are represented in the engineering faculty by the instructors who teach the engineers. The faculty thus constituted meets every Saturday morning for a systematic study of its educational problems. A syllabus stating the objects, the methods, the subject-matter, and the mechanism of the school as a whole was prepared by the dean and discussed at length by the faculty. After many changes and amendments, the syllabus was finally adopted as an adequate expression of the basic conceptions toward which the school as a whole is working. Each department in turn then presented a similar syllabus setting forth in detail the objects, methods, subject-matter, and mechanism by which it proposed to contribute to the general result. These departmental syllabi were discussed freely by the whole faculty, and approved only when a general agreement had been reached. In this way there has been developed a very effective coordination of effort among the several departments. A full description of the system, including several of the syllabi, has been published by the United States Bureau of Education in Bulletin 31, 1916, on *The Cooperative System of Education*, by Professor C. W. Park.
is as important an element in the Cincinnati experiment as is the cooperation of the school with the industries. The University of Pittsburgh and the Massachusetts Institute of Technology are cooperating on a part-time basis with industries, but their faculties are organized on the autonomous-department plan.

The cooperative type preserves one of the main advantages of the military type in that its jurisdiction extends within departmental boundaries. Since it uses this jurisdiction not for autocratic control but as a means of converting a government by majority vote into a community of effort for the student’s good, it also possesses another of the effective factors of the military type, namely, homogeneity of action. When skilfully organized, as at Cincinnati, the engineering faculty is a coordinating centre for the entire engineering curriculum. Nor does it appear to have lost any of the nominal advantages of the autonomous-department type in the way of personal freedom of its members and inspiration for creative work.
CHAPTER VI
STUDENT ELIMINATION AND PROGRESS

ENGINEERING schools as a rule keep accurate account of the number of students in attendance each year in each class. These figures, however, do not show how large the actual elimination is, because a number in every graduating class have pursued irregular courses—have entered with advanced standing or been retarded a year or more. Hence the difference between the number of graduates in any given year and the number of freshmen four years back does not indicate the true mortality. In order to determine this it was necessary at each of the schools visited to pick from the records of the graduating class all students who had entered four years before and proceeded through without break. The ratio of this number of what may be called regular graduates to the total number of freshmen four years previously is one expression of the manner in which a school is meeting the needs of its locality.

Only one of the schools visited already knew how large its elimination is when counted in this way. Among this selected list of schools the lowest mortality was found at Pennsylvania State College, where just half of the freshmen went through regularly and graduated in four years. The highest losses were found at the Universities of Illinois and Wisconsin, where only about one-quarter of those admitted as freshmen graduate regularly on schedule time. The figures vary from year to year at every school, so that no fixed figure can be given for any institution; but from the counts made for two years at twenty schools it is clear that less than 40 per cent of all freshmen at engineering schools complete the course in the allotted time. While this record is sufficiently striking, it is better than it was in the early days. Then in some cases the elimination was as high as 91 per cent and the average was nearer 75 than 60. This change for the better is in large measure the result of the increased efficiency of the secondary schools.

While it is interesting to compare the elimination of 66 per cent at the Massachusetts Institute, which admits only by examination, with the elimination of 75 per cent at Wisconsin or Illinois, which admit almost wholly by certificate, it is not safe to draw any conclusions as to the relative merits of the two methods of admission. Elimination depends on too many other variable factors, such as physical health, family conditions, financial resources, college spirit, the appeal of the college work, and the friendly personal interest of the faculty. For example, the date of Dean Burton’s appointment as counselor to freshmen at the Massachusetts Institute is recorded by a sharp drop in the freshman mortality figures. Because of the complexity of the problem it is perhaps not surprising that the schools have no records as to the reasons for withdrawal.

Nearly half of the elimination takes place in the freshman year and about one-quarter more in the second year. During these years almost all of the time is spent on Eng-
lish, mathematics, foreign languages, chemistry, and physics, and little opportunity is afforded for contact with real engineering projects. Hence many engineering students are eliminated before they have a chance to show their ability at their chosen profession. At one of the schools several cases were found where engineering students had been eliminated during the freshman year for failure to meet the demands of the department of German. At another English literature was a fertile source of discouragement for freshmen. A large amount of pertinent information concerning the success of school administration and instruction may be secured from a study of the reasons why students leave engineering schools, especially since many who do leave before graduation persist in engineering and make a success of it.

The variations of the average grades of a group of students thru their four years of work supply an interesting basis on which to judge of student progress and the adaptation of the work to student needs. The following table presents for each of the four years the weighted average grades\(^1\) of a group that entered regularly, progressed normally, and graduated on time at the several schools named:

<table>
<thead>
<tr>
<th>Institution</th>
<th>Cases</th>
<th>Fr.</th>
<th>So.</th>
<th>Jr.</th>
<th>Sr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNIVERSITY OF ILLINOIS</td>
<td>64</td>
<td>86.9</td>
<td>84.1</td>
<td>83.7</td>
<td>83.2</td>
</tr>
<tr>
<td>UNIVERSITY OF VIRGINIA</td>
<td>17</td>
<td>86.0</td>
<td>84.0</td>
<td>82.0</td>
<td>85.0</td>
</tr>
<tr>
<td>PURDUE UNIVERSITY</td>
<td>51</td>
<td>84.7</td>
<td>83.0</td>
<td>80.7</td>
<td>81.6</td>
</tr>
<tr>
<td>RENSSELAER</td>
<td>22</td>
<td>83.7</td>
<td>81.7</td>
<td>82.5</td>
<td>83.7</td>
</tr>
<tr>
<td>UNIVERSITY OF WISCONSIN</td>
<td>47</td>
<td>84.5</td>
<td>83.3</td>
<td>83.2</td>
<td>86.3</td>
</tr>
<tr>
<td>PENNSYLVANIA STATE</td>
<td>54</td>
<td>80.6</td>
<td>80.4</td>
<td>78.4</td>
<td>79.6</td>
</tr>
<tr>
<td>VIRGINIA POLYTECHNIC</td>
<td>48</td>
<td>79.6</td>
<td>77.0</td>
<td>77.3</td>
<td>87.3</td>
</tr>
<tr>
<td>STEVENS</td>
<td>51</td>
<td>78.1</td>
<td>73.4</td>
<td>75.5</td>
<td>74.0</td>
</tr>
<tr>
<td>CINCINNATI</td>
<td>19</td>
<td>77.4</td>
<td>76.5</td>
<td>74.9</td>
<td>76.7</td>
</tr>
<tr>
<td>COLUMBIA</td>
<td>56</td>
<td>77.2</td>
<td>76.2</td>
<td>75.8</td>
<td>74.9</td>
</tr>
<tr>
<td>UNIVERSITY OF PENNSYLVANIA</td>
<td>55</td>
<td>74.5</td>
<td>72.0</td>
<td>70.0</td>
<td>71.5</td>
</tr>
<tr>
<td>OHIO STATE UNIVERSITY</td>
<td>46</td>
<td>72.0</td>
<td>71.0</td>
<td>70.6</td>
<td>71.2</td>
</tr>
<tr>
<td>YALE (SHEFFIELD)</td>
<td>79</td>
<td>67.0</td>
<td>65.2</td>
<td>68.2</td>
<td></td>
</tr>
<tr>
<td>MASSACHUSETTS INSTITUTE</td>
<td>67</td>
<td>66.8</td>
<td>64.7</td>
<td>65.6</td>
<td>64.0</td>
</tr>
<tr>
<td>CORNELL (SIBLEY)</td>
<td>40</td>
<td>75.2</td>
<td>79.9</td>
<td>73.2</td>
<td>73.9</td>
</tr>
<tr>
<td>CORNELL (C.E.)</td>
<td>30</td>
<td>76.3</td>
<td>76.0</td>
<td>72.1</td>
<td>75.2</td>
</tr>
<tr>
<td>TUTTS</td>
<td>39</td>
<td>72.0</td>
<td>68.0</td>
<td>70.0</td>
<td>73.0</td>
</tr>
<tr>
<td>Average</td>
<td>785</td>
<td>76.9</td>
<td>74.9</td>
<td>74.8</td>
<td>76.9</td>
</tr>
</tbody>
</table>

\(^{1}\)The weighted average is found by multiplying each grade by the number of credit hours it represents, adding the products, and dividing by the total number of credit hours for the year.

In every case the standing of this random group of the regular graduates is higher in the freshman than it is in the sophomore year. In the general average for the 785 cases studied the drop of points persists thru the junior year and is recovered in the last year. The phenomenon is general, altho some schools exhibit it more markedly than do others.

While several interpretations of the meaning of this sag in the average grade curve are possible, its cause may be located statistically by noting in what subjects the

Average age of graduation 22 years, 11 months.
students had the greatest number of low grades in those years. For this purpose thirty
or more records of regular graduates were taken at random and the number who re-
ceived low grades in each subject was counted for each school. The meaning of the
term “low grade” was determined at each institution from a study of the local grading
system. At schools that grade numerically with 60 as the pass mark, like Virginia
Polytechnic Institute, Stevens Institute, and Cornell University, all marks below 70
were counted as low. Thus, for example, at Stevens Institute out of 51 cases studied,
31 had at least one grade below 70 in physics and the average mark in that subject for
these thirty-one students was 63.2. In calculus 26 had received grades below 70, the
average being 63.1, and so on. When 70 was the pass mark, as at the Universities of
Illinois and Wisconsin and Pennsylvania State College, marks below 80 were count-
ed. At the Massachusetts Institute of Technology, where 50 is the pass mark, L,
which stands for a rating between 50 and 60, was considered a low grade. At Shef-
field Scientific School and Rensselaer Polytechnic Institute, which grade on a scale
of 4 with 2 as the pass mark, marks below 2.4 were counted. The grading systems of
the University of Pennsylvania, Ohio State University, and Purdue University could
not be used for this purpose because they recognize only three grades, A, B, and C,
above pass mark and the lowest grade covers too wide a range. At Ohio State Univer-
sity a new grading system with five steps between pass and 100 has recently been
introduced.

The table on page 35 gives the results of this count for twelve schools. Every stu-
dent whose record was counted was a regular student who had entered without condi-
tions, had passed thru normally in the regulation time, and had received his degree.
The low marks of the 60 per cent who were “weeded out” are not included; if they
had been, the percentages would be much higher. The figures in the table are there
fore a fair statement of the results achieved by a school under the most favorable
conditions.

Taken in connection with the facts of elimination, these figures show that out of
every 1000 freshmen not more than 400 graduate in the specified time, and that half
of these just “get by” in physics, calculus, and mechanics. The percentage of low
grades is about the same in English and modern languages when these subjects are
required. This means that out of every 1000 who are admitted only about 200—20
per cent—adapt themselves creditably to the requirements of the schools in these so-
called “fundamentals.”

The two tables make it clear that the drop in the average grades occurs when physics
and calculus with an average low grade record of 49.5 per cent replace chemistry and
freshman mathematics with an average low grade record of not over 25 per cent. It is
not possible to give this last percentage exactly because the freshman mathematics
courses are not comparable; but the low grade counts in advanced algebra, trigonome-
try, and analytics are all below 20 per cent. Altho the third year program and courses
differ so much from one another that the figures from various schools cannot be com
### Number and Percentages of Low Grades in Particular Subjects

<table>
<thead>
<tr>
<th>Institution</th>
<th>Number of Cases</th>
<th>Physics</th>
<th>English</th>
<th>Modern Languages</th>
<th>Calculus</th>
<th>Mechanics</th>
<th>Chemistry</th>
<th>Descriptive Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67</td>
<td>43-64%</td>
<td>37-53%</td>
<td>38-57%</td>
<td>22-32%</td>
<td>21-31%</td>
<td>20-29%</td>
<td>13-19%</td>
</tr>
<tr>
<td>2</td>
<td>79</td>
<td>40-51%</td>
<td>47-60%</td>
<td>51-64%</td>
<td>48-61%</td>
<td>47-60%</td>
<td>31-40%</td>
<td>26-33%</td>
</tr>
<tr>
<td>3</td>
<td>51</td>
<td>31-60%</td>
<td>11-21%</td>
<td>4-8</td>
<td>26-51%</td>
<td>26-51%</td>
<td>11-21%</td>
<td>21-41%</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>21-47%</td>
<td>37-77%</td>
<td>34-69%</td>
<td>13-29%</td>
<td>20-42%</td>
<td>7-14%</td>
<td>5-10%</td>
</tr>
<tr>
<td>5</td>
<td>43</td>
<td>30-69%</td>
<td>not required</td>
<td>not required</td>
<td>32-74%</td>
<td>28-65%</td>
<td>14-32%</td>
<td>16-37%</td>
</tr>
<tr>
<td>6</td>
<td>54</td>
<td>38-70%</td>
<td>not required</td>
<td>not required</td>
<td>33-61%</td>
<td>35-65%</td>
<td>15-28%</td>
<td>21-40%</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>10-52%</td>
<td>10-52%</td>
<td>6-31%</td>
<td>9-47%</td>
<td>13-68%</td>
<td>11-58%</td>
<td>4-21%</td>
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<tr>
<td>8</td>
<td>46</td>
<td>13-28%</td>
<td>13-28%</td>
<td>16-35%</td>
<td>18-40%</td>
<td>25-54%</td>
<td>7-15%</td>
<td>6-13%</td>
</tr>
<tr>
<td>9</td>
<td>64</td>
<td>24-37%</td>
<td>31-48%</td>
<td>not required</td>
<td>27-42%</td>
<td>27-42%</td>
<td>14-22%</td>
<td>4-6%</td>
</tr>
<tr>
<td>10</td>
<td>22</td>
<td>15-68%</td>
<td>16-72%</td>
<td>7-33%</td>
<td>15-70%</td>
<td>5-23%</td>
<td>15-70%</td>
<td>10-45%</td>
</tr>
<tr>
<td>11</td>
<td>44</td>
<td>13-30%</td>
<td>7-16%</td>
<td>not required</td>
<td>22-50%</td>
<td>24-55%</td>
<td>12-27%</td>
<td>5-11%</td>
</tr>
<tr>
<td>Totals</td>
<td>621</td>
<td>317</td>
<td>249/534</td>
<td>198/416</td>
<td>298</td>
<td>330</td>
<td>201</td>
<td>165</td>
</tr>
</tbody>
</table>

|               | 31.0%           | 46.6%    | 47.5%    | 48.0%            | 53.1%   | 32.3%     | 26.5%     |

pared, it is fairly evident that the mechanics, which is common to all and which has a low grade record of 53.4 per cent, is largely responsible for the continuation of the low average grade thru the junior year.

While many professors regard a high percentage of low grades as proof of efficient teaching, experience has proved that an excessive number of low grades in some particular subject in the records of regular graduates is a sign of some trouble that can usually be removed by a little attention. For example, 80 per cent of the regular graduates of 1914 in Cincinnati had low grades in History 50. This course had been introduced the previous year to give a broader outlook. It consisted of a rapid study of geologic evolution, of biologic evolution, and of the evolution of civilization given by the respective heads of the departments of geology, biology, and history in the Faculty of Arts, Literature, and Science. The first year it proved a great success, and the engineering students in the class of 1913 gathered much information and inspiration from it. But the class of 1914 had much trouble with it until it was discovered that it had been turned over to a young instructor who was drilling the class on Guizot’s History of Civilization by the textbook-recitation method. The course was promptly dropped and the students absolved from the requirement by the engineering faculty.

Since employers regard college grades as precarious guides in selecting men for jobs,
an effort was made to find out whether the fact that about half the graduates of engineering schools have received low grades in physics, calculus, and mechanics means that half the graduates are on that account low grade engineers or not. The direct method of doing this would involve tracing the later careers of those who received the low grades to see if they were relatively less successful than those who ranked high in these fundamental subjects. This method is impracticable because there is as yet no valid definition of what constitutes success in engineering. There are, however, a number of large industrial firms that employ several hundred college graduates each year and keep records of their accomplishments. A comparison of the records of the same men in college and in industry would indicate how close the correlation between them is.

Thru the courtesy of Mr. A. L. Rohrer of the General Electric Company of Schenectady, copies of his records of the 168 graduates in their employ from the class of 1913 of all the schools visited were secured. On these records each man was rated by each of the foremen under whom he worked as A, B, or C in each of the five qualities, Technical ability, Accuracy, Industry, Ability to push things, and Personality. Thru the courtesy of the schools copies of the full college records of these same men were secured. An extended study of these two sets of records by Professor E. L. Thorndike of Columbia showed that the correlation between the two was very slight; that is, that ability to secure high grades in college was no indication of ability to meet the requirements of the General Electric Company. On the other hand, the college grades signify something, since the grades for the senior year correlate closely with the average grade for the entire course, showing that ability to secure high grades in college is a stable and permanent characteristic of an individual. A similar study was made thru the courtesy of Mr. C. R. Dooley of the Westinghouse Electric and Manufacturing Company of Pittsburgh of a group of 40 college graduates in the employ of that company. The results were practically the same.

While these studies have not yet settled the problem, they serve to define it more clearly. The facts are that half of the college graduates are rated low in the fundamental subjects by their college instructors, and that college grades show little correlation with the ratings of two large industrial companies that “take on” several hundred college graduates each year.
CHAPTER VII

TYPES OF INSTRUCTION IN ENGINEERING SCHOOLS

The method of instruction employed at Rensselaer during the first five years (1824-29) was new in America, tho it resembled the methods inaugurated in 1806 by Pestalozzi in the Fellenberg School at Hofwyl, Switzerland (page 9). It was designed by the first senior professor, Amos Eaton, who was a graduate of Williams College and had done graduate work with Silliman at Yale. At no other school was the student given the place of the teacher and compelled to rely on his own resources in preparing subjects for presentation to his classmates. The observation of industrial processes as the basis for class discussion and laboratory problems which led by inductive processes to general principles after the manner of real scientific investigation were at this time unique in elementary instruction. No other school treated beginners by the same methods that were used so successfully in advanced study. But altho the method as practised proved successful, it had to be abandoned in 1829 because it was too expensive for the slender resources of the school. As the number of students increased, still more didactic methods were introduced; until in 1850, when the French curriculum was adopted (page 12), the student lectures had become blackboard demonstrations prepared from texts followed by “interrogations” and recitations conducted by the professors.

At the opening of the Massachusetts Institute in 1865 instruction was given mainly by lectures, in which the professor presented to the class a logically well-organized explanation of the general principles and theories of the subject in hand. Lectures were illustrated by experiments and accompanied by blackboard demonstrations. The students took notes, recited on them at regular quiz hours, and worked problems that illustrated the principles and theories presented. Frequent and thorough examinations were given for the double purpose of testing knowledge and inciting to diligence. As soon as the facilities were available, laboratory work was introduced, in which the student reproduced standard reactions, measured known constants, verified theories, visualized principles, and acquired skill in manipulating delicate instruments.

The use of the illustrated lecture in instruction in science was not new, but the organization of laboratories for undergraduate students in physics was a striking innovation, suggested by President Rogers and carried out by Professor E. C. Pickering in 1869. The course consisted of a series of simple experiments illustrating fundamental principles or scientific methods of study and involving the use of important instruments. The administration of the work was made practicable by having complete apparatus for each instrument ready for use together with carefully prepared written directions for its correct manipulation. When a class entered the laboratory each member received a number directing him to the apparatus and written directions for making the required measurements and recording the results. In this way Professor
Pickering was able to care for a class of twenty-five students at one time, because, as he himself tells us, the written directions prevented the students from making serious mistakes.

The marvelous expansion of this method of laboratory work into all branches of science in all grades of schools and the profound impress made by this expansion on the American school system are matters of common knowledge. Here it is important to note that this type of laboratory work was devised as an adjunct to the illustrated lecture, for the purpose of giving training in pure science, to foster industrial production, and develop the scientific or professional engineering spirit.

Besides the innovation of the laboratory, new methods of teaching English were introduced at the Massachusetts Institute by Professor W. P. Atkinson, who sought to cultivate a taste for good literature and a love of reading on subjects of interest to the student as a man and a citizen. After a rapid review of composition and rhetoric the classes read and discussed Duruy’s *Histoire des temps modernes* and Guizot’s *History of Civilization in Europe*. In the fourth year contemporary problems of politics, economics, and sociology were discussed and written reports on subjects of their own selection were read by the students in class. Two hours a week throughout the four years were devoted to this work.

Since 1864, but especially since 1900, the increase in the number of students and the migration of students among the schools have tended to standardize methods of teaching in both high school and college. In the secondary school the process has been accelerated by the pressure of college entrance requirements and the accompanying definitions of the units framed by the colleges, while in the colleges the process has been retarded by the universal respect for departmental autonomy and academic freedom with the consequent “laissez faire” attitude toward the problem. Under these conditions some college subjects have become more standardized than others, but it is seldom possible to point to any one method in any one subject as generally accepted. At present there is a marked tendency in certain subjects to break away from the traditional forms. Some of the efforts in this direction are noted in subsequent chapters.

While there are many differences in the details of curricula and methods of teaching, the first two years of work are more nearly uniform than the last two in content and general treatment. The freshmen in almost all schools take mathematics, chemistry, English, drawing, and shopwork; while sophomores usually study mathematics, physics, English, drawing, and shopwork. The methods of instruction in some of these fundamental subjects, like mathematics and physics, are very much the same everywhere; while in chemistry, English, drawing, and shopwork there are wider variations and several distinct types. Still the salient features and the underlying philosophy of the instruction in each subject are enough alike at most institutions to make possible a description of the typical treatment accorded to engineering students during their first two years in college. Certain striking exceptions in which totally different conceptions and methods prevail are discussed in the later chapters.
The aims and methods of teaching mathematics to engineering students have been fully described in the report of Sub-committee IX of the International Commission on the Teaching of Mathematics.\(^1\) From this report it appears that mathematics teachers are generally agreed that mathematics should be taught as a science by professional mathematicians and not as a tool by engineers. While all regard professional efficiency in the use of mathematics as the test of success, they hold that this efficiency is best secured by teaching mathematics by itself, so that the student’s mind is not distracted from the mathematical form by the engineering applications. The limited amount of time allotted to mathematics is barely sufficient to enable the mathematics teacher to cover the required ground thoroughly. If the teacher of engineering would familiarize himself with the mathematical subjects, the methods, and even the notation his students have learned, he could then teach them how to use their mathematics with a success and completeness not possible to his mathematical colleague.

Inasmuch as the professors of mathematics are generally agreed on this point of view, the mathematical instruction to freshmen and sophomores is almost universally based on the use of a standard text, in which the successive propositions are deduced by logical processes from definitions, axioms, and postulates. A definite portion of the text is assigned as a lesson, and in the daily recitations the students are required either to reproduce demonstrations given in the text or to solve mathematical problems that illustrate the theorems under discussion. The customary division of mathematics into trigonometry, analytics, and calculus is preserved at all but two of the schools visited. In short, mathematics in engineering colleges, as in the high schools, is still taught by the standard methods that are so well known as to need no further description. According to the report just mentioned (page 30), “There is nothing to indicate that many changes have taken place during the past 10 years, or that many are contemplated.”

In chemistry the basis of the instruction is the demonstration lectures, at which the entire class assembles two or three times a week. For the quiz and laboratory work the class is divided into sections, usually in charge of assistants. A standard text is generally followed by the lecturer and used by the students as a source of information for the quizzes. A separate manual containing directions for the laboratory experiments is customary.

In most of the schools visited the presentation of the subject-matter in chemistry begins with general statements about atoms, molecules, chemical equations, Avogadro’s law, molecular weight, chemical affinity, diffusion, valence, and formulas. Then follows descriptions of the non-metals, oxygen, nitrogen, carbon, etc., — their occurrence, preparation, and properties, — leading to the metals in due order. The facts discussed in the lectures are learned for the quizzes and verified in the laboratory. The purpose of this type of instruction is to familiarize the student with the elementary

\(^1\)United States Bureau of Education, Bulletin No.9. 1911.
facts and reactions of chemistry as a means of identifying substances and therefore as a preparation for qualitative and quantitative analysis.

Recently another type of course in chemistry has been introduced in a number of schools. In this the data are presented not as elements prerequisite to a mastery of chemical analysis, but as vehicles for the elucidation of modern chemical theories. In courses of this type the study of oxygen includes such topics as the diffusion and liquefaction of gases, critical temperature, endothermal and exothermal reactions, the gas laws, and the kinetic-molecular theory of matter. Similarly the facts about hydrogen are used to elucidate reversible reactions, chemical equilibrium, equivalent and atomic weights, and chemical equations. The study of water furnishes a natural thread on which to string the law of combining volumes, Avogadro’s theory, molecular weight, solutions, and the kinetic theory of solution. The properties of chlorine serve as a basis for the presentation of electrical conductivity of solutions, osmotic pressure, ionic theory, degrees of ionization, electric charges on the ions, valence of the ions, and the electron theory. About ten weeks is required to cover these topics, and then the remainder of the year is spent in studying the more important reactions from the standpoint of the ionic theory. Incidental references are made to the industrial uses of chemistry.

Altho these two types of courses in chemistry differ in content, both use the lecture-quiz-laboratory method of imparting information. In one case the information is being stored for later use in chemical analysis; in the other it is being organized for the elucidation of ionic theories. In neither case is the student given such a project as: “Make baking powder and determine whether it is better and cheaper than any you can buy.” His problem is always in the form: “Determine the chemical composition of this powder.”

Physics is generally taught in the second year as a one-year course, tho five of the schools visited devote some time to it in the first year. As in chemistry so here, the typical course consists of three parts, demonstration lectures, quizzes, and laboratory work. In the lectures, of which there are two or three a week, the professor presents the essential facts and principles in a logically well-arranged order, beginning with definitions and statements of laws, followed by their mathematical or experimental demonstration, and ending with a few brief remarks concerning practical applications. Usually the entire sophomore class attends the lectures in a body, so that, in the larger schools, there are as many as three or four hundred students at each lecture. For quizzes the class is divided into sections of from twenty to twenty-five each, and these are turned over to assistants who listen to recitations on assignments in the text, question the students on the content of the previous lecture, and assign illustrative problems to be solved at home. With large classes of from twelve to twenty sections the quiz and laboratory work requires a large corps of assistants, many of whom are graduate students or fellows who receive a modest stipend (from $200 to $500 a year) for this service.

In the laboratory work the methods and aims defined by Professor Pickering in
1869 are still dominant everywhere. About one-third of his original experiments are still in use, and the new ones that have been introduced have as their objects the verification of some known law, the visualization of some known fact, or the determination of some known constant. When the same experiments are used year after year, as is the case at most schools, the students soon discover that the number of failures and low grades in physics can be materially reduced if the results of the physics experiments are carefully preserved from year to year and judiciously used as occasion may require. Projects of the form “Which of these 3 electric motors is the best for the price?”—a question that cannot be answered without making the experiment—are almost never used. The prevailing type is “Measure the efficiency of this electric motor.” In other words, physics instruction, like that in chemistry, aims to stock the student’s mind with information as a preparation for solving real problems should they ever arise.

The proficiency and the progress of students in mathematics, chemistry, and physics is measured by periodic examinations, which as a rule call for the statement of definitions, the mathematical demonstration of principles or theorems, and the solution of illustrative problems. For small classes the professor himself is usually alone responsible for the questions, and is also sole judge of the rating of the replies. For large classes the examination is sometimes set by the professor in responsible charge and sometimes by the entire group of instructors in conference. In either case the papers are as a rule distributed among the instructors for rating so that the grade assigned is often determined by the judgment of a single observer. The final grades assigned for the year are a combination of the examination grades, the quiz grades, and the laboratory grades. In making the combination the weights given to these several elements vary enormously, some treating the examination as the sole factor and others relying mainly on the quiz and laboratory grades. The students are generally well posted on the system used in each department, and their grades are fairly accurate statements of their successes in meeting the requirements of the various professors.

With regard to instruction in English, the engineering schools may be divided into two approximately equal groups, the one composed of those schools that maintain the current standard college course; and the other composed of those that are trying to discover a type of work better suited to engineers. In the standard type of course, the student studies a textbook of composition and rhetoric, learns the rules of correct punctuation and paragraphing, together with the four forms of discourse, and then writes themes on assigned subjects selected by the instructor to give practice in either description, narration, exposition, or argumentation. In some schools the strict adherence to this plan is mitigated by allowing a choice from among several assigned subjects. The accompanying study of literature consists of a brief survey of the lives of the great writers and the analysis of selected passages from their writings. This well-known type of course was developed during the latter half of the past century.
for the purpose of making English an acceptable substitute for the classics in high schools and colleges.

Doubtless because the professional engineers have been so frank in their demand for better training in English, about half of the engineering schools are experimenting with their methods of teaching this subject. These experiments are so varied in plan and execution that it is not possible to classify them. One of the more radical of these is described in Chapter X.

But if it is impossible to describe the types of instruction in English because of their number and diversity, it is still more difficult to select any one type of drawing, descriptive geometry, or shopwork as characteristic of even a majority of the schools. In drawing the aims of the instruction range all the way from imparting enough technical skill to enable a graduate to earn his living as a draughtsman, to developing the power of visualizing solid objects from flat drawings. At some schools the subject is introduced with geometrical drawing for practice in the use of instruments, at others the first plates are merely copied, while at still others freehand sketching in perspective takes the lead. In some cases descriptive geometry is closely correlated with drawing from the beginning; in others it is treated independently and even by a separate department.

The variations in types of shopwork are no less numerous. At some few schools no shopwork whatever is required; at others students merely visit shops and listen to lectures on the subject, but do no actual work with tools; at still others the emphasis is placed on acquiring a certain amount of manual dexterity in typical operations with tools, but nothing is actually constructed; at others production of salable articles is placed foremost; the shop is used in some cases as a means of acquiring practice in scientific management and business administration; while under the cooperative plan the school conducts no shopwork, but the students gain practical experience with tools, production, and management by working half time for pay in industrial plants. It is a striking fact that the three subjects in which there are such wide variations in teaching practice are the three that are constantly exposed to objective test. English, drawing, and shop are three subjects in which a student’s ability is expressed objectively if at all; and these are the subjects in which experiments in methods of teaching are most numerous.

These six subjects—mathematics, chemistry, physics, English, drawing, and shop—occupy the major part of the time for the first two years in all engineering curricula. The majority of schools also require one or more foreign languages, taught almost invariably by the standardized method of grammatical study and analysis. The civil engineering curriculum usually includes in the first or second year the theory of surveying, followed by a summer camp for practical work. Apart from this work in surveying, there is as a rule very little that makes the freshmen or the sophomores vividly aware of the fact that they are studying engineering. This has been recognized as a defect by some schools, which have sought to remedy it by “orientation” lec
tures and talks by professional men describing the nature of real engineering work in the field. Still there are cases on record where freshmen in engineering have been “weeded out” entirely because of deficiencies in English and German.

The instruction during the last two years is almost wholly devoted to professional work. The prevailing methods of teaching are very similar to those used in the earlier years in chemistry and physics, the difference being that the topics and problems are technical rather than purely scientific. Since specialization has now divided the juniors and seniors into groups, the classes are generally small and they receive the attention of the older and more experienced professors. Theory and theoretical design are strongly emphasized throughout and some attention — frequently very little—is given to the practical problems of labor, organization, values, and costs.

Twenty-five years ago every senior was required to prepare a graduation thesis as an exercise in the application of all he had learned and a training in engineering methods of attacking real problems. At present only half of the schools require theses of all graduates; in one-tenth the thesis is elective, in one-tenth the better students only are allowed the privilege of preparing one, and in the remaining three-tenths no thesis is required. Formerly the thesis was frequently the only opportunity given the student to exercise his originality and express his initiative in constructive work. At present engineering projects are being used more and more as problems and exercises in the regular class work of the last two years. In a few cases real engineering problems are freely used with freshmen and sophomores. These tendencies to encourage a spirit of investigation among the younger students and to give even freshmen opportunities for creative work are becoming more marked each year. Several significant changes of this kind are discussed in the later chapters.
PART II
THE PROBLEMS OF ENGINEERING EDUCATION
CHAPTER VIII

ADMISSION

THE Society for the Promotion of Engineering Education has always had a standing committee on Entrance Requirements. This committee has made periodic reports, which are published in the Proceedings of the Society. Yet the variations in the requirements for admission to engineering colleges are still very striking (cf. page 22), the content and methods of instruction in many of the accepted units have been partially standardized by the effective work of the College Entrance Examination Board and of numerous committees on the definition of the high school units.

From the point of view of their success in limiting admission to engineering schools to those who have some aptitude or ability for engineering, it is evident that when 60 out of every 100 admitted fail to continue thru the course, present systems of admission are not satisfactory. Even when due allowance is made for those who leave for financial reasons and for the praiseworthy desire of faculties to give every boy who has any claim to consideration a chance to prove his mettle, a fairly large number of students who ought not to try to become engineers are permitted to undertake a course of study for which they have little natural ability. Nor is this condition justified by the plea that an engineering training is good discipline for a journalist or a banker; because the spirit of the work is spoiled for true engineers by the presence of the temperamentally unfit, while these do not get the maximum benefit from work they cannot really do well.

Fifty years ago every college gave its own entrance examinations. But as the secondary schools grew stronger, the custom of accepting their certificates as satisfactory credentials for admission gradually expanded; with the result that for a number of years two ostensibly rival systems have existed side by side, and many a wordy debate over their relative merits has been held. In engineering schools the statistics of elimination (page 32) indicate that the success of present admission systems does not depend seriously on whether the colleges give their own entrance examinations or whether they accept certificates from the secondary schools.

Reasons for the similarity of results by the two methods of admission are not hard to find. For every high school teacher who has in his class one boy preparing to take a college entrance examination is fairly sure to drill the entire class on old college entrance examination questions, large collections of which have been reprinted by publishers of textbooks and individuals interested in maintaining the examination system. Under these conditions if both college and school are sincere in their work,—which unfortunately is not always the case,—it clearly makes little difference in the boy’s real attainments at the end of the course whether he takes his examination at school or at college. In the one case he is admitted by examination, in the other by certificate; in either case on the average at least 60 out of 100 admitted fail to
finish the course. Evidently the source of the difficulty does not lie in the machinery of admission, but in the controlling factor that is common to both, namely, the nature of the test itself. For engineering the question, therefore, is not which of the two methods of admission is the more efficient, but whether current college entrance tests really measure engineering ability or not. Ability to secure high grades in school is a stable characteristic of an individual; but is ability to pass current school and college examinations a valid criterion of engineering ability? And if not, what type of test can be safely used? This is the real problem of admission as it is the real problem of the entire college course, for tests control teaching.

Trustworthy hints as to the ways and means of discovering better types of tests for admission to engineering colleges are expressed in the recent developments of entrance systems. For when every college gave its own entrance examinations in its own way the secondary schools were confronted with a perfectly impossible task. In each subject there were as many different examinations as there were colleges; and since each examination measured rather the degree to which the candidate conformed to the examiner’s conception of the subject than the student’s real ability, great confusion prevailed. It was to abolish this confusion that the College Entrance Examination Board was organized in 1900. By having the examination questions framed by committees instead of by individuals, by giving the same examination for a large number of colleges, and by having all the rating done by one group of readers, conditions were vastly improved, and have continued to improve as the board has gained in experience and skill.

In the central and western states, where admission has for a number of years been by certificate, the development has been nominally somewhat different. There the decision as to whether the work of a high school was of such quality as to warrant the acceptance of its certificate for entrance to college was made first by professors sent out by the colleges; then by state high school inspectors, who visited each school periodically and reported their findings to the state universities. On the basis of their reports a list of “accredited schools” was constructed for each state, and these lists were combined by such organizations as the North Central Association of Colleges and Secondary Schools to include the schools over a wide territory. Recently there has been a tendency to check the findings of the high school inspectors by the ratings received in college by the students from the various schools.

While the respective developments of admission systems east and west appear to be quite different, they are in reality very much the same. In the examination system committees instead of individuals both set the questions and grade the papers. In the certificate system the work of a high school is now judged more by the ratings of its students by a college faculty than by the personal judgment of one high school inspector. Hence in both cases the growth has been away from reliance on the personal judgment of individuals toward acceptance of the combined judgment of a group. Under the certificate system this combined judgment is based on daily observation
of the student’s labors for a number of months, while under the examination system the judgment in each subject is based on the reading of one paper.

From the foregoing facts it appears that the real difficulty with college admission systems has been instinctively recognized everywhere. The determination of a candidate’s fitness to enter college depends ultimately on tests of some kind; and the tendency in selecting and applying tests has clearly been to eliminate the fallacies and vagaries of individual personal judgment, in order that grading may become more a measure of ability and less an expression of how far the student conforms to the established convictions of individuals. But tho very encouraging progress has been made of late, all recognize that still greater improvement is possible, and that the forward movement is in the direction of reducing the personal equation to a minimum by making examinations and tests as objective as possible.

The expenditure of an enormous amount of time and energy has been necessary to liberate college entrance tests from personal bias and to achieve even the degree of objectivity that has been attained. The precipitation of the instinctive feeling for the direction of progress into a well-defined statement of conscious aim has proceeded slowly. Now that the aim is clear and generally recognized, more rapid advance is possible, provided the schools are ready to undertake the arduous and plodding work involved; for both the invention and the interpretation of satisfactory tests require long and careful statistical studies by competent men who have been specially trained for the task. The work is worth while because admission to college is an important division of the central problem of education — vocational guidance. If any reasonably trustworthy method of discovering what work each individual is best fitted for can be found, the other problems of education will in large measure solve themselves.

Since engineering is perhaps the most objective of all professions, it offers excellent opportunities for the scientific study of objective tests. A study of engineering education therefore provides an appropriate opportunity to initiate experiments and to attempt to sort out the more promising methods of investigation from those that prove to be less fruitful. To this end Professor Edward L. Thorndike of Columbia University undertook a special series of experiments with freshmen in engineering at Columbia, Massachusetts Institute of Technology, the University of Cincinnati, and Wentworth Institute. The experiences with the Columbia group are here described as typical of the principles and methods applied. Further details with samples of the tests used are given in the Appendix (pages 117—125).

Thru the courtesy of Dean F. P. Keppel, an invitation was extended by Professor Thorndike to forty freshmen in engineering to spend two successive Saturdays (fourteen hours) in taking the tests. Each of the thirty-four students who completed the series was given a small fee and a full statement of his record. Fifteen tests in all were used, each designed to record the student’s relative ability in some one particular activity which was complete in itself, altho it involved a rather complicated series of
reactions. Thus each student was asked to read paragraphs and write answers to questions on their meaning, to identify words as proof of his range of vocabulary, to supply missing words in sentences, to solve arithmetical and algebraic problems, to perform algebraic computations, to draw graphs from given data, to give geometrical proofs of stated theorems, to solve problems in physics described in words, to arrange physical apparatus to secure stated results, to match each of a series of pictures with one of a series of verbal statements, to supply missing lines in drawings of machinery, and to construct simple mechanical devices from their unassembled parts.

Each test was constructed as a series of graded steps of increasing difficulty, the first being so easy that every one was sure to accomplish it, and the last one so difficult that only the ablest could master it. The grading of the steps is secured by first submitting a large number of problems of a given type to about a dozen successful teachers of the subject and asking them to divide them into groups numbered 1, 2, 8, 4, etc., in what they consider to be the order of difficulty. Problems common to group I are used as the first step, those common to group 2 as the second step, and so on, in making up a preliminary test, which is then tried on a number of classes in different schools. The relative difficulty is then in inverse order to the number who accomplish each step. Much further experimenting and computation are necessary if it is desired to make sure that each successive step is more difficult than its predecessor by the same amount. Most of the tests used in these experiments with engineering students were graded in steps of equal difficulty.

The advantage of tests of graded difficulty lies in the fact that a student’s grade is determined by the number of steps he accomplishes in the assigned time. Since the questions used are as a rule of a type that cannot be answered from memory, but must be answered by a short statement, judgment concerning the correctness of the answers is seldom ambiguous, so that personal bias in assigning grades is almost wholly eliminated. Independent scorers in these tests repeatedly made ratings that were practically identical (correlations .95 to .98. Cf. page 119).

The ultimate criterion of the validity of these tests is the future careers of those tested. Since extensive data of this kind are not yet obtainable, the results of the tests were compared with a composite rating compiled by combining the students’ high school marks in English, mathematics, and physics, their ratings in the Regents’ examinations in these three subjects, their freshman records in English, mathematics, and chemistry, the combined judgments of the students concerning one another’s intellectual ability, the judgment of the teachers who were acquainted with the men, and the age of entrance to college. This composite is the best obtainable summary of the current school judgment concerning the relative intellectual abilities of the students tested. By it the thirty-four who took the tests were ranged in a series in the order of their relative standings as determined by current school methods.

The students were then arranged in 15 similar series, the order of merit in each being determined by the ratings in one of the 15 tests; and each of these 15 series
was compared with the series defined by the schools’ ratings by the method of Pearson correlation coefficients (Appendix, page 119). Every test showed a positive correlation with this composite school series, the correlation coefficients varying from .2 to .8.

This indicates that all the tests are symptomatic of the qualities which enable a student to enter college young, make a good record in high school and in the Regents’ examinations, do well during the freshman year, and be regarded as of high general ability by his classmates and teachers. When all fifteen tests are combined into a single measure, the test series and the composite school series are almost identical (correlation coefficient .84).

The records of the thirty-four men tested at Columbia have been followed for three years. Five of the seven who stood highest in the tests received general honors, while five of the seven lowest in the tests failed in more than half of their work and left school. The top seven all made more than 125 credits in three years, the middle seven averaged 92 credits each in three years, and of the lowest seven the two who did not leave averaged 56 points each in three years.

The tests, however, differ in their validity as symptoms of intellectual ability and should therefore have different weights in making up a summary. The computation of the relative weights was carried out by Dr. Truman L. Kelley by the method of partial correlation coefficients. His investigation shows that a suitable combination of the ratings from only seven of the tests gives a closer correlation with the composite school series than does the composite of all fifteen (coefficient .87 as against .84). These seven tests are the five in mathematics and the two in supplying the missing words from sentences. These seven tests require five hours of the student’s time, and their results arrange the students in an order of intellectual ability practically identical with that of the composite school series. At present the composite school judgment is universally accepted as determining fitness to enter college. College entrance examinations consume from fifteen to twenty-five hours of the student’s time. These seven tests gave in this experiment at Columbia as good a rating in five hours, and the scoring is independent of personal bias. Similar results were obtained at the other schools.

To this rather striking fact must be added another no less important; namely, that the other eight tests contributed practically nothing to this result. These eight were paragraph reading, range of vocabulary, giving opposites of words, laboratory problems in physics, matching diagrams with sentences, completing imperfect diagrams, physics problems stated in words, and the construction of mechanical devices from their unassembled parts. The fact that these eight tests are unnecessary in determining an order of ability that closely resembles the order defined by current school practices does not mean that they are on that account useless. On the contrary, they are particularly valuable because they evidently measure abilities of which the current school methods take no account. Further experimentation is required to determine just what these other abilities are. They probably include language abilities that depend on interest in reading, clear grasp of the meaning of single words and phrases, power to
keep in mind past context in reading a connected passage, skill in working with dia-
grams and apparatus, and mechanical sense. All of these are of prime importance in
engineering. The development of all the men tested is being followed for the purpose
of throwing more light on the questions here raised.

The same fifteen tests were given by Professor Thorndike thru the courtesy of Dean
A. E. Burton to forty freshmen at the Massachusetts Institute of Technology, thru the
courtesy of Dean Herman Schneider and with the cordial cooperation of Professor B.
B. Breese to forty-one engineering freshmen at the University of Cincinnati, and thru
the courtesy of Director A. L. Williston to sixty students at the Wentworth Institute in
Boston. The students in these groups came from so many different schools that it was
not possible to make a composite rating of their abilities on the basis of their school
records. The college records of these men have been followed for two years, with the
result that in Cincinnati the tests prophesied academic achievement in these two years
as accurately as the college rating for one year prophesied the rating for the succeed-
ing year (correlation coefficients .64 and .6 At the Massachusetts Institute the tests
prophesied the college ratings for the two years four-fifths as well as the ratings for
one year prophesied those for the succeeding year (correlation coefficients .49 and
.64). The implication is that such tests as these tell as much about a student before he
enters college as the college now knows of him at the end of his freshman year.

The same tests were given to groups of students at four different institutions. A
comparison shows large differences among the average abilities of the four groups.
This indicates that certain schools, whether because of their locations, their reputa-
tions, their student activities, or the excellence of their training, attract boys of greater
innate ability. When further developed and perfected, tests of this type may make it
possible to construct a scale of freshman abilities, by which each school can measure
the quality of each freshman class. It is conceivable that a similar scale to measure
the abilities of the seniors may some day be constructed. Then the difference in the
positions of the freshmen and the seniors on these scales would be a much more valid
criterion of the success of the school work than any now available.

Neither present admission systems nor objective t
ests take account of several im-
portant factors that in many cases have an important bearing on a student’s efficiency
in schoolwork. For example, Professor Thorndike found that during their high school
course two-thirds of the freshmen examined had spent more than 8 hours a week on
work other than school work. The median number of hours per week of such work
reported was 1 during school time and 40 during the summer vacation. Out of 72
freshmen at Columbia and the Massachusetts Institute, 21 reported no outside work,
37 reported from 1 to 9 hours of outside work, 11 from 10 to 19 hours, and 3 more
than 20 hours. At Cincinnati all the engineering students spend half their time in out-
side work. One student, who was rated low in the composite school series but who
made an excellent record in the tests, was found to be doing over 40 hours a week of
outside work. It is clear that a record of the amount and the kinds of outside work done by students would be of value in determining fitness to enter college.

A record of boyish interests and activities might also help to reveal to college examiners the presence or absence of real engineering bent or temperament. The freshmen tested by Professor Thorndike were asked to indicate by numbers their present preference for bargaining, managing people, studying books, clerical work, mechanical work, farm work, work with animals. In the replies from 90 freshmen mechanical work was rated first or second 82 times out of a possible 200, which is three times as often as chance would give, and over three times as often as was the case for a group of school superintendents at the same age. Out of 103 engineering freshmen who reported on the matter of boyish activities, 91 had constructed on their own initiative mechanical or scientific devices such as cannons, telegraph lines, telephones, electric motors, arc lights, gasolene motors, lathes, steam engines, water wheels, boats, etc. None of the engineering schools at present record this type of information or make any systematic effort to use it or to interpret its meaning; nor do parents and elementary school teachers realize the importance of giving young boys and girls opportunities of expressing their innate mechanical sense in creative work.

Let no one imagine that the tests presented in the Appendix are a final solution of the college entrance problem. They are but the beginning of an effort to proceed one step farther in the direction indicated by the development of college entrance systems during the past twenty years. A large amount of experimentation and cross checking among different schools must be done to determine the validity of this type of test and to interpret the results of its use. Enough has been done to show that the principles of testing here presented are worthy of further investigation and that methods of procedure have been indicated that point to a safe road of real progress. As these principles are applied and these methods are developed by many observers in many schools, it may be possible to liberate college entrance from its present fetters and place it on a more rational and scientific basis.

The effect of such a development on the quality of preparation for college is sure to be most beneficial. College professors are at present the only teachers in the school system who are permitted to teach without one hour of special training for teaching. With mastery of their respective subjects and the highest idealism and sincerity, they devise specifications for the content of high school courses, and then enforce those specifications directly or indirectly by entrance examinations that do not really measure ability or create the best conditions for its development. When the colleges are able to define their admission requirements in terms of abilities as measured by objective tests, instead of in terms of subject-matter covered, it may be possible to lift the great incubus of ignorance that now oppresses the secondary schools, to supply the colleges with freshmen much better trained and sorted on the basis of ability, and to reduce the mortality of 60 per cent to a more reasonable figure.
CHAPTER IX
THE TIME SCHEDULE

WHEN faculties were small and the number of subjects that seemed essential were relatively few, the problem of the time schedule was a fairly simple one. All the necessary courses could be arranged in a compact and consistent program that required the student to carry not more than 18 credit hours of work at one time and to study not more than four or five different subjects each term. But as science expanded and became more intricate, specialization was unavoidable. By 1890 the civil engineering student had to choose either general civil engineering, or railroad engineering, or topographical engineering. Similarly the prospective mechanical engineer had to decide by the end of his second year whether he would follow the general curriculum in mechanical engineering, or one that specialized in marine, in locomotive, or in mill engineering. Since 1890 this process of subdivision and specialization has advanced rapidly, pushing the student’s choice of a specialty back into the first year, increasing the required number of credit hours in some cases to as many as 27, and at times loading his weekly schedule with from eight to thirteen different subjects.

If there is any one point on which practising engineers and teachers of engineering are in substantial agreement, it is that at present this specialization and subdivision of curricula has gone too far. The congestion that inevitably results is universally recognized to be a fruitful source of confusion to the student and a real cause of superficial work. Attention is distracted from mastery of the subject and encouraged to seek ways and means of securing passing grades with minimum effort; so that a rigid and exacting department is likely to get more than its share of time and labor. There is too little time for persistent thinking, too little opportunity to realize the joy of achievement, and too much inducement to join in the scramble for credits.

There are two obvious methods of relieving congestion, namely, more time or fewer subjects. A few years ago Harvard University and the University of Missouri expanded their engineering curricula to six years, partly to relieve congestion and partly to raise engineering to the rank of a graduate professional study like law and medicine. Both of these efforts have been abandoned, but Columbia has undertaken to continue the experiment. The University of Wisconsin for a number of years offered a five-year curriculum along with the regular four-year one, but this was given up because it proved to be a haven for “lame ducks” who could not accomplish the regular work in four years. Cornell still maintains a five-year curriculum and is much pleased with its operation. The five-year curriculum at Yale consists of two years of specialized graduate work added to the regular three-year curriculum that leads to the Ph.B. degree in engineering.

In the matter of fewer subjects a number of the best schools are succeeding in keeping the required number of credit hours below 18 per term, as at Cornell, Ohio State,
Illinois, and Wisconsin. Under these conditions the tendency to congestion is relieved to a certain extent by having a fairly large number of specialized curricula and allowing some small choice of electives among the technical subjects in the last two years. Both of these devices really result in a reduction of the amount of subject-matter by a limitation of its range, and thus bring the schools face to face with the charge of training narrow specialists instead of broad gauge professional men.

Thus far neither more time nor fewer subjects have as a matter of fact cured congestion. For the amount to be learned in every field is so vast and is increasing so rapidly that whenever a professor gets more time for instruction, he usually tries to cover more ground; and this tendency is supported by many of the younger alumni, who keep suggesting the addition of this that, or the other bit of information that was not given them in college, but would have been useful to them on their first jobs if it had been included in the curriculum. This pressure to keep up to date, combined with the natural reluctance of every teacher to abandon material he has once worked up for presentation to the class, is fairly certain to produce congestion even after it has been temporarily relieved. The real causes of congestion, however, with its well-known symptoms of mental confusion, superficiality, and scurry for credit, lie deeper. Their roots penetrate to the methods by which curricula are constructed and the educational conceptions on which they are based.

Engineering curricula were originally organized on a very different basis from those in other professional schools. The earliest instruction in law and medicine was given by the apprenticeship system. As these professions grew, it was found convenient to gather the apprentices together in groups for class instruction by some particularly well-qualified practitioner. These classes were then organized into schools controlled and managed by practitioners, who, until recently, also gave the greater part of the instruction on a part time basis. The first law and medical schools at universities were practitioners' schools appended to, but never fully assimilated by, the institutions to which they were attached. Full time college professors of medicine and law are of relatively recent date, and even now much of the instruction in these subjects is still given in university schools by practitioners on a part time basis. The curricula of these schools, therefore, developed out of apprentice courses and were framed by men in daily contact with professional work.

In engineering, on the other hand, altho the apprenticeship method of training was originally employed and is still in extensive use,—about half of the professional engineers in America to-day being shop-trained men (page 19),—this system of training never developed into engineering schools to any extent. The first engineering schools were founded by colleges, their professors were college-trained men, and their curricula were devised by college faculties; professors also gave practically all the instruction with very little assistance from practitioners. For this reason the first technical schools had a serious struggle to prove that engineers could be trained in schools. Even now technological schools are classed in the Reports of the United States Bureau

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of Education with universities and colleges; while schools of law, medicine, theology, dentistry, pharmacy, and veterinary medicine are classed together as professional schools.

This dominance of the college of liberal arts in engineering schools has undoubtedly been a powerful factor in the development of the engineering profession. The emphasis still placed in the curriculum on pure science, pure mathematics, and the humanities, in spite of numerous vigorous attacks on them, is evidence of the extent to which the ideals of the American college still dominate the technological schools. But tho this protection of the conception of culture within the engineering schools has tended to liberalize them and to prevent their becoming too materialistic, it has not been an unmixed blessing; for that conception has been slow to adapt itself to the changed conditions produced by engineering, and has tended to preserve several fundamental practices that are now regarded as the probable causes of congestion and of other serious difficulties in current curricula.

Prominent among these outgrown practices is the method of constructing and changing curricula. When the students’ hardships have become so obvious that they can no longer be ignored, a committee is appointed to study the problem and suggest changes. This committee usually requests each department to submit a statement of its requirements and desires; and, while this is being prepared, compiles a table showing how much time is allotted by other schools to each of the subjects included in the curriculum. The departmental statements are also compiled so as to show how much time is needed to fulfill all their requests. Generally the number of topics each department considers essential is so large that the hours required to cover them all would be double or triple the number available. The various claims are then discussed in committee, reduced within reasonable limits by a process of cut and fit, and the result reported back to the faculty. In the faculty debate that follows, each department presses its claims for more hours, and numerous changes are suggested, debated, and ordered made or not made by a majority vote. When the matter is settled each department takes the time awarded to it and uses those hours in any way it likes. In short, distribution of time among the departments is usually regarded as the chief function of the faculty. Respect for departmental autonomy forbids any investigation or scrutiny of the aims, the methods, or the results of the work of any one department by the faculty or by any of its committees.

Under present conditions the members of the various departments in engineering schools are selected in the main because of their abilities as specialists in their respective fields. Since every competent specialist is always an enthusiast over his specialty, there is no limit to the number of hours he would like to fill or the amount of information he would like to impart to the students, especially when the work is conducted by the lecture method. Therefore congestion of the curriculum is inevitable so long as each department remains sole arbiter of the content of its courses, and there is no coordination among departments with respect to the amount and the
nature of the subject-matter in courses, and no scrutiny of the results of each department’s work by some agency outside the department. The problem of congestion is evidently not merely a question of the time schedule, but leads at once to such specific departmental questions as: What is the minimum mathematical equipment essential to every engineer, no matter what his special line may be? What fundamental principles of mechanics must be mastered by every engineer? In developing a mastery of these principles of mechanics, what coordination of work among the departments of mathematics, physics, mechanics, and engineering is most effective? Until such interdepartmental investigations and experiments are the rule everywhere, instead of the exception, congestion is likely to persist and grow more and more disastrous.

Investigations and experiments of this type are already under way at several schools. Thus at the Naval Academy an effort is being made in the postgraduate department to coordinate mathematics with engineering by scanning the subject-matter of both to eliminate non-essentials, so as to make the treatment of each topic as brief as is consistent with clear understanding; there is also an earnest effort to arrange the material in both departments so that the presentation of the practical by the engineer and of the theoretical by the mathematician come at about the same time and complement each other. Similarly at Cincinnati, many of the problems used in the mathematics classes are actual industrial problems brought in by the students from their practical work in commercial shops; and the work in English is so organized that theme writing gives outlook to the technical courses and technical reports are also exercises in English composition.

Important as are experiments of this sort in indicating present tendencies, their benefits are limited to the schools where they are made, because their results are not tested by methods easily recognized as valid, and the conclusions derived from them are not expressed in terms intelligible and convincing to all. To be widely effective, experiments must be checked by tests that are as free as possible from the personal equation and the errors of subjective judgment on the part of the experimenter. There fore, ultimately, the problem of congestion leads, like the problem of admission, to the need for more impersonal and generally intelligible methods of testing and measuring the growth of abilities. The invention and perfection by experiment of objective tests of ability seems to offer the most promising road to progress toward a type of instruction that places less emphasis on information and more on ability to use information intelligently—toward greater cooperation among departments and less of the specialized exclusiveness of departmental autonomy, and hence toward the relief and the ultimate cure of congestion. This question is discussed further in the following chapters.

The seriousness of the problem of congestion has been widely recognized. There is; however, another closely related and equally important problem the significance of which has not been so fully apprehended; namely, the order of sequence of the various

courses. In this matter the 1849 curriculum at Rensselaer (page 12) imported a French style that has been followed implicitly ever since. The conception underlying this and all later curricula is that engineering is applied science; and therefore, to teach engineering, it is necessary first to teach science and then to apply it. In conformity with this conception the first two years of college work are almost universally devoted wholly to learning the fundamental principles of chemistry, physics, and mathematics. Only when the student has passed a satisfactory examination on these fundamental principles and their various non-technical applications is he permitted to work on engineering projects.

Some of the peculiar effects that result from this universal habit of teaching first the theory, then the practice, are now beginning to attract attention. Instructors who are close to freshmen and sophomores tell how bewildered and discouraged the underclassmen often are because, having come to college to study, as they supposed, the dynamic agencies for doing the world’s work, they find themselves merely continuing their elementary and high school drudgery with books and abstract symbols. Doubtless some of the freshman elimination is due to this discouragement, and it has been suggested that the drop in student grades in the sophomore year (page 53) may be attributed mainly to this cause. The question has also been raised whether failure to make good in these preliminary studies as taught, or to succeed in the tests as given, is really conclusive evidence of lack of engineering ability.

Several of the schools visited have found that the introduction of “orientation” courses and talks by practising engineers on the real experiences of the engineer’s life are effective means of increasing the interest and strengthening the morale of the freshmen. A moving picture of an engineering enterprise in action is not without results. These realistic portrayals of the technique of practice lend reality to the book work and arouse the professional ambitions of the hearers. The actual participation in technical work under the cooperative plan at Cincinnati, Akron, and Lafayette, the summer vacation work in industrial plants, and the summer surveying camps all tend in the same direction.

Recently the conception that beginners might learn more quickly and thoroughly if real experiences were coordinated with their study of theory, has been carried one step further by introducing real work into the class work itself. Perhaps the most striking of the several recent experiments of this kind is that conducted by Professor C. C. More of the University of Washington. Mechanics is generally placed in the third year so that the students may be well prepared for it in physics and calculus. The conventional course begins with the statement of definitions and the deduction of general principles, followed by the solution of typical problems. Professor More begins by asking the student to report on the safety of the sheet piling in a certain cofferdam whose dimensions and location are pictured and described. Theory and principles are worked out and proved as they are needed to solve the problem. Calculus and physics are freely used. This complete reversal of the conventional order proved so success-
ful that last year the same course was tried, including the calculus, on one section of engineering freshmen, who mastered it with little more trouble than the juniors. As a result, the entire engineering faculty now sanctions this order of topics from application to theory as a great improvement over the older conventional one. Other similar experiments are discussed in subsequent chapters.

Altho the engineering faculty at the University of Washington approve of Professor More’s new order for teaching mechanics, other instructors in mechanics who cannot personally observe the results will be slow to follow or inaugurate similar experiments because there are no generally intelligible objective tests and scales of ability in terms of which the results may be expressed. For this reason experiments with the curriculum, either to relieve congestion or to secure more enthusiastic and intensive work thru variations in the nature and the order of the topics, have at best a limited effect. So this problem too settles down ultimately to one of inventing and defining tests and scales to measure variations in ability. Further uses for such scales are explained in Chapter XI.

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CHAPTER X
CONTENT OF COURSES

ONE of the most striking and universally recognized features of the technological schools is their lack of agreement on the content of courses that bear the same or similar titles. Some of the more marked differences in elementary chemistry, English, drawing, and shopwork have been mentioned in Chapter VII (page 88). Obviously the 52 hours of calculus at Rensselaer cannot have the same content as the 216 hours of calculus at the University of Florida (page 24). Some of the courses in mechanics place great emphasis on the absolute system of units while others use only the engineers’ units. In the treatment of descriptive geometry the number of essential problems varies from 27 to 86 and the number of fundamental conceptions from 6 to 12. The teachers of each subject not only do not agree on what equipment in their subject is essential for an engineer, but they have not yet taken the first step toward such an agreement, namely, the definition of the criteria that must govern the selection and the organization of the content of their several courses.

The prevailing wide diversity in the content of courses is clearly a necessary result of the general confusion as to ends, aims, methods, and rating of instruction. But while the many strong points in the present system are duly appreciated, it is gradually becoming evident that in training men for so definite a vocation as engineering, in which the various elements—science, mathematics, language, economics, and hand work—are so intimately interrelated, some agreement as to aims and some cooperation among departments in determining the content of courses is absolutely essential. That this need is recognized at all the schools is evidenced by the numerous common complaints among departments. The departments of engineering insist that the preliminary work in mathematics and physics is unsatisfactory because students who have passed these courses cannot use either mathematics or physics intelligently in the later technical work. Conversely the teachers of mathematics and physics claim that the students are poorly prepared in these subjects in high school and that the engineering departments make unreasonable demands. All the other departments decry the work in English and foreign languages as inefficient and wasteful of the students’ time.

To remedy these well-recognized difficulties, conference committees are frequently organized and friendly meetings are held, in which each side explains its point of view. The resulting changes, however, are few. At one school a professor of mathematics voluntarily attended numerous classes in engineering subjects to get some notion of the mathematical needs of these courses. The course he devised on the basis of the information thus secured was so successful that he was called to a more responsible position in another institution; yet his colleagues did not carry on his experiment. At another school a professor of chemistry conducts a volunteer class in Ger
man in order that the students in chemistry may have a chance to get the practical mastery of German that every chemist needs. One professor of civil engineering and one of electrical engineering were found giving regular instruction to volunteers in English composition, both written and oral.

In spite of the fact that deviations from established practice in teaching are not encouraged, so that there is an almost universal disinclination to make changes, a few import experiments are being made for the purpose of discovering more appropriate content for courses. Prominent among these are two in mathematics, one at the Massachusetts Institute of Technology and one at the University of Wisconsin. In both the aim has been to construct a single two-year course in mathematics in place of the customary but somewhat unrelated courses in algebra, trigonometry, analytical geometry, and calculus. Both courses have been published in textbook form; the former in Woods and Bailey’s *Course in Mathematics* \(^1\) and the latter in Slichter’s *Elementary Mathematical Analysis* \(^2\) and March and Wolff’s *Calculus*. \(^2\) While the particular categories under which the various topics are arranged are very different in these two courses, the underlying conceptions are similar, in that both attempt to reorganize the content of the mathematics courses for the purpose of securing a more logically coherent presentation. Each is a consistent working out of a mathematician’s conception of the mathematical equipment needed by every engineer. This emphasis on logical sequence has undoubtedly a fascination to certain types of mind—teachers of mathematics, for example. Its effectiveness with the great majority of students may well be questioned, especially when the logic is expressed in curves and symbols carefully detached from technical applications. Both of the courses just considered claim to pay particular attention to applications, but these are mostly of the non-technical variety. In the Woods and Bailey text, out of 2Q88 problems for drill in the application of mathematical principles, only 105 even mention material things; while in Slichter’s book, only 146 out of 110 problems discuss concrete realities.

The experiments just described are typical of one method of attacking the problem of finding more significant content for engineering courses. The emphasis in reorganization is placed on more logical and coherent sequence of topics and a better adaptation to modern scientific theories, with little attention to the introduction of engineering content into the mathematical forms treated. To some extent the content of courses in physics and chemistry is being reorganized into more logical and coherent presentations of current kinetic and ionic theories of matter. The methods of instruction followed in experiments of this type are usually much the same as those of the old standard courses.

A second type of reorganization of content is being worked out by Professor H. M. Goettsch at the University of Cincinnati. After sixteen weeks of preliminary training very similar to that ordinarily given in courses in elementary chemistry, the freshmen work in the laboratory from 8 a.m. to 4:30 p.m. for ten weeks solving problems

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1 Two volumes. Gino & Co., 1907.  
of industrial chemistry. Projects such as “Make baking powder and determine whether it is better and cheaper than any you can buy” are assigned without any instructions or references, and the student is required to work out his own salvation in the library and the laboratory. In the period of ten weeks he completes a number of these projects covering a wide range of topics, but little effort is made to present the topics in logical or any other sort of orderly sequence. Much emphasis is placed on synthetic work and on the cost of a given product by different processes; while chemical analysis and the ionic theories of matter, which usually occupy the centre of the stage in chemistry courses, here take a subordinate place. The course in mechanics devised by Professor C.C. More at the University of Washington (page 58) is another example of this type of reorganization of content in which the logical sequence of topics is subordinated to project work, and theory is evolved from rather than illustrated by problems and experiments. Professor R. M. Bird conducts his course in elementary chemistry at the University of Virginia on this plan with great success.

The content of courses of this type is clearly determined by considerations both of logical completeness and of pedagogical vigor. For a series of interesting projects that does not eventually compel the student to work out a fairly complete conception of the large theories and the important principles of chemistry is obviously inadequate, no matter how enthusiastic the students are in their work. On the other hand, altho the suggestion that an effective course can be constructed as a series of apparently disconnected projects comes as a shock to those who have grown up with logically rigorous courses, the value of the enthusiasm engendered by well-chosen projects must not be overlooked. Our most valuable information and training come from working out projects that are really worth while; and if this method works in life, why not in school? Especially since in educational institutions it is always possible to organize significant projects into a connected series that leaves a well-developed conception of the whole subject in the student’s mind. This has been accomplished in the courses just mentioned, where the summing up is done after sufficient facts to warrant summaries have been secured. Their success should encourage others to further experiments. The inclusion of considerations of values and costs in the content of these courses is also an element of enrichment that deserves careful attention.

Those who find a series of projects an unsatisfactory course of instruction, but who nevertheless wish to make the content real and of great value to the students may find many worthy suggestions in Professor R. H. Fernald’s course in power plants at the University of Pennsylvania. While the topics in this course follow one another in a logical sequence, they are chosen largely from engineering practice, and include much of the practical information every engineer must have when he goes to work. Many of the problems are actual cases that really occur in engineering, so that they appeal both to professional instincts and to the sense of values and costs—in fact, many of them are openly problems that deal with costs of operation and maintenance in working plants. Yet the course is not a mere mass of useful information; rather useful
information is the vehicle for conveying to the student a firm grasp of fundamental principles and engineering methods of attacking and analyzing problems not only from the point of view of scientific theory but also with due consideration of the limitations imposed by practice and by costs. Professor Fernald’s course has been published in textbook form, ¹ and a number of other schools have adopted it and are following it with satisfaction.

The emphasis given in this course to the economic aspects of power plant problems is an encouraging sign of the dawning recognition of the profound importance of this side of engineering in technological schools. Most of the technical colleges now include short courses in economic theory, banking, contracts and specifications, etc.; a few give some small amount of practice in figuring costs and making bills of materials from drawings assigned by the instructors. Here and there the attention of the students is directed to the practical difficulties of construction and the controlling power of costs. There has always been and still is a strong aversion on the part of colleges to placing emphasis on the material and financial aspects of the engineer’s work. Yet it is a burning question whether the commercial bearings of each subject cannot be introduced into every course in such a way as to increase enormously its use and its vitality without in the least impairing its inherent scientific value. The enrichment of the content of courses by judicious appeal to practice and costs is a problem that offers rich opportunities for further experiment.

But if experiments of this sort are undertaken in large numbers in every school, there is obviously serious danger of actually becoming too materialistic, thereby sacrificing powers of abstract thought and humanistic ideals on which real progress ultimately depends. Efficiency in the mastery of materials without humane intelligence to guide and control it is now recognized in all civilized countries as a curse. Hence great care must be exercised in making these experiments, and every effort must be made to enforce the truth that mechanical efficiency, while essential to success, is servant and not master. The opportunity offered to the humanistic studies by this situation has already been perceived at a number of schools, and many efforts are being made to alter the content of the courses in English, in history, and in economics to meet the obvious need. Perhaps the most striking experiment with this aim is that now being made by Professor Frank Aydelotte in cooperation with the members of the department of English of the Massachusetts Institute of Technology. At this school English is a required subject for all students throughout the first two years. The first half of the freshman year is devoted to general composition, with the object of eliminating the more common errors of construction and of leading the student to see that excellence in writing comes not so much from the negative virtue of avoiding errors as from the positive virtue of having something to say.

The work of the second term of the freshman year begins with a class discussion of such questions as: What is the difference between a trade and a profession? What

is the meaning of the professional spirit? What should be the position of the engineer in society in this new era of the manufacture of power—that of hired expert or that of leader and adviser? Is the function of the engineer to direct only the material forces of nature, or also human forces? Such questions readily arouse the interest of engineering students and bring on thoughtful discussion, in which different points of view are expressed by the students and debated with spirit. Essays by engineers are then assigned for reading, and after further discussion each student is asked to write out a statement of his own position on the mooted questions. These themes are criticized in personal conferences in which faults are corrected by asking the writer first what he intended to say; and, second, whether the sentence or phrase in question really says it, rather than by reference to formal rules of grammar and rhetoric. Those who have had experience with this work claim that once the habit of self-criticism from the point of view of the idea is established, the student makes astonishing progress in the ability to express himself clearly and independently; he gathers hints from all sources; and in ways too complex for pedagogical analysis he is more likely to acquire such power over language as he is naturally fitted to possess, than he is by current formal methods. For the achievement of this complex end, the conventional instruction in technique is too crude and clumsy to be of more than incidental use.

Having discussed the question: What is engineering? the class proceeds in the same manner to wrestle with such problems as: What is the aim of engineering education? What is the relation between power of memory and power of thought? Is there any connection between a liberal point of view and capacity for leadership? What qualities do practical engineers value most highly in technical graduates? What is the relation between pure science and applied? What is the relation of science to literature? The authors read in connection with the discussion gradually change from engineers to scientists like Huxley and Tyndall, and then to literary men like Arnold, Newman, Carlyle, and Ruskin. The student seems to read this material with no less keen interest than was shown for the writings of engineers; so that thru his own written and oral discussion of masterly essays each comes to work out for himself some rational connection between engineering, with which he began, and literature, with which he ends. No orthodox point of view is prescribed; his own reason is the final authority. The aim is to raise questions which it may take half a lifetime to answer, but the thoughtful consideration of which will give a saner outlook on life and on his profession.

A similar experiment along analogous lines is being made by Professor Karl Young and his colleagues in the department of English at the University of Wisconsin. Reports indicate that this type of course is a great success there also. The materials used in both these courses have been reprinted in book form for the convenience of the classes. ¹

The four typical experiments just described indicate that the reorganization of the content of courses is being attempted with a wide variety of aims, such as more logical coherence, better pedagogical organization, greater emphasis on the economic phases of the work, or a broader and more humanistic outlook. Many other aims are conceivable, and many combinations of these four are possible, so that there is unlimited opportunity for the further experiments that are needed as a basis for the reconstruction of the curriculum. The current method of framing curricula by first distributing the student’s time among the various subjects by faculty action and then allowing each department to fill in its quota as it sees fit leads to the impossible conditions discussed in the preceding chapter. The way out lies in the direction of reversing the process; that is, first determining by cooperative faculty investigation what equipment in each subject is essential to every engineer, and then requiring each department to discover by experiment how much time is necessary to give adequate control of that essential equipment to the promising students.

In order to carry out this suggestion, entrance requirements must first be placed on some such basis as that described in Chapter VIII, so that the technical school can be reasonably sure that the majority of the students admitted show promise of success in engineering. Then for each of the fundamental subjects common to all engineering curricula an answer must be found by cooperation among all departments to the question:

What is the minimum equipment essential to every engineer, no matter what specialty he may eventually choose? The answers to this question must be stated in terms of ability to accomplish rather than in the customary terms of topics to recite; for example, the familiar “algebra through quadratics” must read “ability to make algebraic computations as difficult as required in solving for $x$ in

$$\frac{x+a}{x-a} - \frac{x-a}{x+a} - \frac{x^2}{a^2-x^2} = 1$$

After such statements of the minimum essentials have been secured, the respective departments will be able to construct their courses intelligently and to devise objective means of testing their progress.

There are at present two serious obstacles to carrying out the plan here proposed. One is the reverence for departmental autonomy, which makes all departments reticent about making suggestions to one another and inclines each department to regard any suggestion from another as unwarranted tampering with vested rights rather than as an intelligent effort to benefit the students. The other is the lack of generally intelligible and transferable scales and methods of testing. These two obstacles deprive such experiments as are being made of the greater part of their potential usefulness, — the former by limiting the scope of the experiment by the bias inevitable to every specialist, and the latter by making it impossible for the experimenter to state his conclusions in terms that are convincing to others. The chances for real progress in vitalizing the content of courses are increased in proportion as departments cooperate...
in defining the minimum essentials and as scales of ability and methods of testing are liberated from the errors of individual judgment. It is here that the teacher has his greatest opportunity for creative work; for when the content of a course is well chosen and the subject-matter is effectively organized to meet both the scientific and the human requirements, the game is worth the candle for the student and he plays it with energy and zest.
CHAPTER XI
TESTING AND GRADING

About half of the schools visited grade students on a numerical scale of 0 to 100, with pass marks varying from 50 to 70. Two grade on a scale from 0 to 4, one having 3 and the other 2 for the passing mark. The remaining schools ostensibly grade on literal scales (with per cent values attached); but of these, three have three grades above pass, designated respectively by A, B, C, or M, P, C, or C, P, L; and two have four grades above pass, indicated in the one case by A, B, C, D, and in the other by D, G, P, N. As a result, whenever a student transfers his credit from one school to another, it is very difficult to evaluate his record and determine his status in the institution to which he comes. Tho all student grades are apparently reducible to numerical values, a grade of 88 is hard to interpret even when you know the school and the instructor that gave it, because each school and each instructor has a personal equation in grading.

After one year’s experience with a group of students, a teacher of mathematics, for example, undoubtedly possesses more information concerning the mathematical interests and abilities of these students than can possibly be ascertained by a few hours of examination or testing. But his knowledge is largely in the form of personal experience and intuitions based thereon, which cannot be expressed in the usual record blanks and so is seldom transferred to other departments. The knowledge now possessed by the teachers in a school of engineering, tho abundant, is not accessible thru records; but is segregated in departments and individuals, and confused by personal equations. Even tho ability to secure high grades in school and college seems to be a stable characteristic of an individual (page 36), employers have long since learned that college records are precarious guides in selecting men for jobs.

About ten years ago Professor Max Meyer of the University of Missouri started a campaign to eliminate the personal idiosyncrasies of individual instructors from academic ratings by requiring every professor to distribute his grades over his classes approximately according to the probability curve. It was pointed out that when all the students at a university are arranged in the order of their average grades, about fifty per cent are found grouped about the middle grade, with about 25 per cent higher and 25 per cent lower. Hence the University of Missouri defines its grading system thus: “In classes sufficiently large to exclude accidental variations, approximately 50 per cent shall receive the grade M (medium); to the great majority of the 25 per cent above M the grade S (superior) shall be given; and to the few most excellent students the grade E shall be assigned; the majority of the 25 per cent below M shall receive the grade I (inferior), and the minority shall be given the grade F (failure).” In order to render the grading significant to the students, 30 per cent

excess credit is granted for all work done with a grade of E, 15 per cent excess for work of grade S, and a 20 per cent reduction of credit is made for work of grade I. The results of this experiment at Missouri and of similar investigations at other schools indicate that considerable progress is being made toward reducing the number of professors who either mark most of their students A or else fail a large percentage of them. The mere presentation without comment to each member of the faculty of his own grade distribution curve superposed on the average curve for the whole institution has been found to reduce abnormalities in grading without discussion or faculty action. Clearly this work is developing in the same direction as are the entrance requirements (page 49); namely, toward a reduction of the errors in grading that result from personal equations. There is need and opportunity for further effort to stabilize the distribution of grades along the lines of this experiment.

The study of the distribution of grades is now expanding in the direction of searching for the reasons for strikingly anomalous curves. In the schools visited a number of cases were found in which from 50 to 75 per cent of the students who graduated had received grades just slightly higher than the pass mark (page 34). Experience shows that when so large a fraction of a class receive such low grades there is some serious difficulty, which can usually be removed by investigation (page 35). As a result of numerous such studies it appears that the grading systems in current use possess several inherent characteristics which have been accepted so long as a matter of course that their normal effect on the distribution of grades seems to have been largely overlooked. Prominent among such characteristics are the convention of granting the same amount of academic credit for all grades of work above the pass mark, and the habit of leaving the definition of the basis of testing and grading in each subject wholly in control of the instructors who do the teaching.

The harmful influence of both of these characteristics of current marking systems is very generally recognized. Every college teacher knows well that many of the ablest students regard it as an evidence of poor management on their part if they get grades very much above the pass mark. College authorities have sought to break up this student tradition by offering academic honors of one sort or another, like Phi Beta Kappa, Tau Beta Pi, Sigma Xi, or honorable mention on the commencement program. A further and more effective step has been taken by the University of Missouri in granting excess credit for high grades, as just described. Other schools are trying the experiment of adding to the regular grading a system of honor points, so framed as to prevent the student from graduating on mere pass grades. But even these devices do not render the grades intelligible to employers and to other colleges, nor do they always inspire the student to maximum effort. The West Point grading system (page p28), on the other hand, does act as a real incentive to good work and as a genuine support for the maintenance of the honor system.

The reasons why grades under present conditions do not act as real incentives to good work are very similar to the reasons why payment of wages to workers on the
basis of time spent at work fails to result in maximum output and even tends to scale
down the efficiency of the skilful to that of the slothful. So long as the credit in both
cases is determined mainly by the time consumed, the only accomplishment demand-
ed being a certain minimum below which the job cannot be held, so long there is no
real incentive to speed up and show mettle. Hence workmen “soldier” and even de-
liberately unite to deceive their employer as to how much work an able and ambitious
worker can do in a day; and students have been known to practise analogous tricks on
professors. All of which has a decided tendency to concentrate grades in a small area
on the safe side of the pass mark. The device of granting bonus credit for high grades,
while it improves the situation, is not likely to effect a real cure until grades are a tru-
er measure of achievement than is at present the case. For the students know as well
as anybody that college grades are very ineffective measures of the type of ability
that wins recognition in the world’s work—they know of too many notable examples
that fortify their own personal observations and convictions in the matter.
The real cure for “soldiering” in college work as already been found and put into
practice in one department, namely athletics. There the students submit gladly to rig-
orous discipline and exert themselves to the utmost in the games because the work
appeals to them as thoroughly worth while and the score is a valid and objective mea-
sure of achievement. In their studies, on the other hand, the game does not always
seem worth the candle, and their scores often depend as much on their ability to con-
form to the personal points of view of their instructors as on their real achievement in
mastering materials. For under present conditions each department—frequently each
individual instructor—sets all examinations and tests and determines the relative
merits of the students by means of individual, subjective standards. College boys un-
derstand this perfectly, for it is not unusual to find bright ones among them who win
high grades by studying the instructor rather than the subject. Obviously here, as in
the case of admission, the need is for more objective methods of measuring student
progress and more assurance that the tests used are tests of the abilities the engineer
needs to have developed, rather than of something else the exact nature of which is at
best vague, uncertain, and undefined.
The analysis of a large number of the examination papers and quiz questions in
current use reveals the chief reasons for the vagueness and uncertainty of the results
secured by conventional methods of testing. A large proportion of the questions can
be answered by reciting or writing memorized words, phrases, or equations. How can
the instructor decide whether correct answers to these questions mean merely a reten-
tive memory, or whether they indicate clear understanding of the relations involved,
or an ability to use them in practice? Again, many of the questions call for verbal de-
scriptions of apparatus or processes. The answers to questions of this sort are fre-
quently so ambiguous that it is impossible for the teacher to tell whether the students
do not understand the subject, or whether they are unable to express themselves.
Hence different instructors make estimates that may vary from 30 to 80 on the same
paper; and there are no means of deciding as to which estimate is best. Finally, little effort is made to arrange the questions in their order of difficulty, by placing the easiest first and the most difficult last. Occasionally some questions are given greater weight than others, but the assignment of weights is apt to be an act of arbitrary judgment on the part of the instructor.

Since tests control teaching, it is obvious that one of the most effective methods of attacking the teaching problem is thru the study of tests. For the purpose of making a beginning of such a study aimed at removing some of the ambiguities of current examination practice, Professor E. L. Thorndike of Columbia University devised for seniors in electrical engineering a series of objective tests, analogous to those used in his experiments with freshmen (page 49). In planning the tests, and selecting the types of activity that seemed most likely to reveal abilities essential to engineering, Professor Thorndike was assisted by a volunteer committee consisting of Messrs. E. B. Katte, Chief Electrical Engineer of the Grand Central Terminal, New York; L. D. Norsworthy, Professor of Civil Engineering at Columbia University; F. P. Keppel, Dean of Columbia College; J. W. Roe, Professor of Mechanical Engineering at Sheffield Scientific School at Yale; the secretary of the Carnegie Foundation; and the author of the present study. Descriptions of the tests used in this experiment are given in the Appendix (pages 117, 118).

While some of these tests appear at first sight very similar to ordinary examinations, they are, as a matter of fact, constructed on very different principles. In the first place, each test is intended to measure a specific ability, such as arithmetical computation, geometric construction, paragraph reading, understanding of words, mechanical dexterity, or comprehension of diagrams. Each of these is a single activity, although requiring a complicated coordination of psychological processes. Then the tasks are so selected that their accomplishment can be indicated with little or no use of words, so that ability to perform the task is not confused with powers of verbal expression; and the errors of personal judgment in deciding whether an answer is right or wrong are reduced to a minimum. Because of this independence of the personal equation, results obtained by these tests at different schools, or at the same school at different times, are comparable with one another. Moreover, tests of this kind are capable of indefinite extension by alternative tests that give commensurable results. In this way the danger of cramming for any one set test may be avoided; since after the successful type has been found, it is a relatively simple matter to construct ten or twenty alternative tests on the same pattern. Again, the successive tasks on each test are arranged in the order of difficulty, beginning with one that can be correctly met by almost all students of the degree of training in question, and progressing gradually to one that can be done by only a very few of the most gifted. Such a test is a scale up which the student climbs to the extent of his ability in the particular type of activity under scrutiny; so that, when the test is well constructed, his relative rank is determined without ambiguity by the difficulty of the task he can successfully
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master, rather than by an estimate of how much credit must be given for a partially
completed task.

Thru the courtesy of Mr. C. R. Dooley of the Westinghouse Electric and Manufac-
turing Company at Pittsburgh, these tests were tried out on a group of forty engineer-
ing graduates employed by that company as graduate apprentices. These apprentices
are given very varied tasks, are observed by superior officers with a view to perma-
nent employment, and are given ratings on a series of essential characteristics by eve-
ry foreman under whose direction they work. The essential characteristics used in
these ratings are: physique, personality, knowledge, common sense, reliability, open-
minedness, tact, initiative, attitude, originality, industry, enthusiasm, thoroughness,
system, analysis, decision, English, and ability. In addition to these ratings by fore-
men, the two officers of the educational department of the company, who are in clos-
est touch with the work of the apprentices rank them after they have been there about
nine months, for general ability and for order of choice for employment by the com-
pany. The apprentices themselves were also asked to rate one another, as far as ac-
quaintance permitted, for promise of success in engineering.

The ratings thus obtained from the records by foremen, the estimates by the educa-
tional experts, the opinions of the apprentices themselves, and the tests were com-
pared in many different ways. Unfortunately the college records of the apprentices
could not be used, because so many different colleges with incommensurable grading
systems were represented in the group. As a result of the analysis it appeared that the
foremen’s ratings would give as good a record if they used the six qualities—ability,
analysis, originality, thoroughness, enthusiasm, and common sense—instead of the
eighteen just mentioned. The order determined by the ratings by half the foremen
agreed fairly well with the order determined by the ratings of the other half (correla-
tion coefficient .48); and the order of merit in the judgment of one expert agreed fair-
ly well with the order according to the judgment of the other (correlation coefficient
.53); but the foremen’s order and the expert’s order did not agree so well (correlation
coefficient .24). The correlation of the order given by the tests with the foremen’s
order was also .24 and with the expert’s order .37.

The orders of merit given by the four different ratings were finally combined into a
single order, which most probably represented the best order as determined by all
available information. The individual orders were found to correlate about equally
well with this composite (correlations are: foremen’s records .73, tests .71, apprentic-
es .70, experts .60). Hence in this case the tests, which require eight hours’ time, ap-
ppear to give as reliable an order of merit as do the judgments of either the experts, the
foremen, or the apprentices themselves after six months of experience with the men
in a specially well-organized industrial company. This does not mean that these tests
are infallible, for even a perfect measure of achievement under one set of conditions
would probably be in error, just as the judgment of experts would be in error, as a
prophecy of later years of work under different conditions. The subsequent
careers of those tested must be followed for a number of years and many other similar experiments must be made before the validity of any set of tests can be definitely established. It does mean, however, that, iii a given case, a systematic test of eight hours may detect engineering ability and prophesy engineering success as effectively as expert personal inspection of actual work over a period of several months. It is this possibility that makes experimentation with this type of test so well worth while. The tests herewith presented are in no sense final. They are first approximations, requiring much study and trial for their perfection. Those who have studied these experiments closely are convinced, however, that the method of attack here used is sound, and that progress in the direction here indicated is both safe and sure.

Many experiments with objective tests of the type here described have been made in recent years in elementary and secondary schools. Similar tests are being tried on a very extensive scale on the members of the new national army by Major Yerkes, the well-known psychologist, who has accepted a commission in the army for this purpose. Industries, too, are beginning to look to these tests to guide them in the selection and placing of workmen, in the hope of reducing the labor turnover that is costing the country several hundred million dollars a year. Altho the movement is still in its infancy, enough has been done to forecast what may be accomplished by further scientific work in this field. In engineering, for example, it is conceivable that before long admission to college and achievement in college may be liberated from the bondage of personal equations as grading becomes less a matter of individual bias and more a valid record of actual accomplishment. Then college grades may be transferable among colleges; then academic marks may become significant to employers; then the results of educational experiments may be stated in convincing terms; and then students may come to respect their records and strive to beat them without artificial stimuli in the way of academic honors and credit bonuses.

The greater the number of schools that undertake experiments with tests, the more rapid the progress toward the attainment of these ends. It is not a question of merely superposing a few tests of the type described on the present examination and grading system. Such superposition may well be a first step; but ultimately it is a question of working the whole testing and marking system to a more objective basis, and this is a long and laborious task. For the final rating must include and express the enormous amount of information which teachers now gather about students by inspection of their work and by the regular examinations, quizzes, and reports, in terms that are intelligible for scientific and practical use. Then a rating becomes a safe instrument for vocational guidance, which is, after all, the fundamental problem of the schools.

When grading is conceived as an instrument of vocational guidance, rather than as an expression of the degree to which an individual has succeeded in conforming to an established order of things, more information is needed than can be secured from present tests and examinations. It is a striking fact that while most schools grade merely
on academic work, most industries rate men on personal traits like character, initiative, tact, accuracy, responsibility, and common sense. This fact has led a number of schools to supplement their regular grades with estimates of personal qualities such as these. At Purdue, the University of Kentucky, Pennsylvania State College, and other engineering schools, elaborate records of personal impressions of students are kept on file and used with effect in guiding students into suitable positions. Usually the record card has the names of a number of the desired qualities printed on it, and the instructor is asked to place a grade mark opposite each. Sometimes each instructor does this in private, sometimes the grades are assigned after discussion in departmental meetings. In either case considerable difficulty is experienced in selecting the qualities to be graded and in deciding on the proper grade to be given to each individual for each of the qualities selected. Among the many schemes that have been devised for this purpose two seem to be particularly suggestive to schools of engineering.

The first of these schemes was devised by Professor W. D. Scott of the Carnegie Institute of Technology for the use of large business organizations in selecting employees and executives, and is now being used by the War Department at Washington for grading army officers. The qualities selected for grading in this case are: 1. Physique, including bearing, neatness, voice, energy, and endurance; 2. Intelligence, including ease of learning, capacity to apply knowledge, ability to overcome difficulties; 3. Leadership, including self-reliance, initiative, decisiveness, tact; and ability to command obedience, loyalty, and the cooperation of men; 4. Character, including loyalty, reliability, sense of duty, carefulness, perseverance, and the spirit of service; and 5. General value to the service as a drill master, a leader in action, an administrator, and one who can arrive quickly at a sensible decision in a crisis. Each officer who grades candidates on these qualities is required to construct a personal scale of reference for each quality by writing down a list of five officers of his acquaintance, the first of whom seems to possess the specific quality in a preeminent degree, and the last of whom has as little of it as any one he knows. The third man is then selected as a mean between the two extremes, and the second and fourth as means between the middle and the top men or the middle and the bottom men respectively. The various grades are given numerical ratings from 15 for the highest to 3 for the lowest. The advantages of such scales are apparent, since it is obviously easier to place a candidate on the scale by comparison with other men, than it is to make a numerical estimate of such composite and abstract conceptions as intelligence or leadership. The method has proved so successful in operation that an Army Personnel Committee with Professor Scott in charge has been established as an addition to the Adjutant General’s office in Washington to supervise this and other activities involved in sorting, grading, and testing men for all kinds of army work.

The second suggestive method of rating personal qualities as a help to vocational guidance has been used in the University of Cincinnati for a number of years. The characteristics selected for rating in this case are of a very different sort, and are ar-
ranged in pairs of related opposites as follows: (a) physical strength—physical weakness; (b) mental—manual; (c) settled—roving; (d) indoor—outdoor; (e) directive—dependent; (f) original(creative)—imitative; (g) small scope—large scope; (h) adaptable—self-centred; (i) deliberate—impulsive; (j) music sense; (k) color sense; (l) manual accuracy—manual inaccuracy; (m) mental accuracy (logic)—mental inaccuracy; (n) concentration—diffusion; (o) rapid mental coordination—slow mental coordination; (p) dynamic—static. These pairs of related opposites are printed on blanks, and each instructor is asked to express his judgment of each student by checking one or the other of each pair. The independent votes of the instructors are summarized in the central office. The method of using this type of rating is obvious. No one would think of advising a man of settled, indoor, dependent, self-centred, and static temperament to undertake a job as superintendent of construction on a large viaduct or bridge.

Under present conditions, when current testing and grading systems are more largely estimates of the amount of static information possessed than of dynamic abilities, it is evident that ratings of personal characteristics and dispositions are essential for vocational guidance. Whether this will be so or not when grades have been made to express abilities, whether correlations will be found between various temperaments and various types of ability or not remains an open question for further study. In the meantime there is no investigation that is likely to give larger returns in fruitful progress than the scientific investigation of testing and grading systems; for tests control teaching, and objective records of achievement are one of the most potent means of releasing creative energy in both students and faculty.
CHAPTER XII
SHOP WORK

IN American technical schools shopwork still occupies a rather anomalous position. Few teachers of the mechanic arts have been granted the title “Professor,” and the work itself is seldom recognized as being intrinsically of “university grade.” Yet no one denies that it is an essential element in the equipment of every engineer; and therefore it has been tolerated by engineering faculties and allowed to develop as best it could. As a result there is no agreement as to the purposes and methods of shopwork. Nearly every school has a shop philosophy and a well-organized shop method of its own.

The first engineering school, Rensselaer Polytechnic Institute, was not financially able in the beginning (1824) to support shops of its own. Therefore the founder directed “that with the consent of the proprietors, a number of well-cultivated farms and workshops in the vicinity of the school be entered on the records of the school as places of scholastic exercises for the students, where the application of the sciences may be most conveniently taught.” The students were required in the first three further weeks of the first term (page 11) to “examine the operations of artists and manufacturers at the school workshops under the direction of a professor or assistant, who shall explain the scientific principles upon which such operations depend, four hours on each of six days in every week.” This plan is identical in principle with that now in use at the Sheffield Scientific School at Yale. There the students spend their whole time for three weeks before the opening of the second year in a well-organized course of this sort called “mechanical technology.” The boys do no actual manual work in shops. The purpose of the course as stated in the catalogue is: “to acquaint the student with the terms and processes in use in manufacturing and power plants, and to give him some personal contact with engineering work before taking up his studies in the classroom and the drafting room.”

It will be noted that this type of course gives the student opportunity for first hand observation, study, and discussion of the mechanical technique of production under real commercial conditions, but does not give him either manual skill and the “feel” of the machine that come only from actual use of tools, or acquaintance with the habits and the outlook of workmen. Hence the benefits derived from this work are perhaps more like those derived from inspection trips, the value of which is unquestioned.

A totally different solution of the shop problem is presented at the Worcester Polytechnic Institute. At the founding of this school (1868) the Hon. Ichabod Washburn gave funds with which to establish a small manufacturing plant on the campus. In order to furnish a real shop atmosphere, twenty or more skilled journeymen are regularly employed and articles of commercial value are manufactured and sold in the
open market. The students work side by side with these journeymen, but are relieved by them of much of the drudgery that comes from the too frequent repetition of the same operation. The instruction is given by means of a series of graded exercises upon machine parts required for the business of the shop.

In his inaugural address as first president of Rose Polytechnic Institute in 1883 President C. O. Thompson, who originally organized the shops at Worcester, tells us that this work was guided by the conviction that the more the students understand the nature and the difficulties of actual practice, and the more they use theoretical principles under conditions as like as possible to those of real practice, the greater are their chances of becoming competent and successful engineers. Mere contact with practical work, however, is not enough. For the best results the student’s work must be subjected to the inexorable tests of business, so that he feels responsibility in the use of valuable materials, and the stimulus that comes from knowing that he is making something that some one else wants but cannot make for himself. Without the construction of articles whose workmanship is subjected to the objective test of salability in the open market, shopwork is liable to exalt the purely abstract aspect of mechanical knowledge.

The shops at Worcester are still run as a manufacturing plant on a commercial basis. But in addition to the regular instruction in shop practice and the construction of articles for sale, much attention is now given there to modern methods of “scientific management.” The students analyze the cost of production into its elements, and determine the relative values of different methods of construction to meet the limitations of manufacture and the market price. The organization and operation of the manufacturing work of the shop furnish materials for the study of accounting, time cards, depreciation, inventories, overhead costs, purchasing, and selling.

The Worcester plan, it will be noted, seeks to coordinate the shop instruction with real conditions of industrial production in such a way that the students secure, in the least possible time, manual skill with tools, understanding of the principles of machine construction, and first-hand knowledge of manufacturing and commercial methods. The manufacturing shop is a working model for the study of the technique of business and of practice. The productive nature of the work and the objective test of its salability are two of its important characteristics that tend to make the experience significant to the students.

Among the schools visited, two others, the University of Illinois and Pennsylvania State College, regard the production of salable articles as an essential element of school shopwork. At the University of Illinois the shop has been recently organized as a manufacturing plant for the production of a two-cylinder gasoline engine. No effort is made to market the machine, yet no difficulty has been experienced in disposing of the entire output to the students and their friends. Manual skill is not made a special aim, and there is no series of graded exercises to teach the fundamental operations. The 300 or more operations required for the construction of the machine are all stand-
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ardized, and instruction sheets, like those regularly used in scientifically managed shops, are carefully followed by the students in all their work. All finished parts are tested and faulty ones rejected.

No paid journeymen are employed, but each section of the class is organized as a working unit, consisting of workmen, foremen, tool-room attendants, production manager, storekeeper, inspectors, etc. Each student is moved periodically from one type of work to another in such a way that when his three semesters of shopwork are completed he has performed all the essential functions of operating the plant.

Each student is graded according to his efficiency in production. Since every shop operation is standardized and has an experimentally set time limit, efficiency is defined in terms of the actual time taken and the standard time. Grades are posted each week and, like all objectively determined grades, they stimulate great rivalry for maximum efficiency. The importance of careful planning and complete utilization of time is forcefully impressed, for the several sections are regarded as rival teams, and no student dares waste time in shop lest his team fall behind.

In this Illinois plan construction is still an integral part of instruction; but the omission of the journeyman mechanics shifts the emphasis from actual commercial production, subject to the objective test of salability in the open market, to instruction about methods of commercial production. The shop becomes a “shop laboratory,” and the manipulations there partake of the nature of experiments designed to verify the principles of production that are operative in the industrial world, rather than to solve problems that arise in connection with their productive activities. As in most current laboratory work, the chief problem for the student is likely to be that of following directions intelligently, rather than that of finding the answers to questions that cannot be answered without making laboratory tests.1

The shopwork at the great majority of American technical schools is based upon a notion that is very different from those that have just been presented. This notion has existed for many years, but it was given great prominence by President Runkle of the Massachusetts Institute of Technology in 1876. President Runkle was so much impressed by an exhibit of Russian shopwork at the Centennial Exposition in Philadelphia that he immediately addressed a special report on this subject to the Corporation of the Institute under date of July 19, 1876. He explains that in the Russian system all construction has been analyzed into a number of typical operations which may be arranged in groups, each of which involves the use of a distinct type of tool. The novice makes most rapid progress if he is first trained in the so-called “fundamental shop operations” without any idea of making any useful article. Instruction in the use of tools is thus entirely separated from construction or production; so that only after the student has satisfactorily achieved skill in filing, turning, boring, forging, and the like, is he permitted to construct anything. Since the tools

required for instruction in the fundamental operations are relatively simple, it is possible at reasonable expense to equip an “instruction shop” that will accommodate as many students as one teacher can instruct at the same time, thereby securing the greatest economy of both time and money. Besides, the more expensive construction shops are not essential at a school, since the young engineer, after graduating in such a course, will find no difficulty in completing his practical education in great manufacturing works.

President Runkle was very enthusiastic about this type of shop organization, calling it “a fundamental and complete solution of this most important problem of practical mechanism for engineers.” As a result, instruction shops were established at the Massachusetts Institute and are still being operated with great success as instruction shops pure and simple. The work is now so thoroughly well organized that about 300 hours of training suffices to give a young mechanic skill in the fundamental operations of his trade. The director of these shops, Mr. R. H. Smith, has published his instruction sheets in two excellent handbooks of shop practice.

The inference that President Runkle drew from his study of the Russian exhibit at the Centennial Exposition, namely, that the instruction shops might be totally separated from the construction shops without loss of educational value for engineers, was very generally accepted as sound; so that the majority of college shops were and still are organized on that basis. Undoubtedly the fact that the instruction shops were less expensive to equip and maintain than the construction shops made this division even more attractive at a time when funds were scarce and the financial problem loomed large before the schools. Certain it is that in the great majority of schools there is no direct connection between shopwork and industrial production.

This type of shopwork met a real need when it was first introduced, forty years ago. At that time skill in machine tool work was often a real asset to a young engineer in securing his first job. Manufacturing shops were not so numerous nor so well organized as they are today. Under the present changed conditions, the question is now being seriously debated whether the shop courses in the engineering colleges ought to be altogether abolished. This question has been answered in the negative at the University of Illinois by the recent conversion of the shops into shop laboratories designed to teach the principles of industrial production, as just described. On the other hand, the University of Cincinnati has answered it in the affirmative by the establishment of its well-known cooperative plan.

The Cincinnati plan was first formulated by Dean Herman Schneider in 1899, while he was an instructor in civil engineering at Lehigh University. In 1902 Dean Schneider presented a full statement of his scheme to the directors of several large industrial firms which were considering the establishment at Pittsburgh of a new technical school to give an engineering training that would be better suited to industrial needs than that then given in the engineering colleges. This plan was abandoned when Mr. Carnegie founded the Carnegie Institute of Technology in the City of Pittsburgh. Finally,
in 1906, Dean Schneider found an opportunity to make his experiment at the University of Cincinnati.

The mechanism of the scheme is very simple. The students are divided into two groups, one of which is assigned to work in industrial plants while the other goes to school. At the end of each bi-weekly period the two groups change places, so that the shops and the school are always full-manned. In the shops the students work as regular workmen for pay, but the nature of their work and the length of time each stays on any particular job are subject to approval by the university. The emphasis of the school work is on theory and principles, but these are well interrelated with the shop-work by “coordinators,” who visit each student during each shop period and then meet the several groups during the university periods in special “coordination” classes for this purpose.

The curriculum is completed in five years of 11 months each, so that each student receives 27 months of university instruction. Since the regular four-year curriculum in other schools requires about 36 months of actual instruction, it would seem at first glance that the Cincinnati curriculum could not give as full a training in fundamentals as is given elsewhere. This inference, however, is wholly unwarranted, because in the 27 months of industrial work the student gets a vast amount of practical knowledge which is given in other schools in information courses, and because the close coordination with practice makes the theory more intelligible and significant to the students. The graduates of Cincinnati have unquestionably as extensive a training in theory as have those of other first class schools. In addition, the Cincinnati graduates are able to command engineering positions at graduation without one—or two—year “apprentice” courses, such as are required of men from other schools by a number of the large corporations.

About one hundred of the industrial firms of Cincinnati and the vicinity are now cooperating with the university in this work. These firms represent every important phase of engineering, so that the university is able to arrange the work schedules in such a way that each student progresses regularly thru every phase of his specialty, from the crude and rough work to the more difficult and responsible positions. For example, a civil engineer usually begins with pick and shovel as a member of a gang repairing track. If he elects railroad work, he will progress to switch and signal work, to bridge work, to general engineering work in the engineering department, and to evaluation work. He will learn how to run regular trains and work trains, how to place and operate the equipment for repairs or new construction, and how to calculate cuts and fills—all as part of the regular work on a “real railroad.” The employers, on the other hand, also benefit by the arrangement; they have found the labor of the “co-op” students both reliable and profitable.

Financially the cooperative plan is very economical both for the university and for the students. The university has access with expense to shops and shop equipment that are worth millions of dollars and are never allowed to deteriorate or be-
come antiquated. Since only half the students are in school at any one time, the same school equipment is adequate for twice as many students as elsewhere. The result is that the total cost to the university per student per year at Cincinnati is about $1. At no other school of equal grade is this cost less than $250, and at the large endowed schools it runs as high as $600 or even more. The money earned by the student during his shop periods, while not sufficient to pay all his expenses, is of great assistance, and makes possible an engineering education to many a worthy boy who could not otherwise afford it.

In addition to the obvious financial advantage, the cooperative plan has many educational advantages. Not only is instruction combined with construction so that its social use is obvious to the students, but the construction has three marked points of superiority over that done in college shops. In the first place it is real commercial production that must succeed or fail on its merits. A shop atmosphere does not have to be artificially created. In the second place the variety of construction work is much greater than is possible in any college shop. The students' experiences are not limited to those of making a gasolene engine or a drill press, but may include any of the activities of one hundred different manufacturing plants. In the third place the student is thrown into close personal touch with workmen. He thus comes to know their point of view in a sympathetic way and secures a conception of the human problems of industry and of the appraisement of human values and costs that is invaluable to him and cannot be acquired so well in any other way.

Another striking educational advantage is secured by this method of conducting the shop instruction. Because it is obviously impossible for an industrial plant to permit its workmen to spend time giving instructions to green college boys, many have thought that the student must waste an enormous amount of time doing routine manual labor. This loss is prevented by the “work observation sheets” that are given the student when he begins a new job. These sheets contain from fifty to two hundred questions concerning the details of the job, and direct him to sources of information where he can find the answers. He is required to be able to answer and discuss these questions during the “coordination periods.” In this way the manual labor is made the source of problems that are solved in the class-room and the laboratories. Shopwork thus becomes a series of exercises in defining and solving problems. Under these conditions it is much more likely to be intellectually fruitful than when it consists in carefully following the specifications of standardized direction sheets.

But if the Cincinnati plan has proved stimulating to the students, it has been revolutionary for the faculty. Cooperation and business methods outside have compelled cooperation and business methods at home, with the results already discussed in Chapter V (page 30). Departmental autonomy has practically disappeared, the spirit of investigation has been liberated in the field of education, and it is probable that more experiments in teaching are being made and objectively checked there than anywhere else.
Dean Schneider’s experiment is clearly much more than a novel and inexpensive method of handling the shopwork. It is an effort to create a type of school that meets the demands of an industrial age. It frankly recognizes that the present need is for masters of materials who can humanize industry. It tries to emphasize rather than to discourage the appraisement of values and costs, and endeavors to express idealism in the mechanics of life rather than build ideals that are unrelated to human experience.

Because the educational conceptions on which the Cincinnati plan is founded are so different from the currently accepted conceptions of school practice, it has taken some time for other schools to recognize the significance of the venture. The scheme was scoffed at as unworthy of a real university and more likely to produce skilled “boiler makers” than professional engineers. The graduates are still too young to prove whether this criticism is to any extent valid or not. Meanwhile the cooperating firms in Cincinnati eagerly absorb all the product of the school, while other schools are introducing similar organizations. For several years the University of Pittsburgh has been cooperating on the same principle with a number of firms, the new municipal university at Akron is organized as a cooperative school, and the Massachusetts Institute has just completed arrangements whereby juniors and seniors in chemical and electrical engineering spend a number of months under school guidance in industrial plants before graduation. A detailed account of the Cincinnati Cooperation System, written by Professor C. W. Park, has been published in Bulletin 37 for 1916 by the United States Bureau of Education.

With such rich opportunities for education lying plentifully about in every industrial plant, it is a striking anomaly that the schools make so little use of them. The situation is all the more impressive because the cooperative use of industrial plants results in a large reduction of the cost of schooling and gives the student the chance to support himself partially in college. The neglect of the possibilities of shopwork is responsible in large measure for the professional criticism that the graduates cannot apply theory to practice, for the establishment by large corporations of apprentice schools in which engineering graduates may complete their training on the practical side, for the preference shown by many firms for shop-trained rather than college-trained men, and for the insignificant percentage of production managers who are college graduates.

On the other hand, the neglect of shopwork is not the result of carelessness or of chance. It is due to a consistent effort to meet the professional demand that emphasis in school be placed on the fundamentals of engineering science. But while practising engineers are unanimous in this demand, they recognize that something is wrong with the present system. The fundamentals that are presented in college do not seem to be mastered in such a way that they function readily in practice. Yet common sense instinctively feels that there is no essential contradiction in the practitioner’s position, but that it is possible for colleges to teach the principles of science and develop a scientific attitude of mind in such a way that both are readily transferable to practice.
The University of Cincinnati endeavors to do this by using the practical problems of the shop as the basis of the theoretical work in the school. But the established engineering schools hesitate to approve this solution. In spite of the fact that their real aim is to develop men for intelligent production, they fear too close an intimacy with industry. They shrink from offering short courses and extension work in mechanic arts, like those which have done so much to advance agricultural production, because this type of instruction does not seem to be “of university grade.” This fear is justified so long as shop practice is limited to training in the so-called “fundamental shop operations” wholly divorced in “instruction shops” from production and contact with workmen. But when the students are systematically guided, as they are in Cincinnati, by work observation sheets and coordination classes, the shopwork not only develops mechanical skill and imparts practical information concerning shop practices, but it also serves as a source of problems and projects for theoretical analysis and solution in the university classes in physics, in chemistry, in mathematics, in mechanics, in economics, in sociology, and even in ethics. The problems thus defined are not the stock type of book problems that were made up to illustrate theories already demonstrated in class; they are the real engineering problems of production that constitute the warp and woof of the engineer’s life. On this basis shopwork is perhaps the most effective type of professional training, since it is a direct application of the adage — Learn to do by doing.

Recently Dean Schneider has been able to express this fundamental educational conception of the cooperative system in a manner that is easily comprehensible to university men. Several of the industrial firms cooperating with the university are supporting industrial research laboratories for the purpose of increasing production. These laboratories are treated by the university exactly like every other section of an industrial plant; so that upper classmen, who have shown ability in investigation by the way in which they have discovered and defined problems in industry during their earlier years of shop experience, are assigned here as assistants on research problems for their regular bi-weekly industrial tasks.

During the past decade a number of large industrial companies have established in their plants research laboratories manned by eminent scientists of pronounced research ability. These laboratories are supported by the industries, and are excellent investments, because the increase in the efficiency of production resulting from their labors saves each year more than the cost of their maintenance. Now that increased production has become a national necessity, a large amount of attention is being given to the question of the relation between the universities and the industries in the matter of research. Up to the present the Mellon Institute at the University of Pittsburgh is the only instance of cooperation between a university and the industries in the maintenance and operation of a strictly research institution. The success of this experiment, originally devised and inaugurated by the late Robert Kennedy Duncan at the University of Kansas, has been so gratifying to the univer-
University in bringing its professors in contact with industrial life, and to the industries in reduced costs of production, that other similar institutes will undoubtedly soon be established under the pressure of the present great national need. Industrial shops are literally bursting with problems that call for scientific investigation of the highest order; factories are filled with masses of observation and of empirical data whose coordination and theoretical analysis would be of the utmost value to production if scientists competent to accomplish the task could be found. Millions of dollars are annually wasted in the United States by the duplication and repetition of investigations and experiments in several different plants because there is no pooling of problems or of scientific interests and no central bureau of information, record, and research to which all could look for scientific enlightenment. The missing link is a technique for coordinating learning and labor so that each may serve the other to the fullest in increasing the intelligence and the economy of production as the basis of mutual strength. The experiments with cooperative shopwork at Cincinnati and with industrial research at the Mellon Institute at Pittsburgh are rapidly developing such a technique. The engineering colleges are beginning to grasp the real educational significance of cooperative shopwork, and industrial research laboratories at universities will surely be forthcoming as soon as the conception of their national scientific and industrial importance is clearly defined. Some combination of the two will undoubtedly supply the ultimate solution of the problem of shopwork in engineering education.
PART III
SUGGESTED SOLUTIONS
CHAPTER XIII
THE CURRICULUM

In the preceding five chapters the larger problems of engineering education are discussed and a number of suggestions are offered concerning methods of investigation that promise progress toward effective solutions. It remains to indicate how the various conceptions presented may be integrated in a consistent and workable curriculum.

The question of admission requirements is treated with sufficient detail in Chapter VIII. If a group of schools will take up the careful study of their entrance systems and make experiments with objective tests and records of the students’ youthful interests and achievements, it is certain that the percentage of elimination can be reduced to at least a fourth of its present size, with an enormous saving of time, energy, and money for both student and school. The effect on secondary education would also be most salutary, in that objective entrance tests that measure ability require a shifting of the emphasis in high school from learning facts to developing ability, and tend to liberate teachers from the bondage of detailed syllabi and cramming methods. In order to accomplish these ends it is necessary to expand the recorder’s office into a bureau of investigation, and to equip it with a competent personnel for this work; for at present most college record offices are overburdened with routine work and so cannot undertake this experiment without both expert guidance and additional clerical help. It is more than probable that the expense thus added will prove a real economy, because intelligent selection of students at entrance is bound to reduce the waste that comes from trying to teach engineering to boys who have no real engineering interest or ability.

The reorganization of the college curricula to accord with the suggestions in the preceding chapters requires several radical changes from current practice. In the first place the number of required credit hours per week should be less than eighteen — preferably sixteen. This recommendation is not intended to decrease the number of hours of work done per week by the students, but to make it possible for them to do all of their work more thoroughly. It is, of course, obvious that such a reduction of required credit hours cannot be satisfactorily made without extensive changes in the content of the courses, for it would be disastrous to leave the distribution of time among the departments as it is and merely try to organize them on a sixteen-hour-a-week basis instead of on a twenty or twenty-four hour basis.

In the second place, the few experiments that have been made on the subject indicate that college students do their best work when the number of different subjects studied at a given time is not greater than five. In constructing a curriculum it is desirable, therefore, to limit the number of simultaneous courses to four or five at the outside. At Rensselaer they are limited to three, but the advantages of this are to a certain extent offset by frequent changes in the three (page p25).
A third essential requirement of all engineering curricula is adequate provision in the first two years for “orientation,” contact with real engineering projects, and practical experiences that make the boy feel that he has actually left high school and entered upon a professional career. Orientation lectures to freshmen meet this requirement to a certain extent; practical work in surveying parallel with trigonometry during the first term of freshman year is perhaps more effective for this purpose; a course in mechanics, such as is now given to freshmen at the University of Washington (page 58), is excellent; but the cooperative system at Cincinnati (page 78) is the most complete and thoroughgoing solution of this problem yet presented.

Practical engineering work is essential for the freshman not only because it appeals to his professional ambition, arouses his enthusiasm, and gives him training in practice, but also because it helps him to master the theoretical work more fully and more quickly. Every one knows that at present the engineering professors are seriously handicapped in their work with juniors and seniors because the students are notoriously unable to make professional use of the principles of physics, of mathematics, and of mechanics with assurance and accuracy. One of the most common complaints of employers is that even college graduates have serious difficulty in applying theory to practice. As has been pointed out (page 80), this weakness may be overcome by suitable coordination of theory and practice during the learning process. Hence to the three other requirements of effective curricula must be added this interrelation between the concrete and the abstract throughout the entire college course.

Besides the four requirements that have been mentioned there are a number of pertinent suggestions that demand attention in framing curricula. Thus there is a widespread agreement among professional engineers that the college curriculum should aim to give a broad and sound training in engineering science, rather than a highly specialized training in some one narrow line; that considerable attention should be paid to humanistic studies like English, economics, sociology, and history, not merely because of their practical value to the engineer, but also because of their broad human values; and that the young graduate should have some conception of business management and of the most intelligent methods of organizing and controlling men.

It is well-nigh impossible to construct curricula that will meet all of these requirements and suggestions without giving careful consideration to many of the recent investigations of experimental psychology and to the rapidly increasing literature of the new science of education. Every professor who takes a responsible share of this work will find much to help him in the books listed iii the Selected Bibliography on page 1 for until college faculties appreciate the necessity for experiments in teaching and grasp the significance of the results already obtained, progress is likely to be slow. Therefore the first step for any school desiring to reorganize its curricula is the appointment of a small standing committee composed of men who are interested in the problem of better teaching and able and willing to give considerable time to
the work. This committee will need ample facilities in the way of clerical help, and
effective service on it will soon be recognized by everybody as one of the surest and
most expeditious ways of winning academic advancement. Unless a school is pre-
pared to place this study of education on a basis of unquestioned respectability, it is
just as well to continue the present methods of constructing curricula by debates on
the time schedule and of measuring educational progress in terms of hours plus a
passing grade.

When a suitable committee on instruction has been appointed and given adequate
support, its first big problem is that of the relations of the school with the industries.
Here the solutions are bound to be varied because, tho there is general agreement that
some actual experience in practical work is an essential part of the training of every
engineer, the environments of the schools are so different that no single type of ar-
rangement is likely to prove most effective for all. Even in industrial centres like
Cincinnati, Pittsburgh, and Boston, quite different schedules for handling cooperative
shopwork are in use; and still others may be found that are more effective for institu-
tions in rural communities, like Cornell, the University of Illinois, or the University
of Colorado. The important point is that in some way adequate provision be made for
personal participation in industrial work, for supervision of that work by the school,
and for stimulating the student to be ever on the watch for practical questions and
problems which may be brought back to the school for discussion, theoretical analy-
sis, and solution. Professor Thorndike found from his study of engineering college
freshmen that 95 per cent of them do engage in productive labor; so the problem is to
make the time so spent fruitful by some form of supervision that may prevent their
wasting their energies as ushers in theatres or bell boys in hotels for the sake of sup-
porting themselves in college.

Having selected the type of cooperative industrial work that seems best suited to
the peculiarities of the environment of each particular school, the committee on in-
struction may proceed to formulate a curriculum for the school work itself. In this it
is conceivable that the schools will reach conclusions that are more similar to one
another than, is probable with the cooperative industrial work; for if it is agreed that
the chief function of school work is to give the greatest possible mastery of the essen-
tial principles of engineering science, then there is a common foundation on which all
curricula must be built. The first step, therefore, in framing a course of study is to
define this common basis of all engineering as clearly as possible; that is, to make a
list of all the facts, principles, and processes that are essential elements in the equip-
ment of every engineer. Theoretically this is the plan on which present curricula are
founded, for they all have a common core made up of three distinct parts, namely,
science (mathematics, chemistry, physics, and mechanics), mechanic arts (drawing
and shop), and humanities (English and foreign languages). All of this common core
is usually explicitly required of every student, no matter what specialty he may
choose.

In addition to this explicitly recognized core of common material it is customary
at present to require civil engineers, for example, to take brief courses in mechanical and electrical engineering, since it is necessary that a road or a railroad builder know something of steam machinery, turbines, electric machinery, and gas engines. Conversely, the modern electrical engineer must know something about steam engineering, girders, trusses, factory construction, and even tunneling; and the sanitary engineer finds it necessary to understand at least the elements of hydraulics and the mechanism of pumps and pumping machinery. This instruction in one specialized branch of engineering for students who are specializing in another is now generally supplied by technical courses in the third or fourth years, sometimes by combination courses required of all students, and sometimes by special short courses in one branch for students in the others. Evidently there is a large amount of material which is now presented in technical courses after specialization has begun, but which is really essential to every engineer, and therefore might well be explicitly recognized in the core of common material.

Without regard to the question as to whether the subject-matter of this common core is well or poorly chosen and irrespective of the success with which the work is given, there is a fundamental difficulty in the current organization of the common core of all engineering; namely, the fact that it recognizes no inherent or intrinsic relationships among the three categories under which the classification is made. The sciences are usually treated as sciences pure and simple without regard to their function in engineering (page 39); in the mechanic arts the instruction shops are as a rule purposely separated from the construction shops (page 78); and the humanities generally strive consciously and vigorously to get away from engineering in order that the student may get at least a glimpse into the mysteries of language and of literature and a touch of culture. As a result of this lack of inherent connection, many schools have already dropped the requirement of foreign languages, because some faculties recognize that French and German when taught as they are for purposes of drill in grammar have no vital connection with engineering. Similarly some schools are seriously considering giving up the shopwork, since it is not at clear why skill in the handling of tools is essential to every engineer. There has even been some talk of ceasing to require calculus of every student, because there is very little obvious connection between some forms of calculus and engineering. Thus before a more effective common core for all engineering curricula can be constructed, it is necessary to adopt a classification of the subject-matter that obviously expresses the intrinsic relationships of the several component parts to the needs of every engineer.

The categories for a new classification of this kind may be deduced from the fundamental aim of engineering. As has been frequently pointed out (pages 3 the real purpose for which engineering schools were established is to increase industrial production, because the ultimate aim of engineering is more intelligent production. But every production project requires the coordination and adjustment of three factors, namely, scientific theory, mechanical practice, and cost. A theoretically perfect ma-
chine that cannot be built is no more useless than one that costs so much that no one is willing to buy it. Success in engineering comes to him who most often judges soundly concerning the best adjustment of these three complex factors. Therefore engineering education is likely to be more effective in proportion as it fosters the development of skill in determining the most expedient adjustments among theory and practice and cost.

It is customary in designing curricula to keep these three essential phases of engineering distinct from one another and to teach them as independent units, leaving their synthesis into well-organized mental processes to the student's own efforts. This practice is so widespread that its validity is naively accepted as a matter of course, and few seem to suspect that it may be connected in any way with the year or two of floundering thru which most graduates pass after leaving college and before finding themselves. Universal experience, on the other hand, seems to indicate that the most effective method of learning is by doing; so that if engineering depends ultimately on power to interrelate theory and practice and costs, a training that requires the student frequently to interrelate these three fundamental factors is likely to yield a better product than is secured from a training that largely ignores their interdependence. A curriculum that recognizes the intrinsic relationships involved is not difficult to construct after the fundamental common elements of all engineering have been selected; but until these elements have been chosen, it is impossible to give more than a general outline or skeleton, on which any school may easily construct a program by filling in with subject-matter appropriate to its environment and its educational aim.

A curriculum that satisfies all of the requirement mentioned above would include at least four types of work. In the first place there must be actual participation in real industrial work, either during summer vacations or better thru some form of continuous cooperation with industries. This industrial experience must be supervised by the school and used as a source of problems and projects for scientific analysis and study in laboratory and class-room. It should begin at the beginning of the freshman year and continue at least until the work common to all branches of engineering is completed. In the later years it may well take the form of cooperative work with an industrial research laboratory (page 82). It is not necessary or desirable that all students do the same type of thing, provided class meetings are held for the discussion and exchange of experiences.

In the second place there should be engineering laboratory work, including drawing and descriptive geometry; and this, too, should continue throughout the common portion of the course. Here the student would make the measurements and carry out the operations needed to enable him to solve the problems and projects that originate either in his industrial or in his class work. These problems and projects should be as far as possible framed in such a way that the desired solution cannot be secured without making the experiment; they should not consist of mere verification of known
results or of repetition of standardized manipulations. Elementary surveying is a fruitful source of problems of the right kind; the energy transformations and efficiencies of different sorts of machines, prime movers, and motors require endless investigation, much of which is simple enough for freshmen yet rich in engineering content. Questions concerning the kind of material to select under given conditions of stress, wear, and cost are also excellent. Attention has already been called to similar problems now in use in mechanics (page 58) and in chemistry (page 61). All of this material should require the constant use of the fundamental principles that every engineer must know, and frequent problems involving the computation of relative costs under various conditions should be discussed and solved.

The third type of work essential to the new curriculum is mathematics and science, which should be developed systematically in logical order so as to furnish the backbone of the course. The determination of the sequence of topics for the laboratory projects and for the classes in mathematics and science offers an opportunity for investigations of the highest order, because it is obviously desirable that theory and experiment be closely interrelated, and this requires agreement as to what are the fundamental conceptions of mathematics, mechanics, and physics. The Society for the Promotion of Engineering Education has made an admirable beginning of such investigations thru its committees on teaching mathematics and on teaching mechanics; but the reports of these committees have not yet been generally accepted, and the laboratory side of the problem has not yet received serious attention.

The humanistic studies make up the fourth type of work essential to the training of every engineer. The professional criticisms of the schools indicate that this field offers the greatest opportunity for effective changes in current practice, because lack of good English, of business sense, and of understanding of men are most frequently mentioned by practising engineers as points of weakness in the graduates of the schools. The criticisms point out two types of weakness, namely, lack of technical facility in expression, in business, and in handling men; and lack of appreciation of and interest in literature, economics, and social philosophy. Clearly the humanistic departments are not alone responsible for these weaknesses, for no amount of drill in the technique of language will make a student write and speak clearly if he does not think clearly; and training in clear thinking is as much the function of the teachers of science, mathematics, and engineering as it is the function of the teachers of English. And if the professors in the technical subjects rigidly exclude from their instruction all discussion of human values and costs, is it reasonable to expect the students to appreciate economics and social science? As every one is aware, languages, economics, and social sciences are generally treated as “extras” in curricula, and are as generally regarded as superfluous “chores” by the students.

The difficulty in present school practice evidently lies in the exclusion from the technical work of all consideration of the questions of human values and costs; and, conversely, the isolation of the humanistic studies from all -technical interest. The
theory has been that engineering at best is tied to materials; but that it can be made less materialistic by ignoring the question of dollars and cents in the technical work, and by teaching science, mathematics, economics, and literature for their own sakes entirely isolated from inherent technical relationships. This conception, however, is gradually giving way, for the experiments described in the last four chapters indicate that technical work is more impelling, and is, therefore, more fully mastered, when it includes the consideration of values and costs; while humanistic work becomes significant, and therefore educative, when it starts from and builds upon the professional interest. And after all, the ultimate control of all engineering projects, as of all activities, is vested in some man’s decision that the game is really worth while; and this control is likely to be more salutary, the more completely the man who decides comprehends the full import of the values and costs involved.

A good example of one method of treating the study of English so as to develop skill in expression, appreciation of literature, and a philosophy of values and costs may be found in Professor Aydelotte’s experiment with freshmen and juniors at the Massachusetts Institute (page 63). If work of this kind were continued thru several years, it might readily be made to include some study of all the political, economic, and social problems which every engineer is compelled to meet. The experiment of organizing a series of projects and problems in these subjects for class discussion, outside reading, and report, into a consecutive course that would give young engineers some conception of the present social situation and of the engineer’s relation to it, is well worth trying. It may be that such a course, by developing in students an intelligent understanding of the meaning of engineering in modern life, would be a powerful factor in defining the status of the engineer and in liberating his creative energies for still larger service.

The best time schedule for a curriculum built along the lines suggested cannot be determined in advance. It is therefore necessary at first to make an arbitrary distribution of the 15 credit hours available and then make adjustments as experience may dictate. Two schools, Brown University and the University of Washington, are trying a new curriculum of this kind this year. At Brown the time of the freshman year is divided in this way: mathematics 4, drawing and descriptive geometry 3, engineering mechanics 3, English 3, and chemistry 3. If military science is required, it might be well to reduce the time for mathematics from 4 to 5 in order to make place for it. It is also impossible to decide without experiment how many years will be required to give this training in the essential common elements of all engineering. After the essential topics have been selected, as much time as is required to teach them thoroughly should be taken for this purpose. Two years maybe enough, but if this is found to be inadequate, more should be assigned to this fundamental portion of the work. The important thing is that the essential elements be first selected and then that time enough to master them be given, instead of the current practice of assigning the time and then “covering” as much as is possible within the set limits. No time schedule
of the proposed curriculum is offered here, lest schools be tempted merely to fit pre-
sent courses into the suggested schedule without first making the thorough analysis
of the problem here demanded. Such a simple rearrangement of the old bricks in a
new pattern will not be likely to accomplish the required results.

No provision is made for foreign languages in the curriculum just suggested. They
have been omitted because three-quarters of the 1500 practising engineers who re-
plied in writing to a question on this subject agreed that they had never found foreign
languages essential to their professional careers, and half of them thought that they
should not be required. In addition, there is a growing conviction among the schools
that for students of engineering the time now spent in college on foreign languages
may be much more profitably spent in other ways. If it appears that the foreign ex-
pansion of the national outlook necessitates facility in one or more foreign languages,
every effort should be made to ensure the acquisition of that facility be fore entering
college. At West Point the cadets acquire all the control an engineer needs over
French in 200 hours of intensive training; and the technically minded student is far
more likely to become broad-minded and cultured thru studies of literature and social
conditions in the manner just described than he is thru the type of linguistic drill that
is now universally given under the name of foreign languages in high schools and
colleges.

The organization of curricula here proposed is very different from that in general
use. Therefore it would not be wise to attempt to produce a curriculum of this kind by
merely substituting, say, engineering laboratory for foreign languages and the new
type of English for the old, without in any way changing the content or the methods
of instruction of the other courses. The new plan is based on the proposition that it is
possible to analyze engineering practice and to make a list of all principles, facts, and
theories that are essential to the equipment of every engineer, and then to organize
this subject-matter into a curriculum in which the several types of work are interrelat-
ed in such a way that their inherent relations are obvious to the learner. Such a cur-
riculum satisfies the professional demand for broad and fundamental training for all
engineers and renders superfluous the requirement of two or three years of pre-
engineering work in a college of liberal arts. It does not prepare specialists, and hence
specialization is the topic of the next chapter.
CHAPTER XIV

SPECIALIZATION

THE preceding chapter suggests methods that may be profitably employed in framing a well-coordinated curriculum designed to give all students of technology a broad and solid foundation in engineering science and practice, through personal contact with industrial work, experience in solving practical problems in the engineering laboratories, systematic instruction in mathematics and science, and thoughtful consideration of the significance of human values and costs. The criterion by which to determine what subject-matter may be included and what excluded is that of common necessity; so that all those principles, processes, facts, and theories which are approved by a board of expert judges as essential to the equipment of every engineer are included, and all others are excluded. The course of study thus organized will be called the common core of the curriculum. How may provision best be made for specialization when a student has satisfactorily mastered this common core?

Evidently the first step toward successful specialization is intelligent sorting of the students, so that each is led as definitely as possible into that type of work for which he is best fitted temperamentally. This requires that while the students are working through the common core of studies every effort be made to discover the particular abilities and specific bent of each, not only by means of ordinary examinations and academic grades, but also through objective tests of graded difficulty (page 50), personality estimates by members of the faculty (page 73), consideration of boyhood interests (page 53), and observations of each student’s reactions to the different portions of the common core. In other words, the work of the common core offers an excellent chance for vocational guidance; so that the student would not choose but rather be claimed by the special field for which he is best fitted. Probably nothing would contribute more to the success of the later specialized work than a systematic utilization of this opportunity. A number of schools are ostensibly doing this now, but none has yet achieved the degree of success that is easily attainable by intelligent experiment with the various methods now in use in many places.

By the methods provided for sorting the students during the first two or three years of their courses it should be possible when they finish the common core of the engineering curriculum to divide them into five or six groups, each of which contains all who have special qualifications for one of the major lines of professional work. For each such group a curriculum must be framed on the same plan as that used for the common core. Thus for the civil engineering group a competent committee would first select all the elements essential to all civil engineers but not already included in the common core, and these essential civil engineering elements would be organized into a consistent curriculum composed of the same four types of work required
for the common core. A similar selection of subject-matter has to be made for the mechanical engineering group, for the electrical engineering group, and for each of the other major groups which the school desires to develop.

As with the common core, so here, the amount of time needed to master the materials selected as essential in each group has to be determined by experiment. It may well happen that more time is required for electrical engineers than for civil or mining engineers, but this is no real objection; the conception that four years of study makes any kind of an engineer is a habit rather than a rational conclusion. If the subject-matter chosen can all be shown to be really essential, and if the instruction is intensive, then the school may well insist on time enough to do its work thoroughly. This does not mean necessarily that more than four years will be required for thorough going training, for the present congestion of curricula is in large measure due both to the presence of subject-matter which cannot be justified on the ground that it is essential, and to the teacher’s habit of underestimating the student’s actual ability and capacity for significant work.

The number of these semi-specialized groups at any one school may well depend on the location and the capacity of the school. The great majority of institutions will probably have one for each of the commonly accepted branches, as civil, mechanical, electrical, and chemical engineering. The mining group has already been somewhat separated from the others by the establishment in mining districts of state schools of mines, so that a number of strong schools elsewhere no longer offer courses in mining engineering. While it is clear that every technical college should offer the common core, it is an open question how many of the semi-specialized groups each should attempt to supply. It is conceivable that some schools might do much more thorough work if they followed the example of Stevens Institute and specialized on one or two groups. It may even happen that a number of the smaller schools will find it to their advantage to give only the common core and send their students for specialization to the stronger schools. It may also be best for many of the students to leave school when they have completed this general work, especially if leaving should be dignified by the award of a suitable certificate or diploma.

On the other hand, there is an urgent need that a number of the schools add to these semi-specialized groups one in production engineering or engineering administration, as it is called at Pennsylvania State College and the Massachusetts Institute of Technology. The seriousness of this need has been emphasized by war conditions, which have demonstrated how essential it is to apply engineering methods to accounting, to the management of men, and to the organization of business, if maximum production is to be attained. Until recently most schools have specialized in design, with the result that at present fully ninety-five per cent of the production managers in manufacturing plants are not college but shop-trained men. The opportunity for the college-trained engineer is now very much larger in the field of production and administration than it is in the field of design, so that the most striking
development of the engineering schools in the next twenty years will probably be made in the direction of the former.

Throughout the period of semi-specialization it is desirable to continue all of the four types of instruction comprised in the common core, but the technical work of the several groups may be very different, each along the line of the group specialty. In the humanistic work, however, the subject-matter presented may well be the same for all, because the engineering attitude which these studies foster is the same for all. By this means it is possible to develop among the engineering students a unity of purpose and outlook which will be a great asset in developing a professional consciousness among engineers, because it tends to establish engineering standards by which to interpret and attack the industrial and social problems of the day.

The systems of grading and personality analysis used during the early portion of the course should also be retained, in order that the semi-specialized work may furnish the basis for more accurate guidance of each student into the particular line of work for which he is best fitted.

When the student has completed the semi-specialized work he should be well grounded in the fundamental principles of engineering science and in the theory and practice peculiar to some one of the major branches of the profession. If during this training he has shown particular ability in some specific line of work, opportunity should be given him to pursue his specialty in elective courses of highly technical content. These courses, however, should not consist, as many of the senior electives do now, of detailed study of the technique of such subjects as heating and ventilating, telephone wiring, roads and pavements, sewage disposal, and the like. If the student has been trained as he should be in methods of attacking problems and gathering information, he will probably make better progress in this kind of work in the industries than he will in school. Since these courses are for specialists who have elected them after a long process of vocational selection, they should deal with the more abstract and general phases of each subject. For the industrial phase of it, current problems in industrial research with practice as assistant on some of them are appropriate; for laboratory practice, expert testing and trouble hunting might serve well; on the scientific side, thermodynamics, the ionic theory, differential equations, functions of a complex variable, wave motion, spherical harmonics, electromagnetic theory, and all types of design, might be given for those whose bent and abilities warrant.

The plan of curriculum here proposed may seem to many very similar to the one on which curricula are at present constructed. In a general way this is true, since both the present plan and the one proposed agree in requiring all engineers to take the same training at the beginning and in gradually separating them into specialized groups later. The two schemes, however, differ radically in a number of important ways. In the first place, current curricula are made by first setting the time limits for each of the several subjects involved and then allowing each department to use its time allotment as it may see fit (page 56). The new plan suggests that the faculty first
select the subject-matter that is essential to the equipment of every engineer and then ask the several departments to determine experimentally how much time is needed for their respective parts. The former is a centrifugal system, which magnifies departmental differences, causes confusion as to the aims of the instruction, and wastes an immense amount of time; the latter is centripetal, in that it operates to bring about mutual understanding and hence definiteness of aim and economy of time.

Again, the proposed plan calls for the student’s participation in real industrial work and the utilization of his experiences there as a source of problems for theoretical analysis and solution in the class-rooms. This is suggested as a substitute for most of the current shop practice, such elements as should be retained in school being included in the engineering laboratory work.

In the third place, the suggestion is made that engineering laboratory work be required throughout the first two or three years. At present such work is given almost entirely in the last two years, because teachers generally believe that the students are incapable of working intelligently at practical engineering projects until they have been well drilled in theoretical principles and mathematical processes, in spite of the astonishing manner in which boys of high school age learn without assistance to manage wireless telegraphy or gas engines. The proposed arrangement makes it possible for the faculty to assign tasks that tax the boy’s capacity and challenge his ingenuity and his natural instinct for mechanism. Such tasks are almost sure to be effective means of releasing creative energy and of directing it so that it brings the greatest educational returns. Besides, under these conditions a student finds himself constantly in need of the principles and methods developed in the classes in mathematics and the sciences. In this way these subjects may be made significant to boys with an engineering bent; and, as is well known, the probability of learning thoroughly increases with the significance of the lesson. The fact that a boy elects engineering indicates that his mind is probably of the type that thinks most clearly in terms of specific objects, and that grasps general principles most firmly when it has built these up by the synthesis of a number of specific concrete cases. In combination with the cooperative industrial work this engineering laboratory work furnishes also a rational foundation for the proposed industrial research of the later years (page 82).

In the fourth place, the suggested organization requires a close coordination between the scientific courses of the common core and the practical work. At present mathematics and the fundamental sciences are usually taught for their own sake, with independent laboratories and little attention to technical applications. Under the arrangement proposed the essential portions of the laboratory work in elementary physics, for example, would be absorbed and taught in the engineering laboratory. The elementary class work in physics would then be limited to the study of those fundamental conceptions and principles of physics that are embodied in all engineering work; while the more elaborate and recondite portions of the subject would be reserved for elective courses in the later years, where they would be better appreciated.
by students qualified to grasp their significance. The same suggestion applies to chemistry and especially to mathematics, in which much that is ordinarily imposed on unwilling sophomores would be eagerly grasped by selected seniors.

A fifth departure from current school practice is made in the recommendation to emphasize the problems of values and costs. This topic has obtained scant recognition in higher education for fear of contaminating university ideals with those of the marketplace. Such a fear is justified when the discussion is limited to monetary values and costs. But when the subject is treated in some such manner as Professor J. A. Hobson treats it in his *Work and Wealth, A Human Valuation*[^1], it may be made the most potent means of expressing the highest type of university spirit. Hence in urging extended consideration of this subject it is taken for granted that the discussions will not be limited to questions of dollars and cents. The control of engineering lies in the hands of those who judge most accurately what enterprises men value sufficiently to be willing to assume the cost. Because engineering education has confined itself largely to technological training, engineers are seldom placed on state highway commissions and other public boards that must decide how public funds shall be expended on engineering enterprises. Too frequently the engineer is employed to do the technical work of construction only after a board composed of doctors, lawyers, clergymen, bankers, merchants, or politicians has made an appraisal of values and costs and decided which project shall go forward and which not. The conception is rapidly developing that the public interest might be better served if the engineer had more voice in making such decisions, and to win greater influence in this direction he must be trained to appraise correctly what men consider to be most worth while.

Because the appraisal of values and costs is the controlling factor in engineering, the final important change from current school practice that is suggested deals with the humanistic studies. The usual method of treating these subjects in short in dependent courses in the technique of composition, literature, history, economics, and so on, seems less likely than the method proposed (page 92) to develop the desired insight into these profound problems of value and cost. The experiments at Wisconsin and the Massachusetts Institute have progressed far enough to show how successful this type of work is with freshmen in developing powers of both forceful expression and appreciation of good literature. Therefore it seems reasonable to expect that the extension of this work into a consecutive course extending thru the entire curriculum and consisting of live discussions and extensive study of the best that has been thought and said concerning the immediate and the ultimate values in life, offers the most promising solution of the problem of culture for engineers.

The organization of curricula suggested in the foregoing chapters does not solve the problem of engineering education. It does, however, create conditions that are more favorable than those now prevailing for progress toward the desired solutions of a number of the major questions. Thus objective tests for admission will undoubtedly

enable the schools to reduce elimination by permitting only those who have some demonstrable degree of engineering ability to enter, but much time and many experiments will be required before this end is accomplished. Similarly the engineering work in the common core, when measured by a suitable system of testing and grading, makes the experiences of the first two or three years both valuable to technical men of all grades and a further means of sorting the students according to their varying degrees of engineering talent and ability. On completion of the common core an opportunity is given for those whose capacities and temperaments lead them to prefer the practical phases of production to leave school with credit and go to work immediately. Finally, specialization, which has been the source of so much trouble to curriculum makers, is subordinated in the proposed plan to vocational guidance. Because the common core contains real engineering work, it can be made a measure of engineering ability that is much more searching and valid than is possible with the current abstract, linguistic type of work. And because the common core contains the essential elements of all branches of engineering, it gives the student a chance to choose his specialty on the basis of experience, and furnishes the faculty with a broader range of activities on which to base its judgment of special aptitudes for particular jobs. Hence it diverts the attention of the faculty from the construction of specialized grooves down which the student may be shoved by routine administrative mechanisms, to the study of the personalities, the temperaments, and the capacities of young men who are eager to do the work for which they are best fitted. The required change in attitude on the part of the instructor may be materially encouraged by changing the conditions under which faculties serve along the lines suggested in the following chapter.
CHAPTER XV

TEACHERS

IN the summer of 1824 Amos Eaton was employed by Stephen van Rensselaer to deliver a series of lectures on natural science, with experimental illustrations, at a number of towns in New York State. The undertaking was so successful as an educational venture that a school was founded to train teachers to instruct farmers and mechanics in the applications of science to industrial production. Thus the first American Engineering School owed its existence to the fact that a man of rare power as a teacher had been found to conduct it. Following the inspiration embodied in it by Amos Eaton, the Rensselaer School was for forty years a Mecca for teachers of applied science. The published works of Professor Eaton prove that he was also a scientific investigator of rare merit.

Thirty years later (1853) William Barton Rogers, also a geologist and pioneer investigator of the geology of Virginia, moved to Boston to find opportunity to teach industrial workers how to utilize science in their work. For twenty-five years Professor Rogers had taught natural science at the University of Virginia with such spirit that the aisles and window-seats of his lecture room were often crowded by young men eager to listen to the eloquent words of the teacher they so much admired. It was in this spirit that he founded the Massachusetts Institute of Technology, and the nine men whom he called to be fellow members of the first faculty were all enough interested in the educational problem to give a large share of their time to its study.

The interest in the teaching problem has never disappeared wholly from engineering schools, as it has from some of the universities. The first, and for many years the only association for the study of education in colleges was the Society for the Promotion of Engineering Education, which developed from the engineering congress at the Columbian Exposition in 1893. For twenty-five years this organization has carried on extended and valuable studies in its field, and there can be little doubt that the recent rapid progress in engineering education has been in large measure due to its activities. At present about one-third of all the teachers in American technological schools are enrolled among its members, yet in spite of this, a series of questions on educational aims, methods, and practices, which was personally presented to the faculties at the first seven of the schools visited, proved highly unpopular; and from eighty-five answers that were turned in it appeared that 38 per cent of the professors spend no time at all in study to increase their understanding of educational methods, 60 per cent spend from one to ten per cent of their time in this manner, and but 2 per cent spend more than this. Obviously it is essential to pay much more attention to the study of education if serious progress is desired.

Fifty years ago little was required of the college professor beyond his teaching. The opportunities for participation in industry were relatively few, and scholarship
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was universally regarded as a valid excuse for the impracticality of academic life. But as industrial production has become more and more scientific, the bonds between the engineering school and the industries have become closer, until now it is generally recognized that intimate cooperation between the business man and the teacher is of the greatest benefit to both, for thereby businesses grow more creative and colleges more business-like.

The infusion of business methods into colleges is of fundamental importance for good teaching. The tradition that scholars and investigators have no interest in the material rewards of their labors is true only with regard to rewards over and above what may be considered as a living wage. It is therefore just as essential for good teaching as it is for good work of any other sort that the worker be relieved of worry over the means of material support for himself and his family. During the past twenty years schools have made very striking progress in the way of stabilizing teachers’ tenures and salaries both by larger endowments and appropriations of public funds and by better business management. Nevertheless much still remains to be done; for, tho teachers’ pay has been slowly increasing, the median salary for a full professor at state-supported institutions is now only $2500, and his appointment at some schools has to be renewed formally every year. Even at universities where professorial appointments are ostensibly made for life, teachers of distinction and even entire faculties are at times summarily dismissed by the board of trustees.

Two other phases of the problem of laying firm foundations for the profession of teaching have already been the subjects of extended investigation and report by the Carnegie Foundation for the Advancement of Teaching. Bulletin Number Five, on Academic and Industrial Efficiency, indicates how modern business methods may be advantageously applied in university organization to liberate teachers from such drudgery as care of buildings and grounds, purchasing supplies, publicity, keeping records, financial management, and supervision of the material welfare of students. At some of the larger schools professors are now free from duties of this sort, but many a university man still spends much time and energy running a typewriter, posting accounts, keeping records, or making out requisitions. Bulletin Number Nine (1916), on A Comprehensive Plan of Insurance and Annuities for College Teachers, describes the principles and methods that have been proved by ten years of experience and exhaustive study to be essential to a sound and effective system of insurance and annuities for college teachers. An organization for putting this plan into action has been formed and financed, thereby supplying one of the most essential ingredients of the business basis on which a new liberalized education may safely be built.

The creation of stable financial conditions, the assurance of permanency of tenure, of a living wage, of relief from routine clerical work, and of safe insurance against old age, however, are not the only requirements for encouraging good teaching. Institutions that have already achieved these fundamental prerequisites are still hampered by educational conceptions and practices that discourage rather than encourage
progress in teaching. Prominent among the usages that tend strongly to preserve the status quo is the common practice of employing large numbers of recent graduates or even of undergraduates as assistants in elementary instruction where the classes are large. These assistants have usually received all their training in engineering schools that pay not the slightest attention to the professional education of the teacher. When such a novice begins his apprenticeship as teacher, his instruction depends entirely on the attitude of the head of his department. He may be turned loose with out directions of any kind, or he may be given such minute directions that he is apt to become a cog in a machine. In any case he instinctively imitates the methods and practices of his own teachers, and is kept so busy with routine work that he has neither the time nor the inclination to study or make experiments in teaching. That so many eventually turn out to be good teachers is a tribute to Yankee adaptability rather than to educational foresight, but the energy losses due to inevitable blunders during the teacher’s period of incubation are a serious drain on the intellectual out put of the schools. In some of the best institutions the number of assistants is greater than the number of full time professors.

In selecting young graduates for assistants in teaching it is customary to pick out those who have won high grades in the subjects they are called upon to teach, because mastery of subject-matter is obviously a first essential for teaching. Several schools, however, have recently recognized that this apparently worthy practice may be a serious handicap both to progress and to good teaching. Under present systems of grading, high marks are quite as likely to indicate adaptability to the professor’s point of view, as they are to stand for either mastery of the subject or independence of mind. Hence the inbreeding process, even when based on high grades, in reality tends strongly to maintain a stolid conservatism which deplores innovations and inhibits experimentation.

As a remedy for this condition, at one or two schools appointments to the teaching staff are made only after the candidate has had one or more years of successful experience in some phase of engineering practice. In a few of the more progressive departments no man is ever appointed to a full professorship until he has won the recognition of the technical experts in his own line of work. In this respect conditions may be still further improved by freer use of graded objective tests and of personality ratings (page 73). Schools of engineering might also do well to consider seriously cooperation with departments of education in the professional training of teachers of applied science and in the scientific study of their teaching problems.

While the recruiting of the teaching staff from recent graduates tends to maintain conditions as they are, and therefore to inhibit experiments in teaching, the current indifference of colleges to problems of education is more directly traceable to the lack of effective incentives for this work. After the teacher has been liberated from worry over material support, his most impelling incentive is his desire for self-expression in creative work. Universities recognize this fact, and have for forty years been struggling
to develop conditions that would free creative imagination and expand the bounds of knowledge. In this they have been marvelously successful in the field of natural science—so much so, that research and the publication of the results of research have become the measure of success and the criterion of promotion in most institutions of higher education in the United States. So completely has this conception of research won recognition that academic promotion is now determined almost wholly by success in it. This fact has produced the impression, prevalent in many quarters, that research and teaching are in some way antithetical. Hence the question has often been raised whether research should not be discouraged at educational institutions in order that teaching might receive a larger share of attention.

It is unquestionably true that research, as at present treated, does interfere seriously with teaching. Hundreds of college instructors whose interests lie in the human problems of education, rather than in the material problems of natural science, are now being diverted from a study of the teaching problem and induced to undertake research because academic promotion so obviously depends on the latter. Many a young man with promise of making an excellent teacher is sidetracked by the requirements for the Ph.D. degree and becomes instead, a mediocre researcher. Yet the much that is done under the name of research is but pseudo-research, the university is clearly right in its position that the spirit of investigation is an essential factor of university life.

The difficulty does not lie in research itself, but in the limitations that still cling to the common interpretation of it. Because research has been developed in the field of natural science and has wrought such marvels there, its activities have unconsciously been thought of as restricted to the problems of the material world. Because the technique of research and the units and methods of measurement have been so perfected in the domain of natural science that great accuracy and definiteness of conclusion are now possible, the early struggles for objectively defined standards and scales have been forgotten. Hence it seems to many grotesque to talk about research in education and the impersonal measurement of the vaguely defined and elusive qualities of human beings. The fact that such measurements have as yet been rather crude and inconclusive is no reason against trying to improve them, especially now when the greatest need of education is a technique and a terminology that will make the results of experiments in teaching intelligible to every one. The inability of teachers to carry conviction as to the merits of teaching and the meaning of experiments in education is one of the chief reasons why teaching fails to receive the recognition accorded to research. But as soon as it is possible to measure the results of teaching by impersonal means, successful teaching will be as easy to recognize as profitable research. Objective records of achievement have been found in industry to be one of the best incentives to creative work. Hence the line of progress in education does not lie in the direction of making arbitrary distinctions between research and teaching, but rather in the direction of removing the limitations placed upon the spirit of enquiry so as to encourage its expansion to education and human relations generally.
If university trustees, presidents, and faculties will unite in insisting on a scientific study of their educational work, they will create the conditions needed to release teaching power in the engineering schools. The professors who have teaching interest and ability will welcome the opportunity to win recognition in work that arouses their enthusiasm and stirs their imagination to creative effort just as the professors who are interested in natural science have responded to the opportunity to promote research. This should not result in a diminution of output in research, but in a decided increase, because it tends to give each man the work he is best fitted to do, and therefore leads ultimately to maximum efficiency.

The practical carrying out of this suggestion in any school is relatively simple, provided the faculty is ready and able to undertake it in a spirit of disinterestedness and helpful cooperation, that is, in a real scientific spirit. Many practical hints concerning essential details of operation have been given in preceding chapters. Any faculty that will get together and take time to think out their problem can create an organism that will be a live influence in education; and the doing of it will in two years bring more joy to all concerned than forty years of weary effort to maintain things as they are.

The good effects of an interest in the scientific study of education in institutions of higher learning are not limited to the institutions themselves. For a number of years objective methods of measuring the results of training have been gaining favor in the lower schools. Until very recently the colleges and universities have looked askance at the progress, and refused to do their share by giving professional training to those whom they send out to teach. The colleges have thus been a positive hindrance to this development, and even now, when more than half of their graduates teach, for a time at least, no professional work in education is as a rule required outside of the so-called teacher’s colleges. Meanwhile the industries have been compelled by the slowness of the academic development to establish schools of their own, and have organized the National Association of Corporation Schools with an active membership of more than one hundred and twenty-five large corporations, which are as much interested in the scientific study of vocational guidance and methods of training as they are in industrial research. The scientific study of industrial education thus ranks with industrial research as a bond of union between the engineering schools and the industries. On the fuller development of both teaching and research depends the realization of the ultimate aim of engineering education, namely, more intelligent production.
CHAPTER XVI

THE PROFESSIONAL ENGINEER

At the first meeting of the Joint Committee of the National Engineering Societies with representatives of the Carnegie Foundation for the Advancement of Teaching it was agreed that an analysis of the requirements of the engineering profession was one of the first essential steps in this study of technological education. Accordingly a number of representative engineers were questioned in personal interviews concerning the factors that are most powerful in determining success in engineering work and most effective in building up the engineering profession. These interviews, together with a study of the methods of rating college graduates in several large manufacturing companies, indicated that personal qualities such as common sense, integrity, resourcefulness, initiative, tact, thoroughness, accuracy, efficiency, and understanding of men are universally recognized as being no less necessary to a professional engineer than are technical knowledge and skill.

The statement that individuality counts for as much as learning for the engineer, just as it does for the lawyer or the physician, seems like a veritable platitude. Yet because the engineering schools have always made it their chief aim to impart the technical information needed in industrial production, and because both scientific knowledge and industrial practice have grown so rapidly, the attention of technical schools has been focused chiefly on keeping up to date in science and practice. The university emphasis on research in natural science has also tended to magnify the importance of technique and to minimize the importance of personality; until curricula have become so congested with specialized courses that students generally regard literature and sociology as unnecessary chores, to be endured rather than enjoyed. Therefore it seemed necessary to consider the question whether this emphasis on technique is producing a new and higher type of engineer, or whether the engineering profession still stakes its faith on the fundamental thesis that personal character is, after all, the real foundation for achievement.

The results of this enquiry have already been published. Briefly, they showed that fifteen hundred engineers, who replied in writing to the question: What are the most important factors in determining probable success or failure in engineering? mentioned personal qualities more than seven times as frequently as they did knowledge of engineering science and the technique of practice. A second circular letter stating this result was then sent to the thirty thousand members of the four large engineering societies, and each was asked to number six groups of qualities headed respectively Character, Judgment, Efficiency, Understanding of men, Knowledge, and Technique, in the order of importance which he gave them in judging the reasons for engineering success and in sizing up young men for employment or for promotion.

More than seven thousand engineers replied to this request, and their votes placed the Character group at the head of the list by a majority of 94.5 per cent, while Technique was voted to the bottom by an equally decisive majority. A very similar definition of the essential requirements of the engineer was formulated by Mr. A. M. Wellington and published by him in the Engineering News for May 11, 1893, as the conclusion of his well-known series of articles on the engineering schools of that time.

This definition of the essential characteristics of the professional engineer is important, because it proves that in spite of the enormous development of scientific information and technical skill, the engineers of America have not been beguiled into thinking that efficient control of the forces of nature is the sole requirement for achievement in applied science. Therefore the schools that intend to train engineers cannot afford to neglect wholly the personalities of the students. While it is obvious that personal traits like integrity, initiative, and common sense cannot be taught didactically like the rule of three, it is no less obvious that the growth of these essential characteristics in students may be either fostered and encouraged or inhibited and discouraged by the manner in which the school is organized and the subject-matter presented. The problems of finding the best organization, of constructing the best curriculum, and of discovering the best methods of teaching cannot be solved by logic alone or by research in natural science. As has been abundantly shown in the preceding chapters, their solution requires extended experiments in education under conditions that command respect.

The enquiry just described was completed in 1916—a year that will always be memorable in the history of engineering because it marks the beginning of a deeper public recognition of the importance of the engineer’s function in national life. In that year the Federal Government, for the first time in its history, formally recognized the engineering profession in the organization of the Naval Consulting Board, the Council of National Defense, and the National Research Council. The first of these invited the National Engineering Societies to nominate the members of the state committees on Industrial Preparedness which compiled an inventory of the industrial resources of the country. Representatives of these societies are also members of the National Research Council which has so effectively mobilized the scientific resources of the country for national service. The establishment of the Engineering Foundation, the United Engineering Societies, and the Engineering Council, and the recent appointment of one man as secretary of them all, indicates the progress that is being made toward the conception that there is really but one profession of engineering, in spite of its apparent division into the several well-known branches.

War conditions have not only hastened public recognition of the engineer as an expert in applied science and fostered solidarity of the profession, they have also opened to him new fields of activity. Back in 1914 most people believed that the war could not last long because enough money could not be found to finance it. But three years
of experience have made it clear to every one that altho money is plentiful, it is use
less if there is nothing to buy; so that winning the war depends on increasing produc-
tion by an amount which has been estimated as the output of at least ten million addi-
tional industrial workers. This extra production may be secured either by training
more workers or by increasing the output per worker by engineering methods. Hence
there has arisen a pressing demand for men who can deal with labor and with busi-
ness administration in the engineering spirit. This demand is further emphasized by
the fact discovered by the Federal Trade Commission, that only ten per cent of the
manufacturers in the United States know their actual costs of production. The deter-
mination of these costs requires a scientific study of production which only an engi-
neer can make. This work involves the analysis and apportionment of overhead ex-
penses, and thus leads at once to such fundamental questions of economic justice as:
Should the capital invested in idle machinery be paid wages tho idle workingmen are
not?

These new opportunities for the engineer have been gradually developing for a
number of years, but the profession as a whole has been slow to discern them. The
war has focused attention on them and precipitated a general recognition of them. It
is also evident that the mastery of these new activities depends in greater measure
than does mastery of the traditional types of engineering on the personality of the
man. The success of a designer of bridges or of machinery is not necessarily impeded
by lack of insight into human nature or of failure to comprehend the things that man-
kind considers most worth while. But to the man who would deal successfully with
human labor and with business, personality is usually a greater asset than technical
knowledge and skill. Therefore as engineering expands into the new fields now open-
ing before it, the conception that character, judgment, efficiency, and understanding
of men are no less necessary than technical knowledge and skill will become more
and more impelling, and it will become more and more essential that schools of engi-
neering pay greater attention to the effect of their work on the personal development
of the students. Altho many specific suggestions as to how this maybe done have
been made in the preceding chapters, a connected summary of the educational con-
ceptions on which the suggestions are based may serve to make clearer why the cur-
rent organization is inadequate and how the proposed plan more fully meets the pre-
sent requirements and also supplies a sound basis for future growth.

The ultimate aim of engineering education has always been and still is more intelli-
gent industrial production. Technical schools were founded when industrial evolution
had progressed so far as to create a pressing demand for men who knew how to uti-
lize the new and rapidly expanding knowledge of natural science to increase and im-
prove production. Science was then little taught in high schools and colleges, so that
both the public and the manufacturers were ignorant of it. Under these conditions the
obvious need was for scientific enlightenment; and this the engineering schools were
organized to supply. President Rogers’s statements that the immediate
aim was to supply the intellectual element in production, and that this meant knowledge of the fundamental principles of science, were accurately true when he made them (1861).

The schools have loyally pursued this aim, and have thereby contributed enormously to the achievement of two striking results; namely, the extension of science instruction into the school system generally, and the development of public recognition of engineering as a profession, coordinate with theology, medicine, and law. At the present day an encouraging fraction of the people are reasonably intelligent in science, the worker in applied science has become socially respectable, and there has been developed a large conception of the engineering profession. Meanwhile the methods of dealing with the material problems of industry in a scientific way have been in a measure established, while the more intricate problems of organizing and managing men are rapidly pressing forward and demanding engineering treatment. The net result is that the curricula and methods of instruction that were devised to supply the intellectual element in production by imparting knowledge of natural science must be reorganized to meet the new industrial demand for engineering administrators and the larger professional demand for men of strong personality. The general plan of the proposed reorganization is based upon an analysis of engineering practice into its three essential factors; namely, knowledge of engineering science, skill in technique of application, and judgment in the appraisement of values and costs. In every engineering project the overlapping claims of these three essential factors must be harmonized with respect to the two fundamental elements of production, namely, materials and men. Surely every engineer should have some conception of the present conditions and problems in at least the general aspects of all these essential factors and elements. If this be granted, it is easy for any school to discover where its curriculum is overloaded and where it is deficient.

This analysis also indicates how the present organization of school work can be modified so as to furnish a more vital training for professional engineers. Thus, with regard to materials, the schools do give careful instruction in the laws of physical science and in the properties and uses of materials. Students are taught the relative strengths of substances in the materials laboratory, kinematics teaches the principles of gearing, the shapes of gear-teeth are worked out in the drawing room, the chemical properties are taught in chemistry, mechanics deals with the forces required to overcome inertia, machine work is relegated to the shop, and so on. But seldom is all this information coordinated in a single practical problem, such as determining whether mild steel, nickel steel, or phosphor bronze is the best thing to use in making a particular gear wheel; nor is the student ever asked to judge what combination is likely to produce the most valuable result for the price. Yet this balancing of value and cost is the controlling factor in all intelligent production.

Again, little consideration is given in courses in machine design to the comfort and safety of the operator. Yet a punch press, for example, that requires a workman
to use both hands to operate it is far more intelligent than one that takes a large annual toll of fingers because the driver has one free hand. Similarly the importance of good heating, lighting, ventilation, and sanitation in increasing the output of workers and in keeping them strong and healthy should always be taken into account. These human factors enter in large measure into the determination of the values secured for a given cost.

It thus appears that an adequate treatment of the first element in production involves not only a scientific presentation of the laws of nature and the properties of materials, but also an estimation of the values and costs from both the material and the human points of view. The chasm between the school and practical life is due largely to a failure to appreciate this fact. The introduction of the study of values and costs in all their phases is the most direct method by which the schools can bridge this chasm. Such study is also one of the most potent means of liberating creative energy and of developing the spirit of investigation.

With regard to the second element of production—men—most schools at present are doing practically nothing to arouse the students to an intelligent appreciation of the problems of personal and human relations in production. Yet these problems are every day becoming more acute, as indicated by such movements as Americanization, human engineering, industrial engineering, and scientific management, with their various efforts to improve the condition of the workman and to increase his output in production. Many of the burning questions of the time lie in this field. The loss to industry from turnover—the hiring and firing of workmen—is variously estimated at from $150,000,000 to $400,000,000 a year. This expense adds from 7 to 20 per cent to the cost of production, and yet it injures rather than benefits the product. What are the means to prevent turnover—better housing? better social conditions? higher wages? profit sharing? opportunity for self-expression? juster economic treatment? or more kindliness? Does the time-study method of speeding up work pay? Does it really relax or wear out the worker? Does it produce the best type of citizenship among the industrial classes? These and many other similar unanswered questions are now waiting for an engineering analysis, and the country looks to the engineering schools to train men who shall be able to answer them.

The training of men for the solution of these human problems cannot be carried out in the schoolroom alone. The students must have some vital, first-hand, personal contact with labor and workmen’s conditions, either by a cooperative system, as at the Universities of Cincinnati and of Pittsburgh, or thru the industrial service movement, or in some other real and living way. Hence meeting this demand requires some form of closer cooperation between the engineering school and the industries, better understanding of their mutual relations, and willingness on both sides to approach the problem with the, true research spirit. Such cooperation is needed not only to give the students a vital conception of the workman’s point of view, but also to furnish that intimate personal knowledge of the details of production which cannot be secured
in college laboratories and shops. The lack of this sense of the physical properties of materials is one of the chief reasons why less than five per cent of the production managers in this country are college-trained men.

It is, however, in the matter of estimating values and costs that this problem assumes its most far-reaching consequences. The following are some of the typical problems now pressing for solution in this field. What is the effect of good housing on the development of the men, the efficiency of production, and the size of the profits? What is the most effective incentive to maximum output—the bonus system? opportunity for cooperation in management? opportunity for creative work? or shorter hours? Does the assurance of justice and a square deal always tend to increase output and also to foster the growth of a social spirit and of patriotism? Does a plant pay better when profits and output are increased by efficiency methods which give workmen no chance for self-expression? or when the development of the workmen is made an aim as well?

Every manager will estimate the values and costs of these various methods of treating workmen in accordance with his own philosophy of life. There is as yet no conclusive evidence to prove these cases one way or the other. The successful manager to-day is the one who estimates most accurately the human values involved. Therefore, one of the most important contributions that the school can make toward the education of the engineer is to guide him in developing an attitude toward life and a philosophy of living that will enable him to judge rightly as to the things humanity considers most worth while. This is the meaning of the professional demand for larger opportunities for cultural and literary studies. It cannot be met by merely requiring more work of the ordinary academic type in history, in economics, and in languages; but rather by introducing the consideration of values and costs into the regular engineering instruction in some such way as that described in Chapters XIII and XIV.

Some attention has already been paid by the engineering schools to the problem of organizing men into effective working groups. At the Massachusetts Institute of Technology, Pennsylvania State College, and several other schools special courses in engineering administration are now given regularly. These courses deal mainly with the various types of organization, the technique of different kinds of management, accountancy, banking methods, and economic theory. All of this is, of course, essential to every engineering administrator. Industry sorely needs men thus trained; for the determination of costs is relatively easy so far as materials and labor are concerned; but the overhead, because it includes the cost of maintaining the organization, is a matter of great difficulty. Analysis by engineers shows that the largest wastes in production are in the overhead expenses, and result from faults in organization, such as idle machinery, inefficient maintenance, poor routing, lack of foresight in purchasing, delays from lack of instruction from the office, and so on. The study of overhead expenses has led to many searching questions of economics and industrial justice,
with which the student will have to deal after graduation, but to which the schools have not yet given serious attention. But it is gradually becoming evident that the ultimate success of any organization depends on its spirit; and this, in turn, is determined by the manner in which those in control coordinate and interrelate the intelligences and imaginations of men. Great organizers and leaders in industry are those who not only master the laws of nature, but who also shape and control their organization thru their power of estimating accurately the value which each worker esteems most highly. The engineers instinctively recognize this fact and the educational implications of it when they declare that character, judgment, efficiency, and understanding of men are even more essential to the practising engineer than is knowledge of the science and technique of engineering.

The educational interpretation of this professional demand is not nearly so mysterious as many have tried to make it. For the schools have already discovered that students learn best when they are inspired by the conviction that the work is really worth while. One of the most effective ways of making work seem worth while is by constantly relating it to the consideration of the whole range of values involved arid all the costs. Every decision in daily life is an answer to the question whether the value is worth the cost. The omission of this mainspring of all investigation and enquiry from school work is perhaps the chief reason for the breach that separates the schools from life. Hence the first message of the profession to the schools is—Motivate your work by making it worth while; liberate the spirit of investigation by making the game worth the candle; for character, judgment, efficiency, and understanding of men develop best in men who work with enthusiasm and intelligence at things that they believe to be worth while.

But there is a second message in the professional demand. For the spirit of investigation accomplishes valuable results only when the investigator is resourceful, accurate, and efficient in mastering facts, and when he has judgment, common sense, and a wide perspective. These qualities depend on the ability to put things in their proper places at the proper times, which ability depends in turn on the perception of intrinsic relationships. The most successful organizer and executive is the one who perceives relationships so clearly that he can build an organization which acts to liberate the creative energy of each in ways that prove most helpful. Hence training in ability to perceive relationships —interrelation—is one essential for the development of resourcefulness, judgment, common sense, perspective, efficiency, and the rest. This is also one essential to the acquisition of knowledge. Therefore in so far as the school work develops the student’s ability to perceive relationships, in so far do knowledge and the desired personal traits increase together.

It thus appears that so far as the school work itself goes, the professional demand for upbuilding of character along with increase of knowledge suggests at least two promising lines of educational experiment, namely, motivation and interrelation. The lower schools have long ago recognized the possibilities of these fields of investigation.
In fact, the educational progress of the past century has centered around these two conceptions. Many fruitful experiments and a large literature have gathered about the subject of motivation and the related topics of interest, formal discipline, and transferable training. In like manner much has been accomplished toward interrelation thru efforts that have been made to correlate various subjects, as indicated by the terms commercial-geography, business-arithmetic, household-science, domestic-economy, agricultural-chemistry, soil-physics, and the like.

The organization of curricula proposed in Chapters XIII and XIV is suggested as one practical method of harmonizing the conflicting demands of technical skill and liberal education. It coordinates the results of numerous individual experiments in a consistent program. It recognizes all the essential elements and factors of engineering as well as the educational requirements of motivation and interrelation. It is not a utopian dream, but a summation of the best that has been thought, said, and done in education during the past two centuries. Finally, it embodies the modern conception of the professional engineer, not as a conglomerate of classical scholarship and mechanical skill, but as the creator of machines and the interpreter of their human significance, well qualified to increase the material rewards of human labor and to organize industry for the more intelligent development of men.