Design Education: Theories and Practice

by

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Abstract

Many practicing engineers feel graduating students lack necessary design experience for their careers. In order to solve this problem a better understanding of design and its education is necessary. Rapid technological advancement will also provide an incentive to continue efforts in improving the quality of design education. A literature survey was performed to examine the importance and current quality of design education. The study focuses on design theories and current methods used in teaching design in the undergraduate curriculum. Further research on design methods and their application in education and practice is recommended.

Thesis Supervisor: Herbert H. Einstein
Title: Professor of Civil Engineering
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Thanks, first and foremost, go to my parents. Their continuous support for my education will never be forgotten. Without them I never would have gotten as far as I have.

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1. INTRODUCTION TO DESIGN EDUCATION

There is little debate that education is a constant presence in our lives. We learn and gain experiences that affect our future actions every day. Our learning does not end with the formal educational process, but continues into the careers we pursue and beyond. Part of this continuing education includes the ability to design, or create new things. It is difficult to determine when an individual first learns the basic ability to design. Such research is better left to psychologists. However, a more formal approach devoted to the education of design is found in the world's colleges and universities. Education in design received prior to the collegiate level is usually of a more general nature and not specific to a particular profession. Hence, design education shall be the term used to describe the approach used by colleges and universities to teach students how to design. Design education seems to have become something of a catchphrase in the past decade. It is something that every university or college likes to include in their curriculum, yet also something everyone complains there is not enough of.

It is this author's purpose to show the importance of formalizing this kind of education in the undergraduate curriculum, before graduates enter the workforce and are presented with open ended problems their analytical minds cannot find the "right" answer for. Some argue that design education need not be formalized; basics for design are learned in laboratory classes and the more intricate design procedures should only be learned once an individual has
entered his chosen profession or area of expertise and is actually performing it. However, it also seems clear that students who concentrate their efforts in technical subjects have a difficulty in understanding and embracing the synthetical and creative side of the subject, even if they are exposed to it while pursuing their career.

The literature survey underlying this work is aimed at reviewing various theories of design and looking at current methods used in universities to teach design. Although these efforts are concentrated within civil engineering as the framework for the study, various approaches from the fields of architecture and mechanical engineering are discussed since they are similar in scope and purpose.

There are certain questions about design that need to be asked in order to find out how to improve upon its education:

(1) What are the theories of design?
(2) What is currently being taught?
(3) What are students actually learning?
(4) What is currently being practiced?

This study focuses mainly on the first 2 questions and spends a little time on the third. The fourth is not researched, but further research in all four of these basic questions is encouraged.
2. CREATIVITY AND DESIGN

Engineering texts generally spend little time explaining what design is before they teach its more detailed aspects. For example, the first page of Steel Structures: Design and Behavior by Salmon and Johnson defines structural design as a mixture of art and science, combining the experienced engineer's intuitive feeling for the behavior of a structure with a sound knowledge of the principles of statics, dynamics, mechanics of materials, and structural analysis, to produce a safe economical structure which will serve its intended purpose [Salmon 90]. Two more pages are spent on explaining design as an optimizing process and its procedure. The remainder focuses on the analysis and behavior of steel structures, in a text which contains over a thousand pages. Design of Concrete Structures by Nilson and Winter does not even bother with a definition or procedure of design, it proceeds directly into analysis [Nilson 86]. It is the author's opinion these books would be more accurately entitled Steel Structures: Analysis and Behavior and Analysis of Concrete Structures.

Structural design, and other forms of design, can either be routine or innovative. Routine design follows a preset pattern to achieve a solution, much like an equation is solved to get an answer, much like the information taught in the above texts. This process is essentially like analysis. Innovative design may follow a pattern similar to routine design, but also includes creativity, where something original is produced. Civil engineers often have the option in their work projects to decide which design approach to
use. Because of constraints of time, economics, or even personal ability many will choose the former.

Another way to view the importance of creativity in design and the civil engineering profession is to break up a civil engineer's time spent working. Much of a civil engineer's time is spent performing general activities, i.e. activities not involving specific analysis or detailing, one estimate is 85 percent [Feldsher 90]. Two tasks that involve considerable 'general' time of the civil engineer are communication and using engineering judgement.

Communication has a variety of forms including speaking directly to co-workers, writing memos or faxes, using the telephone, even preparing reports and drawings. Preparing reports and drawings that communicate an engineer's design to others involves a synthesis of engineering and creativity. Engineering judgement also involves synthesis, and thus creativity and imagination. This judgement is based on previous experiences, but is more than simply referencing these experiences in one's mind. It involves a complex thought process that sorts and combines these experiences that allows one to extrapolate beyond them [Feldsher 90], essentially synthesizing experience and creativity.

In the late 1800s, Oliver Wendell Holmes observed that there are one-story intellects, two-story intellects, and three-story intellects. Those who collect information and have no aim beyond that information are one-story intellects. Two-story intellects compare, reason, and generalize using their knowledge and that of others. Three-story intellects idealize, imagine, and predict. Their best illumination
comes from above - through the skylight [Buhl 60]. Although Holmes may be implying that creativity is a natural talent, more recent authors have asserted it can be acquired or learned [Alexander 64, Kagan 67, Schon 87, et al.]. Unfortunately, there is evidence that supports that traditional engineering courses reduce the creativity of students [Holgate 86]. Not only is there an increasingly vast array of knowledge to be assimilated, but one cannot teach standard clear-cut answers to problems without implying that there are standard clear-cut problems. Once the mind becomes set in this view it becomes more difficult to break out of it at a later date. Clearly, more emphasis on education involving creativity is needed [Eck 90, Fenske 90, Santamarina 91, et al.].

Creativity depends on being able to use a base of knowledge in a sort of 'free-wheeling' process [Santamarina 91]. Figure 2.1 represents Santamarina's use of this idea to identify the peak of productive creativity in an engineer. There are two merging knowledge curves which represent two possible shapes the generation of knowledge may take. [Fuhrmann 90] points out that while it is not possible to force knowledge into a student which is equivalent to that of an experienced engineer, it is possible to train a young person not to lose his ability of unrestricted thinking. She illustrates this in figure 2.2, whose dashed lines represent figure 2.1. By positively influencing unrestricted thinking while a person is young, more of his ability in unrestricted thinking will remain later in life. This produces not only a higher peak in productive creativity, but also a more gradual decline of productive creativity with
Figure 2.1: Schematic representation of the growth and prolongation of creative productivity in the life of an engineer through training of unrestricted thinking. [Santamarina 91]

Figure 2.2: Increase of productive creativity in the life of an engineer through early emphasis on training of unrestricted thinking. [Fuhrmann 90]
age. How this can be accomplished is the subject of later chapters, but it is an over-simplification of the problem to state that there is not enough creativity emphasized in engineering courses. "The problem is not that the curriculum has contained too much analysis and not enough synthesis. Rather, it has not contained some of the right techniques of analysis, nor how to use analytical techniques as part of the synthesis process." [Liebman 89].

So design can be a combination of creativity and optimization in a problem solving process. Yet, it is even more; it is a science [Simon 69, Eder 88, Liebman 89, et al.]. Herbert Simon's work, The Sciences of the Artificial, written in 1969, explains the concept further. Traditionally, science schools have studied natural things and how they work. In contrast, engineering and other professional schools have focused on artificial things and especially on how to design them. "In the view of the key role of design in professional activity, it is ironic that in this century the natural sciences have almost driven the sciences of the artificial from professional school curricula. Engineering schools have become schools of physics and mathematics; medical schools have become schools of biological science; business schools have become schools of finite mathematics." [Simon 69] The reason this has happened, he claims, is the desire of professional schools to gain academic respectability which comes with teaching subject matter that is "... intellectually tough, analytic, formalizable, and teachable." [Simon 69] In the past, artificial sciences, like design, were "... intellectually soft, intuitive, informal, and cookbooky." [Simon 69]
"The older kind of professional school did not know how to educate for professional design at an intellectual level appropriate to a university; the newer kind of school has nearly abdicated responsibility for training in the core professional skill." (by which he means design) [Simon 69]. Simon agrees that the current emphasis on natural sciences in professional schools cannot diminish, but artificial science must also be integrated. Simon goes on to say, "The professional schools will resume their professional responsibilities just to the degree that they can discover a science of design, a body of intellectually tough, analytic, partly formalizable, partly empirical teachable doctrine about the design process." [Simon 69]. More recent authors agree that considerable research still needs to be done in the science of design in order for professional schools to best educate their students [Schon 87, Lieberman 89, Fuhrmann 90].
3.0 INTRODUCTION TO DESIGN THEORY

Since Simon's statement of the need for a 'science of design,' and even before, there have been a multitude of theories and strategies presented to help organize design into a coherent subject. Whether design is more of a problem-solving approach or a creative approach, whether optimizing or satisficing [Simon 69] is more important, whether ethics or just 'bottom line' cost analyses should decide a project's fate have all been and continue to be debated. Of all the existing theories, four are described and discussed below, which are meant to be illustrative of the broad range of what design can be, and how it should be taught.
3.1 FUNDAMENTAL APPROACH TO DESIGN

During the sixties there was much literature published on the systemization of design. This was mostly due to the increasing complexity of technologies and designs they fostered. Because of the more complex problems posed to the engineer the potential for errors magnified. The demand for a design methodology was also encouraged by the entrance of computers into the workforce. The computer was seen as a device that would greatly accelerate and thus economize calculations and other systematic processes. As a result, these factors caused the design process to be reevaluated which led to the demand for a more systematic approach to design [Asimow 62, Kagan 67, Fuhrmann 90]. Several approaches that are basically representative for their time were those proposed by [Asimow 62], [Krick 65], and [Woodson 66].

These approaches are all similar in content in that they emphasize the systemization of design. They, along with many others, break this operation down into phases, stages, steps, or similar entities that roughly correspond with one another. Figure 3.1 is a compilation by Woodson that shows a variety of descriptions on how to solve a problem. How to approach design would have an equally long list, but an analysis of Asimow's approach shows that not only is it an adequate representation of the others, but that essentially his methodology is still followed today [Biggs 86, Lin 88, West 93].

Asimow explains engineering design as an activity that
<table>
<thead>
<tr>
<th>Design Process (Asimow)</th>
<th>Thought Process (Wallas)</th>
<th>Professional Method (Ver Planck and Teare)</th>
<th>Engineering Method (Smith)</th>
<th>Problem-solving Method (Buhl)</th>
<th>Scientific Method (General Electric)</th>
<th>Law (Ballantine)</th>
<th>Management (General Electric)</th>
<th>Military (Staff College)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis</td>
<td>Preparation</td>
<td>Define problem</td>
<td>Preliminary analysis</td>
<td>Recognition</td>
<td>Collect existing facts</td>
<td>Reject irrelevant material</td>
<td>Plan</td>
<td>Recognize, gather data</td>
</tr>
<tr>
<td>Synthesis</td>
<td>Incubation</td>
<td>Plan treatment</td>
<td>Statement of question</td>
<td>Preparation</td>
<td>List of missing facts</td>
<td>Translate and restate</td>
<td>Organize</td>
<td>List possible solutions</td>
</tr>
<tr>
<td>Evaluation</td>
<td></td>
<td></td>
<td></td>
<td>Analysis</td>
<td>Synthesis</td>
<td>Measure</td>
<td>Test possible solution</td>
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<tr>
<td>Decision</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>State legal issues</td>
<td>Select best possible solutions</td>
<td></td>
</tr>
<tr>
<td>Optimization</td>
<td>Elaboration</td>
<td>Execute plan</td>
<td>Design and conduct</td>
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<tr>
<td>Revision</td>
<td></td>
<td>Check as a whole</td>
<td>experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Implementation</td>
<td></td>
<td>Learn and generalize</td>
<td>Interpretation</td>
<td></td>
<td>Develop theories which prove valid</td>
<td></td>
<td>Apply</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.1:** The horizontal alignment does not really imply functional correspondence; only an approximate stage-wise agreement with column one is attempted. [Woodson 66]
fulfills a need. Later authors, [Woodson 65, Fuhrmann 90], use "fulfillment of a need" as part of their definitions for design. Clearly this need must be sufficiently complex to require actual engineering design work and not just simple calculations. However, Asimow does not define engineering design as much as he establishes a philosophy for it.

There are many principles this philosophy is based upon. They all, however, contain a mixture of two different types of content: factual and ethical. Factual principles are not changeable since they are defined by the laws of physical reality. Ethical principles, however, are a generalization of our current culture and personal beliefs and are readily subject to change.

For example, "economic worthwhileness" is more a factual principle, to the extent that the consumer must gain a certain amount of utility that equals or exceeds the effort required to develop it. Should the utility become negative at some point in the development of the project then it is abandoned. The term "utility" is meant not just in the economic sense, but in the broadest terms for the consumer. "Minimum commitment," on the other hand, is a principle falling more in the realm of ethical content. We generally feel it is best at any stage of the design process to make only the minimal commitment in design decisions in order to maximize the freedom of finding solutions at the later levels of the design. Yet, one could conceive of a more headstrong culture that looks to hammer out solutions quickly and bluntly. This culture might favor making all the decisions as quickly as possible and so would have a principle of
"maximum commitment." These are two typical examples of principles Asimow mentions that encompass his philosophy of design.

Two other very important principles of Asimow's philosophy are "morphology" and the "design process". They deal with the structure of a design project. "Morphology" describes how the design progresses from an abstract concept to its completion, this gives a vertical structure to a design project. The "design process" described as an iterative problem-solving process, provides the horizontal structure to the design project.

The phases describing morphology of design is shown in figure 3.2. These phases form a chronological order which, in general, follow the sequence of a design project. Naturally, they are not always rigidly followed. Phases may overlap or even be omitted in particular projects. In the realm of construction, the primary design phases are generally associated with the work that civil engineers and architects perform. Contractors generally deal with the later phases.

The first step, the feasibility study, has the purpose of determining whether the original need, as defined by the consumer, is a valid one to pursue. The approaches used in a feasibility study are very general and empirical. While there is design work performed, it is usually meant as a quick survey of alternative solutions to the problem. For a civil engineer designing the site for a building feasibility is determined mostly through economics. Does the cost of placing the building on the site fall within the client's
Figure 3.2: The Phases of a Complete Project [Asimow 62]
financial limitations? It can also involve checking the applicable laws and restrictions imposed such as zoning, environmental, or other municipal, state, or government laws. Another task is to consider all possible alternatives for the project: which site, what the layout will look like, what will be in the layout, and so forth.

Aside from financial reasons, there could be many others that indicate a project should not or cannot continue. Continuing with the civil engineering example of a building, there are many reasons to abort a project. Perhaps the only site available is not large enough to handle the building. This could be due to zoning laws which may require a minimum amount of green space on the site, it may involve environmental issues such as wetland mitigation, or perhaps the soil on site would not adequately support what might be placed upon it. If the feasibility study determines one or more solutions are possible then the design project may continue.

Next comes the preliminary design phase which looks at the set of possible solutions from the feasibility study and attempts to narrow the design choices to only the preferred one. Ranges for the major design parameters are also approximated. For civil engineers these parameters might include the types of materials or the style of architecture to be used.

The detailed design phase begins with the preferred concept selected in the preliminary design phase and concludes with a complete representation of the design. The form this
representation takes is most often in the form of engineering drawings which are increasingly being drafted by computer draftsmen rather than by hand. This phase is often, incorrectly, considered to be where the major design decisions take place. Although more time of a project is spent in this phase, hence the adage "the devil is in the details," the important design decisions are made in previous stages. Figure 3.3 shows how the ability to influence the total cost of a project decreases further into the project as more and more design decisions become fixed.

Here, in the detailed design phase, the size of steel reinforcement in concrete, the spans of beams and girders, or the size and slopes of drainage pipes are chosen. Although designing for these specific tasks are design problems in themselves, one must keep in mind that it is part of a greater design task. All the previous steps taken to determine that reinforced concrete would be used as opposed to other materials are in themselves also solutions to design problems. In order to solve each of these problems one must follow a design process.

The design process for engineers is a specialized process of problem solving. Asimow stated that this is the horizontal structure to a design project and is found in each vertical phase. In other words, within each phase of the vertical design structure in figure 3.2 there exists a design process. "Since every step in the morphology poses a particular problem which has to be solved, it is clear that the design process should appear in every step." [Asimow 62] Even by the sixties there had been a multitude of attempts to break down this process into steps or stages. Asimow's
Figure 3.3
method to design based on even earlier authors [Von Fange 59, et al.] is widely accepted and used today [Suh 90] as it was then. Asimow's comparison of the design process to the scientific method is insightful. Research proceeds from an abstract concept to general hypotheses that may be applied to many different situations. Design proceeds from an abstract concept to one or more specific solutions that can only to be applied to nearly identical problems.

Asimow's approach to the analysis stage of the design process is essentially a mathematical one. Matrices, probabilities, and linear optimization are all used as examples to choosing the best design alternatives. Suh's use of functional requirements (FRs) and design parameters (DPs) is preceded here by Asimow. Input variables are independent variables that must be followed to solve the design problems, equivalent to FRs. Output variables (dependent) are associated with the input variables through a transforming expression that includes design parameters. There are also constraints which limit the range of both the variables and the parameters to ensure they are physically realizable, another principle of Asimow's philosophy to design.

There are three constituent elements of Asimow's general optimization problem. First, the criterion function which, by the proper choice of design parameters, is to be brought to a maximum or minimum. It is represented in figure 3.4 as constant level lines which proceed from intersecting the origin to the solution points and are parallel to the line \(x=-y\). Second are the functional constraints which essentially constitute the mathematical description of the
Figure 3.4: [Asimow 62]
archetype of the proposed object. Third, the regional constraints set the allowable limits on design parameters or on derived groups of parameters which represent more complex attributes of the proposed object. The functional constraints are distinguished by equalities and the regional constraints by inequalities. While the mathematical representation is similar to that of Suh's equations, a graph, figure 3.4, depicts how the design solution(s) is determined in Asimow's design process. Figure 3.4 shows only three regional constraints and because they are inequalities the allowed region exists. Otherwise, if they were functional requirements the acceptable solutions would fall only on the lines and not in the region above.

The optimization process used by Asimow is similar to numerous other optimization techniques [Woodson 66, et al.], with definition of terms differing slightly. The general premise that one optimal solution exists for a particular design problem is valuable up to a point. The clear advantage of an optimization approach is to be able to sort through all the requirements and constraints of a design. Its limitation lies with exactly what is defined as the requirements and constraints. As with computers or any other analytical tool, this process is only as effective as its operator.

Asimow also describes the influence of socio-ecological factors on an engineering design and how one pattern of this influence is represented by the diagram of a production-consumption cycle. Figure 3.5 is perhaps a more complex way of explaining how the system designed will interact with the
Figure 3.5 - Production Consumption Cycle [Asimow 62]
environment. At first glance this cycle may seem less important to the civil engineer than others, but there are significant points to be made.

Consider a building as the product demanded by the consumer. What was in place before? Can anything be recovered from it to use for the new construction? Civil engineers might not be able to often reuse physical materials, but they make extensive use of previous information collected by the engineers who designed what was there initially or if there is nothing there those who first surveyed the site. What the soil conditions are on the site, access to utilities, reports on environmental factors acting on the site, and how what was on the site affected the environment around it is just some of the knowledge that would be useful for the engineer. The production phase comprises both the design and construction of the edifice, which is where the civil engineer's duties begin to diminish and is where the contractor's begins. The distribution phase is of minimal importance because once the building is produced it is in place as well. Although it is not completely irrelevant because much use is currently being made of precast materials and fabricating large parts of buildings off site. Finally, the consumption phase is of importance in realizing the intended use of the building and insuring the design meets those needs.

While the design must be compatible with all four processes, often the demands of these phases are contradictory and a compromise must be reached. Reconciling these conflicts is one of the principal problems of design.
[Asimow 62]. Consumers are often concerned with things like ease of maintenance, longevity, appearance, and reliability, while the producer is looking for ease of production, standardization of parts, availability of resources, etc. The tradeoff for the civil engineer is the optimization of cost. Clearly the civil engineer will design whatever the consumer wants, but it is also his responsibility to look for the opportunities where significant savings in cost can be made at small expense to the consumer's needs. Compromises like these are necessary to better complete the design to the satisfaction of all involved.

One must note however, that physical objects are not the only objects that flow through this cycle. There are also the more abstract objects of economic utility and information that follow the same processes. The utility of a product has a considerable influence on how the object proceeds in the cycle. For example, there is a flux of value through the process of distribution, accompanied by an augmentation in value, arising from a more favorable time and location for marketing. The consumer who purchases the product pays the elevated price because it has more value to him than the production price. Additionally, information has influence on the cycle. Not only is information required for each step of the way, but latent information is of great importance in the redesign of products, or new products with similar characteristics [Asimow 62].

The philosophy for design Asimow described 32 years ago is still very much in place in society today. Its change in terminology from philosophy to science marks its progression into a more technologically complex society. Another change
that has occurred is the continued increase in complexity of problems and their solutions. Increased demands for more accurate optimization techniques led to the design practice that follows.
3.2 AXIOMATIC APPROACH TO DESIGN

One systematic method to design is presented by Nam Suh [Suh 90]. His theory is based on an axiomatic approach, which can be used to create a new design or to analyze an existing one. He proposes two axioms as the foundation for finding solutions to all design problems:

Axiom 1: Independence Axiom - maintain the independence of functional requirements (FRs) of the design

Axiom 2: Information Axiom - minimize the information content of the design

In order to fully comprehend these axioms one must understand some of Suh's definitions. Two concepts crucial to these axioms are functional requirements (FRs) and design parameters (DPs). Functional requirements (FRs) are defined as specific requirements the design must achieve in order to be successful or optimized in order to be the best design. These requirements are placed in the functional (or imaginary) domain. Design parameters (DPs) are the physical, or real, parameters that must be followed to optimize the design. Their selection also has a hierarchy. In virtually all designs certain design choices must be made prior to designing more specific ones. For example, the material used in designing a column must be chosen before a decision is made on what kind of connection to use to connect it to a beam. A third term, constraint, is defined by Suh as something that constrains selecting particular DPs. It should not be confused with FRs, as FRs are goals for the
design and constraints are limits imposed on the design. Cost minimization is perhaps the most common constraint, as it can be placed on almost any design.

Suh describes as an example a refrigerator door, albeit not a civil engineering example, it is useful here in understanding these concepts. The following is a rough exercise in expanding his refrigerator door example to one of the whole refrigerator in order to more fully illustrate his ideas.

Two FRs for the refrigerator are to provide an insulated enclosure while minimizing energy loss (E) and to provide access to the food inside (F). These requirements are not defined in any physical sense, hence they are functional requirements and not design parameters. Several design parameters (DPS) for the door might be how tall the refrigerator should be (H) and in what direction the door should open (D). Suh uses matrix equations to represent the relationship between the FRs and DPS. This is also a mathematical representation of the Independence Axiom.

\[
\{FR\} = [A]\{DP\}
\]  \hspace{1cm} (1)

Here \(\{FR\}\) is the functional requirement vector and \(\{DP\}\) is the design parameter vector. \([A]\) is the design matrix that relates the two vectors. Using the previous example the design equation may be written as:

\[
\begin{bmatrix}
E \\
F
\end{bmatrix} = [A]\begin{bmatrix}
D \\
H
\end{bmatrix}
\]  \hspace{1cm} (2)

30
The \([A]\) matrix can be represented in the differential form:

\[
[A] = \begin{bmatrix}
\frac{\partial E}{\partial D} & \frac{\partial E}{\partial H} \\
\frac{\partial F}{\partial D} & \frac{\partial F}{\partial H}
\end{bmatrix} = \begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\] (3)

This form is useful in conceptualizing what each value of the design matrix \([A]\) represents. For example, \(A_{11}\) represents the effect the direction of the door opening (D) has on the minimization of energy loss (E).

In proceeding to evaluate equation (2) it is helpful to split it into two linear equations which can be represented in the form:

\[
E = A_{11}D + A_{12}H
\] (4)

\[
F = A_{21}D + A_{22}H
\] (5)

Now if we are able to determine that the height of the refrigerator has nothing to with the amount of energy conserved then \(A_{12} = 0\). This eliminates \(H\) as a parameter that would effect the value of \(E\) and creates a triangular matrix equation that can be solved. By designing and optimizing \(A_{11}\) or how the energy loss relates to the direction the door opens we can conclude it is best to open the door from above, such as a horizontally hinged door on chest-type freezers. This way the cold air, being heavier than warm air, will remain in the refrigerator with a nominal amount escaping. Another option would have been to use a door hanging on hinges aligned vertically. This would cause cold air to fall out toward the ground and be replaced be warmer air increasing the energy loss.
We can solve equation (5) by assuming the kind of door does not inhibit the ease of food removal so $A_{21} = 0$. Then $A_{22}$ can be optimized by determining the precise height to maximize ease of use by the most people.

$$\begin{bmatrix} E \\ F \end{bmatrix} = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \begin{bmatrix} D \\ H \end{bmatrix}$$ \hspace{1cm} (6)

Equation (6) is considered by Suh as an optimal design since the FRs and DPs are uncoupled. That is, the FRs are not dependent on more than one of the DPs in order to be solved. Mathematically, the design matrix must have nonzero values on the diagonal to be uncoupled.

Unfortunately, most designs are never that simple. For instance, the direction a door opens may interfere with accessibility so $A_{21} \neq 0$.

$$\begin{bmatrix} E \\ F \end{bmatrix} = \begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} D \\ H \end{bmatrix}$$ \hspace{1cm} (7)

This is an example of a quasi-coupled design. The independence of FRs can still be maintained by adjusting the DPs in a particular order. By varying $D$, $E$ can be optimized which also fixes the value of $D$. Then the only variable left to solve for $F$ is $H$. Words may better describe the concept, if the direction a door opened ($D$) somehow reduces accessibility to the food ($F$) then finding the optimal choice for minimization of energy loss ($E$) must be performed first. If you try to solve for $F$, without first solving for $E$, $D$ and $H$ are still unknowns which is 2 unknowns and one equation.
A civil engineering example further illustrates the use of Axiom 1. Figure 3.6 shows a cantilever beam subjected to a load \( P \) [Albano 92]. The design of the beam is governed by functional requirements pertaining to strength \( (FR_1) \) and serviceability \( (FR_2) \), i.e. bending stress and deflection. \( FR_1 \) shall not exceed \( \sigma \), the bending stress, and \( FR_2 \) shall not exceed \( \delta \), the vertical deflection. These requirements are then mapped onto a set of design parameters associated with cross-sectional properties.

The choice of DPs is up to the designer. If one chooses to define a solution in terms of the beam's moment of inertia, \( I \), and depth, \( d \), the design matrix for elastic design is triangular and the appropriate first step is to establish \( I \). This approach corresponds to designing for stiffness. If plastic design is assumed, selecting the beam's moment of inertia, \( I \), and plastic modulus, \( Z \), as design variables reduces \( [A] \) to diagonal form and appropriate values for \( I \) and \( Z \) can be established independent of each other. If a rectangular cross-section is assumed selecting beam depth, \( d \), and beam width, \( b \), as design variables couples the requirements on bending stress and deflection, which means they cannot be satisfied independently from each other and the Independence axiom is violated [Albano 92].

The second of Suh's axioms is the information axiom. Matteo describes the information axiom and its mathematical representation [Matteo 93]. The term information is meant as a measure of the probability of success in meeting a particular FR. Information takes on a different meaning. By
ELASTIC DESIGN \( \{\sigma\} = \begin{bmatrix} X & X \\ 0 & X \end{bmatrix} \{d\} \) DECOUPLED

PLASTIC DESIGN \( \{\sigma\} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \{Z\} \) UNCOUPLED

RECTANGULAR CROSS-SECTION \( \{\sigma\} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \{d\} \) COUPLED

Figure 3.6: Axiomatic Design of a Cantilever Beam

[Albano 92]
measuring information associated with a particular combination of FRs and DPs, one can objectively compare alternative DP selections. In other words, if two DPs fulfill the corresponding FRs and satisfy the independence axiom, the information content associated with each potential DP should be used to base the decision of which is the best design solution [Matteo 93].

Information can be quantified by using a logarithmic measure of the probability of success. For a given combination of FRs and DPs a design range and system range can be defined. The design range describes the range of availability, or tolerance of the particular DP chosen. For example, if density is chosen as a specific DP then the design range would equal the range of available densities for the item being considered. The system range would, in this case, be equal to the range of allowable densities. This is shown graphically in figure 3.7.

The distance where the ranges overlap is the common range. The probability of success and the information content is:

\[ I = \log \left( \frac{\text{system range}}{\text{common range}} \right) \]  

(8)

I represents the information content for the choice of FR and DP. Since the system range and common range have the same units, I is always dimensionless. In an uncoupled design each I value of each FR and DP combination are added to give a total information content for the design. Joint probabilities are multiplicative, but because the information content is expressed logarithmically, the total information
Figure 3.7: Design Range, Common Range, and System Range [Matteo 93]
is a sum [Matteo 93].

Although Suh's method to design may seem complex, there has been much research performed in this area. One example of this research is by [Matteo 93]. He looked at steel and concrete beams designed in shear and flexure and a complete bridge example in relation to axiomatic design principles. He found that "In both the steel and concrete beam examples the potential usefulness is great. Each characteristic of each beam is selected according to the requirement that affects it most. Therefore design paradigms developed should produce efficiently designed sections." [Matteo 93]. Studying an entire bridge proved more difficult since Suh has no system for weighting the importance of various design requirements other than through the assignment of tolerances. It seems the greatest advantage to Suh's approach is also his weakest point. By paying such close attention to detail there is little a designer can overlook, however, he also often can find himself mired in all the calculations.
3.3 HANDS-ON APPROACH TO DESIGN

A long debated theory in the education of design is hands-on design. Its protagonists argue that there is no substitute to learning design than actually performing it. Its detractors agree to its usefulness, but feel once out of school a student will learn design quickly enough and so learning theory should be the priority in engineering education. There are numerous arguments on both sides to hands-on design, enumerated below, which vary in magnitude depending to the extent hands-on design is concentrated in the curriculum. Typical current practice of hands-on design is generally included in one or two laboratory courses through the undergraduate curriculum.

The general theory to hands-on design is quite simple in its approach. Instead of devising a method of systematizing design as Suh or other authors have proposed, hands-on design relies more on the student choosing his own approach to solving a problem. In this sink or swim scenario the student quickly realizes the importance of embracing some form of methodology to design, and also begins to understand the interdependence of the various fields of engineering as well as architecture, construction, and manufacturing. With no specific design approach necessary to follow any could be selected. For example, either Asimow's or Suh' method to design could be incorporated with hands-on design. The importance lies in the actual performance of a physical design. With the actual implementation left to the student, a closer look at the arguments surrounding its validity is more appropriate to concentrate further.
[West 90] provide a brief summary on the support for design-and-build projects and also discuss their pros and cons. In the early sixties, [Mann 62] advocated integrating design and laboratory experience so students could experience physical realization of their formulae. In the eighties, [Flowers 87] and [West 89] argued hands-on design leads to an increase in creativity and a better understanding of the design-and-manufacture process. [Henshaw 89] also explained a curriculum based solely on theory can sap a student's enthusiasm. Finally, [Churches 82, 86] after 15 years experience, concluded design-and-build competitions are a high point in teaching the creative and practical aspects of engineering design.

Stated advantages to a hands-on design approach are clear and difficult to debate. The practical experience provided by hands-on design exercises give immediate feedback to a student's understanding of engineering science. This is of considerably greater value than a grade on a problem set. The flip side also holds in that a mistake means a tangible goal has not been reached. A student can also learn from his classmates by viewing their solutions to the same problem, correct or incorrect.

Hands-on experience helps a student in other ways as well. It reveals that simple analytical tools can be used to make design decisions without wasting time through experimentation. The limitations of design are also revealed when the student realizes the real world does not conform to his theoretical analysis. Applying simple, realistic techniques, rather than theoretical ones, to complex problems
shows another approach that is accessible to students. For example, once a student realizes the model structure he is designing to withstand lateral loading can be approximated as a cantilever beam his analysis becomes much simpler.

Realizing the interconnections between different branches of engineering is another lesson learned by students taught with a hands-on design approach. They have to select the most appropriate techniques from their previous experience and draw on that body of knowledge to solve the problem. A civil engineering student designing a model for a building should take all aspects of the problem into consideration. Not only structural integrity and aesthetics, but seemingly minor problems such as heat and ventilation flow within the building need to be considered.

Finally, hands-on experience clearly shows the connection existing between design and manufacturing or design and construction. The difference between manufacturing and construction is important to note. Manufacturing a product implies mass production which changes a designer's approach. He often has the ability to construct a prototype with which to better determine the final product. Construction, which is a primarily civil engineering concern, does not really have that luxury. Clearly, designing a full-scale prototype of a building is ludicrous, and often smaller scale models show difficulty in accurately representing reality, especially when considering environmental concerns. However, to account for manufacturing or construction concerns while designing is of paramount importance to a designer. Students learn this lesson quickly when their design takes more effort.
than they are willing to exert. Hands-on design does well in showing the difference between what one can conceive and what one can build.

The arguments against hands-on experience are based on both valid reasons and on several misconceptions of the intended purpose of hands-on design. Since most graduates will not be doing hands-on work in their future careers it could be argued they do not need to concern themselves with hands-on design education or any manual skills. This shows a misconception of the purpose of teaching hands-on design. The intent is to learn what manufacturing or construction is and its importance in the design process, not to learn only to be good at it.

Another view of hands-on design is that it is only indirectly related to engineering science, or separate from the main thrust of the curriculum. This more practical approach to design, however, reinforces the connection between the actual and the analytical sides of a problem which might not be discovered until a student enters the workforce. [West 90] found that student's grades in 2.70 corresponded with their overall grade point average, indicating the skills required are not fundamentally more or less difficult than the rest of the curriculum.

Practical experience could also be viewed as a waste of time in an already crowded curriculum. It takes considerably more time to create and then test the maximum flexural capacity of a reinforced concrete beam than to simply perform the calculation on paper. Although the most reasonable concern so far, this example can teach students the
appropriate level of precision in calculations, and shows students the necessity of making trade-offs between design optimality, manufacturability, and the cost of their time.

A related argument to the previous one is that hands-on design education is simply not cost effective. This is perhaps the most difficult argument to debate. There is much fabrication space and equipment required, materials are expensive, teaching requires a high ratio of faculty to students, and finding faculty with the necessary range of analytical and practical skills is difficult. [West 90] argues that although the value of the experience is enhanced through state-of-the-art equipment, it is of nearly equal value in teaching hands-on design with older materials. Companies that often employ graduates of a university are often willing to make donations of material to help support design programs. Also, faculty are easily capable of developing the necessary skills to teach basic manufacturing or construction techniques to students.

Although there is clearly still debate over whether hands-on design should be mixed into an already crowded curriculum its detractors do not cite reasons for why this form of education is inherently flawed. The problems are overcrowded curricula and expense. The same basic problems are enumerated over the further integration of design in general into universities. West provides a final warning to those who argue against having some form of hands-on design into engineering curriculum. "Without the ability to estimate well and recognize reasonable answers, the computer-aided engineer can be more dangerously ineffective than the
handbook engineer we all learned to fear years ago." [West 90]
3.4 Architectural Studio Approach to Design

So far, the previous approaches to design have been described as steps which lead to an optimal solution. Since few would argue that the conclusion to a design process will always end in one optimal solution, there must be something that has been omitted. There must be considerations and options that lead designers to a number of comparable solutions to a single design problem. The extreme to this situation that two equally qualified engineers given the same task, will never end up with the same solution is also espoused [Schlaich 91]. Donald Schon provides an answer to this dilemma. His view of designing and how students should learn design is by learning artistry which is based on a process he calls reflection-in-action [Schon 87].

The meaning of artistry is best explained when the top performers of a particular field are scrutinized. What makes an architect or engineer perform above others in his practice? There will always be those whose technical knowledge of a subject will give them superiority, but often this is not the attribute that distinguishes one professional over another. Those who are exceptional are often said to have wisdom, talent, intuition, or artistry [Schon 87]. This is roughly equivalent to the concept of unrestricted thinking shown in figures 2.1 and 2.2. Schon accurately explains that since descriptions like these are difficult to explain or measure in conventional senses, there is a tendency to close off further discussion that might better explain these abilities. Schon explains artistry as an exercise of intelligence, a kind of knowing, though different in crucial
respects from our standard model of professional knowledge. The difference comes as a result of having to modify applying one's professional knowledge to each design problem, as each are unique.

This ability to modify and respond as necessary to challenges that are presented describes two processes: knowing-in-action and reflection-in-action. Firstly, knowing-in-action is the kind of knowhow revealed in our actions. It is a spontaneous, skillful execution of a performance that is often difficult to make verbally explicit. An example that illustrates this skill is catching a ball. It is a continuous activity in which awareness, anticipation, and adjustment are used to cup our hands around the ball. Attempting to explain the procedure is difficult because the constructions used to describe the action are static and the knowing-in-action is dynamic, or the knowing is in the action.

Reflection-in-action must be used when knowing-in-action isn't enough. When a familiar routine produces an unexpected result or when a familiar routine and result are seen in a different light reflection-in-action has taken place. The surprise brought forth in the action causes one to reflect on his previous experiences and reshape what we are doing while we are doing it, or reflection is in the action. These may seem like complicated ways of describing "following a routine" and "drawing from past experiences", but in this way they are linked more closely and the explanation becomes standardized.

The design process can be viewed as reflection-in-action.
Designing in a broad sense involves complexity and synthesis, where things are created and put together [Schon 87]. This creative process must include reflection of previous experiences and often their integration into the outcome. As a result, learning to design must include performing reflection-in-action.

Schon feels the architectural studio is an ideal setting, "... I have become convinced that architectural designing is a prototype of the kind of artistry that other professionals need most to acquire; and the design studio, with its characteristic pattern of learning by doing and coaching, exemplifies the predicaments inherent in any reflective practicum and the conditions and processes essential to its success." [Schon 87] Studios are typically organized around design projects, either individual or in groups, and are generally based on projects from actual practice. Schon explains how they have evolved their own rituals, such as master demonstrations, design reviews, desk crits, and design juries, all attached to a core process of learning by doing. Also, in order for studio instructors to make their approaches to design understandable by students, the studio offers privileged access to designers' reflections on designing, which objectifies Schon's concepts.

The relevance of architectural studio to engineering education may be called into question. There is little argument that the visual language and graphic notation used by architects often differs from engineers use of mathematics to approach design problems [Holgate 86, Peters 91]. Increasingly, however, engineers are using computers to solve
the more analytical tasks in design. Although use of computers will not preclude formal education in analysis, especially in order to not become reliant upon it, analysis could soon be replaced as the basis of engineering education by synthesis [Peters 91]. Not everyone agrees, some feel what really separates engineers from architects is their different education and approach to design [Schlaich 91].

Regardless, there is agreement that engineers would learn to become better designers from more synthetical and creative subject matter placed in the undergraduate curriculum. These subjects are dominant in architectural studios. Figure 3.8 shows Kruckemeyer's view of the design capabilities of architects and engineers. This corresponds to figures 2.1 and 2.2 in that the unrestricted thinking curve is higher for that of an architectural student and actually dips for an engineering student who is exposed to more analytical material.

A difficulty with design being taught in a classroom setting is that designing is a holistic process [Schon 87]. Schon feels that without coaching and considerable interaction between teacher and student the process of design cannot be holistically taught. Component design skills cannot be understood in a list as well as they can be understood in the context of the whole process.

The extent to which the instructor interacts with his students in this holistic approach changes his role from that of a lecturer to that of a coach. The term, coach, has a dual meaning. Primarily, it relates to the master in a master and apprentice relationship where apprentices learn
Figure 3.8: Differences in Design Capability of architects and engineers over time. [Kruckemeyer 91]
not only by observing the master perform, but also performing themselves and receiving continuous constructive criticism. Coach also implies someone who encourages and motivates students as well as instructing them. This is perhaps why Schon preferred the term coach over others.

Yet, Schon also presents a paradox to learning design: the student must begin to design before he knows what he is doing, so that the studio master's demonstrations and descriptions can take on meanings useful to further designing. This paradox breaks down in the communication between the coach and student. Between every design step taken by the student and coach, forward or backward, there must be interaction where learning and reflection-in-action take place. The student reflects-in-action on the coach's demonstrations and comments and his own while the coach also reflects-in-action on the students steps and his own running commentary and examples.

Essentially, the goals of an architectural studio and Schon's reflective practicum are the same. Emphasis is placed on learning by doing and on coaching, not just teaching. Action and interaction are the keys and engineers would benefit tremendously from only a marginal increase in a curriculum change that favors these principles.
3.5 SUMMARY OF THEORIES

The order in which the above theories were presented was not accidental. It was meant to show a logical progression of how design has come to be viewed. In grossly simplified terms the fundamental approaches to design have been a categorization of what was done in practice with some mathematical optimization. The axiomatic approach proceeds to the extreme theoretical end of optimization by explaining that everything can be optimized if you can just define the exact problem. A return to the basics by hands-on design espouses that learning is best performed by physically doing. An architectural studio and Schon's theories argue that not only is learning by doing important, but so is coaching instead of teaching. This is not meant to imply that the final theory is better or more accurate than the others, each has its own merits. For example, in manufacturing assembly line parts perhaps an axiomatic approach would save considerable effort in repair and increase efficiency. Also in civil engineering, recent research performed on the axiomatic approach report moderate success [Albano 92, Matteo 93]. Only by an equitable exchange and interaction of all design principles will a better design theory evolve or emerge.
4.0 INTRODUCTION TO METHODS OF TEACHING DESIGN

The second half of this thesis contains a general evaluation of the possible approaches to teaching design. It also takes a look at what is and has been performed in universities worldwide. By no means is this a thorough or exhaustive search of all the forms of design education. It is more of a sampling or survey of what has been attempted and is currently practiced. A limitation to this research is that it is literary, no actual classroom observation took place, aside from the authors own experience as an undergraduate and graduate student in the Civil and Environmental Engineering department at MIT.

While few would argue that there exists a difference between what is taught and what is learned, it is an extremely complex undertaking to pinpoint the variances so they can be corrected. The difficulty lies not only in the inconsistency of presentations of the subject matter, but also the lack of consensus by psychologists on ways students learn. Of general agreement is that different students learn different ways.

One classification of cognitive styles suggested by the cybernetician, Gordon Pask, in the early seventies is that there are two principal ways in which people learn: as a serialist or as a holist [Cross 86]. Briefly, neither approach is judged to be more effective than the other just distinct ways of learning and solving problems. The serialist best proceeds in small logical steps, trying to clarify each point before proceeding to the next. In
contrast, the holist prefers learning things in many different ways, putting concepts together similar to a jigsaw puzzle. The way in which he might reteach the material he just learned would generally be different and of his own reconstruction.

Another distinction between cognitive styles is that of convergent and divergent thinking [Cross 86]. Convergent thinking is primarily concerned with gathering information in order to produce, converge, on a single answer. Divergent thinking is not concerned with a correct answer, but emphasizes the generation of a wide range of answers. One study performed in the late sixties showed that approximately 30 percent of students are convergent thinkers, 30 percent are divergent, and the remaining 40 percent have a roughly equal mixture of the two [Cross 86].

A third distinction between cognitive styles is made between flexible and focused thinking, which could also be categorized as lateral versus linear thinking [Cross 86]. A simple example that illustrates flexible thinking follows. In a bare room are two pieces of string hanging from the ceiling and a hammer. The objective is to tie the two pieces of string together, but the strings are such a distance apart that holding one you cannot quite reach the other. A flexible thinker would look at a hammer, not in its usual context of hammering, but as a weight that could make a pendulum. The pendulum can swing to allow you to catch the second string. It is important to note, however, similar examples exist that are advantageous to focused thinkers.

While these are three ways of looking at how students learn
there are also ways in which professors teach. Since there are bound to be conflicts in using the extreme of any method it seems prudent to use equal mixtures, varying only when necessary to best illustrate concepts.
4.1 SEVERAL COURSES VS. CAPSTONE COURSE

Universities have long debated the pros and cons of having a capstone course in the civil engineering curriculum. Whether design is taught only in the capstone course or in all engineering courses has also been an issue for debate. Both issues are still not resolved and perhaps will never be since each approach has its advantages.

At MIT, there is a capstone course called 1.52 Integrated Engineering Design. There is also an introductory capstone course for graduate students who might not have been exposed to one as undergraduates entitled 1.543 Planning and Design of Structural Systems. Although the graduate level course is slightly more rigorous, both courses are similar in content and there is also a major design project involving all aspects of civil engineering. Previous projects have included designing a building encompassing a pool and an interchange system for highways and city streets. Both design projects have involved subprojects or steps where individuals or group assignments are completed, culminating in a final design presentation both written and oral. These courses have emphasized design and the design process and are successful examples of capstone courses. Additionally, virtually all civil engineering courses at MIT that teach theory also include final design projects as a culmination of what was learned as well as final exams. These are also successful examples of how design can be learned.

Other universities vary in their views of if and how a capstone design course should be presented. A general
sampling of universities illustrates this. At Memphis State
there is a capstone design course that is writing intensive
in order to emphasize the need for communicative ability in
civil engineering [Smith 90]. Purdue University also has a
senior design course with 5-person design teams who divide
design responsibilities into environmental, geotechnical,
hydraulic, transportation, and structural systems [Miles 90].
Marquette University emphasizes their use of practitioners in
their senior design course to provide a meaningful 'true to
life' design experience [Kipp 90]. By allowing a
professional engineer to be the 'client' for the students'
design projects they receive projects that are real and
feedback from engineers who have already performed designs
for their project.

The University of Rhode Island offers a more unique
approach to the capstone concept. Not only is there a
capstone design course, but there is also a single design
project that is integrated into all of the preceding civil
engineering courses [McEwen 90]. The capstone design course
forms teams to complete the project. Its main advantages lie
in more clearly seeing the interconnections between courses
and being able to spend more time and thus enter into more
detail of a comprehensive design project.

Watwood offers a dissenting opinion on the use of a
capstone course. Assuming, like MIT, there are design
projects in most civil engineering courses the space occupied
by a capstone course could be better served by having an
additional civil engineering course with a design project.
The primary ingredients of the capstone design experience can
best be learned after the student graduates [Watwood 90].
Yet another view is that capstone design courses might be feasible only if there is a preceding course that teaches the theory of design [Liebman 89]. The courses illustrated in the following section are perhaps a realization of Liebman's concept.
4.2 LAB/HANDS-ON DESIGN COURSES

Laboratory courses are offered at all universities and their usual purpose is to show in real life what students have learned theoretically on paper. There are also courses solely dedicated to learning the process of design, without any of the laboratory influence. These courses advocate the importance of design as a form of theoretical knowledge that should be learned before performing actual design. This author proposes a combination of these two approaches is a successful and worthwhile way to learn design and to better appreciate the theoretical subject matter learned in other courses.

One of the more renowned, and successful, of all design courses is 2.70. This course entitled, Introduction to Design, is a sophomore level course taught at MIT in the Mechanical Engineering Department but available to all students. Since there are no prerequisites many students, about one quarter of the class, who take the course are from outside the Mechanical Engineering department.

The stated goal of this course is to teach the process of design from brainstorming through detailed design, fabrication, and testing [West 91]. West emphasizes three additional lessons learned through the course. First, the connection between the real world and scientific principles is better realized. Second, students learn to incorporate manufacturing and construction considerations into the design process. Third, students experience the satisfaction of creating a design of their own. These lessons are the same
as those many argue as the advantages to incorporating hands-on design into a curriculum.

The course is taught in both lecture and lab sessions. The lab sections typically consist of 12-15 students, and are led by a faculty member or teaching assistant. Instruction is focused on four projects. The first three are small projects that concentrate on particular phases of the design process: machining a part from a set of drawings, disassembling some standard machines to understand the elements from which they were embodied, and developing a conceptual design for a human-centered problem. The fourth project which occupies the last 5 weeks of the semester is a complete design-and-build assignment. Each student designs a remotely controlled electromechanical device to perform a simply defined task such as a "tug of war" with another machine. The machines compete against each other in a contest at the end of the course.

This course encompasses and incorporates all aspects of design. The theory and implementation of the design process is learned through lecture and actually following to completion a design project. Additionally, electrical, mechanical, and material engineering techniques are learned and applied in designing and creating for the three projects. Drafting and manufacturing skills are learned and performed throughout the course. Finally, the competition that is included in the final design project brings motivation and enthusiasm to the students participating. Not only is the student motivated to do well for the sake of learning or the grade, but he has the additional motivation to succeed over his classmates, which for certain students precedes the
The spirit of competition is also seen in a civil engineering laboratory course also taught at MIT. 1.105J, entitled Structural Engineering Laboratory, uses two design projects, considerably less involved than 2.70 and described below, to teach students about the design process. The course also has no prerequisites and is popular with both civil and architectural students.

The stated goals of the course are to introduce basic structural concepts and the structural design process [Leung 91]. The additional lessons espoused by West for 2.70 also apply here. The course is taught in both lecture and lab sections although both are the same small size of about 10-12, which allows more interaction in the lecture than most other courses. The course is also only half the units of an average MIT course and as a result is roughly half as demanding.

The course follows seven laboratory assignments, each with a specific structural concept to illustrate. All assignments are team efforts. Two of the lab assignments, however, are open ended in their procedure and their design, fabrication, and testing are left to the students to perform. The first is designing a spanning structure like a bridge to be tested for load bearing capacity, stiffness, and weight. The second project is to design a space enclosure that will also be tested for load bearing capacity, stiffness, weight, and additionally aesthetic appearance. The competition for these two projects is to have the optimal combination, determined
by points, of the judging criteria.

The benefits this course offers are relatively clear. Working as a team means that architects and civil engineers can interact to make a product better than either individual could. Although not as intense or involved as 2.70, this course is an excellent educational tool. Much of what 2.70 tries to accomplish is done here in half a class. However, changing this course to further implement hands-on design would increase a student's understanding of design. Additionally, implementing a more hands-on design approach into this course, as a lab, is not difficult. Also as a lab it is better suited than others to handle these changes. A more formal effort could be made to teach design with several lectures devoted to design process and methodology and more lab projects requiring a student to design. A more involved design, similar to 2.70's final project, could be implemented with a box of parts given out to students and an annual competition held. Perhaps by increasing the course load to that of a regular course more of this formal design education could be integrated.
4.3 USE OF COMPUTERS

In recent years the need to adapt man to machines, has been replaced by the need to adapt machines to man [Santamarina 91]. This change in attitude is exemplified by the changing use of computers. Computers are becoming increasingly prevalent in society; the software industry alone has been increasing sales steadily at the phenomenal rate of 12 percent a year since 1980 [Modesitt 91].

There are three major software solutions that can augment human expertise [Modesitt 91]. KBSs, or Knowledge-based Systems, are a general category of software which include expert systems. Expert systems are able to perform roughly equal to human experts in narrow domains. Computer-based Learning, CBL, is meant to assist in the learning process. CBL has several features: as a tutor, to teach students and as a tool, to use graphics, word processing, or analysis software and students programming the computer to perform tasks. Third, software engineering, SWE, is an engineering technological tool that is meant to solve the real needs of the customer. These categories of software only recently have begun to mix with each other and benefit from all their advantages.

The advantages that could lead to improved engineering design education, however, are still being realized. What then should be the role of computers for design education? Several roles are presented by the Education Task Committee of ASEE to improve engineering education are [Epstein 87]:

61
• Computer as Simulator of Complex Systems
• Computer as Laboratory Instrument
• Computer as Virtual Laboratory
• Computer as Tutor
• Computer as Textbook
• Computer as Blackboard
• Computer as Communications Medium

Effective use of all these roles could also enhance learning design, especially in its ability to graphically display more complex systems in order to conceive of an appropriate design. Computer use to enhance design should be twofold: using software to assist in teaching design and becoming proficient in software design packages used in practice.

However typical software used in practice such as CAD, computer-assisted design, which incorporates CBL and SWE is only marginally used for design. CAD, so far has basically performed as a drafting tool [Harris 88]. Civil engineering designers still generally work with scratchpads and tracing paper to envision their design and give it to a draftsman to put it on CAD. The flexibility and ease of use for CAD systems still has not materialized. Perhaps, with the increasingly computer literate graduates this problem will disappear.

A survey performed in 1988 [Law 90] showed that the average university offered only one computing course in the civil engineering curriculum. Generally, schools offered from 0 to 4 computing courses. The survey also showed a general consensus among academicians and practicing engineers for an increased emphasis on civil engineering computing courses.
Primarily professionals were concerned with students learning design, management, analysis, and drafting software. Three suggestions are made to help take care of the needs described by the survey [Law 90]:

1. Designate one course to introduce the necessary computing tools and techniques early in the program of study, say in the sophomore year.
2. Incorporate the teaching of computing into existing civil engineering courses as needed.
3. Designate one course to introduce the application of computing to specific civil engineering problems late in the program of study, say in the senior year.

These three suggestions are current practice in the civil and environmental engineering department at MIT. The first course offered is 1.00, Introduction to Computers and Problem Solving, which presents C as a programming language. Most students choose to take it their freshman or sophomore year. In most of the engineering courses offered there is some integration of computers. This usually takes the form of using Growltiger, an interactive structural analysis and design program, or similar software dependent on the subject matter. A second required computer course is 1.12, Computer Models of Physical and Engineering Systems, which emphasizes finite element methods, graphics, CAD, and interactive analysis.

The two required computer courses in the civil engineering curriculum serve to strengthen a student's computer literacy and the software packages assist students in learning design. By being able to perform sensitivity analyses on structures
much quicker than by hand, students get a better feel of how variables affect their designs. Also, through the faster analysis performed by computers students can better spend their time conceiving their designs. With the limited time available to spend on the education of and with computers the above combination seems to perform ideally in furthering knowledge of design.
4.4 SUMMARY OF METHODS

Much of what is being sought after in the process of learning design are courses, projects, and tasks that most accurately emulate the real world. Courses which bring in practitioners, design projects which copy real life projects, and exercises that follow ACI or LRFD codes are examples of this emphasis. Care should be taken to step back and observe if what is actually being learned is beneficial in the long run. Clearly, students will benefit from a smoother transition into the workplace, but will companies benefit in the long run from students having learned much of their future job in college? Is the actual theory of design learned or are more practical applications of design?

An approach that takes a complete turnaround in teaching design is a design exercise in the mechanical engineering department at MIT called 'Delta - A Design Exercise' [Bucciarelli 91]. This exercise involves a design team whose task it is to design a residence for the inhabitants of an imaginary 2-dimensional plane. This plane skews the x and y axes where a right angle measures 60 degrees, and the gravitational field occasionally shift its direction from the y to the x axis. The building blocks of this world are equilateral triangles whose color, connections to other triangles, and whether they are anchored all influence the design project with respect to thermal, structural, and aesthetic considerations. A sample structure is illustrated in figure 4.1, which also shows the structure's center of gravity (cg), its anchors to the plane, which are the dark circles, the primary direction of the gravitational field,
Figure 4.1: Sample Delta Structure [Bucciarelli 91]
and some dimensions. A more thorough description of the game is presented in the appendix.

This exercise features several advantages over real world scenarios. Firstly, its fantastical aspect removes preconceived notions of what good or bad design may be, students are not able to skip steps like 'Obviously since the span is so long we'll need steel.' As a result, this can better explain the theory and process of design than realistic projects. Secondly, it is presented in the atmosphere of a game. While real world projects can involve competition with opposing design teams, this game could be viewed as more enjoyable and might motivate students more than designing a reinforced concrete bridge.

The point to be learned is that there is not one best solution to solving the problem of educating students in design. Even arguing that students should be exposed to all approaches to design will not work because of time restraints and a cursory sweep of so much material. Depending on the resources and staff of the university the ideal curriculum for students will also vary. Most important are the university's ability to be flexible with constantly changing approaches to design and technology and to teach students how to continue to learn once they have graduated.
5. CONCLUSION

(1) What are the theories of design?
(2) What is currently being taught?
(3) What are students actually learning?
(4) What is currently being practiced?

Partial answers to the first two questions presented in the introduction were made. A cursory look at the third was also attempted.

The first question has a broad range of answers. The number and variety of design theories proposed throughout history is enormous. All theories, however, are based to some extent on two polar premises: optimization and creativity. Generally, the predominance of one inhibits the other. Theories on both extremes and some in between were presented. As with uncertainty in any question, the answer to the best approach seems to lie somewhere in a mixture of the two extremes.

The second question is answered more specifically, by examples of MIT and other universities. Most schools' approaches are rather similar to one another, but vary in quality and quantity depending on resources and staff. Generally, a more fundamental approach to design is still predominantly taught, similar to Asimow's approach to design, which includes emphasis on design as a stepwise process and optimization techniques to determine the solution. Newer theories [Schon 87, Suh 90] have yet to gain widespread acceptance and the hands-on approach is used only when
universities have the necessary resources. A proper formalization of methods of teaching design education is needed in the undergraduate curriculum. Learning the appropriate material could involve several full courses. With an already crowded curriculum, something must change. Either material is eliminated from the curriculum, courses are made more efficient, or the length of an education is extended.

The third question was ventured into somewhat briefly. Practitioners feel graduating students lack design capability. Depending on the style of teaching some students learn better than others. Students with more methodical, logical minds learn better when they are taught in that manner. Students whose minds often freewheel or are looking at many aspects simultaneously learn better in that manner. Neither is more advantageous than the other and generally, students fall between the two.

The fourth question is of considerable concern and continued research is encouraged not only in this question, but all that concern design and its education. Increased improvement in design and its education bring progress and innovation which, when well managed, will cause our society and the individuals within it to directly benefit.
Appendix

Introduction

Congratulations! You are now a member of an expert design team. Your collective task will be to design a new residence suitable for inhabitants of the imaginary Deltoid plane. These written materials, provided to help you prepare for this task, are organized in four sections. The first section provides an overview of life on the Deltoid plane, DeltaP as it known to the natives. The second section describes your team, and the third your design task. The final section, different for each team member, provides the specific information you will need to perform the role you have been assigned within your team. Each team member will contribute different expertise to the project, and each has different design responsibilities to fulfill. All must work together for your team to create a first-rate design.

Life on DeltaP

Life on DeltaP, residential and otherwise, is quite different from what you have grown accustomed to here on Earth. First off, DeltaP is a plane, not a planet, so your team will be designing in two-dimensional rather than three-dimensional space. If your design "meets spec" and is considered attractive and functional by your Deian clients, one view on a single sheet of paper will convey to those responsible for constructing it all the information they need to do so.

The view on this single sheet may not be quite what you expect, however, because in addition to lacking a z axis, Deltoid space has unfamiliar relations between the x and y axes as well. What we think of as "perpendicular" is hopelessly skewed to a Deltan, and vice-versa. In our units, a right angle on DeltaP measures 60° or \( \pi/3 \) radians. Thus all sides of an equilateral triangle form lines considered perpendicular to all others. If there were such a thing as a "circle" on DeltaP, it would be composed of only \( 4/3 \pi \) radians.

But there is no such thing as a "circle" on DeltaP, nor even the concept of continuity embodied therein. In this flat though angular world, residents construct their artifacts strictly with discrete triangular forms. Of these, the equilateral triangle — with its three perpendicular sides — is considered the most pleasing. Accordingly, your team will design the residence by assembling into a cluster the most prized building materials on DeltaP, equilaterally triangular components called "deltas." Deltas come in red and blue versions and always measure 2 lynes per side. Four QDs, triangular units of area measure with sides of 1 lyn, fit within a delta.

Lynes? QDs? Not surprisingly, Deltan systems of measurement are as unfamiliar as that for spatial coordinates. Table 1 summarizes the measurement schemes on DeltaP that you will need to know to carry out your design task.
Table 1: Measurement Systems on DeltaP

<table>
<thead>
<tr>
<th>Object of Measure</th>
<th>Unit of Measure</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Wex</td>
<td>Wx</td>
</tr>
<tr>
<td>Distance</td>
<td>Lyn</td>
<td>Ln</td>
</tr>
<tr>
<td>Area</td>
<td>Quarter-Delta</td>
<td>QD</td>
</tr>
<tr>
<td>Heat</td>
<td>Deltan Thermal Unit</td>
<td>DTU</td>
</tr>
<tr>
<td>Temperature</td>
<td>Degrees Nin</td>
<td>*Nn</td>
</tr>
<tr>
<td>Force</td>
<td>Din</td>
<td>Dn</td>
</tr>
<tr>
<td>Moment</td>
<td>Lyn-Din</td>
<td>LD</td>
</tr>
<tr>
<td>Currency</td>
<td>Zwig</td>
<td>!</td>
</tr>
</tbody>
</table>

All of DeltaP's units of measure share the divisibility and extensibility conventions of the metric system: in the measure of time, for example, there are both microwex (μwx) and megawex (Mwx). In relation to the attention- and life-spans of Deltans, these units are roughly equivalent to seconds and years, respectively, here on Earth.

As building components, deltas have functional and aesthetic characteristics that are more complex than their simple form and even dimensions would suggest. Especially when assembled into a cluster, as you will be doing, they behave in interesting ways. Deltas conduct heat among themselves, radiate heat to outer space, melt if too hot, and grow if too cool. Ped deltas produce heat. All deltas are subject to DeltaP's two-dimensional gravity (which is itself subject to axial shifts during DeltaP's not-infrequent gravity waves). Three different kinds of cement are needed to join them together, and joint alignment with respect to gravity affects producibility as well as structural integrity. Different colors and different quantities of deltas cost different amounts of money per delta, and can be assembled in clusters that are either exceedingly ugly or very attractive to the Deltans. Your task will be to create a design that meets prescribed goals for all of these characteristics.

De. Team Roles & Responsibilities

Your design team is organized such that each of you will be responsible for a subset of the design goals. One of you will be PROJECT MANAGER. Your main concerns will be with cost and schedule, the interpretation and reconciliation of performance specifications, and negotiations with the contractor and client. You want to keep costs and time-to-build at a minimum, but not at the expense of quality. When your team submits its final design, the project manager must report the estimated cost (in zwigs) and the time (in wex) that it will take to build.

Another of you will be the STRUCTURAL ENGINEER. Your main concern will be to see that the design "holds together" as a physical structure under prescribed loading conditions. You
must see to it that the two points at which your structure is tied to ground are appropriately chosen and that continuity of the structure is maintained. When your team submits its final design, the structural engineer must attest to its integrity by identifying the strongest and weakest joints, and estimating the average load on all joints expressed as a percentage of the failure load.

Another of you will be the THERMAL ENGINEER. You will want to insure that the design meets the "comfort-zone" conditions specified in terms of an average temperature. You must also ensure that the temperature of all individual deltas stays within certain bounds. When your team submits its final design, the thermal engineer must estimate internal temperature and identify the hottest and coldest deltas.

Finally, one of you will be the ARCHITECT. Your concern is with both the form of the design in and of itself and how it stands in its setting. You must see to it that the interior of the residence takes an appropriate form and that egress is convenient. You should also develop a design with character. When your team submits its final design, the architect should be prepared to present a sketch and discuss generally how and why the Deltans will find the residence attractive and functional. The architect will also be asked to estimate a few more quantitative measures of architectural performance.

The following section describes the specifications that your design must meet to be accepted by your clients on DeltaP. Familiarize yourself with these specifications. Then, for schooling in your specialty, turn to the separate primer you have received that discusses the science and technology of your domain. The primer contains the knowledge and heuristics you will need to estimate the design parameters for which you are responsible. If you have questions that it does not answer, do not hesitate to ask. You should be expert in your role before your team begins the design phase.
THE DESIGN TASK

Your Deltan clients have cleared the space shown on the site map and come to your team with their need for the design of a new residential cluster. The cluster itself must meet the following specifications.

The client wants the cluster to provide a minimum interior area of 100 QDs (Each diamond on your gridded site map defines an area of two QDs). The shape of this space, which can of course exceed the minimum, is a matter of design. The client has expressed enthusiasm for the newer mode of segmenting interior space, a mode that breaks with the two-equal-zone tradition and values the suggested privacy of nooks and crannies. Still the space must be connected, i.e. no interior walls can cut the space into completely separate spaces. There must be one and only one entrance/exit.

The client is known to be color sensitive blue; too much blue brings on the blues, so to speak. No more than 60% blue ought to be allowed; certainly blue deltas are not to exceed 70% of the cluster.

The residence, as all clusters, must be anchored at two points and two points only. There is a limit to the amount of force each anchor can support, as well as to the amount of internal moment each joint can withstand. Exceeding either limit would cause catastrophic failure and send the unwary residents tumbling into the void. The cluster should be designed for a life of thirty megawex. Gravity waves, rare but always possible, should be considered.

The average interior temperature must be kept within the Deltan comfort zone, which lies between 55 and 65° Nn. The temperature of the elements themselves must be kept above the growth point of 20° Na and below the melt-down point of 85° Nn. Delta temperatures outside of this range will result in catastrophic structural failure with little more warning than excessive load.

All of this – design, fabrication and construction – must be done under a fixed budget and within a given time period. At your team meeting you are to develop a conceptual design that meets or exceeds all design goals. When each team submits their design, individual members will be asked to report design performance on parameters for which they are responsible.

<table>
<thead>
<tr>
<th>TABLE 2: SUMMARY OF DESIGN SPECIFICATIONS</th>
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<tbody>
<tr>
<td>Functional Interior Area</td>
</tr>
<tr>
<td>Maximum Blue Delta % of Total</td>
</tr>
<tr>
<td>Average Internal Temperature Range</td>
</tr>
<tr>
<td>Individual Delta Temperature Range</td>
</tr>
<tr>
<td>Maximum Load at Anchor Point</td>
</tr>
<tr>
<td>Maximum Internal Moment</td>
</tr>
<tr>
<td>Overhead Factor (%) - Ask instructor if blank</td>
</tr>
<tr>
<td>Total Budget</td>
</tr>
</tbody>
</table>
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