# Toward "Reality-Based" Integrative Laboratories in ChE:

# INTRODUCING REAL-TIME, HANDS-ON TROUBLESHOOTING

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In McMaster University's chemical engineering program, students receive hands-on experience in key chemical engineering concepts primarily through two dedicated laboratory courses, one in the third year and one in the fourth year. These courses run for three hours per week, and each student performs three three-week experiments over the course of the semester (selected randomly in the third year and by preference in the fourth year among 7-8 total experiments per year available in the lab).

The labs are designed principally to demonstrate key concepts in transport phenomena, thermodynamics, fluid mechanics, and reactor design taught in the core curriculum courses, with specific topics (*i.e.*, fermentation, hemodialysis, polymer extrusion) chosen to emphasize the real-life applications of such principles in various fields. The first two weeks of any laboratory involve more prescribed learning goals, although the exact methodologies used to achieve those goals are somewhat open-ended; the third week of each experiment is reserved for "self-directed learning," in which students design an experiment with specific learning outcomes outside of the core laboratory activities and execute this experiment during the laboratory session. As such, on the taxonomy of laboratory instruction practices[1] the labs begin as being essentially expository and, by the final week as students gain familiarity and confidence with the equipment and process, the labs switch to inquiry by which students must formulate a hypothesis, test that hypothesis, and critically analyze both the results and the process in their final report.[2] The main deliverable of the course is the effective oral and written communication of lab results, with the quality of that reporting weighted more heavily in evaluations than the quality of the lab results. As such, the laboratory courses are structured to give students experience in designing an experiment; consolidating subject knowledge with hands-on experience; implementing the scientific method through observation, data collection, data processing, and data interpretation; and communicating this work, consistent with the goals of practical work in education.[3]

However, despite the potential of these courses to deliver a hands-on, experiential learning opportunity that cannot be delivered in a traditional classroom, our undergraduate laboratory courses are consistently unpopular with students relative to more traditional lecture-based courses, with lab courses historically receiving among the lowest student evaluation scores. In particular, students give lower marks to the value they give the lab courses compared to more lecture-based technical courses; this is disappointing given that the key pedagogical goals of the courses are to provide an experiential learning opportunity for students and to improve their capacity for technical communication (essential to whatever future career they pursue). In discussion with students, and parsing course evaluations, three other themes consistently emerge that can be addressed in the context of designing better undergraduate laboratory experiences.

***(a) Lack of integration between concepts –*** While chemical engineering is a practice that uniquely combines thermodynamics, kinetics, mathematics, and chemistry to solve integrated problems, students largely learn these concepts as individual, stand-alone courses. This "silo-ized" approach to course-based instruction, while perhaps unavoidable to some degree, often spills into the laboratory components of the curriculum, with labs designed to illustrate a specific fundamental of chemical engineering. As such, students appear to perceive the lab activities to offer minimal added value relative to the courses in which they originally learned the theory covered in the laboratory; indeed, many students expressed frustration regarding the amount of time they spent performing the lab and writing the reports relative to the degree of new knowledge they perceive to acquire through those activities. In this sense, the quality of the experiential learning experience in the lab is considered to be low and not particularly translatable to a future career—increasingly the focus of the average undergraduate student. As such, developing lab experiences that demand that students synthesize multiple aspects of the curriculum (*e.g.*, control parameters, unit operations) may assist in both better engaging students and in expanding student recognition of how to solve practical engineering challenges.

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***(b) Lack of student engagement –*** Engagement of students has long been a challenge in the undergraduate lab. Indeed, based on the necessary group-based learning environment in a lab, the generally prescribed nature of most undergraduate laboratories, and the general unfamiliarity of students with the equipment used in the lab prior to the experiment, the comment of Johnstone, *et al*. that "students can be successful in their laboratory class even with little understanding of what they are actually doing"[4] is absolutely true. More recently, a variety of additional factors are converging to make it even more challenging for laboratories to be truly engaging. First, as equipment is becoming increasingly automated (particularly in chemical engineering process laboratories), there is typically less for a student actively to do in terms of measuring a pressure, flow rate, temperature, etc., than in the past when manual sensors were used. Second, increasingly stringent safety regulations coupled with increasing cost pressures at universities have made it more difficult to provide students with a truly open-ended lab experience. Indeed, in our "self-directed learning" modules, students generally recognize that there are limited options for customizing or modifying most experiments based on: the typically hard-wired and hard-piped equipment used for undergraduate labs (limiting the options for reconfiguring or "playing" with the equipment); the limited available chemicals/equipment; and the limited time available for the students to perform the experiments. Coupling these factors with the typical response of students to default to the familiar and easy where possible, most self-directed learning modules that are proposed are not particularly creative and offer only minimal engagement to students.[5] Finally, as class sizes increase, the number of students in each lab group increases, making it difficult for quieter students to find a role and/or making it easier for less-engaged students to detach from the laboratory experience.

Developing teaching approaches to increase the degree of critical thinking required during the laboratory period, increasing the need for hands-on interaction with the equipment during the experiment, and requiring (or at least strongly encouraging) the active involvement of all group members in lab activities is essential to alleviate this issue. Technology approaches such as the use of YouTube or related videos[6] or text messaging[7] may be helpful to some degree to enhance student engagement on their own terms, but are no substitute for active, in-person, group-based learning activities. Similarly, while active team-building activities are extremely useful to equip students to work effectively together,[8] giving an effective team a task that does not engage them effectively as a unit makes such activities less valuable.

***(c) Focus on technical knowledge rather than professional skills development –*** Students tend to focus on the immediate tasks to which they are assigned as opposed to recognizing the big picture of how each task fits into a comprehensive training program. This is understandable given the demands on their time in an undergraduate engineering program. Student evaluation comments make it clear that the current lab design does not make evident the links between the specific theory and equipment being used in the experiment and the development of key soft, translatable skills such as effective problem solving, teamwork, and communication of scientific knowledge that is taught concurrently with the experiment. Realigning lab activities and/or evaluations such that the pedagogical goals of developing these skills (increasingly demanded by employers of engineering graduates[9]) are more apparent may make the laboratory experience more directly relevant to the students.

## APPROACH AND LAB FRAMEWORK

In response to these challenges, in this contribution we describe an approach we are currently applying at McMaster to introduce fault-based troubleshooting modules into existing traditional laboratory experiments. By automatically switching one of multiple solenoid valves built into the instrumentation on or off to simulate system leaks, sensor failures, and/or system blockages, we force students to troubleshoot the system to identify the fault through the application of problem-solving techniques within their laboratory team. We will show how this approach helps to address each of the three above challenges with undergraduate laboratory courses by representing a "hands-on" lab activity that much better exemplifies experiential learning and practical problem solving. Specifically, students are encouraged to approach the troubleshooting task using the McMaster problem-solving approach (pioneered by Don Woods) following the steps of Engage, Define, Explore, Plan, Implement, and Evaluate.[10] This general approach to problem solving has been applied specifically and successfully to troubleshooting processes[11] and is already taught in the second-year communications course at McMaster as well as in parallel to the lab course. Given that students are presented with a defined goal (identify the fault) but are not told how to reach that goal, this module presents students with an opportunity to use the "Explore" tool that, while possible to do in a classroom setting,[12] can likely be facilitated at a significantly higher potential level of student engagement in a lab.

## LABORATORY DESCRIPTION

The lab selected for piloting troubleshooting-based modules was an experiment on membrane gas separation. Educationally, the lab offers an ideal forum for teaching separations and mass balances using an extremely safe and inexpensive separation feedstock (air). In addition, gas separation (and more specifically air separation) using membranes is a highly relevant process in industry, with oxygen-rich streams used in the petroleum industry and other combustion-related

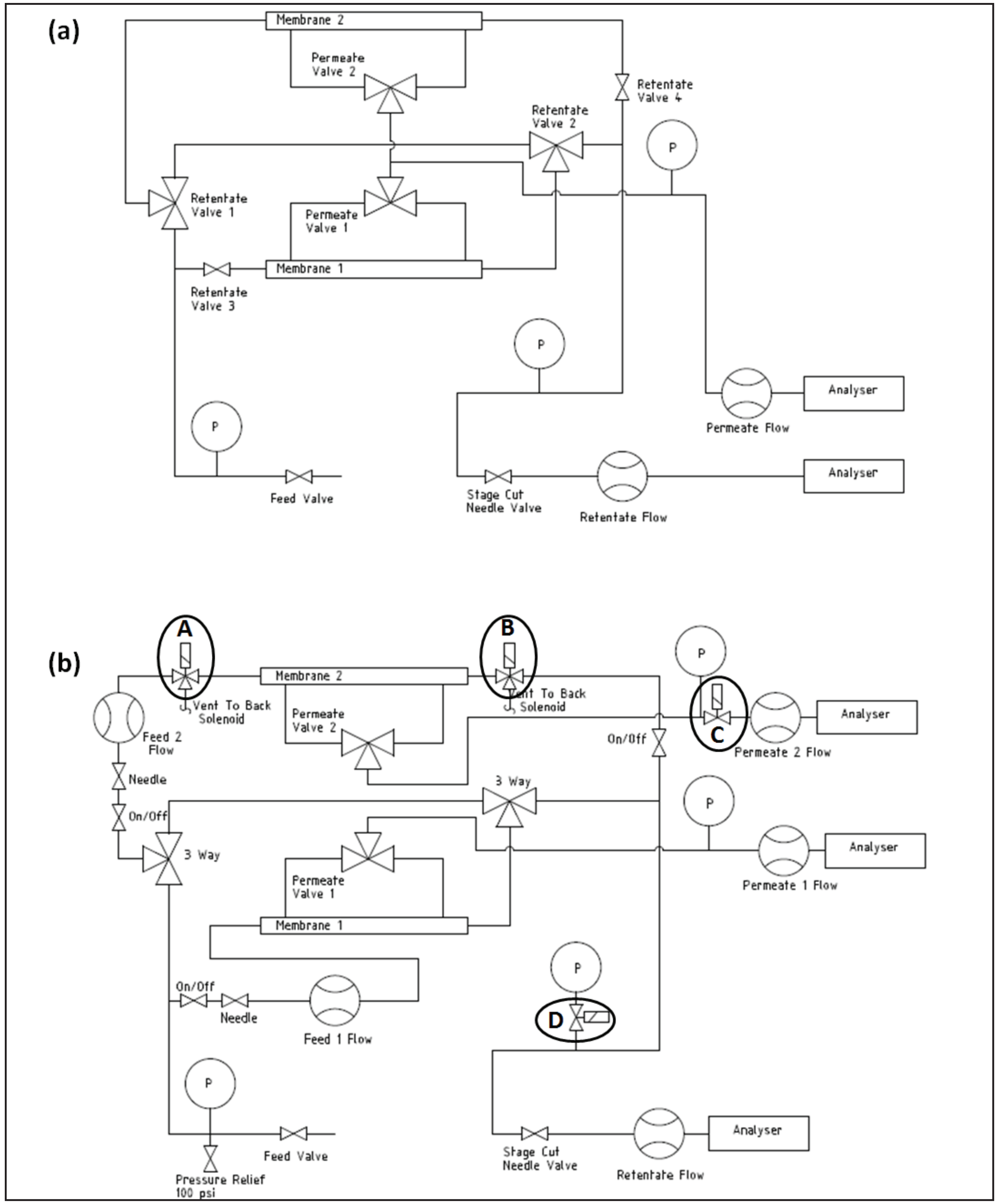

***Figure 1****. Process flow diagrams of (a) the original gas membrane separation experiment and (b) the revised gas membrane separation experiment including the capacity for troubleshooting and parallel flow (solenoid valves added labeled as A-D).*

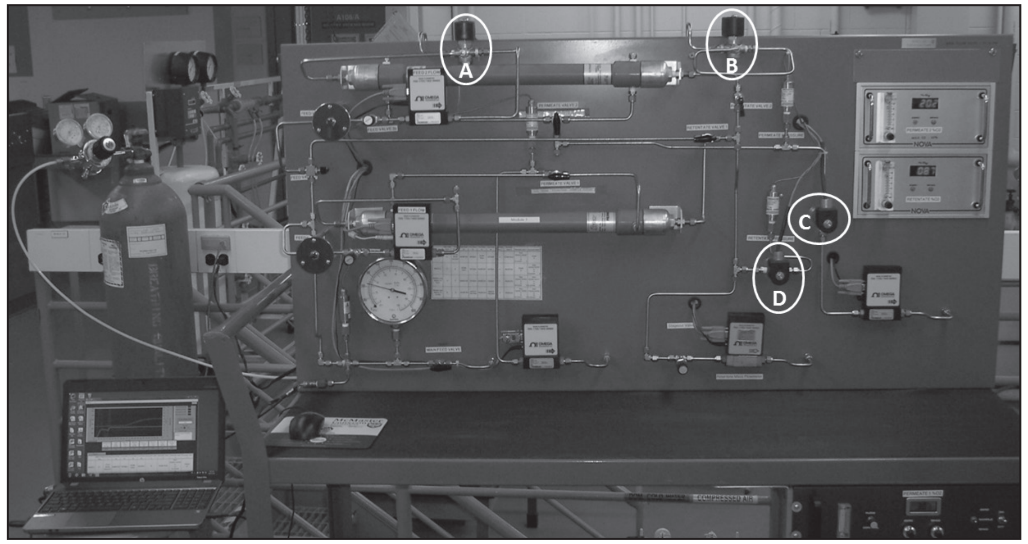

***Figure 2.*** *The gas membrane experiment incorporating the troubleshooting module infrastructure. Solenoid valves used for troubleshooting are circled and labeled with letters to match the process flow diagram in Figure 1(b). The rectangular boxes are the flow meters, and the round switch valves are the new metering valves allowing for parallel flow.*

processes,[13] and nitrogen-rich streams used to create inert environments for various reactions (*e.g.*, polymerizations), as well as facilitate shipping of highly flammable chemicals or perishable food.[14] Indeed, membrane-based separation processes are gaining increasing traction in industry as energy costs rise and environmental regulations become stricter, making other methods of gas separation such as cryogenics more expensive.[15] As such, the technology itself may be directly applicable to the students' future careers in chemical engineering. However, the membrane gas separation experiment was for many years noted in the student course evaluations as being the least engaging lab among those offered in our fourth-year laboratory course.

The original process flow diagram of the membrane gas separation experiment (before modification) is shown in Figure 1(a), while Figure 1(b) shows the revised process flow diagram following modification to introduce both more flexibility into the hard-plumbed instrumentation (facilitating more potential self-directed learning opportunities) as well as introduce the potential for automated fault triggering. Figure 2 shows a picture of the resulting experimental platform showing how the process flow diagram in Figure 1(a) was practically implemented for ease of use during the experiment. The basic principle of the experiment is to investigate how two membrane-based separator units (both Prism Alpha units, purchased from Monsanto and now available from Air Products) can separate air into nitrogen-rich and oxygen-rich streams as a function of the inlet pressure, the flow conditions (*i.e.*, co-current versus counter-current flow, single unit versus series flow), and the "stage cut"—the fraction of the inlet flow that is allowed through the membranes (*i.e.*, in the permeate stream). In the original design, students could change the inlet pressure (controlled by the inlet tank pressure), the stage cut (controlled by a needle valve, center bottom of the process flow diagram), and the directing valves to control the direction of air flow. Students then measured the flow rates and oxygen concentrations of each of the streams in the process and compared results to the theoretical performance of the membrane based on separation models previously taught in their fluid mechanics and unit operation/mass transfer courses (see Geankoplis' transport phenomenon textbook[16] for the relevant equations).

When the lab was first developed, flow rates in various streams were assessed using manual flow measurement devices, demanding significant student participation; however, in more recent years, upgrades to electronic sensors and, more recently, connecting these sensors for automatic data collection via LabView, made this among the most passive experiments offered, with direct student interactions with the equipment limited to turning on the air flow and switching valves to change the direction of air flows within the system. As such, students in this lab were typically relatively inactive, with one or two students dominating the experimental activities while the other group members sat around. In addition, the number of self-directed learning options associated with the equipment was extremely limited, with most groups selecting the same idea (co-current versus counter-current flows between the two modules) that offered minimal added educational value above and beyond the prescribed experiment.

Relative to the original process flow diagram [Fig. 1(a)], two major changes were implemented for the troubleshooting and self-directed learning modules [Fig. 1(b)]:

> *(a) New valves were installed to allow for routing of the inlet air in parallel to the two modules at any desired ratio (the block valves were included before the needle valves to ensure that truly zero flow conditions could be met if desired). Coupled with the new flow sensors to measure the actual flow rates of air into each module and the extra oxygen sensors incorporated to enable independent measurement of the permeate and retentate streams from each module, students can now investigate*

**TABLE 1**
**Summary of solenoid valve function for troubleshooting module**

| Valve | Default State | Triggered State | Fault Simulated |
|---|---|---|---|
| A | Open | Closed | Leak before top separation module |
| B | Open | Closed | Leak after top separation module |
| C | Open | Closed | Blockage in permeate line |
| D | Open | Closed | Sensor failure |

*any kind of parallel flow between the two membranes. This has significantly improved the options available for self-directed learning-based experiments.*

*(b) Four solenoid valves, labeled A-D in Figures 1(b) and 2, were installed to simulate various faults in the system. The role and on/off states of each valve are summarized in Table 1. Valves A and B are in-line valves that, when triggered "on," vent air to the back of the vertically mounted setup (Figure 2); as such, valves A and B simulate leakages in the systems both before (valve A) and after (valve B) the top separation module (Membrane 2). Valves C and D are open in the default position but switch closed when a fault is triggered. Valve C simulates a blockage in the line, with the flow meter after the valve reading zero when the valve is closed. Valve D simulates a sensor failure in that the pressure sensor of the combined retentate streams from both membrane modules is isolated from the rest of the apparatus when the valve is closed; as such, the pressure sensor will continue to read whatever pressure was present at the time of fault no matter what the user does to the system. Each solenoid could be triggered rapidly (<1 s), and system re-equilibration to the new operating state typically occurred within 30 s at the most following fault triggering. Single fault triggering, simultaneous triggering of multiple faults, and/or sequential triggering of the valves (to model cascades of faults that may occur from the initial failure) are all possible with this system through software control. We chose to trigger only one fault at a time to ensure each fault could be independently diagnosed in a systematic way as well as limit the amount of time students spent on the troubleshooting so as not to disrupt the other mandatory lab activities, although multiple fault triggering may be of interest in future implementations of this work.*

In the first year of implementation, students informed the instructor or teaching assistant when they were ready then the fault was manually triggered. However, in this implementation, the educational value of *recognizing the fault had occurred in the first place* was sacrificed for the sake of student convenience. As such, the identification of what fault had occurred was typically fast (particularly for valves A, B, and C, which were easier to detect than valve D). Instead, in the second year of implementation, students were informed that a fault would occur within the first hour of the lab during the final week of experiments, and a single fault was randomly triggered at a random time within that period. We found this approach to be significantly better given that fault detection (*i.e.*, recognition of the problem) was now an essential part of the problem-solving process. The drawback of this approach was that it was also more difficult for the instructor or teaching assistant to recognize when the problem had occurred and thus assist with student questions during the experiment; effective training of the teaching assistants certainly minimizes this problem. Some students also complained that the random fault triggering unduly interrupted their regular lab and led them to collect data that was not ultimately usable due to their failure to recognize that the fault had been triggered. While such issues may lead to a few unpleasant teaching evaluations, ultimately the onus is on the student to understand the parameters of the task, critically analyze the data during collection (*i.e.*, to ensure mass balances close, as the students were expressly told to do during the lab), and react quickly if they feel a fault may have occurred—analogous to expectations of them in a real plant environment.

It should be noted that the chosen locations of the valves may make it difficult or impossible for students to detect a given fault immediately, depending on the type of experiment the students were performing at the time of the fault. For example, if students were using only Module 1 for an experiment, faults based on triggering valves A, B, or C would not impact measurements, as there would be zero air flow to vent in valves A and B and a steady-state zero flow rate measurement in the flow meter after valve C; similarly, if students were doing a series of experiments at constant inlet pressure, the retentate pressure (which remains similar to the feed pressure under any state of operation) would not significantly change even under normal operation with or without triggering of valve D. In our view, these design "quirks" are not problematic for the learning process provided that the design of the rest of the experiment ensures that students must use both membrane modules and change the inlet pressure during the prescribed experiment on the day the fault is triggered, ensuring that students at some point work under conditions in which fault identification is possible without compromising the integrity of the rest of the data the students collect during the lab.

For evaluating the troubleshooting module, a two-step method was used. First, students were asked in week 1 to produce a process flow diagram of the system, giving students practice in drawing such diagrams as well as forcing them to learn how the system worked in preparation for the exercise. Interestingly, some of the better-performing students in the class immediately asked what the solenoid valves were for as they were drawing the system process flow diagram in the first week, helping them isolate the fault when it was triggered in the final week. By the end of the lab in the third week, students submitted a copy of this process flow diagram on which the location and nature of the fault (*i.e.*, did the valve open or close?) was clearly identified; this counted for 5/100 marks on their final lab evaluation. Second, students were asked to write one to two paragraphs in the discussion section of their final lab report describing how they identified that a fault had occurred (in year two only, as this was obvious in year one), which fault had occurred, and why that fault affected the process in the way it did. This maximum two-paragraph statement was intended to give students practice in communicating experimental results and ensure that each student understood the process, and was allocated 5 of the 15 total marks allotted to the discussion, resulting in the troubleshooting module overall accounting for 10% of the final lab mark.

## ASSESSMENT AND STUDENT FEEDBACK

***Instructor observations –*** Students were observed as they approached the problem-solving-based troubleshooting task to assess what kinds of approaches they pursued to identify the faults. The approaches differed dramatically between year 1 (when the exact timing of the fault was known to the students) and year 2 (when the exact timing was randomized). In year 1, the mere sound of the solenoid valve switching closed and/or the hotter feel of the activated valve relative to all the open valves was used by a few groups to identify the change without any other interaction with the equipment. Similarly, since venting of valves A and B creates noise that can be heard even within the relatively noisy lab environment, some students used that noise to identify where the venting was occurring and thus identify the fault (students have full access to both the front and back of the set-up during the exercise). While we did not anticipate these approaches to solving the problem, they still indicated that students recognized how solenoid valves work; furthermore, a thorough understanding of the system and the output of the sensors was still required to fully answer the questions posed for the discussion section of the lab report. However, one minor modification was made to the infrastructure for year 2 in which each of the vented streams were piped directly into a single muffler tube, both reducing the noise generated upon venting as well as delocalizing the source of that noise to make fault identification by sound alone less likely.

In year 2, when fault generation was random, very few students successfully identified the fault using the sensory cues that were widely used in year 1. Real-life plant operators are likely to be physically separated from the equipment that may go into failure, such that sensory cues may not be as translatable to a real-life situation. Avoiding these sensory cues also forced students to engage more fully in the problem-solving paradigm as a process and a group activity. In particular, it was interesting to observe how different groups approached the key step of fault detection. Some groups continually evaluated their data via mass balances (as they were directed to do) and, in some cases, returned to a "known" configuration before switching to a new experimental condition to perform repeat measurements, ensuring they were still getting the same result as during a time they knew no fault had been triggered. Given the capacity for very rapid switching of this equipment between different states, such validation runs are possible in the context of experimental timing and reflect a good student understanding of how to ensure quality control during experimental data collection. On the other hand, other groups virtually ignored the possibility a fault was scheduled, with one group in particular obliviously working into the third hour of the lab (*i.e.*, at least one hour past the last possible time at which the fault could have been triggered) without realizing a fault had occurred. In such cases, this ignorance of the framework of the task resulted in significant wasted time and ultimately a failure to complete the prescribed lab tasks. We do on this basis recommend slightly down-scaling any accompanying prescribed experiments if troubleshooting-based modules are implemented to ensure that students who bungle the module still receive the full educational benefit of the rest of the experiment.

In terms of subsequently identifying which fault had occurred, we were pleasantly surprised by how many groups tended to follow at least the principles of the McMaster Problem Solving Method, soliciting feedback within the group as to potential sources of the problem, executing an experiment (*i.e.*, by inspecting data and/or changing an experimental condition to see what impact that change would have) to test their hypothesis, and then validating their solutions. While students were encouraged to use a problem-solving method to do this task, it was not mandated, nor was there a specific evaluation related to the problem-solving framework. Typically, a more formal problem-solving approach was used by groups with one or two strong leaders and/or the stronger, more motivated students; other groups without a clear leader tended to take a much less systematic approach to fault identification that typically resulted in taking longer to complete the task. One group took over half an hour to do the troubleshooting module (most groups required 5-10 minutes) and ultimately required direct intervention from the teaching assistant (who was routinely told to stand back during the task) to identify which fault had occurred; a clear lack of understanding of the equipment plus an avoidance of using a more structured problem-solving approach appeared to be the major issues in this case.

Following the lab, students were asked to participate in a voluntary, open-ended survey providing written feedback under four general categories: what did you like, what did you not like, how could the troubleshooting module be improved, and what (if any) valuable experiences do you feel it provided. Twelve lab groups returned comments, with feedback overall quite positive. A summary of the top four positive and negative comments is provided in Table 2, together with the number of groups (of the 12 sampled) noting each comment. More detailed analysis of the student feedback is provided in the following sections.

***What the students liked* –** Students (9/12) were particularly enthusiastic about how the troubleshooting module forced them to think about how the whole system worked and then use that understanding, coupled with their fundamental knowledge about the gas membrane separation process as well as the unit operations involved in the experimental set-up, to solve a problem. Specific feedback on this point included that the module "ensures those doing the lab have an actual understanding of the system, instead of simply following directions in the lab manual." Students also largely appeared to recognize the value of such an experience in terms of equipping them to solve future industrial challenges (5/12), noting that the module provided "a more realistic scenario for industry." This was in sharp contrast to the comments regularly received on the lab courses, in which students expressed skepticism that the lab tasks were useful to their future careers. The troubleshooting task was also recognized as an opportunity to practice key problem-solving skills (6/12), forcing students to understand the problem quickly and then isolate the problem in a logical and systematic manner. One student noted that troubleshooting "promoted problem solving and critical thinking which seemed more practical than following a step-by-step procedure or directions from the teaching assistant." Students who did the experiment after the induction of the fault was switched to being random particularly noted the educational benefits of the module in this respect, in that they were forced to analyze the data critically in real time to ensure that the data were valid (*i.e.*, the fault had not yet been triggered). Students also noted that the somewhat open-ended guidelines as to how to identify the fault enabled an opportunity for self-directed, experiential learning far more than the core experiment or even the self-directed learning portion of the experiment. One student in particular noted that "the troubleshooting module provided me with more understanding and more flexibility to explore the experiment than any of the designed experiments did." The value of this exercise for promoting real teamwork within the lab groups (typically 3-4 per group in this course) was also noted by multiple groups (5/12), with one student writing that the module "engaged all of the students... it was really nice to have all the group members working together for the first time," and another writing that it was "a good team exercise, with everyone in the group working together to try to identify the problem." We were pleasantly surprised to read this feedback, as promoting group interactions was not an explicit goal of designing the task but seems to be a consistent positive outcome of such activities. The nature of troubleshooting lends itself to facilitating structured interactions between group members and consideration of different points of view in a context that is immediately testable, making it a particularly rich potential setting for fostering effective group interactions.[17, 18] Finally, the fact that students were in effect presented a puzzle to solve as opposed to a rote series of tasks to perform was noted by multiple respondents to be "fun" and "interesting" (4/12). These comments suggest effective engagement of students (*i.e.*, the "I want to and I can" of the McMaster Problem Solving method[19]) beyond that achieved with the other lab activities, particularly among the weaker and less-engaged students in the lab. This comment was supported by observing the responses of the students to the exercise; many (although not all) students who barely touched the equipment and passively let other group members run the more defined part of the experiment started looking, touching, and exploring the equipment in a way that was not previously facilitated. This may be the greatest asset of such a troubleshooting-based method of lab teaching.

**TABLE 2**
**Summary of most common positive and negative comments from student survey**

| Most popular "What I liked" responses | Most popular "What I did not like" responses |
|---|---|
| Tested a true understanding of whole system as a process (9/12) | Troubleshooting not directly linked to general topic of the lab (4/12) |
| Promoted problem solving and critical thinking (6/12) | Evaluation in the context of the full lab report awkward (4/12) |
| Perceived value in terms of preparation for practical industry challenges (5/12) | Problem could only be identified, not actively fixed, by the students themselves (3/12) |
| Effective at promoting true group work (5/12) | Troubleshooting should be an individual, not group, exercise (3/12) |

***What the students did not like* –** There were also several negative comments returned about the module, although most of these comments focused on the way the task was run rather than the idea of doing troubleshooting, and were not nearly as consistent in appearing between surveys as were the positive aspects. The main negative comment, interestingly, was that some groups felt that the troubleshooting module (focused on understanding the unit operations involved in the context of the full process) was not closely enough related to the rest of the lab (focused on mass transfer fundamentals of membrane gas separation) (4/12). Indeed, one student wrote that she "did not feel that this was very valuable, as it did not improve my understanding of membranes or gas separation." In a way, we consider this "criticism" to be a good thing in terms of the ultimate goal of the exercise, which is to provide an integrated chemical engineering laboratory experience that covers as many courses and fundamentals as possible using a hands-on experiential approach. However, based on this feedback, we now recognize that it is not enough to introduce troubleshooting to the end of an existing laboratory description; instead, a thorough re-writing of the lab background to ensure students recognize how various aspects of the curriculum are being incorporated into the laboratory experience coupled with consistent instructor/TA interactions throughout the lab emphasizing those linkages are required to gain the full educational benefit from the exercise.

The other negative comments were more substantive and made it clear that the method of implementing such modules (particularly when they are intended to supplement a more traditional lab, as was the case here) is critical for students to gain the most from the exercise. Students in particular noted that the original method of evaluating the troubleshooting task (*i.e.*, including a paragraph on the results and process of the module in their final lab report) did not closely fit with the content or style of the rest of the report and was awkward to write (4/12). We agree with this criticism; indeed, the optimum type of assessment for a lab-based troubleshooting activity is likely a combination of communicating the result (*i.e.*, identifying the fault on a process flow diagram of the system—what is the solution?) and reflecting on the process through a brief journal-style reflection (submitted separate to the final lab report) on how the problem-solving process was employed to identify the fault (*i.e.*, how can I use this experience to address similar problems in the future—what was learned?). This change would not only address this student critique but also facilitate self-reflection and self-evaluation of the problem-solving process that is a key attribute of problem-based learning[20] and better emphasize the real-life "soft" skills (teamwork, logical deduction, whole process understanding) targeted as learning outcomes.

Multiple students (3/12) also noted that they were disappointed that the troubleshooting ended at the identification of the problem and did not include fixing the problem, as the TA or instructor simply reset the valves in the software to their default positions after students correctly identified the fault. While we agree that allowing the students to fix the problem themselves would be ideal, it is difficult to do this without giving students direct control over the valves through LabView, at which point the triggering a valve on or off would be somewhat obvious (*i.e.*, the software would directly report it to the students). One potential way to address this comment is to make the solenoid valves switchable by the students but hide the state of the valve (on/off) from the student screen view; this would both give the students the opportunity to fix the problem actively as well as give them an alternate, more software-based option to approach the troubleshooting process. We intend to pursue this approach and then compare student feedback regarding the value of the exercise, as there is a potential in our view for a loss of impact if students are not forced to interact with the physical equipment but rather are enabled both to identify and fix the fault based on software controls.

Several comments were also directed toward the timing of the troubleshooting. Student opinions differed significantly on the timing of the fault in the context of the rest of the lab, with some students indicating the fault should have been triggered in a much narrower window than the 1-hour window ultimately used (2/12) while other students suggest leaving the time completely random and open-ended to increase the difficulty and gaming aspect of the exercise (2/12). We believe the 1-hour time window is a good compromise on these viewpoints, as it does not consume a huge amount of the overall (9-hour) lab time if the students miss the fault (and thus collect useless data in the meantime) but still forces students to pay attention and critically assess data in real time, as a plant operator would be expected to do. Students also had very different responses to how they perceived pressure during the troubleshooting process. One student wrote that the module was very stressful to complete and noted that the gaze of the TA added undue pressure to their problem-solving process; in contrast, another student suggested timing how quickly the group could identify the fault and incorporating that time into the grading process. Based on our experience, neither suggestion is likely beneficial for the majority of students. Indeed, incorporating a timed element may detract from the key practice of systematic problem solving of emphasizing accuracy as opposed to speed[21] and may introduce unfair biases into the assessment given that some faults (A, B, and C) are easier to identify than others (D). Multiple students (3/12) also noted that they would prefer working on an individual troubleshooting task. However, this would both detract from the teamwork benefits observed as well as reduce the relevance of the experience to a real industrial situation, in which team interactions in such situations are common.

***Implementation* –** In terms of implementing troubleshooting components into laboratories, the major barrier in our experience is a technical one, as capable and engaged technicians in both construction and electronics are essential to implement this type of module in a student-friendly way. For the particular modification performed to the membrane gas separation experiment, the cost of the physical equipment required for the modification was relatively low (four solenoid valves with electronic control and some piping, approximately $450 in direct costs), and there are no ongoing operational costs aside from a slight increase in air usage if valves A or B were triggered; however, the cost of staff time was relatively higher, particularly in terms of writing the troubleshooting code into LabView and ensuring safe continuing operation of the entire module both during and after each type of fault was triggered (~80 technologist/manager hours). While it may be possible for a senior undergraduate student with experience in LabView to implement the code, technical staff support and buy-in is essential to transition traditional turn-key experiments hard-wired and designed for consistent performance into more flexible experiments that can introduce potential for self-directed experimentation and/or fault-based learning without negatively impacting the reliability of performance required for the prescribed lab tasks. The cost associated with any fault triggering, the safety of any modifications to the experiment to the students, and the kinetics of a given fault having a measurable effect in the context of a limited-time laboratory experience must all be considered to translate such an approach to other types of experiments. In this case, the rapid response of the system to switching and the high level of safety associated with the experiment generally (using air, maximum pressures of 600 kPa, and maximum permeate oxygen contents of <40 mol% regardless of which valve is switched or how the students interact with the system) are both highly favorable to a troubleshooting-based approach.

While not all students in the course participated in the membrane gas separation laboratory, student scores regarding the overall value of the laboratory course relative to others taken at McMaster increased from 3.60/5 the year before the troubleshooting module was introduced to 3.94/5 the year the module was fully implemented. While a direct correlation cannot be drawn between these results and the introduction of a troubleshooting component, it is clear from the overall course evaluation comments that students in general appreciate a more skills-based training approach to a laboratory course and that this skills emphasis was more apparent in a troubleshooting context relative to a more traditional prescribed laboratory design. It should also be noted that 10/12 student survey respondents suggested (without direct solicitation) that similar modules should be implemented in other labs, as they perceived such exercises to be valuable and relevant to training for their future careers.

## CONCLUSIONS

Introducing troubleshooting or other "real-life" fault-based experiences into undergraduate laboratory courses (and particularly integrative laboratory courses aiming to combine several parts of the curriculum) gives students hands-on experience in implementing problem solving techniques in the laboratory while also promoting team-based learning and a more in-depth, systems-based understanding of key engineering instrumentation. We are now implementing similar troubleshooting-based learning experiences in other experiments, starting with process control-based experiments in which faults are easily implemented and then diagnosed based on controller responses. In our view, implementing fault-based, experiential learning in the undergraduate laboratory helps to make the laboratory experience more interactive and relevant for the student without significantly increasing operating costs or introducing safety concerns that can result from more conventional, open-ended, self-directed learning approaches.

## ACKNOWLEDGMENTS

The success of such modifications to the laboratory curriculum is dependent on the staff involved in the laboratory course, and the exceptional work of Paul Gatt (departmental mechanical technologist/machinist), Dan Wright (departmental instrumentation technician), Justyna Derkach (departmental undergraduate laboratory supervisor), and Douglas Keller (departmental laboratory manager) was absolutely essential to make this troubleshooting exercise a success. Dan Wright is also acknowledged for providing the process and instrumentation diagrams for the experiment. Kevin Dunn, teaching professor at McMaster Chemical Engineering, is thanked for his critical reading of the manuscript. McMaster engineering students, via their macLAB fund, are thanked for providing the funding to perform the equipment modifications necessary. Finally, all educational activities in our department related to problem-based learning are heavily indebted to the work of the late Don Woods, who was (and continues to be) an inspiration regarding how to engage students in the learning process; he is greatly missed.

## REFERENCES

1. Domin, D.S., "A Review of Laboratory Instruction Styles," *J. Chem. Ed.*, **76**, 543 (1999)
2. Raths, L.E., S. Wassermann, A. Jonas, and A. Rothstein, *Teaching for Thinking: Theories, Strategies, and Activities for the Classroom*, Teachers College, Columbia University, New York (1986)
3 Garratt, J., "Laboratory Work Provides Only One of Many Skills Needed By the Experimental Scientist," *University Chemistry Ed.*, **6**, 58 (2002)
4. Johnstone, A.H., R.J. Sleet, and J.F. Vianna, "An Information Processing Model of Learning: Its Application To an Undergraduate Laboratory Course In Chemistry," *Studies in Higher Ed.*, **19**, 77 (1994)
5. Mun, R., "How to Provide Effective Undergraduate Laboratory Sessions To Undergraduate Engineering Students," in K. Martin, N. Stanley and N. Davison (Eds.), "Teaching in the Disciplines/Learning in Context," Proceedings of the 8th Annual Teaching Learning Forum, The University of Western Australia, 293-297 (1999) <http://lsn.curtin.edu.au/tlf/tlf1999/mun.html>
6. Hrenya, C.M., "Active Learning in Fluid Mechanics: YouTube Tube Flow and Puzzling Fluids Questions," *Chem. Eng. Ed.*, **45**, 114 (2011)
7. Walton, S.P., D. Briedis, S.D. Lindeman, A.P. Malefyt, and J. Sticklen, "Text Messaging As a Tool For Engaging Chemical Engineering Students," *Chem. Eng. J.*, **46**, 80 (2012)
8. For example, see CATME Smarter Teamwork, <http://info.catme.org>
9. Leonard, W.P., "Teach Students Soft Skills," *University World News*, **324** (2014)
10. Woods, D.R., "Problem-Based Learning: How To Gain The Most From PBL," Watertown, Ontario (1994). Available at <http://chemeng.mcmaster.ca/problem-based-learning>
11. Woods, D.R., *Successful Trouble Shooting for Process Engineers: A Complete Course in Case Studies*, Wiley, Weinheim, Germany (2006)
12. Marlin, T., and D.R. Woods, "Trouble Shooting for CAPE Undergraduate Education," *ESCAPE 12*, The Hague, Netherlands, May 26-29, 2002
13. Baker, R.W., *Gas Separation: Membrane Technology and Applications*, Wiley, San Francisco (2012)
14. Bernardo, P., E. Brioli, and G. Goleme, "Membrane Gas Separation: A Review/State of the Art," *Industrial Eng. and Chemistry Research*, **48**, 4683 (2009)
15. Freemantle, M., "Membranes for Gas Separation," *Chem. and Engineering News*, **83**, 49 (2005)
16. Geankoplis, C., *Transport Processes and Separation Process Principles*, 4th Edition, Prentice-Hall, Inc., Englewood Cliffs, New Jersey (2003)
17. Bahar, M., "The Effects of Motivational Styles On Group Work and Discussion-Based Seminars," *Scandinavian J. Ed. Research*, **47**, 461 (2003)
18. McManus, S.M., and M. Gettinger, "Teacher and Student Evaluations of Cooperative Learning and Observed Interactive Behaviors," *J. Ed. Research*, **90**, 13 (1996)
19. Woods, D.R., "An Evidence-Based Strategy for Problem Solving," *J. Eng. Ed.*, **89**, 443 (2000)
20. Woods, D.R., *Preparing for PBL*, Watertown, Ontario (2006)
21. Woods, D.R., A.N. Hrymak, R.R. Marshall, P.E. Wood, C.M. Crowe, T.W. Hoffman, J.D. Wright, P.A. Taylor, K.A. Woodhouse, and C.G.K. Bouchard, "Developing Problem Solving Skills: The McMaster Problem Solving Program," *J. Eng. Ed.*, **86**, 75 (1997) ❒