The Compatibility (or Incompatibility) of How we Teach Engineering Design and Analysis*

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This paper begins with an overview of some of the issues and challenges of teaching engineering analysis and design. It continues with a summary of a design exercise that was run as part of the Mudd Design Workshop II; this exercise was intended to be the foundation and springboard for a discussion on analysis and design education by workshop participants. The design exercise demonstrated that there is both compatibility and incompatibility in how we combine/juxtapose the teaching of engineering design and analysis. Our educational system has many elements that support our students becoming competent in both design and analysis. What is generally missing are opportunities for their use in an integrated manner. Some ideas are presented about how this integration might be fostered.

THE SITUATION

SINCE THE LATE 1980's there has been a national movement to increase the exposure undergraduate engineering students get to engineering design. This has been particularly true at the freshman level with the creation of 'Introduction to Design' courses at numerous institutions across the country (References 1 and 2 contain summaries of many of these courses). Some schools (e.g. Northern Arizona State University) are developing programs that include design experiences in all four years [3]. This is consistent with the idea that [4]:

... design ought to be both the cornerstone and capstone of the engineering curriculum, and it should be present throughout the program... in each and every year... Properly motivated and fundamentally grounded, students can learn and apply much of what is (or has been) in the advanced engineering science courses on their own.

There are several factors behind this movement, including the NSF Engineering Education Program [5], ABET 2000 criteria [6], outspoken individuals from industry [7, 8], student activism [9], trends in student selection of majors [10], and educational theory [11, 12]. It is difficult to know which of these are motivating factors and which are the products.

While this movement is exciting, desirable and laudable, the way in which it has been implemented may (in my opinion) make the dichotomy and perhaps incompatibility of how engineering design and engineering analysis courses are taught more apparent. It has been my experience as an educator, that many upper-division engineering students become frustrated when they attempt to apply the formal analytical methods they learned in their 'fundamentals' classes to verify or direct design decisions. This frustration may be because:

1. Students are unable to create a map between the complex and/or incompletely defined design situation (both hallmarks of design!) and simplified analysis models they have learned. Prior coursework may not have adequately illustrated the procedures and techniques for decomposing a complex problem into a form that maps to an analytical model.

2. Students see that simplified models may account for only a subset of relevant factors, and therefore totally discount the models' value. Students also fail to see the potential value of approximate models in looking at general trends.

3. Students are unable to plan a design and development strategy that uses simplified analysis models in conjunction with other engineering tools (e.g. experiments, simulation) to predict product performance.

4. Students are unable to utilize and/or recognize the need for ‘qualitative analysis procedures’ and ‘analytic reasoning’ throughout the design and development process.

5. Students are given inadequate time to complete a design project, particularly if the project requirement includes a hardware demonstration. It has been my experience that students will generally default to a cycle of ‘build-test-build’ rather than a cycle that includes analysis if project time is short and/or

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there are not explicit analysis requirements associated with the design task. Unfortunately, since they have not learned an alternative strategy to ‘build-test-build’, as students, many engineers in industry follow this same pattern when confronted with time pressures. While this list may sound like a criticism of student abilities, it is not intended as such. It is rather offered as a criticism of how students are taught to utilize analysis tools.

THE DESIGN EXERCISE

The participants in the Harvey Mudd Workshop were almost all experienced design engineers and/or engineering educators with backgrounds in teaching design. In order to tune them into the issues listed above, and facilitate discussion among them on the compatibility (or incompatibility) of today’s approaches to teaching analysis and design, the participants were engaged in a 30 minute design exercise. This design exercise occurred during the opening noon session of the Workshop. It was followed by a post-exercise discussion that lasted about one hour. In this section, details of the exercise are outlined. In the next section, observations and comments from the post-exercise discussion are presented.

The design exercise was crafted to meet several high level objectives; including that it serve as an ‘ice breaker’ for the workshop; serve as a ‘reference’point for subsequent papers being presented on student design experiences; and (last but not least) that it serve as a springboard for further discussions on the integration of analysis and design in undergraduate engineering classes. From an engineering perspective, the exercise should present a challenge that:

4) pleasing to look at.

5) as small a mass as possible, since the structure will be constructed off site, then trucked into the Valley for final installation.

6) construction materials: 1 standard deck of playing cards, 1 roll of tape, a pair of scissors.

7) the final structure must contain the roll of tape and the pair of scissors.

8) completed construction in 30 minutes. This may seem like a short period, but given that the life span on a Bear is only 2 days, there is no time to waste!

9) a two minute client presentation, where the design features and rationale are discussed (overhead and pen supplied)

<table>
<thead>
<tr>
<th>Item mass (grams)</th>
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<tbody>
<tr>
<td>Card Box = 5.13</td>
</tr>
<tr>
<td>1 Card = 1.63</td>
</tr>
<tr>
<td>5 Cards = 8.15</td>
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<tr>
<td>10 Cards = 16.30</td>
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<tr>
<td>15 Cards = 24.45</td>
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<tr>
<td>20 Cards = 32.60</td>
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<tr>
<td>25 Cards = 40.75</td>
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<tr>
<td>30 Cards = 48.90</td>
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<tr>
<td>35 Cards = 57.05</td>
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<tr>
<td>40 Cards = 65.20</td>
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<tr>
<td>45 Cards = 73.35</td>
</tr>
<tr>
<td>50 Cards = 81.50</td>
</tr>
</tbody>
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There is no doubt that the design exercise was provided to make an impact. It is also clear that the participants left the Harvey Mudd Workshop with a different set of challenges. The exercise is an example of how a well-constructed design exercise can be used to facilitate effective teaching and learning.
interpret/define design ‘intent’ and deal with trade-offs.

The actual exercise given to the Workshop participants is presented in Table 1. A single set of materials (i.e. playing cards, tape, scissors, etc) was supplied to each team of four. Most teams were self-selected based on who they were sitting with at lunch. One team member served as the ‘observer’ for the team, and used a pre-defined framework for making and recording observations on his or her team’s design activities. The ‘observer’ was not to participate in the design activities.

During the exercise I served as a consultant, answering clarification questions posed by participants, and as a timekeeper. In addition, I wandered around the room, making my own observations on activities.

OBSERVATIONS

The post-exercise discussion by participants, observer notes, and my own observations made during the exercise are summarized below. I will qualify this summary by saying that it is not intended to be comprehensive, and reflects some of my own biases regarding design, analysis and education. I have organized the summary around the goals of the exercise:

- Design challenge that is attainable (but just barely) within the time frame of the exercise. Most of the eight teams felt pressured for time. All started building a tower within 15 minutes of the start of the exercise. None of the teams asked to try out the ‘wind load’ on their design during the 30 minutes design period. (I have run a similar exercise with numerous groups, ranging in age from 10 to 70; it has been common for several groups to ask to try the hair dryer out to ‘get a feel’ for how much air flow will be involved in the ‘wind loading.’) In spite of this, all of the final designs did meet the ‘wind load’ requirement (in some cases by use of external guy wires to the table top). All designs also met the height requirement. It is not clear if all of the teams had created an overhead for presenting their design to their client (as required in the design specification); those that did, were creating it in the last minutes of the exercise. Most teams were observed to have members working in parallel (e.g. one member cutting cards, another taping them, and a third member assembling them) during the second half of the exercise.

- Design challenge that has multiple solutions, none of which is obviously ‘best’. The skyscraper solutions varied from a single cylindrical tower, to a triangular-interlocking modules, to a design based on a ‘wedding cake’ metaphor. While there was considerable design variation across groups, it is not clear how many design concepts were considered within a particular group. One team commented that very early on in the exercise, each team member shared their image of the design (e.g. ‘I picture it looking like the Transamerica building in San Francisco’). Another team took the first few minutes of the exercise to read the design requirements out loud and inventory the materials before focusing on one design concept (they worked on refining and implementing this concept for the rest of the period). Another group jumped onto a single idea from the beginning. Still another team ended up modifying a design that they had been working on for most of the period during the last few minutes when it became clear that they would not finish construction before the end of 30 minutes.

- Design challenge that allows (and even encourages) unconventional thinking. The exercise seems to be ‘off-the-wall’ enough to encourage unconventional thinking; there is certainly ample room for creative interpretation of what the needs are of gummy bears! After one team was assured by me that it was OK to cut and bend the playing cards, they went on to design a very unconventional skyscraper. It seems that a few people’s thinking was also challenged by thinking of construction elements (e.g. scissors, tape) as engineering (e.g. counterweights) and aesthetic elements.

- Design challenge that has a context. The skyscraper has a reason for existing – to serve the citizens of Bear Valley. While this is certainly ‘fanciful’, it provides a context or ‘story’ for the design. One team may have been put off by the overall ‘playfulness’ of the exercise; they complained about the imprecision of the design criteria, and expressed frustration with the materials. Their reactions point to one of the challenges in designing a design exercise – how to achieve a balance of design challenge, use of engineering principles, and fun!

- Design challenge that has goals that are testable and quantifiable. The exercise had some requirements that were ‘testable’ (e.g. stands-up during the ‘wind load’) and that were quantifiable (e.g. mass, height). There was some confusion expressed by participants on the mass requirement; was the intent to minimize mass or produce a minimum mass design? In addition, none of the participants used the mass table that was provided to all design teams to aid teams in making quick mass estimates. This may have been because the table was on the back side of the assignment sheet and they did not see it.

- Design challenge that has enough ambiguity to require the designers to interpret ‘intent’, choose their own focus, and deal with trade-offs. All teams focused firstly on achieving the height and wind load requirements. There was variability as to which requirement was selected as the next priority; most chose mass, but a few chose to focus on the aesthetics and ‘usability’ of the skyscraper by gummy bears. Several teams
found the words ‘contained’, and ‘portability’ in
the requirements to be ambiguous, and asked
clarification questions during design.

Overall, the design exercise seemed to achieve its
high-level objectives and engineering level goals.
That certainly does not mean that participants did
not have suggestions for its improvement. For
example, it was recommended that ‘portability’
be defined in the exercise description, the verbiage
of the exercise description be reduced, and that the
time for the exercise be longer. In addition, partic-
pants felt that the framework that the observer
was required to use in making and recording
observations was too complex. Several observers
also expressed frustration at not being allowed to
participate in the design.

IMPLICATIONS

What are the implications of this exercise to
analysis and its role in design and design educa-
tion? Certainly the post-exercise conversation with
the participants and my own observation of their
work strongly suggest that there are a number of
analysis-type activities that design engineers
engage in. Two will be discussed here. One of
these I refer to as conventional analysis which
involves formal modeling of a system. The
second type I refer to as improvisational analysis.

Conventional analysis involves extraction of
basic elements from a design. This is the type of
analysis whose results are commonly reported in
the appendix of a design report. Furthermore, this
is the type of analysis that is often taught in
engineering science courses. Conventional analysis
is particularly relevant when:

• the questions being asked about a design are not
easily addressed by experiments (e.g. experiment
too costly, will take too much time, or is not
physically possible);
• the criticality of the design is such that analysis
(often in conjunction with experiments) is
imperative; and/or
• there is incentive to optimize or justify the
design.

Little of this sort of analytical work was observed
in the exercise. One participant commented in the
discussion period, ‘Equations are something that
do people in private’.

I believe that in general, engineering education
does a good job of covering the basics of conven-
tional analysis. However, it is not clear that we
teach how to conceive and execute analysis in
conjunction with experiments, how to pose and
frame questions to be addressed through analysis;
or how to extract, define and verify an appropriate
model from a real engineering system. Dixon in
1964 [13] makes similar points in saying, ‘Recent
engineering graduates were criticized for unwilling-
ness to consider a complete problem such as a
design problem. Instead they showed a desire to
seek a fully specified problem which could be
answered by analytical methods.’ These deficien-
cies could in part be addressed in a series of
‘engineering problem solving’ modules spread
throughout the undergraduate experience; these
modules would focus on the application of analysis
methods to address engineering questions, as
opposed to being focused on the execution of
specific analysis methods. Doing this would put
conventional analysis into a context which might
better prepare student to employ it as part of
design. An example of one of these modules is
the freshman design course being taught by
Pionke, et al. [14]; learning and practice of engi-
neering science principles are integrated in designing
and building simple structures.

The second type of engineering analysis is what I
will call improvisational analysis. Some might call
this ‘back-of-the-envelope’ analysis, or ‘engineer-
ing estimation’ [15]. I use the word improvisation
(or improv. for short), as this word captures the
idea of ‘fabricating out of what is conveniently on
hand’ and ‘composing . . . extemporaneously’ [16].
Participants pointed out that this sort of analysis
‘behavior’ is grounded in a solid foundation of
conventional analysis and involves posing (maybe
not explicitly) questions that are addressed in the
‘heat of the moment’. Often the manipulation of
physical materials are used to analyze the situa-
tion. For example, a card may be bent, taped and
flexed about various orientations to address a
question about relative stiffness; or a rough esti-
mate of cross-sectional area might be done to
estimate wind drag. This form of analysis typically
leaves little written record. And this was the form
of analysis that participants reported using to
address questions about the performance of their
design ideas.

I believe that in general, engineering education
does not do a consistent job of covering improv.
analysis. We seldom model this behavior for our
students. Furthermore, there are few opportunities
for us to observe our students while they are amid
their design work; it is this sort of observation
that would enable us to assess and reinforce
their use of improv. analysis. These deficiencies
could be addressed by showing examples of the use
of improv. analysis in design; for example, a
videotape of a design team working might serve
as a venue for a class discussion on analysis. In
addition, creating a design studio environment in
which our students could engage in the work of
design would afford us the opportunity to observe
(and reinforce) student team behaviors related to
analysis. Kuhn makes similar observations in her
paper on the value of learning in an architecture
studio environment [17].

So is there compatibility (or incompatibility) of
how we teach engineering design and analysis? The
discussion above indicates that there is some
compatibility and some incompatibility. It also
indicates that there is a certain tension between
educating students to be good analysts and good designers. Our educational system has many elements that support our students becoming competent in both design and analysis. What seems to be missing are many opportunities for educating students to be good analysts and good practice the place of ‘design’ [18]:

... that is, in nearly every form of professional education, students perceive the practicum experiences as truly valuable, while barely tolerating the academic experience (theoretical preparation). The central feature of all professional education is indeed the tense relationship between theory and practice. It is an essential tension, as unavoidable as the tensions found within families whose members have become highly dependent on one another. It is a painful tension because theory and practice are not only competing conceptions. Different stakeholders in the social and political worlds exercise control over these domains, and any preferences given to theory over practice, or to conceptual mastery over technical proficiency, for example will have serious consequences for the future of institutions, the allocation of scarce resources, and the conferral of valued prestige.

This is from an article by Lee Schulman [18], president of the Carnegie Foundation for the Advancement of Teaching. Dr. Schulman was writing on the work of John Dewey. Dewey’s work (early 20th century) was focused on teacher education. It is interesting how accurately the quote describes the tensions and challenges of engineering practice and education as we approach the year 2000. It gives us pause to reflect upon the (possible) desirability of the tension An exploration of the tension between theory and practice in the professions of engineering, medicine, law, social work, and the clergy is part of a larger study currently underway at the Carnegie Foundation for the Advancement of Teaching [19]. And it gives us time to think of ways to work with it, as suggested by Dixon [13]:

I think engineers who must resolve the apparent invention-analysis dichotomy should try to avoid settling out on a spot somewhere midway between the two extremes. We might better be a little schizophrenic about this and try to find a way of switching rather completely from one kind of thinking to the other as needed.

Creating an engineering education system that supports and encourages this flexibility is quite a challenge.

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REFERENCES

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