Integration of Critical Thinking and Technical Communication into Undergraduate Laboratory Courses

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The ability to communicate technical concepts well distinguishes an outstanding engineer from a merely competent one. Widespread consensus holds that writing should form an integral part of an engineering education, but there is considerable debate over how best to achieve this goal. Most engineering programs require courses in technical writing and oral presentations through their English departments. While these courses can provide useful instruction, they inevitably suffer from certain drawbacks. First, these courses teach students one, optimal approach to technical writing and speaking, overlooking the significant differences that exist in the ways that engineers in various domains communicate technical information. Second, the courses seldom provide students with adequate, targeted training (or exercises). Third, the courses do not address critical thinking concepts or apply critical thinking to discipline-specific issues and/or examples.

The concept of critical thinking is sorely lacking in the contemporary education of technical communication. The technical communication courses provide instructions driven by format. Also, the feedback and evaluation pr.ocedures focus on text mechanics. This approach is inadequate because writing is kept separate from thinking. The popular approach assumes that (i) writing skills are static, (ii) students have mastered their subject matter, and (iii) students have solved the "audience puzzle."

This paper argues for the unique benefits of maintaining an in-house writing program for undergraduate - and graduate - level engineering students. It holds that only an in-house program can integrate technical content with writing and critical thinking to teach students. This paper focuses specifically on our efforts to incorporate these features into our undergraduate laboratory courses. The benefits of such an approach are several-fold: (i) conceptual environment is stable, (ii) reports address pertinent and challenging problems, and (iii) the approach emphasizes critical thinking, training students to focus on the core questions that drive scientific method.

The School of Chemical Engineering at Georgia Tech

Originally established as a state engineering school in 1885, Georgia Tech has been regarded as one of the best technological universities in the nation. The School of Chemical Engineering at Georgia Tech was established in 1901, making it one of the first such programs in the country.

The School has undergone great change during the last decade: more than 50% of its current faculty have been added, the graduate program has grown significantly, and the undergraduate enrollment is approximately 900. These statistics place the School in the ranks of the largest chemical engineering programs in the country and give it the ability to provide both diversity and excellence in its academic and research programs.

Georgia Tech offers its courses on a quarter-based system, which involves ten weeks of classes followed by one week of examinations. In a calendar year, there are four equal-size quarters: Fall, Winter, Spring, and Summer; the first three quarters constitute an academic year. This quarter-based system has been very convenient for the students participating in our co-operative educational plan (almost 35% of our students participate in this plan.) However, it necessitates that every required undergraduate level course in chemical engineering be offered at least twice a year. Many are offered more than twice, whereas the laboratory courses are offered every quarter.

The undergraduate curriculum in Chemical Engineering has three categories of laboratory courses. The first consists of two courses, ChE 3302 and 3303, addressing transport phenomena; the second also consists of the two courses, ChE 3309 and 3310, broadly covering unit operations, but also including chemical reaction analysis and catalysis and new technologies such as those associated with microelectronics and biochemical engineering; and the third, ChE 4418, which introduces modern control techniques and instrumentation. Although the two transport phenomena laboratories (ChE 3302, 3303) are offered as separate courses, we will describe these as a unit. The students working in groups of three or four generally take those courses during the third year of their course work. The principles of momentum and heat transfer are illustrated in eight experiments which are divided evenly between the two courses. The prerequisites for these courses are Fluid Mechanics (ChE 2310) and Heat Transfer (ChE 3311.)

The two unit operations laboratories (ChE 3309 and 3310) are offered as separate courses and are taken generally during the fourth (and final) year of the undergraduate studies. The prerequisites for these laboratory courses are Stagewise Operations (ChE 3313) and Mass Transfer (ChE 3312.) Applications of heat- and mass-transfer and reaction kinetics are illustrated by the eight experiments in these two laboratories.

These four laboratory courses (one credit hour each) are offered during each quarter. This frequent offering is mainly attributed to the number of students that can be reasonably accommodated in the given quarter without compromising the quality of laboratory instruction. For the past several years, the enrollment in these combined four courses has averaged about 160 students per quarter during the academic year and about 100 students per quarter during the Summer Quarter.

Laboratory Courses Structure

The need to accommodate such large numbers requires some creativity in the scheduling of lecture periods as well as the laboratory periods. Each of the four laboratory courses (ChE 3302, 3303, 3309, and 3310) has four sections: A, B, C, and D. These sections have a common lecture period but different periods for the laboratory. For example, if there are 56 students in ChE 3302 divided in sections (A: 15, B: 16, C: 10, D: 15), they all would attend a one hour lecture on Monday. Only Section A (15 students) will do the laboratory experiments on Monday, whereas Section B (16 students) will attend the Tuesday laboratory session. Likewise, Section C has Wednesday as its laboratory day and Section D has Thursday as its laboratory day. Concurrently, the course ChE 3303 has a lecture period on Tuesday, but again its four sections have laboratory sessions scheduled between Monday and Thursday. Since we have an upper limit of four students per group, the approach outlined above allows us, theoretically, to have as many as 256 students enrolled in the laboratory courses every quarter.

Table I shows a time-table for the laboratory courses during the quarter. The first week of lecture begins on Monday following the start of the normal classes (generally Wednesday.) During the first two weeks of lectures, (i) the students become familiar with the four experiments, (ii) they form groups of (no more than) four students, and (iii) they are given a list of the graduate teaching assistants (GTA's) with whom they will participate in the pre-laboratory meetings.

Table I. Laboratory Courses Timetable

Week No.	Lecture No.	Lab No.	Lab Report Due	Oral Exam.	Written Exam.
1					
2	1				
3	2				
4	3	1			
5	4	2			
6	5	3	1		
7		4	2	1	
8			3	2	
9			4	3	Yes
10				4	

Each of the 16 GTA's is designated for a specific experiment. It should be pointed out here that the lectures of the experiments are given by the chemical engineering faculty (each of the 16 experiments have 20 minute lectures from different faculty.) The laboratory begins after the first two weeks of lectures since the students have now been familiarized with all the four experiments. Once an experiment has been conducted, the group has 14 days to submit a formal report. This report is graded for its technical content by the ChE faculty, and for its writing

effectiveness by the Writing Program Specialist (more about it later) who works full-time within the School of Chemical Engineering. Only one report per group is required for a given experiment. Those taking the first laboratory course, ChE 3302, are required to meet as a group with the Writing Program Specialist. This meeting comes several days ahead of the deadline of the formal report. A rough draft of the report is presented by the students to the Writing Program Specialist who then would provide them feedback for revisions/corrections.

When a laboratory report is submitted, the students receive feedback in the form of a detailed grading sheet one week later. The feedback has information pertaining to both technical content as well as writing effectiveness. One of the group members would make a formal oral presentation on the report after it has been submitted. The oral presentations are graded by the ChE faculty and are video-taped; the video tape is returned to the student for review and to use it to improve oral communication skills. Finally, towards the end of the quarter, there is a closed book examination for each laboratory course. The examination tests the students' learnings of each of the four experiments. The final grades in the course are awarded on the following basis:

Pre-laboratory meetings	(4)	20 points
Written Reports	(4)	40 points
Oral Presentation	(1)	10 points
Written Examination	(1)	30 points
		100 points

From this score, we subtract five points for each absence in the lectures, pre-lab meetings, laboratory, as well as for not having safety glasses on while one is inside the laboratory. Since the penalties are substantial, their major impact is to serve as a deterrent which they do quite effectively. It should also be noted here that the first two items constitute 60% of the grade and are group grades, i. e., each member in a group receives the same grade. The last two items, on the other hand, are individual grades. Thus, the team dynamics within the group plays an important role in the evaluation of students' performance.

The last, but not the least, item about the course structure concerns the resources devoted to our laboratory courses. We have (i) two faculty members organizing the entire set of courses (ii) sixteen faculty giving lectures on the experiments, (iii) about eighteen GTA's handling pre-lab meetings, helping students conduct the laboratory experiments, and video-taping the oral presentation, (iv) three faculty grading all the laboratory reports for the technical content, (v) 31 faculty grading the oral presentations, (vi) one full-time Writing Program Specialist, (vii) one laboratory coordinator (half-time) devoted to maintaining the experiments as well as building the new ones, and (viii) 3-4 other faculty members giving specialized instructions.

What Should We Teach in a Laboratory Course?

Having detailed above the structure of the laboratory courses, it is pertinent to ask the question: what do we expect our students to learn from these courses? The school faculty recognized in its strategic plan six years ago that these laboratory courses should serve to provide a bridge between theory and practice by illustrating the basic principles and the physical models

important to the practice of chemical engineering. We can summarize the following objectives for our laboratory courses:

Our students should be familiar with the:

(i) critical thinking in the planning and execution of experimental work,

(ii) statistical analysis of experimental data as well as critical evaluation of mathematical models
used to correlate data,

(iii) Instrumentation, instrument calibration and sensitivity, and data acquisition, and

(iv) effective communication skills for both technical writing and presentation.

As stated earlier, working effectively as a team member within a group is not only essential for the success, but it also provides the students a unique opportunity to engage in brain-storming/critical thinking within a group setting.

Our review of the instructional laboratories five years ago led us to conclude that we were not utilizing our laboratory courses to teach students those concepts which can best be taught in a laboratory course only. It was also clear that our laboratory courses suffer from the same lack of attention which is painfully evident throughout the engineering programs across the United States. The School administration made a commitment to strengthen the pedagogical approach as well as the learning objectives for our laboratory courses. We embarked on the changes four year ago, and it has been an evolutionary process. Much has been accomplished (while still more remains to be done) and there is a consensus among the faculty that the path traveled so far is not to be revisited.

The structure of the laboratory courses as described earlier, required significant allocation of personnel resources. For example, three faculty members grade all the laboratory reports which in the past had been graded by the GTA's. Furthermore, we have two 1-hour lectures given by faculty on Statistical analyses of experimental data. We also have two 1-hour lectures (in two courses) on oral presentation skills. Then about three years ago, we embarked on a new mission: to incorporate writing training in the curriculum, the School hired a Writing Program Specialist to work with the students on their report writing skills. Again, it has been an evolutionary process. What began as an initiative to help the students write more clearly and effectively has now been expanded to include critical thinking as part of the laboratory course. We have gone from one 1-hour lecture on technical writing to a set of lectures (totaling 6-7 hours of lectures/workshops) in addition to the students working directly with the Writing Program Specialist.

Critical Thinking: What It Is, Why It Matters?

Teaching that emphasizes critical thinking moves Socratically, that is by questions to students, not pre-prepared lectures at students. It abandons a didactic style of instruction for a more interactive, speculative approach to course material. What does that mean? It might mean

> thinking through problems in front of students instead of presenting them with a final analysis.
>
> asking students "what is wrong with this picture?" and letting them discuss flawed assumptions, premises, etc. instead of listing flaws for them.
>
> questioning students about their purpose, evidence, reasons, data, claims, interpretation, and the implications of their analysis.
>
> using and analyzing concepts in problem-solving applications.
>
> requiring regular writing for classes and involving students in critiquing one another's writing.

This pedagogical shift is fundamental, not cosmetic; it affects not only how we interact with students but also the material itself. Yet, however effective this approach can be shown to be, it is also true that engineering faculty are already charged with conveying a substantial amount of technical information. They might reasonably argue that there is not time to cover the volume of the material that they must address using these methods. This is where an in-house Writing Program Specialist plays a pivotal role. He or she will present critical thinking to students as the foundation of effective communication, illustrating how "good writing" and "good science" mutually reinforce one another.

As stated before, critical thinking is driven by questions. It begins during the planning stages of the experiment as the group of students prepare for the pre-laboratory meeting. Some of the questions raised here might include:

> Why are we doing this experiment? What is the issue?
>
> What is expected to happen in this experiment? What leads you to these expectations?

The process continues while the group performs the experiment in the laboratory. Some of the questions raised here might include:

> How do you know if your results are any good? How did you develop such a benchmark?
>
> What can you do to check the accuracy, precision, and consistency of the data? How can you verify the calibration of the instrument?

Are the results being collected consistent with the expected pattern or are there deviations?

Finally, during the analyses and interpretation of their experimental data, the group is expected to brain-storm with the following questions:

How well do the final results compare with theory/model?

How can you account for experimental discrepancies? (Actual results almost never match expectations.)

What would you study next to account for the discrepancies?

What are the possible sources of error? How can we quantify the impact of sources of error?

What new questions does this experiment raise?

Why should people care about this stuff?

If one has engaged in critical thinking at these various stages, the task of preparing the written report becomes easier, as will be briefly discussed below. It should also be pointed out that the core questions to be addressed remain the same in oral and written communications.

What is Good Writing?

A text is considered to be well written if it demonstrates at least two qualities: it must be easy to read and it must demonstrate critical thinking. It is usually not necessary to distinguish between these two qualities in a text, and for most readers it is not possible to do so. Instructors, however, do need to understand the complex relationship between critical thought and textual complexity; and they need to recognize that this relationship is complicated further when student writers try to master an entirely new skill.

Writing skills are dynamic. We know that people write clearly and smoothly when they are discussing subjects that they know well, and when they are writing in a format (or mode) with which they are comfortable. And we know that people write poorly-using poor punctuation and malformed sentences - when they take on subjects that are new to them. This is true even of students who are otherwise fine writers; it is common for students to write fine honors theses during their last undergraduate years, yet be unable to write coherent briefs six months later in their first law school courses.

These students have not forgotten how to write good sentences and paragraphs; confusion in their texts is symptomatic of their imperfect grasp of the issues that their teachers want them to

think and write about. When they resolve their large conceptual problems, these students' text skills always reappear.

The process described above reflects the students' learning curve. Students write well when they have advanced relatively far on the learning curve - when they understand how to do critical thinking. So in order for us to teach good writing we must focus on critical thinking. If we do the reverse - if we criticize the writing more than the thinking - we can actually retard the learning process. If we want the students to learn to write well, we need to focus our comments on the conceptual issues that we want the students to think about.

In summary, the approach outlined here requires a paradigm shift in the way we think about our laboratory course instructions. However, we would serve our students well in the long run if we are willing and able to make those changes.

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