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A Multimodal Approach to Classroom Instruction: An Example from a Process Control Class*

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The use of active, cooperative and inductive learning approaches has been shown to be beneficial to student learning. Traditional engineering activities of projects, simulation exercises and laboratories provide cooperative and active experiences outside the classroom. By bringing these traditional engineering activities into the classroom a multimodal approach to education can be used where a variety of activities enhance the classroom experience. A process control course has been developed that integrates the use of experimental kits, simulations, problem solving exercises and instructor content delivery in a single setting. In this setting any of the above modes of instruction can be used as is appropriate to the progress of the course. Multiple assessments have been used to evaluate and refine the modular kits and the multimodal approach of this class. These assessments include observations by different instructors, anonymous student surveys, student focus groups, and observed student problem solving sessions. Overall the kits and the integrated approach have had a positive effect on the class. Student focus groups brought up all of the approaches used when asked what helped them to understand and remember the material. Students like the integration of kits and simulation in the classroom setting and have shown a particular preference for class sessions where a short activity is used to raise an issue and then followed up with detailed content on the issue. For these sessions students have suggested returning to the experimental kits at the end of the section—encouraging instructors toward a learning cycle approach.

Keywords: inductive learning; cooperative learning; process control; cycles; classroom experiments; simulation

1. INTRODUCTION

THIS PAPER PRESENTS and exemplifies a diverse approach to the engineering classroom. This approach takes engineering's traditional use of laboratories, projects and problems outside the classroom and brings them into the classroom to enrich the effectiveness and experience in class. Much has been learned about engineering education in the past decades yet many classes are still taught the way they were fifty years ago. Classrooms that are more engaging increase student interest and success. This paper reviews some of the literature that supports the concept of a classroom with multiple styles of learning experience and presents an example of our new approach in a chemical process control course.

1.1 A multimodal strategy for the engineering classroom

Education research over many years has shown the advantages of active, cooperative and inductive approaches to education. In 1986, Chickering and Gamson, with support from a number of colleagues and organizations published *The Seven Principles for Good Practice in Undergraduate Education.* [1] They stated that:

Good practice in undergraduate education:

1. encourages contact between students and faculty,
2. develops reciprocity and cooperation among students,
3. encourages active learning,
4. gives prompt feed back,
5. emphasizes time on task,
6. encourages high expectations, and,
7. respects diverse talents and ways of learning.

Engineering education has long supported these principles with its use of regular problem sets, projects and laboratories outside the lecture hall. All of these approaches involve active learning that at their best encourage contact between students and faculty. Projects and laboratories are usually conducted with small groups of students; encouraging cooperation among students. Regular problem sets and laboratories can provide an opportunity for prompt feedback on student learning. These activities can also emphasize time on task and encourage high expectations. These varied approaches to problem solving, laboratory and project work also have the possibility of respecting diverse talents and ways of learning.

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Meeting the needs of students of varying leaning style preferences has also been recognized as an important issue. Felder and Silverman's Index of Learning Styles provides one look at learning style preferences [2, 3]. In this four axes of contrasting style preferences are used:

1. Active—Reflective
2. Sensing—Intuitive
3. Visual—Verbal
4. Global—Sequential.

Traditional engineering lectures often tend to favor reflective, verbal, intuitive, and sequential sides of these scales. Experiments, group problem solving and simulation naturally address the active, sensing, visual, and global ends of these spectrums providing a natural balance to the traditional lecture. In addition to reaching varied learners, presenting material using multiple methods also aids every student's retention of the material.

These additional modes of instruction (problem solving, simulation and laboratories), with proper planning and resources, can be brought into regular class time where they provide a more engaging and diverse classroom experience. The thesis of this work shows these approaches function best when they are not simply "add ons" to the course but are integrated with the lecture material in a single learning space.

In a follow up article to the *Seven Principles* . . . Chickering and Ehrmann state that technology in the classroom can be used to help leverage the implementation of these principles [4]. Using computers in the classroom to supervise or simulate experiments provides one way to move these principles into the classroom.

In their review article on *Teaching Methods That Work*, Felder, et al. [5] discuss seven theme areas of techniques that have repeatedly been shown to be successful. Their seven themes are:

1. Formulate and publish clear instructional objectives.
2. Establish relevance of course material and teach inductively.
3. Balance concrete and abstract information in every course.
4. Promote active learning in the classroom.
5. Use cooperative learning.
6. Give challenging but fair tests.
7. Convey a sense of concern about students' learning.

Themes 2 through 5 can be addressed by bringing this variety of teaching options (modes) into the classroom including laboratory exercises, simulations, and group problem solving. The use of laboratories is one of the distinctive features of engineering [6]. Laboratories are helpful for problem identification, motivation, discovery, experience with equipment, and for memorable experiences. All these features are often needed in the regular classroom.

Simulations and laboratory experiments provide an excellent opportunity for inductive learning processes (theme 2). Wankat and Orevits note "Laboratory experiments appear to be most effective with the solution is not known ahead of time" [6]. Placing these laboratory exercises in the classroom as the start of an inductive process can yield a very effective and motivating learning process. Hesketh, et al. [7] give examples and a recommended procedure for experiments as part of an inductive learning process. Dahm [8] builds on the work of Haile [9] to provide an example of experiment and simulation in a learning process to build student understanding of distillation.

The use of these normally out of class assignments in the classroom also provides a balance of concrete information to the abstract material often presented in lectures (theme 3). They are naturally active and cooperative approaches (theme 4 and 5). Strategies and examples of bringing experiments in to the classroom can be found in a previous paper [10]. Simple experiments can be completed in any classroom but there are distinct advantages in designing our classroom space with collaboration and multiple instructional modes in mind [11].

A classroom experience that includes a diversity of approaches including short lecture, laboratory, group problem solving and simulation exercises can engage students and improve their understanding. These multiple approaches can and should be used in inductive and/or problem-based approaches that encourage students to obtain ideas themselves.

Carrying this out requires significant effort to develop new educational activities, classroom-friendly laboratory experiences, and even new leaning spaces. Computer classrooms are common in all universities and offer many opportunities. However, they are often arranged as a series of fixed rows facing front which can limit the flexibility of the room and the opportunities for student-to-student and faculty-to-student engagement.

1.2 Expanding the engineering classroom

A number of universities have experimented with designing learning spaces that allow for more flexible, collaborative and student-centered learning. An *Educause* e-book edited by Oblinger provides a summary of learning space design principles and a range of example case studies of innovative learning spaces [12]. The SCALE-UP (Student Centered Activities for Large Enrolment Undergraduate Programs) project is an excellent example of a different learning space that allows for multiple modes of instruction including simulation, simple experiments, group work, and instructor presentation [13–15]. The setting is a large room with no "front", round tables that accommodate three teams of three students each. This approach makes use of laptop computers, simulations and simple portable experiments. There are projection screens on all walls so students in any position can see a screen. The instructor's base station is in the middle of the room. This project originally focused on introductory Physics classes but its goals and scope extend well beyond that. In addition to developing a specialized learning space they have also developed student activities to go with the space. They have found "In comparisons to traditional instruction we have seen significantly increased conceptual understanding, improved attitudes, successful problem solving, and higher success rates, particularly for females and minorities" [14].

Another innovative approach is the various studio classrooms used at a number of universities but particularly experimented with at Rensselaer Polytechnic Institute (RPI) over several decades [16]. These classrooms have taken various forms but generally include a shared computer and table among a small group of students as well as good sight lines to a place where the instructor can present.

In addition to modifying the learning space various educators have also worked to bring more varied activities into the regular classroom. Piergiovanni [17] provides examples of a series of separate simple inexpensive classroom-based experiments to introduce various mass transfer unit operations. Development of simple classroom-friendly experiments is one approach that can increase an instructor's options for developing multiple modes of instruction in a single setting. Kits of parts that can be used for multiple experiments or design activities in the classroom have also been used. Snap circuit kits, an educational children's toy, have been used to teach simple RLC circuits to Chemical Engineering students [10]. The University of Virginia has developed a series of Engineering Outreach Kits for use in teaching engineering design in the middle schools. These kits consist of a series of parts that students can test and then combine to develop a design that meets specific goals [18].

Washington State University has developed a particularly interesting approach to expanding the classroom experience in their Fluid Mechanics Class. They have developed desktop learning modules that are complete and self-contained experimental systems requiring minimal services or space, and that can be brought into a classroom environment. They use these in their fluid mechanics class using Cooperative, Hands-on, Active and Problem based learning (CHAPL) approach [19]. They have seen success with this approach both at WSU and Ahmadu Bello University in Nigeria.

These cases of redesigning the learning space or designing classroom-friendly laboratories are examples of expanding the engineering classroom to include engineering activities traditionally done outside the classroom. They fit the direction advocated in this paper. They can be taken further to include not only experiments but a diversity of learning experiences in a single setting.

1.3 Chemical process control

Many courses can benefit from the idea of breaking down the walls between the classroom, the laboratory, and other places of learning. By bringing the full range of educational modes used in engineering into the classroom, students have a richer educational experience. In this paper a process control course is examined as a case study in using a broad and diverse classroom approach.

Process control is a course that can particularly benefit from a multi-modal approach. Maintaining student interest in process control is challenging. Lant & Newell have noted that most students find process control conceptually difficult, perceive it as peripheral and have trouble integrating it with other material. As a result they "find it more of a chore than fun to learn" [20]. This difficulty often comes from the fact that students in their life, including previous classes and laboratories, have little previous experience of the dynamic systems discussed in process control.

One of the key challenges of undergraduate engineering education in general is providing students with an experience that includes both solid theoretical underpinnings and a clear connection to industrial practice. Nowhere is this felt more acutely than in process control. Students often have difficulty connecting the analysis they learn to the practical application of process control, resulting in low student interest in the subject. They do not have a full appreciation for the importance of dynamics in real processes.

George Stephanopoulos has accurately described the nature of this problem for process control:

> The design of chemical process control systems is a particularly synthetic activity and as such it requires skills which transgress the conventional analytic context of process control education [21].

Process control courses tend to focus primarily on analysis using frequency analysis techniques, (e.g. Laplace transform analysis). Stephanopolous goes on to suggest that in process control instruction we are "preoccupied with the analytical leg" of process control largely because we do not know how to teach the other issues involved in the synthesis of a process control system. Important control system synthesis skills which students need include: defining specific operational objectives for the controls system from broader product and process needs, conceiving of possible control structures, selecting sensor and control element locations in the process, choosing among alternative structures, understanding control in a multivariable environment (i.e. being able to develop Multiple Input/Multiple Output control systems), and designing appropriate safety and override systems.

Attempts to answer these practical problems in process control education have been addressed using three broad approaches:

1. computer simulations;
2. laboratory experiences;
3. case studies/projects.

A number of authors have reported on their use of simulations to assist in process control education [22–25]. One creative option is a simulator game developed by Woo [27]. Rhinehart, et al. describe a fairly thorough approach using a flash drum as an example that includes control system synthesis and realistic issues such as statistical noise in the system [25]. The course described here, like many others, uses the process control simulation software, Control Station [22]. Simulation exercises help students connect their analysis with simulated process dynamics. Simulation exercises have the advantage that the designer can control how much of a full control problem is simulated. However, the characteristic is also a disadvantage as it is impossible to include all aspects of a real system in a simulation. The general purpose simulation capabilities of MATLAB/Simulink have been increasingly used in recent years [26]. In most cases, simulation exercises are conducted outside the classroom as separate homework, project or computer laboratory exercises.

It has been suggested that laboratories may be the most important experiences we give our students in a process control class [28]. Most process control courses use some form of laboratory to supplement the lecture material and several have been described in the literature [29–33]. These laboratories can be the key to balancing theory and practice [34]. Laboratory experiments are most often in a separate facility and time from the lecture. The level of integration between the laboratory and lecture components of a course can vary widely. Mississippi State uses a very open-ended project approach to their laboratories where students must define exactly how they use the lecture material with the laboratory experiments [35]. It is also not unusual to mix simulation and experiment. At Washington University (St. Louis, MO) the separate laboratory component starts students doing simulation experiments using MATLAB/Simulink and then moves to computer interfaced experiments controlled using MATLAB as well [33]. They describe a very intentional integration of the laboratory progression with the progress of the lecture but do not indicate how the lecture and laboratory learning processes connect.

Separate laboratory setups are often expensive and there is usually only one or a limited number of each experiment so students must rotate through the equipment. This creates difficulties in coordinating the laboratory learning experience with what is happening in the lecture. Holt & Pick [36] address this difficulty, as well as the difficulty students have when learning a different apparatus and interface for each experiment. They have developed a single system that allows students to do a wide range of control experiments on a single consistent piece of equipment. In addition they have kept the cost of this set up low so that all students can be working on the same experiment simultaneously.

Operating experiments remotely via the internet is beginning to be seen in different places. At the University of Tennessee—Chattanooga Dr Jim Henry has developed control experiments that can be operated remotely over the web. This arrangement allows students to operate experiments when they want from their own computer. This has also allowed a university in Africa to make use of the equipment in Tennessee, taking advantage of the time difference [37]. These virtual experiments are still separate from the classroom setting but the setups do allow greater access to the equipment, allowing students to do experiments when they best fit the learning design. In addition, they could be used as a demonstration in the classroom setting.

One problem, which many authors note, is the difficulty of incorporating all the material we might like to take into the undergraduate process control courses [28, 38]. In particular, the explosion of inexpensive digital computing has added importance to discrete as well as continuous control algorithms while opening the way for easy and inexpensive implementation of much more advanced control strategies and multilevel control. Because of these advances, process control practices are constantly changing and becoming more diverse than in the past [39]. To accommodate the changes in industrial practice and in our understanding of what issues must be taught, it is crucial that new laboratories in process control be flexible enough to accommodate a wide range of control structures and algorithms.

Case studies and/or projects on specific control problems are also used in many courses [21, 40]. It is common that these projects/case studies include simulation of the system of interest [25, 26]. Beauchamp-Báez and Meléndez-González included a project/cases study with both a simulation and an experimental component [40].

In most of the examples mentioned the simulations, experiments or projects/cases have been implemented separately from the lecture in a laboratory session or as out of class work. There are some examples integrating these approaches with the lecture. Silverstein (2005) reports on the use of five laboratories intentionally integrated into a lecture course in spite of being carried out in a separate space from the lecture. [41] The first of these labs is completed during the first class period as an inductive introduction to the course. The other four laboratories happen at a time separate from the lecture but are integrated into the lecture material.

Morales-Mendex, et al. [42] also report on a course with laboratories in a separate location but intentionally integrated into the overall course. They report the use of problem– based learning (PBL) and cooperative learning approaches to integrate lecture and laboratory material.

The approach that comes closest to that described in this paper is Rensselaer Polytechnic Institute's (RPI) widespread use of a "Studio Classroom" approach in many of their classes. This is a multimodal approach. In process control they initially used a special studio classroom where lecture, simulation and laboratory were all possible in the same space [34]. They note the value of this approach in maintaining a balance of theory and practice in a process control course. In this control studio there are multiple copies of each piece of experimental apparatus but not enough for all students to be working on the same experiment at one time.

More recently they have moved their process control course to a laptop studio classroom partially to accommodate more students [26]. This facility allows for the integration of extensive simulation into the class but does not have the capability for experiments. They conduct classes in a two-hour block where they use the first 50 minutes for lecture and discussion of content and problems and the second 50 minutes for simulation exercises done by the students on laptops in pairs. They note active engagement of their students when completing these laboratory and simulation exercises.

The course described in this paper shares a similar diversity of approaches but differs from these examples in several key aspects. All activities can take place in the same space including lecture, problem solving, experimentation and simulation exercises. In addition, there are sufficient computers and experimental setups so that all student groups can work on the same activity at the same time or work on varied activities. The learning activities for each class are specifically designed for the topic being covered. This allows for a variety of learning approaches including problem-based learning and inductive learning. This course makes use of the experimental kit approach. The experimental kits used in this course are very flexible allowing students to set up the piping for their experiments and experience some unique aspects of control system synthesis. In addition this flexibility allows for easy update of experiments to illustrate different techniques as they evolve.

2. PRESENTATION

2.1 Course context

This chemical process control course is generally taught in the second semester of the junior year of study, concurrently with a unit operations class and a unit operations laboratory. For the first semester studied (F03) the course was taught in the fall of the senior year. The course is scheduled to meet for two hours twice a week to allow plenty of time for a variety of activities. There are 15 to 25 students in a section.

Students were well qualified individuals at a selective private university. They had completed most of their general technical classes (mathematics, physics and chemistry) and had previously taken chemical engineering classes in introductory mass and energy balances, thermodynamics, fluid mechanics in a fluid mechanics laboratory. They generally had high expectations of their classes and instructors.

The class was conducted in two different classrooms. One room was specifically arranged for this type of class. The room had five group work tables for groups of three to five students. Each table had a computer for the groups to use for simulations, experiment kits or problem solving. The second room was a more traditional computer laboratory with tables arranged in rows facing front and each student having his/her own computer. Rows were on either side of a center aisle with two computers on each side.

2.2 Multiple classroom activities

Throughout the class, different modes of instruction are used depending on which approach best suits the material being covered. These modes include different types of activities and different approaches to how these activities are used. This section examines the activities that are being used. The next section looks at the approaches to using these activities.

Activity options include brief lectures, classroom problems, worksheets, simulations, and the use of specially designed experimental kits that can be brought into the classroom. One to three of these options are used in each two-hour classroom session. In addition, students are involved in out of class reading, homework, simulations, and projects.

Brief Lecture: Lecture presentations are generally limited to less than twenty minutes. These presentations often took place after using an experiment or simulation to introduce an issue.

Classroom problems: Short problems done in class allow students to get started on an approach that has been taught and allow the instructor to see how well students have grasped basic concepts. These are equivalent to short versions of traditional homework problems.

Worksheets: Worksheets are often used to present derivations of a theory or a technique. The worksheets walk the students through the steps of a derivation by asking them to perform the various mathematical manipulations themselves. This results in a more interesting and active class for the students as well as a very clear and accurate set of notes. An example worksheet is shown in appendix A.

Simulations: The simulations are from Dr Doug Cooper's Control Station software [22]. Modifications of his workshops are used both as in-class and out-of-class exercises.

Modular Experiment Kits: Classroom experimental kits were developed for this course. These kits consist of modular LEGO®-based hardware and a control system implemented on a personal computer using LabVIEW™ software and the LEGO RCX or NXT brick as an interface to process sensors and control elements. Students can construct multiple experiments with these kits. More details on these kits can be found elsewhere [43, 44] and on the web [45].

Developing the modular experimental kits is a key portion of this effort to develop a multimodal approach to process control. The use of experiments enables students to connect theory to practice and shows some of the equipment side of process control. It can help motivate students to learn a subject many find abstract, and provides a different way of learning that can help reach students with varied learning styles.

2.3 Multiple classroom approaches

Except for the brief lecture, the various activities listed in the previous section are active approaches requiring that the students engage with the material. In the majority of cases these activities were implemented in a cooperative fashion where students worked together in small groups.

There are many approaches to how these activities and lecture content can be integrated together. They can be presented using a traditional deductive approach where the activity follows an introduction of the general concepts or an inductive approach where students encounter particular issues in the activity and these are generalized later. With this range of teaching options it is also quite easy to integrate a learning cycle approach such as Kolb cycles [46] or problem-based learning approaches such as the Legacy Cycle [47].

Below are listed several examples of how the activities and approaches were integrated in the classroom. These examples are taken from several class topics which the instructors have found particularly difficult to convey with a traditional lecture approach.

Introductory Sessions (interactive full class with the LEGO® kits): In the first class students set up a simple draining tank with PID level control using our LEGO process control kits. Using the LEGOs was a popular way to start. Students were given written instructions on setting up the experiment and the control system software. In some cases the instructors preset up the kits in order to get into experimenting with them more quickly. The session was very interactive going back and forth between the instructor pointing out important issues and terms and the students "playing" with the system to see what happened. The key goals of this session were to give the students an overall concept of what a control loop was, and to begin introducing them to the many terms used in process control (sensor, controller, final control element, manipulated variable, controlled variable, setpoint, etc.). In addition to operating and observing the physical systems, students could look "under the hood" of the control software and begin to see how it was working. The visual nature of the LabVIEW™ software used was very helpful for students being able to understand quickly what it was doing. The effectiveness of this approach was apparent during this first class. The use of this simple level control set up was continued into the second class and used to introduce some of the hardware used in process control.

First Order Modeling (worksheet and interactive class with the LEGO® kits): The students first complete a worksheet where they develop a dynamic model for a temperature sensor. Various parameters are provided to the students so they can estimate a time constant for the LEGO® temperature sensor. They then perform a simple experiment where they transfer the sensor from cool water to hot water, and monitor the dynamic response. Using the response at 62.3% and a model available in ControlStation, they estimate the actual time constant and compare to the calculated value. The differences are discussed in class.

Proportional Only Control and Offset (A quick simulation exercise): Students often find it difficult to believe that a well functioning proportional controls system can easily end up with offset from the setpoint. To start this topic, students completed a quick exercise on Control Station using its Gravity Drained Tanks case study. This exercise was organized along the pattern recommended by Hesketh, Ferrell and Slater [7]. The class is started with a brief discussion of what students expect will happen when a proportional control is used (generally no one suggests offset would result). Students set up proportional-only control of level and then introduced step changes in the setpoint. Because Control Station uses a bumpless transfer approach, there is no offset at the initial conditions. However, the minute students introduced a step change they see offset (and of course initially they thought the simulation wasn't working correctly). This leads to a discussion on the conceptual reasons that offset occurs. Students then complete a worksheet that leads them through determining the closed loop transfer function and shows that offset would result. As a result of this session students seem to grasp the nature of proportional control and the issue of offset. In addition to covering offset, the setup of the controller is used to introduce the nature of bias and gain in a controller.

Development of PID Velocity Algorithm (A worksheet exercise and interactive class): Soon after students had been introduced to the continuous PID equation, a class session was held where they worked through the Discrete Control Algorithm Worksheet shown in Appendix A. Students could easily complete the steps on this worksheet and see how the mathematics was adapted to a discrete control system. By walking through the worksheet they were able to see how a discrete control equation is developed, the difference between a position and a velocity equation and how derivative kick is avoided. They then compare the equations they derive with the equation in the control software (they should be identical). Throughout, the instructor can both assist individuals and also interact with the entire class over what they are learning.

Control Valve Sizing (A worksheet exercise and interactive class): The textbook covers the basic equations for sizing valves, but includes limited details about choosing the correct valve. In this class, the students complete a worksheet to determine the valve size, which is where textbook examples typically end. After finding the valve size, however, the students use ValveSpeQ [48], a valve sizing program available from Masoneilan and a worksheet to choose the specific valve. The students learn that many more variables remain to determine which valve they would purchase. This experience is helpful when they work on their senior design project.

Frequency Analysis (a full class simulation session): A complete two-hour session in the computer laboratory was devoted to an introduction to simple frequency analysis, particularly amplitude ratio, phase shift, and Bode plots. In this case Control Station's Jacketed Reactor case study is used. The first quick exercise is for students to set up an oscillatory setpoint change and observe the result. Students observe that the frequency is unchanged but that there was an amplitude difference and a shift in phase. Next students learn how to use the control station to measure the change in amplitude and the phase lag. They carry out a series of experiments using different input frequencies to examine the result and construct a Bode plot from these simulated experimental results.

Students also performed a doublet step test on the system and determined a first-order-plus-dead-time model. This model was entered into the software "ProgramCC" [49] to determine the Bode plot based on the transfer function. In the next lecture the student's ability to calculate these values from known transfer functions were developed. This exercise resulted in the best introduction to frequency analysis these instructors have had. The students quickly understood the basic concepts and terms of Bode plots.

Adaptive Control/Tuning Scheduling (a one-hour simulation exercise): To introduce the concept of scheduling the tuning for a nonlinear process Control Station's Heat Exchanger Case study is used. Students performed a series of doublet step tests at three different setpoint levels. They determined the IMC tuning parameters for these levels, entered them in Control Station's Adaptive PID Controller Schedule and tested the resulting controller set up. Students seemed to quickly understand the need and concept of scheduling the tuning for a nonlinear process (note they had previously observed the problems with this particular nonlinear process during tuning exercises). This exercise does not take long and is immediately followed up with a discussion on tuning scheduling.

3. DISCUSSION—ASSESSMENT

3.1 Inductive learning approaches observation and survey

Table 1 lists several class topics where the Experiment Kits or the Control Station Simulations were used. More information on the specific exercises is included in the references ([43] [44]). As has been shown, several different approaches were used to integrate these activities into the class period including:

1. a full interactive class where activity and explanation are interspersed and followed up in the next class;
2. an experiment or simulation followed immediately by explanation in the same class period;
3. a full two-hour workshop of experiments or simulator where explanation is in another class;
4. a longer experiment that took approximately half of the two-hour class time followed by explanation.

In addition, in some cases a more traditional approach of lecturing about a concept and then having a follow up activity was used. As development of this course progressed, inductive approaches were used for an increasing number of activities. In one term where both traditional and inductive approaches were used, a student survey was taken to examine student response to these different approaches. In this survey students were asked to rate the effectiveness of three specific approaches used in class for simulation exercises:

1. *Full Class:* A topic is introduced with an inductive exercise that takes the full class period and then following up in a subsequent lecture;
2. *Quick Exercise:* a topic is introduced with a quick inductive exercise followed by an explanation and expansion of the results;
3. *Follow up Exercise:* a topic is introduced using a more traditional approach where a lecture is followed up with an illustrative exercise.

Students were asked to rate the effectiveness approach when used with simulation exercises. A

Table 1. Examples of various approaches for using the experimental kits and the Control Station Simulator in class

Area	Exercise	Experiment Kits	Control Station Simulator
Control Introduction	Observing a level control Loop	Full class interactive with kits and explanation	
	Response to a step (gain and time constant)		1 hr simulation followed by explanation
Modeling	1st order response of a Temperature Sensor	Quick experiment followed by explanation	
	Impact of a non-linear process		Quick simulation followed by explanation
	Inverse response	Quick experiment followed by explanation	
Simple control	Calibration of a level sensor	1 hr experiment followed by theory development	
	On-Off Control	Quick experiment followed by explanation	
	P-only control (offset)		Quick workshop followed by explanation
	Proportional plus integral control		
	PID control		
Tuning	Ultimate Gain		Quick workshop followed by explanation
	IMC		
	Field Tuning		
Advanced Topics	Frequency Response		Full class workshop followed up in a later class
	Adaptive Control		1 hr workshop followed by explanation
	Casade Control (Flow & Level)	Quick experiment followed by explanation	
	Feedforward Control		Quick workshop followed by explanation
	Interacting Systems (Parallel Tanks)	1 hr experiment followed by explanation	

six-point Likert scale was used where 6 was very effective and 1 was not effective.

Figure 1 summarizes the results of this survey using a box plot for each of the three cases. These plots give a quick view of how the ratings were distributed. The box defines the inner quartile range of the responses, i.e. the middle 50% of students rated in the range shown by the box. The line in the box shows the median score and the lines coming off the box show the full range of responses except outlier points. An asterisk is used to show the single point substantially out of the range of the other data. Students rated all three approaches highly with means between 4 and 5 out of a possible 6. Outside a single low outlier, the Quick Exercise inductive approach appears higher with a narrower distribution.

To test the significance of this difference a paired sign test was used. This sign is the non-parametric equivalent of a paired t-test and was chosen because of its robustness relative to the distribution and to outliers. In this case each of the inductive approaches was compared to the Follow up Exercise deductive approach. Each student's rating for the Follow up Exercise approach was subtracted from their rating for one of the inductive approaches. This results in two new variables: one for Full Class approach score minus the Follow up Exercise approach score, and one for the Quick Exercise approach score minus the Follow up Exercise approach score. Each of these variables will include values that are positive if the student rated the inductive approach higher and negative if they rated the deductive approach higher. The sign test examines the probability that the resulting distribution of positive and negative numbers would result if the two were equivalent, i.e. if the expected value of this difference column was zero.

Table 2 shows the result of these tests. This table shows no significant difference between the introductory Full Class approach and the more traditional Follow up Exercise approach. In fact the median difference was zero with 9 students rating the Full Class inductive approach higher, 10 students rating the Follow up Exercise approach higher and 7 students rating them as equal. While students rated these two approaches as equivalently effective, instructors observed a more engaged class and an improvement in student understanding for the Full Class approach. The topic for this full class activity was frequency response and Bode plots which are difficult topics for most students and may have influenced the outcome. In addition it is important to remem-

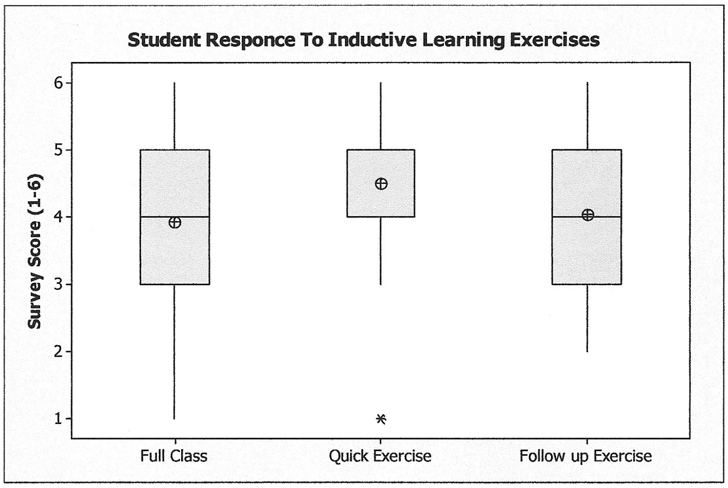

Fig. 1. Box plots comparing student response to the effectiveness of various teaching approaches. A score of one means not effective and a score of six means very effective. Students were asked to rate (1) starting a topic with a full class period exercise, (2) starting a topic with a quick exercise followed by lecture or (3) starting with lecture and using a follow up exercise.

ber that the Follow up Exercise approach while not inductive is still very active and cooperative. The introductory lecture is brief (usually less than 20 minutes) and is immediately followed by the activity in the same setting and class period.

Significantly more students rated the quick exercise above the traditional Follow up exercise approach. Fifteen students rated this approach higher and only four rated it lower, with seven students showing no preference. The median students rated the *Quick Exercise* approach a full point higher on the Likert scale. While the sample size for this survey was not large the effect size was large enough to show a clear impact.

3.2 Focus groups

Student focus groups were used to further understand the impact of this multimodal approach, particularly the use of the experimental kits. These groups involved students who had taken the course one year previously (seniors) and students who were currently in the course at just before half way through the term (juniors).

The seniors were divided in two separate small groups. The current instructor met with one of the groups and an instructor no longer at the school met with the other group. Students were first asked to design a control system while being observed. The problem used is shown in Fig. 2. Once they had completed the control system design they were asked to describe how they would come up with a model for this system.

Table 3 summarizes the observations of this group process. Both groups successfully completed the basic design and came up with the basic ideas for a process model in a relatively short time. They both clearly avoided the error of trying to control the same stream twice. In addition both groups recognized ratio control as an option; however neither group implemented a ratio control approach. In all they did very well given the limited time (20 minutes) for this exercise.

When asked what helped them remember concepts and solve this problem, students pointed to a range of exercises done in the class, including the experimental kits, diagrams, class problems and homework problems. Some students did note in an aside that they had trouble connecting the Lego kits with the theoretical equations. They asked if the equations could be put on the screen in the control program.

Discussion was continued with these two groups asking them what approaches were the most helpful to their understanding for three specific concep-

Table 2. Sign Test comparison of Student Responses for the two inductive approaches to the more traditional approach of an introductory lecture followed by an exercise

Comparison	Total (N)	Number of students rating: Follow up approach Higher (Below 0)	Approaches Equal	Inductive Approach Higher (Above 0)	Probability difference would result by random chance	Median difference in ratings
Full Class Inductive Activity rating—Follow up Activity rating	26	10	7	9	1.0000	0.00000
Quick Inductive Exercise rating—Follow up Activity rating	26	4	7	15	0.0192	1.000

Below is a simple mixing tank where a hot and a cold stream are mixed. Please draw control loops (using simple P&ID symbols) that could control the outlet temperature, flow and the level of this tank. Please show the sensors, the controllers and the final control elements for each loop.

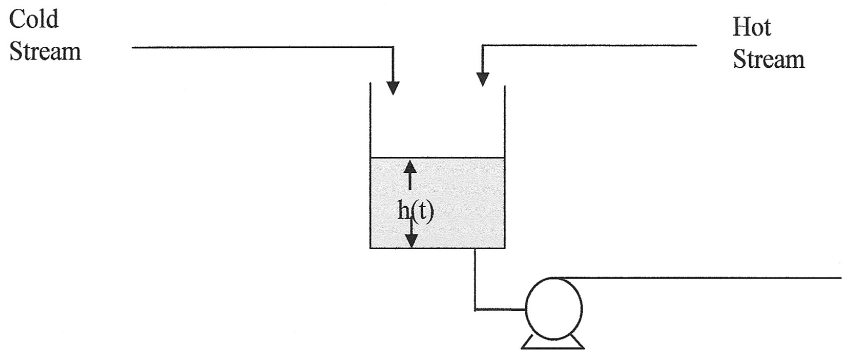

Fig. 2. Assessment problem used with students who had completed the course just shy of one year earlier. After students drew in the control system, they were asked to describe how they would model this process.

Table 3. Focus group—observed problem solving

	Senior Group 1	Senior Group 2
Group Composition	one woman, two men	one woman, three men
Overall Group Process	Started off one stream at a time. Took some wrong turns but corrected them.	Two students dominated the working of the problem, after a few false starts, the group. worked out the problem correctly.
Avoided two control values in one line	They never seemed tempted to make the mistake of putting two valves in one line	One students said "Don't put two control valves in one line".
Identified three independent loops	Succeeded with just a bit of a hint on the level control loop.	Got there after a few false starts.
Ratio Control	Had some thoughts on ratio control but could not come up with it.	Student said "Could do ratio control, in a box (on P&ID)".
Process Model	• Thought of variable lists and block diagrams first. • Got a mass balance (with prompting & some mix up of accumulation and generation terms). • Worked on the energy balance fairly successfully.	• Remembered In – Out = Accumulation, and energy = m Cp ΔT. • Worked out units, and used them to create the model.
What from the course helped you solve this problem?	– diagrams (P&ID diagrams, block diagrams) – a project with Lego kit – Lego kits good for "believing" what we were being taught – the pattern of lecture—class problem—homework problem – Aside: some students noted a disconnect between Lego kits and equations	

tual areas in process control (Introductory terms and concepts, Transfer function modeling, and Feedback control). In addition, the instructor not at their school held this same discussion with the group of juniors who were currently taking the course. Table 4 summaries the discussion with all three groups.

In Table 4 note that students brought up all of the techniques used in the class: experiment kits, simulation (Control Station), class problems, homework problems, formal approaches taught and the text book. The two senior groups seemed to differ on whether or not the experiment kits were helpful as an introduction. This could simply be the type of student variation that the multimodal approach addresses. In the feedback control discussion students mentioned different techniques as helpful with different topics. Again, this is a strength of a multimodal approach.

3.3 Process control survey

Table 5 shows trends in the results of an overall survey that asked several Likert-scaled questions after students had completed a simple control problem. A six-point Likert scale was used with 6 representing strongly disagree and 1 strongly agree. The final question was written in negative fashion (I would try to avoid this type of assign-

Table 4. Focus group—what was most helpful for understanding?

	Senior Group 1	Senior Group 2	Junior Group
Group Composition	one woman two men	one woman three men	nine women three men
What teaching techniques where most helpful for you understanding—			
1. Introductory concepts & terms?	Looking at controls in the UO laboratory Diagrams (P & ID, Block Diagrams) (Some thought the experiment kits were less helpful because they did not understand what was happening having same operator limited learning for other members)	Experiment kits allowed students to see how set point changed visually	Experiment kits for introduction, though not helpful for doing differential equations Class exercises helped with initial problems UO laboratory visit was helpful for every day applications
2. Transfer function modeling (Laplace transforms)?	The steps/protocol they were taught to follow for problems Text example problems	Class problems and homework	Class exercises, class examples— Lecture definitely helps Experiment Kits Text, not so helpful
3. Feedback control?	PID control—Control Station Simulator Advanced control—The diagrams (P& ID, Block Diagrams) and how they expanded	On/off control—Experiment Kits. It showed the problems of on/off control Tuning—Control Station Simulator	On/off control—Experiment kits allowed students to see how this worked Proportional offset—Control Station Simulator class session

Table 5. Overall attitude survey

	F 01	F 02	S 04	S 06	average
I feel I am prepared to make a contribution in this area	2.8	2.8	3.0	2.7	2.8
I would enjoy working in this area	3.5	2.9	3.3	3.4	3.3
I would seek out assignments like this	3.6	3.6	3.9	3.7	3.7
I would like to learn more about control modeling	3.2	3.2	3.0	3.4	3.2
I would try to avoid this type of assignment (scale reversed)	2.7	2.7	2.7	2.6	2.4
Average	3.2	3.0	3.2	3.1	3.1

ment) relative to the other questions. The results for this question were recoded so that the scale is reversed (i.e. the answers were recoded so that 1 is strongly disagree.)

The averages in this table show a tendency toward the center (a score of 3.5), with more positive scores on feeling prepared and "not" avoiding and barely negative on "I would seek out assignments like this". The scores barely change from year to year in spite of changes in the course, particularly increasing use of the experimental kits.

3.4 Instructors observations

With a so many options to work with instructors found it easy to keep the class active, cooperative, and inductive. A classroom space especially designed for these classroom activities made it easer to carry them out. However, it was also possible to maintain this approach in a traditional computer classroom. Students generally dove into activities, they were very engaged and showed a high level of interest.

Classes that involved the LEGO experimental kits or the control station simulations were particularly active. Students always had a very positive response when they arrived for class and the experimental kits were out. In the first class, which used the experiment kits as an introduction, there were a lot of student initiated questions and exploration. This was very different from what instructors had observed in introductory classes without the kits. In addition the kits allowed students an opportunity for completing design projects. More detail on the LEGO Experimental Kits is covered elsewhere [43–45].

As mentioned earlier, students did not rate the full class session developing a Bode plot as significantly different from the lecture then activity format. However instructors found the results quite different, with a greater student understanding and interest than previous classes. Typical student difficulties with basic frequency analysis and Bode Plots were nearly eliminated.

Instructors were pleased with the results of the laboratory kit and the simulation exercises. They observed that students understood the concept of offset and its association with proportional-only control. They performed quite well and showed confidence with tuning approaches. They lacked some confidence with frequency analysis but students displayed much less confusion with the basic frequency analysis concepts than in the past when this topic was taught by straightforward lecture. They also seemed to better understand the advanced topics of tuning scheduling and feedforward control.

The in-class problems were also important in student learning, but success was varied. In the classes through Spring 2005, there were about 18 students in the class, arranged in five working groups (the clustered classroom arrangement). While the students were working in small groups on in-class problems or worksheets, the instructor was able to circulate among the groups and give help as needed. This arrangement also helps the students interact with each other as they fill in the blanks. In Spring 2006, there were 24 students in the course, which was taught in a standard computer classroom. Because the students were arranged in rows, there was less interaction, and the in-class problems and worksheets were less effective. Often, near the end of class, several students requested that the instructor go over the sheets quickly to explain them again. Due to space limitations, it is necessary to continue to use the computer classroom. To increase interaction and improve the worksheet effectiveness, the instructor makes sure s/he discusses the major points of the exercise with each group before class ends.

The two-hour twice a week time slot was found to be very helpful in implementing such a range of activities. While this may not be essential to other courses it gave time to develop and/or explore some of the complex topics within process control. The time went very quickly and students did not seem to mind the longer format.

3.5 Assessment of student learning

Seven ABET learning objectives are associated with the process control course, and each is assessed every time the course is offered (see Table 6 for information from 2006–2008). Students have three exams during the semester, and data are collected on how each student performs on each question. The questions are tied back to the learning objectives. Annual ABET reports note the percentage who scored 100% on exams questions pertaining to each learning objective, the percentage who scored 80–100%, and the percentage who scored below 60%. Over the years 2006–2008, no student scored below 60% on an exam question pertaining to these learning objectives. The same final exam was used for 2006 and 2007, and a more challenging final exam was prepared for 2008, with multiple questions covering the same objective.

Table 6 shows that the students learn through the multimodal approach, even with less time devoted to instructor lectures. For example, one objective is "Students will be able to choose appropriate manipulated and controlled variables". The Lego in-class exercises will not work unless students have set them up correctly, and often the instructions are vague. The students work in small groups figuring out how to accomplish the task. Over the past three years, after setting up the Lego kits in various (correct and incorrect) configurations, up to 78% of the students have perfectly answered a challenging final exam question corresponding to this objective, and 100% of the students received a score of at least 80% on this problem. Another objective is "Students will be able to

Table 6. Assessment of ABET learning objectives associated with the Process Control course 2006–2008

Students will be able to . . .	**Presentation Method**	**Computer simulation?**	**Lego Exercise?**	**% who scored 100% on exam questions on this outcome**		
				2006 (26)	**2007** (8)	**2008** (18)
Model simple dynamic systems	Workshop and interactive class		x	50–65	70–80	89–94
Solve ODE using Laplace transforms	Lecture			100	100	27
Choose appropriate manipulated and controlled variables	Full two-hour workshop	x	x	100	75	44–78
Predict the dynamic response of process systems with and without control loops	Experiment followed by explanation	x	x	69	75	56
Tune a PID controller	Experiment followed by explanation	x		69	75	56
Select sensors and controllers	Full two-hour workshop		x	100	100	44–78
Size control valves	Learn concept then apply with simulation	x		69	100	22–61

predict the dynamic response of process systems with and without control loops". At the beginning of the semester, a pretest showed that only 8% of the students could predict the dynamic response, but 56–75% of the students can do so correctly by the end of the semester for a simple level control process. In 2008, the final exam asked the students to predict the response of a cascade control system. 56% of the students answered totally correctly, and 94% received a score between 80 and 100%. Both the computer simulations and the Lego exercises contribute to student understanding.

4. CONCLUSIONS

Six different presentation methods were used in the multimodal course (lecture, text, simulation, class problems, homework and experiment kits). Different instruction techniques were chosen depending on the topic. When asked what helped them learn the subject, students indicated all methods. This hints that the different modes are succeeding at teaching a broad range of material to a group of students with diverse learning style preferences. Assessment of student learning showed that the students are able to meet the objectives upon completion of the course. In addition, students remembered what they learned a year after the course. Student attitudes toward process control did not appreciably change over the years that this approach and the experimental kits were evolving.

Inductive teaching methods are easily implemented in the multimodal course. Students showed a significant preference for a quick inductive exercise, followed immediately by discussion and lecture to explain what they had just seen. When the students repeat the exercise after the discussion, the learning was reinforced.

Using these approaches is aided by a time and space structure that supports them. A two-hour time slot allowed for a greater range of options in this particular course. The interactive approaches were easier to effectively implement in a classroom that placed students in natural groups where interaction was easy and the instructor could circulate among the students easily.

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APPENDIX A: EXAMPLE WORKSHEET:

(Gray background show what the students are expected to fill in. These spaces would be blank on the worksheet students are given).

Proportional + Integral + Differential Discrete Control Algorithms

1. The usual "position form" algorithm for PID control is:

$$c(t) = c_0 + K_c\left[e(t) + \frac{1}{\tau_I}\int_0^t e(t)dt + \tau_d \frac{d\,e(t)}{dt}\right]$$

2. Transfer Function: For this equation determine the transfer function $G_c(s) = \dfrac{C(s)}{E(s)} = ?$

$$C(s) = K_c\left[E(s) + \frac{1}{\tau_I s}E(s) + \tau_d sE(s)\right]$$

$$\frac{C(s)}{E(s)} = K_c\left[1 + \frac{1}{\tau_I s} + \tau_d s\right]$$

3. Our Lego kits, and most modern controllers, are digital and operate with a discrete sampling time (data is taken every so much time) and the equation in 1 above must be converted to a discrete from. The discrete form replaces the derivatives with ratios of finite changes and integrals with summations.
   For a constant Δt and n being the number Δt intervals since $t = 0$:

$$\frac{de(t)}{dt} \approx \frac{\Delta e}{\Delta t} = \frac{e_n - e_{n-1}}{\Delta t} \qquad \int_0^t e(t)dt = \sum_{i=1}^{n} e(i)\Delta t$$

   Use these expressions to convert the equation in 1 into a discrete form:

$$c(t) = c_0 + K_c\left[e(n) + \frac{\Delta t}{\tau_I}\sum_{i=1}^{n} e(i) + \tau_d \frac{e_n - e_{n-1}}{\Delta t}\right]$$

4. Often it is helpful to write the PID equation in terms of the required change in $c(t)$ rather than its absolute value—this is called a velocity algorithm. Lets try and create one.
   a. Rewrite the equation you developed in 3 except for one time interval earlier (i.e., replace each "n" with "n–1").

$$c(t) = c_0 + K_c\left[e(n-1) + \frac{\Delta t}{\tau_I}\sum_{i=1}^{n-1} e(i) + \tau_d \frac{e_{n-1} - e_{n-2}}{\Delta t}\right]$$

   b. Now subtract the equation in 3 from the equation above to get a velocity algorithm.

$$\Delta c(t) = K_c\left[e(n) - e(n-1) + \frac{\Delta t}{\tau_I}e(n) + \tau_d \frac{(e(n) - 2e(n-1) + e(n-2))}{\Delta t}\right]$$

   You should get:

$$\Delta c(t) = K_c\left[e(n) - e(n-1) + \frac{\Delta t}{\tau_I}e(n) + \tau_d \frac{(e(n) - 2e(n-1) + e(n-2))}{\Delta t}\right]$$

5. What happens to the value of this equation if you make a sudden change in Setpoint?

There will be a sudden and large increase in the control action, which is not desirable

6. Replace the $e(i)$ terms in the derivative term above with $y_{sp}(i)–y(i)$ and cancel out the y_{sp} terms.

$$\Delta c(t) = K_c\left[e(n) - e(n-1) + \frac{\Delta t}{\tau_I}e(n) - \tau_d\frac{(y(n) - 2y(n-1) + y(n-2))}{\Delta t}\right]$$

7. How will the performance of this algorithm differ from the velocity algorithm developed on the first page (step #3)?

It will respond similarly except:
1. It will not be subject to reset windup.
2. It will not have an integral kick on set point change.

8. Compare these equations to the formula in the formula node in the Control Lab software (i.e., 1) Open the PID experiment, 2) open its diagram, 3) double click on the controller to open its front panel, 4) then open the diagram for this controller).
9. You can also replace the $e(n)$ in the proportional term with $y_{sp}–y$ and cancel out the y_{sp} terms (this is a less common modification to eliminate a proportional kick on set point change).

APPENDIX B: DETAILS OF TABLE 1

Control Introduction—On the first day of class, the students construct a level control system using the experiment kits. They observe what happens if they make changes in the set point, or add a disturbance by pouring water into the tank. They learn to read the control screen, figuring out what set point, controlled variable and manipulated variable are, as they make the changes. They observe the shape of the response to a change in set point. Some students look at the diagram behind the control panel and see the math behind the process.

Modeling—The students move a temperature sensor from warm water to ice water, and the data-logging program collects the temperature-time data. The students transfer the data to Control Station, and estimate the gain and time constant for the sensor.

Using an energy balance, and given the diameter and length of the temperature sensor, its density and heat capacity and an estimate of the heat transfer coefficient, the students calculate the gain and time constant from a first order model. They compare this with the experimental estimates (usually there is less than 5% error).

Simple Control—The students set the *min calib* and *max calib* parameters in the software to 0 and 1023 respectively so that the program reads out actual raw binary output from the brick. They fill the tank to various heights and record the reading from the pressure sensor on the brick, and then use linear regression to find an equation relating the height to the raw data. The equation is input to the software as the calibration parameters, after the instructor gives a short explanation of how the software uses these parameters.

Once the sensor is calibrated, the students operate the system as an on-off level control system. They change the *setpoint* and *deadband* values in the control panel, and through investigation fig. out a good idea of what they mean. Later, the students change to PI control and observe how it eliminates the effects of disturbances and set point changes.

On other days, the students investigate P, PI and PID control using the Control Station simulator, observing the offset, the elimination of offset, reset windup and derivative kick. After the students have run the simulations, a mathematical explanation is provided.

Tuning—The Control Station simulator provides the tools and simulation of a heat exchanger to practice field tuning, the ultimate gain method and IMC tuning for a process. The students do the workshop during class, and we discuss their observations briefly at the end of class.

Advanced Topics—The Experiment kit can be used for cascade control of flow and level. The students set up their own control system, with little instruction. This allows them to choose the primary and secondary controllers, valve and sensor placement, and flow path. While some groups complete this quickly, other groups make several poor choices—and learn more through the process of improving the system control.

Control Station provides workshops for students to practice adaptive control and feedforward control. After the simulations, we discuss their observations to make sure the students learned the main points.

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