Design Projects for Mechanics Courses

Nicholas J. Salamon and Renata S. Engel

The Pennsylvania State University

Abstract

In teaching undergraduate mechanics, it is important to regularly relate the theory to applications in a meaningful manner. We believe mechanical design is the most important and convenient application to employ for the following reasons: (1) it closely follows the mechanics theory, (2) it requires an understanding of the theory, (3) it introduces markets and mechanical technology to students, (4) it connects students with information available on the Internet and in libraries and (5) it broadens their world view of engineering through human factors, reliability, environmental, international diversity and other concerns. In this paper we select one student design project from an introductory strength of materials course and show how these reasons, when converted into course objectives, are met. The positive outcomes are clear in that students learn far more than analysis. Less clear is whether 'learning by doing' motivates and enables all learners. The negative outcome is that such a full-featured course is not for every student. Some simply cannot put abstract equations into practical use; others find it difficult working in teams. We summarize these and other challenges to implementing a design-based curriculum in undergraduate mechanics courses.

I. Introduction

Very few undergraduate students of the current generation are receptive to rote learning of the science and mathematics of engineering subjects. Today's students, raised from childhood to ask 'why', demand to know why they are learning what is being taught. This liberalization in learning is standard procedure in secondary schools. Indeed in this 'information age', we need to know 'why' in order to evaluate and filter out what is to be retained from the glut of information available. 'Why' is part and parcel to the contemporary emphasis on *learning* rather than *teaching* in higher education. In part, it has prompted questions about the effectiveness of the traditional lecture for the learner and has led to a revolutionary change in engineering education. This change is manifested in the *what*, *why* and *how* of teaching and learning. (This is a slight variation of the "learning cycle" in figure 2 of ref. 1.)

A. What and why?

What is new about learning engineering? We summarize below a few of the common goals of engineering education and provide a reason why they are important.

- Learning the theory, science and mathematics underlying an engineering subject in order to model phenomena.
- Learning the application of theory in order to understand its purpose in engineering.
- Learning to gather, filter and sort data in order to use it meaningfully.
- Learning skills to work in teams, develop a coherent plan, organize and subdivide a project, formulate solutions and make decisions in order to write reports and communicate results.
- Learning how a course fits into the broad scheme of engineering in order to plan a career.

B. How? (Is Learning Accomplished)

How is learning accomplished today? Here we list common modes of teaching and learning practiced in the contemporary engineering classroom.

- Lecture: although de-emphasized, it remains the most efficient means of disseminating information.
- Learning through practice in the classroom rather than outside of it.
- Learning by relating concepts together as in concept maps.
- Learning by doing projects—team or individual.
- Learning through hands-on activities.

Teaching and learning today involves some combination from these lists (which are not intended to be complete). On the one hand, it is similar to the curriculum of post World War II which included both theoretical and practical aspects of engineering, however it did so through separate and unequal courses and the delivery was authoritarian. During the 1970's and 80's, this curriculum evolved into one with little practicum due primarily to growth in class size. On the other hand, today's curriculum is evolving toward an integration of theory and practicum[2-4] within the same course. Not only is the delivery much more open and interactive but the student engagement has changed to include other pedagogical approaches such as demonstrations, group work, and computer-based exercises[5]. As it was then, learning includes development of the skills to do engineering, but now it also includes understanding of the integrated, holistic process of engineering. Moreover, students must demonstrate these skills as particular outcomes of a course, aside from the overall grade, or as outcomes of the curriculum. Finally, today's curriculum expects formal presentation of goals, rubrics for grading, and the principal outcomes expected.

One vehicle to use to implement some of this new thinking on teaching and learning is the design project. In mechanics courses, this is particularly useful because it relates the theory to applications in a meaningful manner and is comprehensive: (1) it reinforces understanding of the theory, (2) it introduces markets and mechanical technology to students, (3) it connects students with current information sources, e.g., databases codes and standards, manufacturers and suppliers, and (4) it broadens their world view of engineering through human factors, reliability, environmental concerns, international diversity and ethics and responsibility. In short, design projects provide a means to bring modern pedagogy into the mechanics curriculum and plug mechanics education into the engineering mainstream.

In this paper we focus on teaching and learning through a design project in introductory Strength of Materials with Design (SOMD). After setting out the learning objectives for a design project, we summarize the primary milestones employed so that learning occurs in steps and so that the eleven-week-long project remains on schedule. Highlights of student learning are annotated by actual student work. This is followed with a sampling of typical projects: as assigned and student solutions. In the conclusion, we address the outcomes achieved, both positive and negative. It should be noted that the ideas presented here can be implemented in other engineering courses and are not limited to mechanics.

II. Design Project Learning Objectives

The learning objectives for a design project in SOMD are:

1. Students will be able to apply the theory and analysis methods to size a structural component with respect to strength and deformation.
2. Students will be able to plan, organize, work in teams and execute component design of a simple structure.
3. Students will be able to find data, standards and codes relevant to design of a structural component.

It should be noted that the emphasis here is on design of structural elements or ’component design’; it is neither on structural design nor the design of frames even though design objects fall into these latter categories. All design is done up to the limitations of introductory strength of materials. Of course this is only a matter of the level of sophistication of work; all engineering work is subject to some cap on knowledge.

These objectives are compatible with the traditional strength of materials course objectives, primarily: *students will be able to analyze the linear deformation modes: axial, bending, torsion, plane stress and buckling.*

III. Project Milestones

Project milestones commence with assignment of the project and end with submission of the final design report ten to eleven weeks later. Milestones serve to keep teams on schedule and insure that they learn in a sequence of steps how to do the design. In this section, we address important features of milestones leading up to the final submission.

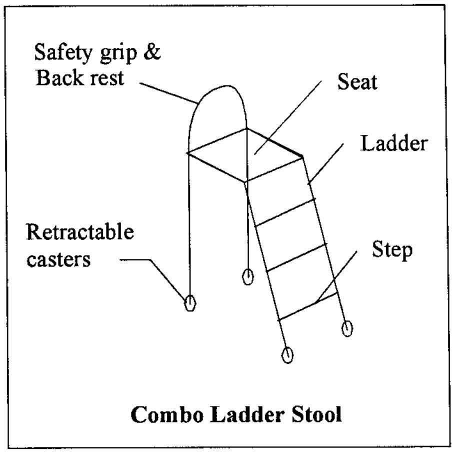
A. Design Project Assignment

The design project begins with assignment of the problem by the instructor who, acting as the *client*, requests design service from the students who act as design engineers. For second-year students, the assignment is reasonably structured in that key specifications are established, a systematic design procedure is taught and guidance is provided. Moreover, complicated design solutions are discouraged. A typical assignment, design of a combination ladder-stool, is shown in Figure 1 and its development will be followed through submission of the final design. (The illustrations and discussions pertain to work submitted by several student teams.)

Problem

Design a Combination Utility Ladder and Stool per the concept sketch shown. Key specifications:

- Dimensions to accommodate the 50th percentile range of U.S. adults.
- Load to accommodate the 95th percentile range for weight of U.S. adults.
- Height of the seat to be accessible for seating to the 50th percentile range of U.S. adults from the lowest step.
- Compact storage is highly desirable.
- Structural materials: metal is preferred, but plastic materials will be accepted if grip dimensions do not exceed specifications.
- Deflections must not exceed 1/64 inch under normal load.
- The set must ship disassembled and be able to be assembled using basic household tools.
- Safety factors are 1.3 for material yielding and 2.2 for buckling.



Design objective

The design objective is low cost, but not at a loss in appearance. (Costs are to be estimated using nominal retail prices.)

Special concerns

- Joints made by commercially available connectors must be adequate.
- Safety in general is a major concern. The Stool should be stable under normal use.

Figure 1. Typical design project assignment: Combination Ladder-Stool.

Fundamentals such as load and geometry are implicitly given: students find this information through research on data for people and/or equipment; guidance is provided on what is required and on how to go about doing this. In general, we prefer a design object that requires human factors research. For instance, the combo ladder-stool must accommodate U.S. adults in the 50th percentile range for geometry and 95th percentile for weight. Students are directed to the library and Internet to find data and often find new sources of scarce data, i.e., cost data. Furthermore, through classroom discussions, students may offer specific sources and make further suggestions. The instructor must facilitate these discussions in order to draw out ideas, concerns and unforeseen circumstances worth considering. In this manner, teams are guided and coached toward their goal. For the ladder-stool, a further specification added by students to the original assignment was weight of a package which might be carried by a person climbing the ladder. This additional specification requires further investigation into the maximum load an average person can carry. Often data is difficult to come by. Simple experiments may be performed. In this case, class discussion can lead to a range of reasonable values and how best to specify one, but student teams must make specific decisions on their own and support these decisions with rational and convincing arguments.

What is learned? Students learn that a wealth of technical information resides in the library and on the Internet. (Ironically, someone usually asks: "Where is the library?") They learn to double check information, especially if found in textbooks or on the Internet. They begin to discover that there is no one answer. Importantly, they begin to interact with each other on a technical level and with the instructor in the classroom. And they learn that the factor of safety for buckling is independent of any others.

B. The Concept Plan

The Concept Plan, collected one week after the design project assignment, launches the project and the design process. It is done first individually, then working from individual reports, condensed into a team plan; both individual and team plans are deliverables (submitted). The primary goals of the plan are to research competing products, determine primary applied loads to be supported, draw a concept sketch of the design, select major components for design, rank in order both material properties necessary to the design and candidate materials which comply with this list of properties. A form is provided to guide this effort.

Figure 2 is a sketch submitted by one student team. The ability to fold appears creative (it is certainly thoughtful; it was not specified by the client), but this may be a copy of a competing product. Overall it is stylized according to the client’s concept sketch. It is crudely done. Nonetheless, it is sufficient to initiate engineering design and exhibits thoughtfulness, in particular, note the safety grip in the upper sketch.

Although most teams conform to the client's concept, some are more adventurous and unique and interesting concepts can emerge. Alternatively, other teams have difficulty rendering their concept and some appear deficient in spatial acuity[6].

What is learned? Development of the Concept Plan requires the group to come together as a team and apply team organization skills learned in first year design. Hence, the project provides a degree of continuity of learning.

Researching the market for competitive products introduces the use of product catalogs and the Internet. By physical examination of a product, students learn about overall form, function, structural assembly and engineering materials. They may copy ideas, but not those covered by a patent, hence ethics and legal restrictions may arise in class discussions. Importantly, they may generate new ideas for design by noting deficiencies in competing products.

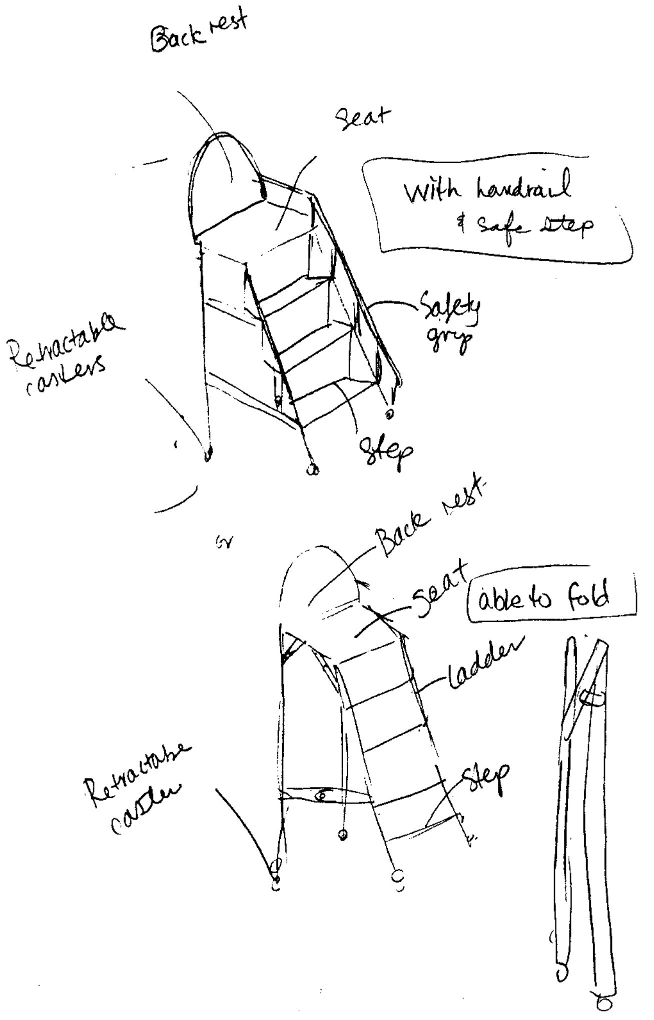


Figure 2. Student concept sketch of a combination stool-ladder.

Determination of primary applied loads requires study of how the product will be used (but the client provides specifications which set requirements to reduce this work) and research of anthropometric data, equipment and other loads that the structure must bear. Students learn where to find this data and how to use it. Most important, they learn that determination of loads is not a given, but an important engineering function, a concept most textbooks ignore.

Selection of major components for design requires application of statics to their concept. Selection of material properties requires an understanding of material strength, geometry and stiffness, the environment and resistance to it, and other properties. By ranking these in order of priority, students learn the physical meaning of properties and a valuable tool for decision-making. Statics is taught in a prerequisite course; fundamental material properties are taught 'just-in-time' in this course. Selection of materials is not taught, so students teach themselves with some guidance through class discussions (this may be viewed as an introduction to life-long learning).

C. The Status Report

The aim of the Status Report, collected three to four weeks after the design project assignment, is to bring all teams up to par. Deliverables include one part on modeling and design of a component (done individually) and parts on organizing task assignments and compiling data on materials and loads (done as a team). The primary goals of the plan are to insure: (1) that each team member knows the procedure for modeling, applying the theory, using data consistent within the team, and making design decisions, (2) that data is correctly compiled and interpreted and (3) that applied loads satisfy minimum client specifications and are reasonable. A form is provided to guide this effort.

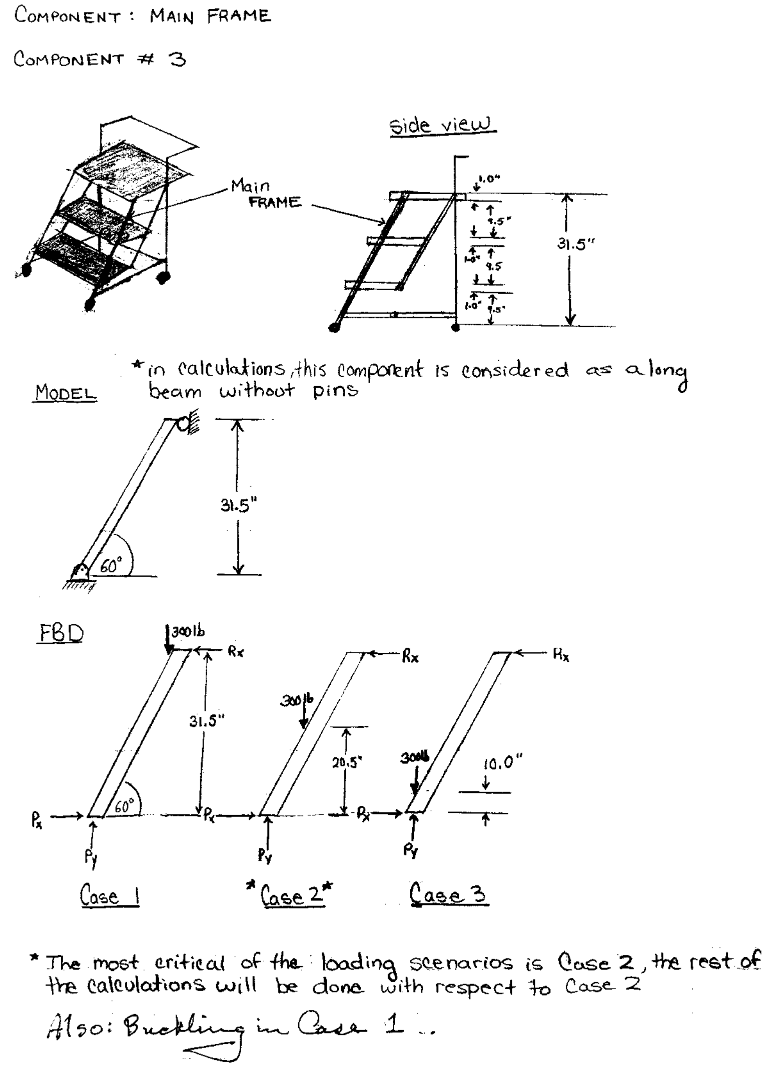
What is learned? Completion of the Status Report requires assignment of task responsibilities, compilation of data for use in all calculations and modeling and design of a component.

The assignment of task responsibilities follows a strict breakdown set by a Report Format which is provided to each team. Students learn that each task requires both a Leader and Workers. Since there are enough tasks, everyone must serve in both positions. Indeed leadership and followership are discussed in class and students learn that everyone must serve as a leader sometime. We suggest to the class that leadership is proactive volunteering for responsibility and emphasize that both leaders and workers are vital to success of the project. Everyone is responsible for communicating results to the team and knowing the rudiments of each task. The team is central; individual distinction follows team distinction.

In compilation of a materials data table, students learn the meanings of stiffness, yield, factors of safety and how to determine allowable stresses. Importantly, they learn how to contend with missing data. Completion of this table insures they know resources for raw data and how to interpret (consider for instance different notations used for strength) and use this data.

Compilation of anthropometric data insures an introduction to human factors engineering and appropriate design for both weight and geometry. For instance, the design of the seat in Figure 2 requires knowledge of the size of humans within a specified range. Similarly, this knowledge is required to size objects for grasping (the outer radius of the tube in Figure 3a) as well as to limit certain dimensions in order to discourage use of objects by over-sized humans.

Compilation of applied load data includes weight of humans (listed above) and that of equipment and other objects. Notably, dead loads, which add nonlinearity to a design, are usually not necessary in most projects assigned.



*in calculations, this component is considered as a long beam without pins

* The most critical of the loading scenarios is Case 2, the rest of the calculations will be done with respect to Case 2

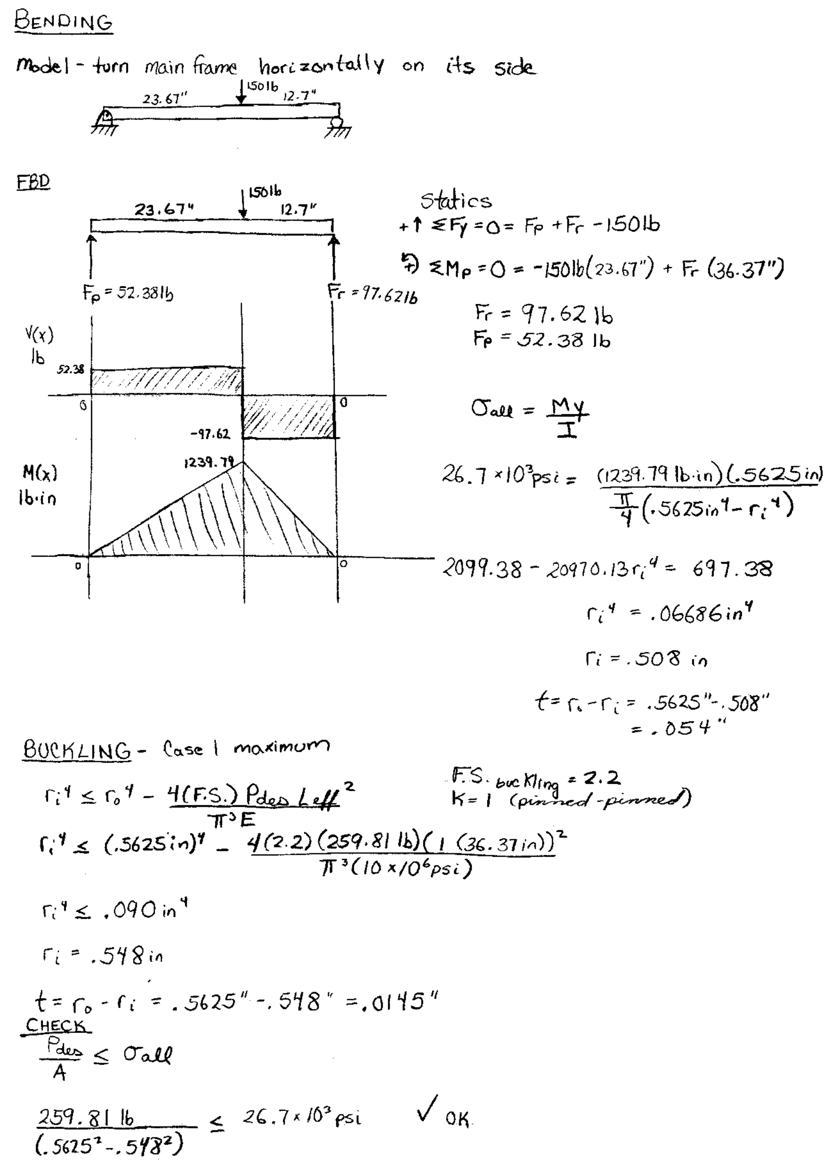
Also: Buckling in Case 1 ..

Figure 3a. Modeling and design of a component: Main Frame member, a round tube.

The heart of the status report is modeling and design of a component. Each team member must lead in design of at least one component. A sample for a frame component is shown in Figures 3a and 3b. (Note: this is extracted from a final report because it is similar to one in a status report, yet contains more detail of interest.) This procedure follows a strict format that begins with illustration of the component *in situ* and then a model. The model sets up the component for calculations using idealized boundary conditions: it is now typical of illustrations for problems in engineering textbooks. Students learn that textbook models can deviate considerably from reality and it takes some insight, experience and intuition to create a good model. Next comes free body diagrams for each loading scenario: in Figure 3a the applied load is placed at three plausible locations. Students learn to rank order these scenarios so that for each mode of behavior, only the worst cases need be treated. In Figure 3b, only two (out of several) design analysis calculations are presented: (1) bending strength, which is used to determine the inner radius of the tube, and (2) buckling, which in this case is used to check stability of the member. (In an actual status report, treatment of more than one or two scenarios (axial and bending) would be unusual because the report is due prior to covering buckling, deflection and torsion.) Clearly students learn to apply the theory in a comprehensive fashion; specifically, they learn to model, rank order, and size members to satisfy allowables.

D. The Preliminary Report

The Preliminary Report, collected six to seven weeks after the design project assignment, should contain all or most of the sections required in the final report. (A Report Format is provided to guide report organization.) The goals of the Preliminary Report are to keep teams on schedule, supply them with information on the quality of their report and provide them with another team's report for comparison with their own. (It should be noted that each design should be unique.) At this stage in the process, all major components should be designed. Each team report is reviewed by another team who follows a form to guide their review. The reviewing team writes a critique of the report and transmits it to the team who authored the report. The instructor may also perform a cursory review of each report. Hence each team receives feedback on its report prior to final submission. Students learn the importance of clarity in report writing when they have to interpret what another team is trying to communicate.



BENDING

Model - turn main frame horizontally on its side

Statics

$+\uparrow \sum F_y = 0 = F_p + F_r - 150 lb$

$\circlearrowleft\!+ \sum M_p = 0 = -150 lb(23.67") + F_r(36.37")$

$F_r = 97.62 lb$

$F_p = 52.38 lb$

$$\sigma_{all} = \frac{My}{I}$$

$$26.7 \times 10^3 psi = \frac{(1239.79 \text{ lb·in})(.5625 \text{ in})}{\frac{\pi}{4}(.5625 in^4 - r_i^4)}$$

$2099.38 - 20970.13 r_i^4 = 697.38$

$r_i^4 = .06686 in^4$

$r_i = .508 in$

$t = r_o - r_i = .5625" - .508"$

$= .054"$

BUCKLING - Case 1 maximum

$$r_i^4 \le r_o^4 - \frac{4(F.S.) P_{des} L_{eff}^2}{\pi^3 E}$$

$F.S._{buckling} = 2.2$

$K = 1$ (pinned-pinned)

$$r_i^4 \le (.5625 in)^4 - \frac{4(2.2)(259.81 lb)(1(36.37 in))^2}{\pi^3(10 \times 10^6 psi)}$$

$r_i^4 \le .090 in^4$

$r_i = .548 in$

$t = r_o - r_i = .5625" - .548" = .0145"$

CHECK

$$\frac{P_{des}}{A} \le \sigma_{all}$$

$$\frac{259.81 lb}{(.5625^2 - .548^2)} \le 26.7 \times 10^3 psi \quad \checkmark \text{ OK}$$

Figure 3b. Modeling and design of a component: Main Frame member, a round tube. Example of analysis.

In Figure 4, the final result of the work evolving from Figures 1 and 2 is displayed. A distinctive feature is its simplicity. If it were not a copy of a competing product, its creativity could be attributed to the student team. Regardless, it is a nice design and learning took place.

IV. Typical Projects

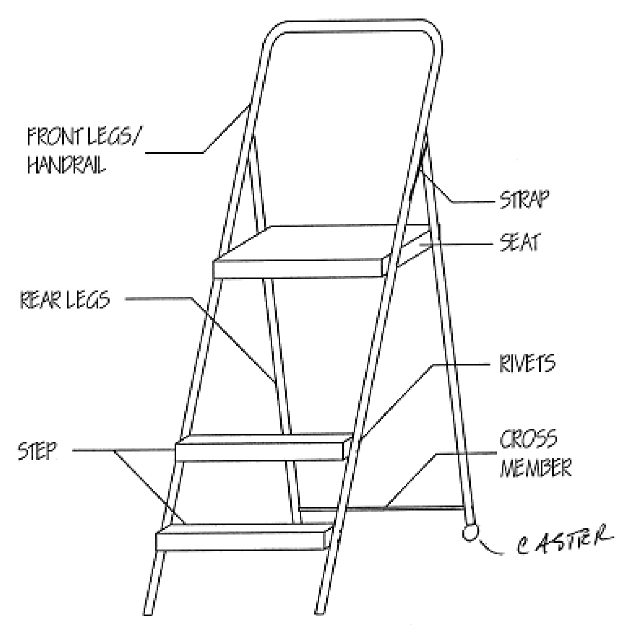


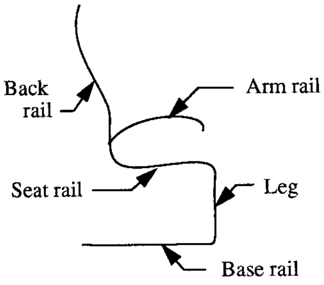
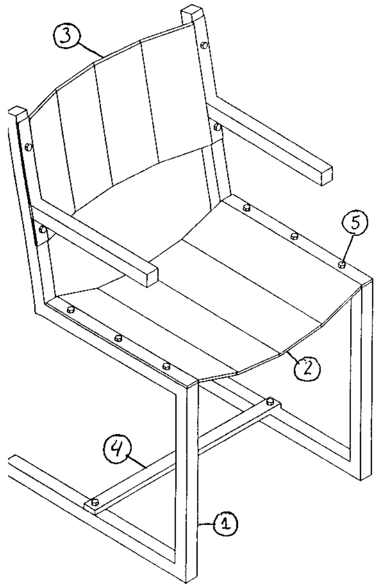
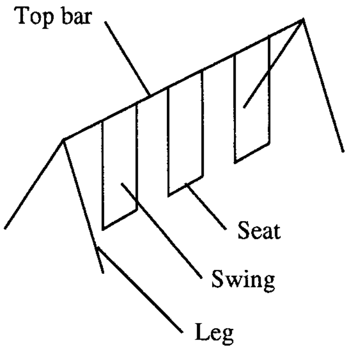
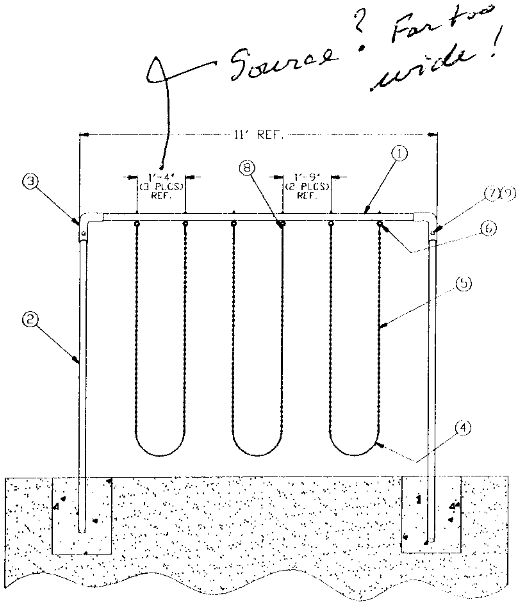
Figure 4. The final result of the work evolving from Figures 1 and 2.

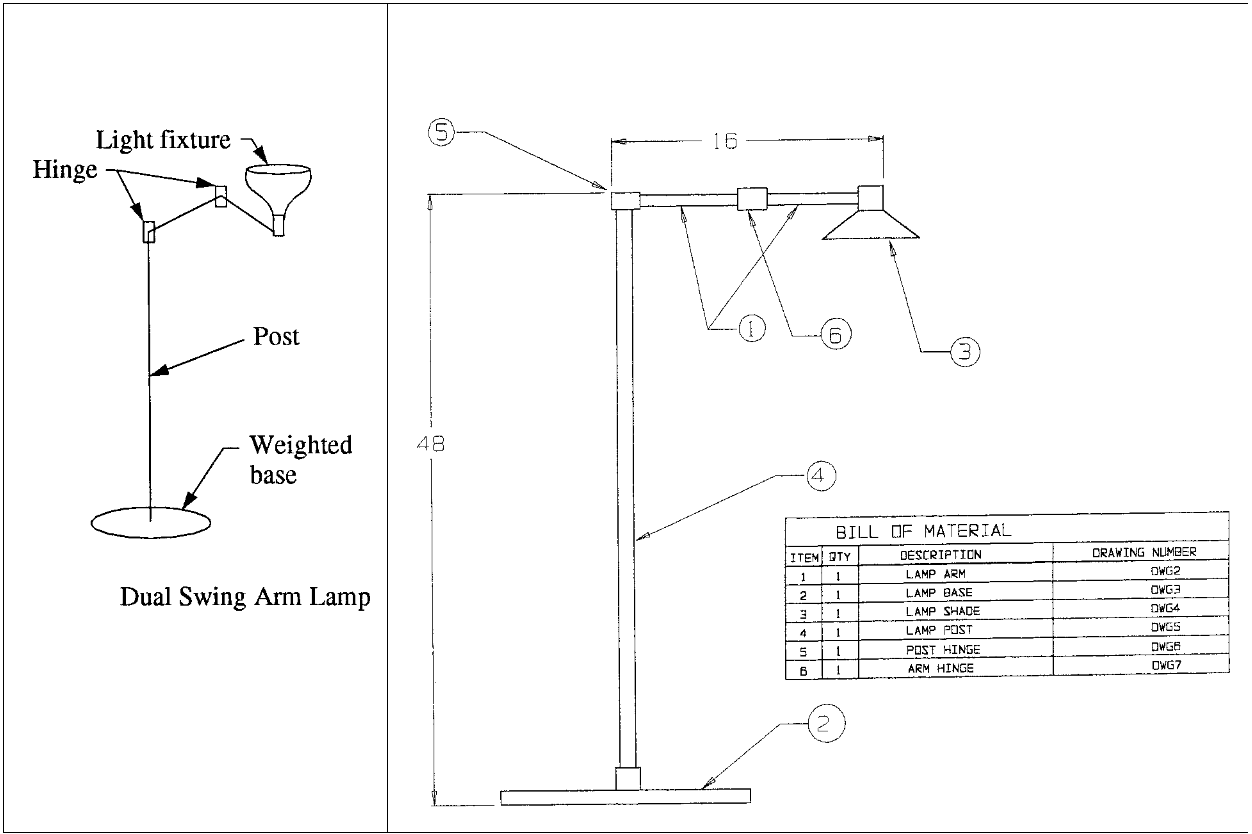
Three projects are shown in Figure 5, the client's concept on the left, a student team solution on the right.

The curved back and seat of the Deck Chair design is complicated. One simplification would be to use cloth, which requires strength data and this is not easy to find. Although the analysis of fabric is complicated and uses nomenclature unfamiliar to engineers, e.g., denier, it can be reasonably treated using approaches standard in strength of materials. A rational argument with some data to support it is sufficient. In addition, one may wonder what loads should be applied to member 4. A response might be in the form of questions: What if the chair was lifted by this member? …Or if lying upon its side, how might member 4 come under compression? …Or if someone were to step on this member…? It is particularly in situations like this that instructor guidance is most needed. But simplicity is a distinctive feature of good design. This provides a reason for discouragement of complicated designs.

Only one view of the solution for the Swing Set design, specified for children up to age twelve, is shown here, but the sides are two-legged as in the concept sketch. It is constructed of pipe. This solution even prescribes how the set is to be anchored into the ground. One error in the design is noted: the width of each swing is too wide to discourage an adult from using it, hence it violates a client's specification.

Almost all students found something of interest in the Lamp Design project because of the opportunity to address aesthetics, mechanical features, such as joints, and the general familiarity with the product. One solution was a Frank Lloyd Wright copy. The one shown here is specified to be of tubing; a few specified pipe. Several teams specified specialty brass tubing. How did we specify loads for a lamp? Well, what if a child was to hang from it? Hence we again require anthropometric data. This project required calculations for tipping instability and safety was a major issue. Students were expected to design for a reasonably large critical tipping angle. We include the 'Bill of Material' to show the extensive detail some teams get into: instructors must also discourage teams from getting carried away.

Concept sketch: Deck chair  	
 Concept of swing set	 Source? Far too wide!



BILL OF MATERIAL			
ITEM	QTY	DESCRIPTION	DRAWING NUMBER
1	1	LAMP ARM	DWG2
2	1	LAMP BASE	DWG3
3	1	LAMP SHADE	DWG4
4	1	LAMP POST	DWG5
5	1	POST HINGE	DWG6
6	1	ARM HINGE	DWG7

Figure 5. Typical design projects. Client's concept (left); Student-team solutions (right).

V. Conclusion

A design project offers significant enrichment to analysis courses and provides a catalyst for change in the delivery of instruction, one that encourages class discussions and increased interaction. Nonetheless, in mechanics, challenges remain to implementing a design-based curriculum. We conclude first with learning and then our choice for good design projects.

A. Learning Outcomes

The positive outcomes are clear in that all students learn more than analysis. They learn to apply mechanics theory and hence learn its purpose within the engineering process. They gain insight into the concept of modeling real structures, keeping assumptions to the minimum necessary. They learn to rank-order candidate materials and loading scenarios and to focus upon the most critical situations and then, after applying analysis, to make decisions.

Enrichment comes in the form of engineering skills and technical knowledge that students gain from doing a design project. They not only learn where the library is, they learn what is in it and how to use it. They broaden native skills on use of the Internet. Perhaps most important, they learn of the technological knowledge base, from human factors to cost data, and encounter situations which might otherwise not be addressed: safety, environmental, ethical, legal and diversity issues. And they learn to plan, organize and work in teams.

The negative outcomes add to the challenge. Two, which afflict a minority of students, are:

(1) Some students simply cannot learn the mechanics. To wit: Student A is failing a design version of the course and drops it the last day of the late drop deadline. (His team feels badly, but appears relieved.) Student A retakes a nondesign version of the course under the same instructor (by choice) and fails it. Such students usually, but not always, find the design project a burden.

(2) A very small minority of teams is dysfunctional. Realism is a double-edged sword: it provides great experience, but some students are too immature to let professionalism over-ride personality conflicts. If discovered soon enough, the instructor must intercede by breaking up the team and re-distributing its members.

It is our opinion that positive outcomes so overwhelm the negatives that a design project is a definite advantage in mechanics courses.

B. Choice of Design Project

The choice of a design project is influenced by the level of the course and the population of students who will do it.

For introductory Strength of Materials, the design object must be sufficiently simple to reasonably design it without reference to advanced theory, for instance plate theory or even complicated failure theories like the von Mises or distortion-energy theories. Our design theory employs no more than stress allowables, or maximum stress theories, and focuses on components within a system and simple connections. We instill in students that one never knows enough to rely on a virtual design as if it were the real object. The significance of knowing more, applying a more refined theory, is lower factors of safety. The design procedure, no matter how sophisticated in analysis, is more or less the same. For examples of design objects from the simple to more advanced, see the Granta web site[7].

The design object must relate to the population of students in the class. In our introductory classes, students come from most engineering disciplines, hence we avoid discipline-specific projects and try to choose generic objects: furniture, playground equipment, tools, etc. We also try to bring human factors into play because it introduces general and important design concerns and is an excellent subject for data research. Ideas for projects can be found in catalogs and hardware stores.

In closing, teaching design requires infrastructure. A start can be found at our web site[8].

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NICHOLAS J. SALAMON

Nicholas Salamon received a BS in Mechanical Engineering from Drexel University and degrees in Theoretical and Applied Mechanics from Iowa State and Northwestern Universities. After stints in industry, at NASA Marshall and in Saudi Arabia, he taught at The University of Wisconsin - Milwaukee and West Virginia University. His present work at Penn State is to instill in undergraduates the relevance of mechanics to engineering and continue with research in computational mechanics and its applications.

RENATA S. ENGEL

Renata S. Engel is an Associate Professor in the College of Engineering and the Director of the Schreyer Institute for Innovation in Learning at Penn State. She received a BS in Engineering Science from Penn State and a PhD in Engineering Mechanics from the University of South Florida. She conducts research in process modeling of fiber-reinforced plastic composites and powder injection compacts.