# An Experiential and Inductively Structured Process Control Course in Chemical Engineering

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**Abstract**

An inductive approach to teaching chemical engineering courses has been demonstrated to improve student learning in courses such as mass transfer and stoichiometry. One course particularly well-suited to elements of inductive structure is chemical process control, where experiential learning can also be applied to maximize student learning. This paper discusses the first two implementations of an inductive course structure in this three-hour senior-level course at the University of Kentucky Extended Campus Programs in Paducah, Kentucky. Six chemical engineering oriented laboratory experiments in process control are integrated into the course to enable students to make observations, draw conclusions, and establish relationships for specific cases. During subsequent lecture periods students develop the observations they make into general relationships, many of which they later test in the laboratory.

Assessment conducted on student learning indicates that laboratory exercises were most valuable when they preceded classroom discussion (in an inductive structure), provided that the instructions for the experiments and their analysis were very detailed. Non-inductive exercises were preferred for difficult material to aid in developing practical understanding of theoretical concepts. The biggest flaw with incorporating labs into a course scheduled around traditional lecture periods, according to students, was the time it took to complete labs involving heat transfer processes. Processes with shorter time constants, such as flow, level, and pressure control, were preferred.

## Introduction

Process Control has often stood out in the chemical engineering curriculum as a necessary topic that is oddly disconnected from the rest of the curriculum. While control modeling still relies on conservation laws and other fundamentals of chemical engineering, its mathematical focus on process descriptions in the Laplace domain has made it appear to students as a course distinct from "regular" chemical engineering. In reality, process control is key to industrial practice and will draw upon an engineer's theoretical knowledge and practical experience to be effective. Still, the effect of months spent talking about "s" seems to be a lack of motivation for students to grasp the fundamentals of process control.

The goal of the changes made to this course's structure has been to restore the student's perception of the linkage between the course and engineering practice. Additionally, the changes are tied to improved pedagogical methods for student learning, inductive learning and experiential learning. There was not an option to add a laboratory course at this time, a remedy taken by other institutions to address this issue.

**Experiential and Inductive Learning**

Experiential learning is one approach to engaging students actively in the learning process. Farrell and Hesketh[1] suggest that students typically recall only 20% of what they hear, while if they hear and see something done, they may recall closer to 50% of the experience. If they actually do something, such as conduct an experiment, they are likely to recall as much as 90%. This is one active-learning approach recognized as contributing to common student learning-styles in engineering.[2]

There are numerous examples of incorporation of experiential learning in process control courses.[3,4,5,6,7,8] Most involve development of experiments, typically required as apart of a distinct 1-hour laboratory section extending the course length from 3 to 4 semester hours. Clough[9] incorporated experiments directly into the lecture course prior to the addition of the 1 hour laboratory section[10]. Others have attempted to add this active learning component through use of web accessible experiments.[11] More recent efforts to include experimentation in process control courses include development of kits using LEGO® RCX® brick and quick disconnect piping to build desktop process control equipment for in-class use.[12]

Inductive learning refers to the organizational approach by which specific observations are used to lead the learner to more general conclusions. This is effectively the inverse approach of deductive learning, where general principles are used to deduce consequences for specific applications. Most teaching is performed in the deductive mode, but most discoveries, or things learned for the first time, are made inductively. This suggests that induction is a more natural learning style and more effective for many student learners[2].

Moor and Piergiovanni[12] describe their application of classroom kits for inductive experiments in a process control course. An inductively structured course in Heat & Mass Transfer is described by Farrell and Hesketh[1]. Hesketh, Farrell, and Slater[13] describe the role of experiential learning when using an inductive style of teaching.

**Course Description**

The course described here is a 3-hour lecture course offered during the spring of the senior year. There is no formal pre-requisite other than “Consent of Instructor”, although it draws heavily upon a course in modeling offered during the spring of the junior year. The expected outcomes for the course are that students should be able to:

- Apply knowledge of mathematics and science to process dynamics and control
- Analyze and interpret different control systems’ transient and frequency response data
- Design simple control systems for distillation columns and chemical reactors

- Identify, formulate, and solve linear control problems
- Use engineering tools for control systems

When preparing to modify the course to add experiments and increase inductive content, the following topics were selected for emphasis:

- Instrumentation
- Relationship of first and second order model parameters to responses of real systems
- Empirical modeling
- Signal conditioning and interpretation
- PID controllers and tuning
- MIMO interaction

In order to modify the course still and conform to reasonable student expectations of time formally committed to the course, lecture time was reduced 10 minutes for every 30 minutes of expected laboratory time. Labs were scheduled at least one to two weeks in advance, with the exception of the first laboratory. Credit for the lab work was given as part of the student homework grade, which was increased to account for 25% of the total grade for the course. The lab reports were kept simple (mostly fill-in-the-blank and short answer questions to be filled in), and the number of textbook-type problems assigned was reduced.

Two class sections at the University of Kentucky have engaged in this modified course to date. The first cohort consisted of 10 students, and the second class had 2 students. The assessment described later in this paper is based upon the first cohort.

**The Equipment**

The commercially available equipment described herein is typical of many devices offered by a number of vendors, including Creative Engineering[14], Armfield Limited[15], and Feedback Instruments Limited.[16]

Two devices were used over the course of the semester. The first is a pressure regulation apparatus (Figure 1) consisting of a pneumatic control valve, various pressure gauges, and orifice meter, a square-root extractor, I/P transducers, and a storage tank. The apparatus can be connected to a control panel (Figure 2) which incorporates an ammeter, a voltmeter, and signal conditioner ports, and an industrial-type digital PID controller.

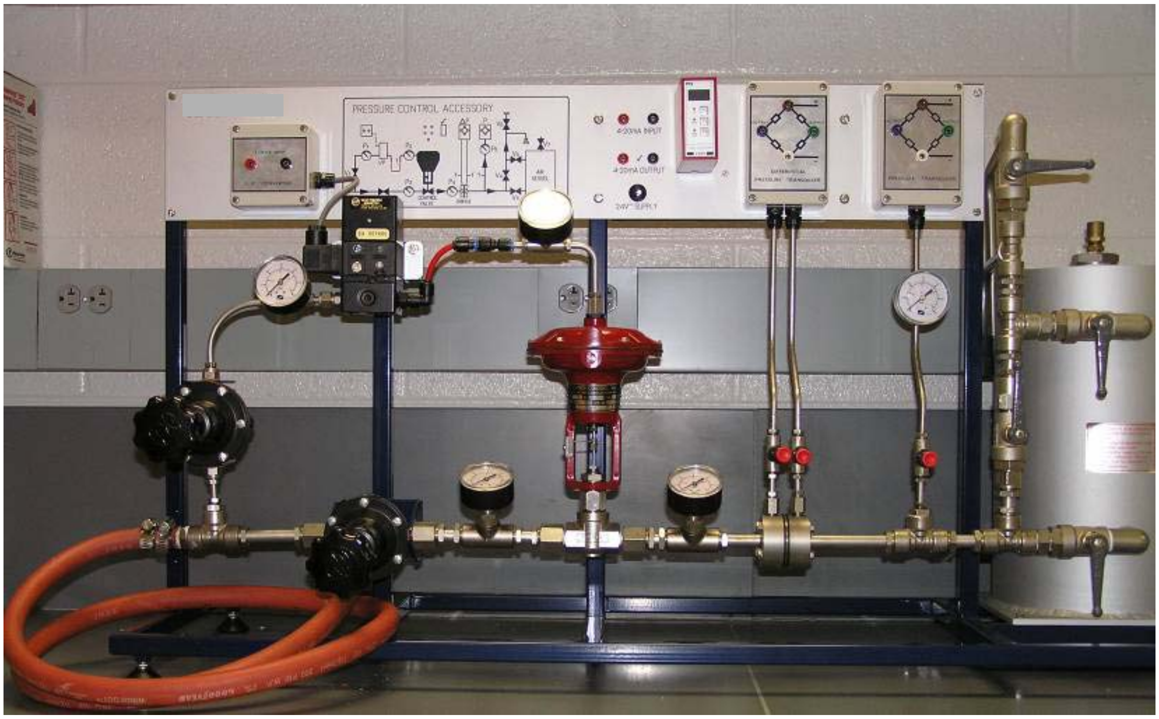


**Figure 1**. Pressure regulation apparatus

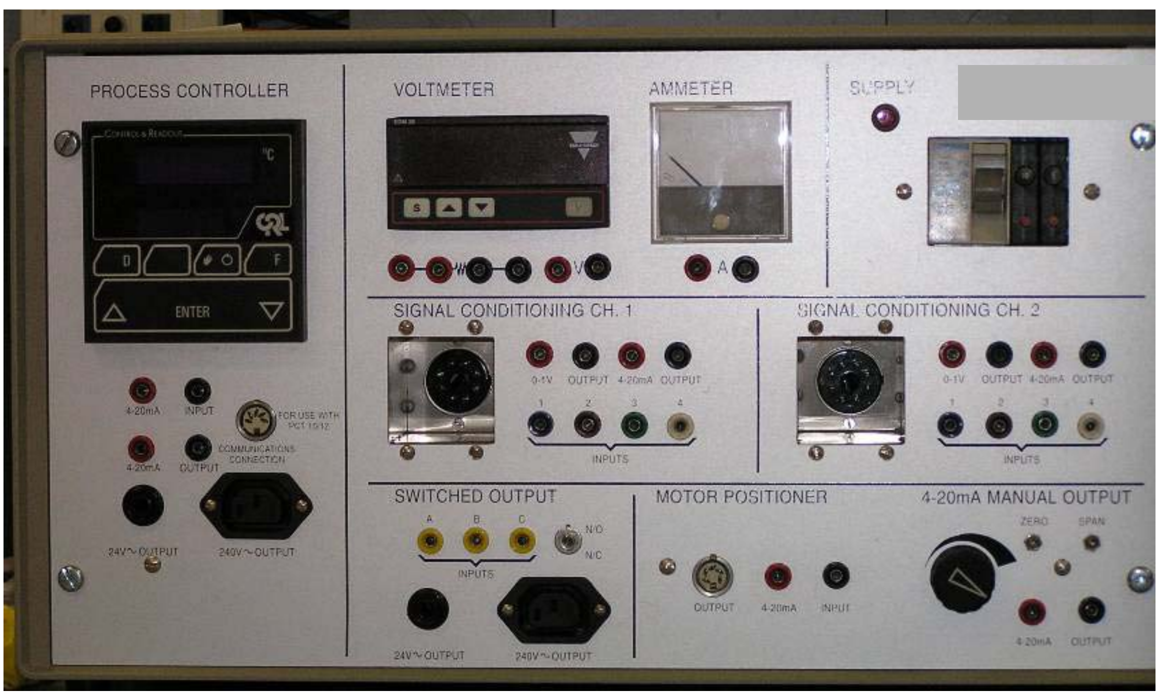


**Figure 2**. Control panel for pressure regulation apparatus

The second device is a "Process Plant Trainer" (Figure 3), which combines three plate heat exchangers, two feed tanks, a dead-time segment of tubing, various solenoid valves, level sensors, flow sensors, and thermocouples enabling simulation of a variety of fictional processes and control scenarios. This device can be connected to a control panel with an interface board (Figure 4). For some experiments, the apparatus is connected to a PC with MS-DOS based acquisition and control software. A PLC is also available for use with the system (Figure 5).

**The Experiments**

The first experiment was conducted the first day of class. Students were presented a syllabus, a homework assignment (including the laboratory assignment), and told to leave their books in the classroom (which was then locked) and come down to the controls lab. Students were briefed on safety rules for the lab, had the exercise explained to them, and then proceeded to complete the first assignment. The objectives for this 30-minute assignment were to:

- Induce a conceptual understanding of process time constant and gain
- Establish justification for automatic control
- Demonstrate intuitive use of proportional control
- Sketch process behavior
- Introduce elements of instrumentation

Not all objectives were immediately met, but the experience was used in subsequent lectures to form a basis for instruction. For example, students were asked to maintain a particular pressure in a (leaking) tank by adjusting the current signal sent to the I/P transducer connected to the pneumatic control valve. We discussed immediately after the lab what everyone did to set the pressure in the tank—starting with big changes when the tank pressure was far from the desired pressure and making smaller adjustments when the error was smaller.  Proportional control was introduced a month later referring to this initial experience. Students appreciated the meaning of time constant noting how quickly the pressure apparatus responded (small time constant) compared to a level control response in the process plant trainer (large time constant). We later modeled both processes and determined the relative magnitude of the time constants, confirming their observations. Figures 6a and 6b are the assignment sheet provided to students. Note that the deliverables were kept simple so that students could focus on observation and not recording data. This also helped maintain student morale, as they were leery of the added workload of labs in a traditionally lecture course.

This exercise was clearly inductive, since students had no background in control prior to the lab. After completing the experiments, we returned to the classroom and discussed what we observed. The benefits were immediately evident in the following class meeting, since students understood why they were learning control. Class discussion quality was far better than in previous offerings by this instructor, since we had a common experience to

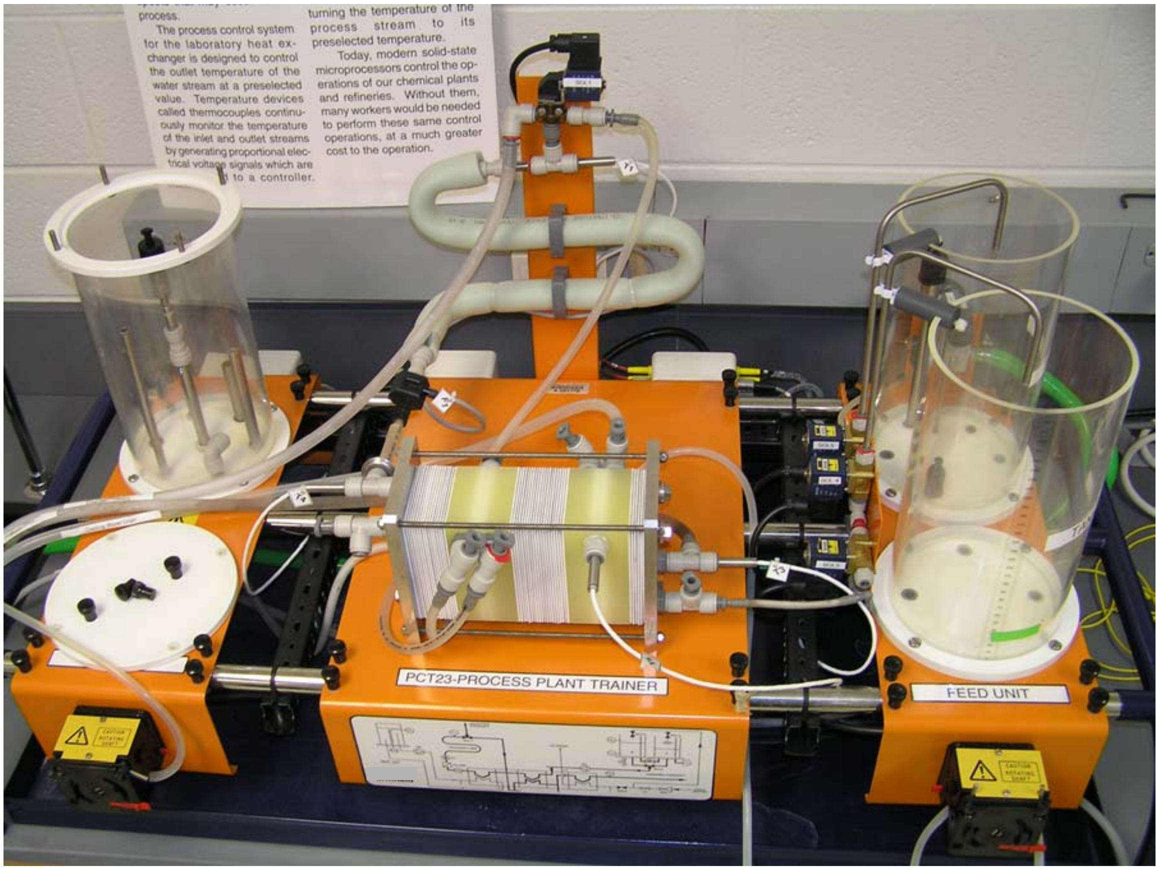


**Figure 3**. Process Plant Trainer

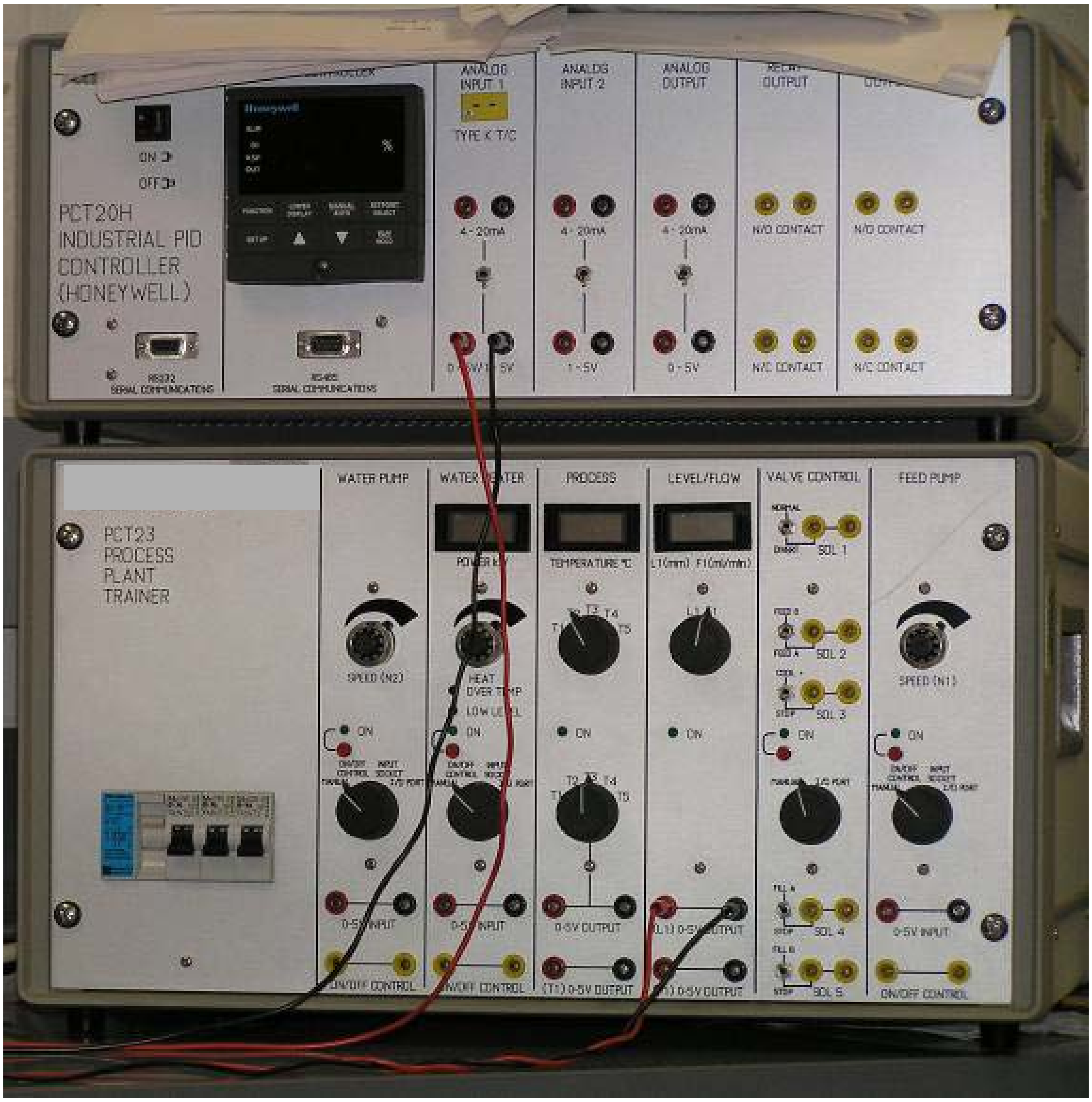


**Figure 4**. Control panel and interface board for the plant trainer.

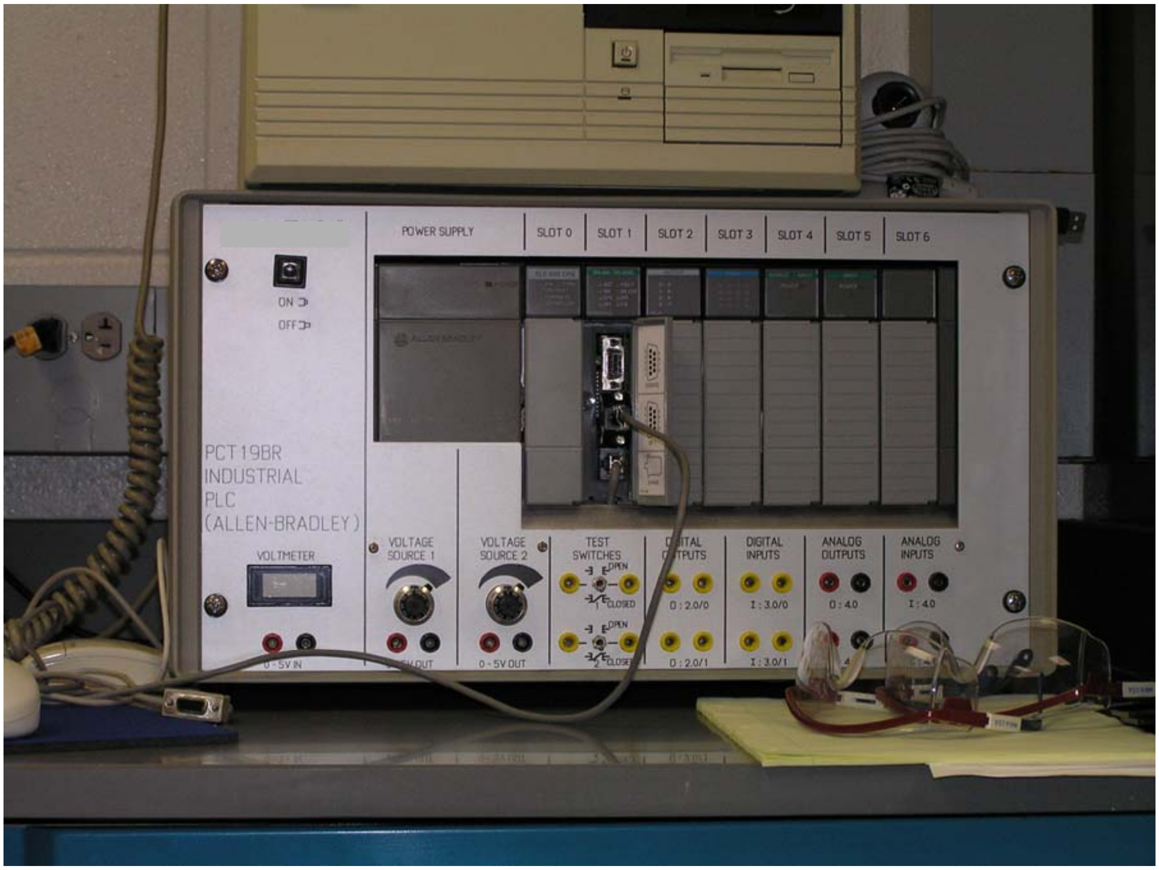

**Figure 5**. PLC connected to the plant trainer

CME 462
Process Control
Spring 2005

Laboratory Exercise 1

Due: Tuesday, January 18, 2005

## What's Process Control About?

Neither of these activities require you to set up equipment. Simply follow the instructions and CAREFULLY NOTE EXACTLY WHAT AND HOW YOU DO what you do. Safety glasses must be worn while in the laboratory.

### Part I: Operating Under Pressure (pressure apparatus)

Your goal in this experiment is to maintain a constant pressure of 0.5 bar gauge in the tank.

Using the Manual Output knob, adjust the position of the control valve such that the pressure in the tank is maintained at 0.5 bar. Note how far and how fast you turn the valve in response to the pressure you read. Note the reading on the ammeter when you reach steady-state

Instead of 0.5 bar, you decide to keep the tank at 9 psig. Note again how the system behaved in response to your adjustments.

Be prepared to comment on the following: to achieve the desired pressure, did you turn the knob "all the way". Did the pressure exceed the desired pressure? Which gauge did you use?

### Part II: Keeping It Level (plant process trainer)

You want to keep the tank at a level of 50 as indicated by the level meter. While the water is flowing, adjust the rate of rotation of the peristaltic pump to achieve this goal.

### Part III: Stuff you have to submit

1. For the pressure apparatus, sketch (qualitative) desired $P_{tank}$, actual $P_{tank}$, ammeter reading, and knob position as a function of time over the course of the entire experiment. Include a legend to distinguish between traces.

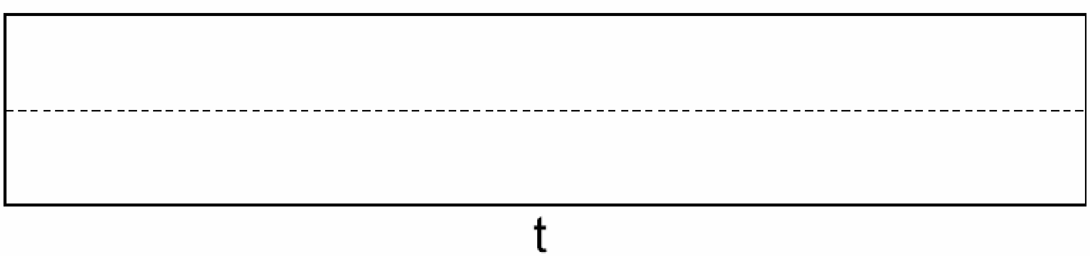


**Figure 6a**. Page one of lab assignment conducted during first class meeting

2. For the level apparatus, sketch desired level, actual level, and relative pump rotation on the same plot. Include a legend to distinguish between traces.

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3. Draw process schematics of both pieces of equipment. For multiple lines going to the same place, draw a single line. Do not include equipment not in use. A process schematic uses pictures and lines to represent equipment and connectivity. See Figures 1.1 and 1.2 in your text.

4. Draw a control schematic of each system. A control schematic contains equipment representations along with indication of what is being measured and what is being manipulated. See Figures 1.4 and 1.5 in your text.

5. What was the key difference (in context of control) between the pressure and level systems?

**Figure 6b**. Page two of the initial exercise form a basis for that discussion. The specific observations made in the lab were developed into more general principles of process control.

The second laboratory exercise was designed to reinforce the students understanding of dynamic modeling. They collected data for a two-tank gravity drainage system, with both tanks connected at their bases. Students then prepared an analytical model of the system, and compared their results with the data they collected. It was a profitable exercise, as some students claimed it was the first time they had theory match experimental data in their chemical engineering laboratory experience. Since students had prior experience in writing balances and designing experiments, this exercise was designed deductively, but still engaged students actively in the process of convincing them of the validity of theory discussed in class.

The third exercise in process identification was designed deductively as well, since students had previously performed regressions of experimental data. Students collected step response data of a multi-step heat exchange process controlled by changes in three process variables. After the lab, they selected an appropriate model and determined model parameters. While it was not part of the official assignment, the highlight of the exercise was the opportunity to wire a controller to a feed valve to eliminate the need to manually maintain an adequate level in a feed tank. Students were provided wiring, a manual, and were told the controller was configured to maintain the level. During the 30 minutes or so required to allow the system to come to steady state, all three groups managed to deduce the appropriate wiring connections to set up automatic feedback control. This experience was also used during lecture when defining terms such as "deadband" and "direct action".

The fourth exercise was the first foray into closed-loop systems. Since closed-loop behavior, PID controllers, controller tuning, and stability had not been discussed in class, this was an inductively designed exercise with detailed instructions on what to do and what to observe. The pressure apparatus was used in conjunction with its orifice meter to maintain a desired flow rate of air. Students utilized an industrial PID controller and varied the controller gain to make the system marginally stable and unstable. They then observed the difference in response with P and PI control. They rewired the system to bypass the square-root extractor (conditioning the orifice meter signal), observed the difference in system behavior, and were asked to show why it was required.

A fifth exercise involved a multi-loop system involving both temperature and flow variables. Students were asked to observe which variables interacted, and then to suggest why from general models. They also observed the effect of detuning to account for interaction.

The last exercise required students to run through an exercise in PLC usage involving a ladder program simulating a five step batch process using the process plant trainer. This exercise was not completed due to communications issues with the PLC.

Time required for each of these exercises varied widely. The first exercise, which involved only flow control, took 30 minutes during the first class period. The second and fourth, which also involved flow control, took 30 minutes to an hour, depending on the preparation of the students (did you read the instructions?). The remaining exercises took about 3 hours, due to the thermal nature of the experiments.

**Assessment**

After the final exercise, students were asked to submit responses to a free-answer survey assessing their perceptions of the labs. Of the ten students in the sample, nine responded.

1. Were the laboratory exercises a valuable part of the course?
2. Did they help you better understand the course material?

All nine students indicated that they were valuable and helped them in understanding the course material.

3. Were they more valuable when they served as an introduction to course concepts, or when they reinforced lectures and reading?

This question was intended to determine whether they preferred the inductively designed labs or deductively designed labs. One-third preferred the inductively designed labs, while the remaining two-thirds preferred the deductive labs. The learning styles of these students were not assessed, so the only conclusion by this instructor is that the students were not considering the learning value of the experience, but were focused on their comfort level during the lab.

4. Which labs would you recommend be kept? Should any be removed from the course?

Students expressed a distinct preference for the faster experiments, since much of the time spend on the slower (thermal) labs was spent idly waiting for the system to reach steady state. Future offerings will have the apparatus "preheated" provided the students schedule their lab times far enough in advance.

5. What changes to the lab/lecture balance would you recommend?

Students were concerned about the time spent on the thermal labs, and preferred having a regularly scheduled lab section. Due to the number of hours in the current curriculum, this is not an option at this time. This is, however, the historical evolution of such improvements to a process control course[9,10].

Other requests include "make the equipment work", referring to problems with a peristaltic pump and with air in a pressure measurement line.

The labs seemed to improve student performance on exams, but more noticeably students seemed more "tuned-in" during lectures where the lab results were used as examples. Interviews with students indicated that the experiments truly did improve their understanding and provided a framework from which they were able to better analyze process control problems. The key improvements made for the second offering of the modified course were more detailed instructions for inductively designed labs, and efforts made to reduce waiting times during thermal labs.

## Addressing Larger Classes

Clearly, it is not feasible in all institutions to require all students to participate in a half dozen lab exercises in small groups over the course of a semester. For larger classes, some options include in-class kits such as those developed by Moor and Piergiovanni,[12] or remote, internet based labs such as those developed by Henry[11]. One additional option takes advantage of newer equipment that is controlled via computer. By adding a remote video camera and using a remote access technology (such as Remote Desktop in Microsoft Windows), students can get familiar with the equipment in one hands-on lab exercise, and then use the remote access technologies to control the equipment in later labs. This paradigm emulates the experience of an industrial operator, where most of the control is performed by wire with only occasional visits to the equipment being controlled.

## Conclusions

Restructuring a chemical process engineering course to include significant elements of experiential learning seems to significantly improve student learning. Inductively designing some of those exercises seems is noticeably more effective at introducing new topics in process control than traditional lectures. Six laboratory exercises were developed within the context of a traditional lecture course and integrated into the lecture course to improve student learning. Student feedback indicates they value the lab experiences, provided they do not perceive they are wasting time waiting for systems to reach steady-state.

## References

[1] Farrell, Stephanie; Hesketh, Robert P.; "An Inductive Approach to Teaching Heat and Mass Transfer", Proceedings of the 2000 American Society for Engineering Education Annual Conference & Exposition, 2000.
[2] Felder, R.M.; Silverman, L.K.; "Learning and teaching Styles in Engineering Education," *Engineering Education* 78(7) 674, 1988.
[3] Lennox, Barry; Brisk, Michael, "Network Process Control Laboratory", *Chem. Eng. Ed.*, Fall 1998.
[4] Skiliar, Mikhail; Price, Jesse W.; Tyler, Christopher A; "Experimental Projects in Teaching Process Control", *Chem. Eng. Ed.*, Fall 1998.
[5] Joseph, Babu; Ying, Chao-Ming; Srinivasagupta, Deepak; "A Laboratory to Supplement Courses in Process Control", *Chem. Eng. Ed.*, Winter 2002.
[6] Ang, Siong; Braat, Richard D.; "Experimental Projects for the Process Control Laboratory", *Chem. Eng. Ed.*, Summer 2002.
[7] Muske, Kenneth R., "Simulation and Experiment in an Introductory Process Control Laboratory Experience", *Chem. Eng. Ed.*, Fall 2003.
[8] Toghiani, Hossein; Toghiani, R. K.; Hill, Donald O.; Wierenga, Craig, "Enhancement of Instrumentation and Process Control Studies at the Undergraduate Level", Proceedings of the 2000 American Society for Engineering Education Annual Conference & Exposition, 2000.
[9] Clough, David E., "The Integration of Laboratory Experience with a Senior Course in Chemical Process Instrumentation and Control", Proceedings of the Frontiers in Education Conference, Champaign-Urbana, 1977.
[10] Clough, David E.. "Bringing Active Learning into the Traditional Classroom: Teaching Process Control The Right Way", Proceedings of the 1997 American Society for Engineering Education Annual Conference & Exposition, 1997.
[11] Henry, Jim, "Web-based Controls Laboratory Hardware and Software," available via Web at http://chem.engr.utc.edu/Henry-Pub, 1996.
[12] Moor, S. Scott; Piergiovanni, Polly, "Experiments in the Classroom: Examples of inductive Learning with Classroom-Friendly Laboratory Kits", Proceedings of the 2004 American Society for Engineering Education Annual Conference & Exposition, 2004.
[13] Hesketh, Robert P.; Farrell, Stephanie; Slater, C.S.; "The Role of Experiments in Inductive Learning", Proceedings of the 2002 American Society for Engineering Education Annual Conference & Exposition, 2002.
[14] Creative Engineering website, http://www.reallabs.net, accessed January 2005.
[15] Armfield Limited website, http://www.armfield.co.uk, accessed January 2005.
[16] Feedback Instruments Limited website, http://www.fbk.com/, accessed January 2005.

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