Inductive Learning in Process Control

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Abstract
Different forms of inductive learning were used to help keep student interest high and to help some aspects of process control become intuitive to the students. Both simulation software and laboratory kits where the students could conduct an experiment in the classroom were used for the exercises. The exercise either lasted for the full two hours of the class, or was a short introduction at the beginning of class. The students' response to the methods showed that they preferred a quick inductive exercise, followed immediately by discussion and lecture to explain what they had seen. However, we also saw value in exercises that lasted the entire class period, and are continuing to work on incorporating both types of processes in the course.

Introduction

Maintaining student interest in process control is challenging. Lant & Newell note that most students find process control conceptually difficult, perceive it as peripheral and have trouble integrating it with other material.[1] As a result they "find it more of a chore than fun to learn". The attempts to answer these practical problems in process control education have been addressed using three broad approaches: (1) computer simulations, (2) laboratory experiences and (3) case studies.[2,3,4,5].

In our course we are taking the approach of using both a simulator (Control Station)[6] and experiments based on classroom experimental kits.[7] In many case we are using an inductive approach with these tools. The inductive approach to teaching and learning is to begin with particulars and build to generalities. This is "backwards" from how we often naturally teach starting from general principles and then applying them to particulars. The inductive approach is the way most things are discovered and clearly how an infant learns, but it is not the way most courses are taught. It, therefore, requires we think differently about how we approach the classroom.[8-13]

A clear and helpful critique of traditional teaching approaches can be found in Thomas Magliozzi's "The New Theory of Learning".[14] Magliozzi is best known as one of the hosts on the NPR radio show "Car Talk" but he was also for many years a professor of management. He starts off describing the weakness of the traditional lecture model of instruction noting, "Listening does not lead to understanding; doing does lead to understanding."[14] He also provides a popular level description of a problem-based style of inductive learning under the title, "The backwards learning theory." Of particular interest is his emphasis on the ways a problem can provide motivation to increasing learning.

At last year's ASEE meeting we discussed some of the general principles of inductive learning and particularly the use of experiments as a start to the inductive approach.[15] In this paper we examine our use of physical experiments and of simulator "experiments" in an inductive approach to process control education.

Example Approaches

Our process control class met two hours per week in a two sections of 14 students each. The room was equipped with four discussion tables each with a personal computer. Throughout the courses, whether teaching inductively or not, active approaches were used as much as possible and the time spent on traditional lecture was minimized. Two main types of inductive approaches were used: using the full two hour class to work with the experimental kits or simulator before introducing the detailed explanations during the next class; or quick exercises where the kits or simulator would be used briefly followed immediately by discussion, lecture or problem solving to understand and generalize the particulars observed.

Introductory Sessions (full class with the LEGO® kits): In the first class we had students set up a simple draining tank with PID level control using our LEGO process control kits. This was a popular way to start, playing with LEGOs. Students were given written instructions on setting up the experiment and the control system software. 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.

Proportional Only Control and Offset (A quick simulation exercise): We have often found it difficult for students 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.[9] We started with a brief discussion of what they expected would happen when we introduced proportional control to the system (no one suggested 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 saw offset (and of course initially they thought the equipment wasn't working correctly). This led to a discussion on the conceptual reasons that offset occurs. Students then completed a worksheet that lead them through determining the closed loop transfer function and showing that offset would result. As a result of this session students seemed to grasp the nature of proportional control and the issue of offset. In addition to covering offset, we also used the setup of the controller to introduce the nature of bias and gain in a controller.

Tuning PID Controllers (a full class simulation session and follow up): For tuning we took an entire two-hour period, in a separate computer laboratory where each student could work on their own computer. We used the Control Station's Heat Exchanger case study for this exercise. Students used four different techniques to determine the tuning parameters and then tested the results on the simulator. The approaches used were: (1) a trial and error approach based on a map of how the system might respond to different relative conditions[16], (2) Internal Model Control (IMC) tuning based on the results of a doublet step test[16], (3) a Ziegler-Nichols approach where students adjusted the controller gain to find where the system oscillated and (4) a trial and error approach using a systematic set of rules[17]. At the next class meeting these approaches were discussed in detail and the IMC equations were derived. Finally this was followed up with the assignment of a Control Station workshop on tuning.[16]

Students quickly became familiar with a range of tuning techniques with this approach. They particularly came away with a clear concept of the impact of nonlinearity on control system response (the Heat Exchanger case study is highly nonlinear). If logistics allow, it might be effective to break this session up with more detailed discussion.

Frequency Analysis (a full class simulation session): Another 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 we were using the Control Station's Jacketed Reactor case study. The first quick exercise was for students to set up an oscillatory setpoint change and observe the result. Students observed that the frequency was unchanged but that there was an amplitude difference and a shift in phase. Next students learned how to use control station to measure the change in amplitude and the phase lag. They then carried out a series of experiments using different input frequencies to examine the result and constructed 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"[18] to determine the Bode plot based on the transfer function. In the next lecture we developed the student's ability to calculate these values from known transfer functions. 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 quick simulation exercise): To introduce the concept of scheduling tuning for a nonlinear process we used Control Station's Heat Exchanger Case study again. Student 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 their tuning exercises). This exercise did not take long and we were able to immediately follow up with a discussion on this approach.

Feedforward Control (a quick simulation exercise): Control Station's Jacketed Reactor case study was used to introduce feedforward control. Students set up and tested three different control systems: (1) feedback control, (2) feedforward control with feedback trim and (3) feedforward only control (this was achieved in Control Station by setting the feedback gain to a very tiny number). Students noted the maximum deviation, the settling time and the steady state offset for these three setups in response to a step up and a step down of the disturbance by 5^{o}C.

This exercise clearly showed the advantages and potential problems of the various configurations and a good discussion of the nature of feedforward control resulted. This discussion was followed by a worksheet where students derived the lead-lag form of the feedforward controller.

Response:

We were pleased with the results of these exercises. We 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 we observed much less confusion with the basic concepts than in the past. They also seemed to understand the advanced topics of tuning scheduling and feedforward control.

Overall student response to these exercises was positive. Students liked the hands-on experiments with the LEGO process control kits. They indicated that they would like to see them more, which we are working on. Detailed response to these kits is covered in another paper.[7]

Figure 1 is a series of box plots summarizing a survey taken on the student response to the use of the Control Station simulator. Students were asked to rate their agreement with three statements about Control Station using a 1 to 6 Likert scale. The three statements were (1) I found Control Station easy to use and understand, (2) I enjoyed using Control Station, and (3) I learned a lot using Control Station. In all three cases students, half the students choose a 5 or 6, where 6 was strongly agree. Virtually all students found the software easy to use and most seem to enjoy using it. There was a subsection of the class who did not seem to find it as valuable (one quarter giving a rating of 3 or lower).

Figure 2 summarizes a student survey used to examine student response to the inductive learning approach. Here students were asked to rate the effectiveness of three approaches (1) introducing a topic with an entire-class inductive exercise, (2) introducing a topic with a quick exercise followed by a lecture and (3) introducing topic with a lecture and having the exercise follow. Students were again asked to respond on a six point Likert scale. They rated all three approaches similarly. However, the quick introduction seems to have gotten a little higher rating and possibly a narrower distribution (with one extreme outlier).

Sign tests on the difference between each of the inductive approaches and the traditional approach were used to determine if a significant number of students rated one of the inductive approaches higher than the more traditional approach. To carry out this test the Likert score for the "follow up exercise" option was subtracted from the Likert score given to an inductive option. This results in two new sets of data that are positive if the inductive exercise rated higher and negative if the inductive exercise was rated lower. The nonparametric sign test was then used to test whether a significant number of students rated the inductive approach more highly. The sign test was chosen because of its robustness relative to the distribution and to outliers. Table 1 shows the result of these tests.

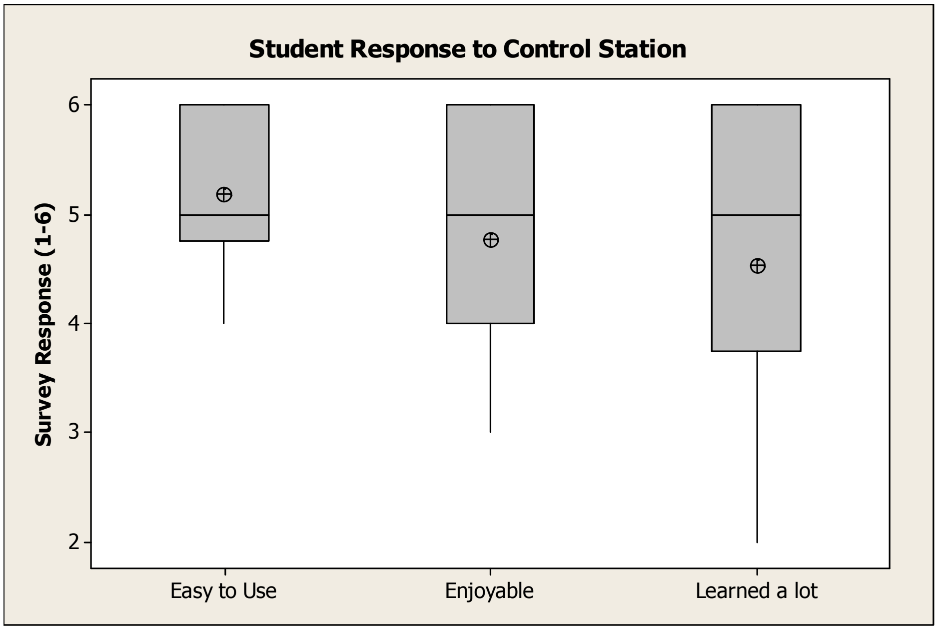

Figure 1: Box plots comparing student response to statements about Control Station. A score of one means they strongly disagree and a score of six that they strongly agree. The three statements students responded to were:

1) I found Control Station *easy to use* and understand,
2) I *enjoyed* using Control Station, and
3) I *learned a lot* using Control Station

The centerline of the box is the median value the top and bottom of the box represent the third and first quartiles. The line(s) outside the box continues on to the maximum or minimum. Asterisks are used when an outlier is detected.

There is clearly no significant difference between the introductory full class exercise and a more traditional approach. However, significantly more students rated the quick exercise above the traditional approach. Fifteen students rated this approach higher and only four rated it lower, with seven students showing no preference. We observed more positive result to the full class exercises than most students did. This was the first time we used these approaches and they will be refined for future use.

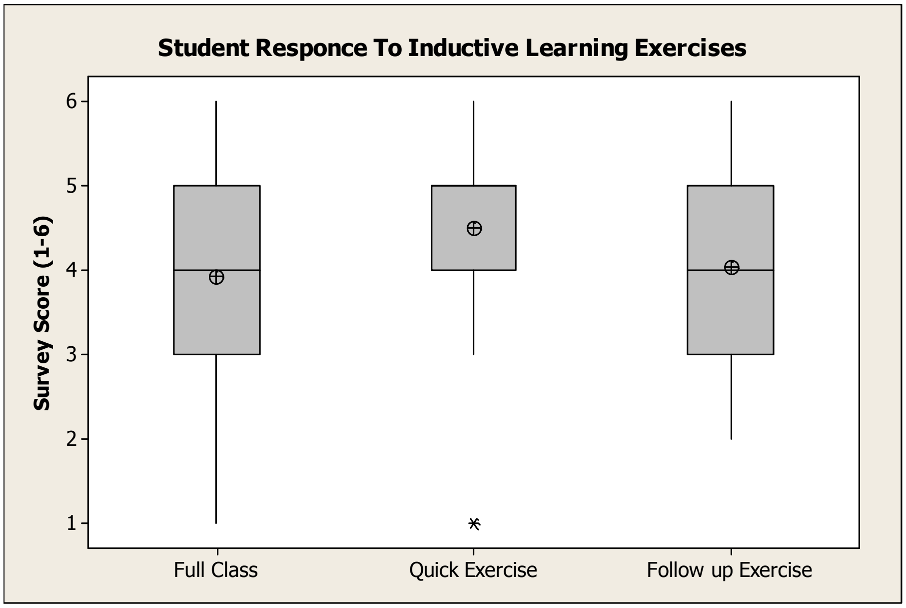

Figure 2: Box plots comparing student response to the effectiveness of various teaching approaches. A score of one means not effective and a score of six very effective. Students were asked to rate (1)starting a topic with a *full class* period exercise, (2) starting a topic with a *quick exercise* followed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

Additional Kit Developments

Since the kits were used during the Fall 2003 semester, several additional applications have been developed and are currently being tested[7]. These include using the kits for tuning PID loops, on/off control, and cascade control. In addition, one student used the kits in a sequence control project. She programmed LabVIEW software to fill the tank to a certain level, turn on an aquarium heater until a set temperature was reached, and then turn the heater off. This process showed the students how a batch process can be controlled. The student was also very pleased with how quickly she learned to work with LabVIEW.

Table 1: Sign Test comparison of Student Responses

Sign test of median = 0.00000 versus not = 0.00000

	N	Below	Equal	Above	P	Median
Full Class - Follow up	26	10	7	9	1.0000	0.00000
Quick Exercise - Follow up	26	4	7	15	0.0192	1.000

Conclusions

The inductive approach is easily integrated into process control using classroom experiments and simulated control systems. Simple in-class process control kits facilitated a helpful inductive and hands-on introduction to process control. We found the inductive approach, using the process simulator, particularly helpful with introducing proportional-only control and the problem of offset, and with introducing frequency analysis. Students showed a significant preference for quick inductive approaches followed immediately by discussion and lecture to explain what they had seen. We saw value in longer exercise as well but these exercises may need more refinement. We are continuing to work on incorporating both experimental and simulation inductive exercises in our process control class.

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