Circuits to Control:
Learning Engineering by Designing LEGO Robots

by

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Abstract

The nature of an undergraduate degree in engineering has undergone significant change since the end of the second World War. There is more theoretical content and less hands-on project work, reflecting both rapid advances in the state of scientific theory and educators' ideas about what engineering students need to know.

Since the 1960's, engineering educators have been aware of problems with this new curriculum: students graduate with the ability to analyze clearly presented problems, but little or no background in doing design, which is the central work of a practicing engineer. In the past, employers accepted that design skills—including the ability to transform under-specified and messy design situations into actual problems to be solved—would be learned on the job, but this has become increasingly less acceptable in today's global economy.

The focus of this thesis is an analysis of the situation through the development and evaluation of a model class experience for undergraduate engineering students that addresses the deficiencies in the traditional education. The model course has been developed with and tested on MIT undergraduate students over the past four years. It consists of a month-long intensive design workshop in which students are responsible for the conception, design, implementation, debugging, and competitive demonstration of an autonomous robotic device.

The core work is the task of developing and testing this design-rich learning environment with the goal of discovering the characteristics of the setting which most powerfully encourages students' learning. The methodology employed is the implementation of a "living laboratory" in which a series of design environments (i.e., workshop design classes) are successively developed, tested, and evaluated. The evaluation is based on a variety of observational tools, including interaction with students during the progress of their projects, student written reports and journals, and analysis of the actual products of the students' work—robotic hardware and software systems. The purpose of the evaluation is to understand the issues that the students face in accomplishing their design task, in order to ascertain what and how they are learning, and to improve the materials and the classroom environment in the future.

The outcome of this work is several-fold. Most importantly, it is a re-evaluation and further understanding of the role of design work in the undergraduate engineering degree program, with a focus on specific ways to build empowering experiences into the undergraduate curriculum. Secondly, it reveals that students have pre-existing conceptions of systems and control that make it difficult for them to deal with sensor noise and other erratic phenomena in their robot designs. Thirdly, it develops a set of technological tools for learning—a kit optimized for students to work on robotic design projects. While the particulars of this technology may become outdated in a few years, the more important nature of its interactive qualities and theory behind its design will not.

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Preface

Traditional educational methods rarely consider the role that design activity can play in the learning process. In the United States, kindergarten is often both the first and last place in formal education in which exploratory and constructive play is the central way that learning happens. Beginning in the first grade and continuing through secondary school into the university, school is predicated on telling (i.e., lectures and readings) and testing (i.e., worksheets, problem sets, and written examinations). The narrowness of this pedagogy is part of the reason our educational system is presently dealing with a crisis of relevancy and performance.

In the field of engineering education at the university level, there is a more specific problem. Students are required to learn more and more theoretical material as part of their education. This material has squeezed design-oriented material from the curriculum; at the same time, universities have moved away from design, as it has seemed too practical and lacking in scientific basis. As put by Daniel Whitney in a recent article, "Mathematical analysis replaced design, manufacturing disappeared from the curricula, and both faculty and graduates lost touch with how engineering, design, and manufacturing interact in the 'real world'." (Whitney, 1990)

Yet the problem goes deeper than the level of the content of a university curriculum. In 1961, a committee at the Massachusetts of Technology published the *Report on Engineering Design* in which it raised serious concerns with the predominating pedagogy of the day, characterized by a preponderance of "single-answer problems" (M.I.T., 1961). The Committee believed that the goal of an engineering education must be not only to provide students with necessary technical backgrounds, but to inculcate certain skills and dispositions, including things like an ability to work in the face of incomplete and contradictory data (which are commonplace situations for practicing engineers). One of the Committee's overriding concerns was the effect of having the bulk of a student's education be performed by having him or her solve problems that had only one correct answer. The Committee believed that this sort of education could greatly hinder students from developing the type of ability they believed to be central to the practice of engineering design.

The very pedagogy criticized in the committee's 1961 report is still in full force today, largely due to practical reasons, like ease of evaluation and ease of teaching, that were even cited in the committee's report. Since the time of the report, however, the engineering education community has come to a greater recognition of the need for design experiences in the undergraduate curriculum. A concrete manifestation of this awareness is the recent addition of a one-term engineering design requirement to the program specifications of the Accreditation Board of Engineering and Technology (ABET) (Jones, 1991).

Most universities satisfy both the ABET requirements and their own sense of the need for a design activity with the capstone design course. These courses have the distinguishing characteristic of being taken by students at the end of their undergraduate careers—and possibly their formal educational careers, as most students enter industry upon graduation. As such, the premise of the capstone course is that *students must learn analysis before they can do "synthesis"* (i.e., design).

This curriculum fix, the capstone course, indicates a lack of depth in the understanding that most educators have about the role of design in the learning process. The development of designer's attitudes, called for by the MIT Engineering Design committee, will not be significantly affected by one or two terms of design activity at the end of an educational career. By relegating a design course to this position, educators may have students learn *about* design, but they miss the opportunity to have them learn *how to* design. Those who create more eccentric design courses have a greater sense that many students learn *through the act of* designing. Unfortunately, most university courses do not entertain this possibility, and the ones that do often have a marginal status in the university curriculum.

Acknowledgments

I've had the great fortune of an incredibly supportive and wonderfully perceptive thesis advisor, Professor Edith Ackermann. Edith was extremely generous with her time, and was able to find the strands of meaning in what initially seemed to me as only a mess of interesting issues. Throughout she was always encouraging, excited, and also firm when necessary. Edith, I am truly grateful to you for your kindness and wisdom.

I began working with Professor Seymour Papert and his research group just after finishing my Bachelor's degree from MIT in 1986. Since that time, as I have matured in my thinking, I have been profoundly influenced by Seymour's ideas and those of the people he has brought together around him. Seymour would always find the little idea buried in a pile of other considerations that needed to be let out and given a chance to grow. Seymour, I will always be indebted to your for your gracious support and advice over these years.

About a year ago I asked Professor Don Schön to join my committee, and he has since contributed more to my thinking than I ever could have anticipated. I remember one meeting with Don when he was trying to explain to me an important theme he saw in my work, and after going around in circles for a bit, I realized that I just didn't "get it." We met again a couple weeks later, and he brought the conversation back to the same point. This time, something clicked in my brain, and I suddenly had a whole new lens with which to look at my work. I hope that some of Don's insights come through in this document. Don, I want to thank you for both for your extremely valuable contributions and your warmth and friendliness.

At an earlier stage in the writing of this dissertation, there was a section that none of my committee really liked. Well, they believed there was something of value in this section, but it was largely obscured by a poor structure. I have Professor Pattie Maes to thank for putting her foot down and saying, “No Fred, this just isn’t working.” Fortunately she also had some good ideas about how to fix it, and looking back the surgery wasn’t too major. Pattie, I’d like to thank you for your determined attempts to keep me honest. Any shortcomings in this final document are surely my own responsibility.

This whole project would not have happened without the collaboration I shared with Pankaj (“P.K.”) Oberoi and Randy Sargent. When the three of began developing materials and ideas for this project, I doubt that any of us knew how much attention it would receive and excitement it would generate in the student body. We each brought different talents to the project, including Randy’s technical prowess and P.K.’s enthusiasm and organizational ability. I hope that this document gives the reader some sense of the extent to which this project has been a joint intellectual effort; while I present my own interpretations and conclusions here, my perspective has been greatly influenced by conversations we had and decisions we made while working together. P.K., Randy: I had a great time working with the two of you, and I wish you the best in the future.

I have enjoyed many valuable relationships with my colleagues at the Media Laboratory. To Mitch Resnick: it’s been great working with you since the early days of LEGO/Logo. To Yasmin Kafai: your hard work and self-confidence is a constant inspiration to me. I appreciate how you have gone out of your way on my behalf. To Aaron Falbel: your ideas about learning always keep me on my toes. To Carol Strohecker: thank you for interesting conversations and helping me find an interesting title. To Paula Hooper, Michele Evard, and Alan Shaw: thank you for caring.

Three faculty members of the Electrical Engineering and Computer Science department have been staunch supports of this project from the beginning. Professor Leonard Gould gave us encouragement and helpful advice, Department Head Paul Penfield made necessary funds available, and Professor Jeffrey Shapiro helped us figure out that we really wanted to give away the project’s hardware and software technology (which we did).

As a sponsor of the work of the Epistemology and Learning Group and as a direct contributor to the Robot Design project, the LEGO Group has been a wonderful friend. As a company, they have provided valuable funding and even more valuable LEGO parts, shipped straight from Denmark; at a personal level I have enjoyed conversations and support from Robert Rasmussen and Lars Bo Jensen.

For several of my years as a doctoral student, I was a graduate resident tutor at Bexley Hall (an undergraduate dormitory on the MIT campus). During this time I enjoyed a friendship with Professor William Orme-Johnson, the housemaster at Bexley. Professor Orme-Johnson took a genuine interest in my personal well-being and my work at MIT. Bill, I thank you for your thoughtfulness and perspective.

I always felt that Jacqueline Karaaslanian and Mai Cleary, the administrative staff for the Epistemology and Learning Group, were on my side. They more than did their jobs; they cared about me and my work, and were always a pleasure to be around.

Wanda Gleason has been my friend, confidante, and lover since before I began writing this thesis. She has been incredibly supportive and confident in me at times when I was down. Wanda, it has been wonderful to have you by my side during this endeavor. I thank you for everything.

My mother and father have encouraged me to do my best since I was a little child. They have always helped me discover what I really wanted to do, which is the work I'm presenting here. Mom and Dud, thank you and I love you.

Finally, I would like to acknowledge all of the students who participated in this activity and often gave it their best. This project would not have happened without your no-holds-barred participation.

Overview

This dissertation is organized as six chapters, four appendices, and a bibliography:

1—Background. The background chapter presents an historical context based on work in the fields of engineering education, design theory, and constructionist educational technology.

2—Introduction. This chapter presents the motivations that shaped the development of the *LEGO Robot Design Competition*—the workshop course and student competition used as a basis for this research project.

3—Technology for Learning. This chapter discusses the three aspects of the educational technology developed for the Robot Design project: the contest designs and specifications, the robotic hardware and software toolkit, and robotic sensor devices. This discussion illuminates key characteristics behind the design of this media, including features like the structure of a design space, and the interactivity, transparency, and level of abstraction of technological tools.

4—Ideal and Real Systems. This chapter analyzes the students' robots from a control-systems point of view. The most striking result is students' recurring inclination to build robots that will only perform correctly in an ideal world, which is a far cry from the actual situations that their robots face.

5—Design Styles. Students approach the design task with a range of design styles. Our intention in creating the workshop and its materials was to encourage playful, hands-on explorations of new ideas and phenomena. While partly successful, we found that this investigative style is uncomfortable for many students.

6—Conclusion and Future Directions. The workshop provides an unusual and evocative space for engineering students to face genuine design challenges, express personal creativity, and learn in unfamiliar ways. Extensions of the design environment could support deeper inquiries by university students, broader ones, or similar projects at other educational levels.

The appendices provide reference material for the reader who is interested in further details about the project's materials and history:

A—Robot Glossary. Each of the robot projects discussed in the dissertation is cataloged here, along with page references to the main text.

B—Contest Design. Full text for each of the robot contests discussed is presented here, along with additional motivations behind the contests' design.

C—Administrative Considerations. This appendix presents the guidelines that were established for awarding academic credit. Of particular concern was the desire for non-graded participation.

D—Technology Development. Technical details concerning the hardware and software developed for the project are presented here.

The final section is the dissertation bibliography.