Reverse Engineering and Redesign: Courses to Incrementally and Systematically Teach Design

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ABSTRACT

A variety of design-process and design-methods courses exist in engineering education. The primary objective of such courses is to teach engineering design fundamentals utilizing repeatable design techniques. By so doing, students obtain (1) tools they may employ during their education, (2) design experiences to understand the "big picture" of engineering, and (3) proven methods to attack open-ended problems. While these skills are worthwhile, especially as design courses are moved earlier in curricula, many students report that design methods are typically taught at a high-level and in a compartmentalized fashion. Often, the students' courses do not include opportunities to obtain *incremental* concrete experiences with the methods. Nor do such courses allow for suitable *observation* and *reflection* as the methods are executed. In this paper, we describe a new approach for teaching design methods that addresses these issues. This approach incorporates hands-on experiences through the use of "reverse-engineering" projects. As the fundamentals of design techniques are presented, students immediately apply the methods to actual, existing products. They are able to hold these products physically in their hands, dissect them, perform experiments on their components, and evolve them into new successful creations. Based on this reverse-engineering concept, we have developed and tested new courses at The University of Texas, MIT, and the United States Air Force Academy. In the body of this paper, we present the structure of these courses, an example of our teaching approach, and an evaluation of the results.

I. INTRODUCTION

In all of the material that is considered to comprise an engineering education, no subject is more enigmatic than design. Indeed, the very term "design" defies a common definition amongst engineering educators. Some represent it as a "creative, intuitive, iterative, innovative, unpredictable"[8] process, a "compound of art and science,"[1] that by its very nature cannot be fully described or explained. Others, eschewing such a nebulous definition, choose to think of it as a method of solving open-ended problems that is "a sub-set of the decision-making process in general."[18] Despite the varied definitions, however, virtually everyone acknowledges the unique nature of "designing" and agrees that "design, above all else, defines the difference between an engineering education and a science education."[16] Design, however we define it, represents the bridge between theory and reality. It is the process by which our ideas enter and influence the world around us. In short, "designing" distinguishes us as engineers.

Considering the variance in its very definition, it comes as no surprise that little agreement exists over how to teach design to undergraduate engineering students. Yet we must. One approach that has proved successful is teaching students a structured, problem-solving method that they may use to tackle open-ended design problems. Of these methodologies, four of the most popular are those of Otto and Wood,[75] Pahl and Beitz,[29] Ullman,[42] and Ulrich/Eppinger.[52] Indeed, many of the papers reviewed here base their teaching methods upon one of these three. Yet even if the overall methodology is the same, the specifics of the various ways engineering design is taught vary substantially. Given this diversity, the questions arise: what underlying deficiencies exist in current design education, and what new approaches can we recommend to address these deficiencies and fulfill our roles as engineering design educators?

In this paper, we answer these questions based upon a new approach for teaching engineering design methods,[43] that of *product evolution* or redesign. As with any design problem, redesign includes the process steps of understanding customer needs, specification planning and development, benchmarking, concept generation, product embodiment, design for manufacturing, prototype construction and testing, and production. Yet, redesign also focuses on an additional and critical step, referred to here as r*everse engineering.*[43,53] Reverse engineering initiates the redesign process wherein a product is predicted, observed, disassembled, analyzed, tested, "experienced," and documented in terms of its functionality, form, physical principles, manufacturability, and assemblability. The intent of this process is to fully understand and represent the current instantiation of a product. It is here, through this process, that we can impact design education. By providing reverse engineering projects and new techniques to support the projects, we can provide concrete experiences for students as they learn design methods. No longer will students face a blank drawing board as they encounter their first design experience, but they will have clay they can mold, test, and refine. No longer will students be asked to experience only a single capstone design with no chance at observation and reflection, but rather can incrementally experience a design process and observe and reflect on each step (with a previous existing product) to compare their results.

The following sections build on our theme of reverse engineering and redesign. We first summarize a number of recent advancements in the teaching of engineering design methods, followed by our approach, its implementation, and an assessment.

II. RELATED WORK

A wide variety of methods for teaching engineering design are in use today. A review of papers from a number of universities, both domestic and international, reveals several interesting techniques, summaries of which follow.

In response to the suggestion of ABET that design be integrated into all portions of the curriculum, a number of universities have begun introducing more "design-like" problems into their undergraduate analysis courses taught to freshman and sophomore students.[7,18,23,31,2,3,13,6,15,26] One particular example is Miller's work at the Massachusetts Institute of Technology.[20,21,22] Miller has developed approximately a dozen small, hour-long, hands-on, design-like exercises that aim to give sophomore engineering students a feel for some of the engineering concepts they have learned in theory. While the material tested well in development, actual implementation in MIT analysis courses has been limited. Other approaches to using design early in the curriculum include the Tip-A-Can project described by Freckleton of the Rochester Institute of Technology,[9] and the well-known 2.70 course at MIT developed by Flowers and West.[48] These courses embody the "best way to learn design is to do design" philosophy championed by Flowers,[48] Ullman[42] and others.

A number of researchers suggest design projects that differ from the usual industrial product design projects seen in academic courses.[51,36,10,14,32] Furman of San Jose State University encourages his students to choose their own design problem.[10] He notes that "students learn the most and produce the best results by working on something they are personally interested in." His students have rewarded him with numerous projects, from a prosthetic knee joint to and a hands-on exhibit for the San Jose Children's Discovery Museum. Puett at the United States Military Academy (USMA) worked the problem of limited teaching resources by designing a course with LEGOs at its heart.[32] Working with Ullman's design text,[42] Puett's students are required to progress through three phases: specification development & planning, conceptual design, and product design. Every design team has a hypothetical budget that must be used to "purchase" LEGO pieces, and each type of piece has a set cost associated with it. Further, teams can only purchase their LEGO parts at three specified times during the semester. Puett notes that this forces the teams to "work in a constrained design environment in which cost is a realistically important consideration." At the end of the semester, the LEGO devices compete in a competition of sorts. Along the way, they make use of methods such as quality function deployment (QFD), design for manufacturing (DFM), design for assembly (DFA), concurrent design, and the theory of gears. The benefits of using LEGOs to teach design are best summed up in Puett's own words: "They allow design students to fully appreciate, experience, and internalize all phases of design—right through the construction, testing, and refinement of an actual product." They help to "teach design by doing design." On the other hand, LEGOs are artificial, commercial products that we strive to make our students adept at designing are not made of LEGOs, and so there remains a gap the student must traverse.

One technique that is popular with educators is incorporating "hands-on" projects into engineering courses.[49,2,5,14,25,34,35,38] A new effective approach is to use *mechanical dissection*.[2,5,14,25,34,35,38,27] The underlying philosophy is explained in the paper "Mechanical Dissection: An Experience in How Things Work," by Sheppard of Stanford University.[38] The basis of the philosophy is to provide a fun experience for the students, to get them to probe the working principles of a mechanical system, to understand it hands-on, and to motivate them to stay with engineering as a course of study. Such mechanical "tinkering" courses give beginning engineering students the exposure to industrial products. Sheppard has subsequently extended her work to include multimedia aids to help her students in dissecting a bicycle,[34] and she has also developed mechanical dissection classes for pre-college students.[39]

The use of mechanical dissection, however, is not confined to introductory engineering courses. Garrett at Grand Valley State University has developed a course for seniors that uses the dissection of mechanical devices to teach Design for Disassembly and Design for Recyclability techniques.[12] His students dissected and subsequently recommended design changes to a hand-held electric mixer and a toaster. Gabriele of Rensselaer Polytechnic Institute has also instituted a "reverse engineering" course.[11] He alternatively defines reverse engineering as "the in-depth study and analysis of an existing product to recreate the design decisions and information developed by the original design team." During the first half of the semester, teams of students dissect an industrial product, learn how it works, justify the decisions of the original design team via analysis, and then present their findings at the mid-point of the semester. During the remainder of the course, the teams are expected to redesign the product to achieve a given goal. Gabriele notes that the course helps students "realize that considerable effort and ingenuity goes into the design of every engineered system." Rather than focus on the tear down and design analysis, however, we feel it is also important to emphasize the redesign and improvement of the product. This also necessarily requires customer and function analysis, and then application of this to new design generation.

Nonetheless, these sentiments allude to what we feel is a true benefit of reverse engineering a product: it allows the engineering student to witness a physical creation that is the result of a design process they are being asked to learn. Just as many times students may learn by reading the solution to a homework problem and working "backwards" through the solution, it may be beneficial to show students the culmination of the design process, and allow them to work backwards through the steps to achieve a greater understanding. Furthermore, allowing students to work with a physical product while learning design eases the transition from the analytical courses they have taken previously to the open-ended nature of the design courses they are currently taking. Engineering educators should be sensitive to the difficulty that many students may have in making that transition. They should also be sensitive to the different learning styles of the students. "Arguably, the self-discovery obtained in surmounting a large design problem has its educational benefit. However, the enormous expenditure of time often frustrates the student. The students do not view design as a natural outgrowth of analysis, but as a new technique completely independent of their preparatory analysis problems".[41]

Many other articles have been written concerning methods for improving design courses, including recent works by Evans, Harris, Moriarty, Wood, and Koen.[54,56–58,61,28,76,77] The reader is referred to Dutson,[59] which focuses on capstone courses but is also relevant to lower level design project courses. A narrower branch of this effort to improve the teaching of design includes those that have attempted to take learning styles into account when structuring a design course. A brief overview of this work is given in Felder.[55] Examples of the broad range of applications of learning theory to design, as well as to engineering curriculum in general, include applications of the Kolb model,[60] use of the Piaget's model of early learning,[62] and incorporation of the Felder-Silverman Learning Style model.[63] In addition other notable work exists in.[70–75]

This review provides some insight into the current state of design education. The pendulum of engineering education has swung all the way from the extreme practicality of the apprenticeship programs prevalent early in this century to the extreme theory taught in later decades to engineers who were encouraged to be "applied scientists." Currently, however, particularly in design education, educators seem to be questioning whether the lack of hands-on experience may be harming their students' educational experience. Many schools are striving to include more concrete experience in both their theoretical and design courses. A cause for concern, however, is whether the inclusion of hands-on projects will fully solve the problem. Today's educational system is a far cry from the craftsman/apprentice system of old. Students today cannot simply be given a product to dissect and be expected to learn. If such dissection projects are used to teach design, they should be coupled with structured methodologies that serve to focus the students' efforts. Ideally, a balance can be struck between concrete and theoretical experience that will ultimately serve the best interests of the students.

The following sections detail our own approach to introduce structured, "hands-on" projects into the design education experiences at MIT, UT-Austin, and USAFA. We build on the themes and innovations discussed in this section to design new courses for our students.

III. PAST COURSE STRUCTURES AND HISTORIES

For the purpose of context, one must consider the history of the course sequence structure of past design-methods courses at MIT, UT-Austin, and USAFA. In many cases, the structure pertains to the initial creation of the course in the engineering curriculum, usually within the last one or two decades. We believe that this brief context is reminiscent of experiences at many other institutions. While a full description of this course history is desirable, space limitations allow only for a high-level, skeleton roadmap.

Beginning with MIT, no freshman design experiences exist in the ME curriculum. Instead the focus is on a sophomore-level introduction course (emphasizing the fabrication of a miniature Stirling engine, as developed by Hart and Otto[50]), followed by a number of courses that provide design experiences. These later courses include a sophomore design competition course,[49] a set of design electives, and a senior-level Product Engineering Process course, operating on the principle of large groups and all stages of product development.

At UT-Austin, four courses are of particular interest here: a freshman introductory course to mechanical engineering, a senior-level design methodology course, a graduate-level engineering design course, and a graduate-level product development and prototyping course. The freshman course, historically, has either focused solely on a design-competition project, or on an introduction to the field of mechanical engineering through presentations by faculty. After completing the freshman design introduction course and a significant percentage of their major engineering courses (perhaps including design electives), the next required design course was a senior-level design methodology course. Simple design competitions and academic study of design techniques drove the course material. The remaining relevant courses in Mechanical Engineering at UT-Austin include two graduate courses, the first on engineering design theory and techniques, and the second on product development and prototyping. Students taking this course were interested in graduate-level knowledge on the genesis, mathematics, and empirical basis for contemporary methods. The obvious need existed, however, to provide diverse exercises to apply the techniques, without detracting from the time needed to achieve a successful product. Reverse engineering showed great potential to address this need.

Finally, the USAFA courses have a similar historical background and set of needs. During the early 1990's, the USAFA design course (a sophomore-level introduction to engineering design) emphasized contemporary design methods following the mechanical design process described by Ullman.[42] While the general course material, including a design competition, and creativity exercises (called WHIPS) usually received high ratings, students evaluated the design methods with mixed or low reviews. Typical responses stated that the material was taught at a very high level and in a compartmentalized fashion. Clear relevance and hands-on experiences to deal with abstract topics, such as functional modeling and quality function deployment, simply did not exist.

A. Common Deficiencies in the Design Curriculum

Based on the literature review of student learning and teaching engineering design and based on the critiques and introspection of students and faculty at UT-Austin, MIT, and UASAFA as reviewed above, at least six challenges exist in the mechanical engineering design curriculum.

1. Following the learning cycle. Kolb's cyclic model of learning,[40,60] as composed of concrete experiences, observation and reflection, conceptualization and theory, and active experimentation, is typically only partly fulfilled in previous course structures. More hands-on emphasis with the ability to reflect and modify are critically needed to evolve the courses. This addition of hands-on emphasis also fits well with learning style advances using Myers Briggs Type Indicators,[64,65,37] Perry's learning model[69] and Bloom's taxonomy for learning.[68]

2. Extremely open-ended problems are difficult. They inherently require the development of a process to solve a sequence of more well formed problems. An effective teaching method is to

demonstrate by example, yet we don't do this effectively with a design process. As a first experience, providing a detailed design process for a student to follow might be effective.

3. Some students do not adapt well to having extremely open-ended problems as the first assignments they encounter. This is not necessarily because they have trouble with open-ended problems (intellectual immaturity), but because they lack the mechanical elements to use to fill in a blank sheet design. We desire, therefore, to provide an incremental development of design methods and solutions. We have found that students respond very favorably to reverse engineering projects, as it allows them an experience to learn about how things were designed. That being the case, we viewed reverse engineering and redesign as a cornerstone to enhance students' excitement and learning in the courses.

4. Design is an iterative process, and the teaching of design should reflect this characteristic. Most design courses progress to achieve a working prototype, and then stop.

5. Design should be fun to all (or at least interesting and intriguing). In the shock of beginning a new and different course, such as design, the students forget that what they are learning should be enjoyable. A new structure should further motivate the students to have a good time while they work.

6. Design modeling, analysis, and experimentation remain a frontier for teaching methods.[78, 79] While applied mathematics and science courses build the students' skills in analysis, a chasm still exists in integrating and bringing the skills to bear on a design problem.

With these six motivating factors in mind, we sought to develop and apply reverse engineering as a component in our design courses. A more detailed description is presented below, beginning with an overview of our reverse engineering process.

IV. THE NICHE: REVERSE ENGINEERING AND REDESIGN

A. Reverse Engineering and Redesign in a Nutshell

Our efforts to include mechanical dissection in our courses are based on the reverse engineering methodology presented in[43–47] and inspired by the aforementioned work of Brereton[4] and Sheppard.[38] Its goal is not so much to simply allow students the opportunity to dissect an industrial product (usually in the $10–$100 range), but rather to help the students understand the issues involved in embodying a conceptual product design at a hands-on level.

Figure 1 provides a brief summary of the ten-step reverse engineering and redesign methodology, as detailed in.[43–47] Three phases compose the overall structure of the methodology: reverse engineering, modeling and analysis, and redesign. The first stage of reverse engineering begins with investigation, prediction, and hypothesis of a product being redesigned. Through this approach, the product is treated, figuratively and literally, as a black box to avoid bias and psychological inertia. Customer needs and market analyses initiate the effort. After systematic prediction of the functions and principles that solve these needs, the reverse engineering phase ends with product disassembly and experimentation, wherein the product under study is dissected to understand its actual function and form. Design modeling and analysis follows reverse engineering. The intent in this phase is to fully understand the physical principles and design parameters for the product. Redesign completes the methodology with a choice of three avenues for product improvement: parametric, adaptive, and original.

To understand an example scenario in the classroom, consider the methodology depicted in Figure 1. The students are initially asked to predict how they think the product *should work* and gather customer requirements for later use in a QFD matrix (House of Quality, Engineering Specifications). They then conceptualize both black box and more refined models of the product's functionality and physical principles (without taking the product apart). Only once this predictive phase is completed do they actually disassemble the product (to avoid bias and psychological inertia). They document the steps of disassembly in a disassembly plan (in order to aid in reassembling the product) and also develop a bill of materials that lists all of the parts contained within the product. Exploded view and subtract-and-operate procedures are required to encourage the students to consider assemblability issues and to truly understand how their product fits together. Actual product function is documented (through force-flow analysis and function structures) and compared to the prediction. A morphological matrix is constructed using the parts and their corresponding functions, and function sharing throughout the device is investigated. Once the students fully understand the physical nature of their product and its functionality, they are asked to develop complete QFD matrices for the product, including benchmarking, technical difficulty, etc. They are then expected to use the QFD results, and other data collected, to propose design changes that should be made in the product.

The remainder of the redesign effort is spent mathematically modeling or testing with design-of-experiments some aspect of the design, and creating an evolved product. Whether that evolved product represents only parametric changes from the original design or includes entirely new subsystems is left to the discretion of the students and their advancement level.

B. New Course Structures

Building on our scenario of reverse engineering and redesign, the courses at UT-Austin, MIT, and USAFA were created or revised. Table 1 highlights the organization of these new and revamped courses. The courses fall into two groups, those at the freshmen and sophomore level, and those at the senior and graduate level. Reverse engineering proves effective at both of these level.

At the introductory level, it provides structure and a hands-on project to understand design decisions. For example, the sophomore Introduction to Engineering Design course at USAFA (EM 290) has two portions, design analysis of an existing product, and subsequent redesign. The first half is devoted to reverse engineering and redesign of mechanical toys, such as dart guns, water shooting systems, ball pitchers, and mechanical-energy cars. The project culminates in a design report summarizing justified avenues for redesign, engineering analysis and design-of-experiments results from two executed redesigns, and a discussion for further improvements. Having learned the methods from the reverse engineering project, the students then spend the second half of the semester solving an original design for a end-of-class competition (e.g., ASME competition projects). They must apply the design methods to this project, construct prototypes, carry out detail design, build a final working system, and present their results in design reviews.

At the senior level, the reverse engineering redesign philosophy provides a demonstration vehicle for technical methods in design. Having some design sophistication at this point, students are ready

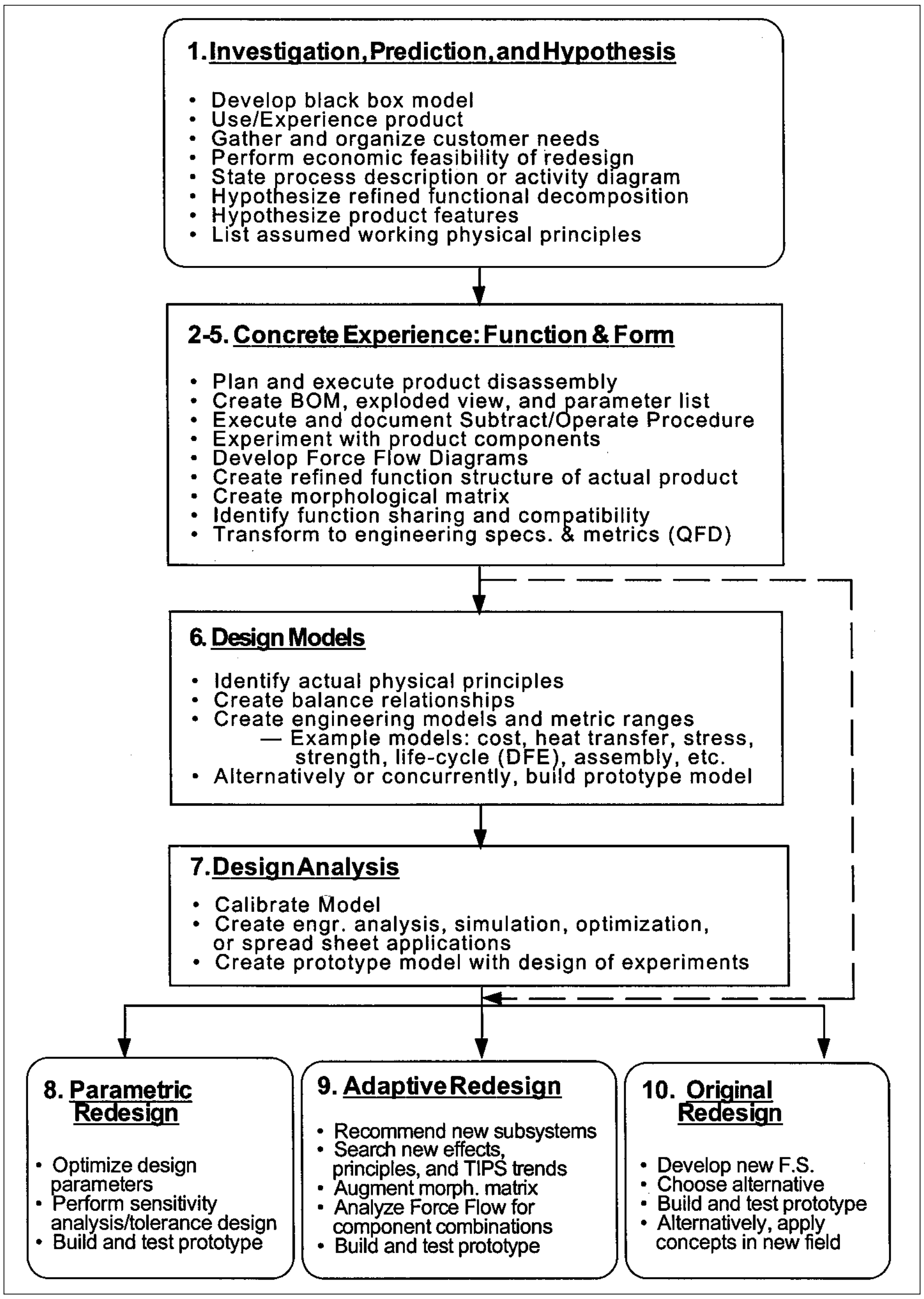


Figure 1. Reverse engineering and redesign methodology.

for understanding underlying theories to the various tasks that must be completed through the design process (understanding the customer, concept architecting, functional modeling, QFD, optimization, design of experiments, etc.). A detailed description is given next.

V. REVERSE ENGINEERING COURSE IMPLEMENTATION

A. ME 366J: First Project—Part One: "Something you've always wanted to do but never had the time..."

Given these summaries of the new courses, let's take a closer look at one course in particular (ME 366J). By so doing, more insight into the actual workings in the classroom can be obtained.

1. Description: Essentially, what we have done is implement the reverse engineering methodology presented in[43–47] as the cornerstone of learning design methods. This approach allows us not only to increase the percentage of course time spent on "hands-on" experiences, but also to iterate-requiring submissions in later reports that are built upon work done in earlier assignments.

The first project of the new structure, then, provides the students with the opportunity to choose an industrial product to reverse engineer. Each team of students (with 4–5 being the recommended group size[17]) should be encouraged to pick a product that interests them in some way (e.g., refer to Table 2). Whether it be a device that they use regularly but never performs to their satisfaction, or simply a device they have always been intrigued with but had never had the opportunity or time to investigate, the important thing is that they *want* to reverse engineer the product. This investigation of an interesting product is the focus of the first project and is captured by the sub-title above: "Something you've always wanted to do but

Course	Institution and Level	Methods and Theories	Activities and Outcomes
ME 202 Introduction to Mech. Engineering	UT-Austin; Freshman	Survival skills, professions in ME, world-wide web, email, modeling, ethics, first team experience, intro. to engr. design, simplified reverse engineering	Skill exer., web search, team dynamics, MBTI, air-water rocket analysis, reverse engr. of mech. products (toys, etc.)
EM 290 Introduction to Engineering Design	USAFA; Sophomore	Design processes, customer needs, functional analysis, QFD, solid models, assembly analysis, force-flow analysis, fishbone diagrams, bill-of-materials, modeling and engr. analysis, intro. to design-of-experiments, intro. to tolerance analysis, concept generation, concept selection, embodiment design guidelines, material analysis	Incremental design notebook review, reverse engr. and testing of toys or simple household products, redesign proposal, parametric redesign results paper, design competition project, CAD drawings, design presentations.
ME 366J Mechanical Engineering Design Methodology	UT-Austin; Junior/Senior	Design processes, customer needs, activity analysis, functional analysis, QFD, solid models, assembly analysis, force-flow analysis, fishbone diagrams, bill-of-materials, modeling and engr. analysis, intro. to design-of-experiments, concept generation and selection, embodiment design guidelines.	Reverse engineering of mech. and electro-mech. products, MBTI, team notebooks, proposal for redesign avenues, concept proposal for original design, design report and testing of product redesign.
2.74	MIT; Graduate/ Senior	Design process models, methods in reverse engineering (Fig. 1), customer analysis theories, product cost models, design for assembly, measurement theory, Theory of Inventive Problem Solving (TIPS), engr. analysis approaches, optimization methods, design-of-experiment theories and methods, Taguchi method, prototyping and testing, product evolution cases	Reverse engineering, redesign, and testing of household or professional products, disassembly and cost analysis, marketing and benchmarking, prototype testing results, limit anal. of design methods, graduate-level design modeling and experimentation
ME 392M -1 Engineering Design: Theory and Techniques	UT-Austin; Graduate	Design process models, methods in reverse engineering (Fig. 1), customer analysis theories, product cost models, design for assembly, measurement theory, Theory of Inventive Problem Solving (TIPS), engr. analysis approaches, optimization theory and methods, design-of-experiment theories and methods, Taguchi method, prototyping and testing, product evolution cases	Small exercises for design methods and theories; reverse engineering, redesign, and testing of household or professional products (individual), proposal for redesign, midterm project review, final report with prototype testing results
ME 392M-2 Product Design Development and Prototyping	UT-Austin; Graduate	Product development process (following methods in Ulrich/Eppinger), project planning, prototyping strategies and rapid prototyping technologies, industrial design, foundations in assistive technologies, mfg. processes and design materials, social work systems analysis	Interdisciplinary teams; one interactive lecture, one reverse engineering or construction lab, and one round table review per week; MBTI; alpha and beta prototypes; final product w/documentation/fabrication.

Table 1. Summary of the course structures at UT-Austin, USAFA, and MIT.

never had the time…" The students should be encouraged to find a product that they truly want to analyze and understand. After all, the team will be writing their first and third reports on the device they choose; it is not a decision to be taken lightly.

Having the first project be a group endeavor necessitates choosing teams quickly so that progress may be made. It is recommended that during the first day of lab the students should be formed into teams using MBTI results[64–66] and a background skills assessment.

Furthermore, to allow for work to begin, the teams should be required to have their particular product chosen by the *second* lab session. It is difficult to describe specifically what an appropriate product should be; however, an ideal product is one complex enough to hold the interest of a five person group throughout a semester's work. In addition, it should provide opportunities for improvement in areas within the grasp of senior-level engineering students and that are demonstrable via college-level modeling techniques. As is apparent, much of the judgment as to a product's appropriateness will necessarily be at the discretion of the course instructors. With that in mind, each team should be asked to present a list of three items to the instructor and explain their reasons for choosing each device (i.e., how they feel the device might be improved). A favored product may be proffered, but in the event that the teaching assistant or the professor judges the device chosen inappropriate, one of the other two selected products can be used.

2. Requirements: Once a product has been chosen, each team is required to perform the following tasks:

- examine the product
- develop a statement of global need/function (black box)
- use the product over its operating range
- interview users of the product and present a summary of their most common likes, dislikes, and suggestions for improvements. Organize this list into prioritized customer need categories.
- compare the product to its competition in a qualitative manner (i.e., explain the advantages and disadvantages of the chosen product in relation to its competition)
- develop a process description or activity diagram for the product
- predict how they think the product works (i.e., fulfills its

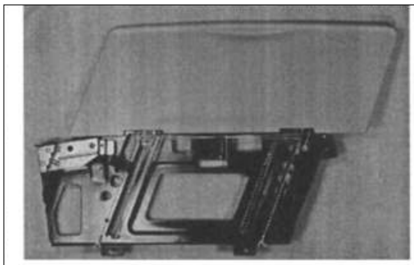
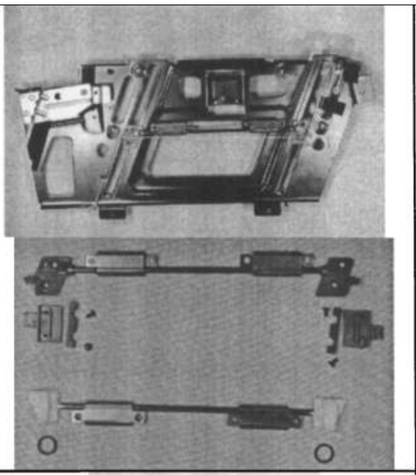
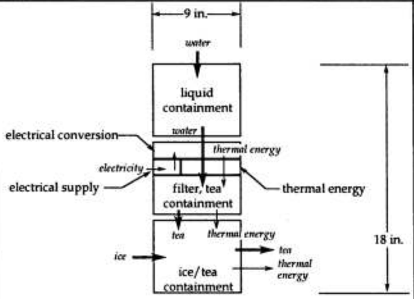
		NEW FEATURES: Significant reduction in part count, single cable redesign, simplified track guides, uniform pullout force, simplified manufacturing process, 6 digit decrease in mfg. cost.
		A removable bowl for washing, a large handle, an on/off switch, removable cord, simple/visible power control, uniform power control in time, compactable volume for storage, and a wide view radiant surface.
		NEW FEATURES: 45% decrease in tank water, improved flow control (1.8 mm flow hole), 71% reduction in bitterness, 20% reduction in time to brew (from 10.5 min. to 8.5 min.), 17% reduction in amount of ice needed, reduced footprint.

Table 2. Example reverse engineering student projects, including shots of before, after, and advancements: Cadillac Auxiliary Visor, Westbend Wok, and a Mr. Coffee Ice Tea Brewer.

customer needs) (e.g., if a team's product is a power screwdriver, they might predict that the transmission consists of a train of spur gears arranged in a particular fashion). Create a predicted function structure and list of predicted components and physical principles.

3. Supporting Lab Exercises: Most of the tasks above can be completed in a straightforward manner, but generating an abstract need statement for the product may prove daunting to some teams. Structured exercises in the laboratory sessions can help to address these problems. Two such exercises are helpful.

The first exercise, to be completed in the second lab session of the first week, focuses on global functionality. The instructor should come prepared with a list of 40 or so items—some commonplace, others not — to be used in the exercise. Examples might be an automobile, a coffee maker, a thermos, etc. After a short lecture on the nature of a global function or a global need statement, accompanied by a few examples (e.g., the global function of a thermos might be stated as "inhibit heat transfer between a liquid and the outside environment"), the instructor should then call on each individual student in turn to think of a global function for a item from the list. The important aspect of this exercise is its iterative nature. As one student suggests a global function, all of the other students in the class hear his/her answer and any subsequent comments from the instructor. Thus, for every instance where the student has to suggest a global function aloud, there are numerous chances for the student to watch another student offer a global need and to learn from the instructor's feedback. The other students could even be asked to offer their own suggestions for another student's item. It is hoped that by including such an exercise in the first week of class, the students will feel more at ease with generating a global function for their own device.

The second exercise is similar in nature, though it deals with more in-depth functionality. Again, the instructor should come armed with a list of items—a corkscrew, a tea bag, etc.—although this time he/she should have only one item per team. In this exercise, each team is assigned an item and is asked to develop a list of ten functional requirements for it. Again, the instructor should precede the assignment with a few examples to show the class what is expected. The teams have one full lab session to discuss amongst themselves and develop their list. Then, during the next lab session, each group will present their list of functional requirements to the other groups. Again, the benefit of this exercise is in the repetition. As a spokesman for each group presents its list of customer needs and explains the reasoning that was used to develop it, the other groups in the class are able to learn from listening to the comments of the instructor. They also learn by considering what customer needs they might have included or not included had *they* been given that particular product. This exercise should be assigned in the first lab session of the second week and presentations should be made the next session. Although this is early in the semester, it is hoped that the experience gained via this lesson will give the teams confidence to develop the customer needs and functions for their own product.

During both of these exercises, it is important for the instructor to not be overly critical. After all, functional decomposition is abstract, so comments should generally be of the sort "did you consider this?" and "can you abstract that particular function to a higher or lower level?"

B. ME 366J: First Project — Part Two: "So How Are You Going To Help Me?"

1. Description: As the second part of the project begins at the start of the fourth week of class, the teams are given the go ahead to disassemble their products. This is often the most enjoyable and "hands-on" portion of the reverse engineering methodology, so it is desirable to have it occur as early in the semester as possible. The focus of this project component is towards gaining a full understanding of how the product works and is assembled, and also towards the potential improvements that might be made in the design. By the time this project is completed, each team should be capable of answering the customers' question "so how are you going to help me?" (i.e., how will you make the product better?)

2. Requirements: The requirements of each team for the second report are:

- create a plan for disassembly
- disassemble the product
- perform the subtract and operate procedure[45]
- create a bill of materials (BOM) as disassembly proceeds
- create an exploded view of the product
- describe how the product actually works (fulfills customer needs)
- compare the actual workings with the predicted
- perform a force-flow analysis of the components
- for each part, describe what it does, then abstract to get its functionality (with a careful eye towards multiple functions being fulfilled by one part
- consider the major flows (e.g., energy, signal, material) that interact with the product and how they relate to the detailed functions of the device); construct an actual function structure
- conduct research into appropriate standards
- map the customer needs to appropriate engineering requirements (QFD — construct a House of Quality)
- include a qualitative and quantitative ranking of the product with respect to its competitors for each customer requirement
- conclude by indicating where opportunities exist to improve the product (according to the customer requirements) and which of those opportunities the team plans to pursue

The teams have approximately three weeks to complete this part of the project. Each team will submit one group write-up; *however,* each individual team member is required to write an abstract of the group write-up and submit it at the same time. Prior to the report submission, the group should chose one of the individual abstracts to be included with the group report. This is a technique borrowed from McMaster at Embry-Riddle Aeronautical University.[19] Not only does it allow for individual grades to be obtained without the laborious process of having each student write a report, it also forces each individual to be in touch with what the group is doing in order for them to write a reasonable semblance of an abstract. In other words, it is difficult for one student to be out-of-touch with the rest of the group and allow his/her group mates to complete the lion's share of the work.

C. ME 366J: Second Project

The second project focuses on original design. Giving the students the opportunity to work on a truly original design problem is too valuable an experience to disturb. Student teams use the same methods to solve the original design problem as they learned through reverse engineering. New topics are also added, including concept generation methods and concept selection.

D. ME 366J: Third Project: "Make it Better!"

1. Description: Having completed their experience with original design, the teams return to their reverse engineering in the third project. Armed with a course of action towards product improvement (as presented at the end of the first project), each team should now be prepared to work to achieve this improvement. "Make it better!" is the sub-title of this project, and the students should be encouraged to strive towards making significant improvements in their products—improvements they would be proud to suggest to the product's manufacturer. Their experience in the first two projects has introduced them to fully-developed QFD matrices and function structures, so they will now be able to use the materials they have gathered to produce effective redesigns.

2. Requirements: The requirements of the third project include:

- decide, concretely, how you will achieve the improvement in question (i.e., modeling, prototyping, etc.)
- develop alternative concepts for effected subsystems
- choose a concepts that maximizes the improvements and justify your choice via engineering analysis
- develop design models of effected subsystems
- calibrate the models and solve for preferred parameters
- conduct design of experiments on the evolved product
- revise bill-of-materials and exploded views
- conclude about the entire reverse engineering effort

Each group submits a single report. Four to five weeks are allotted to complete the tasks above. The teams are also required to include in their final report supplementary material already presented in the first report (e.g., customer needs analysis, BOM, disassembly list, global functionality, predicted functionality, etc.). Although the argument can be made that such regurgitation fosters no learning, in the authors' personal experience, the opposite is quite true. Oftentimes, the students will use the feedback from the teaching assistant and professor on the first report to improve and expand upon the material such that when it is finally presented in the third report, it does in fact demonstrate additional insight and learning (reflection).

VI. COURSE EVALUATION: IN BRIEF

A number of course assessments were developed and applied to our new courses over the last four years. Two important assessments are provided below to illustrate the trends of the students' and faculty's feedback.[30,33]

Tables 3 and 4 provide a summary of the course evaluations for UT-Austin's ME 366J (senior design methodology course) and ME 392M-1 (graduate level course). Compared to previous versions of the course, and compared with the College of Engineering's average reviews, these course assessments are well above the mean and quite encouraging. Similar results occurred at the USAF Academy. Students report that the courses are very difficult, but the hands-on nature and industrial relevance of the course structures are refreshing and greatly advance the understanding of the material. Students also report that they were initially skeptical about the forming of teams with MBTI (instead of self-chosen teams); however, they appreciated the experience and variety of skills offered by different personality types. In conjunction with these positive comments, a percentage of the students also report that the ME 366J course required too much work, especially if one or two team members did not carry their load. While these negatives are true in any open-ended, team-based project course, student peer evaluations and continual monitoring of the students scheduling are implemented to help avoid these problems.

Another important assessment was carried out at the USAF Academy during the fall of 1997 (as further detailed in[68]). To evaluate the effectiveness of the course restructuring from the student's perspective, the students were provided with a brief daily survey requesting their feedback on each lecture. The results from these surveys were used in two different ways. First, the current (restructured) format for the course was compared with the previous format by viewing survey results from lectures on the same topic given before and after the restructuring. Students rated the restructured lectures equal to or higher than previous semesters. The interesting aspect of the reviews, however, was the standard deviation of the evaluations. For fall 1997 (the first semester after the restructuring), the standard deviation between each lecture's rating decreased substantially. The reverse engineering project helped to decrease the "ups and downs" of the course since the students were "grounded" by their hands-on products.

For the second method of obtaining feedback, an assessment procedure was developed and implemented using the Myers Briggs Type Indicator (MBTI). MBTI information provides insight into how students prefer to interact with their environment. Specifically, sensing (S) types usually prefer to process information through their senses (touch, sight, hearing etc.). Intuitive (N) types normally prefer to process information more internally and less interactively, dealing with the concepts in a more abstract manner. With these concepts in mind, students' ratings for each individual lecture were separated based on whether the student had a sensing (S) verses intuitive (N) MBTI preference.[64–67] These data points were then examined to determine if there was a correlation between the S-type or N-type student's rating and the specific content of a given lecture. Four categories of lecture content were used: (1) percentage of "hands-on", (2) quantity of relevant examples (relevant either to the student's design project or to an industrial example), (3) level of abstractness, and (4) amount a given lecture presents a step-by-step process. Each lecture was rated by the instructor as to its level of content for each category. Results of this examination are shown in Table 5.

The table shows the percentile ratings for each of the four lecture content categories separated for the S-type and N-type students. The average percentile lecture rating is, by definition, 50. Therefore, it can be seen from the table that there are 3 times where lectures in a specific content area were rated below average (N-types rated hands-on lectures = 39.7, S-types rated abstract lectures = 41.3 and N-types rated step-by-step lectures = 47.6). In the other 5 cases, the lectures in these specific content areas were rated above average. In particular, note that the relevancy category was critical (61.8 and 63.7 for S-types and N-types respectively) for the students (of both types) to identify with the lecture material. Reverse-engineering projects, as used during the lecture time, helped the students understand how and why design methods can be beneficial. Alternatively, a step-by-step (or cookbook approach) lecture fell approximately on the mean of lecture content. Very little difference could be seen in personality type for the step-by-step content, thus leading us to believe that procedures provided to the students are useful, but not as important as other teaching tools.

Differences between the S and N types became clear in the "hands-on" versus "abstractness" categories of lecture content (as expected). "Hands-on" lectures pertained to classes where students were able to manipulate a product or device as the lecture proceeded. Abstractness, on the other hand, represented the extent to which the content of a lecture required students to exercise a global, creative, or theoretical thought process. Because the restructured course provides numerous lectures with hands-on content as well as numerous lectures with abstract content, this structure captured the preferred learning style of each MBTI type (S and N) during different lectures. The diverse structure allows students ample time to function in their preferred learning environment (hands-on for S-types and abstract for N-types) and also provides sufficient opportunities for students to develop in their non-preferred areas (hands-on for N-types and abstract for S-types). While it was successful in handling this diversity, the assessment also underscored

Category	Excell.	Vy Good	Satis.	Unsat.	Vy Unsat.	No. of replies	Avg. (Max. 5)
Course Well Organized	56	78	20	0	0	154	4.3
Information Communicated Effectively	114	29	9	0	2	154	4.7
Helped to Think for Myself	76	66	10	0	2	154	4.4
Overall Instructor Rating	106	35	11	0	2	154	4.6
Overall Course Rating	42	79	28	2	3	154	4.0

Table 3. End-of-course evaluations, ME 3661, UT-Austin, Spring, 1996–99.

Category	Excell.	Vy Good	Satis.	Unsat.	Vy Unsat.	No. of replies	Avg. (Max. 5)
Course Well Organized	15	14	2	0	0	31	4.4
Information Communicated Effectively	22	8	1	0	0	31	4.7
Helped to Think for Myself	20	11	0	0	0	31	4.7
Overall Instructor Rating	20	10	1	0	0	31	4.6
Overall Course Rating	13	16	2	0	0	31	4.4

Table 4. End-of-course evaluations, ME 392M-1, UT-Austin, Spring, 1996–99.

the need to include hands-on and abstractness for each and every segment of the course material, as time allows. Our next course evolutions will focus on this issue.

Besides lecture-based and end-of-semester evaluations, faculty and students in the follow-on design course at UT were interviewed. These interviews focused on the preparedness of the students for capstone design. They also queried the instructors on the students' skill levels, compared to the course before implementing changes. In all cases, the students and faculty stated that the new design course (ME 366J) assisted greatly in the capstone design course. The instructors further stated that the students' performance was markedly better due to their incoming skills.

Overall, we are very pleased with the assessment results. Reverse engineering tools have proved to be beneficial in addressing the variety of personality types and learning needs of our students. They have also provided a relatively inexpensive avenue for bringing enjoyment to the classroom. Yet, we still have educational hurdles to jump. Of particular importance is the time commitment on the part of the students. Student teams that are able to schedule their time properly, and aggressively delegate tasks to individual team members, perform very well on the open-ended projects. Their time commitment is very similar to any other course in the curriculum. The opposite is true for teams that tend to work on every task as a monolithic unit. The extra time spent as a team can greatly detract from the rewards of developing a new creation. Further teaching techniques are needed to allow a team to stray from the path, but not too far.

In addition to time commitment, students also struggle with iteration on design projects. Quite often, student teams will be so caught up in finishing a given technique, they do not tie their results to previous steps in the process. Improving previous design decisions is very difficult at this point. In fact, the whole purpose of a given design method may be lost as the students struggle with the details. Again, refinements on our course structures are needed to address this issue, assuring that iteration and relevance of each design method is purposefully orchestrated in the course machinery.

CONTENT AREA	S-TYPE (%-ile)	N-TYPE (%-ile)
HANDS-ON	67.3	39.7
RELEVANCY	61.8	63.7
ABSTRACTNESS	41.3	60.6
STEP-BY-STEP	53.2	47.6

Table 5. Correlation of MBTI type to content of lecture material: Gaussian Percentile, where a mean lecture rating is 50%.

VII. CONCLUSIONS

A concerted effort has been made to evolve design-methods courses at UT-Austin, MIT, and USAFA. Reverse engineering and redesign form the cornerstone of our evolution efforts. Six courses at these institutions have been restructured. The advantages of the new course structures provide an exciting way to teach design to students while making use of "hands-on" projects. In addition, many current "hands-on" projects in use in academia are not methodical in their approach. The proposed structure incorporates the benefits of "hands-on" exercises in general, while also stressing the importance of a structured approach towards problem-solving.

If we cannot excite our students to learn design, then in a very real sense we have failed in our efforts to help them become engineers. Of all the statements encountered in the literature review that attempted to define "design," the one that seems most fitting is that of an 11-year-old elementary student:[24]

"design is masterpiece, a feeling; something to be proud of. A design is a treasure that no one else can copy. Because you have a special touch, a design is a gift that you can put your own feeling in—anger, happiness, sadness—any feeling you want, because a design is, in a way, a part of you. Knowing you made it, knowing you went through thinking to make it the way it is—that is what design is."

If the course structures presented in this paper leaves the student with a feeling of wonder about design, the feeling that what they design is a "part of" them, then it will have succeeded, for education and learning are largely self-motivated. The student will tend the flame; we as educators need only provide the spark.

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