Courses in

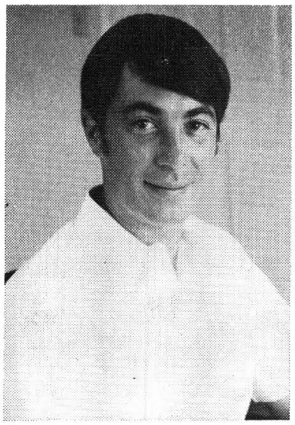
PROCESS CONTROL

LOWELL B. KOPPEL
Purdue University
Lafayette, Indiana

GRADUATE LEVEL EDUCATION in process control poses several challenging questions to chemical engineering educators: What are its objectives? Which topics are of primary importance? To what extent is duplication of subject matter, with that of courses offered in electrical engineering, mechanical engineering, engineering science, etc., desirable and/or justifiable? How much duplication can be afforded with courses in optimization offered in our own departments? Should a single course be a "survey" and appeal to all chemical engineering graduate students, or should it be primarily directed at those who plan to do their thesis research in process control? What can be done to compensate for the enormous differences, in undergraduate preparation in process control, observed among students coming from various schools? Should laboratory work be included? What is a good balance between theory and applications?

Clearly, these questions occur in designing curricula for any area. However, the answers would appear to be less well-established for process control than for other areas of chemical engineering, perhaps because this is a relatively new subject. My purpose is to discuss graduate education in process control at Purdue, and how we have attempted to answer these questions.

SEVERAL FACTORS existing at Purdue may give us somewhat more than the usual amount of flexibility for experimentation in graduate education in general, and in graduate courses on process control, in particular. Our department has a relatively large number of graduate students, thus more nearly ensuring sufficient registration to offer a specialized course such as process control course each year. As a result, the course has been taught six times in the past seven years. There are three faculty members in the chemical engineering department interested in teaching a graduate process control course: Henry C. Lim, William A. Weigand, and the author. Therefore, the course can be offered frequently without unduly restricting the teaching interests of any one faculty member. The average number of resident graduate students performing research in process control or related areas has exceeded ten over the past few years. This leads to a strong research interest on the part of students enrolled in the process control course. Purdue's departments of mechanical engineering, electrical engineering, engineering science, and mathematics offer several courses in control and closely related areas (such as systems engineering, mathematical programming, optimization, etc.). On the one hand, this relieves us of the pressure to cover a wide variety of topics, but on the other hand, increases our responsibility to avoid duplication by being aware of course content in other departments. The Purdue Laboratory for Applied Industrial Control (PLAIC), directed by Theodore J. Williams, supports graduate students from several departments, including chemical engineering, on industrially-oriented projects. Purdue graduate students interested in practical aspects of process control thus have opportunities for training in addition to those offered by the chemical engineering department.



Lowell B. Koppel was educated at Northwestern University (B.S., 1957; Ph.D., 1960) and at the University of Michigan (M.S.E., 1958). He is currently Professor of Chemical Engineering at Purdue University with research interests in process operation, process design, and transport processes.

AGAINST THIS background, our department has taught a 3-semester hour, graduate-level course, Advanced Process Control, hereafter referred to by its number, CHE 656. Over the several years it has been offered, some 35 - 40 graduate students have been enrolled in CHE

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656. Of course, there has been evolution in the subject matter, so that not all these students have studied the same material. However, all these students have studied material significantly more advanced than that covered in undergraduate process control courses. Since many other departments of chemical engineering are actively involved in graduate education in process control, it seems conservative to estimate that there are more than two hundred engineers now in industry who have had graduate training in process control or closely related areas. Therefore, it is not unreasonable to expect that these former graduate students should have had some impact on current process control technology. I wish to more closely examine this question later. To begin the discussion, I now return to the questions posed at the beginning of the article.

OBJECTIVES OF GRADUATE LEVEL EDUCATION IN PROCESS CONTROL

Many worthwhile objectives exist; listed here are those I believe to have highest priority.

The technology of *process operation* has become more complex, and is rapidly increasing in complexity. Use of the digital computer in plant operation is increasing. Plant optimization studies are conducted and result in changes in mode of operation as well as in operating conditions. Thus, I believe we should broaden the scope of the process control topic by calling it *process operation.* This subject has equal economic significance with its counterpart in classical chemical engineering — process design. One discipline attempts to optimize the plant before it is built, i.e., while it is on paper, and the other continues the attempt when the plant is operated. The typical undergraduate chemical engineering curriculum has room for only one course each in process design and process operation (control). There simply is more of practical value to learn about these subjects than can be studied in one undergraduate course.

The language of communication in process operation tends to be mathematical and therefore difficult. This fact generates two purposes for graduate-level courses — education of the students in the mathematical foundations, and simplification of the language (i.e., communication of the same information in simpler terms). Since we have inherited much of the foundations from mathematicians, this simplification aspect is potentially a valuable contribution of the engineer, both educationally and industrially.

The research and development literature on the automatic control and optimization aspects of process operation is widely scattered in a variety of journals, many of which are virtually unknown to chemical engineering students. As in most subjects in the graduate curriculum, familiarity with the current literature is a primary objective; in this subject, it is perhaps even more critical.

To summarize, key objectives of a graduate course on process operation are mastery of practically important subject matter which cannot be included in the undergraduate curriculum, mastery and simplification of the mathematical language, and familiarity with the literature. Granted these objectives are important in any graduate course; I have tried to show why they have high priority in process operation.

TOPICS COVERED

Since there are three faculty members who have taught the course, topics fluctuate slightly from year to year. Presented here is a summary of the topics included when the course is taught by me. The central textbook is reference (1). Supplementary sources in the bibliography are referenced by number in the discussion. In addition, numerous other literature articles are discussed.

Application of the digital computer to process operation: Owing to the growing number of chemical and petroleum plants being operated wholly or partially through a digital computer, I believe this subject must receive careful attention. Key topics are:

(1) Basic theory of sampled-data control systems, including z-transforms, sampling theorem, closed-loop analysis, etc.[2]
(2) Selection of sampling rate for typical processes.[2, 3]
(3) Design of digital control algorithms.[2, 3, 4]
(4) Smoothing and differentiation of computer-sampled signals.[5]
(5) Applications of the computer to process control; direct vs supervisory control, optimization, data reduction and analysis.[6, 5]

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Optimal control: This subject has been the object of some controversy, based on the thesis that research in the area has advanced well beyond proven applications. Arguments for this thesis have been well-presented. Later in the article, I will state some of the counter-arguments which have led to the decision to emphasize optimal control in our graduate course. Topics are:

(1) State variables for continuous and discrete systems; comparison of state variable approaches with classical input-out approaches.[7, 8]
(2) The minimum principle; optimal controllers for various processes designed by this principle, limitations, discussion of frequently occurring misconceptions on theoretical aspects, applications of results to practical situations, numerical methods.[9, 10, 11, 12, 13]
(3) Dynamic programming; same subjects as discussed for minimum principle, with comparison of the two approaches.[14]

Stability theory: Here again, considerable disagreement exists regarding the applicability of existing research results on stability to process control situations. However, there is no argument with the assertion that stability has been the central theme for development of most classical control techniques whose applicability is now unchallenged. It is likely that a majority of process control loops are tuned on the basis of degree of approach to instability. This is true despite the fact that instrument engineers do not in general make daily use of the classical theoretical stability concepts, such as the Routh-Hurwitz or Nyquist criteria. However, it is only through an understanding of these theoretical concepts that we can assert with confidence that control loops tuned in this manner will generally be reasonably close to "optimal" performance. Furthermore, understanding the theory guides us in the exceptional cases when these loop-tuning methods fail (e.g., the process does not exhibit sufficient phase lag) and avoids loss of confidence in the methods. These considerations are much more difficult to present concretely for more recent theoretical stability concepts, such as Lyapunov methods, but this is because we cannot yet use hindsight. An important contribution of our academic courses, in my opinion, is to emphasize similarly practical offshoots from modern stability theory. Thus, just as loop-tuning is an offshoot from the Nyquist criterion, highly sophisticated yet very practical on-off controllers can be designed on the basis of an offshoot of Lyapunov's methods. Topics are:

(1) Definitions of various types of stability.[6, 7]
(2) Stability methods for linear vs nonlinear systems.[6, 7]
(3) Lyapunov's methods.[6, 7, 10]
(4) Relations between Lyapunov's methods and the design and tuning of control loops.[7, 1]

These three topics — digital control, optimal control, and stability—are the central themes of CHE 656. Clearly, these topics overlap; for example, optimal control of discrete systems will most likely be realized by a digital computer. However, the three topics do give the appearance of separate theoretical branches to the student, and we have chosen to treat them in this manner while mentioning interrelations at the appropriate points.

It is also evident that several important topics have been omitted from CHE 656, such as statistically designed control systems, and adaptive control. The time available in a one-semester course, which meets for a total of 45 lecture hours, is barely sufficient to give adequate treatment to the three selected topics. This selection is based purely on my own judgment of relative importance to the student's education. Undoubtedly, strong arguments can be made for alternative judgments.

DUPLICATION WITH OTHER COURSES

This potential difficulty has been less important than was anticipated when we first planned a graduate-level control course. CHE 656 actually has helped us take more advantage of systems engineering and automatic control courses offered in other departments. The preliminary study of automatic control in CHE 656, with a view toward process application, better

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prepares students to absorb the somewhat more mathematical and abstract treatment in courses taught in other departments, which delve more deeply into the subject matter.

More difficult is the problem of duplication with chemical engineering graduate courses on optimization, particularly on the subjects of dynamic programming and the minimum principle. We have not yet taught a graduate course in optimization at Purdue, so have not really faced the problem. However, it is not difficult to anticipate that where both are taught, close commmunication between these two courses is important.

OTHER CONSIDERATIONS

We have decided not to direct CHE 656 primarily to those students doing research in process control, but rather have attempted to teach a course that can appeal to all graduate students. I am convinced that the subject of process operation is important to all chemical engineers and further that the mathematical facility gained from its study is useful to Ph.D. students specializing in all aspects of chemical engineering.

The undergraduate preparation of students from different schools, in process control and related aspects of mathematics, varies drastically. This problem, which seems to affect graduate level process control courses at least as much as any other graduate courses, is one I have only learned to live with. Some relief can be obtained by using time-domain approaches over frequency-domain approaches whenever possible. Frequent examples of small dimension (i.e., 2 x 2) can (very gradually) infuse the student, having virtually no background in algebra, with some confidence in interpreting vector-matrix equations. Other similar measures can be devised.

Some students have little, if any, undergraduate laboratory experience in process control. In such cases, we urge that the graduate student audit the laboratory section of our undergraduate control course.

THEORY VS APPLICATION

Several years ago, at a meeting of process control computer users and vendors, I presented a paper pointing out that sampling the output of a process approximately 4 times per time constant is a breakeven point for process control. In other words, once the sampling rate is this fast, closed-loop performance cannot be significantly improved simply by increasing the sampling rate. This fact has been well-established in theory and in most automatic control applications, with the exception of process control. Instead of this, process control computer users and vendors were attempting to establish industry-wide standards calling for sampling frequencies at once per second for flow loops, once per 5 seconds for pressure loops, and once per 20 seconds for temperature loops, *regardless of process response time.* My remarks elicited considerable discussion, particularly from vendors who already had considerable investment in hardware and software based on the faster sampling rates. Three years later, a former Purdue graduate student telephoned. He was specializing in computer applications for a manufacturing company, one of whose personnel had attended this earlier meeting. Together they had conducted a project to study the use of slower sampling rates. The problem was this: A digitally controlled loop, previously sampled at a frequency of once per 20 seconds, showed a closed-loop oscillation with a period of approximately ½ hour. This indicates a process time constant of the order of 10 minutes. Therefore, according to theory, it should be possible to reduce the sampling to once every 150 seconds without significant degradation of performance. However, when only every eighth measurement was used to decide on a new control valve position (i.e., when the sampling frequency was lowered to once every 160 seconds), the loop performance was much slower and more oscillatory than before. They very kindly invited me to visit the installation, which I did. The difficulty turned out to be this: Exponential smoothing with a constant value $\alpha = 0.3$ was being used to filter noise in the sampled values of the process output. (In exponential smoothing, the smoothed measurement is taken as α times the current raw measurement plus $(1 - \alpha)$ times the previous smoothed measurement.) This smoothing procedure is very similar to using an ordinary continuous filter and the equivalent R-C time constant can be approximately calculated from the values of α and the sampling rate. In the original loop, the filter time constant thus estimated is 1 minute, very reasonable for the 10

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ing that "you can do your present job so well that you become indispensable and can't be promoted." Therefore, he concludes "you should first train a subordinate to do your present job so that you will have someone to take over when the right opportunity presents itself to you." Another expert writing in the Harvard Business Review says "It should be made very clear to the bosses that they will be rated on their success in developing successors." There is no doubt that learning to delegate is an important asset, and that training the men under you can greatly ease your own load and enable the group to get more done. Nevertheless, in some cases, this puts the cart before the horse. In order to win a promotion, you have to demonstrate to your superiors that you can handle a more responsible job. Whether or not you get promoted may be totally unrelated to whether or not you have trained a successor. Your superior may already have someone else in mind as your replacement. In any event, I would suggest that you consider the advice given me many years ago by the vice president for research and development of one of our competitors — "Learn your job well; learn all the aspects of your boss's job; then and *only* then train your successor."

WHAT DOES THIS all add up to? In summary I would say that you don't have to decide now whether or not you should work toward a management position; furthermore, there is much satisfaction to be gained from a predominantly technical career. But if you are sure you are interested in management, and want to work in a large company, it may still be best to take an advanced technical degree rather than one in business administration. Once in industry, or even in government or education, and you decide to head for management, a chemical engineer should recognize that he will be entering an entirely new area loaded with intangibles where his training and background in logical thinking can sometimes lead him astray. There are no completely accepted theories of management that can be studied and learned like a course in distillation or heat transfer. But don't get me wrong. I certainly believe it is wise to learn all you can about good management practices and to apply them in your job wherever possible. At the same time, however, observe carefully how your organization operates, see how these practices are being applied, and above all, make your own evaluations. Remember, that dealing with people is not always subject to logical analysis; even in engineering decisions the "people" or "political" aspects may prove to be more important than the technical phases. Nevertheless as I mentioned earlier, getting the job done is the most important thing. There are many successful managers who don't follow all the rules, but have the boldness, initiative, and drive to get results.

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minute process (see reference 1, page 456). When the slower sampling rate was introduced, the value of α was left unchanged; apparently $\alpha = 0.3$ was a blanket recommendation of the computer vendor. But, with the new sampling rate and this value of smoothing constant, the equivalent filter time constant became 8 minutes, much too large for the 10 minute process. In effect, an additional process lag had been unintentionally introduced into the loop, inevitably degrading the performance, and apparently discrediting the use of slower sampling rates. When the value of α was changed to 0.9 to maintain approximately a 1 minute filter time constant, closed loop performance became practically equivalent to that in the original loop with faster sampling, as expected.

Upon reflection, I concluded that I had previously been far too defensive in my attitudes toward teaching graduate-level process control. Very practical technological contributions should result from such teaching. Care must be taken to ensure reasonably complete treatment of theoretical as well as practical ramifications since one could not always predict the sorts of difficulties to be encountered in application. Thus, at a minimum, digital filter theory must be included in a course which discusses sampling frequencies. More importantly, it became clear that recent advances in control theory would not be widely applied to processes until there were more practicing engineers adequately trained in the theory. Some of the theoretical misunderstandings and evasive recommendations which currently exist are illustrated by the discussion on sampling rates in a recent industrial textbook.[15] Typical is the following: "For best results with easy processes, the sampling interval should be as short as practicable."

The subject of sampling rates is clearly not the only potentially practical contribution of control theory. Many more examples exist; I will illustrate two. Optimal control theory suggests that significant improvement in control of stagewise processes such as distillation columns can result by recognition of the state concept. Conventional control is based on measurement of the process condition on one plate only i.e., only on the process *output*. The theory shows that the control must be based on the *state* of the process, i.e., on consideration of the condition on each plate. Although measurement of every plate is impractical, measurements on a few plates combined with a process model and any knowledge of past inputs can be used to estimate the state. This estimate based on state will lead to a more rational control of the column. since knowledge of current output is not sufficient to estimate future process behavior. A second example is the observation that optimal controllers never have reset action (unless the performance criterion is artificially altered to force inclusion of reset action). This is often cited as a defect of optimal control theory. Rather, I view this as information from the theory which suggests a logical course for practice. Optimal theory does not yield reset action because it assumes perfect knowledge of the process model and inputs. Therefore, reset action is useful only to correct for imperfect knowledge. This means that only the *unexpected* portion of the response should be integrated in the reset action.

AT THE BEGINNING of the article I estimated that more than two hundred practicing engineers have had graduate level training in process control. Current discussions, both written and oral, indicate that a general impression persists that advanced control concepts are not worthwhile in industry. Therefore, either two hundred is an insufficient number to change this, or advanced control concepts are inherently impractical, or the education of the "two hundred" has not prepared them for this particular "selling" task. I am inclined to accept the last reason. I am concerned because (1) I believe there is as much of potential practical value in graduate courses on process control as in any other area of chemical engineering, and (2) more than in any other area, an impression exists that such courses are primarily useful for generating more academic research.

To meet this concern, I have limited coverage to the three broad topics discussed above — digital control, optimal control, and stability. I would feel completely successful if each student (1) understood all the theoretical foundations, (2) could read the literature, (3) were stimulated to think of applications of the theory, and (4) were sufficiently confident of the practical value of the theoretical concepts to persevere in the face of apparent contradiction between theory and practice. To the extent that all these cannot be accomplished in one semester, I give priority in the order (4),(3),(2),(1). I attempt to cover in depth only those theoretical aspects which have the highest probability, in my estimation, of helping to achieve item (4). Thus, for example, I cover in some depth sampling theory, and digital filtering theory, while presenting only a heuristic justification of the minimum principle.

I hope that in the next few years, advanced topics in automatic control will win acceptance in industrial applications by virtue of recognizable economic contributions. I am convinced that graduate level education will contribute to this goal.

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