A Digital Electronics Course Using CPLDs for Manufacturing Engineers

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Abstract: The challenge faced by ECE instructors who teach a one-semester digital electronics course in a manufacturing engineering curriculum is to present a useful fraction of the material to students whose primary interest is not electronics. We have developed a course which accomplishes this goal with the use of complex programmable logic devices (CPLDs) and a term project that involves a robot arm. The term project provides an organizing purpose for the presentation of more conventional digital electronics material earlier in the course.

Introduction

A notable trend in engineering education in recent years is the growth in interdisciplinary degree programs which draw upon a variety of traditional "core" disciplines such as electrical and mechanical engineering. Programs such as biomedical engineering and manufacturing engineering currently account for a growing fraction of the total undergraduate engineering enrollment at many schools. For this reason, there is an increasing need for educational approaches that convey the essence of a traditional discipline to students who are not majors in that discipline. This paper describes an approach to this problem which may be applied in similar situations in a wide variety of disciplines. The basic idea is to involve the students in a project that is drawn from their own interdisciplinary program while showing them the need for knowledge from the traditional discipline that is the subject of the course.

At Texas State University-San Marcos (which was known as Southwest Texas State University until Sept. 1, 2003), the first engineering degree program on campus was initiated in the fall of 2000, a program in manufacturing engineering. For a number of years, Texas State's Department of Technology has offered four-year degrees in industrial technology and engineering technology. As a required part of these programs, a course entitled "Digital Electronics" (TECH 4374) has been taught in a four-credit-hour format of one two-hour lecture and one two-hour lab per week. When we designed the manufacturing engineering curriculum, we decided to reorient this existing digital electronics course toward the needs of the increasing number of manufacturing engineering undergraduates who will take it as a requirement, while keeping it at a level that is accessible to technology students as well.

In 2001 we began a curriculum-improvement project funded by the National Science Foundation's Course, Curriculum, and Laboratory Improvement (CCLI) program. We chose the Digital Electronics course as one of the main targets of our efforts. In this paper we will describe

both an initial offering of the course which was taught with a more conventional approach, and the first offering of the substantially redesigned course that involves a final project.

Initial Offering, Fall 2002

One of us (Stephan) taught the Digital Electronics course for the first time in the fall of 2002. (Before then it was taught by other Department staff and faculty members.) It should be noted that digital electronics is not Stephan's research specialty (microwave electronics is), and he had never taught a course with a substantial amount of digital electronics content before. Being reluctant to make substantial innovations during this first offering, he taught a relatively conventional course outline as shown in Table 1.

Lecture No.	Topic
1	Intro. to analog and digital concepts
2	Number systems: decimal and binary
3	Number systems: BCD, hexadecimal, conversion
4	Logic gates: inverter, AND, NAND
5	Logic gates: OR, NOR, XOR
6	Logic families
7	Logic simplification, DeMorgan's theorems
8	Adders, decoders
9	Encoders, multiplexers
10	Flip-flops 1
11	Flip-flops 2
12	Counters
13	Shift registers
14	Review for final

Table 1. TECH 4374 Digital Electronics Course Outline, Fall 2002 Offering.

The course has no prerequisites other than a basic DC/AC circuits course. Students cannot therefore be expected to know anything about digital systems, so the first three lectures were devoted to basic digital concepts and number systems in common use. Two lectures on the basic logic gates and operations were followed by one "electronics" lecture on the various types of logic families. The abrupt transition from the fairly mathematical and abstract material preceding this lecture to the details of voltage thresholds of TTL and CMOS families proved to be a difficult one to make. A midterm examination was administered after Lecture 7, and the remainder of the course was devoted to more complex digital logic devices, both combinatorial and sequential. Most lectures after Lecture 3 were followed the same week by a lab directly related to the lecture topic. The textbook used was Floyd's *Digital Electronics, 8th Edition*, which is one of a series aimed at students in two- and four-year technology programs.[1] Most laboratories were taken from *Experiments in Digital Fundamentals, 5th Edition* by Buchla.[2] The typical laboratory involved wiring a TTL-family IC (or ICs) in a circuit on a "protoboard" equipped with special digital logic switches and indicator lamps.

This offering did make some minor changes compared to previous offerings. For the first time in the existence of the course, each student team of two had access to a PC in the laboratory, purchased with matching funds from the NSF CCLI project. During the fall 2002 offering, the use of these computers was limited to occasional reference for IC pin diagrams. Near the end of the course, students performed the last laboratory experiment with a Multisim virtual shift register rather than an actual TTL circuit. Multisim is a type of software produced by Electronics Workbench, Inc., which allows the simulation and virtual test of a wide variety of analog and digital electronic circuits. Although the shift-register lab was considerably easier to program in Multisim than it would have been to build, the digital simulation capabilities of Multisim are limited.

An independent educational research firm conducted an evaluation of the Fall 2002 course offering in the form of a customized survey. Results of the survey for the Fall 2002 offering will be presented later in comparison with results from an identical survey administered during the Fall 2003 offering. The evaluations were generally positive for the initial (2002) offering, especially with regard to learning how to work in project teams. But the instructor felt that the conventional approach he followed during this initial offering allowed little opportunity for the students to integrate their knowledge and apply it to a real-world project related to the students' majors. The revised course offering in Fall 2003 addressed this problem.

Revised Offering, Fall 2003

Over the summer and fall of 2003, we used CCLI project funds to develop and build hardware and purchase software to incorporate complex programmable logic devices (CPLDs) in the course. We chose to use the Max+Plus II software package made by Altera Corporation. Altera also markets their UP-2 Development Kit to qualified educational institutions at a cost of $149 each, which is a substantial discount below the retail price of $975. The UP-2 Development Kit consists of a Flex EPF10K-series CPLD and a Max-series IC on a board with a clock oscillator, switches, a two-digit LED display, and provisions for power and interface connectors. It is a revised version of the UP-1 kit around which numerous digital design projects were developed by Hamblen and Furman in their book *Rapid Prototyping of Digital Systems*.[3] Each kit consists of the populated UP-2 board with power supply, a copy of Hamblen and Furman, and a CD with the Max+Plus II application. We found that in order for the application to run properly, we had to request physical software keys from Altera to connect to each PC running the software. Altera provided these keys at no extra charge.

Table 2 shows the outline of the revised Fall 2003 offering of Digital Electronics. This table includes all laboratories and gives a week-by-week description of activities. We used the same textbook (Floyd) but developed all-new laboratories, all but three of which use the UP-2 development kit board and software (indicated by "CPLD" in the lab description column).

Week No.	Lecture Activity	Lab Activity
1	Intro. to analog and digital concepts	Diode matrix 2-bit encoder (discrete)
2	Number systems: dec., bin., BCD, hex	7-segment hex display (TTL)
3	Logic gates	Combination lock (TTL)
4	PLDs and digital systems	Combination lock (CPLD)
5	Adders, decoders	PLD adder/decoder (CPLD)
6	Encoders, multiplexers	(no lab-review for midterm)
7	Midterm	(no lab)
8	Latches and flip-flops	PLD latches and flip-flops (CPLD)
9	Counters and shift registers	Stopwatch & 1-bit data recorder (CPLD)
10	Logic families, interfaces	Motor drive logic (CPLD)
11	Project description and assignments	Project work (CPLD)
12	Project work (CPLD)	Project work (CPLD)
13	Project work, final reports due (CPLD)	Final demonstrations (CPLD)
14	Review for final	(no lab)

Table 2. Revised Outline of Digital Electronics, Fall 2003

As the table shows, we condensed the lecture content of the course from fourteen lectures in Fall 2002 to only ten in Fall 2003. (It should be mentioned that a typical lecture session consists of about one hour of actual lecture followed by one hour of an in-class exercise the students do in groups of two or three. This was true for both offerings.) In the new offering, number systems were covered in only one lecture, counters and shift registers were covered in one combined lecture, and the lecture on logic simplification was omitted. This last omission may have cut a little too deeply into essential material, as we will describe below. But other than that, the students did not seem to be any less prepared for the project than the original series of fourteen lectures would have made them.

The condensed lecture format made time for the final project, which took a total of six two-hour lecture and lab periods. The total class enrollment during Fall 2003 of about 40 attended the same lecture section. The labs were split into two sections of about 20 students each. Since the lab facilities consisted of 10 workstations, this approach allowed the non-project labs to be performed by teams of two (or occasionally three) students. During the final project, the lecture time was split between the two lab sections so that each student had a total of three hours per week of supervised lab access time during the final project (one hour during the lecture time and two hours during the lab.)

Most ECE-based digital electronics design courses would begin with an introduction to VHDL (Very-high-speed IC Hardware Description Language, a high-level programming language used to describe digital hardware designs). Because of the limited backgrounds of the students and the limited time in the course, we decided not to teach VHDL in this offering, except to mention its existence. Instead, all CPLD programming was done with the graphic-

based interface option in Max+Plus II and circuit diagrams using conventional logic-gate symbols. While this leads to some programming inefficiencies in the larger projects, we felt that it was a worthwhile tradeoff in order to avoid the need to teach VHDL to the students along with all the other material. While the Max+Plus II interface itself proved to be relatively straightforward to use, we experienced a considerable number of problems with design file storage and access. Many of these were due to the unfamiliarity of the students (and in some cases, the instructor) with the details of file structures in the PC environment. We plan to address these problems in the next offering by organizing a web-based file storage procedure.

Final Project: Digital Systems to Control a Robot Arm

Robotics is a subject routinely covered in most manufacturing engineering programs. Besides the increasing use of robotics in manufacturing, the technology is showing up more in consumer and hobby applications as well. We decided to design the Digital Electronics course final project around a hobby-quality 5-axis robot arm.[4] The retail price of this arm is about $80 US. A simplified drawing of the arm is shown in Fig. 1.
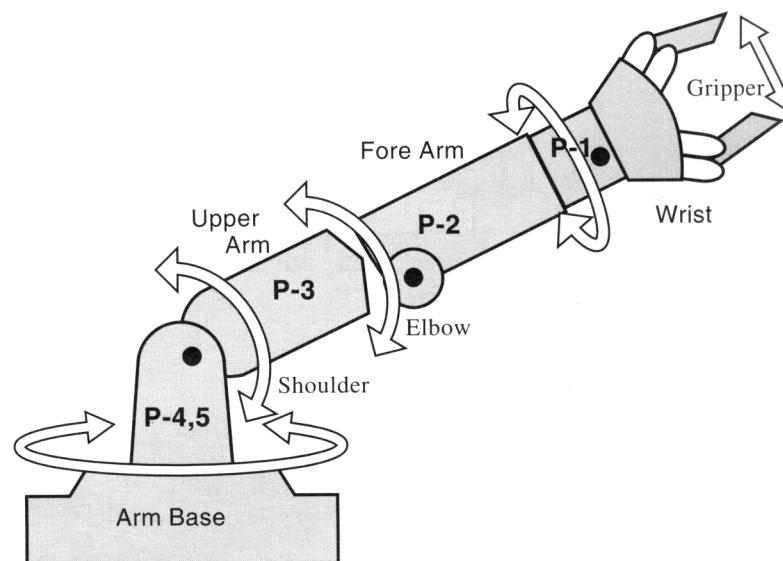

Fig. 1. OWI-007 robot arm used in final project.

The arm comes with a battery power supply consisting of four D-cells and a manual control box with five SPDT-center-off switches that apply either +3 V or -3 V to each of the five DC permanent-magnet motors in the arm. It is an "open-loop" arm in that there are no facilities for monitoring the actual positions of the five axes. (More sophisticated commercial arms use closed-loop systems with position feedback.) Nevertheless, we were able to develop and implement several interesting projects with the arm.

Although a computer interface unit is available for the arm, we chose to develop our own interface circuit between the Altera UP-2 board and the arm. It consists of an interface board with ten single-transistor level-shifting inverters and a set of three H-bridge circuits, each of

which is capable of driving two motors in both directions. The H-bridge circuits were purchased in kit form at a cost of about $25 US each and assembled by a research assistant.[5] The interface circuit was built on a small custom-designed circuit board and is shown in Fig. 2. Cabling from the UP-2 board connects to the smaller header on the interface board. The larger header connects to a set of ribbon cables that feed the three H-bridge circuit boards mounted inside the base of the modified robot arm. Since the four D-cell batteries had to be left in the base for mechanical stability reasons, we rewired the base so that the batteries provide 6 VDC for both the interface board and the H-bridges. Power for the interface board is taken off through a separate coaxial connector, which can be unplugged to disable the arm in the event of a "runaway." Although the interface board function could have been implemented with TTL or CMOS ICs, we preferred the simplicity of transistor inverters so that students could appreciate the basic switching function of the smallest digital-electronics active device. Also, the resistor leads on the interface board provided convenient test points for logic analyzer connections, which several students needed during project development.
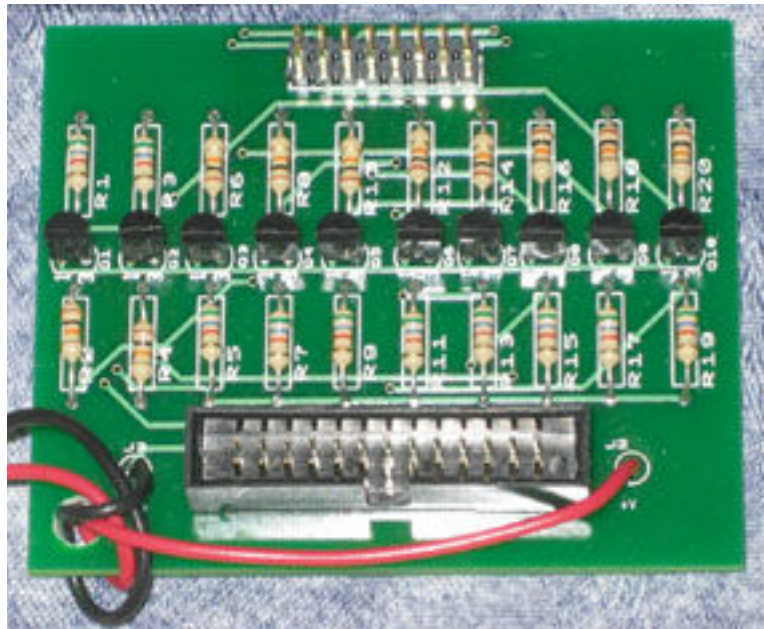

Fig. 2. Custom interface board used in robot arm project. Actual size is 6 cm x 7.2 cm.

Before the final project began, every student completed a regular two-hour lab during Week 10 on motor drive logic for the robot arm. This lab resulted in a rudimentary control system which simply selected one motor at a time via the UP-2 board's DIP switch, and operated it in both directions with two pushbutton switches. The experience gained in this lab ensured that all students started with a basic knowledge of how the UP-2 board could be used to control the robot arm motors.

The lecture period in Week 11 was devoted to preparing the students to do the final project. Students were allowed to self-select into teams of two to four. Each team then decided which final project to undertake. As an experiment, we developed five final projects ranging in difficulty from fairly easy to quite difficult, and assigned different point values to each project as

shown in Table 3. The point value was the maximum number of points a student could earn from the final project. To put the value of these points in context, the overall course score is the sum of up to 15 points for regular labs, up to 20 points for quizzes, up to 20 points for the midterm, and up to 20 points for the final. In other words, the final project points made up between 10 and 40 points, with all other grades comprising 75 points maximum. The total course score was converted into a letter grade using an approximate scale of 90-100 = A, 80-90=B, etc., regardless of the final project chosen.

Project No.	Title	Point Value
1	Basic Robot Arm Motion Control Logic Using Control Box	10
2	Robot Arm Motion Control, Recording, and Playback with Control Box	20
3	Robot Arm Motion Control, Recording, and Playback with Control Box and Record Time Display	25
4	Robot Arm Motion Control Logic Using Mouse	30
5	Basic Robot Arm Motion Control Logic Using Control Box with Magnetic Following Ability and Angular Readout	40

Table 3. Final Project Titles and Point Values.

The intent of this scoring system was to allow students with low expectations to undertake an easy project such as No. 1 while knowing in advance they would not be able to achieve a total course score higher than 85 (B). This part of the experiment was a failure. In the event, neither this option nor Project 2 attracted any teams. Out of 13 total teams, one selected Project 3 (25 maximum points), ten selected Project 4 (30 maximum points), and only two were allowed to select Project 5 (40 maximum points) because of hardware limitations. In future offerings, we will probably limit the range of maximum point values to between 25 and 30 and offer only two or three choices for final projects.

Project Descriptions

We will now briefly describe each of the final projects that were completed during the Fall 2003 offering of Digital Electronics.

Project 3, "Robot Arm Motion Control, Recording, and Playback with Control Box and Record Time Display," required the students to implement a simple command-decoding scheme to allow operation of the robot arm via the original 5-switch control box, since the modified arm no longer interfaced with the control box directly. In order to record and play back up to a minute of motion commands, the students had to implement 10 shift registers and compute the width of the registers from information on clock frequency and data sampling rates. Finally, to indicate recording time, the students had to implement a simple seconds counter based on an earlier regular lab. The one team that chose to do this project succeeded in developing the control box and shift register logic, but had problems with the timer and display circuit.

The great majority of teams chose Project 4, "Robot Arm Motion Control Logic Using Mouse." The software provided with each Hamblen and Furman book includes several library

functions such as a counter and a mouse-control-and-decoding function called "mouse."[6] In Project 4, students used the "mouse" library function to decode the relative mouse position and status of the buttons on a two-button mouse connected to the UP-2 board. We left it up to the students to decide how to use this information to control the direction and on-off status of each of the five robot arm motors. No two teams decided to implement these control functions in exactly the same way, although some approaches worked better than others. For example, some teams chose to assign "up" and "down" to each of the two mouse buttons, and selected the proper robot arm motor via the mouse's position on the workbench. Others assigned each button to a frequently-used motor such as the elbow and base motors and controlled these motors with a toggle sequence (e. g. "on right, off, on left, off" etc.) implemented with flip-flops.   Since the digital circuitry for each scheme was of approximately equal complexity, this feature of the project allowed for considerable variety among projects while keeping the project difficulty about the same for all teams that chose Project 4.

Project 5, "Basic Robot Arm Motion Control Logic Using Control Box with Magnetic Following Ability and Angular Readout," required the students to control the arm with its original control box. Additionally, the students had to make the arm grasp a small circuit board containing three magnetic reed switches arranged in a horizontal row. These reed switches connected to additional interface pins on the UP-2 board and were activated by a hand-held magnet. The project specification required the robot arm in the "follow" mode to track the position of the hand-held magnet as it moved in a circle. Finally, the students were required to show an LED display of the angular position of the arm accurate to 10 degrees. We meant for the students to derive this readout from an estimate of the arm's angular velocity and an integral of the time spent moving clockwise and counter-clockwise. Because only one magnetic switch board was available at the time, we limited this project to one team per section (two total). While implementation of the control box and magnet-following functions was relatively easy, the angular readout proved to be too much of a challenge. One team was only partially successful in its implementation and the other team failed to get their display circuit to work at all. But both teams succeeded in making the arm follow the magnet, which was the more interesting aspect of the project for the students anyway.

Project Schedule

The risk of assigning relatively open-ended projects covering several class periods is that students will lack the discipline to work steadily and will leave everything until the last minute. To forestall this, we adapted several ideas from a paper by Pimmel on team projects.[7] Specifically, we required each *student* (not just each team) to turn in a weekly progress report describing any problems and assessing progress with respect to a team-developed schedule chart (Gantt chart). At the end of the project, we asked each student to turn in a peer evaluation form in which the student estimated the percentage of project work done by each student, including themselves. The results of these peer evaluations were factored into individual student project grades, which were not necessarily the same within a given team. Pimmel found that the peer evaluation forms were a significant source of data that allowed him to customize grades for each student. Perhaps Texas students have more of a sense of team solidarity than Alabama students (Pimmel teaches at the University of Alabama), because all but two teams in the Texas State

Digital Electronics course turned in identical peer evaluation forms which stated that everyone did the same amount of work.

The final project schedule faced by each team was as follows:

<u>Meeting 1</u> (2 hr.): Project description and assignments
<u>Meeting 2</u> (2 hr.): Project work; Gantt chart due
<u>Meeting 3</u> (1 hr.): Project work; weekly progress report due
<u>Meeting 4</u> (0.25 hr./team): Perform Intermediate Demonstration
<u>Meeting 5</u> (1 hr.): Project work; weekly progress report due
<u>Meeting 6</u> (1 hr.): Project work: final report due
<u>Meeting 7</u> (0.25 hr./team): Perform Final Demonstration

The requirement for a definite activity or report due at each meeting kept most teams moving at a pace that enabled every team to finish, although a few teams lagged seriously behind others. During Meetings 4 and 7, the instructor spent 15-20 min. with each team individually. The purpose of the Intermediate Demonstration was to assess progress. The Final Demonstration verified that the final project design operated as specified. To lower the noise and distraction level, the lab was cleared of all but two teams at a time during these two meetings.

After Meeting 5, it became obvious that the students needed more time in the lab interacting with the robot arms. Because of security concerns, robot arms were checked out to individual teams by a graduate assistant who could be present only during scheduled lab and lecture times. Outside these times, students had access to the PCs with Max+Plus II software, but not to the UP-2 CPLD boards or robot arms. We inserted an extra 4-hour session of access to all these items between Meetings 5 and 6, outside the regularly scheduled lab and lecture times. In future offerings we plan to increase such access times even more.

During the final demonstration period, students were required to use their chosen control method to make the robot arm pick up a "hacky-sack" ball and place it into a small paper cup at a specified orientation and distance away from the arm's base. Fig. 3 shows a student concentrating on this task. The instructor timed each team's trial and posted the results on the lab whiteboard. While the overall intention of the final project was not to inspire inter-team competition, the students did put extra effort into practicing arm manipulation when they learned of this public competition.

Fig. 3. Student using mouse to operate modified robot arm that holds ball. Altera UP-2 board(right center) is also shown.

Evaluation of Both Offerings

Evaluation by an independent organization was planned into this project from the start.[8] Accordingly, we worked with the firm to develop a survey instrument that would be useful for both the initial offering and the revised offering. Substantially identical instruments were administered at the end of both offerings of the course. The questions asked and the results from each offering are shown in Table 4. Student responses to the Fall 2002 offering were positive, especially with regard to the helpfulness of hands-on learning using new equipment (item 8). The changes in responses from Fall 2002 to Fall 2003 after the final project was added are statistically insignificant, with the exception that the response to item 8 fell from 8.6 to 7.8. Comparing the revised offering of 2003 with the initial offering in 2002, the responses to seven of the twelve questions increased and five decreased. These results will be supplemented by more extensive survey and evaluation results at the conference.

Survey Question	Mean Results 1=most negatively influenced learning 10=most positively influenced learning	
	Fall 2002 (N=24)	Fall 2003 (N=33)
1. In general, how much do you think the new equipment has influenced your learning the basics of digital electronics?	7.3	7.8
2. How much do you think the new equipment helped you learn how *to analyze combinatorial logic circuits?*	7.3	7.6
3. How much do you think the new equipment helped you learn how *to simplify logic circuits?*	7.2	7.4
4. How much do you think the new equipment helped you learn how *to construct logic circuits?*	7.7	8.0
5. How much do you think the new equipment helped you learn *to analyze sequential logic circuits?*	7.3	7.0
6. How much do you think the new equipment helped you to learn how *to troubleshoot sequential logic circuits?*	7.1	7.3
7. How did *working in teams* during lab exercises influence your learning?	7.8	7.9
8. How did *the "hands-on" learning activities* using the new equipment influence your learning?	8.6	7.8
9. In general how would you describe *your motivation* in this class? (1=not motivated, 10=extremely motivated)	7.4	7.0
10. Did the use of the new equipment *influence your motivation* in this class?	7.5	7.3
11. Did the use of the new equipment help to make class *learning more applied and "real world?"* (1=not at all, 10=very much so)	7.2	7.3
12. Will *the knowledge and skills you gained in this class* be useful to you when you leave SWT? (1=not at all useful, 10=extremely useful)	7.5	6.9

Table 4. Evaluation Survey Questions and Results for Both Offerings.

Conclusions

      We have described a Digital Electronics course designed for non-EE majors, many of whom are majoring in manufacturing engineering. We have shown that CPLD-based labs can be designed on a level that is accessible to students whose only exposure to electronics is a basic DC/AC circuits class. The revised offering in Fall 2003 was designed to provide students with the digital circuit knowledge they needed for the final project. Initial results from a comparison of evaluations during the two offerings indicates that student responses to both offerings are basically similar, despite the rather radical change in course format. Some of the final project designs revealed a need to reinforce a disciplined approach to digital logic design based upon transferring truth tables to circuitry. In the absence of the logic simplification lecture in the revised offering, students fell back on intuitive approaches and came up with some rather eccentric and inefficient designs. We will address this need with further revisions of the syllabus for the next offering of the course.

References

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