Teaching Electronic Circuits Online: Lessons from MITx's 6.002x on edX

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***Abstract*—6.002x is the first electronic circuits course to be taught online to tens of thousands of students. The goal of the 6.002x experiment was to explore ways to use computer-assisted instruction to surpass the quality of traditional residential teaching. By providing superior on-line content delivery and assessment, we hope to both be able to educate people without access to education, and to improve residential education by allowing professors to focus on higher value tasks. We improved on the classroom experience in several ways. Students can actively monitor their current levels of mastery and to self-pace in response. They can identify and break through misconceptions before moving on to more advanced material. The massive scale of the classroom has participants on-line 24/7, allowing students to ask questions and receive peer answers in almost real-time. The platform allows for substantial data collection on testing, allowing us to incrementally and scientifically improve courses. Finally, the amount of effort that can be invested into a course is much greater when it can be amortized across tens of thousands. In order to achieve this, we had to overcome a number of challenges: finding mechanisms to allow automated grading, overcoming the lack of in-person interactions, and overcoming the lack of student access to laboratory equipment. The course was shown successful in both residential and mass-scale settings.**

I. Introduction

Massive open online classrooms have the potential to provide hundreds of millions of people around the world access to the same high-quality education restricted to residential students at some of the world's most elite institutions, to dramatically improve education at elite institutions, and to provide tools to deeply understand how people learn. Pioneered in part by MIT's Open Courseware [1], improved and popularized by the Khan Academy [2], and brought back to higher education through experiments such as the Stanford AI Course [3], and The University of the People [4], 6.002x (Circuits and Electronics) is the first course offered through the edX (formerly, MITx) online learning platform. Designed to be content-identical to the sophomore-level Circuits and Electronics course (6.002) taken by residential MIT students, 6.002x was first offered in the spring of 2012 to both residential students, and to thousands of on-line students. Following its success, it is again being offered in the fall of 2012.

As the first electronic circuits course to be taught online to over ten thousand students from across the world, the course encountered unprecedented opportunities and challenges during development and delivery. In contrast to a traditional residential course, we could provide means for students to actively and continuously monitor their level of mastery, to actively engage in the learning process (as opposed to passively absorbing lectures), to avoid having long-term misconceptions, to self-pace the learning process, and to have rapid feedback. In order to do this effectively, we had to overcome several challenges. We had to create means to make the course as or more engaging than a residential experience involving human contact. We had to find ways to assess complex open-ended problems, including design problems, of the sort found in standard circuit design courses. We also had to overcome the lack of access to physical laboratory equipment. We overcame these through the creation of a platform which supported rich, open-ended problems, including a simulated on-line laboratory.

As a research platform, we captured data on virtually all student activity in the system. A middleware layer tracked all student submissions – up to a size limit – to the server. In addition, user-space JavaScript was instrumented to send usage patterns to the server, and backend code was instrumented to log context (e.g., when a student submitted a problem, it will also log the random number seed for that problem). This data is being actively analyzed within edX, as well as by several research groups. The platform supported AB tests, and several experiments were run over the duration of the course. A key experiment looked at the effects of mixing styles and personalities in a video.

While we have not fully evaluated the engagement and pedagogical effectiveness of the course, preliminary results suggest that it is either on-par with or better than a traditional residential experience.

II. Structure of the Course and Student Body

6.002x is a sophomore-level course in electronic design. The course is taught over 16 weeks, including the exam period. Roughly the first half of the course is spent on memoryless systems, including nodal analysis, small signal models, FET amplifiers, and digital logic. The second half of the course is spent on systems with memory, including second order systems and basic concepts in feedback and stability.

The coursework is organized by weeks. Each week students are expected to watch roughly 2 hours worth of interactive content called learning sequences, which consisted of 5-10 minute video segments interspersed with self-assessment

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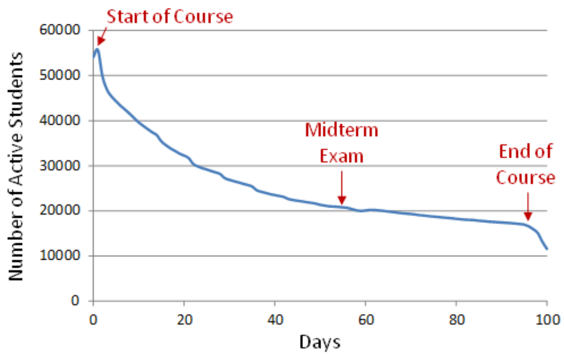

Fig. 1. Number of active students over time. A student is considered active if they registered before a given date, but still viewed a learning sequence, problem set, or tutorial after that time.

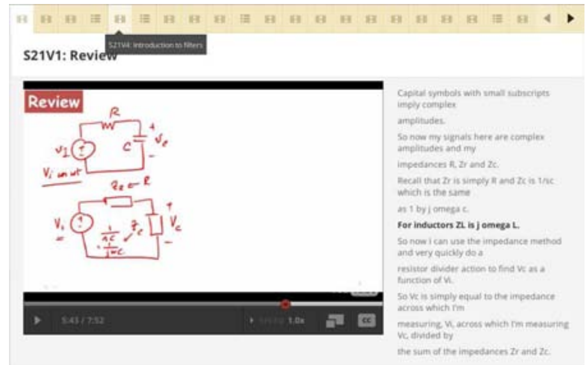

Fig. 2. A sample learning sequence. The icons across the top allow students to navigate to individual segments of the course. The captions on the right allow students to skip forwards and backwards in small increments. A speed control at the bottom allows students to play back the video at 0.75x, 1x, 1.25x, and 1.5x speed (with pitch shifting).

exercises. In addition, each week had varying amounts of essential and optional tutorials. Tutorials provided additional problem solving videos, akin to recitations, as well as additional interesting information, akin to sidebars in books. Both tutorials and learning sequences were frequently supported by video demonstrations of real circuits. In a tutorial, we might derive how a circuit worked, and then characterize a physical implementation of the same circuit.

Students also have to complete a problem set and a design lab assignment, which is carried out using a web-based simulator. Weekly coursework also includes readings from the on-line textbook. A midterm exam is held after week 7 and a final exam at the end of the course. The course is semi-synchronous – students can watch learning sequences and do problems any time, but are expected to complete each week's work by a specified deadline. Those who earn enough points to pass the course receive an honor code certificate from MITx.

While the number of registered students in the Spring 2012 offering of 6.002x was 154,950, the majority were visitors. The number of students seriously taking the course was much lower. 25,750 students were classified as potentially serious students (defined as having attempted the first (baby) problem on the first problem set). 7,157 earned a certificate, indicating a 28% course completion rate. This is on-par or slightly better than similar past online courses [5]. Course enrollment, including students auditing the course, is shown in Fig. 1.

We collected optional student demographic at both the beginning of the course (location, name, and language), and at the end of the course (a 34-question matrix sampled survey). Students came from a fairly broad set of backgrounds, although with a slant towards adult learners. Approximately $\frac{2}{3}$ of the students who successfully earned a certificate were college graduates. The course required differential equations, and indeed, over 95% of those alumni had finished calculus or higher. Approximately $\frac{3}{4}$ of the students worked on the course alone. The students were roughly evenly split between US, non-US developed, and developing world. The course included a substantial number of students in countries with intermittent Internet or power, which meant that exams and assignments had to be designed to be tolerant to outages. Students ranged in age from 14 through 74, with a mean of 30, median 26, mode of 20, and a std. div. of 12.

III. Improvements Over the Traditional Course

Our goal for 6.002x was an on-line experience superior to a traditional residential course. We viewed this as a prerequisite for both enhancing the residential experience, as well as for providing worldwide education sufficient for people to be able to find jobs. We relied on several techniques to achieve this.

A. *Learning Sequences Promote Active Learning*

In place of lecture, the videos were structured as learning sequences (see Fig. 2). Pioneered by Grimson and Lozano-Perez [6], [7], videos were punctuated by both checked and unchecked questions. These were deeply embedded into the structure of the sequence – the goal was to, as much as possible, follow the Socratic method. This gave students the ability to engage with the content on a semantic level [8], which has consistently shown to give very substantial improvements in learning speed [9]. Based on student resistance to active learning techniques on campus, we were concerned that students might prefer more passive learning. We were pleased to find that in discussion forums on both 6.002x and elsewhere, students actually found shorter segments more engaging.

The questions were also designed to allow students to monitor their levels of subject expertise, and to not move on before they reach a sufficient level of mastery, based on research which suggests this can dramatically improve effectiveness of learning [10], [11].

B. *Instant Feedback in Assessments*

Students are given an infinite number of attempts on problems. While in a traditional residential course, student misconceptions can persist for weeks, from the time when a homework assignment is turned in, to the time it is reviewed by the student, in this on-line format, students are immediately shown misconceptions, and allowed to correct. The use of this type of feedback improves learner performance [12]. As with learning sequences, this allows students to continuously monitor levels of mastery.

For this to be effective, problems have to be sufficiently open-ended that students cannot simply guess an answer. As a result, in the original 6.002x, the system did not support simple

> *"I really like the tutorial guys (Gerry Sussman and Piotr Mitros). I find the way they interrupt and correct each other really amusing and informative. Kindof like a serious, focused, introverted version of the brothers on Cartalk."*

> *"I REALLY (REALLY) like the sessions with the guys who use the quadrille paper with cutout overlays and Varsity, Flair Pens and BIC Markers for several reasons! I think that they are BRILLIANT!!!"*

Fig. 3. Sample student feedback on the two-person tutorials from the forums and the TA inbox.

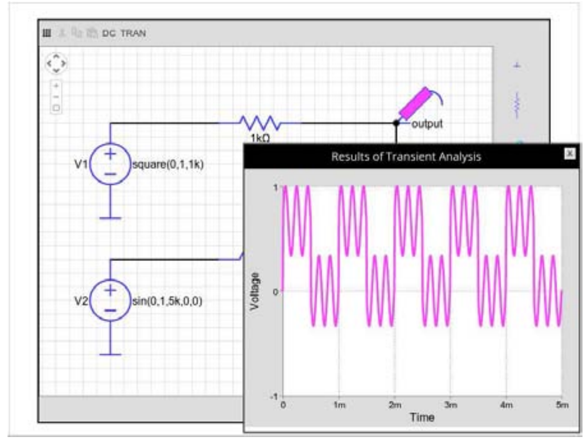

Fig. 4. A sample laboratory. Students design a resistive circuit that mixes two voltage sources into a defined waveform. The system runs a transient simulation. Other laboratories ranged from active op-amp filters to looking at distortion in MOS amplifiers.

formats like multiple choice. The system supported numeric answers, mathematical formulas, and circuit schematics. This set of response types was based on a survey of problems from previous semesters of 6.002, and gave ways to ask almost all of the problems in the regular course.

C. Tutoring-Style Videos

The design of the video content was based on the style of tutoring, as opposed to lecture. This is based on significant, repeated research showing a substantial increase in learning from tutoring [13]. Modeled on Khan, the individual videos are designed to give the illusion that both student and instructor looking at a common piece of paper. Supported by both anecdotal and experimental feedback in the course, the material is, as much as possible, written out by hand, rather than animated by computer. As in a tutorial, students are asked to do much of the work themselves. This is both more active and more engaging than watching derivations.

Within the style of tutoring, we experimented with several formats at the beginning of the course. The format we standardized on for the main learning was Khan-style tablet recordings. This permitted the main lecturer to work in a variety of settings, and allowed for heavy video editing possibilities to, for example, remove disfluencies.

The tutorials, in contrast, were primarily based on Thrun/Norvig-style document camera recordings pioneered in the original Stanford AI course [3]. Based on research that suggests that human interactions in video may be helpful, many of the tutorials were structured as two-person discussions [14]. Many students gave very strongly positive feedback about the multi-person format (see Fig. 3).

D. Self-Paced Learning

Throughout 6.002x, we attempted to allow students to learn at their optimal learning speed. Traditional books permit this, but have an associated high usage of short-term memory (e.g., "In figure 1, resistor R1 acts as a pull-up to resistor R2" requires the student to keep the number of the figure and the names R1 and R2 in short term memory), which can be detrimental to learning [11]. To combine the ability to point e.g., with a finger, rather than to refer to a reference, with the ability to self-pace, we developed a custom video player. This included multiple video speeds, and the ability to use captions to navigate to a specific point in a video, or skim through a video.

We designed the course to make it easy for students to skip past or skim through material which they already know. Labels on the chunks of a learning sequence gave clear indication of what material was covered. In-sequence problems were designed to allow students to determine whether they understood key concepts without watching videos.

E. Instant Question and Answer

In a traditional residential course, students have limited opportunities to ask questions – recitation sections, office hours, and other scheduled periods. On-line, we offered a discussion forum where, with thousands of students, students could ask questions and receive feedback in near-realtime.

In the original spring run, 92% of questions posted in the discussion forums had answers, and median time to answer was just under 12 minutes. In the fall run of edX courses, at the time of the paper submission, 67% of student posts had responses, and the median time to response across all courses was 23 minutes. In 6.002x, specifically, 85% of posts were answered, and median time to answer was 47 minutes.

F. Virtual Laboratories

The residential version of MIT's Circuits and Electronics course has design projects conducted in physical laboratories. As a proxy to physical laboratories 6.002x provided students an opportunity to experiment with circuit design in a web-based schematic capture and simulation tool (see Fig. 4). The simulator was very easy to use, as can be judged by its manual which is only one page long. Simulated labs were graded based on the numerical answers produced by DC, AC or transient analysis in a manner similar to problem sets and exams. When time-domain waveforms or frequency plots were generated, grading was done by sampling these plots/waveforms. A sample lab is shown in Fig. 4. We chose to avoid using a web-interfaced physical laboratory [15] in part due to scaling and physical support issues.

G. Modifications of Assessment for Online Use

Since students could only enter their answers to problems, and we could not evaluate their entire thought process, the traditional ways of granting partial credit were not available. Two techniques were used to overcome this limitation: the first involved asking students to provide intermediate answers to the problems, and the second was to allow the students to check their answer and try again. This second proxy for partial credit was especially important for exams, where students only had three tries to solve problems, as well as for providing better feedback to help students learn [16].

Although the focus of 6.002x is on student learning, we used techniques to reduce the use of unfair means in passing the course. For example, problems often had randomized parameter values. Different students got problems with different numerical values, and so could not copy answers.

Due to the large scale of the course, we were unable to grant extensions on homeworks, laboratories, and exams. The world-wide nature meant that we could not avoid holidays, and that we had students with limited power and Internet. As a result, we allowed students to drop their two lowest homework and laboratory scores. In addition, exams were structured with a multi-day window, where students could work on the exam for a total of a 24 hour window of their choosing, enforced by honor code. The problems on the exams were open-ended, such that students would be unable to complete them in any amount of time if they did not understand the material.

IV. Opportunities in Residential Education

A key goal of the platform is to reform residential learning. We are still exploring ways to integrate the platform, content and pedagogical techniques developed for the online classroom into residential education. The initial experiments used a simplistic model, but we hope to move towards more sophisticated models integrating peer teaching and blended learning [17].

V. Conclusion

Online platforms also create new opportunities for innovation in delivery of information and assessment of knowledge. This paper presents several techniques applicable to both pure on-line and residential use that leverage the power of on-line to improve both student learning and student engagement. A pure on-line format also presents several challenges, in particular with regards to assessment of open-ended questions, and in maintaining engagement throughout the course. This paper addresses those challenges.

Preliminary assessments of the efficacy are incomplete – all suffer from sample bias – but strongly suggest that it is either on-par with or superior to a traditional campus course. Students in an experimental classroom at SJSU using 6.002x materials in a flipped classroom scored 10-11 points higher on a midterm relative to students in previous semesters of EE98 (on a midterm designed around the EE98 curriculum), and showed dramatically lower failure rates. A majority of the students who volunteered to take the on-line version in lieu of the MIT version preferred the on-line course to the residential version. 63% of the alumni who received a certificate in the on-line course rated the course as better than an equivalent university course, 36% as equivalent, and only 1.4% as worse.

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References

[1] "MIT Open Courseware." http://ocw.mit.edu. Accessed November 1, 2012.

[2] "Khan Academy." http://www.khanacademy.org. Accessed November 1, 2012.

[3] "Introduction to Artificial Intelligence." http://ai-class.org. Accessed November 1, 2012.

[4] "University of the People." http://www.uopeople.org. Accessed November 1, 2012.

[5] J. Widom, "From 100 Students to 100,000," ACM Sigmod Blog, February 24, 2012. http://wp.sigmod.org/?p=165. Accessed November 1, 2012.

[6] L. Breslow, "Findings from Ten Formative Assessments of Educational Initiatives at MIT (2000-2003)," *Crosstalk Seminars on Educational Change*, 2004.

[7] J. Newman, E. Grimson, T. Lozano-Perez. "Online presentations show academic performance advantages over auditorium lectures." *American Psychological Society Convention*, 2005.

[8] F.I.M. Craik, R.S. Lockhart "Levels of Processing: A Framework for Memory Research," *Journal of Verbal Learning and Verbal Behavior* vol. 11, no. 6, pp. 67184, 1972.

[9] J.D. Bransford, A.L. Brown and R.R. Cocking, eds., *How People Learn: Brain, Mind, Experience, and School*, Washington, D.C.: National Academies Press, pp. 12-13, 1999.

[10] J.H. Flavell, "Metacognition and Cognitive Monitoring: A New Area of Cognitive–Developmental Inquiry." *American Psychologist*, vol. 34, no. 10, pp. 906-911, 1979.

[11] J.W. Pellegrino, N. Chudowsky and R. Glaser, eds., "Chapter 3: Advances in the sciences of thinking and learning," *Knowing What Students Know: The Science and Design of Educational Assessment*, pp. 59-92, The National Academies Press, 2001.

[12] V.J. Shute, "Focus on Formative Feedback," *Review of Educational Research*, pp. 153-189, March 2008.

[13] B.S. Bloom, "The 2 Sigma Problem: The Search for Methods of Group Instruction as Effective as One-to-One Tutoring," *Educational Researcher*, June/July 1984.

[14] M.T.H. Chi, M. Roy and R.G.M. Hausmann, "Observing Tutoring Collaboratively: Insights about Tutoring Effectiveness from Vicarious Learning," *Cognitive Science*, vol. 32, no. 2, pp. 301-341, 2008.

[15] V.J. Harvard, J.A. Del Alamo, S.R. Lerman, P.H. Bailey, J. Carpenter, K. DeLong, C. Felknor, J. Hardison, B. Harrison, I. Jabbour, P.D. Long, T. Mao. L. Naamani, J. Northridge, M. Schulz, D. Talavera, C. Varadharajan, S. Wang, K. Yehia, R. Zbib, and D. Zych, "The iLab Shared Architecture: A Web Services Infrastructure to Build Communities of Internet Accessible Laboratories," *Proceedings of the IEEE*, June 2008.

[16] G. Gibbs and C. Simpson, "Conditions under which Assessment Supports Student Learning." *Learning and Teaching in Higher Education*, Issue 1, pp. 3-31, 2004.

[17] E. Mazur, *Peer Instruction: A User's Manual*, Prentice Hall, Upper Saddle River, NJ, 1997.