Teaching Engineering Design: A Hybrid Framework

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Abstract

This paper presents a framework that utilizes both behaviourist and constructivist learning models for teaching engineering design. The instructional design methodology is based on the Elaboration Theory that allows a gradual transition from content-based instruction to project-based knowledge construction. The practical steps are detailed for a full-year design course at the sophomore level.

1. Introduction

Design is being reintroduced into the engineering curriculum. Only recently, the leaders of engineering departments have begun to recognize the intellectual complexity and resource implication of effective design education [1]. The traditional engineering curricula, spread from the mid-1950s into 1990s, introduced design at the senior level, hence viewing it as a by-product of engineering education that cannot occur without the solid formation of engineering sciences [2]. Thus, the intellectual merit of design was mainly attributed to system analysis, using scientific principles, and consequently design problems were defined within a “tamed context” to be analyzable, far from the real-life situations. The result was not impressive: the graduating engineers were perceived by industry as unable to tackle real problems and manage professional design practice, because of the change of focus from theoretical to practical [3]. In response, capstone design courses were introduced into the curriculum through which “real” problems were brought in from industry, along with some expertise and financial support. Nonetheless, the emphasis remained on analyzing (and celebrating) fundamental scientific principles [4]. While capstone design courses have proven to be useful [5], an alternative paradigm has emerged for design pedagogy, which argues that analytical knowledge is not adequate for tackling real-life engineering problems, and that design contains an additional body of knowledge that is as vital to engineering education as engineering sciences are [6]. The new paradigm further argues that design can be viewed as a means of learning engineering not a result of it, leading to the introduction of design courses at the freshman and sophomore levels, usually dubbed as cornerstone design courses [7]. Both anecdotal data [8] and hard evidence [9] have indicated that cornerstone courses enhance students’ motivation, their retention in engineering programs, and their performance in senior engineering science and capstone design courses. A major breakthrough in teaching cornerstone design courses, albeit previously practiced in the senior capstone designs, has been the adoption of project-based learning models and student-centred, experiential teaching/learning mechanisms [10]. Despite a number of positive reports [11], the efficacy of project-based education in engineering programs has yet remained to be investigated thoroughly (e.g., [12]). Nevertheless, teaching cornerstone design courses through a hands-on approach seems quite appealing to both instructors and students, partly because bringing abstract notions of design in the classroom and yet maintaining students’ attention and interest in the subject is a great challenge for the instructors, and partly because students seem to be better able to make sense of design notions by experiencing them within the real-life context. A wide spectrum of project-based design instructions has been implemented, from case study to reverse engineering, to studio-based design, to full-scale projects tackling realistic (industry-customer) or semi-realistic (faculty-customer) problems [13]. Despite the diversity of instructional techniques, cornerstone courses markedly tend to pay more attention to conceptual design and less to detailed design and prototype fabrication [10], due to the shortage of time and experimentation/fabrication resources and also lack of adequate knowledge that students will acquire only later in the curriculum. Furthermore, little has been addressed in the literature about how to maintain a balance between direct instruction and self-controlled learning in a design course based on the underlying learning theories. The paper presents a hybrid framework for teaching cornerstone design courses based on the behaviourist and constructivist learning models, which ensures adequate instruction and scaffolding while students develop their design knowledge through hands-on projects. The learning models are discussed in Section 2. In Section 3, the expected design qualities that cornerstone courses should address and their relevance
to learning models are discussed. An instructional design theory that best utilizes learning models for teaching design is also introduced in Section 3. Section 4 details the application of the instructional mechanism to a second-year design course. Some concluding remarks are made in Section 5.

2. Learning Models for Instructional Design

The field of educational research provides a rich supply of learning theories and instructional design methodologies that need to be addressed in order to develop meaningful and effective design courses. The recent reform in the engineering education, emphasizing project-based learning, is broadly based on the constructivist learning theory, which represents a paradigm shift from the traditional behaviourist learning model. The work of Bruner [14], Piaget [15], and Vygotsky [16] among others provides historical precedents for the constructivist learning theory. Constructivism is often articulated in stark contrast to the traditional behaviourist model of learning. Behaviourism conceives learning as a process of changing or conditioning observable behaviour as a result of selective reinforcement of learner’s response to events (stimuli) [17]. The mind is seen as a tabula rasa to be filled by, or as a mirror to reflect, the objective reality [18]. Learning is considered as dissemination of knowledge via abstract representation of reality. Thus, the goal of learning, behaviourism holds, is to understand the reality and modify behaviour accordingly, and the purpose of teaching is to transfer the knowledge from expert to learner [19]. The behaviourist model is still widely adopted for instructional design of teaching factual or procedural knowledge of engineering. Instructors convert the reality into abstract or generalized representations, and transfer them to students through a well-planned, linear and gradual procedure in a “tamed” environment, be it a classroom or laboratory. The students’ performance is assessed by measuring the proximity of their behaviour (answering questions, writing reports and essays, performing laboratory experiments, etc.) to the expected outcome. In contrast to behaviourism, the premise of constructivism is that knowledge is created by learners, rather than transmitted to them. It is based on the epistemological ground that views knowledge not merely as the awareness of objects that exist independent of any subject, but also as a subjective and dynamic product of knower’s experiential world constructed through the senses and social interactions [20]. Thus, the constructivist model of learning advocates that, as von Glasersfeld states [20], “knowledge is not a transferable commodity and communication not a conveyance.” Individuals learn by experiencing the real world and challenging with the real problems. Hence, the role of teacher is not to dispense knowledge but to serve as a creative mediator and facilitator to provide learners with opportunities and incentives to construct their own perception of reality [21].

The implications of the above two learning theories in instructional design are as diverse as the theories themselves are. From a behaviourist perspective, the instructor analyzes the learning subject to develop the learning objectives and break down the learning tasks, and evaluation consists of determining whether the criteria for the objectives have been met. On the other hand, instructional design from a constructivist standpoint seems to be more concerned with the design of learning environments and less concerned with the selection and sequencing of instructional events. It requires that the instructor develop a product that is facilitative in nature rather than prescriptive. The learning content is not pre-specified; learning direction is determined by the learner, and assessment is more subjective because it relies less on specific quantitative outcomes and more on the process and learner’s reflection and self-evaluation. Hence, the guidelines for the constructivist instructional design can be summarized as follows [19, 22]:

- Create real-world environments that employ the context in which learning becomes relevant, and present realistic (multiple) approaches to solving real-life problems.
- Direct the learning exercises towards context- and content-dependent knowledge construction, not reproduction.
- Relate the learning experience to the students’ previous knowledge and background.
- Set the instructor’s role as a coordinator, facilitator, resource advisor, and mentor, and encourage apprenticeship learning.
- Communicate with the learner the teaching/learning strategy, and prepare the learner to take the ownership of her/his learning process.
- Support and promote collaborative construction of knowledge through social negotiation.
- Foster reflective practice, and promote metacognition and strategic self-awareness and self-regulation by learners.
- Devise authentic and integrative assessment based more heavily on the student’s learning process than the learning outcomes, and allow certain errors and mistakes by students as means of knowledge construction.

It has been pointed out by several educators [e.g., 23] that both behaviourist and constructivist learning models have their own merits depending on the
learning subject and circumstances. Some learning situations require highly prescriptive models, whereas others are better suited to experiential models. In the next section, the author attempts to make a point that both models can bring benefits, and thus should be adopted harmoniously, in teaching certain aspects of engineering design. A suitable instructional design theory can make this rapprochement happen, as discussed in the sequel.

3. Relevance to Design Education

Despite the apparent diversity of methods of teaching engineering design, certain characteristics seem to have been accepted almost unanimously amongst both design educators and design researchers. Sheppard and Jenison [13] summarize the expected qualities in a design engineer, and thus the topics that design courses should focus on, in 16 characteristics, which can be further categorized into a number of classes as listed in Table 1 (items are numbered according to [13]).

Several remarks about the list of design qualifications must be made:

- From Table 1, one may infer that some categories may not have been detailed adequately. This could be due to the fact that the majority of design courses, especially cornerstone courses, focus more heavily on conceptual and preliminary design, up to design on paper/computer, and less on detailed design to the level of prototype fabrication. Nevertheless, many researchers (e.g., [24]) have stressed the importance of physical artifacts in the learning process, and that students develop engineering intuition by continuously iterating between mental concepts and real hardware. Some important qualities listed in Table 1, such as teamwork, communication, and team- and self-management capabilities, will show their merit seriously only during the process of building the design concepts into real hardware prototypes. The process of building design artifacts usually proves to be the most challenging part of a design course, due to time constraints, limited resources, intense energy required from the team and instructor, lack of hands-on knowledge, critical need for careful team and project management, and numerous uncertain and unpredictable situations. Yet, design intuition comes to fruition effectively when the developed concepts are reality-checked with the working prototype.

- A major challenge in engineering design is to deal with open-ended, ill-defined problems in a complex world. Good designers are able to comprehend the complexity and dynamics of real systems, handle uncertainty associated with complicated or unknown phenomena, and make reasonable estimates. Hence, the task of system analysis in design involves imperfect models and incomplete information, and addresses issues such as reliability and risk factor. Therefore, as pointed out in [10], students in a design course should learn how to design experiments to better understand the problem, how to make intuitive estimates at various stages of design, and how to handle ambiguous, uncertain, and unpredictable situations.

- Engineering design is more than creating and implementing a technical solution. Today’s engineers must design by following certain standards and regulations. The practice of engineering is recognized in many countries as a profession, thus must comply with the professional conduct and code of ethics. Design courses should,
therefore, provide the awareness of certain standards in the field as well as rules of professional engineering. They should also address various ethical dilemmas that may arise during a design process.

- One important aspect of design that is not highlighted in Table 1, but should be included in the design education, is the ability to make decisions throughout the process and choose rationally among design alternatives based on certain criteria [25].

- Information processing has two ends: collection and dissemination. On the collection end, qualified engineers are experts at discovering just the required information when it is needed (just-in-time), and at distilling, synthesizing, and applying it for the achievement of a goal. The ability to extract the right information from the multiplicity of resources comes from experience and proper training. On the dissemination end, which must be added to the list of Table 1, it may not be an underestimate to say that engineers market their skills through the ability to communicate their knowledge and expertise. This communication occurs in a variety of formats, including design notebooks, proposals, technical reports, presentations, etc. Some documentation procedures have become mandatory elements of design protocols in various disciplines. For example, the ISO 9001:2000, Section 7.3, requires documentation of design activity to be certified for conducting business in the member countries [26]. Collection and dissemination of information should be equally emphasized in a design course.

- It is imperative that qualified designers be able to monitor and assess their performance during the course of design. However, the management capabilities of a good designer must extend beyond self-organization. Several researchers have pointed out that design process, particularly at the early stages, is inherently social but argumentative [e.g., 27]. Consequently, each member of the design team must be aware of the group dynamics and the requirements of forming a productive team and achieving maximum benefit from the diversity in the team. Further, being able to define the statement of work and prepare a plan for an engineering project, including a feasible schedule and a realistic cost estimate, are also part of the qualifications that must be conveyed to students in a design course.

The above discussions would result in a modified list of qualifications as shown in Table 2 (additional items are numbered after 16.) A number of qualifications listed in Table 2 (named here as Group A, i.e., 5, 13, 19, 1, 2, 3, 15, 16, 24, and 29) exclusively refers to the know-how that is built by the students symbolically, when they are making their own representation of the design problem and possible solutions, socially, when they are conveying to and negotiating with others their understanding, theoretically, when they try to explain

Table 2. Expected qualifications in design engineers that engineering courses should focus on. (Modified)

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<th>Qualifications</th>
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<tr>
<td><strong>Design Thinking Capabilities:</strong></td>
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<td>4. Utilize graphical and visual representations and thinking.</td>
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<td>5. Exercise creative and intuitive instincts.</td>
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<td>11. Think with a system orientation, considering the integration and needs of various facets of the problem.</td>
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<td>12. Define and formulate an open-ended and/or under-defined problem, including specifications.</td>
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<td>17. Make rational decisions about design alternatives based on certain criteria.</td>
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<td><strong>System Analysis Capabilities:</strong></td>
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<td>8. Use analysis in support of synthesis.</td>
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<td>9. Appropriately model the physical world with mathematics.</td>
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<td>10. Consider economic, social, and environmental aspects of a problem.</td>
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<td>18. Design experiments to better understand systems and verify ideas/hypotheses.</td>
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<td>19. Handle uncertainty and ambiguity is system modeling.</td>
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<td>20. Use statistical techniques as well as engineering intuition to make reasonable estimates.</td>
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<td><strong>Information Collection/Dissemination Capabilities:</strong></td>
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<td>6. Find information and use a variety of resources (i.e., resourcefulness).</td>
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<td>7. Identify critical technology and approaches, stay abreast of change in professional practice.</td>
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<td>21. Produce viable documentation, and present design ideas effectively.</td>
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<td><strong>Teamwork and Communication Capabilities:</strong></td>
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<td>1. Communicate, negotiate and persuade.</td>
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<tr>
<td>2. Work effectively in a team.</td>
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<tr>
<td>4. Utilize graphical and visual representations and thinking. (repeated)</td>
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<td><strong>Management Capabilities:</strong></td>
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<td>22. Be aware of effective team organization.</td>
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<td>23. Plan a design project, and follow the schedule.</td>
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<td><strong>Prototyping Capabilities:</strong></td>
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<td>15. Build up real hardware to prototype ideas.</td>
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<td>16. Troubleshoot and test hardware.</td>
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<td>24. Integrate various subsystems efficiently.</td>
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<td>25. Understand and dissect existing engineering products.</td>
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<td><strong>Ethical and Professional Capabilities:</strong></td>
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<td>26. Be aware of major standards of the field.</td>
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<td>27. Understand professional conduct and code of ethics.</td>
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<td>28. Can resolve ethical dilemmas.</td>
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relationships and phenomena while analyzing their solutions, and physically, when they are building and debugging their prototypes. Several other qualities in Table 2 (Group B: 4, 11, 12, 14, 17, 18, 21, 23, and 25) represent a mixture of know-how and know-what that can be taught initially by a series of instructions before enabling students to proceed their own experiential learning process. The remaining items in Table 2 (Group C: 8, 9, 10, 20, 6, 7, 22, 26, and 27) are mostly know-what that can be addressed and practiced in class/laboratory environments. Based on this classification, the majority of design qualifications (19 out of 28) contain some know-how that can best be gained by performing authentic tasks within realistic contexts using apprenticeship-mentoring relationships and taking into account negotiational and social aspects of the learning subjects. This analysis justifies the recent trend of introducing project-based design courses at all levels of engineering curricula, which can perfectly line up with the constructivist model of learning as discussed in Section 2. However, a mere project-based format does not automatically guarantee a genuine constructivist approach unless major guidelines mentioned in Section 2 are implemented in the instructional design. Furthermore, while project-based format seems to be a suitable option for a design course, assuming that the requirements of the constructivist model are met, a number of expected design qualities listed in Table 2 (Group C in particular) call for a systemic and procedural instruction, more compatible with the behaviourist learning model. In other words, it is granted that the core content of engineering design consists of know-how that should best be constructed by the learner through experiencing in realistic circumstances, but it also contains a certain know-what that can be transferred/instructed to the learner primarily to help her/him take the ownership of learning advancement effectively.

Several pedagogues have argued that both content and level of learning assign the suitable learning model. For example, Jonassen [18] states that the appropriate learning model directly depends on the learning level. For the introductory learning when the learner has little prior knowledge of the content area, the classical behaviourist model is most effective because it is predetermined, sequential, and constrained, so that learner can develop some anchors for future knowledge construction. For the advanced and expert learning stages, on the other hand, where learner is able to gain metacognition with respect to the content area, a constructivist approach would work more effectively. Similarly, Ertmer and Newby [28] stress that a behaviourist approach can effectively facilitate mastery of the content of a profession while constructivist strategies are suited to teaching expertise in solving ill-defined problems in unfamiliar situations through reflection-in-action. The impact of content and level of learning on the instructional design is effectively utilized in the Elaboration Theory [29]. The theory organizes instruction in increasing order of complexity, and gradually moves from prerequisite learning for introducing the basics of the content to the novice learner to “learner control” where the learner takes the ownership of both content and instruction. A pragmatic interpretation of the Elaboration Theory is the following: present the simplest representations of the learning content that relate to the whole task through simplest techniques (direct instruction) and gradually “enable” the learner to succeed levels of elaboration by “relaxing” the simplifying conditions (more realistic circumstances) so that the task becomes more and more complex [30]. This theory suggests a gradual transition from direct instruction to self-learning, and it is, thus, suitable for teaching subjects that require both behaviourist and constructivist models, such as Engineering Design. The next section details the development of a full-year design course for sophomores based on the Elaboration Theory.

4. Development of A Full-year Design Course for Sophomores

4.1. Background

The Engineering Design course has been part of the second-year syllabus of the Division of Engineering Science at the University of Toronto since 1972. Engineering Science is a special engineering program designed for top-ranked students to provide them with both breadth and depth of engineering fundamentals. The program emphasizes on interdisciplinary linkages in the first two years, and trains students in the third and fourth year in one of the specialized fields of their choice, such as Aerospace, Biomedical, Computer, Electrical, Manufacturing, etc. Since its inception, the design course has been responsible for teaching students the theoretical and practical notions of design and familiarizing them with technology advances. The course had been instructed as a semester course prior to 2001 when it was thoroughly reviewed. This paper is, indeed, a result of the review process and four years of instructing the course in the new format, as detailed in the sequel.

While studying the course goals and its instructional requirements, it soon became apparent that, aside from budgetary and resource limitations, time and workload are major constraints. In other words, a semester-long schedule, with the workload level reasonably balanced with other simultaneous courses, cannot be accomplished without comprising some of the
Two weeks earlier than the official termination of term, design activities in each semester end divided between fall and winter semesters. This would allow some students who may have classes. The course schedule is extended to 22 weeks, equally divided between fall and winter semesters. Consequently, the learning process in these semester courses is extended up to design on paper/computer, or even if they reach beyond to prototype fabrication the artifacts are primitive (such as kit-based projects [31]) and/or discipline-specific (such as remote control mobile mechanisms involving mechanical design only [32]). While conceptual design and system analysis are important aspects of engineering design, the author, along several other educators [24, 33], believes that in many engineering fields it is the process of “building” physical artifacts (in part or full scale) that completes the knowledge-construction process. In the case of Engineering Science design course, the artifacts are expected to convey the multidisciplinary nature of the program. That is, prototypes should involve at least mechanical (structure and mechanisms), electrical (circuits and instrumentation), electromechanical (actuators and drivers), and software (microcontroller coding) design. Consequently to these considerations it was concluded that one semester period is not sufficient for a comprehensive and multidisciplinary design course that addresses major qualities of Table 2 and genuinely implements the Elaboration theory for its instructional design. Relieving the time constraint was a breakthrough in the revised instructional design of the course, which enabled the author to develop a “hybrid” learning model that gradually shifts from an instructional behaviourist approach to a fully constructivist practice while addressing almost all the expected qualifications. An extended time table also alleviated the intrinsic pressure of knowledge construction, and allowed students to develop their engineering intuition and confidence in an evolving fashion. Below, the general format of the course and its elements are described.

4.2. Outline

The course schedule is extended to 22 weeks, equally divided between fall and winter semesters. Consequently, design activities in each semester end two weeks earlier than the official termination of term classes. This would allow some students who may have been occupied by design activities to catch up with other courses. The class has 180 to 200 students depending on the year, divided into four sections. Each section is scheduled for 4 hours per week, except for the first 5 weeks of fall term during which design and technical lectures are presented for 6 hours per week. During the first two weeks, students form their teams of three (or four in special circumstances,) within team-finding sessions and after attending lectures on group dynamics and team/project management. The course centres on a number of full-scale, multidisciplinary projects, as discussed in the sequel, which are introduced in the beginning through formal Request-for-Proposal (RFP) announcements. Each team is expected to elect one project to proceed throughout the course. A proposal must be prepared by each team in Week 8, which concludes the conceptual and preliminary design phases. Upon approval of the proposal, the team proceeds towards detailed design and prototype fabrication. A technical document submitted by the team at the end of the course reports the phase of detailed design. Also, teams will represent their prototypes to a panel of judges in a public event while competing with other prototypes of their category. The first semester of the course mainly consists of design lectures, technical lectures, tutorials, and hands-on preparatory (individual and group) assignments, while teams are conducting the conceptual and preliminary design phases of their project. These instructions initially book the entire weekly schedule, and are gradually reduced to one hour per week in the fall semester. The winter semester mainly consists of detailed design and prototype fabrication, and except for few specialized tutorials there is no further direct instruction for the class.

4.3. Elements

The course consists of the following constituents:

**Design Project:** This is the core activity of the course. Every year, a new set of projects is defined that share a common “theme.” Some examples are shown in Table 3. A common theme enables the instructor to provide the class with a unified set of training materials and evaluation scheme. Consumer market and industry are consulted extensively for defining new projects each year. Design problems are expected to feature mechanical and electromechanical systems, circuits and instrumentation (sensors), and microcontroller applications. Although some projects are modified to illustrate a more traceable and feasible process, the RFP announcements are created so that they give students all sense of real-life meaningfulness. Major design constraints are weight, dimension, cost of the prototype, and some other function-specific constraints.
Table 3. Some examples of projects for the second-year Engineering Design course.

<table>
<thead>
<tr>
<th>THEME</th>
<th>PROJECT</th>
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<tbody>
<tr>
<td>Manipulation with straightforward mobility along a vertical wall</td>
<td>Graffito Machine: moves along a piece of papers hung on a vertical wall, and draws pre-programmed figures of various shape, size, geometry at specific locations. Ball Stocking Machine: moves along a stock rack held against a vertical wall, and places balls of various colour and size (mixed in its container) in specific shelves as initially programmed. Fabric Inspection Machine: moves along a piece of cloth hung on a vertical wall and locates, marks, and records a number of undisclosed spots based on their colour.</td>
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<tr>
<td>Sorting objects based on colour, size, geometry, function, etc.</td>
<td>Battery Sorter: receives a mixture of batteries of various types (sizes and shapes) and voltage conditions (charged or discharged), and sorts them in separate bins. Ball Sorter: receives a mixture of balls of various sizes, types (surface softness) and colours, and sorts them in separate bins. Bottle Sorter: receives a mixture of various types (size, shape) of empty bottles and cans, and sorts them in separate bins. Skittle™ Sorter: receives a mixture of Skittles™ in various colours, and sorts them in separate bins.</td>
</tr>
<tr>
<td>Object handling with controlled mobility within a field</td>
<td>Tennis-player Robot: moves within one side of the tennis court (scaled down to half), and throws tennis balls to the other side at specific times and locations as programmed initially. Mine-detecting Robot: travels within a field, and detects and marks an undisclosed number of metal plates (mine examples) laid on the ground without hitting them. Waiter/Waitress Robot: moves within a court, finds an undisclosed number of metal plates (table examples) on the ground, and puts one can of soft drink on each plate without hitting the plates.</td>
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<tr>
<td>Manipulation with directed mobility along other objects</td>
<td>Nail-hammering Machine: moves on a timber, and hammer in nails at marked spots as well as pre-programmed locations. Pipe-inspection Machine: moves on a PVC pipe, and detects and records spots on pipe’s outside surface based on their colour.</td>
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</table>

The developed prototypes are to perform specific tasks as quickly and accurately as the team’s design permits. Hence, in the final public presentation these machines hold a competition in their category to gain the highest score according to certain criteria also specified in the RFP announcements. In addition to the physical prototype, other outcomes of the design project that will be subjected to evaluation are: *design proposal* that concludes conceptual and preliminary design phases; *engineering notebook* that becomes an instrumental means for each student as a journal, bookkeeper, data-logger, communicator, and report facilitator; and *final report* that describes the detailed design and fabrication, integration, testing, and calibration processes.

**Design Lectures:** This series of lectures presents some practical notions of engineering design that students need to be familiar with to conduct their knowledge construction. Topics include:
- Introduction: Course Outline, Procedure, Expectations, etc. (1 hour)
- Learning Strategy: why you learn (Attitude), how you learn (Metacognition), what you learn (Cognition) (1 hour)
- Project Management: Group Dynamics and Teamwork, Project Planning, Time Management (3 hours)
- Design Projects of the Year (1 hour)
- Fundamentals: Definitions of Engineering and Design, Design Process (1 hour)
- Conceptual Design: Problem Formulation, Concept Generation, Functional Analysis (3 hours)
- Communication and Information: Engineering Sources, Writing Proposals, Technical Reports, Engineering Notebook (3 hours)
- Decision Making Process (1 hour)
- Reliability and Risk Assessment (1 hour)
- Professionalism (1 hour)
- Ethics (1 hour)

**Technical Lectures:** In the first year of their study, Engineering Science students learn theoretical foundations of classical mechanics, circuits, and computer programming. They also become familiar with some system analysis tools such as MATLAB™, and experience teamwork in some course projects. Nevertheless, to perform a multidisciplinary design and build a functional machine they need to possess certain practical knowledge about different disciplines, which is presented to them through a series of prescriptive technical lectures, as titled below. These lectures are designed to bridge between students’ theoretical knowledge and the practical notions that they need to experience throughout the design process. Many of the presented topics will be discussed again in the upper years in greater details.
- Digital and Analog Circuits (5 hours)
- Mechanical and Electromechanical Systems (5 hours)
- Microcontrollers (5 hours)
- Sensors (2 hours)
**Tutorials:** Throughout the course, different tutorials are presented by experts, students from the previous years, and people from industry. The topics include machine shop, printed circuit boards, experiences of previous years, industrial project management, software applications, etc. These sessions are also good opportunities for students to interact with experts of various fields.

**Preparatory Assignments:** During the conceptual design phase while teams develop their design ideas, three hands-on assignments will give them a better practical sense about the systems that they are to develop. These assignments play as means of transition from instructional to experiential learning, and they are of the following types:

- **Reverse Engineering:** In this assignment, teams of students dissect a specific consumer product and discuss its design attributes, functional analysis, and methods of improvement. The selected product is relevant to the theme of the year projects. For example, for the “object sorting” theme a coin-sorter machine, and for the “mobile manipulation” theme an electric scooter were assigned for the reverse engineering practice. Through this assignment, students begin to know their team and also how to generate engineering ideas.

- **Motor Driving:** All individual students build a driver circuit on the protoboard for a gear-head DC or stepper motor, and design and perform a number of experiments to obtain motor characteristics. All the required components are provided as a kit, and circuit schematics and descriptions are discussed in the lectures and course notes. In this assignment, students construct their first circuit, and learn how to design and perform engineering experiments.

- **Microcontroller Integration:** All individual students write simple assembly codes to integrate their circuit and actuator built in the previous assignment with a particular microcontroller. The microcontroller with its driver board is provided to students. It belongs to the low-cost, medium-range family of PICmicro™ units from Microchip Technology, Inc. [34], with a simple set of instructions that are lectured to students a priori. Through this assignment, students learn about the microcontroller that they will use for their project, and also how to integrate and test different subsystems.

### 4.4. Procedure

The course procedure, depicted in Figure 1, implements the guidelines of the Elaboration Theory.
Simple-to-complex Sequence: The course flow is a gradual transition from direct instruction, in the form of lectures and tutorials, to semi-directed learning, in the form of hands-on assignments, to self-controlled experiences of conducting the design project. Needless to say, the content of the course also follows a simple-to-complex sequence.

Organizing Structure: The Elaboration Theory advises that the content of a course be primarily focused on one of the three types of conceptual, theoretical, and procedural, and the other two types be brought up only when they are directly relevant to the core type. In the design course, procedure is the primary organizing content, thus the course centres on a procedural task, i.e., developing a prototype from concept generation to analysis, to synthesis, to fabrication, integration, and testing. During this procedure, relevant concepts and theories are presented directly related to what the procedure requires. For example, the Reverse Engineering Assignment is of conceptual type, but choosing the subject related to the design project (e.g., coin sorter for the “sorting machine” projects) ensures the relevance of the developed concept(s) to the primary procedural content. The same strategy has been applied to the design and technical lectures and tutorials.

Within-lesson Sequencing: For a procedural organizing structure, such as that of design course, the subjects must be arranged sequentially within a realistic context. This requirement is met by defining an initial statement of work for the projects, included in the RFP announcement, and by devising directive assessments so that students follow a certain sequence while conducting their design project. That is, they formulate the problem and develop the concept, then analyze the solution, then communicate the design (proposal), then detail the subsystems, then fabricate them, then integrate the entire system, then test and calibrate, and finally present their design and document the activities (final report). It is worth noting that within-lesson sequencing for the instruction does not contradict the iterative nature of design, i.e., teams are always allowed to step back and modify the previous stages, if need be.

Activators and Synthesizers: The course is enriched by a vast collection of “demonstration boards” that illustrate various tasks of subsystem design, fabrication, and integration, as well as a number of flowcharts and milestones that help teams identify their position throughout the design process.

Learner Control: The ultimate goal of instruction is to delegate the task of learning to the learner through the provision of a context that illustrates the complexity of real life. This constructivist approach has been accomplished particularly in the second half of the course.

4.5. Assessment

The assessment strategy in the course is a balance between outcome-based and process-based and also between individual-based and group-based evaluations, as detailed in Table 4. Process-based evaluations are performed by experienced teaching assistants who constantly monitor students’ performance based on specific criteria and provide them with adequate feedbacks. The criteria for outcome-based evaluations are also detailed sufficiently to ensure a fair and objective assessment.

5. Conclusion

Teaching engineering design involves both direct instruction and learner-controlled knowledge construction. Thus, a hybrid framework is needed for the rapprochement of the two rival models of learning, i.e., behaviourism and constructivism. Such framework can be built based on an instructional design theory, namely Elaboration Theory, which allows a gradual transition from content-based to project-based design education. The instructional format was detailed for a multidisciplinary design course for sophomores, which requires a 22-week schedule. The results of this implementation must be further studied, but students consistently show strong enthusiasm towards the course, despite the heavy workload.
6. References


