Skill-Based Teaching For Undergraduate STEM Majors

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ABSTRACT

This article presents a case study that illustrates the paradigmatic shift in higher education from content-centered teaching to learning-centered academic programs. This pragmatic change, triggered by the STEM movement, calls for the introduction of success measures in the course development process. The course described in this paper illustrates such a goal-driven approach to the development of an entire multidisciplinary curriculum in mechanical engineering and mechatronics. The effectiveness of this new curriculum was confirmed by findings of a survey of graduates of the first six graduating classes who studied on the basis of this curriculum.

Keywords: Learning Outcomes; Course design; Engineering Education; Mechanical Engineering; Mechatronics; STEM

INTRODUCTION

The technological changes in the past thirty years lead to a pragmatic change in teaching methods (Davidovich 2014). The main change - consisting of greater emphasis on teaching learning skills rather than on transferring knowledge - led to a change in the way courses are designed to ensure that the courses meet a set of predefined goals.

Learning-centered teaching is not a new educational paradigm (Seel, 2003), and its roots can be traced to the US progressive education movement in the late nineteenth century. The learning-centered approach is based on the principle that knowledge can best be transferred to learners by causing learners to discover or acquire knowledge independently (Rogoff, 1994). This approach constitutes a radical shift from the traditional approach that conceptualizes learning as a passive process of knowledge reception. In learning-centered teaching, the teacher engages the learner in an active process in which learners go through a process of change (Gehart, 2011) and growth that enhances their abilities to cope with changing life challenges (Kuh et al., 1991). The nature of the learner's process is, in fact, a key focus of the learning-centered approach, which is designed to challenge students and give them an opportunity to grow (King & Anderson, 2004). The learning-centered approach is thus based on the premise that what students do is more important than what they learn in their undergraduate studies (Kuh et al., 2010).

The research literature shows that this approach indeed promotes higher quality learning. One typical study that compared the impact of learning-centered and teaching-centered educational methods on students' knowledge and attitudes in a statistics course (Harpe, Phipps & Alowayesh, 2012) found that students in the learning-centered approach were more knowledgeable, expressed more positive attitudes toward their learning environment than students in a teaching-centered course. Table 1, adapted from Barr and Tagg (1995), summarizes the main differences between the teaching-centered and the learning-centered approaches. This table will be later used to compare the goals set for the teaching program brought here as a case study and those of the newly conceived learning paradigm.

Table 1. A Comparison between the Instruction and Learning Paradigms

The Learning Paradigm	The Instruction Paradigm
Mission and Purposes	
Produces learning	Provides/delivers instruction
Elicits students' discovery and construction of knowledge	Transfers knowledge from faculty to students
Creates powerful learning environments	Offers courses and programs
Improves the quality of learning	Improves the quality of instruction
Achieves success for diverse students	Creates access for diverse students
Criteria for Success	
Student learning and other student outcomes	Inputs, resources
Quality of graduating students	Quality of entering students
Learning technologies development	Curriculum development, expansion
Quantity and quality of outcomes	Quantity and quality of resources
Aggregate learning growth, efficiency	Enrollment, revenue growth
Quality of students, learning	Quality of faculty, instruction
Teaching/Learning Structures	
Holistic; whole prior to parts	Parts prior to whole
Learning held constant, time varies	Time held constant, learning varies
Learning environments	50-minute lecture, 3-unit course
Environment ready when student is	Classes start/end at same time
Whatever learning experience works	One teacher, one classroom
Cross-discipline / department	Independent disciplines / departments
Specified learning results	Covering material
External evaluations of learning	End-of-course assessment
Public assessment	Private assessment
Degree equals demonstrated knowledge and skills	Degree equals accumulated credit hours
Learning Theory	
Knowledge exists in each person's mind and is shaped by individual experience	Knowledge exists "out there"
Knowledge is constructed, created	Knowledge comes in chunks and bits; delivered by instructors, absorbed by students
Learning is a nesting and interacting of frameworks	Leaning is cumulative and linear
Learning is student centered and controlled	Learning is teacher centered and controlled
Learning environments and learning are cooperative and supportive	The learning environment is competitive and individualistic

(Source: Davidovitch, 2013, p. 332).

TOP-DOWN COURSE DESIGN – FROM STEM DISCIPLINES TO ALL ACADEMIC DISCIPLINES

The learner-centered approach or "learning paradigm" was embraced by the STEM movement, which emphasizes teaching of **S**cience, **T**echnology, **E**ngineering, and **M**athematics, which was introduced in the 1990s by the National Science Foundation to encourage technological education (Wiggins & McTighe, 2005). The STEM movement prompted the development of formal goal-oriented course design procedures, or what is known as a "top-down method," which were not common practice at the time (Davidovich, 2014). According to the STEM approach, course design requires instructors to define course goals, desired outcomes, teaching strategies, and assessment methods (Davidovitch, 2013).

The design of a goal-oriented course is based on first defining the goals that the course expects to achieve. In the second stage, instructors define the desired outcomes: They specify the knowledge and skills that the instructors expects the students to acquire during the course, their relevance to the desired outcomes of the program to which the course belongs, and the significance of these outcomes for students' professional career (Daugherty, 2006). Teaching strategies should be designed to maximize students' acquisition of the knowledge and skills defined in the desired outcomes. Emphasis should be placed on the interaction between knowledge and skills (Davidovitch, 2013). Finally, the instructor should select assessment methods that are compatible with the stated goals (Davidovitch, 2013).

Constructing courses using a top-down design is based on the premise that teachers must clarify to students in advance what they are expected to learn, do, and understand by the end of the lecture or course. Top-down course design forces instructors to shift the focus of course design from course contents to course outcomes. As a result, top-down course design enhances students' in-depth knowledge as well as their metacognitive skills and their ability to search for and find information (Thompson & Licklider, 2011). Top-down design specifically is oriented to urge students to maximize their abilities and encourage them to relinquish the position of passive recipients of knowledge.

Until now, emphasis in implementing goal-driven course design has been on the effective design of individual courses, whereas no course should be taught in isolation if it is to ensure that overall program goals are met as well. The following case study describes and analyzes a goal-driven approach to course design that applies the learning paradigm and the STEM approach at a programmatic-curricular level.

CASE STUDY

This case study is based on a multidisciplinary undergraduate teaching program in Mechatronics, developed at Ariel University and described in detail in Shiller (2013). Unlike competing teaching programs, where Mechatronics is taught as a specialization, usually inserted into an existing program in Mechanical Engineering towards the end of the study program, this was designed as a full-fledged four-year program that meets a predetermined set of goals.

The goals of the program include:

1. Educate engineers with a multidisciplinary background in mechatronics
2. Teach students teamwork and project management
3. Provide graduates with the skills to serve as product developers and project leaders in the broad area of mechatronics and robotics
4. Provide graduates with the skills that need to function as traditional mechanical engineers
5. Empower graduates to use their engineering skills to contribute to society through engineering and to assist weak segments in society
6. Encourage students to be creative and entrepreneurial
7. Instill in students lifelong self-learning skills
8. Instill in students professional ethics

The desired profile of the graduating engineer of this program is, therefore, a multidisciplinary engineer, capable of working independently as a product developer, serving as a project leader, working as a mechanical engineer, and being a conscientious contributor to society. This set of goals combines knowledge, teamwork, leadership, entrepreneurship, and self-learning skills (Davidovitch, 2013). They are similar to the STEM goals and they were conceived independently of the STEM approach to higher education in 1996, before learning outcomes were used in 2005 to design science and engineering courses and programs (Woodruff, 2013).

To reach these goals, we began by defining the nature and scope of the capstone design project, and then determined the skills required to succeed in the project, and only then structured the program such that the students would reach the project well prepared. This process is based on the premise that the project will both help students integrate the knowledge they had acquired in the three tracks of the program, experience working in teams, and demonstrate their broad skills as engineers.

The following will briefly detail the program's objectives and structure, including some of the key courses designed specifically to meet the program's goals. The program’s success was evaluated using a survey conducted among graduates. We discuss whether this paradigm of the program's design (as opposed to course design) can be adopted in other disciplines. A detailed description of the program is available in Shiller (2013).

Mechatronics

The four-year mechatronics program was established at Ariel University in 2002 in response to a growing need for mechanical engineers with a multidisciplinary background in mechanics, electronics, and computing. The program was designed to educate engineers to serve as independent product developers and as project leaders of mechatronic/robotic systems for both hi-tech and traditional Israeli industries. It offers a B.Sc. Degree in Mechanical Engineering and Mechatronics.

The program uses a spiral approach that guides students to gradually progress from simple to more complex concepts, corresponding to their expanding levels of knowledge and experience. The program offers four parallel three-year tracks in Mechanical Engineering, Electrical Engineering, Computer Science and Engineering, and Mechatronics. In this structure, students absorb new concepts through repeated encounters in subsequent courses and laboratories; By the time they reach the capstone design project in senior year, they are well prepared for independent project work.

Curriculum

The Mechatronics curriculum was designed to provide students with the analytical and experimental skills required to design and maintain mechatronic and robotic systems. It is based on a mechanical engineering core, with an emphasis on mechanical systems, and three minor tracks in Electronics, Computer Science and Engineering, and Mechatronics. The three minor tracks progress parallel with the core program, such that the students gradually acquire skills in both fields prior to their integration in the final capstone project.

In the *Electronics* track, students study physics in the freshman year, and two courses and two laboratories in analog and digital electronics. The early introduction of these subjects prepares the students for more advanced courses on sensors, actuators, and microprocessors, in the second year. To improve students' hands-on skills in electronic circuits, students build the circuits they need instead of using pre-assembled development kits. The curriculum's emphasis on circuit design helps students develop an intuitive understanding of electronics, which is otherwise quite difficult for mechanical engineers.

In the *Computers* track, students take at least one course in computers every year; starting with a course in C programming. Skills acquired in this course are then used in the next course on data structures and algorithms. Students continue to practice their computer programming skills in the Microprocessors Laboratory, and then in the Robotics and Mechatronics laboratories. Students learn how to program the microcontrollers and also build the interface circuits that are required in electrical motors (DC and stepper), analog and digital inputs, and serial communications. As a result of the effort in building these peripheral circuits independently rather than relying on ready-made kits, students gain the necessary background to design the environments they will need in more advanced Mechatronics laboratory work as well as in their final project.

The *Mechatronics* track runs parallel to the core program and is aimed at gradually integrating mechanics and electronics. First, the course on linear systems trains students in modeling and analysis of electromechanical systems using Bond Graphs. The use of Bond Graphs emphasizes the equivalence between the dynamic behavior of mechanical and electrical components. The ability to model dynamic systems without first converting them to resistors and capacitors (as in electrical engineering) or to springs and masses (as in mechanical engineering) is at the core of the mechatronics curriculum. The theoretical introduction to electromechanical systems is followed by a control course, where students learn how to shape the system's performance using linear control theory. The introduction is followed by a practical demonstration of mechatronics in two laboratory courses: Robotics and Mechatronics. In the Robotics Laboratory, students' learning is focused on classical controls and robotics using analog electronics, while in the Mechatronics Laboratory, students use microprocessors and digital electronics to focus on digital controls. Students learn to apply theoretical knowledge through hands-on experience in the Robotics and Mechatronics laboratories. To conclude their studies, students work on a final capstone design project where, in groups of three, they design and build a robotic device that is able to execute a pre-assigned task. In the final project, students are responsible for the mechanical design, the electronic circuits, the microprocessor interfacing, and the programming of the system. Work on the project extends over two semesters: In the first semester, students focus on design, and in the second semester they proceed to programming and manufacture.

Capstone Design Project

The senior design project integrates the various topics studied in the Mechatronics program, and also meets objectives 3-6 of this program (listed above). In groups of two to three, students design and build a practical robotic device that addresses a true need in daily life. The capstone design project consists of a three-course sequence: Engineering Design, Project 1, and Project 2. In Engineering Design, the students learn the design process, which includes the identification of true needs, translating the needs to engineering requirements, defining product specifications, and selecting a conceptual design. In Projects 1 and 2, the students design and build the system specified in the Engineering Design course. Project 1 is focuses on the design process, while in Project 2, students focus on manufacturing, assembly, testing, and presenting their work. All project courses are taught in large groups of 30-40 students, to enhance a rich exchange of ideas and feedback when students discuss their designs and work. In several brainstorming sessions, peers can criticize and suggest alternative solutions to the project of the presenting group, which helps students learn from each other and improve their designs. The interactions contribute to students' creativity and critical thinking. Although students may be reluctant to share their work in progress with their peers, over time they experience the benefits of these interactions and the exchange of ideas. Therefore, the project is not set up as a competition, but as an activity that is shared with the entire class. Such a climate also encourages teams to collaborate, and encourages students to share their knowledge with their peers. The social experience of working in a group on the project typically creates a positive experience for students and is the source of social support in this highly demanding period of their studies.

The emphasis on addressing a true need is motivated by objectives 6 (creativity and entrepreneurship) and 5 (contribution to society) discussed earlier. The ability to identify a real problem that needs a solution and is commercially viable is a necessary skill of any successful entrepreneur. This stage of the project compels students to think about product design in the context of the market's needs. Projects that cannot be commercially justified are not approved.

Another benefit of this stage of the project is the experience gained in solving an open problem, which includes the selection of the problem. Students are encouraged to identify a true need, and then propose a viable solution to address this need. For this reason, and contrary to common wisdom, cooperation with industry is not encouraged, since industrial advisors often dictate the project's topic and scope, thus skipping the initial stage of problem definition. For many students, this project might be the only chance in their entire career to perform all stages of an entire task from inception to completion. Students who find that they enjoy independent work of this kind may become entrepreneurs, while the majority will become members of established engineering groups.

Guiding the students to address the needs of weak segments of society meets goal five by instilling in them a sense of social responsibility, an issue that is frequently ignored in engineering education. To enhance their awareness of the needs of specific groups, students visit facilities of various kinds, including hospitals, nursing homes, and rehabilitation centers. They also observe potential users and interview them, to gain to better understanding of their true needs. In this process, students develop empathy for these users, and the visits constitute a valuable lesson that has a lasting effect on these future engineers and their practice, and on their role as citizens in society.

Figure 1. Representative projects. Clockwise from top left: a robotic sprinkler; a stair climber; a system to lift patients from beds; a step-free ladder and a mobile platform to move people and heavy items around the house; an automatic page turner; a robotic window cleaner.

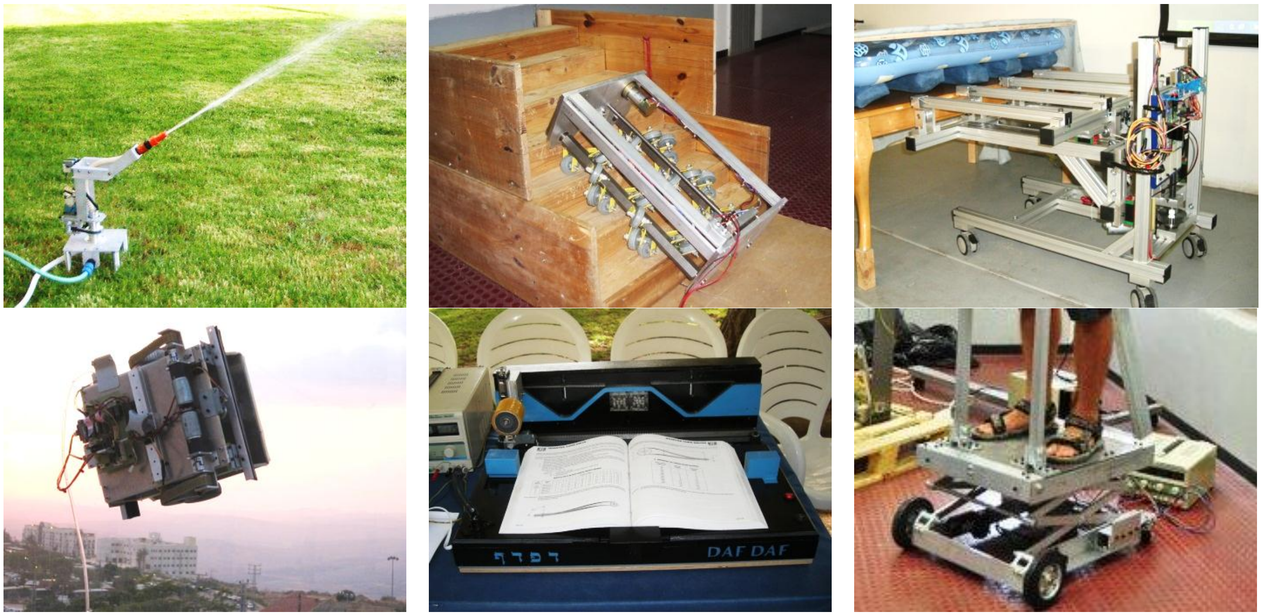

Figure 1 shows six sample projects, each representing a commercially viable consumer product. These projects were designed to assist the elderly or the handicapped in climbing stairs, turning book pages, lifting sick people from their beds, reaching high places in the home and moving heavy items, and performing regular tasks around the house, such as window cleaning and efficiently watering the backyard. In all projects, the main challenge and focus was on the mechanical design. The students were constantly aware of the impact of their mechanical design on the electronic circuitry and algorithms. The end results were working prototypes that successfully demonstrated students' mastery of the material and their skills as product designers and system integrators.

Program Evaluation

The program was evaluated using a questionnaire sent to students who had graduated from 2006 to 2012, a total of 200 graduates of which 66 responded, the large majority of them men. The response to a subset of the questions, which were part of a larger survey (Shiller, 2013) conducted among our graduates as related to the program's goals, are summarized in Figure 2.

From the replies to question 1, it appears that 88% of the respondents are working, to some degree, in mechatronics-related jobs. This high number indicates that our main goal in educating engineers with multidisciplinary knowledge in mechatronics and robotics was accomplished. Furthermore, while the majority (86%) had minimal knowledge of electronics when beginning the program (question 2), most (94%) had gained significant knowledge by the end of the program, and rated themselves as having at least an average level of knowledge in this field (question 3). This response is not an objective measure of knowledge but rather indicates the graduates' sense of confidence in electronics, and is a strong indication of the success of the spiral approach in teaching electronics to mechanical engineers. Notably, electronics is central to electrical engineering, which is a discipline in itself and was not chosen as a major by these students, which makes their response to this question so much more remarkable.

A considerable proportion of the respondents (74%) to question 4 found this knowledge useful in the market place. This finding indicates success in meeting goals 1 and 3 of providing engineers with a multidisciplinary background and skills in mechatronics and robotics. It also indicates that the graduates found ways of practicing their multidisciplinary knowledge and skills.

When asked if they felt they were in competition with the other groups in the project (question 6), 59% responded negatively. This might explain the high number (69%) of students who received help from other groups (question 7). This meets the program's goal 2 of encouraging teamwork.

The responses to this questionnaire suggest that the program's short-term goals (1-3) were largely achieved. Evaluation of other long-term goals, such as self-learning skills, creativity, and entrepreneurship, require a longer time span from graduation.

Figure 2. Graduates' responses to questions regarding the knowledge and skills they had acquired in this program (Shiller, 2013).

	Question	Very high	high	Aver.	low	Very low
1	To what degree is your job related to mechatronics?	29%	30%	29%	8%	5%
2	Please rate your knowledge of electronics at the beginning of the program.		6%	8%	86%	
3	Please rate your knowledge of electronics at the end of the program.		37%	57%	6%	
4	To what degree does your knowledge of electronics help you as a practicing engineer?	13%	24%	37%	11%	16%
5	Please rate the extent to which the program addresses the genuine needs of weaker segments of society.	23%	34%	16%	15%	13%
6	To what degree did you feel that you were in competition with the other groups in the project?	75	12%	22%	12%	47%
7	To what degree did you receive assistance from other groups in the project?	14%	31%	24%	20%	10%

CONCLUSIONS

This article addresses the need for a paradigmatic change in higher education from content-centered to learning-centered academic programs. The need for a paradigmatic change stems from the information revolution that brought knowledge to the masses, not necessarily through traditional academic studies. As a result, the teacher's role has shifted from the main source of knowledge to the role of a motivator who helps and promotes students' acquisition of learning skills.

This pragmatic change was adopted by the STEM movement that imposed success measures on course development such that teachers are aware of course goals and learning outcomes. In contrast to STEM, where the focus has been on individual courses, our case study describes a holistic approach that adopts a programmatic perspective in developing an entire teaching program. The design of an entire program seems no different in principle than the design of a single course; both require a clear mission statement, criteria for success, and an emphasis on learning skills rather than simply on delivering knowledge.

The case study describes a multidisciplinary teaching program in mechanical engineering and mechatronics. It has a top-down design, to provide students with the broad knowledge and skills required to succeed in their senior capstone design project, which served to define the program's goals. The emphasis on developing learning skills, instead of just delivering knowledge, greatly empowers students towards being able to undertake a challenging task such as designing and producing a working prototype of a complex mechatronic system.

A survey of graduates over six years since the inception of this program reveals that the program has met its main short-term goals, such as teamwork and the ability to integrate the multidisciplinary knowledge in solving practical problems. In addition to this survey, the program was evaluated by an international committee that praised the "final projects [as] outstanding capstone experiences," appraised the graduates as "prepared for successful careers as practicing engineers," and noted the "visionary leadership in the design and development of the study program" (CHE).

It is important to note that the program was conceived in late 1999 intuitively without being aware of the STEM movement. Nevertheless, it followed established paradigms that are currently well accepted by the education community. That this approach was applied holistically to the entire program, rather than just to individual courses, may partly explain the program's success. Another contributor to its success is the fact that it was created at the time of the department's establishment, and encountered then little resistance to change as faculty were not clinging to longstanding paradigms and patterns as in more established academic departments. A great challenge in the development of new study programs in established department is the early engagement and consensus of the faculty in the program's design process.

Finally, while the significance of STEM disciplines cannot be denied, the question is whether these fields are superior to others, such as the humanities. We think not. We must strive for effective learning outcomes not only in the STEM disciplines but rather in all academic disciplines.

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