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A Creative Introduction to Mechanical Engineering*

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This paper describes a new introductory course developed at the Technion for freshmen Mechanical Engineering students. Through unconventional teaching methods, this course provides a clear overview of the different fields within Mechanical Engineering, and also provides a clear description of the engineer's work. By challenging the students to design devices that perform specific tasks, this course raises their awareness of scientifically relevant physical phenomena they encounter later in their studies. At the same time, it elucidates the importance and necessity of analysis tools such as simplified physical models of a system and mathematical formulation of its response. Working in small teams, the students conduct research and development and consult with senior peers and faculty, to optimize the design and construction of their devices. The quality of the devices they build is then measured within a framework of a dramatic competition between all teams. The competitive spirit is used to increase the motivation and involvement of the students, and to promote creativity. Following the competition, the projects are scientifically analyzed in class, and relevant physical models and related mathematical tools are presented. It is demonstrated that simple modeling and calculations may help in identifying and characterizing optimal solutions for engineering problems. In addition, the students are required to analyze the design process they have conducted, and many of the conclusions they draw are valid lessons that are relevant even to professional engineers.

INTRODUCTION

UNDERGRADUATE ENGINEERING curricula emphasize fundamental courses in mathematics and physics in the freshmen year. These courses are designed to provide the students with basic analysis tools (physical models, their mathematical formulation, and techniques for solving the related field equations) and are therefore crucial for their success further on in their studies. At the Technion, as in many other universities, these courses are taught by the teaching staff of the mathematics and physics faculties, who are the most qualified for this task. As these courses are given to freshmen students of other faculties as well, they are generally given at facilities that are physically apart from the Mechanical Engineering (ME) faculty. For the same reason, these courses cannot elaborate the significance of the presented material to the specific field of ME. As a result, ME students often have difficulties assimilating the mathematical tools and physical models they are taught, and thus are unsuccessful in implementing them effectively when analyzing engineering problems. Some students even regard these fundamental courses as just 'another hurdle on the way to graduation' because they fail to see their relevance. Many students become frustrated because instead of getting the practical engineering training they anticipated, they are overburdened by 'theoretical material'. Due to this misperception and the lack of direct contact with the ME faculty, some students tend to feel detached and find it hard to identify with the engineering field they have chosen. Consequently, some students feel overwhelmed and lose their motivation to succeed in their studies, while others concentrate on attaining high grades rather than on internalizing the analytical material.

Many students have an ambition to become engineers because of the popular perception of the vocation ('engineering promises financial, professional, and career opportunities'). Also, many students choose ME as their major due to their natural affinity towards the field. However, once they begin their studies, they realize that they lack a clear and comprehensive understanding of the actual work of an engineer. This relevant perspective that they lack, can only be attained through practical experience in 'real life' engineering work. Often, students do not have the opportunity to benefit from such an experience until they engage in engineering projects during their senior year.

These academic hardships have a long-term effect that can be observed in the attitude of many junior and senior students towards their studies (as is evident in the students' solutions of exam questions and project assignments). It may even be argued that the same problems during the freshman year adversely affect the graduates by accustoming them to inadequate thinking and studying habits.

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Due to their superficial comprehension of the basic analysis tools, many students tend to concentrate on the 'technique' of problem solving (i.e. choosing and using the correct formulae) rather than on developing habits of systematic analysis for solving problems. It appears that not only do many students have difficulties assimilating the theoretical material they were taught in their first year, but they also have difficulties in applying it later on in their studies.

To help resolve these issues, a new course for freshmen students entitled *Creative Introduction to Mechanical Engineering* was developed. The objectives of this course are:

1. Provide a clear overview of the different fields within ME.
2. Introduce the essence of engineering work and the process of the design and development of new technological products.
3. Help the students develop an awareness of physical phenomena that are relevant to ME.
4. Raise the students' awareness to the importance and necessity of analysis as a means of finding optimal solutions for engineering problems.
5. Acquaint the freshman students with the ME faculty and their fields of expertise.

The next section presents the teaching methodology developed to best meet these objectives. The course structure is then presented followed by case studies of specific projects carried out by the students in this course.

TEACHING METHODOLOGY

The course is specifically designed for students in their freshman year. In this course, the students are encouraged to develop a personal perspective of the field of Mechanical Engineering and of the *Engineering* vocation. The aim is to simulate the process of design and development of a new product (in a limited scope), and to get the students emotionally involved in this process. Over a semester of 14 weeks the students are given four design projects, each relating to a different field within ME. The project begins with a challenge that is presented in class, which requires the construction of a device that will perform a specific task. The challenge includes a pre-defined explicit formula for measuring the quality of the device, based on the device performance. Working in small teams (cooperative group work, [1, ch. 8]), the students have three weeks to complete their design and build a device. The quality of the different devices is then measured in class within the framework of a competition between all the teams. The grade granted to each device is proportional to its quality relative to that of its competitors.

As a result of this competition, the students are driven to find advantages over their peers (motivation to learn [2]). In search of such advantages, the students consult with senior students, graduate students, teaching assistants, and faculty whose expertise is relevant to the project at hand. In this way the students develop, and learn the importance of developing, a network of professional references. They create a mental map of the various fields of Mechanical Engineering, and familiarize themselves with the faculty and their specific fields of interest. Along with this 'networking', the students also become familiar with sourcing relevant information, using textbooks, Internet sites, and various other sources.

Contest day is conducted in a specific fashion to maximize team interaction and the spirit of competition, while still retaining an academic context by emphasizing the scientific relevance of the observations made throughout the competition. The contest begins with a preliminary popular vote in order to estimate the quality of all the devices based only on their appearance. Next, a member of each group is given five minutes to present his groups' device. This presentation includes the research and development that lead to the final design, the various models built and tested, and the device quality as measured by the group before the contest. A second preliminary popular vote is then conducted in order to estimate the quality of all the devices based on the information provided in the presentation. Then comes the competition that is recorded on camera for later reference.

During the competition, the students are very attentive and closely observe the devices and their performance. Having invested much time and energy to create a product that is now being tested before their peers, the students become excited and emotional. The atmosphere in class provides an excellent opportunity to point out characteristic features of the device response (as will be described in the example projects), and add new notions to the students' vocabulary of physical phenomena (stimulating *Initial Learning* [1]). Strong emphasis is given to the meticulous examination of the device response, and to the process of articulating all observations. Simple, preliminary explanations given at this stage seem to be very well assimilated due to the fact that the considered phenomena are visually apparent to the students. Although 'tearing' devices apart in a competition is fun, the event is made academically meaningful only through the process of verbally analyzing and understanding the reasons for the success or failure of each device [3, pp. 67–71]. This analysis is performed during the next class meeting.

Following the competition, each team submits a scientific report. This report describes the research and development process, the various designs that were considered, and the considerations leading to the final design. In addition, the students are asked to describe knowledge and information that would have enabled them to find better solutions for the problems they encountered. Writing this report encourages the students to consider the project in a broad engineering perspective, and to categorize the problems encountered by order of importance.

This also encourages them to acknowledge weak points in their design process. In our experience, this has shown to help the teams make better design decisions in subsequent projects, and help them prioritize and strategize early on in the design stage. Writing the report helps the students develop a clearer picture of the project as a whole, and helps them elucidate the relevance of the drawn conclusions.

In some cases, as a result of this repetitive process of design, competition, and reporting we have seen complete changes in the performance of weak teams as the semester progressed. These teams realized that it was entirely up to them to determine the quality of their work and by implementing their conclusions they improved their performance in the following challenges.

In the class meeting following the competition, the challenge is analyzed from a scientific and engineering point of view, and basic physical models and mathematical tools related to its analysis are presented. It is demonstrated that very simple 'back of an envelope' calculations can help identify the dominant effects in a complicated problem, and can also help to outline characteristics of an optimal design for a specific problem.

Each of the design projects is in effect a cycle of experiential learning [4]. Through repetition of these cycles the students learn how to approach engineering problems while making use of the broad perspective gained from previous experience.

THE COURSE STRUCTURE

The course is designed for a 14-week semester with a single, 3-hour meeting each week. In the first course meeting, an introductory lecture is given that describes the role of engineering in human culture. This lecture illustrates various things that technology enables mankind to do that nature has not intended. Examples are given from human activities such as:

- travel over land and sea, and flight within the atmosphere and in space;
- information storage and retrieval (from hand-written records to stored digital data);
- instantaneous communication over vast distances;
- food supply; controlled environment;
- medicine and biomedical engineering;
- destruction capabilities (from the revelation of fire to H-bombs).

The changes and advancement in these human activities are considered in perspectives of the last few decades, centuries and millennia. The broad picture that emerges reveals the importance of engineering and the crucial contribution of the technology it creates to modern life. At the end of this lecture the first design challenge is presented to the class.

In the next two meetings, a mini-course on the development of a new product is given. Systematic methods for generating design concepts, and several approaches for categorizing these concepts are presented. Also, various methods for selecting the most promising concepts are described. Due to the fact that at this point in their studies the students do not have sufficient analysis tools, emphasis is given to preliminary experimentation with simple prototypes. Investigation of the reasons for success or failure of a prototype should lead to improvements of design concepts.

In this mini-course, much attention is given to developing design concepts. Real life examples are discussed that demonstrate how the design concepts determine the success or failure of commercial technological products. This lesson is frequently learned in class from their own projects, as will be described in the following section.

Every semester new and original projects are defined. Projects from previous semesters are documented in the course website [5] along with pictures of the various devices built and a few outstanding project reports submitted by the teams. This website serves as a reference source and a testimony to the resourcefulness and creativity of previous students in their effort to create optimal devices.

The four different projects are given in succession; each project being tested three weeks after the problem definition was presented in class. In addition to the projects, the students participate in a 'tear-it apart' laboratory. The objectives of this laboratory are to expose the students to the mechanical engineering aspect of 'hi-tech' devices, and to reconstruct the design considerations that relate to an existing product. In the next section, example projects are described followed by a detailed description of the 'tear-it apart' laboratory.

EXAMPLE PROJECTS

The intention of the first project in every semester is to create drama and competition. This project will typically involve a direct battle between two devices at a time, or will require a controlled destruction of the devices. This dramatic beginning of the semester helps unite the teams into cooperative working groups, and invokes competitive spirits and high motivation.

Subsequent projects, though still competitive, do not involve direct contact between devices. Rather, these projects are more closely related to specific fields within ME, and the competition is between the performances of each of the devices as measured in an isolated environment. These projects can be directly connected to fundamental ME courses. In this way they serve to raise the students' awareness of various physical phenomena that they will encounter later on in their studies.

A typical first project: ramming barrel

The challenge is to build a barrel of limited dimensions and weight that is driven by the elastic energy stored in a single standard rubber band. The barrels compete against each other in a 'head-on' ramming competition within a narrow walled runway. When the barrels have come to rest, that which is farthest from its starting point is declared the winner.

This challenge forced the students to consider conversion of stored elastic energy into kinetic energy, and the rate and efficiency of this conversion. Also, the students had to address rigid body dynamics (axial and angular momentum), and to consider possible competition strategies (preparing for unknown competitors). The winning device built by the students is shown in Fig. 1. Although this device is not a cylindrical barrel, its design is in agreement with the challenge definition. As in this device, most of the devices connected a pendulum weight to the rubber band that was wrapped under tension around the barrel axis. The tension in the rubber band applied a torque that simultaneously lifted the pendulum and propelled the barrel into motion.

In the meeting following the competition, the problem was analyzed by considering a simplified model (i.e. the mass of all parts was neglected except for the pendulum). This analysis proved that the maximal acceleration that could be obtained by this design concept is equal to the gravity acceleration g, and that this result is independent of the mass of the pendulum or the diameter of the device. To optimize the design, using this information, the mass and diameter of the barrel should be maximized within the pre-defined bounds in order to maximize the momentum at impact. This is an example of cases where simple analysis can increase the efficiency of the design process. This meeting also included an overview of physical phenomena that were observed in class and presented a map of the relevant undergraduate courses in which these phenomena are studied.

Bridge of straws

The challenge is to build a bridge from drinking straws and sewing thread only, with bridge span and other dimensions specified. The quality of a bridge is defined as the ratio of the maximal weight it carries to its own weight.

In this project many students made use of their knowledge of trusses, taught during the same semester in the *Statics* course. Some quickly realized that a more creative approach would be required to win the contest. The winning bridge, shown in Fig. 2a, carried 200 times its own weight. The bridge with the worst performance, shown in Fig. 2b, carried only 26 times its own weight.

The winning bridge relied on a primary tension string to carry the load while the beam structure, constructed from parallel straws bonded together, was purely loaded in compression. To impede the first mode of buckling, that the team identified

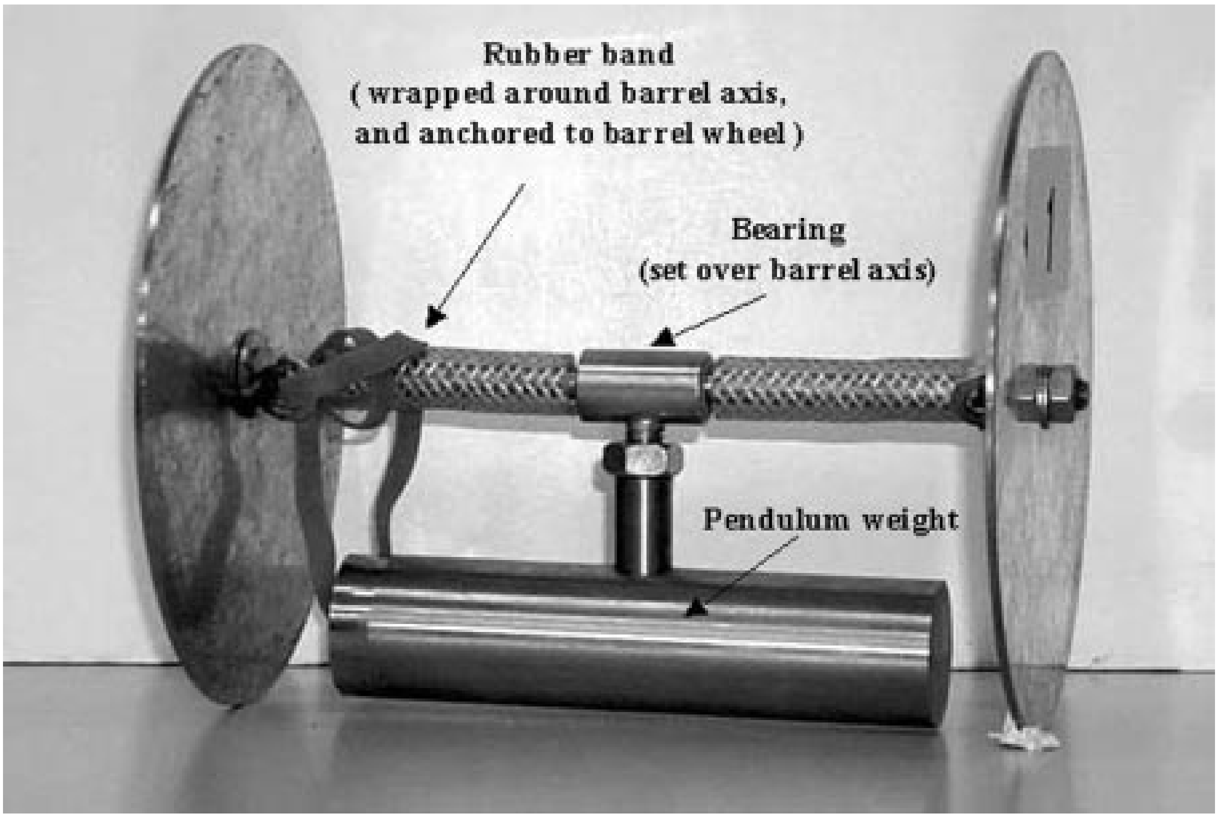

Fig. 1. The winning ramming barrel.

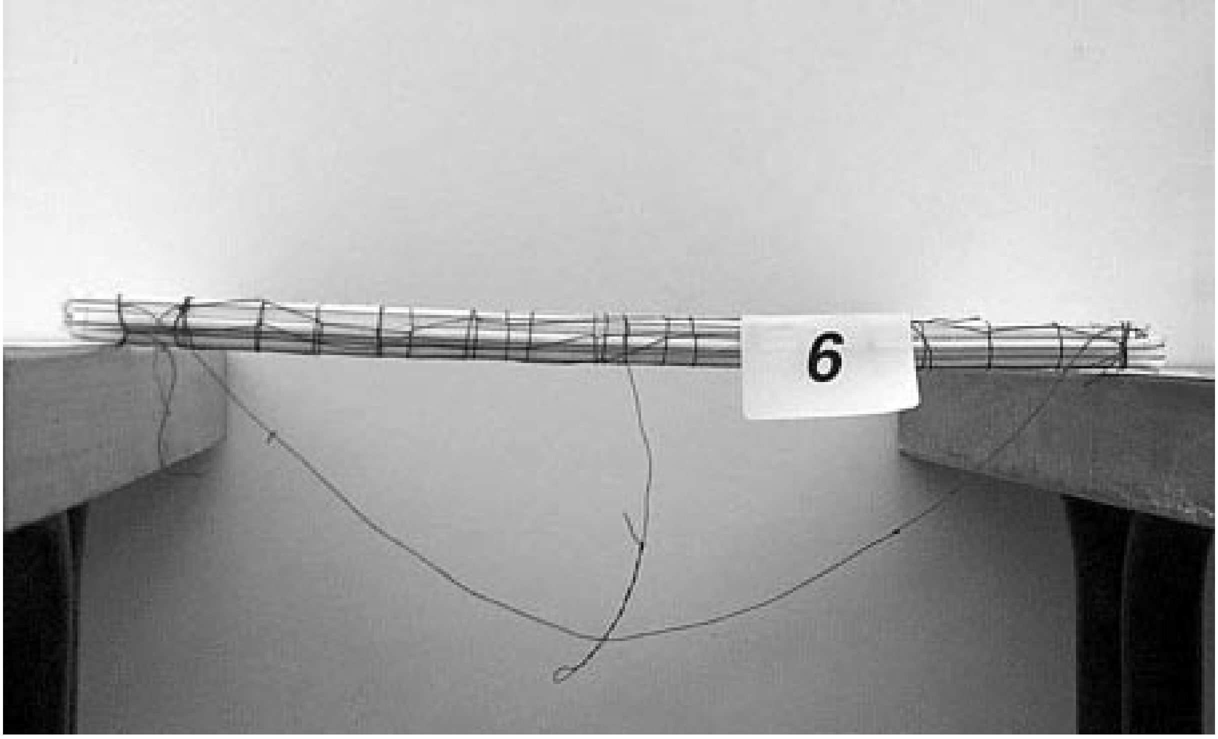

Fig. 2a. The winning bridge of straws.

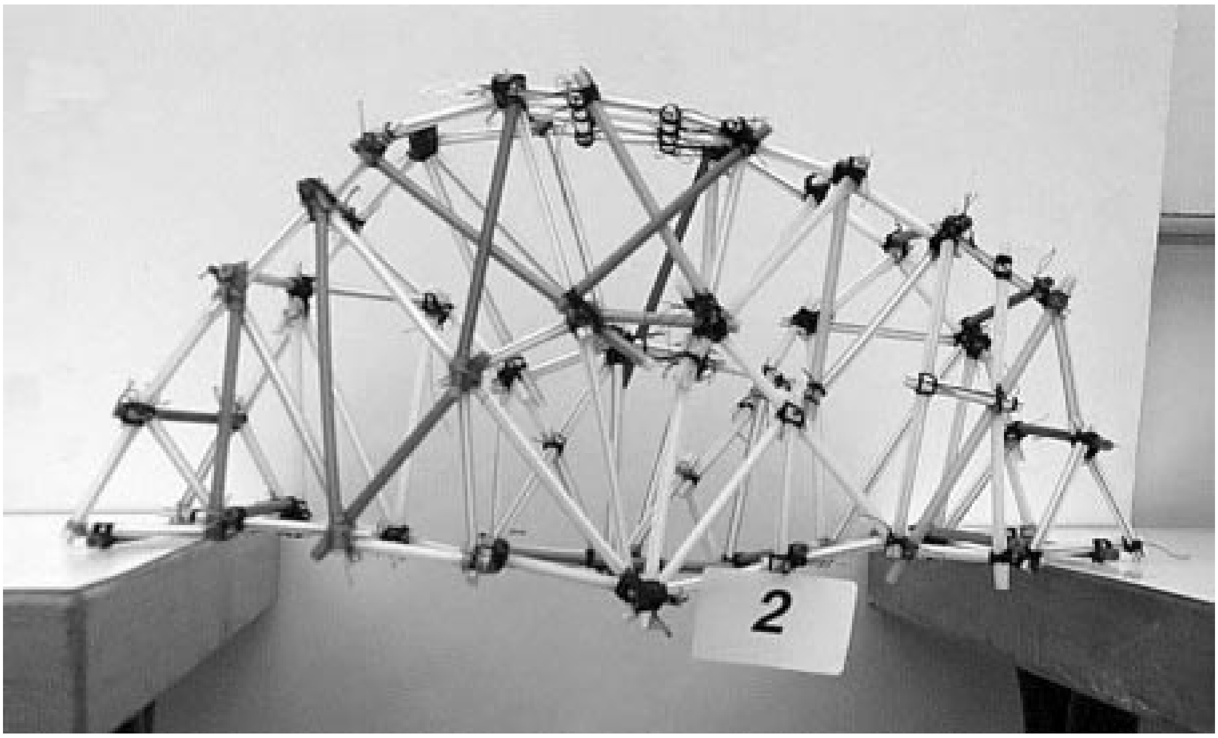

Fig. 2b. The least effective bridge of straws.

in early experiments, a secondary string was connected that impeded the upward deflection of the beam center (Fig. 2c), and consequently increased the load-carrying capacity of the bridge. In their freshman year, ME students have not yet learned about buckling. Nevertheless, the students of the winning group were resourceful enough to identify the mode of failure and to try to impede it.

The difference between the design processes of these two groups was that the winning group devoted 98% of their time to research and development, which included the construction of many simple model structures, and 2% of their time to

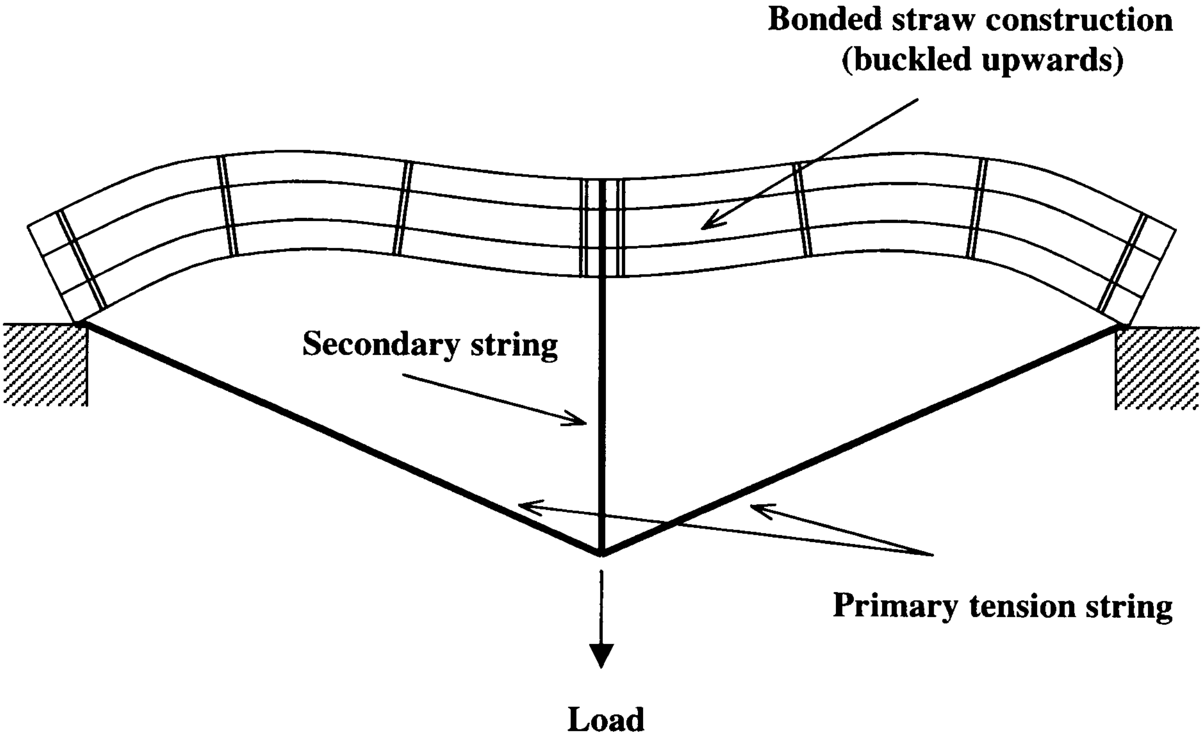

Fig. 2c. Principle of operation of the winning bridge.

build their contesting bridge. In contrast, the other group invested less than 5% of their time to derive the design concept ('beautiful arc bridges are supposed to be strong') and in the remaining time, struggled to build the bridge. The lesson that the concept design was dominant in determining the performance of the product was clear to all.

Following the analysis of the project, a general preview of solid mechanics and of the mechanical response of solid structures was presented. The phenomenon of buckling was described and examples were given of products that make use of buckled elastic components.

Candle-flame driven lift

In most thermodynamics textbooks, a simple system that converts heat into work is discussed. In this project the students were asked to actually build such a system. The challenge is to build a device that will lift a 50-gram weight using the energy emitted by a candle flame. The quality of the device is linearly proportional to the height to which the mass is lifted after 4 minutes of operation.

In search of possible solutions, some teams considered the concepts of hot air balloons or mechanical lifts driven by miniature steam turbines. However, experiments with prototypes revealed the impracticality of these concepts. All teams eventually settled on the general concept of using the candle heat to boil a fluid, and then use the produced steam pressure to lift the weight. While some devices failed miserably, the winning device shown in Fig. 3a lifted the weight to a height of 3.5 meters. The dominant factors that had to be dealt with in order to reach an optimal design were efficient combustion, efficient use of the heat, and thermal isolation to reduce heat loss.

The winning team used a light bicycle pump (minimal heat capacity) that was coated with isolating thermal wool (Fig. 3b). The pump was partially filled with a mixture of ethyl alcohol and water, and was then sealed. The candle was positioned within a chamber that was designed to maximize heat transfer to the bicycle pump, without obstructing the air supply to the flame. A simple mechanism of pulleys amplified the extension of the bicycle pump 14 times (the students verified that the pump could withstand the pressure developed). The optimization of the device was so thorough, that only the exact amount of fluid required was injected into the pump.

During the meeting following the competition, the challenge was analyzed. The physical quantities of heat and temperature were discussed and clarified. To explain why all the produced heat may not be converted into mechanical work, the Carnot cycle was described and simply explained (inevitably using some 'hand waving').

Shaking spaghetti tower

The challenge is to build a slender tower made of spaghetti sticks and glue that will endure an orbital motion of its base with frequency gradually increased from 1 to 5 Hz. The tower is to be at least one meter high, and have a cross-section that does not exceed a square of 4 × 4 cm. The quality of the tower is proportional to the maximal frequency it endures without collapsing, and inversely proportional to its weight. The challenge

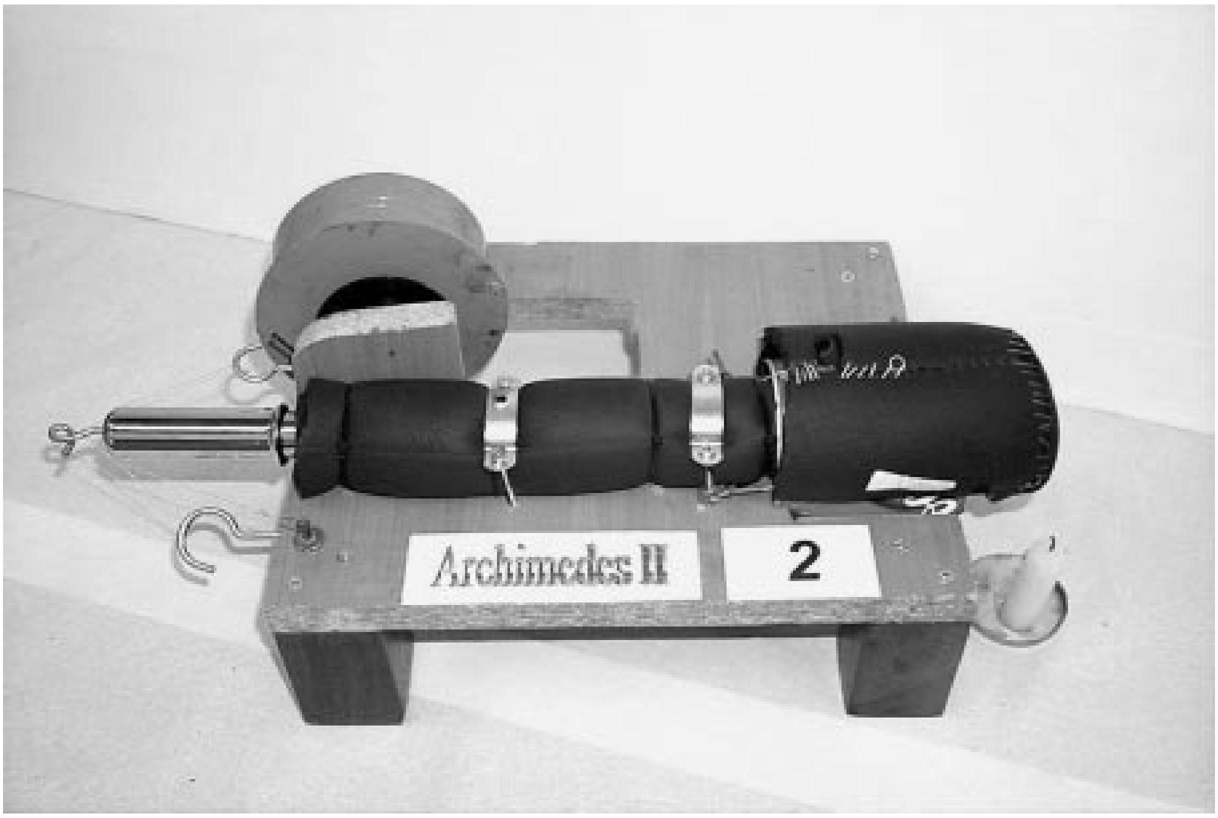

Fig. 3a. The winning candle lift.

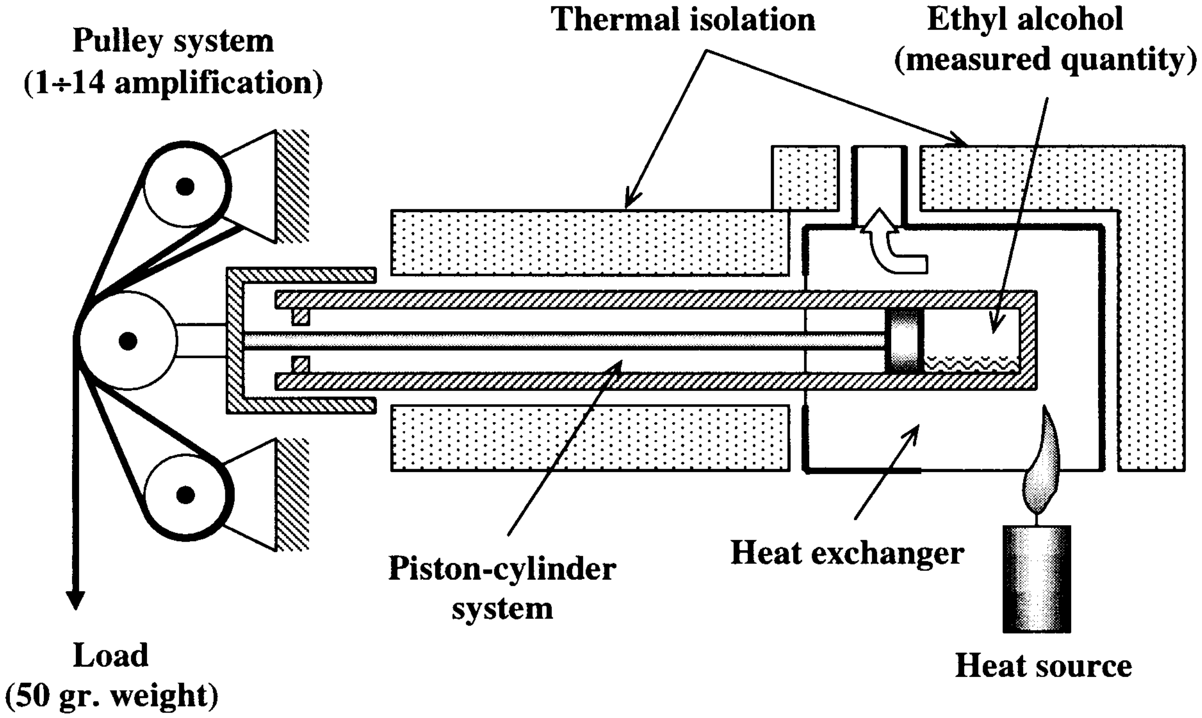

Fig. 3b. Principle of operation of the winning candle lift.

definition does not restrict the amplitude of the structure deflection, as long as failure does not occur.

In an attempt to find the optimal solution, one of the losing teams consulted a Civil Engineering faculty member whose field expertise is structure stability. The team's device ended up looking like a very sturdy building frame designed to withstand an earthquake. The structure however was far too heavy. This team failed to realize that their design aimed at minimizing the amplitude of deflection

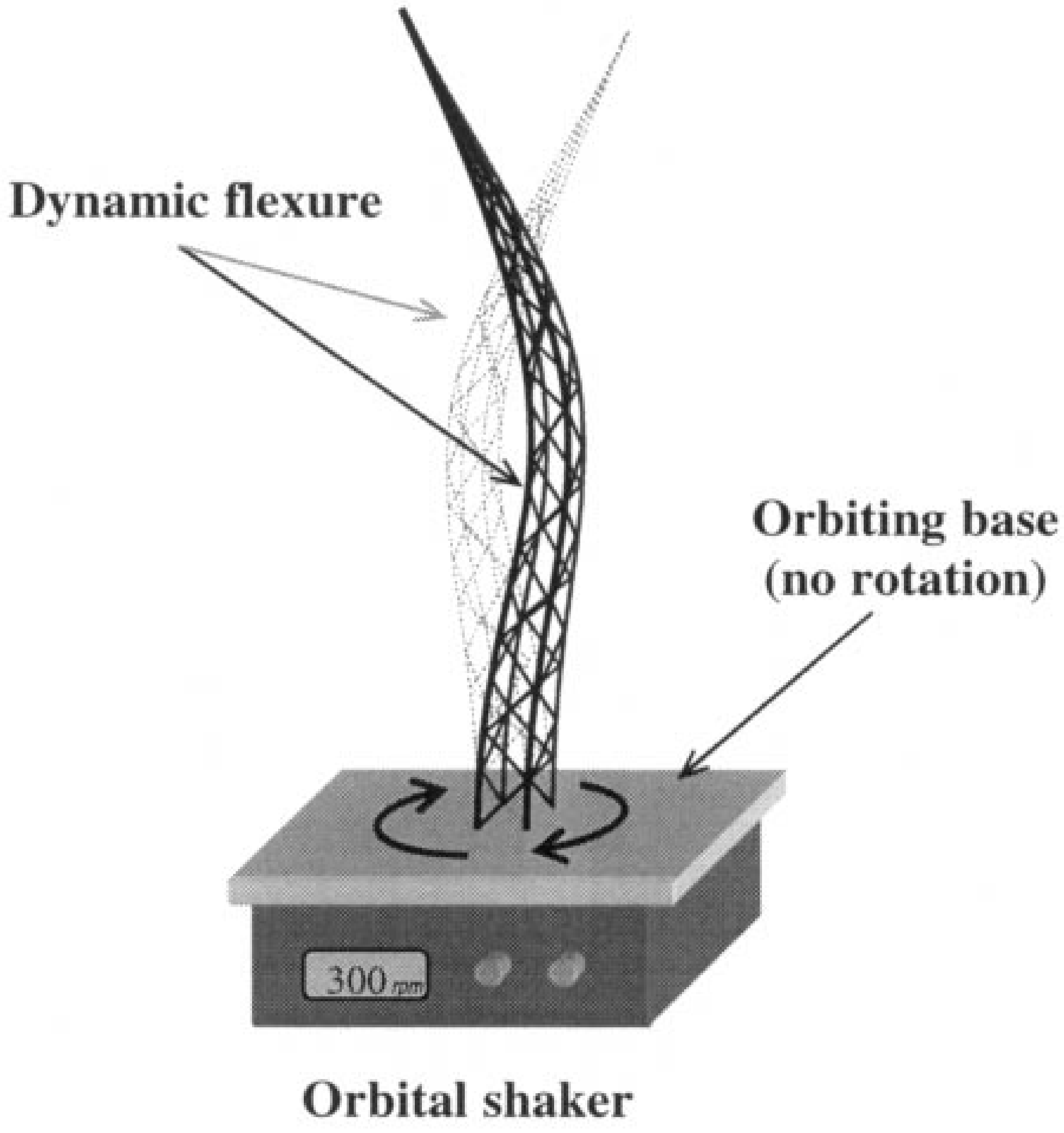

Fig. 4. Schematic description of the shaking tower.

was irrelevant to the problem definition. In contrast, the winning team, through many preliminary experiments derived the optimal concept of a lightweight, slender, and flexible structure, which withstood the orbital motion without failure (Fig. 4). The lesson from this project was that a *complete understanding* of the design requirements is crucially important. Moreover, expert advice is effective only when given within the context of the *exact problem definition*.

In the meeting following the competition the dynamical response of deformable structures was discussed. Specifically the notion of natural frequencies and modes, mode coupling (e.g., 'cross-talk' between bending and torsion modes), resonance, the dependence of natural frequency on the deflection amplitude, and damping were explained. The relevance of these phenomena to technological products was emphasized.

Often in dealing with new projects, students consult with faculty staff members that have relevant expertise. In many cases the students are referred to undergraduate textbooks, and then express typical frustrations such as 'we know we can solve the heat conduction problem by solving this partial differential equation, but PDE's will only be taught next year'. Even though they do not always obtain complete answers, the students gain a preview of the material they will encounter later on in their studies. When they do finally enroll in these courses, they already have a general idea of what they are about to learn and the relevance of the material. From student feedback this early exposure to advanced material helps them assimilate new material more efficiently later on in their studies.

TEAR-IT-APART LABORATORY

The objective of this laboratory is to analyze an existing product and identify the considerations of the engineers whom have designed it. A computer hard-drive was chosen to serve this purpose as it includes many different technologies. By default, ME students assume hard-drives are designed exclusively by electrical engineers and physicists. This device is naturally identified as a 'high-tech' component and the students initially fail to see its relevance to the field of ME. Through this lab the students realize that the mechanical engineer has an important role in designing computer hard-drives and that there is still much work to be done to improve these products.

To give structure to the lab the students are given a list of leading questions that have to be addressed in the lab report. By considering the questions the students realize that there is an intention behind each and every component they see. They are encouraged to identify the problems that these components were designed to resolve. Working in teams, the students systematically take apart the hard-drive while documenting their findings in a way that facilitates writing the lab report.

A few of the features in hard-drives that are related to the field of ME are:

- aerodynamically driven filtering system;
- venting system for pressure equilibration;
- hydrodynamic bearing of the read/write head;
- disk and head driving system—open or closed loop controls, static and dynamic balancing, inertia reduction.

Also, careful inspection of the dismantled device helps identify many manufacturing and packaging considerations. The electronics card is given special attention. A general overview of VLSI fabrication technology is given with emphasis on the mechanical properties of microelectronic devices and of the manufacturing machines. The processes used in microchip packaging, i.e. dicing, wire bonding, and polymer casting, are explained, and the mechanics and machines relating to each process are described.

Although the structure and operation of hard-drives is well documented, it is only by direct personal investigation that the student can internalize the operation principles of the device. Moreover the differences between the hard-drives made by different manufacturers demonstrate that the solution to some engineering problems may be very diverse (even though engineering seems to be an 'exact' science). Occasionally the dismantled devices reveal economic considerations affecting the design. For example, some hard drive models include a few extra disks whose read/write heads are not installed. In this way the production of the next generation of hard drives, with more disk space, can be manufactured in precisely the same process because the old and new models are identical except for the final connection of several read/write heads.

This exercise as a whole educates the students to critically examine engineering products and to try and understand the broad considerations that lead to its design. In addition, this exercise encourages the students to learn from the experience of other engineers and thus make their own design process more efficient.

CONCLUSION

The course presented in this paper, addresses some of the difficulties experienced by freshmen ME students. Many of these difficulties emanate from the lack of a clear perception and understanding of the ME vocation. One effect of this is that many students find it hard to see the relevance of the theoretical material they are taught. Another effect is that the students do not identify with the field they have chosen.

Student feedback confirms that the course helps them develop a clear perception of ME, and also gives them a general idea of what engineering work is about. Moreover, the course prepares them for later studies in the sense that it shows the relevance of physical models and mathematical tools to engineering.

The course provides a positive experience of personal involvement in the learning process. Through teamwork and competition with peers, the students gain an intimate perspective of the process of research and development of new technological products. Also, the course assists in familiarizing the students with the faculty and their different fields of expertise, and in this way promotes the students' identification with the field of ME.

An additional advantage of the teaching methodology is that it gives students an opportunity to considerably improve their performance as the semester progresses. During the course, many teams seemed to have suddenly realized that it was entirely up to them to determine the quality of their work thus stimulating them to demand more of themselves and realize more of their potential.

The course and methodology presented in this work are continuously being improved. The course is currently being monitored by education experts in order to quantitatively measure its quality and its effectiveness in meeting the course objectives.

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