INTEGRATING THE ChE CURRICULUM VIA A RECURRING LABORATORY

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Engineering education literature has found active learning to be beneficial. A review by Prince[1] found support for collaborative learning, cooperative learning, and problem-based learning (PBL), all considered forms of active learning. Collaborative and cooperative learning refer to students working in groups toward a common goal, with cooperative learning further specifying that students are evaluated as individuals. PBL has several possible implementation schemes, but in general all types pose problems at the beginning of instruction and they tend to rely on self-directed learning by the students. Considering the evidence for the positive effects of active learning, many faculty have begun to adopt these teaching methods in the classroom. In a 2011 study of chemical engineering and electrical engineering faculty, 82.1% of the faculty members have used or are using one or more of the 12 Research Based Instructional Strategies (RBIS) as outlined by Borrego, *et al*.[2] with 61% utilizing active learning. Although the response rate to the survey was low, it is qualitatively encouraging to see evidence of RBIS being implemented in the classroom.

In addition to classroom learning, laboratory experiences are a common practice in engineering education, and the benefits are well established.[3-6] As noted by Sheppard, *et al*.,[7] a lab that coordinates theory and practice well can greatly support student learning. Further, labs may aid students who prefer a laboratory setting and view their learning differently than students who prefer classroom settings.[8] While active learning is becoming more prevalent, many chemical engineering curricula (including the curriculum at City College of New York) traditionally focus on requisite courses before letting students engage with the material in the laboratory. Bordogna, *et al*.[9] challenged this method by envisioning a more integrated curriculum. The traditional and integrated

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approaches are juxtaposed schematically in Figure 1. He argued specifically that the integrated approach would teach students to define problems, consider multiple solutions, and experience the emotional/intellectual aspects of confronting an open-ended problem with limited knowledge. With the aid of computers and simulations in particular, first-year engineering students could solve engineering problems before having the requisite knowledge in math and science. The integrated approach could also instill lifelong learning and incorporate the "Just-in-Time Teaching" (JiTT) approach. Benefits of JiTT include students showing higher improvement in pre/post assessments (Force Concept Inventory), increases in classroom attendance, and improved study habits.[10] However, JiTT was the least known RBIS based on the survey of Reference 2.

Some programs have begun implementing an integrated curriculum. To confront the problem of segmented learning associated with the traditional approach, Clark, *et al*.[11] developed a "spiral" curriculum for sophomore chemical engineers at Worcester Polytechnic Institute. Although not extended throughout the entire undergraduate experience, topics were revisited with increasing complexity throughout the term. The approach used open-ended design projects that incorporated cooperative learning and JiTT. When compared with students taught with the traditional approach, the spiral approach students had equal (or better) understanding of chemical engineering principles, better success in teams, higher satisfaction academically, and higher retention rates, and they performed better in subsequent courses.[12] At Michigan

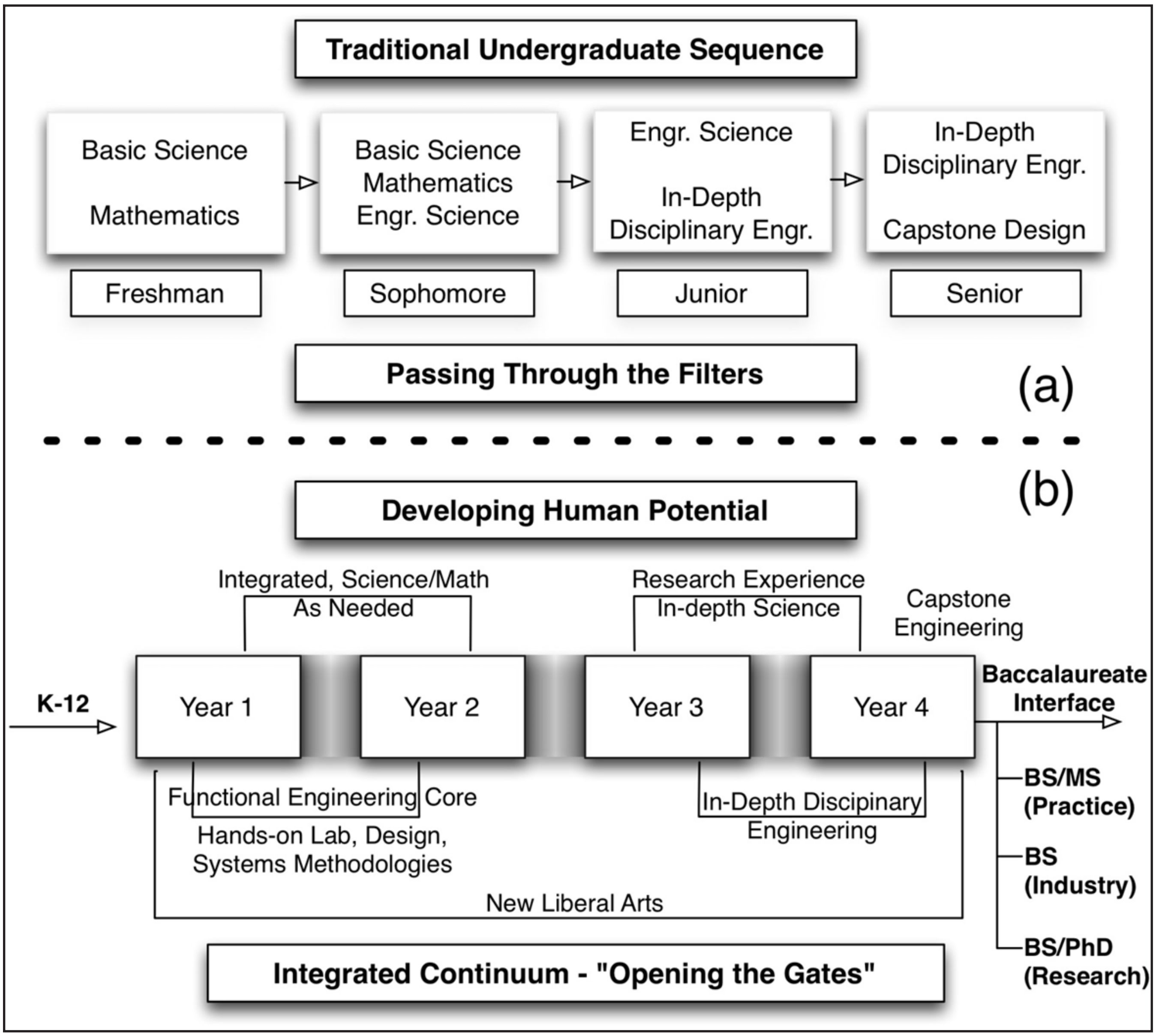

Figure 1. *a) The traditional undergraduate engineering curriculum and b) an integrated engineering curriculum (modified with permission from Wiley).*[9]

Technological University, two integrated curriculum approaches were attempted.[13] Instead of having a laboratory as a component of each course, a set of core labs was created that was separate from the courses but aligned with co-requisites. However, issues in implementation and keeping appropriate coordination between the lab and the concepts in the core course hampered this approach. A second approach was taken where the theoretical matter preceded the laboratory by one semester, which helped reinforce previously learned material. In the second-, third-, and fourth-year labs, the first lab of the term was a traditional experiment, and then subsequent experiments throughout the term were presented as a design challenge with a learning objective just beyond the students' current comprehension.

Recognizing the importance of active learning and laboratory experience, this paper focuses on the implementation of an integrated laboratory experience in chemical engineering at City College of New York (CCNY). CCNY is a recognized minority-serving institution with a college mission focused on serving a wide-range of student backgrounds. The laboratory is associated with the material and energy balance course, which typically enrolls approximately 50 students, and the experiments are based on using a Continuously Stirred Tank Reactor (CSTR). The students solve open-ended problems in groups, and the concepts are not only core to the material and energy balance course, they can be re-examined throughout the entire curriculum. This paper describes the goals, design, and implementation of this approach, survey data supporting the program, a path for integration into other courses, and analysis for future improvement.

DISCUSSION OF THE INTEGRATED CSTR PLATFORM

The discussion starts with motivation and goals of the lab at CCNY. Subsequently, the design and implementation are discussed with a focus on the CSTR construction and then application to a draining tank experiment. Continuity and integration to other parts of the curriculum are also discussed. Survey results are discussed, which show initial success in building community, teamwork, and understanding. Finally, the implementation over three terms is analyzed to suggest practical changes in the future.

Motivation for and goals of integrated lab

The motivation and rationale for this approach are a combination of the literature studies about engineering education previously discussed (knowledge-based) and surveys taken of our department during ABET accreditation (data-based). From a knowledge-based assessment, students benefit when qualitative physical understanding is complemented by quantitative analysis. The CSTR work facilitates such a synchronized approach, allowing students to move from a fact-based to an evidence-based approach toward science. Additionally, the lab platform can be viewed as a cognitive apprenticeship, allowing students with diverse backgrounds to more thoroughly engage in the discipline.

Three data-based surveys identified shortcomings in our chemical engineering educational plan at CCNY. The department's student survey revealed the biggest areas for improvement to be: "Academic facilities, *e.g.*, laboratory" (3.4/5) and the "Student facilities at City College" (3.4/5). The CSTR platform addresses these shortcomings by bringing students into the lab in year 2 instead of year 4. The second survey was an average of three years examining the program outcomes defined by ABET. The three weakest areas (≤ 4.0/5) were: "Design and conduct experiments, and analyze and interpret data" (4.0/5), "Design a system, component, or a process to meet desired needs" (4.0/5), and "Identify, formulate, and solve chemical engineering problems" (3.9/5). The CSTR platform is predicated on open-ended problems that will allow the students to engage in all of those areas. The third survey asked questions to recent graduates (< 5 years) to rate various educational objectives against their satisfaction and perceived importance. These results are shown in Table 1. While the first two objectives are met, the second two objectives are not. A goal of the CSTR platform is to stress the importance of being able to solve open-ended problems and subsequently give students sufficient tools to address these problems.

Before the CSTR lab was introduced, the undergraduate chemical engineering curriculum at CCNY followed the traditional sequence noted by Bordogna, *et al*.[9] However, Bordogna's proposed full curriculum integration can lead to difficulty in implementation: faculty may resist changes to established lecture formats, there may be the perception of accreditation issues, there may be a sense of too much change occurring too quickly, etc. Since laboratory-curriculum integration can be beneficial to the learning process,[3-7] the

TABLE 1
Survey results from recent alumni (< 5 years) focusing on satisfaction and perceived importance of various educational objectives

	Satisfaction		Importance	
Educational Objective	Average	Stdev	Average	Stdev
Ability to perform as design, process, and development engineers	4.10	0.98	3.60	0.61
Ability to pursue post-baccalaureate degrees	4.16	0.86	3.05	1.06
Ability to apply critical thinking to real-world problems	3.33	1.06	2.83	1.00
Ability to apply creativity and innovation	3.46	1.09	3.06	0.92

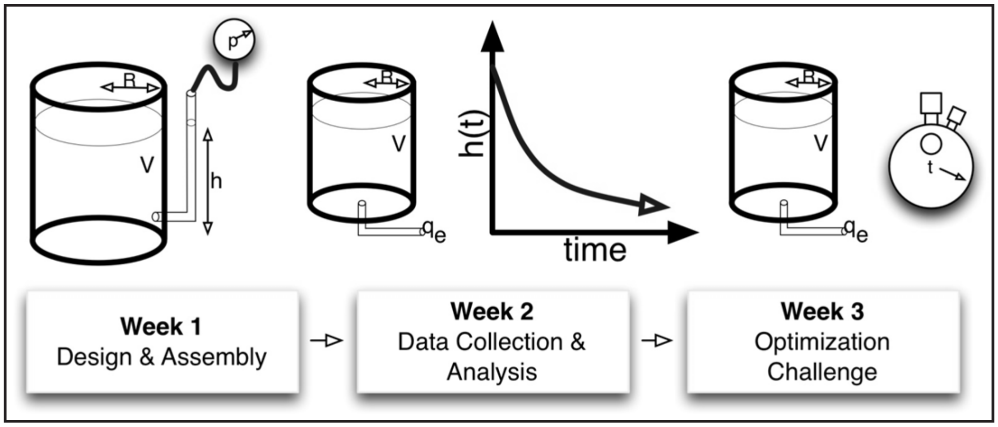

Figure 2. *The three-week laboratory cycle that is applied to a given engineering concept.*

chemical engineering department was motivated to find a way to incorporate the integrated laboratory into the curriculum. The versatility of a CSTR laboratory platform allows for concepts covered throughout the undergraduate curriculum to be connected via a single laboratory setup, all without developing a new lab course or any changes to the overall prerequisite layout. Thus, fewer problems were encountered with implementation.

The integrated laboratory is designed to feature open-ended, design-oriented laboratory exercises centered on fundamental concepts as they are introduced. This integration gets students into a laboratory setting as soon as unit operations concepts are introduced in lecture. Also, immediate exposure to experiments and processes shows classroom learning is applied and realistic. Rather than just employing the lab as a tool to prove that lecture concepts can be observed and measured, the focus is on problem solving and design tasks grounded in lecture concepts. The goal is to develop engineering intuition, problem-solving skills, and an immediate sense of how lecture material is applied and useful. Furthermore, accomplishing this in a shared, practical laboratory framework develops clear connections between the various core classes, even as the complexity of the material covered builds.

Design and implementation

The Continuously Stirred Tank Reactor platform provides an ideal, flexible framework for chemical engineering design problems of increasing complexity. While clearly useful in the study of kinetics and reactor design, its applicability to earlier chemical engineering concepts merits discussion. At the start, mass and energy balances can be designed around the tank's inlet and outlet ports. The key concept in play is simply "(Flow in) - (Flow Out) = (Accumulation)." Flow in can be controlled via stock solutions added either by hand or by a metered pump. Flow out corresponds to the tank effluent. Accumulation can be measured in several ways, with the simplest example being measuring the liquid depth inside. Thus, by varying inlet and/or outlet flow rates, liquid accumulation within the tank occurs. Subsequently, as the concept of component balances is added to the existing understanding of mass balances, a "source" term is added to account for chemical reactions.

Using this concept alone, design problems are possible. For example, with no inlet flow, given an uncontrolled (but variably narrow) CSTR outlet and a tank open to the atmosphere, one can develop a model of the tank's height as a function of time from a given initial height. "Designing" an initial tank height that will result in the tank draining to a given height after a set time becomes an open-ended exercise. Each exercise follows a set design schedule, shown in Figure 2.

The students choose the groups themselves, with a typical size between four and six members. In week 1, students configure their CSTR system to be useful in analyzing and designing toward a fundamental chemical engineering principle. In week 2, students are tasked with gathering enough data on the behavior of their system to be able to engineer its behavior for an unknown challenge during the final week. In week 3, students are given a single try to configure their CSTR system to produce a certain outcome pertaining to the design topic. Groups compete against each other with regard to the effectiveness of their solutions. This implementation scheme is also beneficial as it incorporates components of Kolb's experiential learning theory.[6] The complete implementation of the draining tank laboratory cycle is explained later in this section. Inspiration for various experiments came from Denn.[14]

Construction and design of the CSTR platform

A general schematic of our CSTR is shown in Figure 3. There are currently five CSTRs that we made ourselves from inexpensive pre-made materials (under $100 in terms of just the parts and ignoring labor).

The system is designed to be versatile, including modular components that can be easily disassembled and reconfigured. The outlet piping, mixer, and sensors are not fixed and can easily be exchanged for different pipe or tube diameters, blade configurations, and probes. This allows the setup to be useful in designing around and assessing a large array of variables taken from the complete chemical engineering curriculum. The students are further given design freedom in determining which sensors to use and ensuring what calibration, if any, needs to be done. The vessel body is made of acrylic and the related piping ranges from 1⁄2" NPT to stopper-adapted, smaller-diameter tubings. Students have access to pressure, temperature, salinity, and pH probes, modular with regard to the USB SensorDAQ system (Vernier Software and Technology), as well as individual student-grade UV-VIS spectrophotometers (Ocean Optics). Over-the-side heaters are also available so temperature effects can be studied. Data is logged at a sampling frequency of the students' choice using the LabVIEW software suite (National Instruments). While this equipment was used at CCNY, the choice of sensors and other peripheral equipment is general and easily customized to specific experiments, implementation schemes, and financial considerations.

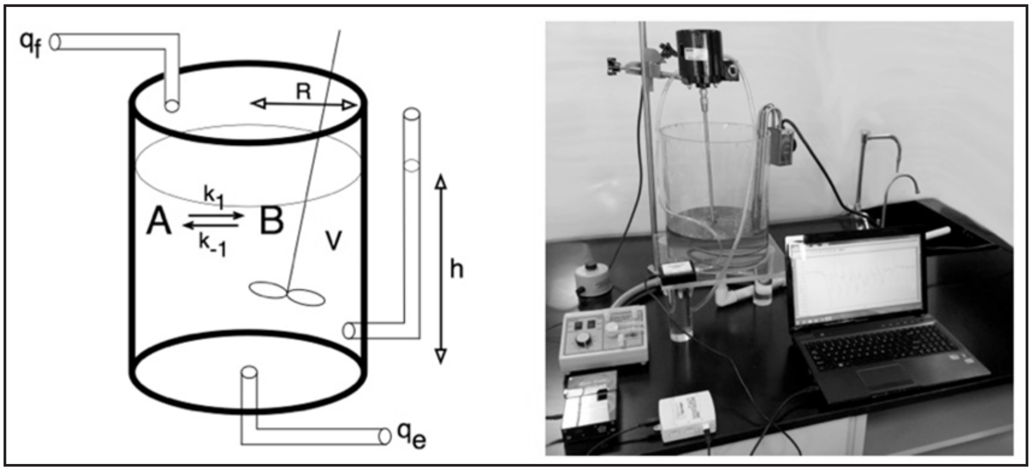

Figure 3. *Schematic of the CSTR along with a first-generation prototype in the lab setting.*

A full laboratory cycle applied to the draining tank problem

The following sample exercise is taken from the material and energy balance course, held during the first semester of students' sophomore year. The three weeks correspond to the stages shown in Figure 2.

Week 1

General Objective: Measure how pressure varies with changing liquid height

Do the following:

1) Set up tube half-filled with water, pressure sensor, and LabVIEW 2009/2010
   a) *Open the program LabVIEW 2009/2010 to read detectors*
   b) *Click on "SensorDAQ Logger.vi"*
   c) *Hint: Press white play arrow followed by green play arrow*
   d) *Adjust the data collection frequency to 0.2 seconds/data point*
   e) *Do the axes make sense? Why or why not?*
   f) ***Clean up*** *after yourself when you are finished*
2) Use output to determine how pressure changes as a function of height.
3) Plot "pressure vs. height" and fit/analyze data (at home). Note: You will need this plot for next week's lab.

Week 2

General Objective: Measure how height changes with time (measuring pressure change)

Do the following:

(in lab)

4) Set up tank with water, pressure sensor, and LabVIEW 2009/2010
   a) *Open the program LabVIEW 2009/2010 to read detectors*
   b) *Click on "SensorDAQ Logger.vi"*
   c) *Adjust the data collection frequency to an "appropriate" time scale*
   d) *Begin draining tank by opening valve*
   e) *Measure pressure change as a function of time*
   f) *Repeat this process two more times*
   g) *Clean up after yourself when you are finished*

(at home)

5) Use plot of pressure vs. height (from last lab) to make a plot of height vs. time

6) Fit first four points to $q_e = k$, $q_e = kh$, $q_e = kh^{1/2}$

7) Does the data agree or disagree with the class predictions

Week 3

General Objective: Use the information from the previous two labs to design a tank that drains to a height of 1 inch in exactly 1.5 minutes.

Do the following:

8) Calculate the volume of the tank (based on the area).

9) Based on previous two labs, estimate the **initial** volume that you need to have the tank drain to a height of 1 inch in EXACTLY one and a half minutes

10) Set up tank with the predicted volume (or height) of water

11) Drain the tank and measure how long it takes to reach the 1 inch mark

Note:

i) You cannot run a trial experiment of any sort. Your initial volume prediction must be based on calculations from the previous two weeks.

ii) After you open the tank, the clock will start, and you cannot touch the valve or tank.

iii) The teams with the times closest to 1.5 minutes will get bonus points on their lab reports.

Lab report

1) Each student must turn in her or his own report.

2) Follow the guidelines given to you in the first class ("Lab report guidelines" on Blackboard). Any deviation will lead to additional work by you and a lower grade.

3) Each report should be no longer than two pages. BE SUCCINCT.

4) The three paragraphs of the results/discussion sections should describe the following three topics:

a) How do you relate pressure and height? Is this a linear relationship? Does it make sense?

b) How does height change with time? Does it make sense? Why or why not?

c) What calculations did you make to predict that the height would be 1" after 1.5 minutes?

5) References, raw data, and sample calculations are optional if you have room left after you complete the ABSTRACT, INTRODUCTION, EXPERIMENTAL, and RESULTS sections, which are mandatory.

The students choose their own teams for system design and data collection, although they are graded on individually prepared lab reports from the shared team data. The switch from group design and competitions to individual lab reports serves two purposes. First, by working as a group, students are engaged with each other in real discussions about the design problems. Since the equipment setups are minimally specified by the lab handouts, students are forced to debate among themselves the merits of various design choices. This, paired with the third week's competition against other groups, keeps students engaged in active thinking about core concepts. Individual lab reports, by contrast, task students with developing a deep, individual understanding of the material covered, which is considered a cooperative active learning method. Further, as the lab report is submitted in the form of a short publication, scientific writing skills are developed and practiced on a continual basis.

Other laboratory experiments have been explored in this class. One laboratory investigated the mass balance of food coloring dye into the system via a step function concentration change in the feed. Another lab examined a two-step reaction scheme that progressed in terms of the system's ammonia concentration [reacting ammonia and copper (II) sulfate]. Both of these experiments made use of the UV-Vis spectrophotometer. A third lab included an energy balance, measuring the power output of the heaters via temperature change. These general examples highlight the broad range of topics that can be studied via the CSTR. Note that while these topics are introduced in the second year, they become major topics studied in depth only later in the curriculum.

Integration into subsequent engineering courses

The organization of our chemical engineering curriculum in terms of prerequisites is shown in Figure 4a. The integrated CSTR platform provides a different way of viewing the same coursework progression, shown in Figure 4b. By studying and designing increasingly difficult chemical engineering challenges within the same apparatus, the way the various sub-disciplines work together and build on each other with regard to practical problems is constantly revisited and expanded. This building of structured complexity is obvious to students as they progress, rather than only accessible in retrospect, near graduation.

This integrated structure reflects the curriculum as it exists at CCNY. For instance, statistics is an important component of the lab, but the class appears outside of the boxed area in Figure 4b because our statistics course is currently taught in the mathematics department, making it harder to integrate features of the lab directly into an externally taught course. Importantly, this model is one example of implementing the vertical integration; different departments can apply this methodology to fit their own program (course layout, specific laboratory experiments, etc.).

Additionally, this approach highlights collaborative and cooperative learning where students benefit by building a sense of community within the department. To augment this sense of open collaboration, we have created an integrated lab space that can be accessed by the students for exploration and monitored by the faculty for safety beyond the prescribed lab hours. The space has an open design and includes experiments from our separations, unit operations, and introductory labs. This integration allows for the inclusion of the CSTR apparatus beyond the mass and energy balance class.

To that end, in the Fall 2013 semester, the CSTR lab framework was expanded to the chemical kinetics class, offered to seniors. These seniors were students who had previous experience with the CSTR lab framework from their sophomore year. A new exercise was given simultaneously to the seniors and current sophomores; neither group had done the exercise before. The work required designing a tank system to target a specified pH value at a given time by reacting a citric acid solution with sodium bicarbonate tablets. Mixing rates and agitator configuration were left as open design variables, building tunable mass transfer resistance into the kinetic framework.

The task was to neutralize a pre-mixed citric acid solution to a near-neutral pH in four minutes. As the time delay was the key evaluation parameter, arriving at the neutralized state too quickly corresponded to a poor design. Prior to the design challenge, all groups were required to collect data correlating system pH to citric acid and bicarbonate tablet concentrations. They were also required to look at the evolution of the system pH during reaction under both strong and weak mixing conditions. Dissolution of the bicarbonate tablets is strongly influenced by mixing configuration. Dissolution times range from erratic tablet breakup in approximately 15 seconds using the most aggressive mixing to a gradual, metered dissolution over approximately 19 minutes using gentle mixing.

The sophomore class universally (10 out of 10 groups) approached the problem as a stoichiometric exercise. All 10 groups measured out a number of tablets that would bring the system to the desired pH when dissolved and reacted completely. They then set up their tanks with aggressive agitators and ran their neutralization designs with high mixing speeds. All groups had accurate calculations for predicting the final pH. Moreover, all groups had correctly observed the available range of mass transfer rates for which they could control. But none of the groups chose to use mass transfer as a controlling mechanism in their design. As a result, their target pH was sensible, but their timing was inaccurate, despite having collected high-quality design data. This outcome is not entirely unexpected, however. The sophomore class had not yet taken either mass transfer or chemical kinetics. As a result, the key concept would have to be inferred almost entirely from the new lab data.

By contrast, half of the senior class (five out of 10 groups) approached the problem using a mass transfer-limited design. Those groups measured out tablets containing bicarbonate in excess of the amount required to neutralize the system. They then chose mixing designs corresponding to the gentle, mass transfer-limited release rates. These five designs, using mass transfer as a tool, demonstrated much greater control of their systems, giving rise to clearly superior designs. The other five (strong mixing) designs were comparable to those of the sophomores. As the seniors had been trained in both mass transfer and chemical kinetics, their ability to better appreciate and design around mass transfer effects is both expected and desirable.

The difference in design choice and performance between seniors and sophomores during this experiment highlights that

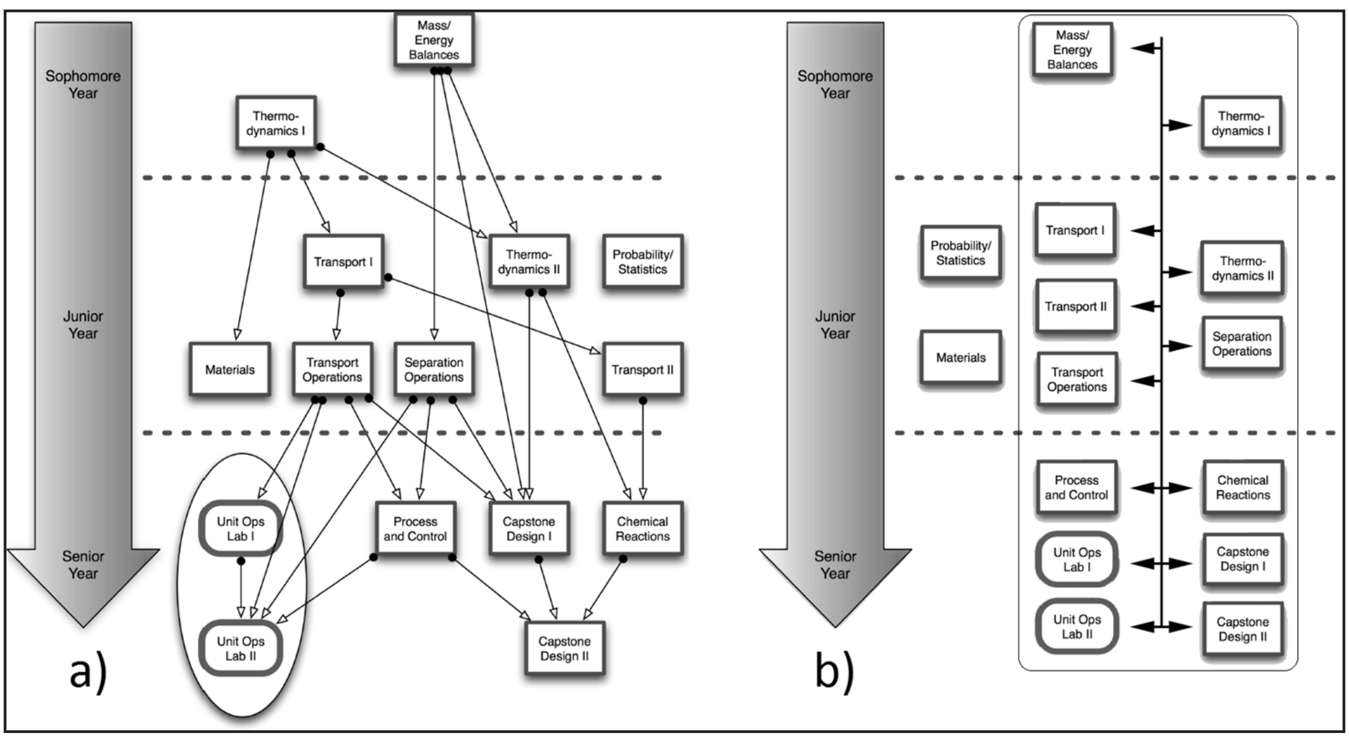

Figure 4. *CCNY chemical engineering curriculum organizational models. a) The original case, without CSTR lab integration. An oval groups courses with a focus on hands-on, applied laboratory experience. Arrows show linkages between classes in terms of prerequisites. b) Vertical integration of courses via the CSTR lab framework. Arrows show classes linked via the design apparatus, where lab experience is now an integral part of all three years of the curriculum. The rounded box replaces the oval, showing a curriculum organized around problem solving and design experience. Prerequisites have not changed, but the rationale behind them is made clearer via escalating complexity of the lab experience.*

TABLE 2 **Results of the junior class survey where 10 = Strongly Agree**		
Survey Question		Score
1.	if the CSTR lab integration helped "develop a sense of community with [their] chemical engineering class year"	8.8 +/- 1.4
2.	if "working on the CSTR labs helped develop a sense of engineering teamwork"	9.0 +/- 1.6
3.	if the lab framework "helped [them] better understand the concepts covered in the chemical engineering curriculum"	8.7 +/- 1.5
4.	if the labs "helped [them] develop practical engineering insight into problem solving for real design challenges"	8.6 +/- 1.1
5.	if the "CSTR labs helped [them] understand the chemical engineering curriculum by introducing topics like reaction design and transport concepts, starting in [their] sophomore year"	8.6 +/- 2.0
6.	if the "introduction to junior- and senior-year concepts demonstrated by the CSTR labs gave [them] a stronger intuition of chemical engineering concepts"	8.3 +/- 2.1

the lab framework can and does scale with the students' class year. This does not necessarily mean there is sufficient data to say earlier laboratory exposure led to increased success, but it does show that the same framework is sufficiently flexible to be used throughout the curriculum to pair classroom learning with experiential learning. All groups were tasked with gathering comparable sets of pH, kinetic, and mass transfer data for their systems. But the seniors were able to recognize mass transfer effects as being the most powerful tool at their disposal. The sophomores, given the same initial data, were not yet at a point where they knew what to do with it. However, it is anticipated that the 10 "failed" sophomore attempts will lead to a better intuition about mass transfer when it comes time to learn the material as juniors.

Building on this example, we plan to continue to expand the CSTR lab framework into the other classes. Following the ideas of JiTT, small modular experiments will be developed to illustrate general concepts with students who are already familiar with the CSTR platform and the sensors available. The *raison d'être* for the chemical engineering curriculum can be opaque compared to other engineering disciplines, but this integration of a single system into the chemical engineering coursework provides an opportunity for students to see connections between the sub-disciplines.

Results to date: enhanced understanding and community

To directly quantify the benefits of the CSTR lab integration, a supplementary survey specifically about the new lab component was given to the department's current senior and junior classes. Only students who had taken the introductory course with the CSTR lab component were asked to participate. The responses from the junior and senior classes are in Table 2 and Table 3, respectively.

In the junior class (33/34 responding), all questions were posed by asking students to rank a statement on a scale of 1-10, with 10 being "Strongly Agree" and 1 being "Strongly Disagree."

The first two questions reveal that the CSTR lab acted as a powerful tool for enhancing a sense of community among our juniors. The remaining questions targeted the students' feelings of how the labs helped them understand core engineering concepts. The responses to this section were also extremely positive, with students estimating that the lab's impact on their sense of understanding was nearly as powerful as its impact on their sense of community as a class year.

TABLE 3 **Results of the senior class survey from "Strongly Agree" to "Strongly Disagree"**			
	Survey Question	% Strongly Agree and Agree	% Neither Agree nor Disagree
1.	if the CSTR lab integration helped "develop a sense of community with [their] chemical engineering class year"	68	26
2.	if working on the CSTR labs "helped develop a sense of engineering teamwork"	89	9
3.	if the lab framework "helped [them] better understand the concepts covered in the chemical engineering curriculum"	71	20
4.	if the labs "helped [them] develop practical engineering insight into problem solving for real design challenges"	83	9
5.	if the "CSTR labs helped [them] understand the chemical engineering curriculum by introducing topics like reaction design and transport concepts, starting in [their] sophomore year"	77	9
6.	if the "introduction to junior- and senior-year concepts demonstrated by the CSTR labs gave [them] a stronger intuition of chemical engineering concepts"	69	22

The seniors (36/39 responding) completed similar surveys after they had finished the new CSTR exercise described in the section on construction and design of the platform. Scaling of the seniors' data is different, as this class responded using the electronic course review system. Seniors selected for each question a response from a list of: "Strongly Agree," "Agree," "Neither Agree nor Disagree," "Disagree," or "Strongly Disagree."

Thus, the seniors' responses to the survey were also positive in terms of the students' understanding and sense of community as a class year.

The seniors answered two additional questions about their experience. Reflecting the fact that the senior class was exposed to the most integrated form of the CSTR lab framework to date, we asked them if "Revisiting the 228 lab environment in 432 Chemical Reaction Engineering was useful in solidifying my understanding of reaction engineering and kinetics": 47% answered "Agree" or "Strongly Agree" while 29% chose "Neither Agree nor Disagree." This type of feedback will allow us to redesign the integration into this particular class to get even better results. We also asked if "[a] recurring lab framework throughout the curriculum would help [them] solidify [their] understanding of the chemical engineering concepts": 83% answered either "Agree" or "Strongly Agree" while 14% chose "Neither Agree nor Disagree." In that response, the seniors agree that expanding the lab to include still more classes is a trend in the right direction. One of the students' open-ended feedback responses supported this theory nicely, stating: "[The CSTR] lab was one of the best labs, if not *the* best I've ever taken. I want more hands-on stuff in our coursework throughout the curriculum. Your work becomes tangible."

Synthesis of current results for improvement

With each iteration of the lab, we have made several minor changes to both the logistics and content of the course. Based on the quality of the data, clarity of the lab reports, feedback from the students, and observations of the group interactions, we would like to highlight three major improvements that have facilitated student learning.

First, the open-ended cooperative learning environment is buttressed in the writing process, but students often need clear guidance in their technical writing. This does not mean that faculty or teaching assistants should provide any sort of remedial support. Rather, a clear set of guidelines, a well-defined example, high expectations, and rapid feedback all enable students to improve quickly.

Second, we found that it was important to calibrate clearly the students' expectations for experimental success. Freshman labs in chemistry and physics are designed to lead students to a prescribed conclusion via a well-defined experimental apparatus. Therefore, students are often unaccustomed to learning through failure. To help remedy this issue, an initial lab was developed coaching students to understand the notion of benchmarking and being willing to quickly surrender their initial assumptions. The 2-hour benchmarking lab is based on Tom Wujec's "Marshmellow Challenge."[15] In this challenge, teams of sophomores compete against each other to build the tallest free-standing structure possible out of fixed amounts of uncooked spaghetti, string, and/or tape. The marshmallow must remain on the top, and maximizing that height is surprisingly challenging.

Third, the initial labs were run effectively as in the standard once-a-week three-hour window, but we have learned that the development of a community around the notion of open-ended cooperative design requires time to adjust the initial experimental setup, reevaluate assumptions, and analyze the quality of data. Our initial lab schedule put students in the lab each week conducting setup, data collection, or competition, but reducing the number of experiments has allowed us to schedule in "team time." This has also been facilitated by creating more accessible lab space where groups that were initially unsuccessful can explore new ideas.

Still, several changes are planned over the next semesters. Based on the described implementation for the last three terms, practical modifications moving forward include an enhanced role of programming in experimental setup and analysis, a module integrating control theory, and a systematic method to connect the CSTR apparatus to existing equipment in the unit operations laboratory.

CONCLUSIONS

A laboratory associated with the mass and energy balance course has been developed that allows for concept integration throughout the remaining curriculum. The laboratory is based on a CSTR that the students assemble and utilize to solve open-ended design problems. Each lab assignment is three weeks and ends with a design challenge based on understanding gained during the previous two weeks. This teamwork experience is complemented by each student writing a laboratory report (cooperative learning).

The knowledge gained in this sophomore-year class can be revisited throughout the curriculum in courses such as kinetics, transport, and controls. Benefits of this integration include earlier exposure to laboratory work, additional group work, and greater understanding of engineering concepts.

Qualitatively, this experience has been a success. The opportunity for students to work in groups toward a common goal across their undergraduate education has enhanced the sense of teamwork and community. Improvements to the lab have been made throughout implementation, and additional changes will be made to enhance the learning experience. This qualitative assessment has been bolstered by surveys of the students, giving initial quantitative support that the recurring CSTR platform is a success.

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