TRANSFORMING UNDERGRADUATE CHEMICAL ENGINEERING LABORATORIES

Dhaneshwarie Kannangara and James Sibley
The University of British Columbia
dhanesh.kannangara@ubc.ca

Over the past 15 years, we have made a series of innovations and systematic improvements to the lab courses offered in the Department of Chemical and Biological Engineering (CHBE) at The University of British Columbia (UBC). Prior to 2003, CHBE teaching laboratories used a more traditional laboratory course model where students performed “cookbook” experiments and individually wrote formal lab reports. Redevelopment began with our second-year course and improvements from the second-year course were progressively added to senior years. The integrated lab sequence now culminates in a capstone problem-based learning laboratory experience. We will present our optimized laboratory sequence model that is currently used in the 2nd, 3rd and 4th year CHBE program at UBC.

Keywords: laboratory, teaching design, communication skills, team-based learning, problem-based learning, workplace skills

1. INTRODUCTION

Laboratories have been a long-standing component of undergraduate engineering programs. A growing number of studies have questioned the effectiveness of the traditional laboratory model where students perform “cookbook” experiments and serially produce reports [1-2].

The Department of Chemical and Biological Engineering (CHBE) at UBC offers a four-year degree program. About 125 students enter the CHBE program in the second-year after completing a common first-year engineering. Students take the following sequence of lab courses: CHBE 262 (Terms 1 & 2), CHBE 362 (Term 1), CHBE 365/366 (Term 2) and CHBE 464 (Terms 1 & 2).

In this paper, we discuss how the CHBE laboratory curriculum at UBC transitioned from a traditional “cookbook” laboratory model to a more skills-development model. The new model focuses on the development of specific skills and competencies that set our students up for success in the workplace. There have

been three aspects to our redesign: 1) development of foundational laboratory skills, 2) enhancement of communication and teamwork skills, and 3) development of workplace skills.

Our initial work focused on the redevelopment of the second-year lab course. As teaching models and resources were built, tested, and improved, these course enhancements have been systematically incorporated into our third and fourth-year laboratory experiences. The application of the same model across the three years has refined the integration of student laboratory experiences. Our integration focuses on building strong foundational laboratory skills early, providing ongoing opportunities to improve communication and teamwork skills, and a shift in later years to ensure the development of strong workplace skills.

In the second-year laboratory course, many scaffolds [3-4] are incorporated in the first-experience learning of each new skill. As students’ competencies grow, these scaffolds are systematically reduced and eventually eliminated to increase students’ autonomy in senior years.

Figure 1: Scaffold fading and increasing student autonomy

Three design priorities guided the laboratory redesign and integration process across the three years:

- I. **Building Foundational Skills:** fundamental laboratory skills including pre-lab preparation, safety procedures, lab techniques, and data management and analysis skills

II. Enhancing Communication and Teamwork

Skills: communication skills (report writing and other genres of writing, oral presentations, poster presentations) and teamwork skills (teaming skills, effective communication skills, giving and receiving feedback)

III. Developing Workplace Skills: learning to use industry-standard software like AutoCAD™ and LabVIEW™, participating in industrial site visits and field data gathering, and becoming increasingly autonomous in design and execution of experimental procedures

2. INITIAL REDEVELOPMENT

Our initial improvements were in the CHBE 262 Chemical Engineering and Applied Chemistry Laboratory course which focuses on experimental demonstrations of important concepts and topics covered in second-year chemical engineering and chemistry lecture courses. Before the redevelopment of the CHBE 262 course, the course assessments were primarily based on eight lengthy individual formal lab reports of traditional “cookbook” experiments.

When we reviewed the course and student outcomes, many issues were identified that needed to be addressed, including poorly prepared students, students struggling with data and statistical analysis, plagiarism issues and rampant report recycling, and few opportunities for students to develop communication (written and oral) and other meta-skills (critical thinking, problem-solving, teamwork, collaborative writing). The challenge became – how do we address these issues in a large course (n=125) while maintaining a reasonable instructor and TA workload?

The initial redevelopment efforts focused on the development of students’ foundational laboratory skills and enhancing students’ communication and teamwork skills. The integrated process now begins in the second year with very structured opportunities to develop foundational laboratory skills, and communication and teamwork skills. In senior years (third and fourth-year), there is increasing student autonomy and a shift to building workplace skills.

Redevelopment efforts in CHBE 262 began in 2004 and integration across third and fourth-year lab courses started in 2006.

The CHBE second and third-year labs are now run with similar course structures using the pre-lab assignment process and Teaching Laboratory Data Management (TLDM) system [5]. The courses share common

documents such as writing guidelines, document specifications, exemplars and sample reports, statistical analysis documents, and templates for lab notebooks, report submission forms, emergency shut-down procedures, etc.

3. OPTIMIZING THE COURSE MODEL

3.1. Foundational Skills Development Pathway

In our first course of the sequence (CHBE 262), we focus on four main aspects of foundational skills development: ensuring adequate pre-laboratory preparation, promoting laboratory safety, development of experimental techniques, and development of data management and analysis skills. The importance of these foundational skills in laboratories are well documented [1,6-7].

Table 1: Foundational Skills Sequence

	2 nd Year	3 rd Year	4 th Year
Pre-lab videos	✓		
Pre-lab assignment	✓	✓	
Draw flow chart as lab start readiness check	✓	✓	
CHBE safety orientation	✓	✓	
Campus safety course	✓		
TLDM system	✓	✓*	
TA supervision	High	Med	Low

* reduced system coaching supports and exemplars

Pre-lab Preparation

Getting students to come to labs prepared has always been challenging. We have tried many strategies to induce adequate pre-lab preparation by second-year students. Currently, we use a 3-stage pre-lab preparation procedure.

Stage 1

We provide pre-lab video clips with embedded questions in our Learning Management System. Students view the video clips of the experimental procedures, lab techniques, and instrument operations for the assigned experiment before attending the lab sessions. The video periodically pauses, and they are prompted to answer questions about the underlying concepts or make predictions about the situations in the video. The students cannot continue the video until they have correctly answered each question.

We received many comments from course TAs at the end of the first semester of using these videos. Generally, they were positive about how students could use the videos but were concerned that some students needed to be held accountable for viewing them. This was our motivation for adding the embedded test questions into videos and connecting the video embedded questions to the course grade book in the Learning Management System. Here are a few typical TA comments about the videos:

“Overall the video for the experiment is good, and the visuals helped students to understand the process clearly.”

“I suspect not all students were going through this video before the experiment. So, we have to enforce the rule strictly to watch the video before the lab.”

Stage 2

Student teams complete a four-page pre-lab planning assignment that includes a concise flowchart of experimental steps, a list of measurements and observations that will be made during the lab, and how the data collected will be used to perform the data analysis. The pre-lab assignment also identifies the high-risk steps and procedures to avoid/minimize the risks, and summaries of the relevant Material Safety Data Sheets (MSDSs).

Stage 3

As a final check, upon arrival at the laboratory, teams are required to draw from memory a flowchart of the experimental procedure on a whiteboard. TAs review these flowcharts before teams can begin their lab.

The Backstory

We originally used pre-lab quizzes in our second-year Learning Management System (WebCT™) in an attempt to increase student readiness for laboratories. The quizzes did improve readiness for some, but not for all students. The lack of engagement may have resulted from low point values assigned to pre-lab quizzes. The students expressed frustration with quizzes since they did not get any feedback and were not allowed to revisit the quizzes later in the semester.

Our next attempt to induce pre-lab preparedness was to incorporate Team-Based Learning's Readiness Assurance Process [8]. Our Readiness Assurance Process consisted of a 10-question multiple choice test with topics drawn from the second-year lab manuals. Upon their arrival at the laboratory, the students first individually took the test. Next, the students joined their teammates to retake the exact same test again. For the team test, we used a special test form known as an IF-AT card (Immediate Feedback Assessment Technique) [9]. The IF-AT cards are “scratch

and win” multiple choice answer cards. This allows student teams to “scratch and see” if they have chosen the correct answer to a given question – this format encourages discussion, consensus building, peer teaching and ensures that every student knows the answer to every question at the end of the team test. The IF-AT card process provides some assurance of student mastery of the preparatory material. While this process proved successful in increasing readiness, it created an unsustainable workload for the lab instructor. Because 12 teams were completing 12 different experiments in any given lab session, there needed to be 12 different versions of the test used in every lab session. Given the complexity and high instructor workload of this process, it was abandoned. This highlights the difficulties in improving student outcomes while working with limited teaching resources. This process was replaced by the current 3-stage pre-lab preparation process.

Safety Training

Prior to the start of the second-year laboratories, all students attend a mandatory CHBE Safety Orientation. Also, all students must successfully complete a university-wide Introduction to Laboratory Safety online course provided by UBC Risk Management. Students are not allowed to enter the lab without completion of both.

We originally used the combination of a safety orientation, a safety manual, and the online safety website to introduce safety procedures to second-year students. Although attendance was compulsory at the safety orientation, we noted that not all second-year students were following the safety protocols once they were in the laboratory. To address this lack of transfer of knowledge [10], we redesigned the CHBE 262 safety orientation to incorporate aspects of Team-Based Learning [11]. Specifically, it included the team task structure from TBL that uses very concrete, real-world situation descriptions and scenarios. These scenarios are written in a way to bring students to a decision point where they are asked to make a very specific choice from a set of possible choices [12]. An example would be helpful here – you could ask – “You have spilled a large amount of acid, what you do?” or “You have spilled a large amount of acid, what would be your FIRST step/response to this situation?” You might recognize that from the first prompt, you would get a long list of responses in no particular priority, but with the second prompt you get very focused responses where the differences in responses would likely spark good discussion – “Why did you want to do that first?”. This specific change has really brought the consequences of safety to life, where students analyze likely scenarios, and imagine and discuss their systematic responses.

Despite both safety training interventions (orientation and online course), students were still arriving at labs

unprepared from a safety perspective. To address this, we introduced a mandatory pre-lab safety assignment that requires them to review relevant MSDSs, identify proper personal protection equipment (PPE), identify high-risk steps, waste disposal methods and know emergency shutdown procedures.

Hands-on Laboratory Skills

Second-year students run labs in teams of four. The small team size helps each student get more hands-on experience.

Students' pre-lab preparations before the laboratory session helps them complete the labs with less TA assistance. The teaching laboratory team is always available to assist the students. The teaching team provides guidance and small demos on lab techniques and equipment operations as required. Students are always asked to spend time to become familiar with the equipment before turning equipment on.

By the end of the second year, students are able to operate analytical instruments such as gas chromatography instruments, spectrophotometers, viscometers, and calorimeters. They also gain valuable hands-on skills by operating experimental units such as pollution control by alkaline treatment and electrowinning, flow through tubes demonstration units, bio-diesel synthesis set-up, etc.

In the third-year, students are given only the bare-bone lab procedure manuals. No videos or other supplemental preparation materials are provided. Students carry out third-year labs with limited teaching-team supervision, using all the skills they acquired in the second-year labs. By the end of the third year, students are able to conduct experiments with less guidance and do so in a rigorous and organized manner, and collect experimental observations and data in a clear and concise manner.

The shift to a student-led process helps ensure that students are ready to conduct open-ended Problem-Based Learning (PBL) labs in their fourth year. In their PBL labs, they have the opportunity to practice experimental design, solve complex problems, use and extend existing laboratory protocols to address issues of sustainability and environmental stewardship.

Data Management and Analysis

Many students find the complexity of data management and analysis in chemical engineering laboratories daunting. Students often struggle with lengthy calculation pathways and often cannot get helpful corrective feedback exactly when they need it. Students have long found these long multi-step calculations frustrating when a small error in an initial step amplifies during subsequent calculation steps to

disrupt their final results. Further, feedback is often delayed until the report is graded and by then the past struggles to understand a calculation pathway is long forgotten. Feedback needs to be more immediate if it is going to be valuable to students.

In an effort to help students with complex calculation pathways, we introduced "Dry Lab" sessions in 2006. These sessions focused on helping students work their way through the calculation process step-by-step. Teams followed detailed instructions provided to complete their calculations. A TA coached and facilitated the student teams through their calculation process. However, we were dissatisfied with the overall effects of the "Dry Lab" sessions. The main issue was that students attended "Dry Lab" sessions poorly-prepared.

The "Dry Lab" sessions were replaced by the Teaching Laboratory Data Management (TLDM) system in 2014. The TLDM system was developed to use just-in-time coaching and eliminate feedback delays [5]. It is a series of linked Excel™ files, which students can use to both manage their experimental data and complete their calculations. The power of the TLDM system lies in the fact that it provides immediate feedback as students work their way through their calculations. The TLDM system can help students see when their calculated values begin to deviate from expected values. The TLDM system recognizes these early errors and gives students timely feedback to put them back on the correct calculation pathway. Another significant benefit is the TLDM system's simplified marking routines. This frees up TA time from marking so that it can be redirected to coaching and supervision.

When students [n=105] were asked in 2014 – "How would you rate the effectiveness of the TLDM system in helping you develop your calculations for generating final results from your raw data?" 88% of students who completed the survey indicated that they found the TLDM system extremely effective. These results are shown in Figure 2.

Figure 2: Student responses to the question "How would you rate the effectiveness of the TLDM system in helping you develop your calculations for generating final results from your raw data?"

When students [n=105] were asked if the TLDM system should continue to be used in third-year labs, the response was overwhelmingly positive (96%) for the continued use of the system. These results are shown in Figure 3.

Figure 3: Student responses to the question "Would you like to continue to use the TLDM system in the third-year labs?"

3.2. Teamwork and Communication Pathway Teams and Teamwork

Learning to work well in teams is an important skill to help our students develop. For the second-year labs, the instructor randomly assigns teams of four at the beginning of each term. These teams work together and conduct laboratory experiments, complete data analysis, write reports, and complete the final team poster presentation. Periodic online peer evaluations (ipeer.cltt.ubc.ca) are used to reward differential effort by students.

We have learned a few lessons about using peer evaluation over the years. First, it is important to have a formative evaluation cycle early in a team's development (typically end of week 4). This evaluation does not count for grades, but qualitative comments from teammates are anonymously shared between teammates to help individuals identify their areas of strength and areas for improvement. Second, when a summative peer evaluation is conducted later in the course, it must have sufficient teeth (grade consequences) to truly reward (or punish) students for their differing levels of contribution. If peer evaluation only counts for a tiny portion of a student's grade, they may sit back and let someone else get them an "A". We feel that a social loafer [13] can only be induced into action if there are real consequences for their inaction.

In the third year, randomly assigned teams of four are used again with peer evaluation to temper student grades to reflect contribution differences.

In the fourth year, students are allowed to self-select into teams based on their interest in the different capstone projects. With the large time and energy commitment to these complex capstone projects, we feel that it is important to respect the motivating nature of working on a project you are genuinely interested in.

Writing

Helping students develop their writing and communication skills is an important goal of many programs [14]. In the second year, the writing development focus is on learning to write short group laboratory reports and supporting appendices. There are in total 8 team writing assignments across the two terms of CHBE 262.

Table 2: Writing Assignment Sequence

	2 nd Year	3 rd Year	4 th Year
Group short reports	✓		
Individual short reports		✓	
Group formal reports		✓	
Individual formal reports		✓	
Project proposal			✓
Final PBL report			✓
Writing supports	High	Med	Low

Over five years, we have tried and discarded several writing models in CHBE 262, including equal division and sequential peer-editing [15]. These models proved to be ineffective. We learned that it is critical that all students complete all calculations to better understand the underlying conceptual underpinnings for each experiment. Now, in preparation for report writing, teams complete calculations together; members are then assigned a different section of the short report to complete on their own. During writing, students have access to detailed document specifications, exemplars, rubrics, and checklists. We have increased the report writing feedback opportunities for students by integrating CHBE 262 lab reports with our second-year Technical Communication course (CHBE 201). This allows students the opportunity to get feedback both from their laboratory instructor and their writing instructor. Students now have the opportunity to complete their first three group short reports in the CHBE 201 tutorial class and also get the CHBE 201 instructor's feedback before report submission. The first three assignments are graded by both the CHBE 262 and CHBE 201 teaching teams. We feel this is an important addition, since the laboratory instructor may overlook a writing construction error if the science makes sense and the writing teacher may overlook a technical error if the writing is good.

In the third year, the students begin to complete some short reports individually, and then they are introduced to the formal laboratory report format. The students still have access to detailed document specifications, exemplars, rubrics, and checklists to support their writing.

In the fourth year, students are introduced to several different writing formats (project proposal and final PBL report). By the fourth year, we want the students to be able to use a variety of reporting formats and pick a reporting format that is appropriate for the intended audience.

Communication Skills

Across all three years of our undergraduate laboratory experience, we want students to develop all communication skills, not just writing skills. We use poster presentations and oral presentations to further build student communication skills.

Table 3: Communication Assignment Sequence

	2 nd Year	3 rd Year	4 th Year
Poster presentations	✓		
Oral presentations		✓	✓

In the second year, students end the year with a poster presentation. Teams prepare posters on one of three topics. They are: 1) connecting laboratory concepts to real-world applications, 2) ideas for enhancing an existing experiment and 3) ideas for a completely new experiment. The development of this poster is integrated with our second-year technical communication course CHBE 201, so they can receive additional feedback and coaching in the development and delivery of their poster. The third year focuses on the development of their oral presentation skills. Student teams have two opportunities to prepare and deliver a series of oral presentations. In the fourth year, students are further refining their oral presentation skills. Fourth-year student teams have four opportunities to prepare and deliver oral presentations.

3.3. Workplace Skills Development Pathway

Table 4: Workplace Skills Sequence

	2 nd Year	3 rd Year	4 th Year
Industry-standard software		✓	
Site visits		✓	
In-situ sampling and analysis		✓	
Problem investigation			✓
Experimental design			✓
Data analysis and reporting	✓	✓	✓

To remind students of the real-world applications of everything they are learning, all second-year laboratory

manuals include descriptions of real industrial situations where the underlying conceptual ideas are shown to have applications in real-world contexts.

In the third-year laboratories, we begin in earnest to develop student workplace skills. The third year includes industrial site visits, collection and analysis of field data, and learning how to use industry-standard software like AutoCAD™ and LabVIEW™.

The fourth and final year focuses on developing student's ability to autonomous research, plan, and execute full laboratory investigations with minimal supervision.

4. THE INTEGRATED EXPERIENCE

In our first course of the sequence (CHBE 262), we primarily focus on foundational skill development (adequate pre-laboratory preparation, laboratory safety, development of experimental techniques, and development of data management and analysis skills) and starting the development of writing skills (short reports with enhanced multiple instructor feedback). We begin communication skills development in the second year with a year-end poster assignment.

The teaching team's focus in our second-year laboratories is to ensure that students get the developmental help they need when they need it. As shown in Figure 4, students indicate that they are getting the help they need when they need it.

Figure 4: Student responses to the following prompt: I am getting feedback when I need it and the feedback is helpful. [n = 90 (2013/2014), n=117 (2016/2017) & n=130 (2017/2018)]

In the third year, we begin to fade supports and scaffolds, and students are increasingly autonomous and use the foundational skills developed in the second year. Foundational skills development continues, but there is a shift in primary focus to communication and workplace

skills development. We continue the development of writing skills with the addition of the formal report genre and the transition to individual writing. The development of communications skills expands to include oral presentations. The third year marks the beginning of the development of workplace skills. Students begin using industry-standard software like AutoCAD™ and LabVIEW™, visit industrial facilities, doing in-field data collection and subsequent analysis.

In the fourth year, the focus really shifts to life-long learning skills and workplace skills. We want to help students develop and refine their critical thinking and problem-solving skills to be successful in the workplace. We do this with a capstone Problem-based Learning laboratory [16] where students with minimal supervision design, execute and report a laboratory investigation of a novel problem. The development of communications skills continues and intensifies with an increased number of oral presentations. For more information on our fourth-year PBL labs, please refer to Potvin's article - *Integrating elements of team-based learning and increasing independence in a 4th-year lab course to promote the development of critical thinking, problem-solving and troubleshooting skills* [16].

Developing students' problem-solving abilities and critical thinking skills are important for their success in the workplace and life. As shown in Figure 5, students report that the capstone experience helps them develop their critical thinking (CT) skills.

Figure 5: Student responses to question "To what extent did the PBL help you develop critical thinking skills?" [16]

Another important workplace skill is problem-solving ability. Students were asked if the course increased their confidence in their problem-solving ability. As shown in Figure 6, 70% of students indicated their confidence in their problem-solving abilities increased.

Figure 6: Student responses to question "How did these labs affect your confidence in your engineering skills and judgement (e.g. abilities to problem-solve unfamiliar problems)" [16]

As shown in Figure 7, the student development focus shifts each year. In the second year there is a focus on foundational skills development and a shift to a focus on workplace skills development in the final years. Communication skills development remains an important thread throughout all the years.

Figure 7: Progression of skills development

We now deliver an integrated, coordinated three-year lab experience that ensures students develop the foundational laboratory skills, the communication and teamwork skills, and the workplace skills they need to be successful in their careers. Here is a student comment that highlights all we hoped to achieve:

"The hands-on training that labs allowed was the most important aspect. Labs in CHBE were all relevant and very well organized. They helped to reinforce many of seemingly abstract concepts that were being taught in lectures and help develop my technical writing skills. It also aided in building interpersonal and critical thinking skills, which are crucial for being a well-rounded engineer."

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