Massive Open Online Courses (MOOC) are an invaluable instrument for bringing higher education opportunities to segments of the population and the globe that would otherwise be deprived of it. In a bricks-and-mortar university setting, however, the opportunity to personally interact with experts (be they professors or assistants) is something to be valued and exploited. A concept of blended learning that aims to make the most of this interaction, is the so-called flipped classroom [1]. Roughly speaking students prepare for the lectures at home through on-line material. The contact time is then devoted to exploring topics in greater depth, for example through illustrative case studies. This concept in principle is applicable to any course and has become quite popular [2], its concrete implementation, however, requires careful consideration as it is highly dependent on the specific course content and the culture of the academic institution.

We present a flipped classroom experiment carried out at the Department of Information Technology and Electrical Engineering of ETH Zurich, under the support of the ETH Zurich TORQUE initiative [3]. The class in question is Signals and Systems II [4], a mandatory 4th semester Bachelor’s course, attended by approximately 150 students each year. The class exposes students to the fundamentals of systems theory and, starting in the Spring Semester of 2014, has been taught in a flipped classroom format. The aim is to:

1) Integrate the power and sophistication of new digital technologies into the classroom, to complement and enhance the unique benefits that come with learning in the brick- and-mortar classroom setting.

2) Provide high-quality educational material online so that the use of the limited time when students have access to the lecturer and assistants is efficient, engaging, and enjoyable.

3) Venture beyond the one-size-fits all model, by providing the means to personalize the course to the needs of each individual student.

4) Provide the instructor with analytics on the progress of the class, to help tailor subsequent coverage.

In Signals and Systems II control theory finds a home both as the topic of the class and as the philosophy of instruction. Teaching is viewed as a population control problem [5], with the instructor providing macroscopic “control commands” aiming to steer the knowledge attained by the students (more precisely the distribution of learning across the class) to a desired state. Samples of the state of student understanding are collected during the semester through an on-line forum (Section II-A) and “clicker” questions (Section II-C). Based on this information, feedback action is taken, tailoring the instruction to the class state of understanding. Though this feedback action is currently implemented manually at the level of the whole class by the lecturer and assistants, we have also experimented with automated, personalized content delivery (Section II-B), inspired by stochastic reachability control [6].

Here we describe our approach and experiences with this flipped classroom model, collected over the past two years; the class is also taught in this format in Spring 2016, as these lines are being written. In Section II we introduce the educational tools used, both standard and novel. We describe the class style in Section III. We comment on our experience in Section IV and provide some concluding thoughts in Section V.
II. MATERIALS AND METHODS

A. Student preparation for the flipped classroom - Moodle

The official e-learning platform of ETH Zurich is based on Moodle [7], a standard open-source learning platform. The platform provides access to video tutorials, quiz questions, and an online forum that the students can use to discuss the material with each other and with the teaching assistants. The videos used in the Moodle were recorded in December 2013 and January 2014 by the lecturer and three teaching assistants, supported by the ETH Zurich Multimedia Services. They cover the key concepts addressed in the class, organized in 7 chapters:

1) “Introduction to modelling”: 3 videos, 25 minutes total duration, introducing the basics of state space modelling and demonstrating them through examples from electrical circuits and mechanical systems.

2) “Review of linear algebra and ordinary differential equations”: 12 videos of 70 minutes total duration, reminding students of background material obtained in earlier mathematics classes. Though viewing the material is optional, many students use the opportunity to refresh their memory on these basics.

3) “Linear Time Invariant (LTI) systems in the time domain”: 4 videos of almost 50 minutes total duration, covering the solution of state space systems in the time domain, the state transition matrix, zero input and zero state transition, and impulse response. The chapter also introduces the fundamental stability definitions and illustrates how stability is related to the eigenvalues of the state matrix.

4) “Controllability and observability”: 5 videos of 55 minutes total duration, introducing the notions of controllability and observability, the standard rank tests, minimum energy control, state estimation, and observer design.

5) “LTI systems in the frequency domain”: 4 videos of almost 40 minutes total duration, starting with a brief review of Laplace transforms (covered in an earlier analysis class), deriving the transfer function from the state space equations and elaborating on its relation to stability and frequency response.

6) “Discrete time LTI systems”: 5 videos of over 32 minutes total duration, introducing discrete time systems as derived through sampling of continuous time systems for digital control. This serves as the motivation to discuss stability of discrete time systems, discrete time transfer functions, etc.

7) “Nonlinear systems”: 4 videos of approximately 30 minutes total duration, introducing nonlinear systems through examples, highlighting their differences to linear systems, and discussing the basics of nonlinear stability analysis based on Lyapunov’s and LaSalle’s methods.

In addition to this material designed to support the lectures, the Moodle platform also provides access to the exercise papers and solutions for the exercise classes, past examinations, as well as a series of videos showing students how to solve prototypical exercises from old exams. Through the platform we also provide access to video recordings of the full lectures from the Spring of 2012 (before the adoption of the flipped classroom format), to support students who prefer the traditional model of classroom instruction.

B. A personalized learning experience - Albie

In addition to the standard Moodle based platform (available to all instructors of ETH Zurich) our team also developed a dedicated online platform, called Albie, to support personalized learning specifically for Signals and Systems II. Albie [9] is an experimental adaptive learning platform that contains a large amount of educational content, both theory (text, images, video, external links, etc.) and exercises (multiple choice questions, ordering questions, fill-in-the-blank questions). Albie was developed by Dr. Sean Summers, a former PhD student of the Automatic Control Laboratory at ETH, and populated with content together with a team of undergraduate assistants. At the moment, Albie contains approximately 700 individual pieces of educational content, making it a valuable source of study material for the students during the semester, or in preparation for the final examination, when access to the lecturer and assistants is limited.

The content in Albie can be organized in the chapters discussed above. Each student,

ABOUT THE AUTHORS

John Lygeros holds the chair of Computation and Control at the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland, where he is currently serving as the Head of the Automatic Control Laboratory and of the Department of Information Technology and Electrical Engineering. He completed a B.Eng. degree in electrical engineering in 1990 and an M.Sc. degree in Systems Control in 1991, both at Imperial College, London, U.K.. In 1996 he obtained a Ph.D. degree from the Electrical Engineering and Computer Sciences Department, University of California, Berkeley, U.S.A.. After a series of postdoctoral research appointments, in 2000 he joined the Department of Engineering, University of Cambridge, U.K. as a Lecturer. Between 2003 and 2006 he was an Assistant Professor at the Department of Electrical and Computer Engineering, University of Patras, Greece, before joining ETH Zurich in 2006. His research interests include modelling, analysis, and control of hierarchical, hybrid, and stochastic systems, with applications to biochemical, transportation and energy systems. Email: lygeros@control.ee.ethz.ch

Tobias Sutter received a B.Sc. degree in Mechanical Engineering in 2010 and an M.Sc. degree in Robotics, Systems and Control in 2012, both from ETH Zurich, Switzerland and is currently pursuing a Ph.D. degree in Electrical Engineering at the Automatic Control Laboratory at ETH Zurich. His research interests include approximate dynamic programming, control under communication constraints, and information theory. Email: sutter@control.ee.ethz.ch

1 A few sample video tutorials can be found in [8].

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however, can also choose to experience the content in an individual, customised sequence. By selecting the “trust Albie” option, the content is delivered automatically to the student by a control algorithm, aiming to maximize the probability that the student will master all the material. Student understanding is modelled through a partially observed Markov Decision Process encoded in a concept interaction map (Figure 1). The concept interaction map defines connections between the concepts covered in the course. Each connection comes with a strength and represents an assumption that the level of understanding attained in one concept affects the way in which another concept can be learned; for example, having understood Lyapunov equations for linear systems makes it easier to understand Lyapunov’s Direct Method for nonlinear ones. Each piece of content available on Albie comes with a degree of difficulty and is connected to one or more concepts. The concepts are assigned to one of the seven course chapters, introduced in Section II-A, which is graphically visualized in the topic cluster in Figure 1(b). The implication is that offering this piece of content to the student will help them understand the corresponding concepts and hence, indirectly, other concepts related to them through the concept interaction map. The improvement in understanding resulting from offering a piece of content to a particular student is related to his/her current state of understanding of the corresponding concepts: Students with a low level of understanding are more likely to increase their level of understanding from easier pieces of content, those with a high level benefit more from difficult pieces.

The exercises contained among the content pieces serve as the sensor of the learning process. The answers provided by the student are treated as measurements and a filter is used to estimate the underlying state of understanding. A feedback controller based on the principles of stochastic reachability and receding horizon control is then used to select the next piece of content to offer to the student.

This adaptive approach to learning eliminates the requirement that students work through the class material in a fixed order and provides a personalized sequence of learning content that allows students to study based on their individual abilities and needs. In addition, Albie provides data analytics to support instructors (monitor the progress of individual students and the class as a whole) and students (monitor their own state of learning and compare with the statistics of the class).

To lighten the mood, Dr. Summers also developed a video game called sigsys. The game can be downloaded from the AppStore and played on iPhones or iPads [10]. The aim is to increase the student’s involvement with control theory and help them develop intuition about dynamical systems in a playful way. By tilting their device or tapping on the screen the player controls a ball whose movement is governed by different types of dynamics (stable and unstable foci, weakly controllable systems, higher dimensional systems, etc.). The player has to accomplish various control objectives (reaching specific regions of the state space, or staying there for a specified amount of time) collecting points along the way. In the process, the player experiences (and hopefully appreciates) the entire feedback control process, intuitively identifying the system, estimating its state, and devising a control policy.

C. Engaging students in the classroom - EduApp

The ETH EduApp [11] is a combination of a mobile and a web application that enables large-scale student engagement during the lecture and exercise classes. Using the mobile app, multiple choice “clicker questions” can be posed and each student can submit their answer via their mobile device. The results (in the form of answer statistics) can be seen by the instructor and, if desired, also displayed to the class. The EduApp also provides a “back channel”, through which the students can ask questions and provide comments, anonymously if desired. In addition to bidirectional questions related to the class material, the instructor and class representatives also use the EduApp to collect feedback from the students in a middle-of-the-semester evaluation, whose outcome can be used
to adapt the class for the second half of the semester.

The EduApp allows the instructor to receive instantaneous feedback, adapting the coverage during the lecture to elaborate on points with which the students appear to be having difficulties. Wrong answers to clicker questions are invaluable in this respect. By introducing in the multiple choice questions answers reached through subtle mistakes, the instructor can initiate a discussion with the students exposing these subtle points. The clicker questions also enhance interaction among the students. In the 3-4 minutes available for answering the students discuss the questions among themselves, learning from each other and fostering a spirit of collaboration.

D. Conventional material

Besides electronic aids and material, the class of course also relies on elements from traditional classroom education. The students are given weekly problem sets, often containing Matlab assignments, to be solved individually, or in groups. Though the problem sets are not graded, we provide support for solving the exercises through exercise classes. Most students take advantage of this opportunity to discuss the problem sets with the teaching assistants since, unlike clicker questions and online quizzes, the exercises in the problem sets are close in style to the questions asked in the examinations. To further help the students prepare for the examinations we make available past examinations, offer weekly office hours during the semester and revision classes over the summer break, leading up to the final examination in August.

III. A TYPICAL SEMESTER

The class is taught in the Spring Semester, which at ETH Zurich comprises 14 teaching weeks from mid-February to the end of May. The final examination takes place in the Summer examination session (mid-August), with a make-up examination in the Winter session (early February). The class is part of a block of 4th semester classes. Students have two chances to pass the block, else risk having to leave the program. The language of instruction for Signals and Systems II is English, but solutions to examinations can also be written in German, the mother language of most students; few students elect to take this option.

The weekly program comprises two consecutive hours of lecture on Thursday morning and two consecutive hours of exercise classes on Monday afternoon. Each week an email is sent to the students asking them to watch specific Moodle video tutorials and complete the corresponding quizzes in preparation for the lecture. Having the key points covered in the videos allows the instructor to use much of the lecture time to elaborate on subtle issues, outline derivations, discuss extensions, illustrate the concepts on examples, and, most importantly, induce student participation using, for example, the EduApp. All of this contributes to a more dynamic in-class experience for the students.

For the exercise classes, the students are assigned to smaller groups being led by a teaching assistant. The first part of each exercise class is devoted to providing hints for the exercises included in the weekly problem set and, when necessary, reminding students of some of the material from the lecture or the video tutorials. The EduApp is again used to more actively involve the students in the process of knowledge acquisition. In the second part of the exercise class, the students work on the weekly problem set individually or in groups, supported by the teaching assistants. Student solutions to the exercises are not graded for credit, but students can nonetheless submit them during the next lecture for comments and corrections. At the end of the week model solutions are provided for all exercises.

During the semester, there are two midterm examinations, providing a possible 30% of the class grade. The midterm examinations are optional and only count if they improve on the student’s grade in the final examination. The majority of students nonetheless attend the midterms hoping to secure this partial credit. Each midterm is organized in two parts, aiming to assess individual performance, but also promote teamwork among the students. In the first half students receive a set of exercises and work on them individually, in the standard style of an open books examination (with access to notes, problem sets, books, but without electronic aids, or access to the internet). For the second half the attendees are divided into random groups of approximately four students. A new set of exercises similar to the ones for the first half, but with some of the easier parts replaced by more challenging ones, is given to the groups to solve as a team with access to all resources at their disposal (including electronic aids and the internet, but excluding consultation with anyone outside their group). The two parts of the midterm are graded separately and the grade received is made up of 60% of the individual and 40% of the team grades.

IV. RECEPTION

Despite the fact that the course structure and concept was completely reworked and despite the inevitable teething problems with the introduction of the online platforms, reception of the new format by the students was warm. End of semester student evaluations (Figure 2) showed high acceptance of the new format and a high degree of satisfaction with the online tools and the way they were deployed. Overall student satisfaction stood at around 4.5/5, making this class one of the highest ranked among all Electrical Engineering classes.

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The student evaluations also showed that the clarity of the lecture improved further when adopting the flipped classroom format. High scores on clarity are especially pleasing since Signals and Systems II is the only class taught in English in the first 2 years of the Electrical Engineering B.Sc. program. Surprisingly, according to the student’s own assessment of the time invested in the class outside the contact hours decreased with the introduction of the new format. Surprising was also the fact that the students liked both the optional midterm (92% acceptance in Spring 2016) and the unconventional two part style of this examination (96% acceptance in Spring 2016).

The grades of the students in both 2014 and 2015 were very good. The results in 2015 were especially pleasing since the mean value of the class grades increased (4.48/6 compared to a historical average of about 4.25/6) even though by general admission the final examination was unusually challenging. Grading the examinations suggested a better understanding of fundamental concepts by many of the students, compared to previous years, though this impression is difficult to quantify.

On the negative side, student evaluations and personal experience suggest that the number of students attending the lecture and exercise classes decreased somewhat with the introduction of the flipped classroom format. Another challenge has been to motivate the students to use the online forum of Moodle and the back channel of the EduApp. Instead of exploiting these online resources, students tend to ask questions during the lecture break, after the lecture, or during the exercise classes, or discuss in private with their friends. It is unclear whether this is due to cultural reasons, or the fact that relatively few classes at ETH Zurich have an on-line forum and the students are unfamiliar with the concept.

In terms of instructor effort, customising the platforms was rather straightforward and adapting course material for blended learning proved to be an interesting and rewarding (though time consuming) experience. The main bottleneck in terms of effort and cost was generating enough pieces of content with adequate coverage and diversity to populate the online platforms.

V. CONCLUSION

With the introduction of increasing levels of technology in education it is tempting to overlook the value of contact in the learning process. Humans have evolved over millennia to learn through personal contact with other humans and the excitement of a “live” performance should not be underestimated. The flipped classroom concept aims to make the most of the personal contact between students and instructor, using online tools to carry some basic material that can be consulted at all times and releasing contact hours for a more creative, dynamic exchange.

Creating intelligent, yet empathetic, digital technology to guide students along a personal, enjoyable, and most importantly, effective learning experience is difficult and expectedly so. Beyond their use as teaching and learning media, on-line tools also serve to monitor class progress, both at the level of individual students and at the level of the class. This information allows the instructor to tailor subsequent material to the current state of learning of the class as a whole. With the help of advanced algorithmic solutions, personalized learning platforms, such as Albie, can do the same at the level of individual students.

Each student has had success with different learning methods in the past making them unique in the way they approach and learn a subject. Fully integrated online courses may be exactly what some students need, other students may benefit most from traditional instruction, while others may thrive with a combination of the two. We hope that with a blended learning approach, and in particular with digital solutions for lecture preparation, classroom engagement, and personalized learning, each student has the opportunity to obtain the best learning experience for him or herself.

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