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How We teach: Unit Operations Laboratory

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Abstract
One of the truly distinctive elements of a chemical engineering undergraduate experience is working with larger-scale process equipment in a laboratory setting. Unit Operations courses seek to expose students to the type and scale of equipment they are likely to see in industry and to equip them with the ability to analyze the behavior of these systems as well as have a true "feel" for how they work (or don't work quite as expected).

For the 2017 survey, the AIChE Education Division Survey Committee focused on the laboratory portion of the chemical engineering undergraduate curriculum. Over 70 programs completed the survey, which asked about course structure, hours, and experiments. The typical undergraduate takes one or two laboratory-focused courses within chemical engineering, completes experiments as part of a team, and has at least some exposure to pilot-scale equipment. Virtual experiments make up about 10% of control system experiments and are otherwise relatively uncommon. This paper reports on the survey's key findings as well as some of the highlights of innovative laboratory experience and pedagogy discussed in the results.

Introduction
This paper presents the results of the ninth survey since the reconstitution of the AIChE Education Division Survey Committee in 2009. These surveys seek to define the state of the art in a given area of undergraduate chemical engineering instruction. Departments use survey results to inform curricular discussions and benchmark their program against national trends. Survey results are also useful for instructors as they select topics, software, and instructional approaches for their courses. Past surveys have considered first-year programs [1], Kinetics and Reactor Design [2], Material and Energy Balances [3], Capstone Design [4], Electives [5], Transport [6], Process Control [7], and the curriculum as a whole [8]. In the coming survey cycle, the survey committee will be considering chemical engineering thermodynamics and thereafter loop through the proceeding topics.

While each instructor may have a clear concept in mind when they say "instructional laboratory" or "lab," the activities and educational outcomes associated with these experiences vary so widely that it's easy to be misunderstood. The term "lab" may be applied to learning experiences that are replications of precise instructions, discovery-based experiences, simulations, or programming; they may occur from benchtop to pilot scale; they may imply a different activity every week or a single semester-long project. United States Department of Education guidelines suggest that the credit hours for lab is typically one half of the credit hours accorded for the same contact hours in class [9], implying that there is a precise distinction between lab and lecture that may have eroded in an age of active learning and readily available computing.

For the purposes of this survey, the definitions shown in Table 1 were used to characterize "laboratories" and associated terms. Respondents were asked to restrict their answer to courses taught by the department, therefore laboratories taught within chemistry and physics are not included in this work. The survey committee explicitly did not bound the activities that constitute "lab" but relied on each department's own judgement.

Table 1: Definitions

Term	Operational Definition
Laboratory	A setting where students are primary actors in experimentation, design, operation, and/or control of equipment. Data collection is a key aspect of a laboratory experience.
Course-associated lab	A laboratory that is typically taken concurrently with a particular course; for example "organic chemistry 1" and "organic chemistry lab 1". These may be courses that students register under the same or different course numbers.
Independent-lab-course or lab course	A course whose primary mode of instruction is laboratory. This should be reflected in the relative distribution of laboratory to lecture hours. This course may not be associated with concurrent registration in a specific lecture course. "Unit Operations Lab" or "Junior / Senior Lab" are common examples of this type of course. *This survey is primarily focused on courses of this type*.
Clinic	An integrative experiential hands-on-course that serves as the experimental lab for all other courses taken that semester. This survey is not focused on experiences of this type.
Lab / Bench / Pilot Scale	The definition of what constitutes "pilot" scale varies by industry and type of product. For the purposes of this survey, we will define "pilot" scale as one with working volumes significantly in excess of those one would typically encounter in a chemistry undergraduate laboratory - If students are working with equipment that operates at a scale of the order of 1-100+ L, that will be considered "pilot" for purposes of this study.

There is broad agreement in the sciences and engineering that laboratory instruction is an essential element of undergraduate education. At the same time, physical laboratories require significantly more space, money (for consumable materials and equipment), and instructional personnel than lecture-based courses. Significant prior work has been devoted to characterizing the educational outcomes from laboratories that justify this additional investment [10–16]. A significant portion of the present study focuses on characterizing the educational objectives of chemical engineering lab and its assessment. The last published survey on unit operations laboratory in chemical engineering was published by Woods and Patterson in 1978 [17], as part of the activities of the first Survey Committee (1957-1994).

Methods

An email invitation was sent to all members of the chemical engineering chairs list (173 schools). Of these, 70 degree-programs responded to at least part of the survey and form the numerical basis for the data set. In some summaries, the total number of responses is less than 70 because not every respondent chose to address every question. After the online survey, preliminary results and analysis were presented at the 2017 AIChE Annual Meeting, which was followed by a small-group discussion of the topic with AIChE attendees. This paper represents a more complete analysis of these results as well as reflections drawn from the discussion.

Results

Curricular Descriptive Statistics

The 70 responding programs ranged in size from five or fewer faculty to over 31 faculty and graduating classes from fewer than 20 to over 200. As shown in Figure 1, the population of responding schools was approximately representative of the population of chemical engineering programs overall. Responding departments were from all regions of the United States and both public and private universities.

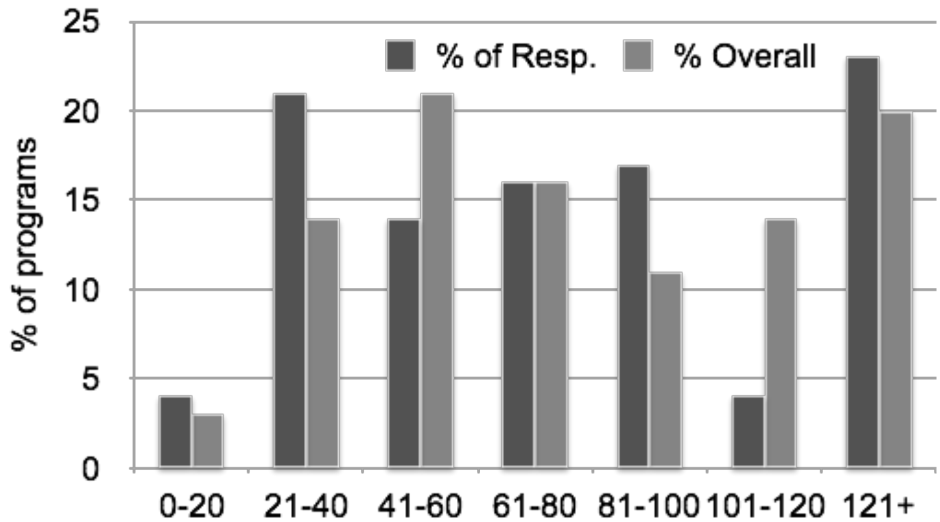

Figure 1: Typical graduating class size by of responding schools and overall

Departments were asked how many courses with laboratory sections were part of their curriculum, counting only courses taught within the chemical engineering department. As shown in Figure 2, the vast majority of programs have two courses with labs, and all programs had at least one. An even larger majority of programs have two required laboratory courses. It is these courses, with titles such as "Unit Operations Lab" and "Senior Laboratory" that is the focus of this survey and of the results from this point onward.

Laboratory courses count for a range of credit hours, with 3.0 credit hours being the most common. The most common schedule is one-or two- meetings per week for 3-4 hours per meeting.

When there are multiple courses they take a variety of forms. For about one third of programs, the two courses are similar but tailored to reflect the concepts of the other core courses that semester. For 30% of programs, the two courses are entirely distinct. For 20% of courses, they are essentially one course that is split between two or more semesters. The remainder of programs are not easily grouped.

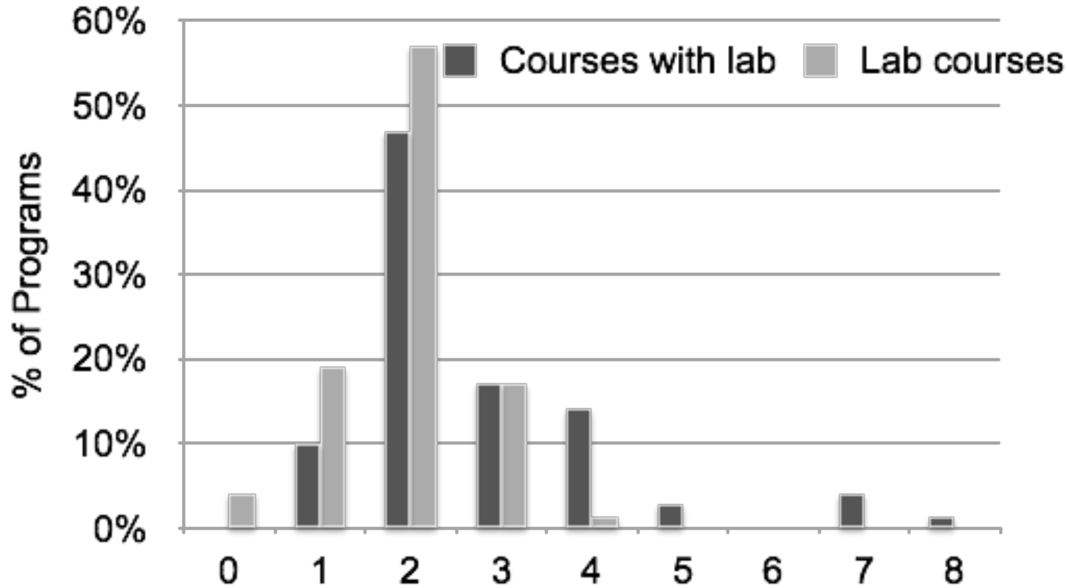

Figure 2: Number of courses with laboratories and number of laboratory courses in the curriculum (as defined in Table 1)

As required courses, overall enrollment in laboratory courses reflects the sizes of the graduating class. Survey results show that departments tend to run multiple sections so that the median number of students per section is 20, with the median number of sections per semester being three. All but one program reported students work in teams or groups within these lab courses, with seven teams per section being the median value.

Experimental Characteristics

In the 1978 paper, Woods characterized [17] experiments by concept area, a practice adopted by the current survey and shown in Figure 3. To help respondents understand the concept area, several examples of possible experiments within that area were listed. “Measurement” experiments are those that focus most closely on measurement of a given experimental parameter or calibration of an instrument (ex: thermocouple calibration). “Fluids” experiments concentrate on flow, friction factors, and the operation of pumps. “Heat” experiments concentrate on heat transfer, with operation of a heat exchanger being the most typical. “Mass transfer” experiments are those that focus on mass transfer or separations, such as membrane operations or distillation. “Reactors” experiments focus on reaction systems, while “control” experiments main focus is tuning the control of a system. “Particle” experiments focus on processing of particulates. “Bio” was added to the categories from the 1978 study. “Bio” includes fermentation and enzyme experiments. A given experiment may hit multiple concept areas.
As in 1978, experiments involving measurement, fluid mechanics, heat transfer, mass transfer are nearly universal, while experiments in particle processing are rare. About half of all programs have a pilot scale version of their experiments, such as larger-scale distillation towers. Also new since 1978 are virtual laboratories; these are in use but are not yet widespread for any area but control systems in laboratory courses. Twelve programs have integrated systems of multiple unit operations that more closely replicate a manufacturing environment.

Unfortunately, the data collection in the 1978 study used a class-hour as the unit of analysis, something we are unable to replicate in the current study. While it's possible to get a sense of the overall distribution of experiments from that study as described above, a direct comparison to Figure 3 is not possible.

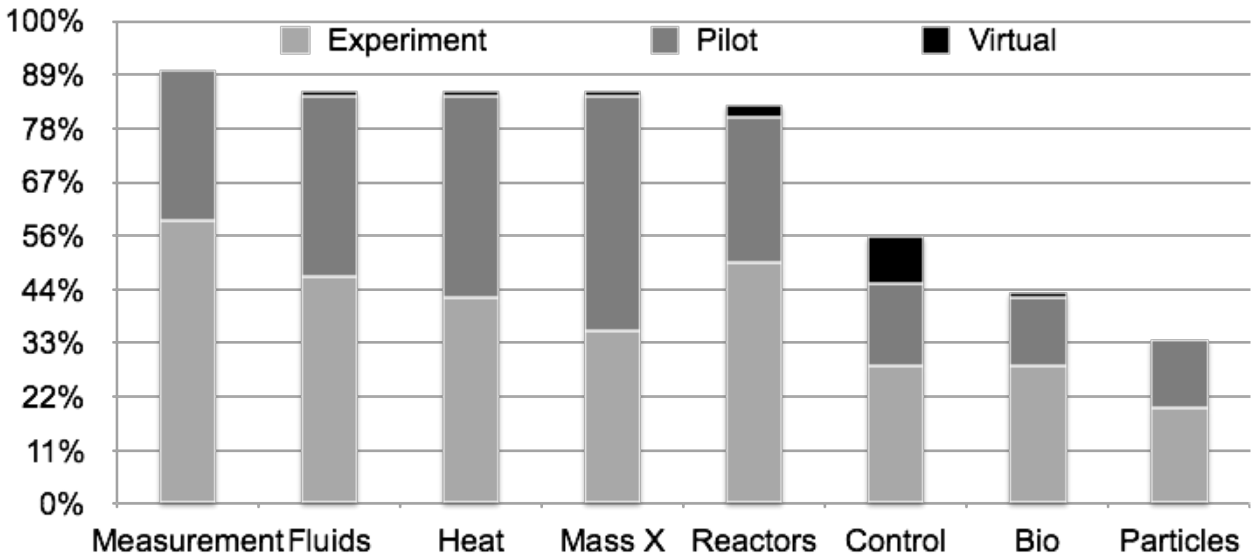

Figure 3: Concept areas and types of experiments

Safety, expense, and observability are important considerations for both mass transfer and reactor experiments. It is challenging to define a practical chemical system that meets all of these constraints for use in these experiments, and the survey asked respondents to share what they are using. For mass transfer, systems included carbon dioxide / water; carbon dioxide / water / NaOH; liquid-liquid extraction of acetic acid from mineral oil to water; distillation of alcohols from water; dialysis or reverse osmosis to remove sodium chloride; and caffeine extraction. Reaction systems included fermentation of yeast, saponification, bleaching whey protein, decolorization of crystal violet, and hydrolysis of acetic anhydride.

<u>Learning Objectives</u>

Feisel and Rosa [13] defined 13 typical learning objectives for engineering laboratories. In the survey, programs were asked to response to the extent to which these objectives were also the objectives of their laboratory courses and if those objectives were assessed within those courses. Table 2 summarizes the results of these questions; surprisingly the only universal outcome for laboratory courses is the analysis of data. Only one of the top five objectives requires a physical laboratory to take place and two of the objectives that can only be met within a laboratory (psychomotor skill development and sensory awareness) are among the least popular. Other objectives reached through these courses include the development of engineering intuition and troubleshooting skills.

Table 2: Laboratory course objectives; unit of analysis is one course

Outcome	Represented?	Directly assessed?
Practice data analysis	100%	93.4%
Practice effective teamwork	98.4%	80.3%
Demonstrate laboratory ethics	98.4%	93.4%
Exercise creativity within an engineering context	88.5%	62.3%
Become familiar with appropriate instrumentation	78.7%	62.3%
Design an experiment	78.7%	62.3%
Identify strengths and weaknesses of theoretical models as descriptors of real-world outcomes	77.1%	57.4%
Practice professional communication	67.2%	24.6%
Practice engineering design	54.1%	39.3%
Learn from failure	45.9%	16.4%
Develop specific psychomotor skills	45.9%	16.4%
Identify health, safety, and environmental issues	45.9%	11.5%
Other	29.5%	6.6%
Develop sensory awareness of chemical processes	14.8%	3.3%

A follow-up question to the "design of experiments" objective (Table 2) asked if students were taught this skill within this course or in a prior course; results indicated a 50/50 split, with a few programs responding "both.

In addition to the technical outcomes given in Table 2, unit operations courses tend to be responsible for assessment of a number of additional ABET outcomes. Table 3 shows the distribution of these assessments. Assessment of communication, both oral and written, is nearly universal.

Table 3: ABET Outcomes assessed through laboratory courses

ABET outcome	% of Responses
Writing/Communication	96.6%
Safety	70.7%
Ethics	41.1%
Evaluation of information sources	34.5%
Knowledge of environmental/political/social impacts	13.8%
Regulatory understanding / compliance	12.1%
Other	10.3%

As noted in Table 3, communication is a frequently cited outcome for the laboratory course. Figure 4 shows how this communication is distributed, demonstrating that most programs courses have both pre- and post- laboratory communication, and that this communication is distributed between both oral and written forms. "Other" comprised a wide variety of additional approaches to communication, the most common of which was posters. Also included were scientific notebooks, proposals, lab practicals, and full-scale designs.

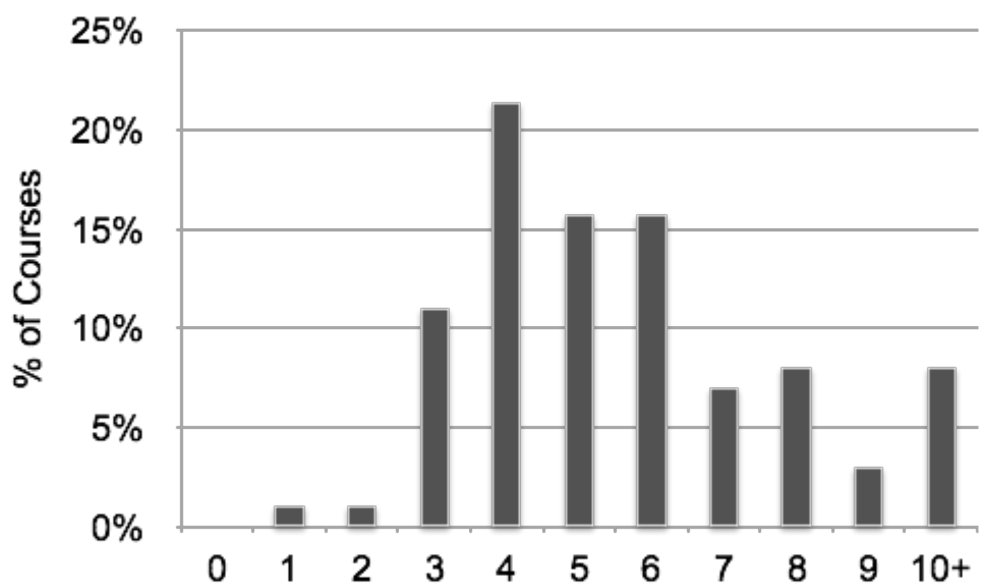

Figure 4: Number of summative communication products (ex: memo/report/presentation)

<u>Teamwork and Safety</u>

Because teamwork in laboratory courses is nearly universal, grading must incorporate both individual and team components. The most common approach to this is adjusting the team grade for each member based on participation and team member/faculty feedback, as shown in Figure 5. Other approaches to grading were also popular, with a mixture of individual and team reporting being the most common.

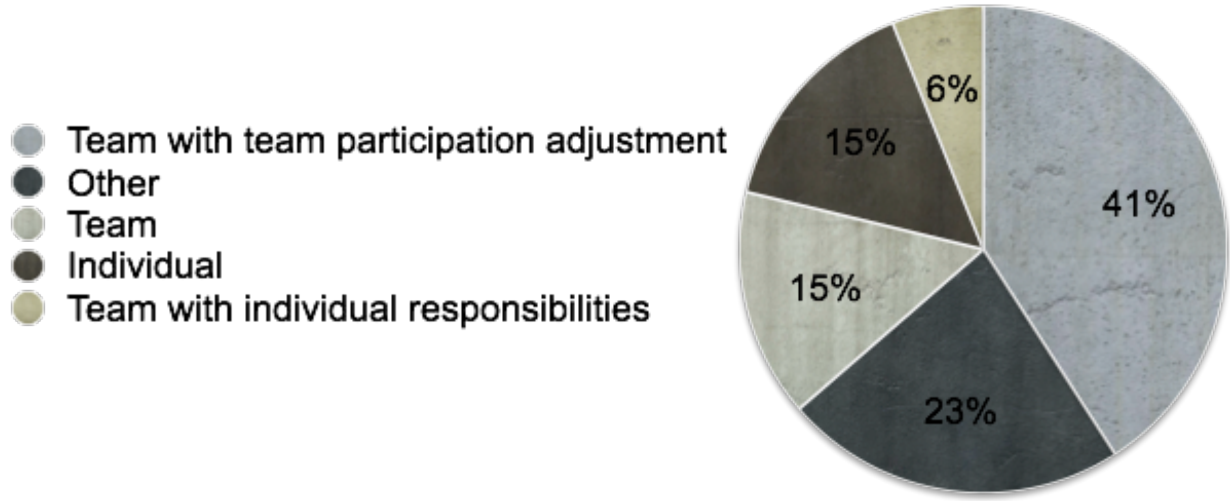

Figure 5: Teamwork influence on laboratory grading

Laboratory safety is an expected part of laboratory course instruction, and all programs reported that it is addressed in some way. Figure 6 shows the diversity of approaches to this important topic; it is important to note that these approaches are not exclusive and many courses reported using more than one.

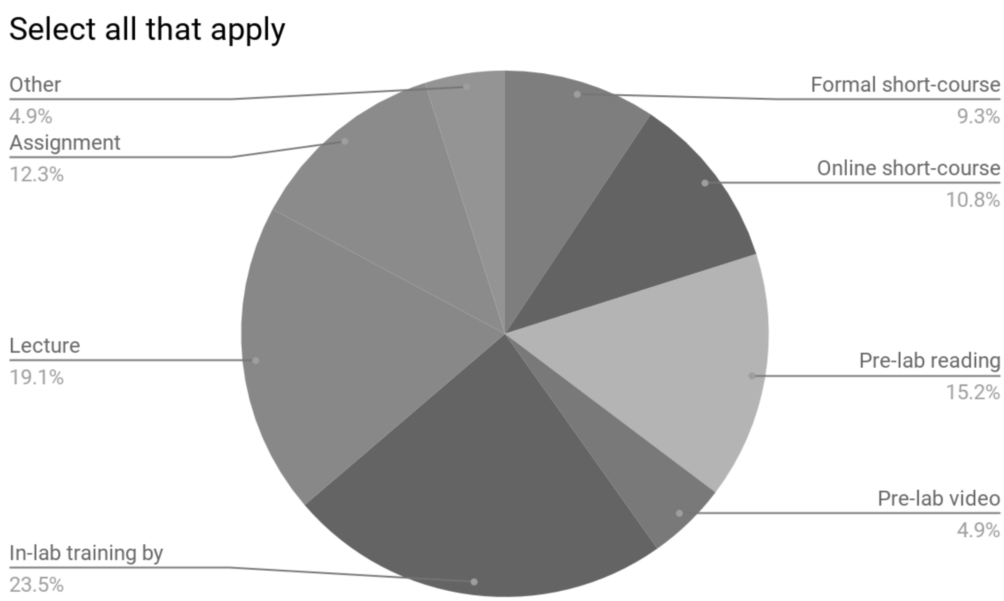

Figure 6: Approaches to laboratory safety instruction

Because of the presence of larger-scale equipment in many unit operations courses, there is the potential to address process safety in additional to laboratory safety. Two-thirds of programs reported that they are addressing or trying to address process safety within their lab courses. They are doing so through a variety of approaches, as seen in Figure 8. In addition to these, respondents reported using case studies from the Chemical Safety Board or in-class discussion of the process safety features (pressure relief valves, for example) included in the laboratory set-up.

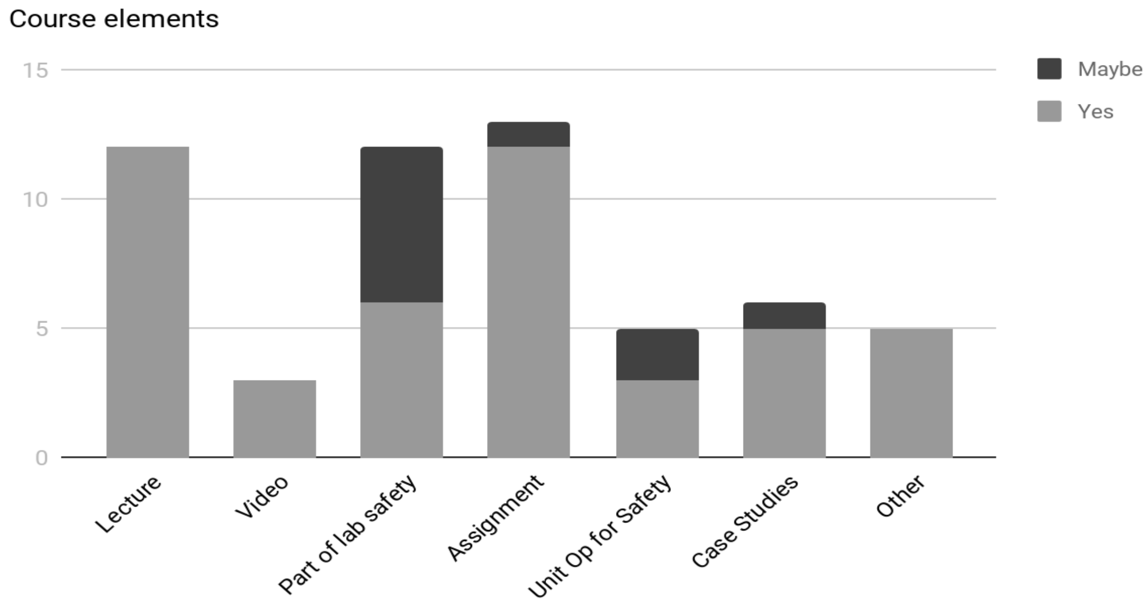

Figure 7: Approaches to process safety in laboratory courses. "Maybe" means the course is trying to address these issues.

Discussion

In addition to the summative numbers, discussion at the AIChE meeting and written responses to survey questions highlight some interesting and innovative practices in laboratory courses. For example, at Northeastern University, the course has been structured to cycle from "discovery to development to design." Discovery operates at the bench scale and development scales-up this work to larger equipment. Students are then challenged to use what they have learned to propose a design addressing one of the NAE Grand Challenges. At the University of Kansas, a number of experiments have been built on wheeled carts so that they are portable and may be brought into a number of courses. First year students are exposed to laboratory concepts at a basic level to build their interest, then students see the same experiments later when they are able to engage with them on a more technical level. At the University of California, Berkley, a sub-set of students are able to take a biological process focused version of the unit operations sequence. Student teams compete for this through a proposal process, and design and operate a bioprocess operation throughout the course.

Laboratory instructors also reflected on new areas for development of laboratory courses. The advent of accessible rapid fabrication (3D printing, laser cutting) and inexpensive microcontrollers such as Arduino is opening doors to not only less expensive analytical equipment, but analytical equipment that is designed and built by students themselves [18]. Faculty at Rowan and at University of Toledo have developed fluid mechanics experiments that rely upon student-designed, 3D-printed elements. This allows students to achieve the standard technical course outcomes for mixing and pumping as well as to practice CAD and engineering design skills.

Discussion at AIChE also highlighted the ways in which the laboratory courses can contribute to recruitment and retention in the major. Several departments have moved their first laboratory course "lower" in the curriculum in order to more rapidly involve students in larger-scale processes. The idea of running the same experimental system at increasing levels of complexity for 1st, 2nd, and 3rd year students was also discussed.

Courses such as unit operations laboratory continue to be at the core of an undergraduate chemical engineering education. Faculty and students alike recognize these courses require significant effort, and feel that the transformative experience is well worth the investment.

Acknowledgements
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