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A Course in Experimentation

What should be the primary function of a laboratory course? Because of the high cost of laboratory instruction in space, equipment, personnel, and maintenance, the teacher has an obvious responsibility to define the objectives of a laboratory course clearly and to use his resources efficiently. It is undesirable to assign to the laboratory functions which can be performed equally well or better at lower cost by classroom or audio-visual teaching. In spite of their common acceptance, such features as report writing and data analysis[1] or familiarization with physical principles[2] should thus be eliminated as primary functions of laboratory courses. The teacher has a number of other possibilities: one of these is teaching the process of experimentation. This is the primary function that we have assigned to our course, Chemical Engineering Laboratory.

Like problem solving or playing golf, experimentation is a process to be performed; it is not a body of knowledge like thermodynamics or social psychology. There are bodies of knowledge associated with processes, but the processes themselves are essentially know-how. The person who learns golf learns not just the rules and terminology, but also how to play. Similarly, learning experimentation means learning to carry out the process.

There are several reasons for teaching experimentation to engineering students. First of all, it is not difficult to find gaps in bodies of scientific knowledge and engineering practice. Experimentation is one of the processes an engineer or scientist uses to fill such gaps. For example, if we want to know the viscosity of 2,4-xylenol at 80°C or the suitability of a certain type of agitator in a polymerization reactor, the question can be answered more quickly and reliably by experimenting than by calculating or referring to authorities. Second, know-how is more durable than knowledge. For example, the process of driving an automobile today is much the same as it was in 1935, but knowledge of maintenance procedures for 1935 automobiles is largely obsolete because many of the details of construction of today's autos are different. The slower obsolescence of the learning of a process like experimentation allows a graduate to extend the useful life of his university degree program through media that only update his knowledge. Finally, process learning is transferrable to a considerable extent from one body of knowledge to another. There are similar patterns of experimentation, for example, in growing agricultural field crops and in rubber compounding, although the bodies of knowledge are distinctly different. Thus, the learning of a process like experimentation could help a graduate to be more versatile.

experimentation

It is frequently stated or assumed that experimentation is "an art that must be learned but cannot be taught."[3] This statement is clearly incompatible with our conception of teaching as facilitating learning: it must be possible to teach something that can be learned. On the other hand, the teaching process may be difficult to design and execute. In this section we examine the characteristics of the process of experimentation to identify essential features relating to the design of a course in experimentation.

The question of what we mean by experimentation is critical, because a large part of the difficulty of teaching any process results from lack of an operational description of what is to be learned. *We see experimentation as the process of performing projects that include at least one experiment, preparation and planning for it, and interpreting and reporting it.* Commonly, a project includes a sequence of several related experiments with interspersed periods of preparation, planning and interpretation. This definition emphasizes that preparation, planning, interpretation, and reporting are as much a part of the project as the experiments themselves, and that the term "experimentation" applies to activities that are extended in time rather than momentary, isolated events.

We may take Bunge's definition of an experiment that is part of an experimental project as a kind of "experience in which some change is deliberately provoked, and its outcome observed, recorded and interpreted with a cognitive aim."[4] This definition implies that an experiment is planned experience. However, its outcome is not completely predictable, because an experiment is expected to produce something novel: information, tangible material, methods, or hypotheses. If the outcome of a laboratory exercise is completely predictable, we prefer to call this a *demonstration* rather than an experiment.

The nature of experiments forces the experimenter to face squarely the problem of planning for uncertain outcomes and limited resources. His project is a one-of-a-kind activity and is usually not repeatable. Therefore a probabilistic or actuarial view of uncertainty is usually not very helpful to the individual experimenter. Even so, his plan should ideally provide both the possibility of attaining an objective of high value, and a high probability of attaining at least one less valuable objective that is worth the expenditure of his resources.

No matter whether the fruits of an experiment are expected to be information, materials, methods, or hypotheses, the interpretation of the outcome can only be made in a context of accepted facts, accepted theories, and practical experience. The experimenter wants to arrange his experiment so that the interpretation of it will be as unambiguous as possible. However, in almost every case he will have some ambiguity owing to random errors and alternate hypotheses that are consistent with his results. The utility to the experimenter of the outcome of an experiment combines the value of the outcome, as he has interpreted it, and the confidence that he has in the interpretation.

a course in experimentation

The above comments are intended to indicate how we visualize the process we wish to teach. We may now outline what we see as the key features of a course of instruction in experimentation. We have analyzed the course into four elements: the context, the process content, the knowledge content, and the format. Each element makes its own contribution to a paradigm for teaching experimentation.

The context of the course is a body of knowledge that can include topics like distillation, optics, and animal psychology.

The context is indispensable, but its nature is not crucial. In order to be a suitable vehicle for teaching experimentation, the context should contain some theory and laboratory procedures, and should allow the setting of problems with some uncertainty in the outcome.

The teaching of experimentation should follow the paradigm developed for teaching other processes like automobile driving and violin playing. For a part of the process, the teacher

1) gives the student a set of relevant facts, concepts, and rules;
2) describes an ideal performance; and
3) models the performance for the student.

Then the student tries to imitate the teacher while the teacher observes. The teacher analyzes the student's trials in terms of deviations from the ideal performance described earlier, and prescribes remedies. Between teaching sessions of this sort, the student practices the parts of the process that have been taught. The teacher intermittently adds parts of the process to the student's repertoire until the student is able to practice the entire process.

This paradigm calls for process content in terms of student exercises. The final evaluation of a student of golf is not a pencil-and-paper test score but a handicap which expresses the student's performance relative to the performance of a first class player. Similarly, a student learning the process of experimentation must do experimental projects and be evaluated on his performance of them. The paradigm calls for an operational description of the performance of the process, because the teacher must be able to communicate deviations from an ideal performance verbally as well as by modelling. In addition, it calls for a set of facts, concepts, rules, and standard procedures that comprise the body of knowledge associated with the process. As examples of elements of bodies of knowledge associated with processes, take the minimum stopping distance of an auto at a given speed (fact associated with driving), "event" (concept in network planning), scoring procedure for a lost ball (rule in golf), and the method of tuning (standard procedure in violin playing). The verbal learning of this auxiliary body of knowledge does not constitute performing a part of the process, but it helps the student to think about what he is doing and it facilitates communication between teacher and student.

Finally, the format of the course consists of the type, frequency, amount, and sequence of interactions between the student and the teacher, other students, written material, and laboratory apparatus. The format should make explicit provision for description, modelling, imitation, feedback, and practice, so that it makes the paradigm described above as easy to follow as possible. The format should provide fast feedback to both students and teachers and flexibility in planning. It should allow the detection and correction of deficiencies in the performance of the students and in the laboratory program while the course is in progress.

This rather idealistic outline of the principles underlying a course in experimentation should prepare the reader for a description of our practice in the following section.

an evolutionary laboratory

Our two-term course is preceded by various science laboratories and a departmental course, Instrumental Measurements Laboratory. It is followed by either an experimental research project or a design project. While the main function of the course is to teach experimentation, including project planning, a secondary function is to teach groupwork skills. These functions are a reflection of the fact that much engineering work, both experimental and non-experimental, is done by teams of engineers and is organized in terms of projects. Laboratory courses with some similarities in functions or format have been described in references (5) to (17), but none of these courses contains all the features of that discussed. The following description of the course includes a sketch of our "evolutionary laboratory" format. Additional details have been presented elsewhere.[18]

The personnel of the course are divided into three groups: students, experiment controllers (EC's), and a general staff consisting of a manager, a technician and one or two assistants. The students are organized in groups of four or five. The teaching is divided between the laboratory manager, the laboratory technician and the EC's as described in the following paragraphs. The interpretation of experimental data is taught by a mathematics teacher in a concurrent statistics course.

The student work is distributed among the various activities of the course as follows:

Term 1
- a) Four weeks of lectures and exercises on groupwork, planning under certainty and uncertainty, and problem composition.
- b) Three three-week lab exercises that include written plans.

Term 2
- a) A three-week planning period for a term project.
- b) Four two-week periods in which each student group executes a part of each of four projects planned by other groups.
- c) A two-week period of interpreting and reporting the results of the projects.

At the beginning of the first term, the laboratory manager gives a description of the process of experimentation, teaches the bodies of knowledge on planning and problem composition, teaches the corresponding parts of the process by means of exercises, teaches the body of knowledge on groupwork, and monitors the group process by means of records written by the students. The description of experimentation consists of a list of fifty-two instructional objectives* The main subdivisions of this list are:

1. Preparation
2. Problem composition
3. Preplanning
4. Evaluation of problems
5. Problem selection
6. Planning the solution
7. Execution
8. Interpretation
9. Evaluating the experiment
10. Reporting

Concepts, rules and procedures for planning are taught in part by a programmed book[19] and in part by lectures and notes on planning under uncertainty. The process aspect is taught through two problems. In the first of these, each student makes a plan for a simulated lab exercise; in the second, each student group makes a plan for solving a lab problem that they have composed. The groupwork teaching is based on notes[20] drawn from books on sociology, social psychology, and organization. The process learning occurs in multiple role-playing exercises involving four person groups. Each of the four roles has an outstanding weakness and an outstanding strength. The students playing the roles must decide how to divide the work, choose their level of aspiration (mark), agree

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*Copies of this description may be obtained from the first author.

on their expectations regarding their time and effort alloted to the course, and choose their policies regarding learning, leadership and group or individual marks.

After this preparatory instruction, the students commence work with the laboratory equipment. Each unit of apparatus is under the direction of an experiment controller. Each EC teaches a body of knowledge associated with a topic of the context, and the process of experimentation as applied to his unit. In the first term exercises, the EC gives references and notes on the theory associated with the problems and the principles of operation of the apparatus. He suggests problems with different levels of difficulty, and guides the students in selecting an original problem if they prefer to do this. He shows the unit of apparatus to the students and discusses possible difficulties in the execution of planned exercises. The EC evaluates the preparation of the student groups, their written plans, their work while in the lab, and their reports on the basis of the instructional objectives. He gives remedial instruction at a conference session which is normally held a week after the students have completed their exercise, and shortly following submission of a brief report containing their salient results.

In the second term, each group of students is required to plan a project to include the work of four other groups on a unit of apparatus, and to present a complete report and seminar at the end of the term. During the middle period of the term, they execute part of the plan of four other groups in turn. Thus each group is a "planning group" for one unit of apparatus and an "executing group" for others, so that every student has an opportunity to teach and be taught by his peers. A "planning group" has a substantial stake in the outcome of the exercise of an "executing group," so that members of a planning group will often spend some time coaching and criticizing members of executing groups. During this term, the EC instructs the planning group on the context of their project. He advises them on the selection of technical objectives and evaluates their plan, the "technical manual" for their project, and their final reports. He evaluates the work of the executing groups and gives them remedial instruction, as in the first term.

In both terms, the conference periods and student reports are used for teaching. A student group that is scheduled to work on a given unit of apparatus is invited to the conference of the preceding group and is given their report to read. This procedure follows from our evolutionary laboratory format.[21] It helps a group to avoid repeating the mistakes of previous groups, and allows the use of exercises that are somewhat more difficult than would otherwise be feasible.

The laboratory technician describes and models laboratory techniques as needed by student groups during their laboratory periods. He also helps them find and correct operating difficulties, and answers their questions on matters of laboratory technique and procedure.

Exposition of the purpose and practice of a course of instruction naturally leads to the question of what results it produces. This is considered in the next section.

evaluation of the course

We have collected several kinds of data: statements of the laboratory staff based on the written and oral reports that they have received and on their observations of the students at work, the written process records of the student groups, and the students' responses to anonymous questionnaires. Some progress has been made toward an evaluation on the basis of the set of instructional objectives that are used to describe the process of experimentation, in that EC's have used the objectives in judging student work. Nevertheless, all the evaluations are relative in that the respondent is making comparisons with other laboratory courses in his experience. The students have previously taken an average of seven terms of laboratory courses, so their bases for comparison should be adequate.

We asked the students which of the first term exercises they perceived as experiments, where "An experiment is defined as a set of controlled operations whose outcome is not completely predictable by the people who plan and execute it." Of the three exercises, one was seen as an experiment by 71 percent of the respondents and the other two were seen as experiments by 54 percent.

The intragroup process (in the sense of social psychology) is a matter of some interest because the students received instruction on it. Fourteen of seventeen respondents perceived their intragroup communication patterns as "all-channel" while two perceived a "wheel" pattern and one perceived a "chain" pattern. Table 1 presents data on how evenly the work was distributed within each group. Casual observations of lab groups at work, and the students' own process records are in

Table 1

Distribution of Work Load Within Groups (from student responses for 1972-73)

The ratio R, of the time spent by the group member spending the most time on the course to that of the member spending the least, was distributed as follows:

	Number of Responses	
	1st Term	2nd Term
$1.0 \leq R \leq 1.2$	10	5
$1.2 < R \leq 1.5$	4	4
$1.5 < R \leq 2.0$	4	4
$2.0 < R$	5	3
	23	16

agreement with the reported results. None of the six groups had permanent designated leaders. Three groups attempted to use a formal leader at the hub of a "wheel" communication net in order to increase the efficiency of their use of man-hours, but all three efforts were abandoned. Two groups defined formal, specialist roles for their members for some lab exercises and others did this less formally. Two influential members of one of the six groups rejected the teaching on groupwork; the work of this group was not well-coordinated. Among the other five groups, only one person was an obvious "slacker." Except as noted above, the lab staff was very favorably impressed with the performance and member satisfaction of the groups in this class.

The student responses to questions about planning are given in Table 2. These data indicate that most of the students made substantial contributions to the planning efforts of their groups. A closer look at the responses shows that every respondent reported that he made some contribution to the planning efforts. The data indicate how much use the students made of their plans in both the first and second terms. Substantial use was made of planning concepts and terminology in the execution of projects in the second term even though no written plans were required by the EC's for these exercises. An author who was an EC reported that, "The planning of the . . . group (compared to the planning of a group in the previous year) was more polished and they were prepared for all contingencies that arose. Their final task of analysis and reporting took relatively little time due to their foresight during the term." Another EC reported that, "The reaction of the groups to project planning is one of the most interesting aspects of this course. The majority of them responded well, some of them with enthusiasm, and most were shown to to be entirely competent. Speaking of my own (planning) group, . . . I feel that they learned an enormous amount from the exercise. . . ." The two students who rejected the teaching of groupwork also rejected the teaching of planning. Their group made written plans as required, but did not attempt to follow them. The EC's perceived the plans of this group as being less satisfactory than those of the others, and rated them below the others on both process learning and achievement. These results would not have been predictable from the academic records of the individual members of this group. With this exception, the instructional objectives on planning

Table 2

Student Responses on Effectiveness of Instruction in Planning

The students were asked to evaluate the effectiveness of the instruction in planning, by answering the following questions on a four-point scale from 0 (= "none" or "not at all") to 3 (= "a great deal"). The results given here and in subsequent tables are averages of 23 responses in the first term and 17 in the second.

Question	Average Evaluation
First Term	
Did you contribute to the planning of your group's lab exercises?	2.2
How much improvement did your group make in planning from the first to the third lab exercise?	2.0
To what extent did your group actually use its plans in carrying out the lab exercises?	2.0
To what extent did your group's plans help it to cope with contingencies?	1.5
Second Term	
Did the practice of planning the exercises in the first term help your group plan the project in the second term?	2.3
To what extent did the members of your group use the planning concepts and terminology that you learned in executing the 4 projects of other lab groups?	1.7
To what extent did the executing groups attain the objective of your project?	2.1
To what extent do you now see the 2nd term project as a useful thing to do?	2.4
How much did you contribute to planning your group's project?	2.4

were achieved by every student group and, because of the participation in planning, by almost every student.

One of the hypotheses proposed regarding our course was that an emphasis on teaching experimentation would necessarily result in reduced learning of the context. This is certainly true, in a sense, because we have reduced the number of context topics from fifteen to eight over a period of five years. However, let us look at the students' perception of their context learning compared to previous laboratory experience, as reported in Table 3. Clearly the course is teaching the smaller number of context topics considerably better than lab courses previously experienced by these students. Unfortunately, we are not able to make a direct comparison with a traditional course in which a smaller number of topics was used. The format of the second term put each student group in the position of being specialists on one project. In many cases they were teaching their peers on the topic of that project. We propose as an hypothesis that this use of students as teachers was one of the reasons for the greater learning of context.

Table 3

Student Perception of Content Learning

The students were asked to compare their learning of facts, concepts, and relations in this course to other laboratory courses. Each aspect was rated on a five-point scale from —2 (= "much less") to + 2 (= "much more"). A positive number indicates a favorable comparison.

First Term	
Drag coefficient experiment	1.0
Heat transfer experiment	1.0
Fluidized bed experiment	1.1
Second Term	
Project with planning responsibility	1.6
Executing experiments:	
Continuous still	1.0
Diffusion cell	0.7
Mixing tank	0.6
Polymer melt viscometer	0.2
Chemical reactor	0.3
Construction project	1.1

An overall self-evaluation of the effect of the course on the students is given in Table 4. For comparison, results are also shown for two earlier years during which the course was under development. In 1971-72, the second term project replaced a set of lab exercises similar to those of the first term. In

1972-73 an explicit description of the process of experimentation and teaching of groupwork and planning were added. We conclude that our instructional objectives and teaching have indeed facilitated learning. A peer evaluation covering the same ground as Table 4 is shown in Table 5. (Note that the scales are different in these two tables). This indicates a widespread satisfaction of students with the performance of their peers. Combining the results of Tables 4 and 5, we can say that the class feels that its members made great improvements in their abilities, but that they feel that there is room for even further improvements.

Table 4
Student Self-Evaluation

The students were asked: "To what extent do you feel that your abilities have improved as a result of this course with regard to the items shown below?"

Each item was assessed on a four-point scale from 0 (= "no improvement") to 3 (= "enormous improvement"). Average responses for two previous years and for both terms of 1972-73 were as follows:

	1969-70	1971-72	1972-73	
			1st term	2nd term
Ability to carry out exercises: operating apparatus effectively, observing the phenomena in the experiment, and measuring the appropriate data.	1.2	1.5	1.6	1.9
Ability to describe exercises (operating procedure, apparatus, observed phenomena, details of measurement) to another person.	1.3	Not asked	1.6	2.1
Ability to analyze and interpret data and observations. This means the ability to ex-explain the phenomena and observations in terms of theories and terminology that are accepted by the engineering and scientific community.	1.3	1.5	1.9	1.7
Knowledge of facts, methods, and terminology (only new knowledge attributable to lab course).	1.1	1.4	2.0	2.1
Ability to plan lab exercises.	0.6	1.2	2.7	2.4
Ability to work effectively in a group of people to accomplish common goals.	0.9	1.5	2.0	1.9

Table 5

Peer Evaluation (1972-73 only)

The students were asked to answer each question on a five-point scale from — 2 (= "very dissatisfied") to + 2 (= "very satisfied"). A positive number indicates satisfaction.

For the 2nd Term only, to what extent have you been satisfied with the contributions of other members of your group in	
1) obtaining background information on your project	1.3
2) lab work on your project	1.2
3) planning your project	1.2
4) managing your project	1.1
5) obtaining background information on other projects	1.0
6) planning for the execution of other projects	0.9
7) work in the lab on other projects	1.1
8) data reduction	1.3
9) interpreting results on other projects	1.1
10) reporting on execution of other projects	1.1

Our course produced several shortfalls in addition to its successes. First of all, we have not made as much use of modelling as indicated by our paradigm on teaching processes. This is a methodological shortfall which may be unavoidable in practice. Second, the students are not attaining the objectives we have set in interpretation of results. They either do not appear to see the need to apply methods from their statistics course, or they apply those methods poorly. There is also a body of knowledge associated with interpretation, including inductive inference, for example, which is distinct from statistics and is rarely taught formally. The addition of some formal teaching in this area will be one of the next steps in the development of the course. Finally, the EC's have found the policy of holding the length of the written reports to a bare minimum and giving most of the interpretation and discussion orally to be unsatisfactory. Apparently, the students do not think through such matters as error analysis unless they are required to write them down. However, this problem is probably linked to the shortfall in interpretation mentioned above.

The novelty of our course does not lie in our desire to teach the process of experimentation; other teachers have the same desire. The novelty lies in the description of what is to be learned, the explicit recognition of the difference between learning knowledge and learning a process, the explicit teaching of the various parts of the process and their associated bodies of knowledge, and the development of a course format that makes these other innovations possible.

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