Introducing Electronics at Scale with a Massive Online Circuits Lab

Tom J. Zajdel, Michel M. Maharbiz
Department of Electrical Engineering and Computer Sciences, University of California, Berkeley

Abstract

This work describes the design and implementation of *EE40LX: Electronic Interfaces*, the first large-scale analog circuits laboratory hosted offered by edX. *EE40LX* revolved around constructing a robot, emphasizing hands-on circuit building over circuit analysis to keep the course broadly accessible. With over 80 thousand students from over 190 nations enrolled across one year, this course is the largest and most distributed open analog circuits laboratory of its kind. Its sheer scale necessitated careful design of the robot project and a robust rubric for peer grading. This paper presents a detailed description of the course and its instructional design. In total, 856 robots were built and over 2233 students earned a certificate of completion, a 2.5% overall completion rate. Students completed voluntary surveys at the beginning and end of the class to provide insight into the approaches that independent learners take when studying electronics at home. These surveys indicated that the peer review process resulted in fair grades and also that the course was well received. Other analytics provided by edX suggest ways to improve the completion rate; particularly by offering continuing education credits, introducing more simulation exercises, and simplifying the hardware acquisition process.

1.0 Introduction

Hands-on laboratory work is an essential component in circuit education because lab exercises expose students to real systems whose behavior deviates from the idealized models studied in class. Therefore, circuit prototyping and measurement labs are a universal requirement for electrical engineering programs[1]. Instructional laboratory facilities are typically only accessible to students studying engineering at a formal institution of higher education. Though the recent proliferation of massive open online courses (MOOCs) have extended access to high quality electronics instruction[2] (see Table 1 for a brief survey of available and proposed electronics MOOCs), globalized access to laboratory education remains prohibitive due to the expense of equipment[3].

Some MOOCs, notably edX's inaugural *6.002x: Circuits and Electronics*, use simulations and virtual labs to give students more experience with experimentation[4]. These experiences are a step in the right direction, but they do not expose students to real systems and students are less engaged by solely virtual labs[5], although learning benefits if both real and virtual experimentation are implemented together[6]. A practical electronics course offered by the Spanish University for Distance Education (UNED) utilizes a remote laboratory platform called Virtual Instrument Systems in Reality[7,8]. Students in this course reserve one-hour blocks of time to work with one of a number of lab setups remotely. This method gives students access to measurement equipment but is limited by the number of available stations (about 50).

Demand for analog training has increased due to recent growth in the maker movement and the burgeoning internet of things, but there are few options for a laboratory-based MOOC that teaches the essentials of analog electronics. This unmet need in the online learning community motivated the authors' development of an accessible laboratory-based MOOC that would introduce fundamental analog electronic principles to a broad audience. An on-campus pilot laboratory was designed to supplement a traditional introductory circuit course. This pilot was then adapted for a global audience and administered twice on edX[9], an online MOOC provider, running first from January 2015 to May 2015 and then again from July 2015 to January 2016.

Table 1: Overview of electronics MOOCs currently available[8,9,10]

Course Title	Institution	Provider	Laboratory Component
Circuits and Electronics	Massachusetts Institute of Technology	edX	Virtual
Embedded Systems - Shape the World	University of Texas at Austin	edX	Physical, auto-graded exercises
Linear Circuits/ Introduction to Electronics	Georgia Institute of Technology	Coursera	Optional project
Principles of Electric Circuits	Tsinghua University	edX	None
Introduction to Power Electronics	University of Colorado Boulder	Coursera	Optional project
"Bases de circuitos y electrónica práctica"	Spanish University for Distance Education (UNED)	UNED	Remote electronics lab
Introduction to Audio Electronics	University of Rochester	Coursera	Optional project
Electrical Engineering Fundamentals Lab	Rice University	Coursera	Physical exercises, myDAQ equipment

This paper first describes the design of the course and then evaluates how it reached its intended global audience, based on course analytics collected by edX and voluntary surveys answered by students. The discussion section that follows proposes directions and opportunities for further instructional development.

2.0 Course Design

EE40LX targets advanced high-school students, hobbyists, and other non-experts. To reach this audience, the course focuses on circuit building and debugging techniques and reduces traditional emphasis on phasor mathematics. The lectures and labs revolve around a hands-on robot project built around the Texas Instruments MSP430 Launch Pad[11], with a total parts cost under 50 USD. The robot uses a simple craft stick frame to keep the mechanical design accessible and amenable to student tinkering and hacking.

2.1 Course Objectives and Format

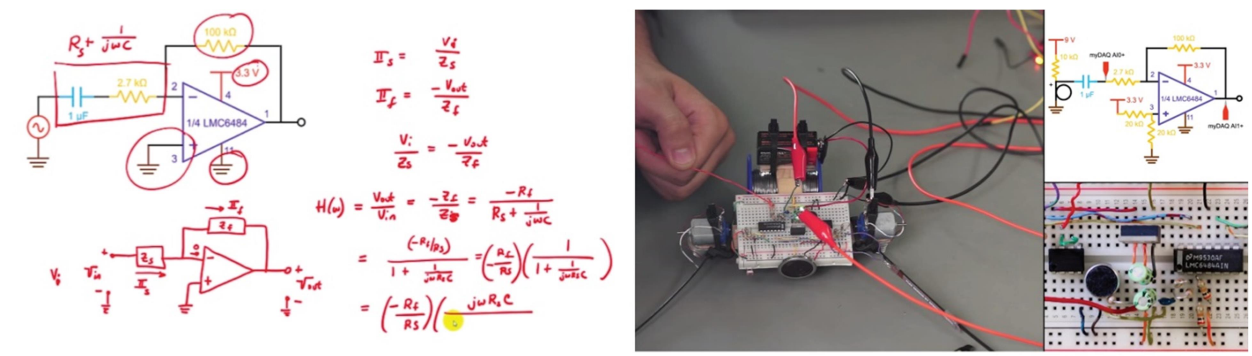
The purpose *EE40LX* is to introduce students to fundamental circuit principles through hands-on circuit prototyping. After taking this course, students should be able to:

- Describe fundamental circuit principles, including
    - Kirchhoff's laws
    - Operational amplifiers and their equivalent circuit models
    - Energy storage by capacitors and inductors

- Prototype circuits on a solderless breadboard
- Read datasheets and compare and contrast electronic components
- Measure circuits with a digital multimeter and oscilloscope

The class is divided into eight modules organized as seen in the course outline in the Appendix in Table A1. Each module consists of a number of instructional sections, designed to take one to two weeks to complete. A group of learning objectives is stated at the beginning of each section to reinforce its main takeaways, followed by a series of lecture videos, laboratory exercises, quizzes and class notes.

Instructional videos are generally six to ten minutes in length and alternate between MOOC style videos and lab bench style videos as illustrated in Figure 1. MOOC style videos cover fundamental concepts in anticipation of the circuits to be explored in the lab, and consist of a screen capture of a presentation of the material. Lab bench style videos use multiple panels to present schematics, electrical measurements, and the bench space.



MOOC Style | Lab Bench Style

Figure 1: The two types of videos used to deliver laboratory instruction. MOOC style videos focus on theory while lab bench-style videos focus on circuit building and debugging techniques.

Every module, with the exception of the first and the last includes a problem set consisting of four auto-graded problems with unlimited retries. In general the problem set for each module features at least one problem of each of the following types:

- Breadboard debugging
- Datasheet reading
- Circuit analysis

Breadboard debugging problems present breadboard circuit drawn in Fritzing[12] and ask students about the operation of the circuit and require them to correct wiring problems. Datasheet reading problems are designed to make students more comfortable with datasheets, presenting a number of manufacturer’s datasheets and asking questions about parameters for different chips and devices. Circuit analysis problems are more traditional and guide students to apply Kirchhoff’s Circuit Laws to understand and predict circuit behavior.

2.2 Robot Project

The *EE40LX* robot is shown in Figure 2. The robot is capable of detecting a loud noise, making beeping noises, driving two eccentric weight motors, and responding to changes in light level. An MSP430G2553 LaunchPad is used to control the robot and every circuit interfaces with it. Since this course does not teach microcontroller programming, scripts are provided to the students that help demonstrate the circuit to be built by generating waveforms and lighting indicator LEDs. Scripts were written in Energia[13], an open-source electronics prototyping platform that emulates the Wiring and Arduino framework.

Though the course is written to use the MSP430G2553, students were encouraged to bring their own development boards or microcontrollers if they already had one at hand. For example, students who had already taken UT Austin's Embedded Systems MOOC[14] elected to use the Tiva series TM4C123 they used in that course while others chose to use an Arduino.

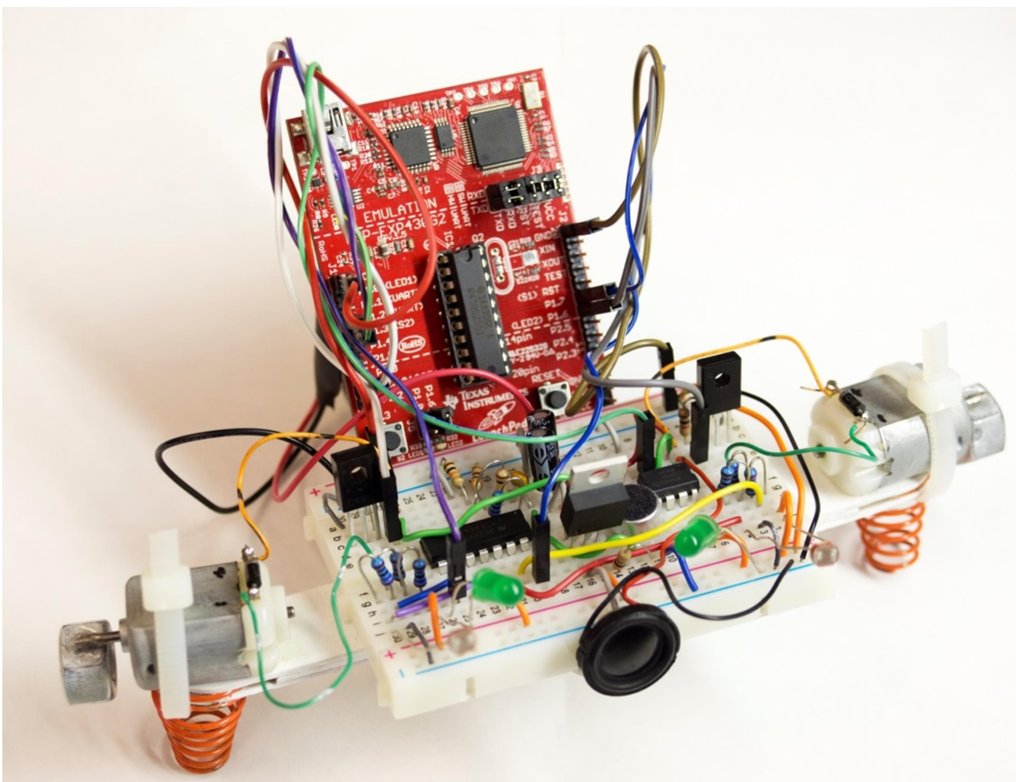


Figure 2: The completed robot

This robot as completed in the course has the following subsystems that interface with a microcontroller. The robot block diagram is given in the Appendix in Figure A1 and the schematic is given in Figure A2:

- Voltage regulator
- Photocell front ends (2)
- Speaker driver
- Microphone front end
- DC motor drivers (2)

2.3 Components and Laboratory Equipment

Given the global scope of *EE40LX*, the bill of materials included part substitution recommendations to accommodate regions with varying parts availability. Newark element14 created a webpage where students could purchase most of the electronic components in one location. A student-curated course Wiki allowed students to suggest more alternatives for parts and suppliers in different global regions.

Students were strongly encouraged to use a digital multimeter to debug their circuits. Some of the lab bench videos used the myDAQ[15] oscilloscope and signal generator to demonstrate the circuits, but most of the circuits could be troubleshot with a digital multimeter. The myDAQ was available to students who wanted to use its oscilloscope functions and other USB-based oscilloscopes were recommended on the course Wiki.

2.4 Course Grading

The course is organized so that purchase of the materials is not strictly necessary to earn a certificate of completion. A student's grade is based on his or her score on six Problem Sets, worth 50% of the course grade, and the peer-graded Robot Project, worth the remaining 50% of the course grade. The passing grade was 50%. With this scale, either completion of the final project, completion of the problem sets, or some combination of the two is required to pass the course.

Because of the large enrollment, edX's peer grading system was used to grade the robots. Students were asked to submit a short video that demonstrated their robot's functionality or a series of photographs and breadboard diagrams documenting its construction. They were then given three sample robot projects to grade so that they would learn how to use the rubric supplied in Table 2.

Table 2: Robot grading rubric

Criterion	Description	Points
Participation	**Robot contains a frame, wiring, and microcontroller**	10 or 0
Photocell	**Robot responds to light**	10 or 0
Buzzer/Speaker	**Robot makes noise**	10 or 0
Microphone	**Robot responds to sound**	10 or 0
Motors	**Robot moves both motors**	10 or 0

Upon successful grading of the sample robots, students were given submissions from five of their peers to grade. To ensure that peer grading could accommodate large variations between individual designs, students were asked to grade based on demonstrated functions as opposed to specific implementation details. Once students graded their peers and had their submission graded by their peers, they were asked to grade their own project. The median score of each rubric component was used for the final score.

3.0 Global Release and Outcomes

EE40LX was offered twice on edX. The first session began on January 20, 2015 and ended on May 8, 2015. Four undergraduate students were hired for this period to moderate the Discussion Forums and provide answers to student concerns and questions. The second session began on July 13, 2015 and ended on January 27, 2016. Two undergraduate students were hired for the first half of the session and the remainder of the course was moderated by volunteer Community TAs.

An optional pre-course survey and exit survey were administered to collect information regarding their experiences, and between both sessions, 14275 students elected to take the pre-course survey and 1197 students elected to take the exit survey. These survey responses inform this discussion of outcomes.

The following questions were answered by the course surveys edX-collected analytics and are addressed in this section:

1. Who enrolled?
2. Who finished?
3. How did students obtain components and lab equipment?
4. How well did peer grading work for robot assessment?
5. How was the course received?

3.1 Who enrolled?

Self-reported student gender, education, and age, were collected by edX when students enrolled in the course and are summarized in Figure 3. Enrollment was large for both sessions, with maximum enrollments of 26214 during the January session and 62624 during the July session, but only a fraction of enrollees was active at any given time. Just over 85% of students were male. Most students had some form of college education, with 68.8% of students holding an Associate’s degree or higher. Median student age was 27.

EE40LX was global in extent and nearly every nation was represented by the enrollees. The top 20 countries accounted for over 70% of total enrollment. The top two countries, the United States and India, accounted for over a third of the total enrollment.

Students who elected to take the pre-course survey also shared their level of experience with electronics. The results pre-course survey for the July 2015 session indicated that over 78% of students had some prior experience with electronics, either as a hobby or career. Over 24% of students claimed that electronics was closely related to their career. Students brought a rich diversity of experiences that benefited *EE40LX*’s learning environment. Some of the experienced students served as Community Discussion TAs, answering questions on the discussion forums and updating the student Wiki with side projects that built on course material.

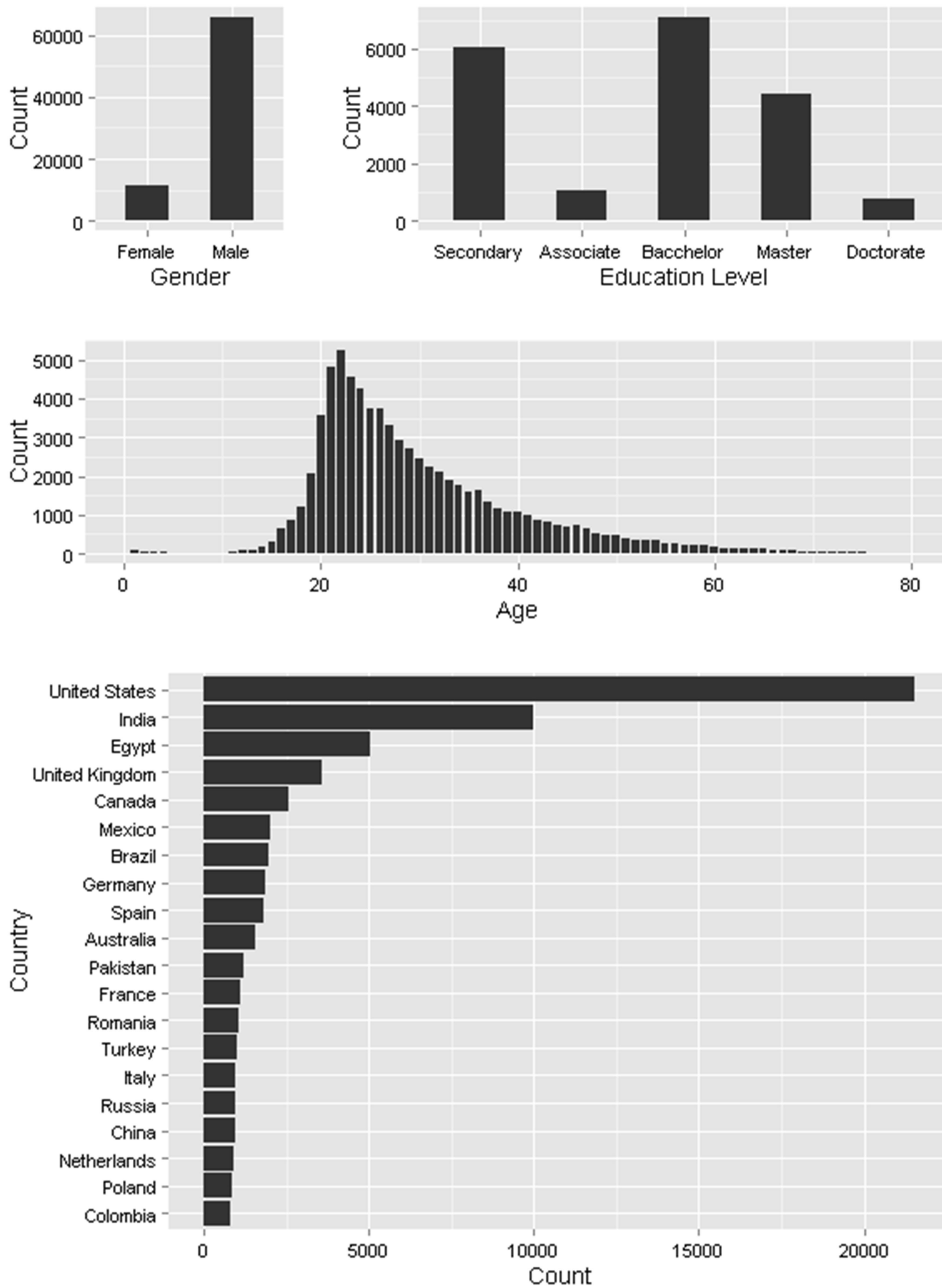


Figure 3: *EE40LX* student demographics: gender (N = 77350), education level (N = 62653), age (N = 19502), and top 20 countries by enrollment (N = 61722)

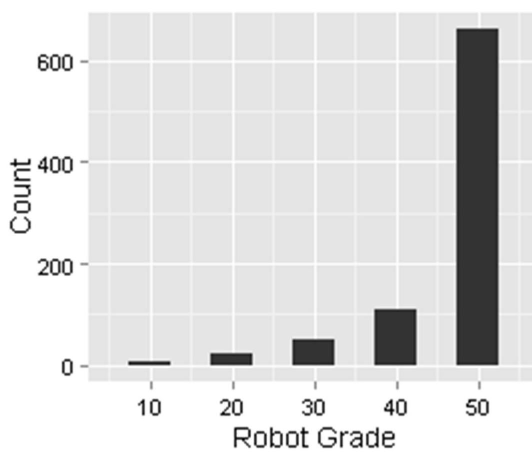
3.2 Who finished?

Since obtaining parts for the robot required extra time and expense, it was not known how many students would elect to complete the robot to earn a certificate of completion. The breakdown of completion certificates awarded is shown in Table 3. Completion rate is defined as the number of students who earned a certificate of completion divided by the number of students enrolled at the end of the class.

Table 3: Completion statistics and rates for both sessions

Session	Students Enrolled	Certificates Earned	Robots Built	Completion Rate
January 2015	25646	1081	525	4.46%
July 2015	62711	1152	331	1.84%

Those who did complete the robot tended to finish it completely. The distribution of submitted robot projects is shown in Figure 4. Though students who received the maximum score of 50 on their robot did not need to complete the robot project to earn the certificate, only four students who earned the certificate during the July 2015 session did not attempt any of the problem sets. A significant number of students who earned the certificate did not submit a robot, likely due to the added cost and time commitment.



Figures 4: Distribution of robot project grades, N = 856; maximum score of 50

Engagement in MOOCs is known to drop sharply with time[16], and *EE40LX* was no exception. Engagement for each session is shown in Figure 5, broken down by students who logged into the course, played a video, or attempted a problem each week. Engagement in each session fell sharply, eventually settling to a group of 2500 active students at any given time.

A sharp influx of new students occurred in late August because a well-known science social media blog featured the course. Many of these newcomers enrolled and did not participate beyond a couple of weeks. Since students could finish the course before a session ended, some of the overall drop-off in engagement was partially due to students completing the course early.

However, the majority was likely due to the time commitment involved in obtaining robot materials and completing problem sets.

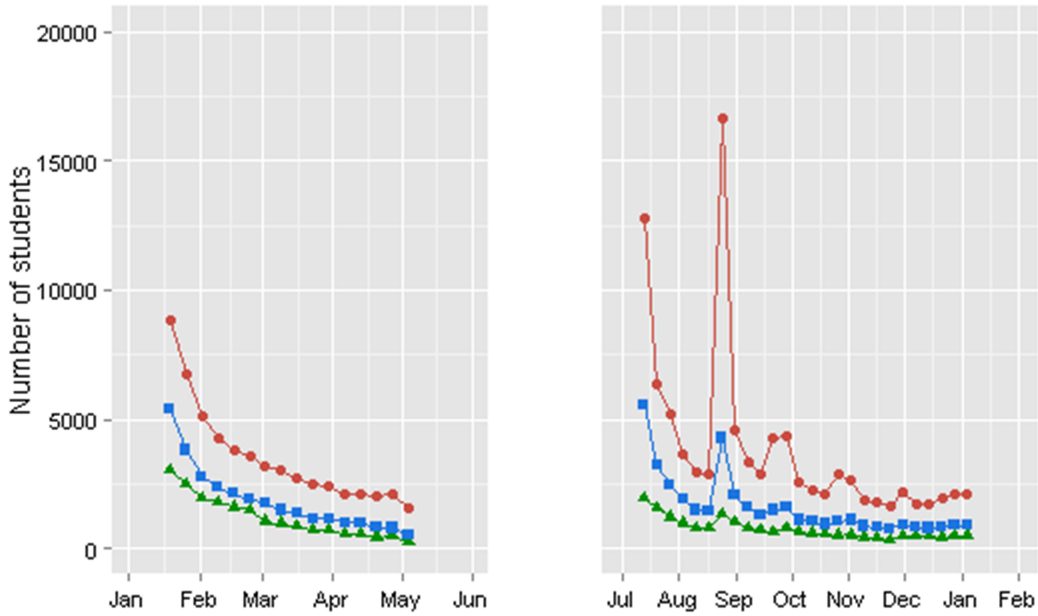


Figure 5: Weekly engagement versus time for both sessions: red circles, students who visited course; blue squares, students who viewed a video; green triangles, students who attempted any problem or exercise

The distribution of student grades for the problem sets, shown in Figure 6, indicates that a large number of students dropped out before completing Module 3: Amplifiers. Only students who attempted at least one of the problems in the course are included in these graphs. The module on amplifiers was much longer than the ones that preceded it, and students were recommended to allot two weeks to complete it. Module 3 introduced a great deal of new material that could have been broken down into two smaller modules. From these plots, it is also evident that students who made it past this section were likely to complete the rest of the course, earning a full score on the problem sets following it.

Also, these results suggest another way to view participation rate. Only 7808 students out of 62624 enrolled in the July 2015 session attempted any of the problems, a participation rate of 12.4%. Of this group there was a completion rate of 14.8%. It seems that many students enrolled out of curiosity but did not commit to working through the problem sets. One reason might be that some of the problems required solving formal circuit analysis. The course exercises may better reach this course's intended audience by including more investigative problems that use virtual circuit building or virtual breadboarding[6].

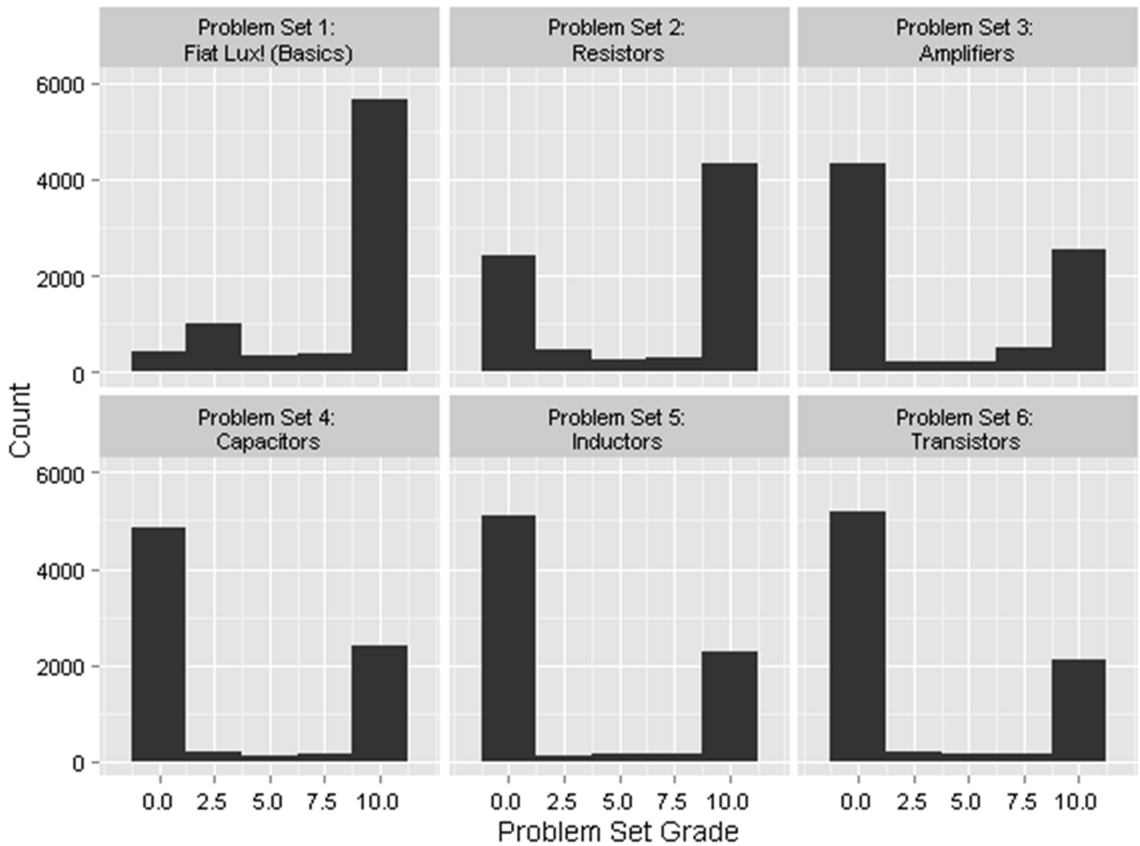


Figure 6: Distribution of problem set grades for the July 2015 session, N = 7808; maximum score of 10 for each assignment

3.3 How did students obtain components and lab equipment?

Since an analog circuits laboratory had not been attempted at this scale before, the authors were interested in how students opted to obtain measurement equipment and components. Newark element14 created a parts purchase page for students in North America, Europe, and India. The purchase of the Texas Instruments LaunchPad was made optional, allowing students to bring their own microcontroller if they already had one.

The course survey results regarding components, microcontroller choice, and lab equipment are shown in Figure 7. These results show that many students opted to purchase their laboratory equipment from other suppliers. One student shared that they purchased parts in bulk from a local market and was selling kits cheaply to fellow students in India. Some other regional electronics hobby retail websites also prepared the materials to make the materials easier to obtain.

A few students elected to use the National Instruments myDAQ, but many used a digital multimeter. Many students opted for other USB oscilloscopes like the Digilent Analog Discovery. The alternate microcontroller option was well-utilized, with half of students who responded to the course survey electing to use an Arduino. Students ported the course-supplied code to the Arduino platform and shared it on the Wiki. These results suggest that more could be done to support students who are using different microcontrollers.

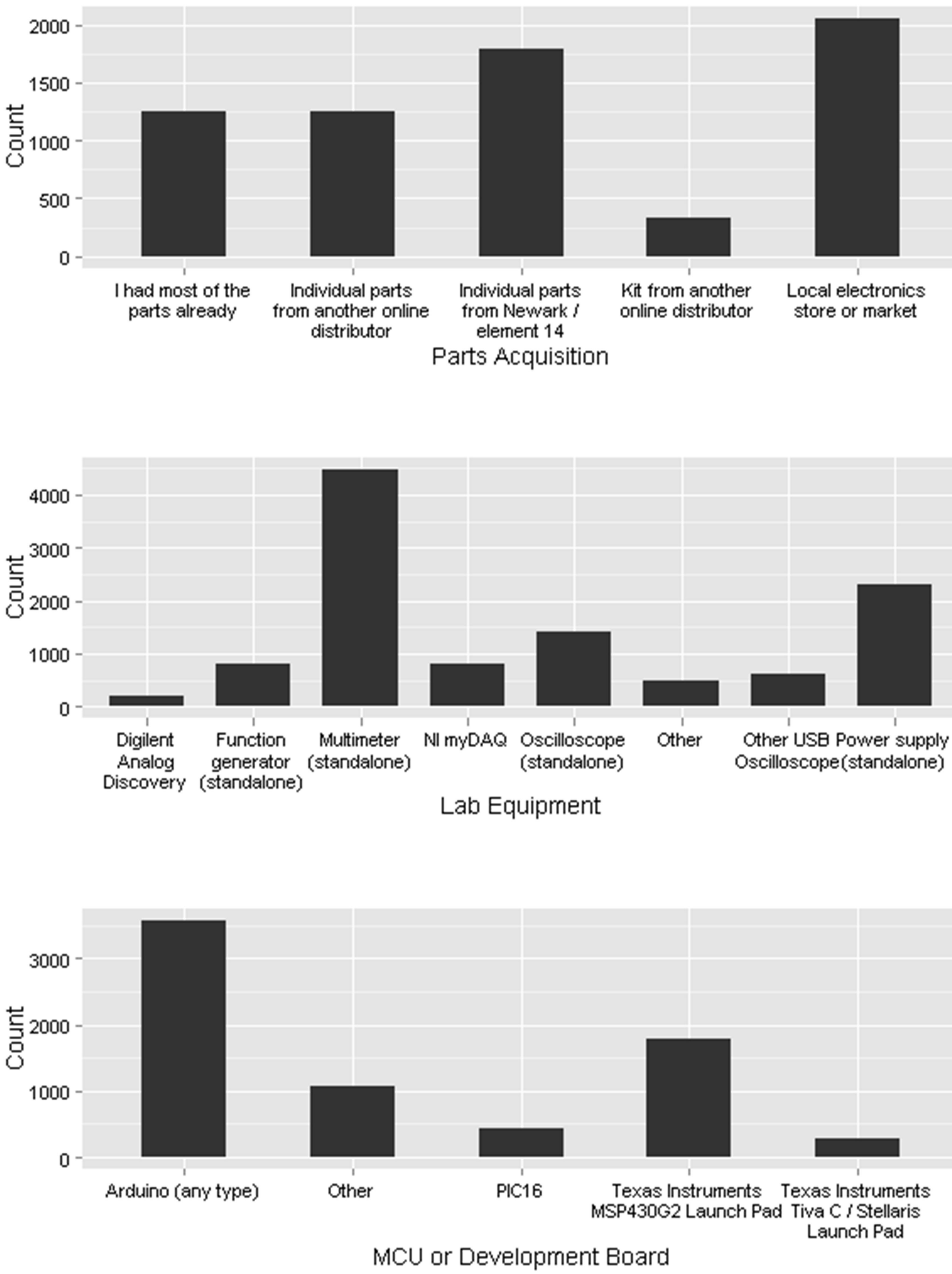


Figure 7: Pre-course survey results pertaining to laboratory components (N = 6603), laboratory equipment (N = 6126), and microcontroller choice (N = 7157).

3.4 How well did peer grading work for robot assessment?

To ensure that peer grading could accommodate large variations between individual designs, students were asked to grade based on demonstrated functions as opposed to specific implementation details. Though the decision peer-grade the robots was initially met with protest on the discussion forums, students overwhelmingly agreed that they received the grade that they deserved on the robot project, based on exit survey results shown in Figure 8.

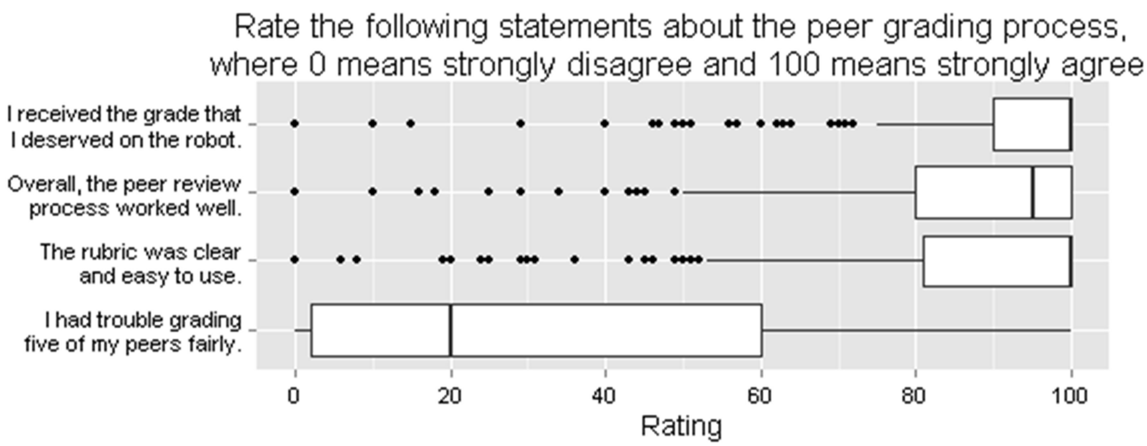


Figure 8: Peer grading exit survey results, N = 461; outliers more than 1.5 interquartile ranges below the first quartile or above the third quartile excluded from the whiskers

Most respondents believed that the correct grade was awarded to them, with a mean agreement (including outliers) score of 92/100. These results suggest that the peer review process worked well for most students. However, there were some issues with the peer grading process. Students were required to upload videos of their robots to a third party video or file sharing website, and then submit a link to the file on edX. Default privacy and sharing settings prevented a significant number of students from grading some projects, requiring a resubmission once the sharing settings were changed. Recent improvements to the edX Open Response Assessment Tool will allow students to share media files directly through edX, streamlining the submission process.

3.5 How was the course received?

EE40LX was received well according to the exit surveys, with 97% of respondents (N = 897) agreeing that they would recommend *EE40LX* to a friend. There is a good deal of interest in more advanced courses, with 96% of respondents (N = 897) affirming interest in related follow up courses.

Survey respondents were also asked to rate *EE40LX*'s components and these results are shown in Figure 9. The overall quality was rated the highest, with a mean score of 89.8 out of 100 and a median of 94. The lecture and lab videos were the next most highly rated parts of the course, with problem sets, notes, and project documentation following close behind with median scores of 90 or above.

The two parts that could use the most improvement are the Discussion Forums and the Wiki. Both of these had a median score of 80, suggesting that these resources were not as useful as the others. During the latter half of the July 2015 session, there were fewer resources for forum moderation and this may have affected the forum score. The Wiki was primarily student-curated and used to list options for obtaining course parts in different world regions and share microcontroller code. The Wiki was only announced once during the first week, so some students joining the course later may not have been aware of it.

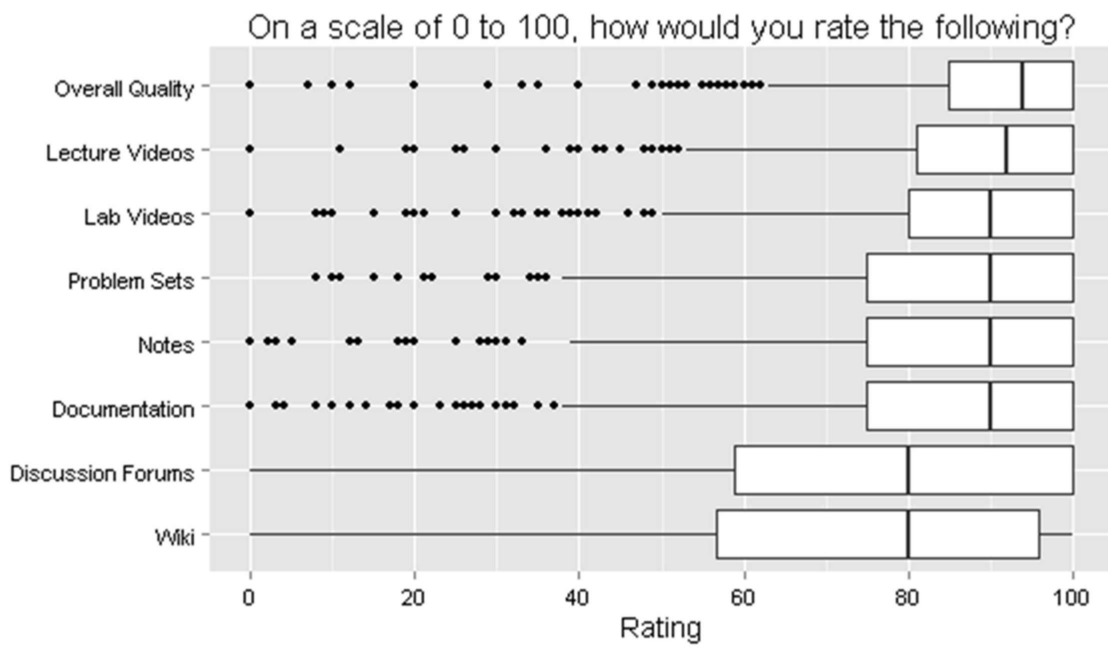


Figure 9: Course evaluation results, N = 868; outliers more than 1.5 interquartile ranges below the first quartile or above the third quartile excluded from the whiskers

4.0 Discussion

Based on the survey and engagement results, some changes could be made to improve completion rates in future versions of this class. Additionally, there is a demand and opportunity for well-designed engineering courses that teach advanced electronics and control theory. This section describes work for future revisions of the course material and suggests directions for further MOOC development.

4.1 Improvements for future sessions

The class' completion rate was partially influenced by the low participation rate. Despite a large number of enrollees, particularly in the July 2015 session, only 12.4% participated in at least one problem set. Within this group, 14.8% of students completed the course. Therefore, there were two significant barriers for completion: initial participation and the class assignments.

Participation could be improved by offering a greater incentive for completion. Some MOOCs offer continuing education credits (CEUs), required by many professions to maintain a license or certification. Accreditation of this course for CEUs for electricians, technicians, or engineers may be a way to recruit a more involved cohort. A number of students asked about the potential for earning CEUs and a group of students reported that they were taking the course to fulfill their workplace's continuing education requirement, suggesting that there is a demand for accredited courses.

The completion rate could be improved by simplifying the robot parts acquisition process. Though most of the electronics could be purchased in one place, students in different regions had to make many substitutions. Additionally, the mechanical parts (wooden sticks and springs) had to be purchased separately since most electronics distributors do not carry these items. More complete robot ordering options, such as pre-packaged kits, may lower the bar to entry to encourage more participation in robot construction.

Revision of the problem sets may also improve the course completion rate. Students who took the campus pilot of this lab on campus sometimes lacked a solid understanding of the operation of the circuit they were to build in each lab. This issue was remedied by requiring each student to simulate the circuits to be built as part of a pre-laboratory assignment. Similar simulations could be implemented and automatically graded in this MOOC with edX's circuit sandbox tool. Including more simulation problems would further reduce the number of traditional circuit analysis problems, which may have discouraged some students from participating further.

4.2 Opportunities for further MOOC development

Reviews of *EE40LX* were largely positive and over 96% of students expressed interest in taking more follow-up courses. Since this course covered basic principles and not advanced electronics, many students were not satisfied with depth of coverage. For example, transistor circuits were not covered in detail, just explaining enough to describe the operation of an electret microphone and transistor switching. More advanced analog concepts such as common mode rejection, noise, feedback, and bandwidth, though outside the scope of *EE40LX*, could be covered in a follow-up course. Rising popularity in remote control vehicles and aircraft have spawned a dedicated hobbyist community that would appreciate more courses on robotics and control theory. An entire sequence of Coursera classes dedicated to power electronics is offered by the University of Colorado Boulder[10], and similar specializations could be a lucrative opportunity for other institutions.

4.3 Incorporating hands-on experiences in MOOCs in other STEM disciplines

EE40LX demonstrates that a peer graded hands-on laboratory component can enhance a circuit MOOC. Similar hands-on projects could be integrated with MOOCs in other STEM disciplines. Since the physical sciences rely heavily on empirical observations, exercises should move beyond the MOOC lecture format to help students connect with the material beyond passive lectures and problem sets. For example, an introductory mechanics course could include a construction project, such as a simple catapult, provided that the parts required are inexpensive and readily available. An ecology class could engage students by having them photograph local flora and fauna and classify them. These exercises could then be peer-evaluated with a sufficiently flexible rubric.

5.0 Summary and Conclusions

This paper described the development of *EE40LX: Electronic Interfaces*, a widely distributed analog circuits laboratory MOOC, wherein students build a robot from scratch out of inexpensive parts. Although there were some issues with parts availability, this course was successful, compelling over 850 students from around the world to build the class' final robot project. Peer grading was successfully employed to grade these projects through the design of a rubric that tolerated differences in robot designs. Though the approach described in this paper has worked for an introductory lab with simple circuits, the authors suggest that more complex hardware courses would require virtual laboratories or remote-controlled equipment to properly teach the material. However, carefully curated kits could introduce students to new fields beyond electronics with a powerful hands-on approach that may inspire additional study.

Though MOOC courses must contend with high attrition rates and low participation rates, the effort is worth it for those people that they reach. Those students that did not finish this course have shared gratitude and appreciation for a positive experience and the opportunity to engage in a meaningful learning experience. Ultimately, this medium has the potential to bring material to students who are normally excluded by geography, income, or age. With additional changes in course structure, exercises, and incentives, more students could participate to advance technical literacy.

6.0 Acknowledgements

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Appendix

Table A1: Complete course outline

Section		Robot Part
Module 0: Prologue		
0.1	**Definitions**	
0.2	**The Robot**	
0.3	**MSP430G2 LaunchPad**	
0.4	**Breadboards**	
D0	**Debug 0: myDAQ**	
E0	**Energia 0: Tutorial**	
Module 1: Fiat Lux!		
1.1	**LED Circuit**	
1.2	**Charge, Current, and Voltage**	
1.3	**Verifying Circuit Laws**	
1.4	**Voltage Regulator**	**Voltage regulator**
D0	**Debug 1: Voltage Regulator**	
E0	**Energia 1: LED Blink**	
Module 2: Resistors		
2.1	**Resistors**	
2.2	**Ohm's Law**	
2.3	**Variable Resistors**	
2.4	**Wheatstone Bridge Analysis**	**Photocell Front End**
D2	**Debug 2: Wheatstone Bridge**	
E2	**Energia 2: Serial**	
Module 3: Amplifiers		
3.1	**Comparators**	
3.2	**Comparator Front Ends**	
3.3	**Amplifier Models**	**Speaker Driver**
3.4	**Speaker Driver**	
3.5	**Ideal Amplifier Models**	**Electret Mic Front End**
3.6	***Microphone Front End**	
D3	**Debug 3: Comparators and Amplifier circuits**	
E3	**Energia 3: Power blocking, tone generation, and analog read**	

Module 4: Capacitors		
4.1	Capacitors	
4.2	Capacitance	
4.3	*Bypass Capacitors	Voltage Regulator Revisited
4.4	Three Observations	
4.5	RC Circuits	
4.6	*Filters	Electret Mic Front End Revisited
4.7	Phasors	
4.8	*Microphone Amp Revisited	
D4	Debug 4: Measuring Frequency Responses	
E4	Energia 4: Tri-Stating	
Module 5: Inductors		
5.1	Inductors	
5.2	Inductance	
5.3	Four Observations	
5.4	RL Circuits	
5.5	Motors and the Flyback Diode	
5.6	Phasors Revisited	
Module 6: Transistors		
6.1	Switches	
6.2	FETs	
6.3	BJTs	Motor Driver
6.4	Adding the Motors	
6.5	Transistor Amplifiers	
Module 7: Epilogue		
7.1	Final Robot	Final Project
7.2	Hacks	
7.3	Thank you!	
E7	Energia 7: Robot Code	

*Sections that demonstrate the use of an oscilloscope

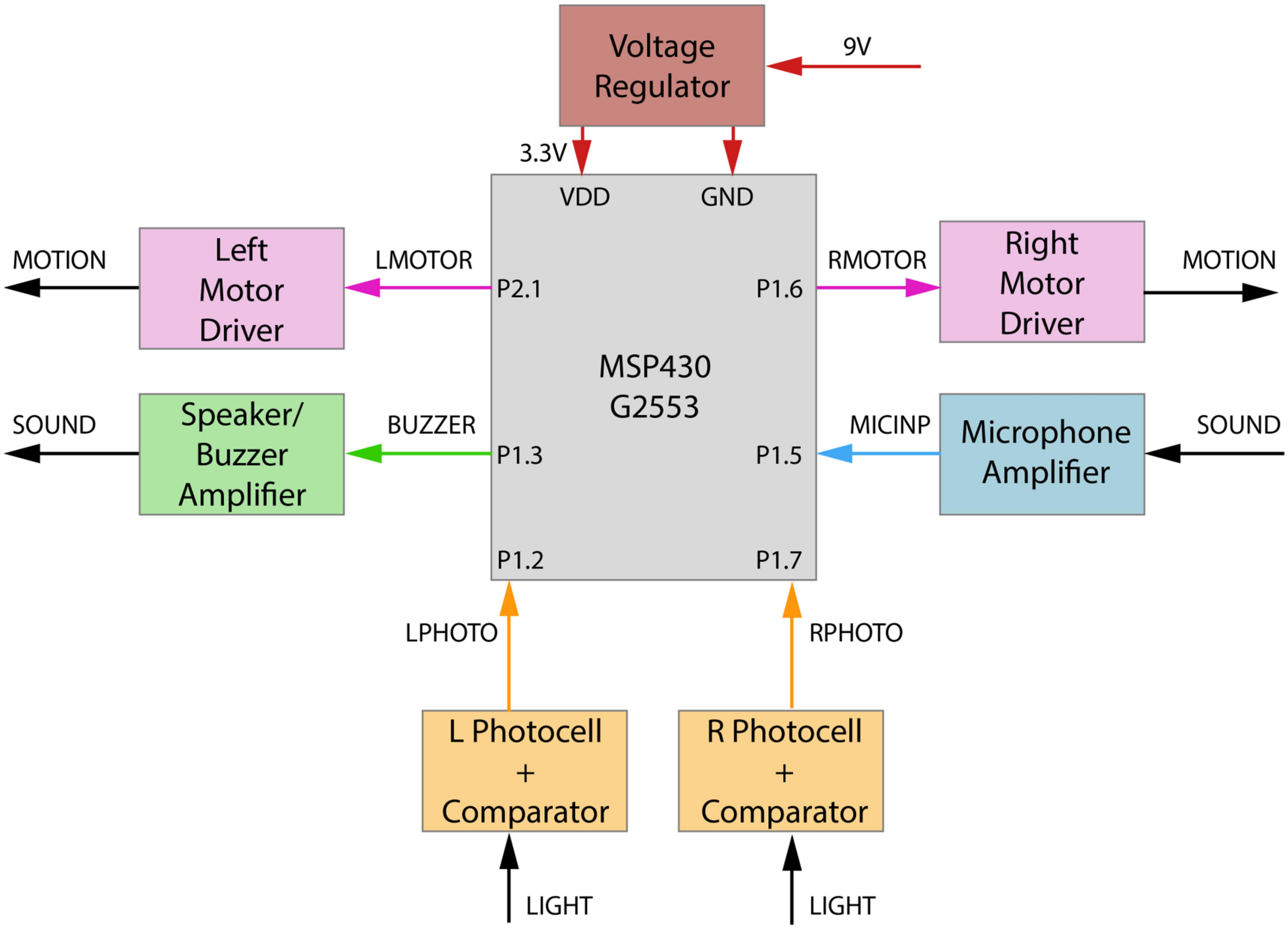

Figure A1: *EE40LX* robot block diagram

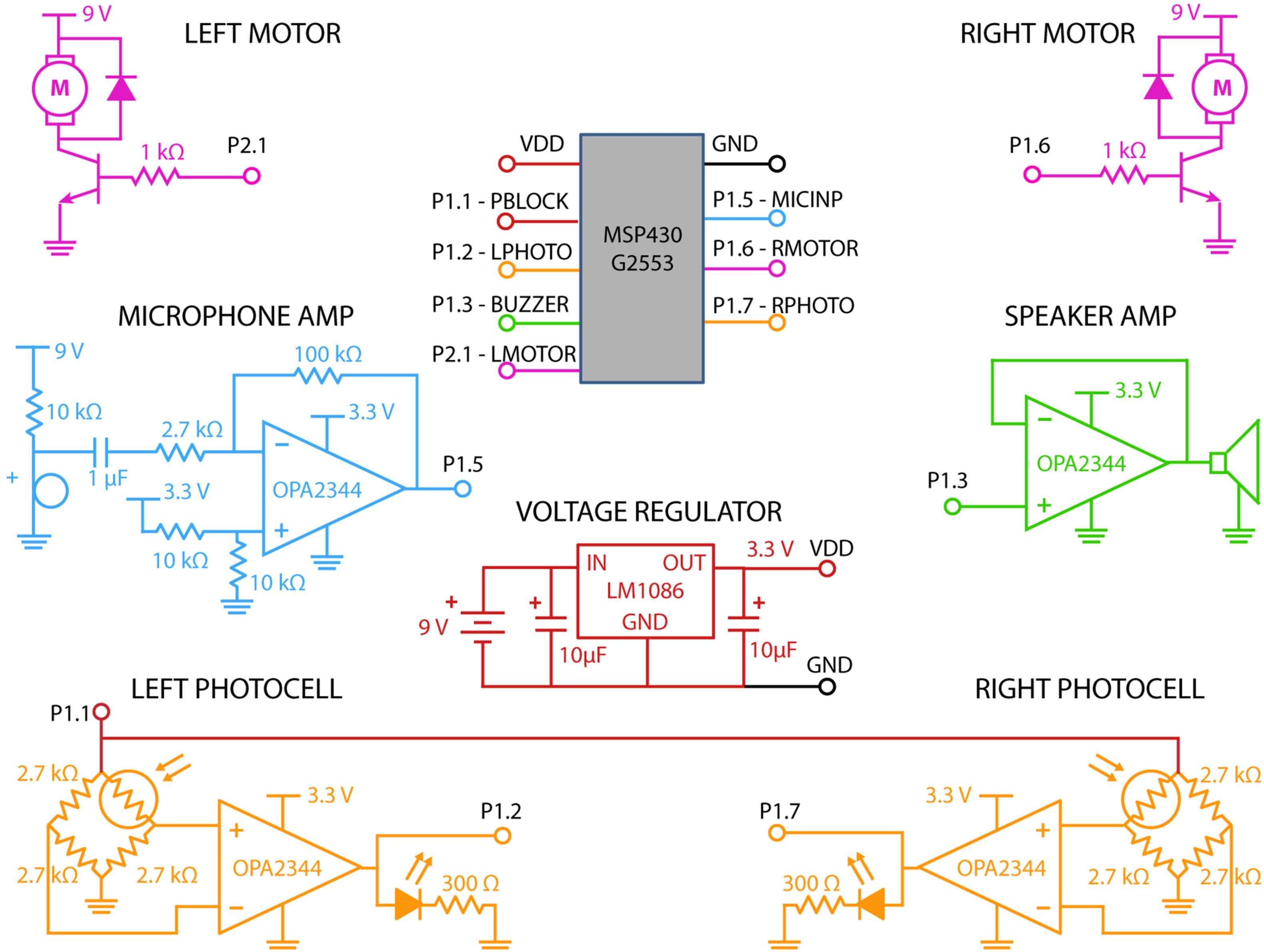

Figure A2: *EE40LX* robot schematic