Towards Evaluating the Content, Assessment, and Pedagogy in Instructional Laboratories

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Abstract

This paper presents a rubric to assess the educational design of instructional laboratory courses in engineering. This rubric can be used as a tool for researchers investigating engineering laboratories as well as by instructors evaluating and improving their own courses. The rubric is based on a rigorous course design framework. It evaluates the content of the course based on centrality to the discipline, challenge to students, and clarity of learning objectives. Assessment is evaluated based on variety of assessment types and purposes and justification of their use. Pedagogy is evaluated based on use and justification of canonical educational principles. Further, the rubric explores the alignment between content, assessment, and pedagogy. In order to develop and assess the usefulness of the rubric, we used it to evaluate the course design of published reports of engineering laboratories. In general, the courses described presented strong pedagogical techniques and demonstrated strong alignment between pedagogy and content, but weak alignment between content and assessment. We also found that while the rubric could be used to evaluate courses based on their reports in conference and journal papers, additional forms of data such as syllabi or course observations might have been applicable as well.

Introduction

Instructional laboratories (labs) have been a cornerstone of engineering education since they were first introduced in 1869[1]. Educators agree that labs help students develop practical and professional skills, enhance and refine theoretical content knowledge, and increase motivation to persist in engineering[2,3], but laboratory environments have become increasingly diverse. Some instructors are adopting design and open-ended activities over traditional "cookbook" labs[4,5]. Others have explored alternative methods of student teamwork[6,7]. Virtual and remote laboratories have become commonplace and researchers continue to develop more realistic and enhanced interfaces for this technology[8-10].

In light of recent advances in educational research[11], and the aforementioned changes in laboratory environments, an empirical study of current practices in engineering laboratories is needed. Towards this end, this paper presents a rubric to assess the educational design of instructional laboratory courses in engineering. This rubric can be used as a tool for researchers investigating engineering laboratories as well as instructors evaluating and improving their own courses. This paper also presents a brief content analysis of the types of content, assessment, and pedagogy demonstrated in current engineering laboratory courses.

Framework for Rubric Development

The analysis in this paper is based on a framework for course design synthesized by Streveler and Smith called the CAP model[12]. In this model, there are three equally important components of course design: content, assessment, and pedagogy. Streveler and colleagues[12] stress the importance of quality content, assessment, and pedagogy; and further stress the importance of alignment between the three.

Content includes the knowledge, skills, and attitudes instructors wish to impart to students during the courses. Strong content, according to Wiggins and McTighe[13], includes material that represents core concepts in the discipline, will be essential for students to know moving forward with their academic and professional careers (i.e., "enduring understanding"), and students would not be able to learn without the guidance of an instructor. The selected content is typically organized into measurable learning objectives. Learning objectives, therefore, act as a bridge between content and assessment.

Assessment includes methods instructors will use to determine whether students are meeting the learning objectives[12]. Streveler and colleagues[12] recommend using both formative and summative assessment. The purpose of formative assessment is to provide feedback to students while summative assessment is used to inform and improve pedagogical practices. Assessment should be aligned with content—i.e., if students are expected to be able to design a low-pass filter, assessment should include low-pass filter design—and should be informed by a learning taxonomy, such as Bloom's Taxonomy of Teaching, Learning, and Assessing, revised by Anderson and Krahtwohl [14].

Pedagogy includes methods, such as in class activities and feedback, instructors use to ensure students meet learning objectives[12]. Perkins[15] describes seven principles of sound pedagogy including: involving students in the whole activity, creating a motivating and comfortable environment, focusing on difficult concepts, promoting transfer through variety of activities and opportunities for reflection, providing opportunities for modeling or scaffolding, employing pedagogies of engagement, and fostering self-regulated learning. Instructors should attempt to employ all seven of Perkins' principles, but also be sure that pedagogy is aligned with both content and assessment. For example, if students are expected to be able to design a low-pass filter, the learning environment and activities should be directed towards that objective and allow assessment of low-pass filter design.

Rubric Development and Design

We designed Laboratory Evaluation Rubric in order to evaluate how well each lab course was designed according to the CAP framework[12]. The rubric (see Appendix A) included sections on quality of content, quality of assessment, quality of pedagogy, alignment between content and assessment, alignment between content and pedagogy, and alignment between assessment and pedagogy. A well designed course would score well in all categories. Much of this rubric was derived from resources described in[12]. These resources included Perkins' Seven Principles of Teaching [15], Wiggins and McTighe's Backwards Design[13], and Anderson and Krahtwohl's revision of Bloom's Taxonomy[14].

We developed the rubric through an iterative process. The purpose of the iterations was to ensure that the rubric was clear and withstood external scrutiny. First, we developed an initial draft of the rubric and discussed it with researchers who had experience in engineering course design. We then revised it based on the researchers' suggestions and tested it on a sample of ten recent peer-reviewed conference and journal papers that described laboratory courses in electrical engineering. We chose peer-reviewed journal and conference papers because (a) peer review ensures a level of acceptance and credibility in the field, (b) the papers describe actual rather than proposed implementations of courses, and (c) papers provide a limited but sufficient description of the courses. Points A and B describe why peer-reviewed papers are preferable over alternatives such as course syllabi or proposals. Point C makes it possible to demonstrate the rubric's usefulness for quick assessment, even without comprehensive course information. Further, these papers represent current educational innovations, thus they not only represent the current status of engineering labs but directions for the future. We revised the rubric a second time based on the results of the initial trial. We made alterations to improve unclear wording, refine the content of categories to better suit the data, and provide clarifying examples in certain categories.

Research Design

Data Collection

We compiled a database of recent peer-reviewed papers describing engineering laboratory courses using the Compendex online research library. We chose this database because it compiles results from many engineering-related journals and conference proceedings including the *Journal of Engineering Education*, *IEEE Transactions on Education*, and ASEE conference proceedings. Search terms included laboratory, course, and electrical engineering. We required both "laboratory" and "course" to be included in the title to ensure that the papers focused on, rather than just included, an engineering laboratory course. By searching for electrical engineering labs only, we ensured some consistency of content focus and teaching practices. Allowing for labs from different disciplines would have allowed too various of a sample to allow meaningful findings to come to light. We further refined the search to include only English-language articles under the "Education" or "Education & Training" categories and papers published recently (2011-2012).

We identified a total of 11 recently published articles suitable for evaluation. Six of these articles were published in *IEEE Transactions on Education*, three were published in the proceedings of the ASEE/IEEE Frontiers in Education Conference, and the remaining two were published in the proceedings of the ASEE Annual Conference and Exposition. Of the labs described therein, all but one were housed in electrical/electronics engineering or related departments. The remaining lab was housed in a general engineering department. Three of the 11 labs were intended for graduate students, seven were intended for upper-level undergraduate students, and one was intended for first- or second-year students. The subject areas included: communications, electronics, induction motors, controls, circuit analysis, radio frequency circuits, and force microscopy. Ten of the courses contained both lecture and laboratory components, in only one of which the lecture supported the laboratory portion. One course was laboratory only. Seven of the courses contained physical laboratories, three contained remote laboratories (one of which allowed remote access after a physical lab session), and four contained simulations. Only two of the simulation courses contained simulations only. Of the remaining two, one used simulations as a pre-lab exercise and one used a combination of simulations and remote lab access. Four of the labs were at American universities, two were from Mexican universities, and of the remaining there was one lab each from Algeria, Canada, Spain, Serbia, and Turkey. These demographics demonstrate that the courses contained within the sample represent a variety of laboratory courses within electrical engineering.

Data Analysis

Content Analysis

In order to facilitate evaluation on the rubric, we found it beneficial to perform a quantitative content analysis on the sample of 11 papers. Content analysis is the search for patterns and themes among documents and other artifacts[16]. While we found no previous example of researchers performing a content analysis on peer-reviewed conference and journal publications to describe engineering instructional practices, Borrego and Cutler[17] performed content analysis on funding proposals to describe current instructional practices of graduate programs.

We took an inductive-deductive approach to coding[16]. First, a researcher open-coded a sample of five papers for information about the course the paper was describing. While we chose this technique to allow codes, and thereby patterns, to emerge from the data rather than an existing framework such as that described in[8], we were expected that many codes would fit into four categories: content, assessment, pedagogy, and background. The first three categories come from the rubric categories and also match the code categories identified by Borrego and Cutler[17]. The final category allowed for additional course information including university, intended student audience, information on previous course offerings, and course implementation that may have been helpful in understanding the context of the course. We did not initially place codes into any of the four categories so that this existing scheme would have little bias on the initial codes, and to allow for additional categories of codes to emerge.

During a second round of coding, we reviewed and refined existing codes of the initial five articles. We also coded the remaining six articles using the emerging coding scheme, while also allowing new codes to emerge. As we completed this round of coding, we also recorded all codes and placed them into the four categories of content, assessment, pedagogy, and background. No additional categories emerged. This second round of coding resulted in a set of 159 codes.

Before a final round of axial coding, we further refined the codebook. We identified six sub-categories within the main categories of content, assessment, and pedagogy. We removed the background category and its corresponding codes, which we used to describe labs in the “Data Collection” section of this paper. Further, we removed any redundant codes and refined existing within remaining categories. The result was a 54-item codebook which we applied to all 11 articles. We report the frequency counts of each code in the “Results” section of this paper not as a demonstration of the current status of all engineering laboratory courses (our sample is too small and narrowly-focused for such generalizations), but as a demonstration of the details of laboratory courses used in this study.

Rubric Analysis

The content analysis helped us to clarify the types of content, assessment, and pedagogy employed in each of the 11 courses and allowed us to create consistent profiles for each course. Using the results of the content analysis and reviewing the original papers, both authors employed the rubric to evaluate each of the 11 courses. We report the average of these scores in the "Results" section.

Results

Content, Assessment, and Pedagogy of Courses in the Sample

Tables 1–3 present the frequencies with which each code was observed. The most common learning objective was familiarity with technology or components. The most common laboratory purpose was to complement theory with practical knowledge or hands-on experience. Among assessment techniques, instructors most often used lab reports to designate student performance and surveys to indicate course effectiveness. The most common lab activity was calculating, plotting, or processing information based on measured data. Computer simulations and cookbook labs were the most frequent pedagogical techniques.

Table 1. Frequency of Content Categories

Sub-category	Code	Frequency
Learning Objective	**Familiarity with technology and components**	**7**
	Conceptual Understanding	**5**
	Measurement	**4**
	Application of science and math	**2**
	Data Interpretations	**3**
	Debugging/testing	**1**
	Design	**4**
	Design Decision-making	**1**
	Write program/script	**2**
	Hardware proficiency	**4**
	Fabrication	**2**
Purpose	**Broad Application/Fundamental**	**3**
	Complex topic	**3**
	Emerging field/technology	**1**
	Theory-to-practice/hands-on experience	**6**
	Industrial importance	**2**
	Based on textbook	**1**
	Topic typically not covered	**1**
	Common technology	**1**

Table 2. Frequency of Assessment Categories

Sub-category	Code	Frequency
Student performance	**Pre-lab**	**2**
	Lab/project report	**6**
	Written exam	**1**
	Oral exam/interview	**3**
	Written problem set	**1**
	Design analysis	**2**
	Lab practical	**1**
Course evaluation	**Survey**	**9**
	Interview	**2**
	Student performance	**2**

Table 3. Frequency of Pedagogical Methods

Sub-category	Code	Frequency
Activity	**Observe**	**3**
	Build/fabricate/prepare materials	**5**
	Design	**4**
	Analyze/Interpret/Compare	**6**
	Measure	**5**
	Calculate/Plot/Process	**7**
	Debug/test performance	**5**
	Operate Hardware	**6**
	Explain	**1**
	Computer programming/modeling	**4**
Environment	**24 hour access**	**3**
	Computer simulations	**5**
	Lecture/Seminar	**1**
	Work at own pace	**3**
	Feedback before/during lab	**3**
	Select own equipment/components	**3**
	Focus on content rather than tools	**5**
	Increase complexity over semester	**4**
	Opportunity for reflection	**1**
	Work in teams	**2**
	Cookbook labs	**5**
	Demonstrations	**1**
	Pre-lab exercises	**4**
	Project	**2**
	Environment altered based on student feedback	**5**

Quality and Alignment of Content, Assessment, Pedagogy

Table 4 presents the mean, minimum, and maximum score labs received. Labs scored the highest in alignment between content and pedagogy and scored lowest in alignment between content and assessment.

Table 4. Rubric Scores of Labs

Category	Mean	SD	Min	Max
Content	**2.82**	**1.33**	**1**	**5**
Assessment	**2.82**	**1.33**	**1**	**5**
Pedagogy	**3.10**	**0.83**	**2**	**4**
Alignment b/w Content and Assessment	**2.40**	**1.29**	**1**	**4**
Alignment b/w Content and Pedagogy	**3.91**	**0.83**	**2**	**5**
Alignment b/w Assessment and Pedagogy	**3.45**	**1.37**	**1**	**5**

Discussion

Rubric Implementation

For the most part, papers were easy to score and the raters agreed on their scores. Because of the nature of the data, however, raters did have to make certain assumptions regarding how certain activities and assessments. For example, alignment between content and assessment or content and pedagogy were often inferred rather than explicitly described in the papers. This level of uncertainty did not seem to affect our ability to evaluate the courses at a reasonable level. With different data, such as syllabi, course proposals, or course observations, the challenges related to evaluation are likely to change.

Having performed the content analysis improved our ability to evaluate the courses in a consistent fashion, as well as to clarify aspects of the courses that might have been overlooked without such analysis. This step is by no means necessary, and would not be applicable for instructors looking to evaluate their own courses based on personal knowledge of classroom observations. However, the coding scheme presented in this paper can be used or modified for use in conjunction with future implementations of the Laboratory Evaluation Rubric.

Notes on Rubric Results

Rubric scores allow us to make some inference of the quality of laboratory environments and potential areas for improvement. The courses in this study demonstrated above average pedagogy and alignment between pedagogy and both content and assessment. The link between content and pedagogy was particularly strong, indicating the learning activities mirrored learning objectives. Innovative assessment techniques such as one-on-one interviews and analysis of lab deliverables show promise in identifying student conceptual understanding and integrating assessment into course activities. These techniques allow less time to be dedicated to assessment alone and allow assessment to occur in more natural settings. Further, three of the 11 labs allowed 24 hour access to laboratories (remotely) and allowed students to work at their own pace. Further, five of the 11 courses used some form of student feedback to improve the course during or after the semester. These pedagogical practices allow students to have more control over their learning which can lead to greater motivation and achievement. A particularly interesting tactic was a combination of pre-lab simulations, a physical lab environment, and remote post-lab access to further explore the topic.

Despite the strong pedagogical practices evident in many of the labs, this small set of lab courses demonstrates significant missed opportunities. Only one course specifically designed activities and assessments to give students opportunities to reflect on their learning and projects. Further, at least five of the 11 labs relied on heavily prescribed laboratory procedures commonly referred to as cookbook labs. When coupled, lack of reflection and cookbook labs present an environment in which students perform laboratory work mechanistically with little understanding of how and why the work they are doing is important or might be applied later in different contexts. Further, scores on the rubric indicate that instructors employ below average lab content and assessments, with below average alignment between the two. Instructors most often struggled to identify learning objectives at the core of the discipline and assessments that were aligned with course learning objectives and evaluated higher-order learning such as the ability to evaluate or create.

There was also much information missing from the lab descriptions. Few papers wrote of the student experience beyond the task they are expected to accomplish and deliverables they are expected to create in lab, or their general responses to course evaluations. It would be interesting to know if and how they worked together on assignments, topics and tasks with which they struggled, how they interacted with the laboratory technology, etc. Without descriptions of the student experience, or how the instructor interacted with the students, it is difficult to assess to what extent students were engaged or actively participated in the lab activities, whether modeling or scaffolding occurred, and whether they completed the labs mechanistically or had more meaningful lab experiences.

Conclusions

The primary focus of this study was the development of a rubric to evaluate the quality of content, assessment, and pedagogy in lab, as well as alignment between the three. We found that the rubric was easy to use. Although we used it as evaluate a small sample of recent electrical engineering laboratory courses, we expect that it can be employed in a variety of settings (both research and practical) to evaluate a variety of engineering laboratory courses based on a variety of data sources.

This paper also presented a content analysis and evaluation of 11 labs described within peer-reviewed journal and conference papers. We iteratively developed a coding scheme to identify content, assessment, and pedagogy in lab courses. Overall, labs scored below average on categories and alignment related to both content and assessment and above average on categories and alignment related to pedagogy. Many labs employed traditional tactics, but the variety of code demonstrated diversity among lab practices. Researchers and instructors might further explore innovative practices for effectiveness in general and specific contexts, as well as focus on quality content, assessment, and alignment thereof. In future work, we plan to further refine both the rubric and coding scheme in order to analyze and evaluate a larger sample of peer-reviewed papers.

References

1. Mann, C.R. A study of engineering education. *Bulletin* **11**(1918).
2. Feisel, L.D. & Rosa, A.J. The role of the laboratory in undergraduate engineering education. *Journal of Engineering Education* **94**, 121-130 (2005).
3. Sheppard, S. & Carnegie Foundation for the Advancement of Teaching. *Educating engineers : designing for the future of the field*, (Jossey-Bass, San Francisco, CA, 2009).
4. Uribe, R., Haken, L. & Loui, M. A design laboratory in electrical and computer engineering for freshmen. *IEEE Transactions on Education* **37**, 194-202 (1994).
5. Domin, D.S. A review of laboratory instruction styles. *Journal of Chemical Education* **76**, 543 (1999).
6. Fila, N.D. & Loui, M.C. Work-in-Progress - Who's Driving? Structured Pairs in an Introductory Electronics Laboratory. *2010 Ieee Frontiers in Education Conference (Fie)* (2010).
7. Brown, S., Flick, L. & Fiez, T. An investigation of the presence and development of social capital in an electrical engineering laboratory. *Journal of Engineering Education* **98**, 93-102 (2009).
8. Ma, J. & Nickerson, J.V. Hands-on, simulated, and remote laboratories: A comparative literature review. *ACM Computing Surveys (CSUR)* **38**, 7 (2006).
9. Andujar, J.M., Mejias, A. & Marquez, M.A. Augmented Reality for the Improvement of Remote Laboratories: An Augmented Remote Laboratory. *IEEE Transactions on Education* **54**, 492-500 (2011).
10. Wolf, T. Assessing student learning in a virtual laboratory environment. *Education, IEEE Transactions on* **53**, 216-222 (2010).
11. Bransford, J. *How people learn: Brain, mind, experience, and school*, (National Academies Press, 2000).
12. Streveler, R.A., Smith, K.A. & Pilotte, M. Content, assessment, and pedagogy (CAP): An integrated engineering design approach. in *Outcome-Based Education and Engineering Curriculum: Evaluation, Assessment and Accreditation* (eds. Dr. Khairiyah Mohd Yusof, *et al.*) (Universiti Teknologi Malaysia, Malaysia, 2011).
13. Wiggins, G.P. & McTighe, J. *Understanding by design*, (Association for Supervision & Curriculum Development, 2005).
14. Anderson, L.W., *et al.* A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives. (2000).
15. Perkins, D.N. *Making Learning Whole: How seven principles of teaching can transform education*, (Jossey-Bass, 2010).
16. Patton, M.Q. *Qualitative research and evaluation methods*, (Sage, Thousand Oaks, CA, 2002).
17. Borrego, M. & Cutler, S. Constructive alignment of interdisciplinary graduate curriculum in engineering and science: An analysis of successful IGERT proposals. *Journal of Engineering Education* **99**, 355-369 (2010).

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Appendix A: Laboratory Evaluation Rubric

Attribute	Poor (1 pt)	Marginal (2 pts)	Acceptable (3 pts)	Good (4 pts)	Superior (5 pts)
Content	Learning objectives are unclear or underdeveloped.	Course operates with well-defined learning objectives but these objectives extend well beyond core concepts in the discipline and need not necessarily be investigated in a laboratory environment.	Learning objectives align mostly with core concepts in sub-discipline **OR** represent enduring understanding and/or things that are good to know **OR** present a challenge to students that likely could not be met outside of a lab environment. These links may be implicit.	Learning objectives align mostly with core concepts in sub-discipline **AND** represent desirable enduring understanding **OR** present a challenge to students that likely could not be met outside of a lab environment. At least one of these links is justified within the paper.	Learning objectives clearly align with core concepts in sub-discipline **AND** represent desirable enduring understanding **AND** present a challenge to students justifying laboratory environment. At least some of these links are justified within the paper.
Assessment	Assessments are not described.	At least one form of assessment is used **AND** focus only on lower-order learning (remember/understand)	At least one form of assessment is used **AND** they include at least some items that assess mid-level learning (analyze/apply)	Multiple forms of assessment are presented **AND** they include at least some items that assess mid-level learning (analyze/apply)	There are multiple forms of assessment **AND** their use is justified in the paper **AND** they include at least some items that assess higher-order learning (evaluate/create).
Pedagogy	Instructors clearly do not follow any of Perkins' seven principles.	Instructors may employ at least one of Perkins' 7 principles, but are missing a key element.	Instructors clearly employ at least one of Perkins' 7 principles, with less successful attempts of at least two others.	Instructors clearly employ at least 3 of Perkins' 7 principles:	Instructors clearly employ at least 5 of Perkin's 7 principles. Use of pedagogical techniques are justified.
Alignment: Content-Assessment	Assessment is not described or in no way aligned with learning objectives.	Assessments only cover some of the learning objectives.	Assessments likely cover at least half of the learning objectives. Link not explicit.	Assessments likely cover each learning objective, but link not made explicit.	Assessments cover each learning objective. Links made explicit in paper.
Alignment: Content-Pedagogy	Learning activities are in no way aligned with learning objectives.	Learning activities cover some of the learning objectives.	Learning activities likely cover at least half of the learning objectives. Link not explicit.	Learning activities likely cover all learning objectives, but link not made explicit.	Learning activities cover each learning objective. Link made explicit in paper.
Alignment: Assessment-Pedagogy	Assessments clearly different than and incompatible with learning activities.	Assessments may be compatible with learning activities, but likely are not. (E.g. paper and pencil exams that may cover skills used in lab)	Some assessments are compatible with learning activities, some are not. (E.g. lab reports and paper-and-pencil exams for all hands-on work)	Assessments are compatible with learning activities. (E.g. practica if all hands-on work)	Assessments are integrated into learning activities. (E.g. evaluation of designs produced in lab)

* *Perkins' Seven Principles*:

- Present whole activity to help understand larger context
- Motivation through comfort, challenge, curiosity, tolerance of failure
- Focus on difficult concepts with frequent actionable feedback
- Variety of applications and domains and opportunities for reflection
- Cognitive apprenticeship (scaffolding, modeling)
- Pedagogies of engagement (active and collaborative learning) [needs to go beyond just letting students work together or "hands-on" learning]
- Self-regulated learning