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Integrating Analysis and Design in Mechanical Engineering Education

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Abstract

Mechanical engineering (ME) departments in research universities face the challenge of educating mechanical engineers who will graduate with a balanced knowledge in engineering science and mechanical design. The source of this challenge is the inherent difference between teaching analytical thinking, which is required for most engineering-science courses, and design thinking, which is required for project-based design courses.

The purpose of this paper is first to propose a new approach that can potentially bridge the educational gap between analytical and design thinking, which we refer to as *integrated thinking*. Second, we show how it can be applied to various ME undergraduate courses, which we refer to as *integrated courses*.

Our approach reforms science engineering courses by (a) stressing the physical interpretation of mathematical derivations; (b) requiring students to analyze, design, and sketch simple mechanical devices based on the learned theoretical material; and (c) modifying project-based design courses to emphasize the importance of analysis as part of the creative design process.

A pilot course focusing on dynamics and vibration, which we called Integrated Design and Analysis, was offered in the ME department at the Technion, where it was well-attended by senior ME students.

The positive feedback of the students who took the course suggests that integrated thinking might be successfully applied in many areas of ME education, such as fluid mechanics and heat transfer, control, and mechatronics, and that our approach may contribute to changing the current divided pattern in ME education.

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1. Introduction

Many mechanical engineering (ME) departments in research universities face the challenge of improving design and engineering education [1]. In the past, engineering schools in the United States and the countries that follow US higher-education methods focused on engineering science and mathematics requirements to help engineering students understand the complex principles of modern technology. However the change toward more theory in the engineering curriculum has produced graduates with far less experience in the practice of engineering and design [2].

Today, the core engineering-science courses are taught using a strong analytical approach. As a result, after two to three years at school most ME students form the notion that analysis or analytical thinking is the only tool or language at their disposal. Senior students who later decide to major in design and manufacturing and become more involved in project-oriented design courses acquire knowledge of design methodology, its language and thinking, and thus gradually learn how to view engineering problems from a new design perspective [3].

Design thinking and analytical thinking differ in numerous ways [4]. Analytical thinking requires that the student learn how to develop a correct solution to a well-defined problem in a specific knowledge domain using the language of mathematics. By contrast, in design thinking the student must weigh several plausible concepts, select the one that best satisfies the customer's requirements, and then describe it in detail using multilingual tools including physics, mathematics,

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graphics, and verbal and written representation. Analytical thinking may be described as a converging process that leads to a single correct answer. Design thinking may be described as a diverging-converging process in which more than one concept may be found suitable [4].

Design is widely regarded as the main activity in engineering [5]. The task of engineers is to create solutions and design systems to meet social, industrial, and commercial needs. Engineering education must, therefore, produce engineers who can design [4]. In order to improve design education, many universities recently started teaching engineering design through senior project courses referred to in the United States as *capstone courses* [3]. Design-educators are responsible for improving the balance between theory and practice in engineering education [6]. Dutson et al. in a thorough review paper of over 100 sources on engineering design courses found that the capstone courses were often developed in order to better prepare graduates to meet the needs of industry [7]. As a result, industry now often offers "authentic involvement" [6] in senior-level project courses by providing needed funding, equipment, and know-how [8]. Industry-sponsored courses also offer instruction and practice in design methodology, conceptual design, and detailed design, ultimately culminating in a product that the student builds and tests [7]. Nonetheless, in some schools, the project-based courses are initiated by internal customers; that is, design professors whose resources are necessarily limited.

Those in favor of industrial projects insist that real engineering is experienced only when students work on a real industrial problem. Those against industrial-sponsored projects argue that many of them require only low-level analyses that do not "push back the frontiers of knowledge" [6]. Both positions are often valid. Students tend to be enthusiastic about working on real industrial projects, but in their preoccupation with creative tasks, design thinking, design methodology, and many additional complex design details, they tend to exert less effort in performing advanced analysis and are content instead with only rudimentary analysis, merely sufficient to guarantee that the product functions.

The disintegration of analysis and design is our main interest in this paper. We will try to answer why it is so common for such little effort to be invested in analysis during the design process and why students, and later on also practicing engineers in industry who studied advanced analytical methods for years tend to "forget" to apply advanced analytical methods when it comes to design. We propose a new approach, which we refer to as *integrated thinking* that can be implemented in what we call *integrated courses*. We will try to close the gap between analysis and design by impressing on students that the application of analytical skills during the design process distinguishes the outstanding design engineer from the merely good one. This new approach to teaching does not feature projects or case-studies [9]; our concept of an integrated course combines design and analysis, which are typically taught as two separate disciplines.

Integrated courses may also be able to generate new opportunities for research faculty who are interested in teaching courses with design elements by enlisting the help of a teaching assistant with practical design experience. Such courses should focus on understanding the physics behind the mathematical derivations and include examples using industrial applications. They may also encourage design-educators to add analytical components to their courses, thus bridging the type of design and analysis divide described by Todd and Magleby [10].

In the second section we describe in detail the inherent difference between design courses that teach design thinking and analytical courses that mainly apply analytical thinking. In the third section we introduce the idea of integrated thinking and integrated-engineering courses, followed in the final section by a brief description of our new course, Integrated Design and Analysis, illustrating how we implemented our integrated teaching approach.

2. The difference between analytical thinking and design thinking

The main language in engineering-science courses is mathematics. Problem solving in this field requires that the data be precisely given; only one correct solution is expected, which can only be arrived at by using analytical skills and which is typically bounded by some learned-knowledge domain. The problem-solving process may be described as a converging sequence of equation derivations resulting in the final solution [4]. Typically, the need for creativity is limited throughout undergraduate studies, whereas students studying for advanced degrees *must* be creative to conduct successful research. Modeling is ideal and that sometimes makes use of synthetic symbols. In engineering-science courses, we discourage a trial-and-error approach except if an analytical or elegant solution is impossible. In most cases, work is performed individually, hence it is the student's personal abilities that are evaluated and individual performance that is either rewarded, or – if errors are found, for example, in the derivation process or in the final result – they are penalized. Engineering-science courses supply powerful engineering tools that mechanical engineers apply throughout their careers. Many research faculty believe that the main goal of analytical courses is the training of the next cadre of researchers in academia.

In contrast, design courses are multilingual and employ the language of physics, mathematics, graphical drawings, and verbal and written statements. As to problem solving, it is the customer's requirements that define what must be designed and the data is only partially provided or not at all; the designer must therefore estimate [11], measure, or assume all the information needed. Synthesis skills are needed to arrive at a design concept, but they must be supported by a thorough analysis. Thus, a design problem is approached using a diverging-converging process [4], which begins with several concepts that the designer weighs, the best of which is selected and finally translated into a detailed design. Limitless creativity may be exercised in the design process, as long as the solution meets the requirements. In the design process, modeling is used as a concrete tool representing real physical elements; for example, a simply supported beam cannot be placed on two hypothetical triangles, but must rather be physically realized. In design courses we encourage an iteration process in order to refine the options under consideration [12], and we use the trial-and-error approach to arrive at an optimal solution. Error making is integral to the design process and is accepted as a common way of gaining experience. Finally, in most cases, design projects require team work [8, 13], and in many situations individual contributions are less important [12]. The