AC 2009-1370: APPLICATION OF LEARNING MODELS TO THE ENGINEERING DESIGN PEDAGOGY

M. Reza Emami, University of Toronto

Application Of Learning Models To The Engineering Design Pedagogy

Abstract

This paper discusses the implementation of 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 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 has changed status from a formal course to a *flagship* stream. There has been a clear transition in the engineering curricula from the traditional approach to the alternative paradigm. The former viewed design as a byproduct of engineering education that cannot occur without the solid formation of engineering sciences[1], whereas the latter argues that analytical knowledge is not adequate for tackling real-life engineering problems, and that design can be viewed as a means of learning engineering not a result of it. *Capstone* design courses are fruits of former approach. They have proven to be useful in addressing the critical feedback from industry perceiving graduating engineers as unable to tackle real problems and manage professional design practice, because of the change of focus from theoretical to practical[2,3]. Yet, the alternative paradigm seeks a more integrative role for design, and thus introduces it at the freshman and sophomore levels, usually dubbed as *cornerstone* design courses[4]. Both anecdotal data[5] and hard evidence[6] 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[7]. A wide spectrum of project-based design instruction 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. An excellent review is provided by Sheppard and Jenison[8] (up to 1997) and Dym *et al.*[7] (recently). These courses, which have been created over the past two decades, demonstrate a great diversity in terms of implementing project-based, team-centred approaches. Nonetheless, they share two major features[7]: **a)** they are scheduled in one semester (or two quarters); and **b)** they tend to focus more heavily on conceptual design methods and less on prototyping design artifacts. 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[9]) and/or discipline-specific (such as remote control mobile mechanisms involving mechanical design only[10]). This is partly because of the shortage of time and experimentation/fabrication resources and partly due to the lack of adequate knowledge that students will acquire only later in the curriculum. Despite a number of positive reports[11], the efficacy of project-based education in engineering programs has yet remained to be investigated thoroughly[12]. 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 argues the need for a hybrid framework for teaching cornerstone design courses based on the behaviourist and constructivist learning models, and presents a systematic instructional design methodology using the Elaboration Theory. 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. Section 4 briefly introduces an instructional design theory that best utilizes a merger of the two rival learning models. Section 5 details the application of the instructional mechanism to a second-year design course, as a case study. Some concluding remarks are made in Section 6.

2. Engineering Design and Learning Models

The emphasis on project-based learning in the recent reform of engineering education sides, mostly unconsciously, with the *constructivist* learning theory, which is a paradigm shift from the mainstream *behaviourist* learning model. This alliance, more than a diligent deliberation, comes from the fact that teaching design through a hands-on approach seems quite appealing to both instructors and students, partly because bringing abstract notions of design into the classroom and yet maintaining students' attention and interest in the subject is a great challenge for instructors, and partly because students seem to be better able to make sense of design notions by experiencing them within the real-life context. *Constructivism* is primarily realized through the work of Bruner[13], Piaget[14], and Vygotsky[15], and it 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)[16]. The mind is seen as a *tabula rasa* to be filled by, or as a mirror to reflect, the objective reality[17]. Learning is considered as dissemination of knowledge via abstract representation of reality. Thus, the goal of learning, behaviourism submits, is to understand the reality and modify behaviour accordingly, and the purpose of teaching is to transfer the knowledge from expert to learner[18]. 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[19]. Thus, the constructivist model of learning advocates that, as von Glasersfeld states[19], "*knowledge is not a transferable commodity and communication not a conveyance*." Individuals learn by experiencing the real world and challenging 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[20].

The implications of the above two learning theories in instructional design are as diverse as the theories themselves. 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[18,21]:

- 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[22] 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. Which Model Better Suits 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[8] 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 the referred article[8]). Several remarks about the list of design qualifications are in order:

- 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[23] 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, 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[7].

Table 1. Expected qualifications in design engineers that engineering courses should focus on[8].

Qualifications
Design Thinking Capabilities:
4. Utilize graphical and visual representations and thinking.
5. Exercise creative and intuitive instincts.
11. Think with a system orientation, considering the integration and needs of various facets of the problem.
12. Define and formulate an open-ended and/or under-defined problem, including specifications.
13. Generate and evaluate alternative solutions.
14. Use a systematic, modern, step-by-step problem solving approach. Recognize the need for and implement iteration.
Analysis Capabilities:
8. Use analysis in support of synthesis.
9. Appropriately model the physical world with mathematics.
10. Consider economic, social, and environmental aspects of a problem.
Information Collection and Dissemination Capabilities:
6. Find information and use a variety of resources (i.e., resourcefulness).
7. Identify critical technology and approaches, stay abreast of change in professional practice.
Teamwork and Communication Capabilities:
1. Communicate, negotiate and persuade.
2. Work effectively in a team.
4. Utilize graphical and visual representations and thinking. (repeated)
Management Capabilities:
3. Engage in self-evaluation and reflection.
Prototyping Capabilities:
15. Build up real hardware to prototype ideas.
16. Trouble-shoot and test hardware.

- 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[24].

- 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[25]. 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 the design process, particularly in the early stages, is inherently social but argumentative[26]. 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 H, i.e., 5, 13, 19, 1, 2, 3, 15, 16, 24, and 28) exclusively refer 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 relationships and phenomena while analyzing their solutions; and physically, when they are building and debugging their prototypes. Several other qualities in Table 2 (Group HW: 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 to their own experiential learning process. The remaining items in Table 2 (Group W: 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 negotiation and social aspects of learning subjects. This analysis justifies the recent trend of introducing project-based design courses at all levels of engineering curricula, which can properly line up with the constructivist model of learning as discussed in Section 2. However, a genuine project-based course should contain a good deal of physical fabrication, testing, and debugging. While conceptual design and system analysis are important aspects of engineering design, in many engineering fields it is the process of "building" physical artifacts (in part or full scale) that completes the knowledge-construction process, as argued by several[23,27]. It should also be noted that 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. Nevertheless, while a project-based format seems to be a suitable option for a design course, assuming that the

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

Qualifications	*Group*
A1: Design Thinking Capabilities:	
4. Utilize graphical and visual representations and thinking.	**HW**
5. Exercise creative and intuitive instincts.	**H**
11. Think with a system orientation, considering the integration and needs of various facets of the problem.	**HW**
12. Define and formulate an open-ended and/or under-defined problem, including specifications.	**HW**
13. Generate and evaluate alternative solutions.	**H**
14. Use a systematic, modern, step-by-step problem solving approach. Recognize the need for and implement iteration.	**HW**
17. Make rational decisions about design alternatives based on certain criteria.	**HW**
A2: System Analysis Capabilities:	
8. Use analysis in support of synthesis.	**W**
9. Appropriately model the physical world with mathematics.	**W**
10. Consider economic, social, and environmental aspects of a problem.	**W**
18. Design experiments to better understand systems and verify ideas/hypotheses.	**HW**
19. Handle uncertainty and ambiguity is system modeling.	**H**
20. Use statistical techniques as well as engineering intuition to make reasonable estimates.	**W**
A3: Information Collection/Dissemination Capabilities:	
6. Find information and use a variety of resources (i.e., resourcefulness).	**W**
7. Identify critical technology and approaches, stay abreast of change in professional practice.	**W**
21. Produce viable documentation, and present design ideas effectively.	**HW**
A4: Teamwork and Communication Capabilities:	
1. Communicate, negotiate and persuade.	**H**
2. Work effectively in a team.	**H**
4. Utilize graphical and visual representations and thinking. (repeated)	
A5: Management Capabilities:	
3. Engage in self-evaluation and reflection.	**H**
22. Be aware of effective team organization.	**W**
23. Plan a design project, and follow the schedule.	**HW**
A6: Prototyping Capabilities:	
15. Build up real hardware to prototype ideas.	**H**
16. Troubleshoot and test hardware.	**H**
24. Integrate various subsystems efficiently.	**H**
25. Understand and dissect existing engineering products.	**HW**
A7: Ethical and Professional Capabilities:	
26. Be aware of major standards of the field.	**W**
27. Understand professional conduct and code of ethics.	**W**
28. Can resolve ethical dilemmas.	**H**

requirements of the constructivist model are met, a number of expected design qualities listed in Table 2 (Group W 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 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. This preparatory stage of learning design, based on a behaviourist model, can indeed have a crucial role in the efficiency (time and effort) and depth of the knowledge construction phase. Hence, a thorough design course for addressing all the expected qualifications calls for a hybrid model of learning, a merger of behaviourism and constructivism through a systematic instructional design strategy. This will be discussed in the following section.

4. An Instructional Design Theory for Implementing the Hybrid Learning Model

The premise of Section 3 was that engineering design involves various types of content at different levels of learning. Several pedagogues have argued that both content and level of learning assign the suitable learning model. For example, Jonnassen[17] 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 the learner can develop some anchors for future knowledge construction. For the advanced and expert learning stages, on the other hand, where the 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.

In order to systematically utilize the impact of content and level of learning in the design education, the author appeals to a relatively-new instructional design technique, called Elaboration Theory[29]. The theory, like any other instructional design technique, helps instructors select and sequence content in a way that will optimize achievement of learning goals. It 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[30]: 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. Hence, one can infer that the approach 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. Consequently, the instructional procedure and its characteristics that are recommended by the Elaboration Theory[31] can be readily tailored to design pedagogy with a hybrid learning framework, as described below:

Simple-to-complex Sequence: The course flow should be 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 should also follow 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 a design course, *procedure* is the primary organizing content, thus the course should centre 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 should be presented directly related to what the procedure requires. For example, the Reverse Engineering Assignment, which will be discussed in the next section, is of conceptual type, but choosing the subject related to the design project ensures the relevance of the developed concept(s) to the primary procedural content. The same strategy can be applied to the design and technical lectures and tutorials, as well.

Within-lesson Sequencing: For a procedural organizing structure, such as that of a design course, the subjects should be arranged sequentially within a realistic context. This requirement is met by defining an initial statement of work for the projects, included in the Request-for-Proposal (RFP) announcement, to be discussed in the next section, 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 should always be allowed to step back and modify the previous stages, if required.

Synthesizers and Activators: The theory recommends the use of **a)** presentation devices, called *synthesizers*, which are designed to help the learner integrate content elements into a meaningful context and assimilate them into prior knowledge; and **b)** means of activating cognitive awareness of learning process, called *activators*, which are designed to help the learner navigate through her/his learning journey and check the progress with certain milestones. Therefore, a design course should be enriched by a 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 situation throughout the design process.

Learner Control: According to the theory, the trend of instruction should be toward delegating the task of learning to the learner through the provision of a context that illustrates the complexity of real life. This is well suited to a hybrid project-based design course, in a sense that the role of instructor should gradually change from information conveyor, to content facilitator, to activity observer and advisor, to design critic and evaluator.

The next section details the development of a full-year hybrid cornerstone design course based on the Elaboration Theory.

5. Case Study: A Hybrid Design Course for Sophomores

A design course was developed, based on a hybrid learning framework and following the guidelines of the Elaboration Theory, for the second-year syllabus of the Division of Engineering Science at the University of Toronto. Engineering Science is a special program designed for top-ranked students to provide them with both breadth and depth of engineering fundamentals. The program emphasizes 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. The course mandate is to teach students the theoretical and practical notions of multidisciplinary design and familiarize them with technology advances.

5.1 Course Outline

The course schedule is extended to 22 weeks, equally divided between fall and winter semesters. The average class size is 185 students divided into four sections. Each section is scheduled for 4 hours per week, except for the first 5 weeks of fall semester 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

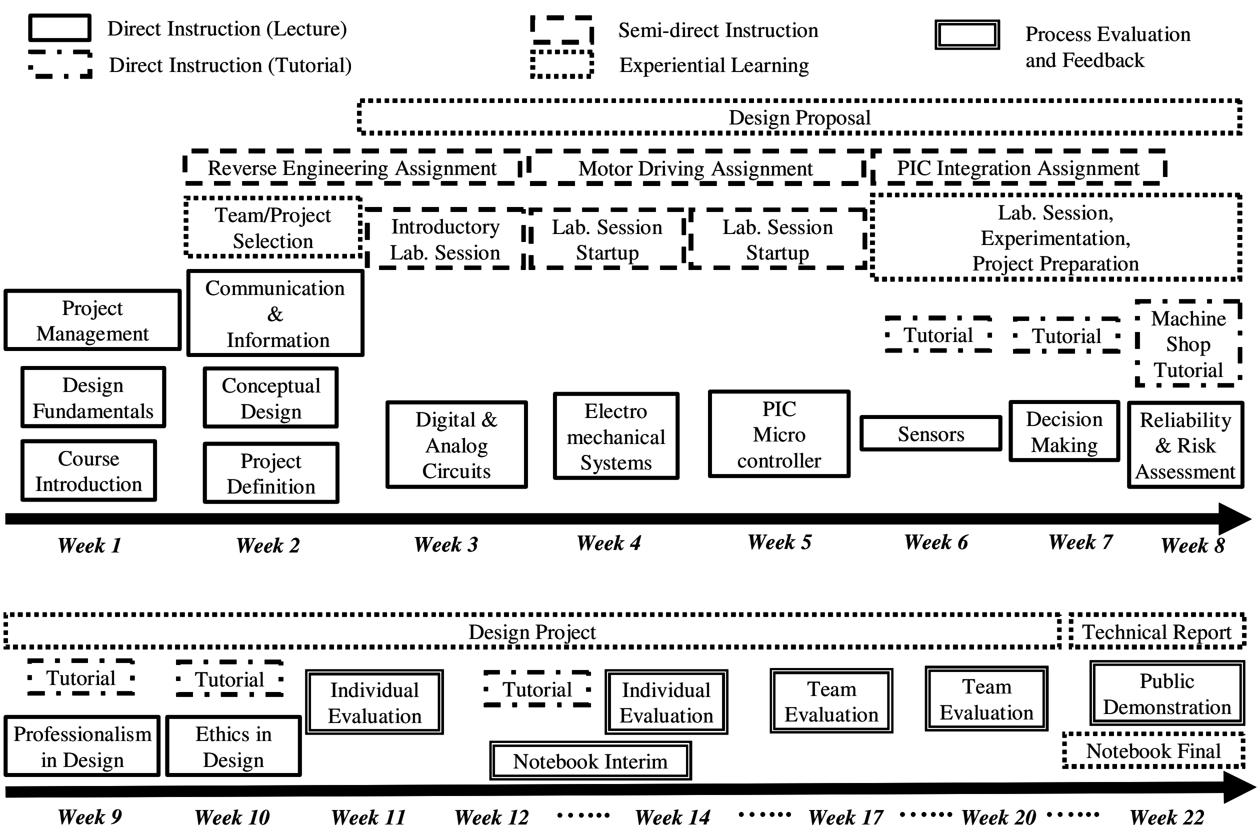

Figure 1. The flowchart of the design course

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 present 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 consists mainly 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. This instruction initially books the entire weekly schedule, and is 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. Figure 1 illustrates the course procedure, as detailed in the following.

5.2 Course Components

The course consists of the following elements:

Design Project: This is the core activity of the course. A set of projects is announced 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 schemes.

Table 3. Some examples of projects for the second-year Engineering Design course.

THEME	PROJECT
Manipulation with straight-forward mobility along a vertical wall	**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) on 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.
Sorting objects based on colour, size, geometry, function, etc.	**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 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.
Object handling with controlled mobility within a field	**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.
Manipulation with directed mobility along other objects	**Nail-hammering Machine:** moves on a timber, and hammers 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 the pipe outside surface based on their colour.

Consumer market and industry must be consulted extensively for defining new projects each year. Design problems 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. Although some projects are modified to illustrate a more traceable and feasible process, the RFP announcements are created so that they give students a sense of real-life meaningfulness. Major design constraints are weight, dimension, cost of the prototype, and other function-specific constraints. 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: To perform a multidisciplinary design and build a functional machine, students 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 detail.

- 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 and soldering, 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 give them a better practical sense about the systems they are to develop. These assignments are 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.[32], 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.

5.3 Performance Assessment

The assessment strategy in the course is a balance between outcome-based and process-based

Table 4. The course assessment scheme

	Individual-Based	**Group-Based**
Outcome-Based	Motor Driving Assignment (5%)	Reverse Engineering Assignment (5%)
		Design Proposal (10%)
	PIC Integration Assignment (5%)	Project Demonstration (7.5%)
		Final Report (20%)
Process-Based	Week-11 Evaluation (7.5%)	Week -17 Evaluation (7.5%)
	Interim Notebook (7.5%)	
	Week-14 Evaluation (7.5%)	Week-20 Evaluation (10%)
	Final Notebook (7.5%)	

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 feedback. The criteria for outcome-based evaluation are also detailed sufficiently to ensure a fair and objective assessment.

5.4 Students' Feedback

At the end of the course each year, students were asked to respond to a survey about their individual learning experience. The survey consisted of two parts. Part one ranks their opinion about the learning experience with regard to the expected qualifications listed in Table 2. There is one additional factor in part one concerning the *life-long learning* (A8), i.e., the ability to learn independently and continuously seek for acquiring new knowledge, and to bring in relevant outside experiences to provide advanced solutions to the problems at hand. Part two ranks their consensus about the following six questions:

Q1: To what extent did you enjoy the learning experience?
Q2: To what extent was the workload worth the learning outcome?
Q3: To what extent do you think this course would be useful for your future career?
Q4: To what extent did teamwork help you develop the design skills?
Q5: Overall, how satisfied are you with the teaching/ learning process in this course?
Q6: Do you think that you could obtain similar learning experience in one semester (instead of two semesters)?

The ranking was based on a five-grade Likert ordinal scale [33], with the following codes:
1: Not at all
2: To a limited extent
3: To a fair extent
4: To a great extent
5: To a very great extent

Table 5. Students' feedback

Rank / Subject	1	2	3	4	5
A1	0	0.64	22.44	52.56	24.36
A2	2.56	15.38	37.82	32.69	11.54
A3	1.92	18.59	37.18	33.33	8.97
A4	0.65	4.52	22.58	41.29	30.97
A5	1.92	6.41	34.62	38.46	18.59
A6	0.64	1.28	21.79	40.38	35.90
A7	7.69	33.33	39.10	14.74	5.13
A8	1.30	10.39	23.38	38.31	26.62
Q1	4.52	12.26	32.90	33.55	16.77
Q2	7.74	28.39	32.90	21.94	9.03
Q3	2.56	8.33	25.64	32.69	30.77
Q4	2.58	14.19	36.13	32.26	14.84
Q5	5.77	10.90	20.26	50.26	12.82
Q6	48.72	28.85	12.82	7.69	1.92

Results of the survey for one year are shown in Table 5, as a sample. Each entry represents the percentage of class (192 students) who selected a rank for a specific subject. For example, 52.56% of class thinks that the course helped them "to a great extent" (scale 4) strengthen their "design thinking capabilities" (A1 in Table 2), and 48.72% of class selected option 1 for question Q6 (above), meaning that this group does not think at all that they could obtain similar learning experience in one semester. As it is obvious from the data, a strong majority of class thinks that with a hybrid format all seven categories of qualifications (Table 2) are satisfied to a fair, great, or very great extent. However, students pointed out that there needs to be more coverage on the "ethical and professional capabilities" (A7). Also, the two capabilities of "information collection/dissemination" (A3) and "system analysis" (A2) may need improvement, albeit the latter is constrained by the students' limited knowledge of engineering sciences in the second year. With regard to the "life-long learning capabilities" (A8), 88.31% of class seemed to have gained confidence in acquiring knowledge independently and continuously bringing in relevant outside experiences for creating new solutions, an expected outcome from a constructivist learning model. Questions Q1-5 examine students' subjective attitude toward the course, which is a measure of success in keeping them motivated throughout the numerous technical and social challenges that they were facing in the course. Although a strong majority of class seemed to have enjoyed the course and appreciated its learning experience for their future career, a notable minority (36.13%) thinks that perhaps the workload was excessive. This remark is admitted, particularly in comparison with other courses that they carry out simultaneously. A number of students tend to become greatly attached to their artifacts. Hence, a major administrative challenge for such hands-on design courses is to ensure that students do not overdo their design activities to the extent that their other assignments (academic and else) are compromised. On the other side of the argument, it should be noted that since the survey was taken at the end of the course activities when students were exhausted as a result, some of the remarks about the excessive workload may become moderated later on when they have a chance to rest. Interestingly, only 22.43% of class thinks that such a learning experience could have obtained in one semester (Q6), which may support a full-year format. Of course, more investigation is needed to justify the full-year duration for a hybrid design course when it is compared with a semester-long similar course.

6. 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 a framework can be manufactured 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. Students' feedback indicates notable enthusiasm towards the course, despite its heavy workload. Based on their evaluation, the course was able to address major qualifications that are expected in design engineers. However, further investigations are needed to improve the course with respect to certain expected qualities, and also to justify the course duration compared to semester-long formats.

7. References

1. C.L. Dym, "Design Systems and Engineering Education", *International Journal of Engineering Education*, Vol. 20, No. 3, 2004, pp. 305-312.

2. A.J. Dutson, R.H. Todd, S.P. Magleby, and C.D. Sorensen, "A Review of Literature on Teaching Design Through Project-Oriented Capstone Courses", *Journal of Engineering Education*, Vol. 76, No. 1, 1997, pp. 17-28.

3. J.V. Farr, M.A. Lee, R.A. Metro, and J.P. Sutton, "Using A Systematic Engineering Design Process to Conduct Undergraduate Engineering Management Capstone Projects", *Journal of Engineering Education*, Vol. 90, No. 2, 2001, pp. 193-197.

4. C.L. Dym, "Learning Engineering: Design, Languages, and Experiences", *Journal of Engineering Education*, Vol. 88, No. 2, 1999, pp.145-148.

5. A. Bright, and C.L. Dym, "General Engineering at Harvey Mudd: 1957-2003", *(CD) Proceedings of ASEE Conference and Exhibition*, Session 1471, 2004.

6. R.S. Adams, J. Turns, and C.J. Atman, "Educating Effective Engineering Designers: The Role of Reflective Practice", *Design Studies*, Vol. 24, No. 3, 2003, pp. 275-294.

7. C.L. Dym, A.M. Agogino, O. Eris, D.D. Frey, and L.J. Leifer, "Engineering Design Thinking, Teaching, and Learning", *Journal of Engineering Education*, Vol. 94, No. 1, 2005, pp. 103-114.

8. S. Sheppard, and R. Jenison, "Examples of Freshman Design Education", *International Journal of Engineering Education*, Vol. 13, No. 4, 1997, pp. 248-261.

9. J.V. Ringwood, K. Monaghan, and J. Maloco, "Teaching Engineering Design through Lego® Mindstorms™", *European Journal of Engineering Education*, Vol. 30, No.1, 2005, pp. 91-104.

10. A.H. Slocum, "2.007 - Design and Manufacturing I", MIT, *http://pergatory.mit.edu/2.007/*.

11. D.W. Knight, L.E. Carlson, and J.F. Sullivan, "Staying in Engineering: Impact of a Hands-On, Team-Based, First-Year Projects Course on Student Retention", *(CD) Proceedings of ASEE Conference and Exhibition*, Session 3553, 2003.

12. J.T. Luxhole, and P.H.K. Hansen, "Engineering Curriculum Reform at Aalborg", *Journal of Engineering Education*, Vol. 85, No. 3, 1996, 83-84.

13. J. Bruner, *Toward a Theory of Instruction*, Harvard University Press, Cambridge, , 1966.

14. J. Piaget, *To Understand Is To Invent*, Viking Press, Inc., New York, 1972.

15. L. Vygotsky, *Mind in Society: The Development of Higher Psychological Processes*, Harvard University Press, Massachusetts, 1978.

16. B.F. Skinner, *The Behavior of Organisms*, Appleton-Century-Crofts, New York, 1938.

17. D.H. Jonassen, "Objectivism Versus Constructivism: Do We Need A New Philosophical Paradigm?", *Educational Technology Research and Development*, Vol. 39, No. 3, 1991, pp. 5-14.

18. D.H. Jonassen, "Toward A Constructivist Design Model", *Educational Technology*, Vol. 34, No. 4, 1994, pp. 34-37.

19. E. von Glasersfeld, "A Constructivist Approach to Teaching", In L.P. Steffe, and J. Gale (Eds.), *Constructivism in Education*, Lawrence Erlbaum Associations, Inc., New Jersey, 1995, pp. 3-16.

20. K.J. Gergen, "Social Construction and the Educational Process", In L.P. Steffe, and J. Gale (Eds.), *Constructivism in Education*, Lawrence Erlbaum Associations, Inc., New Jersey, 1995, pp. 17-39.

21. P. Ernest, "The One and the Many", In L.P. Steffe, and J. Gale (Eds.), *Constructivism in Education*, Lawrence Erlbaum Associations, Inc., New Jersey, 1995, pp. 459-486.

22. R.A. Schwier, "Issues in Emerging Interactive Technologies", In G.J. Anglin (Ed.), *Instructional Technology: Past, Present, and Future*, Second Edition, Libraries Unlimited, Inc., Englewood, 1995, pp. 119-127.

23. M. Brereton, *The Role of Hardware in Learning Engineering Fundamentals: An Empirical Study of Engineering Design and Product Analysis Activity*, Ph.D. Dissertation, Stanford University, Stanford, 1999.

24. G.A. Hazelrigg, "An Axiomatic Framework for Engineering Design", *Journal of Mechanical Design*, Vol. 121, 1999, pp. 342-347.

25. B. Hyman, *Fundamentals of Engineering Design*, Second Edition, Pearson Education, Inc., New Jersey, 2003, pp. 185.

26. L.L. Bucciarelli, *Designing Engineers*, MIT Press, Cambridge, Massachusetts, 1994.

27. D.A. Kolb, *Experiential Learning: Experience as the Source of Learning and Development*, Prentice-Hall, New Jersey, 1984.

28. P.A. Ertmer, and T.J. Newby, "Behaviorism, Cognitivism, Constructivism: Comparing Critical Features From An Instructional Design Perspective", *Performance Improvement Quarterly*, Vol. 6, No. 4, 1993, pp. 50-70.

29. C.M. Reigeluth, and C.A. Rodgers, "The Elaboration Theory of Instruction: Prescriptions for Task Analysis and Design", *NSPI Journal*, Vol. 19, 1980, pp. 16-26.

30. C.M. Reigeluth, and A.N. Darwazeh, "The Elaboration Theory's Procedure for Designing Instruction: A Conceptual Approach", *Journal of Instructional Development*, Vol. 5, 1982, pp. 22-32.

31. C.M. Reigeluth,, "The Elaboration Theory: Guidance for Scope and Sequences Decisions," in R.M. Reigeluth, (Ed.), *Instructional-design theories and models: A new paradigm of instructional theory,* Vol. II, Lawrence Erlbaum Associates, Mahwah, NJ, 1999, pp. 425-454.

32. Microchip Technology, Inc., *PIC16F87X Data Sheet*, *http://ww1.microchip.com/downloads/en/DeviceDoc/30292c.pdf*.

33. W.J Tastle, M.J. Wierman, and U.R. Dumdum, "Ranking Ordinal Scales Using the Consensus Measure," Issues in Information Systems, Vol. VI, No. 2, 2005, pp. 96-102.