Coordinating Laboratory Courses Across Engineering and Science Curricula

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Summary

An emphasis on discipline-specific content in laboratories in higher education can lead engineering and science students to perceive an experience in one course as irrelevant to work in other disciplines, and often even to subsequent course work within the same discipline. This compartmentalized approach compromises the progressive advancement of laboratory skills and acquisition of problem-solving capabilities. In order to address this issue, instructors for laboratory courses in Bioengineering, Chemical Engineering, Physics, Biochemistry and Cell Biology, Chemistry, and Ecology and Evolutionary Biology at Rice University have met regularly to discuss how to develop scientifically literate graduates who build upon prior laboratory experience as students advance through their programs. Discussions have led to several cross-disciplinary initiatives.

Twenty common teaching/learning objectives that transcend the discipline-specific goals of individual courses, departments, and majors were identified. Major categories of teaching objectives include: basic laboratory skills, communication and record keeping, maturity and responsibility, context, and integration and application of knowledge. Examples of teaching objectives include "the ability to measure and report uncertain quantities with appropriate precision" and "the ability to write effectively in appropriate style and depth." Next, all instructors analyzed the emphasis on each of the 20 core teaching objectives in their laboratory courses. To measure student progress toward the teaching objectives, competency standards were developed. This coordinated effort has enabled instructors to target explicit shifts in emphasis from more basic to refined skills as students move through a sequence of laboratory courses.

Student self-evaluations and instructor evaluations have been developed from the core teaching objectives and have been implemented during the 2002-2004 academic years. This collaboration and the resulting assessment tools have enhanced existing outcome assessment methods that are contributing to ABET accredited degree programs at Rice University.

One key benefit of this effort has been the increased communication among the instructors for the existing laboratory courses. Cooperation among laboratory instructors has led to the development of a plan for continuous adaptation and change, aimed at coordinating laboratory courses in the science and engineering departments. Efforts to date have not required the addition of new courses or major changes to existing courses; thus, the costs for this type of

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effort are not significant, making this approach to coordination and reform attractive for many schools across the nation. This presentation covers a three-year ongoing effort at Rice University, the usefulness of the student self-evaluations and instructor evaluations, success and struggles of the group of laboratory instructors, future directions, and tips for coordinating such activities at your university.

Motivation

Traditionally, science and engineering departments are independently responsible for designing and teaching undergraduate laboratory courses. Typically, laboratory protocols and entire laboratory courses are developed and taught without input from other departments and even without coordination with other laboratory courses within a department. Although different departments such as Biology, Chemistry, Physics, Chemical Engineering, and Bioengineering share many of the same students, regular communication on curriculum matters among personnel who are responsible for laboratory education is uncommon. Consequently, the resulting laboratory curricula contain inconsistencies, contradictions, gaps, and redundancies. In addition, students often fail to build their problem-solving skills as they move through laboratory courses.

During the summer of 2001, instructors for more than thirty laboratory courses in Bioengineering, Chemical Engineering, Physics, Biochemistry and Cell Biology, Chemistry, and Ecology and Evolutionary Biology at Rice University began to meet to discuss why their talented undergraduates were underachieving in laboratory courses. Many of the instructors taught students in two or more major programs. In discussing our courses, we began to discover how many common frustrations the group members shared.

One significant area of frustration was student compartmentalization - which we define as the failure of a student to transfer learning from one course or experience to another [1-2]. For example, students cannot prepare biological buffers in a junior level Bioscience laboratory even though they completed a very similar experiment in the Organic Chemistry lab one year earlier. Students frequently claim not to have been exposed to a particular concept or technique, when in fact the material was given significant emphasis in an earlier required course. Another example is correctly applying a statistical technique learned in one course to a different data set in another course. We believe that compartmentalization is partly the result of poor teaching and poor learning skills, and partly the result of student attitudes.

In terms of teaching, we reflected that without coordination, it is nearly impossible to “raise the bar” as students progress through the science and engineering curricula. Without relevant context, students cannot appreciate the value of the generic skills that they are being taught and are unaware if or how they will use them in the future. We also acknowledged that grading of our laboratory courses could lead students to focus on content-specific goals (e.g. sterile technique for maintaining mammalian cells, operating a mass spectrometer) rather than generic capabilities (e.g. attention to detail, trouble-shooting complex equipment). The incorporation of many laboratory courses into a "parent" lecture course (especially freshman courses), to which the laboratory grade makes a relatively minor contribution, does not help the situation. We found ourselves re-teaching generic skills such as graphing, precision, and technical

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communication - often at the same level - throughout the four-year undergraduate sequence. The ultimate goal of laboratory instruction should be to develop strong problem-solving skills in our students. That goal can best be met if students are encouraged to apply learned skills to projects in various disciplines and in various contexts.

In terms of student learning and attitudes, we agreed that many bright students tend to "turn their brains off" when in the laboratory. Some students expect to be told (either through a protocol, teaching assistant or instructor) what each step should be rather than to solve problems for themselves. Because of compartmentalization, students often make the same mistake repeatedly. We surmised that a reason for such an approach to laboratory coursework is the attitude that the purpose of education is certification (grades, diploma) rather than acquisition of knowledge and skills. Without the ability to generalize, students see the required assignments of a course as having no meaning or relevance beyond those particular assignments.

Lecture courses in science and engineering bear the burden of delivering large amounts of discipline-specific content. It may be more difficult for such courses to effectively teach generic abilities such as communication and experimental design that are in demand by employers, graduate programs, and professional programs. Many programs use laboratory courses in order to teach or reinforce discipline-specific content, missing the opportunity to use them in order advance more universally valuable skills. Often students will not have use for specialized content after they graduate. For example, we should not expect a student to become an expert using a particular instrument or specialized computer program, or to recall a specific laboratory protocol. Without a primary focus on generic capabilities, it is especially difficult to hold students to the expectation that as they advance in a laboratory program the quality of their work should advance as well.

Many interdisciplinary capstone design courses in engineering implicitly emphasize generic capabilities. Generic capabilities such as teamwork, communication, critical thinking and maturity, together with content-specific knowledge, are important to a design group's success [3-4]. To facilitate this type of interdisciplinary learning environment, students from different departments may be grouped to work on capstone design or laboratory projects [5-8]. Students may also be required to work on projects or experiments requiring knowledge across several different engineering and science disciplines [9-14]. Efforts to sequence courses with a significant design component to teach these generic capabilities within a department or college are relatively common. To the best of our knowledge, however, we are unaware of a level of coordination of this scope across this breadth of science and engineering laboratory courses in which there is an emphasis on generic laboratory skills.

In order to assess the true effectiveness of a laboratory program, it was important to determine what generic capabilities have been gained by the time the student graduates. The establishment of common teaching objectives was also a major step toward coordinating existing individual laboratory courses into effective programs that cross disciplines. Thus, one of the first goals that this group tackled was to establish core teaching/learning objectives.

Core Teaching/Learning Objectives

Our group identified five major categories of teaching objectives: basic laboratory skills, communication and record keeping, maturity and responsibility, context, and integration and application of knowledge. All students in science and engineering should be competent with the basics of data presentation and analysis, including when and how to plot data, how to select and convert data units, when and how to round numbers, and how to employ basic statistics. All students should be able to communicate effectively in writing, in both formal and informal situations. Students should be able to write an effective factual summary, defend an idea, and present an interpretation. Among the more ineffable qualities, students should be able to detect when a result or conclusion simply does not make sense.

Within these five major categories, a total of 20 core teaching/learning objectives were delineated (Table 1). In order to facilitate the assessment of skills for each objective, each is defined in terms of actions, that is, what the student is capable of doing. For each teaching objective, we expanded each statement of ability through detailed explanations and examples (Table 2). The list of core objectives and the expanded statements are posted at the web site http://www.ruf.rice.edu/~bioslabs/labgroup/index.html . While developing the detailed descriptions of core objectives, all of the laboratory instructors came to consensus on the scope and meaning of each teaching objective. We also used these explanations to clarify teaching objectives with the students (see Assessment Methods and Instruments).

Our 20 objectives have significant similarity with a list developed in January 2002 by a distinguished group of engineering educators during a colloquy that was sponsored by ABET and the Sloan Foundation [15]. The group established learning objectives for engineering laboratories. That group identified 13 objectives that fell into the following categories: instrumentation, models, experiment, data analysis, design, learn from failure, creativity, psychomotor, safety, communication, teamwork, ethics in the lab, and sensory awareness. In addition, the National Research Council, in their document *BIO2010: Transforming Undergraduate Education for Future Research Biologists* highlights the importance of interdisciplinary and cross-disciplinary laboratory courses [16].

Evaluation of Laboratory Courses Using Core Teaching Objectives

Given this set of 20 core teaching objectives, team members evaluated their laboratory courses for emphasis of each of the teaching objectives. Data from 11 laboratory courses are shown in Table 3. This preliminary work helped us to begin to see patterns across our courses.

A chart that summarized the progression of students through laboratory courses is shown as Figure 1. Some engineering majors such as Mechanical, Electrical, Civil and Environmental take only freshman chemistry and physics laboratory courses before entering department-specific laboratory courses. In contrast, Bioengineering and Chemical Engineering majors take courses through their junior year in the Chemistry and/or Biosciences departments. A typical track for Bioengineering students includes PHYS 101, 102 (Introductory Physics Lab) and CHEM 121, 122 (General Chemistry Lab) their freshman year, CHEM 213 (Organic Chemistry Lab) and

BIOS 211 (Introduction to Experimental Biosciences) their sophomore year, BIOS 311 (Advanced Experimental Biosciences) and BIOE 342 (Tissue Culture Lab) their junior year, and BIOE 441 (Advanced Bioengineering Lab) their senior year. Unfortunately, not all students follow the prescribed track (see Limitations and Impediments).

This visual tool helped us track students through courses and to look at shifts in emphasis across required courses for students in different majors. By examining each assignment (e.g. lab report, quiz, research paper) in each course, the relative emphasis of each of the 20 teaching objectives was established. This exercise was accomplished for all the key laboratory courses. An example of this type of analysis is shown in Table 4 for BIOS 211. The data were then summarized into the five major categories of teaching objectives. The percent weight in each of the five major categories of teaching objectives for four representative courses that a Bioengineering student takes is shown in Table 5.

With tracks developed for students in other majors, similar summarizes of emphasis on teaching objectives have been tabulated. Given this data, a few trends are apparent. First, upper-level (and hence lower enrollment) courses emphasize communication and record keeping to a much greater extent. Second, basic laboratory skills tend to be less emphasized in the upper-level courses. Finally, in the upper-level engineering laboratories, integration and application of knowledge/experience is emphasized to a greater extent than in preceding courses.

While this type of analysis points out interesting trends in some objectives and no trends in others, we feel that its primary utility is in the redesign of both lower- and upper-level laboratory courses in science and engineering departments. Specifically, by looking at the ABET objectives in each engineering department and similar goals established in the science departments, the ideal emphasis on the five major teaching objectives can be established. Then, changes can be made to individual courses within and outside of a department to shift to the desired emphasis. For example, a graded assignment has been added in BIOE 342 that helped students improve their technical communication skills and their ability to integrate their experimental results.

This process provided a solid foundation for beginning collaborative activities such as changing the context and content of existing separately developed laboratory courses so as to make them part of an integrated program. However, much work in laboratory redesign to align and coordinate objectives remains to be done.

Development of Web-Based Materials

We have developed an interdisciplinary web site for common resources. Web-based resources that are not discipline-specific have been developed around several major topics. All developed resources include general guidelines as well as examples from the various disciplines, selected journals and the popular press. The hope is that shared teaching resources will help link laboratories that are currently perceived to be unrelated and address several problems that are directly related to a lack of communication among different disciplines in sciences and engineering.

Material on the following topics has been developed my members of our group and posted at the website (http://www.ruf.rice.edu/~bioslabs/labgroup/index.html):

- Dimensions and units
- Fundamentals of graphing
- Graphical errors
- Example: Plotting with Microsoft Excel
- Error analysis and significant figures
- Error representation and curve fitting

All of the resources are written so as to be universally applicable. While examples are used from various disciplines, every effort has been made to point out when students have choices to make depending on the intended objective and on conventions within a particular field. While most of these resources address items under the major teaching objective, basic laboratory skills, work is ongoing to develop web-based resources for other objectives.

Assessment Methods and Instruments

Establishing learning objectives for laboratories and assessing student outcomes is an active area of educational research in engineering and the sciences [11, 17-19]. With the advent of EC2000 criteria for accreditation, it is of paramount importance to engineering programs nationwide that they formally assess achievement of their objectives in order to improve learning [18, 20]. Common forms of assessment in engineering and science courses include formative assessment such as homework and pre-test/post-test formats for summative assessment. Other assessment tools include questionnaires, observations, focus groups, concept maps, and alumni surveys [20].

One of the more important objectives of laboratory instruction is for students to “own” a problem and independently solve it, if necessary, by acquiring new knowledge and skills. We agreed that one of the most troubling problems is how students persistently depend upon instructors for direction and fail to think critically about their work. Consequently, our initial focus was on developing an effective instrument for student self-evaluation of lab skills. A self-report method was chosen because of its promise as a formative method for enhancing reflective thinking skills, and consequently improving student responsibility for their own learning [21-23]. Because of the biases involved in self-evaluation of academic performance, we expect such evaluations to be most valuable if they can be compared and contrasted with instructor evaluations. Student self-evaluations can also be compared with actual course grades if the grading rubric is based on the 20 teaching objectives.

We developed a self-report survey, the Self-Evaluation of Professional Laboratory Skills, based upon the 20 teaching objectives. Students were asked to complete an evaluation at the beginning and end of a course. Pilot data was collected from students in two biosciences laboratory courses: BIOS 211 (Introduction to Experimental Biosciences) and BIOS 311 (Advanced Experimental Biosciences). (Data is not shown.) Based on their judgment of class performance, the instructors concluded that students were grossly overrating their skill levels. This is consistent with results reported in the self-evaluation literature [24], but instructors felt that the instrument could be improved. Also, self-ratings did not correlated with laboratory course grades.

The survey was significantly revised to clarify the levels of achievement, increase student awareness of their self-assessment biases, and introduce the instructors' standard of achievement for comparison purposes.

All proficiency levels were rewritten in first person to emphasize the expectation that students assume personal responsibility for advancing their own level of skill. The six levels are given in Table 6. Level 1 is the highest level of proficiency and requires that students independently identify and master new knowledge and skills. Level 6 indicates that a student has little or no experience in an area. We informed students of a general tendency to overstate one's abilities. To further discourage exaggeration, we required them to report that they had actually demonstrated skill levels. Simply thinking that one could accomplish a task was insufficient to warrant a greater proficiency score. It was also decided that the confidentiality of responses was necessary to encourage students to be more forthright in their appraisals.

The revised survey was posted online for universal use in the fall and spring 2004 semesters at: http://www.ruf.rice.edu/~bioslabs/labgroup/selfeval.html (pre-lab form) and http://www.ruf.rice.edu/~bioslabs/labgroup/posteval.html (post-lab form). Students are first asked to enter their name and campus identification number, identify up to three laboratory courses in which they are enrolled, and then report the date of the survey, their academic status, and major(s). Drop-down menus and radio buttons minimize incidental reporting errors and make it easier to analyze the data. Students are asked to rate their proficiency for each item using the 6-point scale. A sample item describing a basic laboratory skill is presented below.

A1. Measurement and reporting of uncertain quantities with appropriate precision, that is, appropriate use of significant figures. For example, do you always think about significant digits when you present a measurement or perform a calculation based upon measured quantities? Have your answers always agreed with the "correct answer" in terms of significant figures?

Students are not shown their pre-lab responses at the time they take the post-lab survey, although it is possible that some save their earlier responses. Post-lab evaluations also include five additional pairs of questions for each of the major categories of skills. Students are asked whether skills have remained the same or improved that semester, and whether students had overestimated or underestimated their skills at the beginning of the semester. The self-evaluation was used widely in BIOS 211, BIOS 311, BIOE 441 (Advanced Bioengineering Laboratory) and CENG 343 (Chemical Engineering Laboratory). In particular, the series of courses taken by Bioengineering students - BIOS 211, BIOS 311, BIOE 441 - is explored.

We have begun work on instruments for instructor evaluation of student skills in the 20 specific teaching categories. The instructors in BIOS 211 and BIOS 311 selected particular assignments that demonstrated a subset of the 20 teaching objectives. For example, in BIOS 311, the instructor evaluated teaching objectives A1 (precision, significant figures) and A2 (graphing) in various assignments, which totaled 14% of the course grade. In 2003, instructors in both BIOS 211 and BIOS 311 used a "checklist" containing several teaching objectives. Students had to meet teacher-specified competency standards in those objective areas in order to pass the class.

Assessment Results

The pre- and post-lab responses were analyzed for four courses: BIOS 211, BIOS 311, BIOE 441, and CENG 343. Average scores from student self-evaluations of generic abilities for the five major lab categories are given in Table 7. Two trends were clearly evident from the results. Students in three out of the four courses claimed to have significantly improved their proficiency in all five categories of skills (paired t-test, $p<0.05$). Three courses (BIOS 211, BIOS 311, BIOE 441) are part of a sequence that is typically taken by Bioengineering majors (Figure 1). In the fourth and smallest course (CENG 343), there were significant improvements (paired t-test, $p<0.05$) in two categories of lab skills. Assuming that individual courses advance student skills to at least some extent and that student perception is a valid assessment tool, we have developed a valid instrument for assessment of the effectiveness of a single laboratory course in accomplishing our objectives. Assuming that student self-evaluation improves learning, if only indirectly, these results support the use of this instrument for improving student learning.

The second trend was for students in advanced laboratory courses (BIOS 311, BIOE 441) to claim greater competency than those in the introductory course (BIOS 211) (Table 8). Average self-evaluation scores were significantly different among the three courses (ANOVA, $F(2, 57)=17.15$, $p<0.0001$). Pair-wise comparisons between courses using Scheffe method [25] indicated that BIOS 211 students rated themselves as less proficient than BIOS 311 students ($p<0.05$), and that BIOS 211 students considered themselves less skilled than BIOE 441 students ($p<0.05$). This implies that there is some transfer of learning from earlier to later courses in the program, and that we have a valid instrument for assessing the effectiveness of a course sequence in advancing students' skills.

Attempts to compare post-lab student self-evaluation scores with overall course grades did not return significant correlations. This may be partly due to the narrow range of numerical values that the students typically return on the self-evaluations. It may also be necessary to compare evaluations on specific assignments or parts of assignments with self-evaluations in the corresponding category to see significant results. These results also highlight the need to develop general instruments for instructor assessment of student laboratory skills on the 20 specific teaching objectives.

Implementing a general assessment checklist for instructor evaluation of student proficiency skills in the 20 specific teaching objectives was not successful. Unfortunately, students were very concerned about getting their "checks" in particular objective categories and lost sight of the big picture. This practice has been discontinued.

Limitations and Impediments

Although preliminary, there are several apparent weaknesses with our analysis. First, there were significant differences in student scores for skills that were not emphasized in a particular course, implying that we have improved student self-confidence and not necessarily skills. In addition, it still appears that students overestimate their abilities in early courses. Other inherent disadvantages with self-reporting, such as no appropriate goal or comparison group, for assessment purposes also affect the validity of our data [18, 20].

Another limitation of the presented work is that individual students were not tracked through time over the sequence of three or more courses. We have plans to track individual students using self-assessments across three to four years. This type of longitudinal data will be necessary to evaluate the overall impact and effectiveness of the changes made to the laboratory program and the individual courses.

In addition, our group is working on development of other assessment tools such as post-tests and portfolio development as a way to establish improved student performance through the sequence of laboratory courses. Other options include focus groups, senior exit surveys, or alumni surveys [21].

In an effort to "get ahead" or "put off the hard lab," we estimate that ~30% of students take laboratory courses out of sequence. This is particularly common in the pre-medical students at Rice University. Also, students receiving advanced placement (AP) credit for introductory chemistry and physics miss the introductory laboratory courses, where the foundation for laboratory learning is laid. To address these issues, we have begun to talk more with one another to ensure that particular students have completed the listed prerequisites. In chemistry, a new laboratory course (CHEM 157) that is separate from the main lecture/laboratory course (CHEM 101, 102) has been developed. Students receiving AP credit for freshman chemistry are encouraged to take this laboratory course to prepare them for future laboratory work in chemistry and other disciplines.

Summary and Future Directions

Learning from our three-year effort at Rice University, there are several tips that we can share if instructors at other universities are interested in beginning this type of collaborative effort. In terms of forming a team:

- All the laboratory instructors in the key science and engineering departments must be interested and involved.
- A capable leader is needed.
- A person specializing in assessment should be on the team.
- Institutional support (e.g. department heads) is critical.

In terms of identifying areas of weakness in a program and making changes, it is critical that the laboratory instructors in the key science and engineering departments must be willing to work collaboratively to make changes in their laboratory courses to meet needs identified within and outside the department and from other stakeholders.

In terms of future directions, we have identified many areas for fruitful collaboration within our group at Rice University:

- Evaluate the emphasis of science and engineering laboratory courses with department-specific ABET objectives.
- Change laboratory courses to align with desired teaching emphasis. Rework or develop new experiments, as needed, to meet updated goals.
- Include laboratory instructors from other engineering departments.
- Continue and improve assessment of laboratory courses, including self-assessment and instructor assessment.
- Conduct a critical review of the freshman chemistry and physics laboratory courses.
- Develop more web-based generic materials that can be used by many laboratory courses.

In conclusion, an interdisciplinary laboratory program can break down barriers between schools of natural sciences and engineering and between departments within a school. With cooperation among departments, existing sequences of laboratory courses can be redeveloped in order to reinforce the interdisciplinary nature of science and engineering. Integrated programs can deliberately raise expectations as students progress, thereby refining their generic capabilities and aiding students in the development of problem solving skills. The incorporation of interdisciplinary laboratory protocols and even entire interdisciplinary courses into a program will promote the understanding of principles across multiple fields and reduce compartmentalization. A well-planned program can provide a socially relevant context within which to motivate students to develop a passion for learning.

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Table 1. Core teaching/learning objectives listed by category.

A. Basic laboratory skills

1. Ability to measure and report uncertain quantities with appropriate precision.
2. Ability to convert raw data to a physically meaningful form.
3. Ability to apply appropriate methods of analysis to raw data.
4. Ability to carry out common laboratory procedures correctly.
5. Ability to adhere to instructions on laboratory safety and to recognize hazardous situations and act appropriately.
6. Ability to perform logical troubleshooting of laboratory procedures.

B. Communication and record keeping

1. Ability to maintain an up-to-date laboratory notebook (including proper documentation of outside resources) which is of sufficient detail that others could repeat any of your experiments if necessary.
2. Ability to talk about your results in a clear and concise manner.
3. Ability to write effectively in appropriate style and depth.
4. Ability to access relevant information from the library and other information resources.

C. Maturity and responsibility

1. Ability to effectively prepare in advance for laboratory work.
2. Ability to learn from mistakes.
3. Ability to take the initiative and work independently.
4. Ability to work effectively as part of a team.

D. Context

1. Ability to understand your data and to report data effectively.
2. Ability to relate laboratory work to the bigger picture, to recognize the applicability of scientific principles to real world situations, and to recognize when seemingly minor oversights can have serious consequences.
3. Ability to explain the scientific method, including the concepts of hypothesis and experimental controls, and why objectivity is essential.

E. Integration and application of knowledge/experience

1. Ability to integrate and apply information and experience from math and science courses to current and future work.
2. Ability to apply critical thinking in the laboratory.
3. Ability to recognize whether results and conclusions "make sense."

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Table 2. Selected examples of expanded descriptions of core objectives.

A2. Ability to convert raw data to a physically meaningful form.

Conversion of raw data to a physically meaningful form refers to selection of appropriate units and to convert from measured quantities with arbitrary units to quantities with units that have universal significance. For example, a student should be able to read raw sensor data from a chart with a time axis, and convert a slope to a rate in meaningful units versus time.

B3. Ability to write effectively in appropriate style and depth.

You must have fundamental writing skills upon entry into the program, including the ability to properly design paragraphs and to organize ideas in paragraph form. In addition, technical writing requires that you be able to:

- *Introduce a paper, providing a full and complete rationale for a study, including clear statements of hypothesis(es), objectives, and significance of the work.*
- *Convert details, such as specific procedures, to a general process; for example, write up a concise materials and methods section that includes only the minimal information needed to ensure reproducibility of the work*
- *Prepare tables, figures, and graphs that succinctly summarize critical data; appropriate statistical analysis may need to be included.*
- *Organize discussion of data effectively, including explanations of the relationship of each figure, table, and/or set of data to the objectives of a study.*
- *Address one or more questions in a well-organized discussion, incorporating results into the discussion, clearly distinguishing new information and/or speculation from established facts and theories.*
- *Present concepts in sufficient depth to provide a full and complete explanation.*
- *Write up a complete and concise summary (abstract) for a paper, including all major results and conclusions, supported by quantitative data if applicable.*
- *Exercise economy of words and avoid redundancy.*

D2. Ability to relate laboratory work to the bigger picture, to recognize the applicability of scientific principles to real world situations, and to recognize when seemingly minor oversights can have serious consequences.

To demonstrate this objective you need to know that a quantitative error in determining a drug dosage can kill, or misspelling of a chemical name can change the meaning completely. Another example application includes that the time and distance relationships that are learned in Newtonian physics apply to driving a motor vehicle.

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http://www.ruf.rice.edu/~bioslabs/labgroup/expanded_objectives.html

Table 3. Emphasis of core teaching objectives in selected courses.

Legend
3 = Strong (major part of several assignments; major theme of course)
2 = Some emphasis (major part of one or two assignments; minor part of several assignments)
1 = Very little (touched upon, but not a major part of any assignment)
0 = None

	CHEM			PHYS		BIOS			BIOE		CENG
Objective	121	122	215	101	102	211	213	311	342	441	343
A1	3	3	2	2	2	3	1	3	2	2	2
A2	3	3	2	3	3	3	3	3	1	3	2
A3	3	3	2	3	3	3	3	3	1	3	2
A4	3	3	3	2	2	3	2	3	3	2	2
A5	3	3	3	1	1	1	0	3	2	2	1
A6	2	2	2	2	2	1	2	3	0	2	2
B1	1	1	3	0	0	3	1	3	3	1	3
B2	1	1	2	1	2	0	1	2	1	2	1
B3	1	1	3	0	0	3	3	3	3	3	3
B4	1	1	3	0	0	0	3	3	2	1	2
C1	3	3	3	2	2	3	3	3	2	2	2
C2	1	1	3	2	2	2	3	3	1	3	1
C3	0	0	3	1	1	1	1	2	1	2	1
C4	3	3	0	2	2	3	3	3	1	3	2
D1	3	3	2	0	0	3	3	3	1	2	2
D2	2	2	2	0	0	3	3	2	1	2	2
D3	1	1	2	0	0	2	3	1	2	2	2
E1	3	3	3	1	1	3	3	2	2	3	2
E2	2	2	3	1	1	1	3	3	2	3	2
E3	3	3	3	2	2	2	3	3	3	2	3

CHEM = chemistry, PHYS = physics, BIOS = Biosciences, BIOE = Bioengineering, CENG = chemical engineering

Course numbers listed under department heading. Typically 100 is freshman level, 200 is sophomore level, 300 is junior level, and 400 is senior level.

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Table 4. Analysis of the weight of each of the 10 assignments in BIOS 211 on the core teaching objectives.

Assignment:	1	2	3	4	5	6	7	8	9	10		
Weight:	0.013	0.013	0.013	0.013	0.211	0.211	0.211	0.105	0.105	0.105		
Objectives											wt/obj	
A1precision	0.10		0.13		0.04	0.04	0.04			0.08	0.037	Laboratory
A2units	0.10	0.30					0.06			0.03	0.021	skills
A3analysis		0.10			0.12	0.32	0.08			0.14	0.125	
A4procedures	0.40									0.03	0.008	19%
A5safety			0.25								0.003	
A6troubleshooting											0.000	
B1notebook								1.00			0.105	Commun.
B2speaking											0.000	
B3writing		0.30			0.74	0.59	0.58			0.28	0.435	54%
B4library											0.000	
C1preparation	0.20	0.20	0.25	1.00							0.022	Responsibility
C2mistakes											0.000	
C3self reliance									0.50		0.053	13%
C4teamwork									0.50		0.053	
D1relevance of data			0.25								0.003	Context
D2big picture											0.000	1%
D3scientific method		0.10								0.08	0.010	
E1integrate	0.20						0.24			0.36	0.091	Integration
E2critical thinking											0.000	9%
E3make sense											0.000	
other			0.13		0.10	0.05					0.033	Other 3%

<u>Assignments</u>

1quiz 1
2quiz 2
3quiz 3
4quiz 4
5report 1
6report 2
7report 3
8notebook
9lab technique
10final exam

Table 5. Percent weight in each of the five major categories of teaching objectives.

Major Teaching Objective Category	PHYS 125 Intro Phys	CHEM 121 Intro Chem	BIOS 311 Adv Bios	BIOE 441 Adv Bioe
A. Basic laboratory skills	38 %	40 %	14 %	26 %
B. Communication and record keeping	2 %	7 %	35 %	20 %
C. Maturity and responsibility	15 %	17 %	10 %	11 %
D. Context	9 %	22 %	10 %	15 %
E. Integration of knowledge/experience	22 %	15 %	30 %	27 %
Other	14 %	0 %	0 %	0 %

Table 6. Competency levels on student self-evaluation.

Level 1	I have demonstrated this kind of proficiency, even when I had to *independently* identify and master new knowledge and the necessary skills to achieve results.
Level 2	I have demonstrated this kind of proficiency, *even on new problems,* by relying on my existing knowledge and skills to achieve results.
Level 3	I have demonstrated this kind of proficiency by relying on my own independent knowledge and skills to achieve results, *but only when working on familiar problems.*
Level 4	I have demonstrated this kind of proficiency, but only when I have *clear, explicit instructions* for how to perform.
Level 5	Demonstrating this kind of proficiency has been difficult, even when I have clear, explicit instructions for how to perform.
Level 6	I have little or no experience in this area.

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Table 7. Average scores from student self-evaluations of generic abilities for four laboratory courses, by general category. Students rated themselves before and after completing a laboratory course on a scale of 1 (greater proficiency) to 6 (no proficiency). All responses in a given category were compared. For example, for Basic Laboratory Skills each student responded on learning objectives A1 through A6. Degrees of freedom vary because different categories include three to six individual learning objectives and because some respondents omitted responses in some categories.

	Basic Laboratory Skills	Communication skills	Maturity/ Responsibility	Context	Integration
BIOS 211 (*n* = 98)					
pre-lab	3.3 ± 1.1	3.2 ± 1.1	3.0 ± 1.0	3.3 ± 0.9	3.3 ± 0.9
post-lab	2.6 ± 1.0	2.7 ± 1.1	2.6 ± 1.1	2.8 ± 1.0	2.7 ± 1.1
	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$
	(1.96; 564)	(1.97; 369)	(1.97; 380)	(1.97; 282)	(1.97; 287)
BIOS 311 (*n* = 39)					
pre-lab	2.9 ± 1.0	2.9 ± 1.0	2.6 ± 0.9	3.0 ± 0.9	2.8 ± 0.9
post-lab	2.5 ± 1.0	2.6 ± 0.9	2.2 ± 1.1	2.6 ± 0.9	2.3 ± 0.9
	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$
	(1.97; 231)	(1.98; 155)	(1.98; 155)	(1.98; 115)	(1.98; 112)
BIOE 441 (*n* = 24)					
pre-lab	2.7 ± 0.9	2.8 ± 1.2	2.6 ± 1.1	2.7 ± 1.0	2.8 ± 1.0
post-lab	2.1 ± 0.8	2.6 ± 1.0	2.2 ± 0.9	2.3 ± 0.9	2.2 ± 0.9
	$p<0.001$	$p<0.05$	$p<0.005$	$p<0.01$	$p<0.001$
	(1.98; 140)	(1.99; 94)	(1.99; 94)	(2.00; 68)	(1.99; 71)
CENG 343 (*n* = 10)					
pre-lab	2.5 ± 1.2	2.6 ± 0.9	2.4 ± 1.1	2.4 ± 1.1	2.3 ± 1.1
post-lab	2.0 ± 0.7	2.4 ± 0.8	2.1 ± 0.8	2.4 ± 1.1	1.9 ± 0.7
	$p<0.005$	$p>0.05$	$p>0.05$	$p>0.05$	$p<0.02$
	(2.00; 58)	(2.02; 39)	(2.02; 39)	(2.04; 29)	(2.04; 29)

n = number of respondents

Pre-lab and post-lab values are reported as mean ± standard deviation.

Probabilities are from paired Student's t-tests comparing pre- and post-lab scores.

In parentheses are t statistic and degrees of freedom, respectively.

Table 8. For each of the 20 teaching objectives, student responses from the post-test were averaged. The values were entered into an ANOVA, which determined statistical significance ($p<0.001$). Using Scheffe's method for testing contrasts, it was determined that significant differences existed between two sets of courses.

Course	Mean ± stdev
BIOS 211	2.70 + 0.18
BIOS 311	2.44 + 0.22
BIOE 441	2.29 + 0.27

Statistical significance
BIOS 211 and BIOS 311 ($p<0.05$)
BIOS 211 and BIOS 441 ($p<0.05$)

Figure 1. Laboratory courses are boxed. Arrows show the movement of students with that major through the laboratory courses. Except for Bioengineering, upper-level, department-specific courses are not shown on this figure.