Designing and Teaching Courses to Satisfy the ABET Engineering Criteria

RICHARD M. FELDER
Department of Chemical Engineering
North Carolina State University

REBECCA BRENT
College of Engineering
North Carolina State University

ABSTRACT

Since the new ABET accreditation system was first introduced to American engineering education in the middle 1990s as Engineering Criteria 2000, most discussion in the literature has focused on how to assess Outcomes 3a–3k and relatively little has concerned how to equip students with the skills and attitudes specified in those outcomes. This paper seeks to fill this gap. Its goals are to (1) overview the accreditation process and clarify the confusing array of terms associated with it (objectives, outcomes, outcome indicators, etc.); (2) provide guidance on the formulation of course learning objectives and assessment methods that address Outcomes 3a–3k; (3) identify and describe instructional techniques that should effectively prepare students to achieve those outcomes by the time they graduate; and (4) propose a strategy for integrating program-level and course-level activities when designing an instructional program to meet the requirements of the ABET engineering criteria.

I. INTRODUCTION

The accreditation criteria used to evaluate all American engineering programs since the beginning of 2001 have been discussed extensively since they were first introduced in 1996. The intense nationwide curricular revamping that they have catalyzed could lead to dramatic changes in engineering education; however, the potential of the new system to improve instruction depends strongly on how well engineering faculty understand it and appreciate the extent to which their full involvement in it is crucial.

Under the old system, the burden of preparing for an ABET visit resided almost exclusively with the accreditation coordinator, who did most of the work in putting together the self-study report and preparing a display for the visitor. Not any more! In the words of Jack Lohmann [47], "Preparing for an ABET visit is no longer the academic equivalent of El Niño—something to be weathered every six years until things go back to normal." Since the work of equipping students with the attributes specified in program outcomes must be done at the individual course level, all faculty members involved in teaching required courses must now understand and be involved in the accreditation process on a continuing basis, not just in the months preceding each visit.

Understanding the engineering criteria is no trivial goal, however; the jargon they contain (objectives, outcomes, outcome indicators, performance targets, etc.) is dense and confusing, and universally agreed-upon operational definitions of the terms do not yet exist. Moreover, while much has been written in the past few years about the assessment of program outcomes (more specifically, of Outcomes 3a–3k), relatively little attention has been paid so far to the central role of the individual faculty member in attaining those outcomes. The primary purpose of this paper is to examine that role.

Many of the programmatic requirements of the new system are similar to those of the old one and are laid out reasonably well in the documentation on the ABET Web site [1], with most of the departures from prior practice occurring in Criteria 2 (program objectives) and 3 (program outcomes and continuous program improvement). Our focus in the paper will therefore be on those two criteria. In Section II, we overview the engineering criteria, attempt to clarify the terms that regularly appear in the literature related to accreditation, and briefly review the procedure for formulating program educational objectives set forth in Criterion 2. In Sections III–VI we assume that a program has formulated its objectives and compatible outcomes that encompass Outcomes a–k of Criterion 3, and address the following questions:

1. How can learning objectives, assessment methods, and instructional techniques for individual courses be formulated to address each of the Criterion 3 outcomes? Such a formulation is a necessary condition for addressing the program outcomes.
2. What steps might be taken at the program and individual course levels to raise the level of achievement of the outcomes? Taking such steps would address the requirement for continuous program improvement mandated by Criterion 3.

The planning, teaching, and assessment methods we will present have all been used extensively and are well supported by educational research. The paper briefly surveys the methods and cites sources of information about them and the research that supports them; the focus of the paper is the linkage between the methods and the Criterion 3 outcomes.

II. ELEMENTS OF THE ENGINEERING CRITERIA

A. Overview and Terminology

To comply with the ABET engineering criteria, a program must first formulate *program educational objectives* (broad goals) that address institutional and program mission statements and are responsive to the expressed interests of various groups of program stakeholders. The program must then formulate a set of *program outcomes* (knowledge, skills, and attitudes the program graduates should have) that directly address the educational objectives *and*

Journal of Engineering Education, 92 (1), 7-25 (2003)

Programs must demonstrate that their graduates have:

3a	an ability to apply knowledge of mathematics, science, and engineering
3b	an ability to design and conduct experiments, as well as analyze and interpret data [38]
3c	an ability to design a system, component, or process to meet desired needs [2, 15, 65, 66, 79]
3d	an ability to function on multidisciplinary teams [26, 27, 42, 44, 54, 60, 78]
3e	an ability to identify, formulate, and solve engineering problems [15, 19, 21, 23, 32, 78, 81, 90]
3f	an understanding of professional and ethical responsibility [2, 35, 36, 40, 76, 88]
3g	an ability to communicate effectively [3, 8, 14, 39]
3h	the broad education necessary to understand the impact of engineering solutions in a global and societal context [2, 15, 31, 46, 65, 67, 68]
3i	a recognition of the need for and an ability to engage in lifelong learning [12, 16, 22, 24, 25, 48, 51, 53]
3j	a knowledge of contemporary issues [31, 65, 68]
3k	an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice [12]

Table 1. Criterion 3 outcomes and related references.

encompass certain specified outcomes (Outcomes 3a–3k, shown in Table 1). In some required courses in the program curriculum, *outcome-related course learning objectives* (statements of things students who complete the course should be able to do—explain, calculate, derive, design,…) must be written. The program educational objectives and outcomes must be set forth in a self-study report, which must also include statements of where the outcomes are addressed in the program curriculum, how their level of attainment is to be assessed, and how the assessment results will be used to improve the program. Beginning with the second accreditation visit, the program will also presumably have to demonstrate that it has implemented the improvement plan formulated in the prior visit.

When first confronted with the new accreditation criteria, faculty members have an understandable inclination to formulate their program objectives and outcomes to fit their existing curricula. This approach is invariably frustrating and possibly self-defeating. Many existing curricula have never before been scrutinized in the light of desired learning outcomes and are consequently little more than collections of content-driven courses that have only the loosest of connections to one another. This disjointedness is reflected in the blank stares of incomprehension familiar to all engineering faculty members who have ever asked their students about material from a prerequisite or co-requisite course. Tailoring the accreditation process to perpetuate the status quo will clearly not improve this situation.

The engineering criteria constitute an antidote to curricular chaos. The exercise of constructing a clear program mission, broad goals that address the mission (program educational objectives), and desired attributes of the program graduates (program outcomes) requires the faculty to consider seriously—possibly for the first time—what their program is and what they would like it to be. The product of this exercise constitutes a unifying framework for course and curriculum development. If faculty members then structure their course syllabi, learning objectives, and teaching and assessment methods to address the program outcomes, the result is a coherent curriculum in which all courses have well-defined and interconnected roles in achieving the program mission. The course learning objectives—explicit statements of what students in a course should be able to do to demonstrate their mastery of course material—are crucial to the process; among other things, they enable the program to demonstrate precisely how specific program outcomes are addressed in the curriculum. If the outcomes are then assessed continuously and the results are used to improve instruction in the courses that address them, the degree to which the program meets its self-selected goals must inevitably improve.

When a program approaches accreditation in this logical manner, the burden of preparing the self-study may actually be less than what it was under the old system. Lohmann [47] reports that the self-study for the B.S. program in Mechanical Engineering at Georgia Tech occupied 576 pages in 1990 under the old system and only 180 pages in 1997 under the new one, of which 130 pages comprised the required faculty resumes and course outlines.

Creating a course to achieve specified outcomes requires effort in three domains (see Figure 1): planning (identifying course content and defining measurable learning objectives for it); instruction (selecting and implementing the methods that will be used to deliver the specified content and facilitate student achievement of the objectives); and assessment and evaluation (selecting and implementing the methods that will be used to determine whether and how well the objectives have been achieved and interpreting the results). As Figure 1 shows, the three stages are not purely

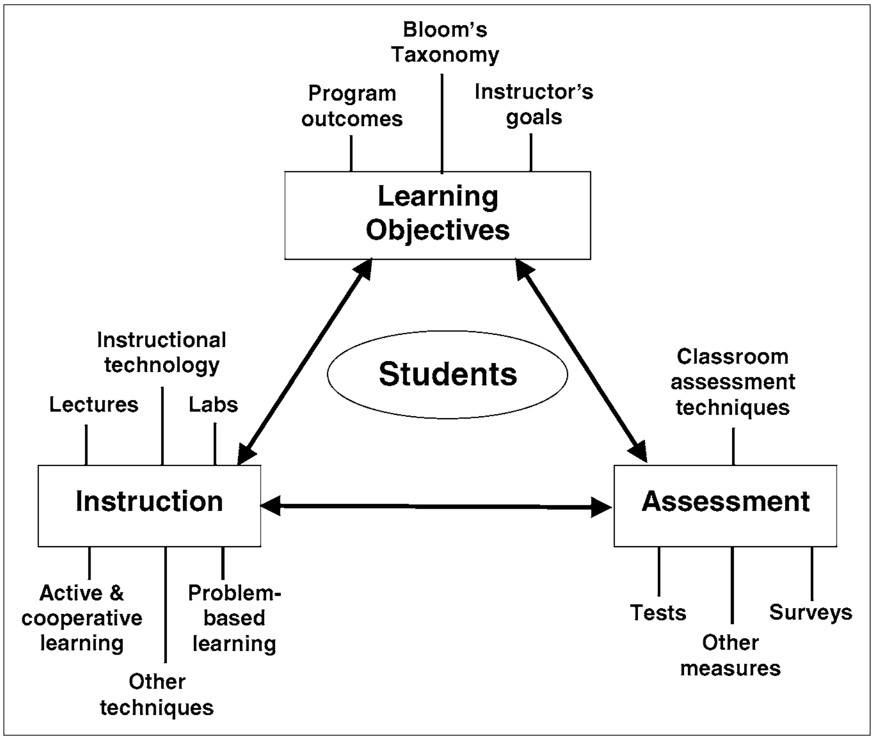

Figure 1. Elements of course design.

sequential—the information collected in each of them feeds back to each of the others in a cycle that leads to continuous improvement. If the assessment reveals that an objective has not been satisfactorily achieved, the nature of the failure may suggest reframing the objective or modifying the instruction used to address it. Similarly, as the quality of the instructional program improves, new objectives may be formulated to encompass higher levels of achievement and the course instruction and assessment modified accordingly.

A particularly confusing aspect of the accreditation literature is its bewildering assortment of assessment terms (objectives, outcomes, outcome indicators, performance targets, *etc. ad infinitum*) and its use of normally interchangeable terms such as goals, outcomes, and objectives to mean different things. A glossary of these terms is given in Appendix A. A reader who encounters a term and is not sure of its meaning is invited to refer to the Appendix.

B. Criterion 2 and Program Educational Objectives

The ABET accreditation criteria in place before 2001 spelled out in fairly precise terms what was required for a program to be accredited (so many credits of engineering science, engineering design, humanities, etc., and adequate faculty and resources to meet the educational needs of the student body). The rigidly prescriptive nature of the system was a source of frustration to engineering faculty and administrators, and the derisive label "bean counting" almost invariably arose whenever ABET came up in conversation.

Requirements related to faculty and resources are still in place in Engineering Criteria 1 (advising students and monitoring their progress toward meeting program requirements), 4 (requirements regarding mathematics, science, design, various aspects of professional practice, and general education), 5 (faculty qualifications), 6 (facilities), 7 (institutional support and financial resources), and 8 (additional criteria for specific programs, normally formulated by the appropriate professional societies) [1]. On the other hand, Criteria 2 (program educational objectives) and 3 (program outcomes and assessment) are dramatic departures from prior practice. These criteria are largely non-prescriptive, a feature characterized by some as "flexible" and by others as "fuzzy." Recognizing that different engineering programs have different missions, student demographics, and resources, ABET leaves it mainly up to individual programs to define their own educational objectives, outcomes, instructional methods, and assessment procedures.

Criterion 2 states that a program seeking accreditation must (a) publish and periodically evaluate a set of educational objectives consistent with the institutional mission and the needs of the program constituencies, (b) implement a curriculum and process to achieve the objectives, and (c) put in place a system of ongoing evaluation to demonstrate the achievement of the objectives and continuously improve the program effectiveness [1, 4, 17, 56, 74].

Carter, Brent, and Rajala [17] offer guidance on how to meet Criterion 2. They suggest that programs seeking accreditation assemble university, college, and program/department mission statements, define the key stakeholders in the program (e.g., students, faculty, alumni, employers of program graduates, and funding sources), solicit their views on desirable program attributes, and write educational objectives that take into account the various mission statements and stakeholder desires. The content of the educational objectives is not subject to challenge by ABET, as long as the formulation guidelines prescribed by Criterion 2 were clearly observed. It follows that objectives might differ considerably from one program to another at a single institution (e.g., the construction option and the transportation option in a civil engineering department) and within a single program discipline (e.g., mechanical engineering) across universities. Additional suggestions for formulating educational objectives and documenting steps taken to address Criterion 2 are offered by Carter et al. [17] and McGourty et al. [56].

C. Criterion 3 and Outcomes 3a–3k

Criterion 3 requires programs seeking accreditation to formulate (1) a set of *program outcomes* that specify the knowledge, skills, and attitudes program graduates should have if the program educational objectives are achieved, (2) an assessment process for the program outcomes, (3) results from the implementation of the assessment process, and (4) "evidence that the results are applied to the further development and improvement of the program [1]." Designing the assessment process involves defining *outcome indicators*—instruments or methods to be used to assess level of attainment of the outcomes—and *performance targets*—target criteria for the outcome indicators. Appendix A provides examples of program outcomes, outcome indicators, and performance targets. As noted previously, the program outcomes must encompass the eleven outcomes (a–k) specified in Criterion 3 and listed in Table 1, but would normally go beyond them to address the complete set of program educational objectives.

An important corollary of the fourth stated Criterion 3 requirement (evidence that the assessment results are being used to improve the program) is that *programs do not have to meet all of their outcome performance targets to be accredited*, at least at the first accreditation visit under the new system. They must only demonstrate that they have in place a sound plan for outcomes assessment and continuous program improvement and are making a serious effort to implement it. When ABET returns to re-evaluate the accredited program, however, the program will presumably have to show that it has made substantial progress with the implementation.

At this point we are ready to proceed with the main topic of this paper—how engineering courses might be designed, taught, and assessed to equip students with the skills specified in Outcomes 3a–3k. Outcomes assessment has been discussed at great length in the literature and so we will spend relatively little time on it, concentrating most of our attention on the less thoroughly examined topics of course planning (specifically, formulation of learning objectives) and instruction.

III. DESIGNING COURSES TO SATISFY CRITERION 3

A. A Matrix-Based Structure for Course and Program Assessment

Suppose that educational objectives have been formulated for an engineering program following the specifications of Criterion 2, and program outcomes that encompass Outcomes 3a–3k have in turn been formulated to address the educational objectives. The next step is to identify the *program core*—a set of courses in the program curriculum designated to address the knowledge, skills, and attitudes specified in the outcomes. Required courses under the control of the program (for example, chemical engineering courses taken by all chemical engineering majors) are obvious candidates for the core. Required courses given by other programs (e.g., mathematics and humanities courses) may also be included, provided that they address program outcomes in a consistent manner. Elective courses and courses whose content varies substantially from one offering to another should not be included in the core.

For each core course, a set of one or more *outcome-related course learning objectives* should be defined. A course learning objective is a statement of an observable student action that serves as evidence of knowledge, skills, and/or attitudes acquired in a course [28]. The statement must include an observable action verb (*explain, calculate, derive, design, critique*,…) to qualify as a learning objective; statements of non-observable actions such as learn, know, understand, and appreciate might qualify as outcomes but not learning objectives. Understanding, for instance, cannot be directly observed; the student must do something observable to demonstrate his or her understanding. For examples of acceptable learning objectives, see Appendix A.

Outcome-related learning objectives are the learning objectives for a core course that specifically address one or more program outcomes and are guaranteed to be in place in all offerings of the course, regardless of who happens to be teaching. Additional learning objectives might be (and normally would be) defined by individual instructors to reflect specific program requirements and their own personal goals, but the outcome-related objectives should be invariant. The program can then reasonably claim that if one or more of these course learning objectives address a particular program outcome, the course addresses the outcome, which is precisely the sort of information that ABET evaluators look for in the self-study. If the course is taught outside the program, having the presenting department sign off on the outcome-related objectives can strengthen the claim.

To keep track of how and where program outcomes are addressed in the curriculum, a *course assessment matrix* might be constructed for each core course, with a column for each program outcome and a row for each outcome-related learning objective. Entries of 1, 2, and 3 inserted in a cell of the matrix respectively indicate that an objective addresses an outcome slightly, moderately, or substantively. Table 2 shows such a matrix. Once the course assessment matrices have been prepared, a *program outcome assessment matrix* can be constructed as shown in Table 3, with columns for program outcomes and rows for program outcome indicators and core courses. Entries of 1, 2, and 3 in the matrix respectively denote slight, moderate, and substantive relevance of the outcome indicators and core courses to the program outcomes. This matrix provides a concise summary of how the program outcomes are assessed and the courses to concentrate on when attempting to raise the attainment level of a particular outcome. The entries for a course should be based on a review of course materials (syllabi, learning objectives, tests and other assessment measures, and the course assessment matrix) conducted by a committee that includes all faculty members who teach the course.

A common concern of ABET evaluators has to do with outcomes addressed in only one or two courses (especially if the courses are taught outside the program), such as communication skills addressed only in one or two general education courses and safety or ethics addressed only in the capstone design course. Programs are advised to distribute their coverage of each outcome throughout the program, not only for appearance's sake but to provide repeated practice and feedback in the skills the students will need to meet the outcome performance target.

Once the program assessment has been carried out, asterisks may be placed next to matrix entries for outcome indicators in a copy of the program assessment matrix to indicate that the relevant performance targets have been met. (This information would not necessarily be included in the self-study but could serve for internal program use only.) Entries without asterisks would identify possible

Outcome-related learning objectives	Outcome 1	Outcome 2	Outcome 3	Outcome 4	Outcome 5	Outcome 6	Outcome 7
- in one or two sentences, explain in clear jargon-free language *specific gravity, purge stream, vapor pressure, dew point,...*					2		
- perform PVT calculations using ideal gas and real gas equations of state	2						
- perform bubble-point, dew-point, and vapor-liquid equilibrium calculations using Raoult's law	2						
- given a liquid mixture of two species, use tabulated physical properties to identify feasible separation processes	3		1				
- determine the absorption capacities of different solvents for a gaseous pollutant from tabulated Henry's law constants, and explain what else must be known to choose the best solvent	3			1			
- calculate internal energy and enthalpy changes for specified species undergoing specified state changes	2						
- given a process description, draw & label a flowchart, do degree-of-freedom analysis, outline material and energy balance solution procedures, and solve for required quantities	3						
- define the four stages of team functioning and the responsibilities of a team coordinator, recorder, checker, and process monitor						2	
- describe and implement effective teamwork practices and strategies for dealing with non-cooperative team members					2	3	

1 = objective addresses outcome slightly, 2 = moderately, 3 = substantively

Outcome 1: Ability to apply mathematical, scientific, and engineering principles to the identification, formulation, and solution of engineering problems
Outcome 2: Ability to design and conduct experiments & to analyze and interpret data using modern engineering tools and techniques
Outcome 3: Ability to design engineering processes and products to meet desired needs
Outcome 4: Ability to analyze important social and environmental problems and identify and discuss ways that engineers might contribute to solutions, including technological, economic, and ethical considerations in the analysis
Outcome 5: Ability to communicate effectively in both writing and speaking in a variety of professional contexts
Outcome 6: Ability to function effectively in both single-discipline and multidisciplinary teams
Outcome 7: Recognition of need for and ability to engage in lifelong learning

Table 2. Course assessment matrix: CHE 205.

focal points for the continuous improvement effort mandated by Criterion 3.

B. Formulating Outcome-Related Course Learning Objectives

Consider the following illustrative program outcome:

The program graduates will be able to analyze important social and environmental problems and identify and discuss ways that engineers might contribute to solutions, including technological, economic, and ethical considerations in their analysis.

It might reasonably be claimed that Engineering Criteria Outcomes 3e (identifying engineering problems), 3f (understanding professional and ethical responsibility), 3h (understanding global and societal implications of engineering solutions), and 3j (knowledge of contemporary issues) all map onto this hypothetical program outcome. For a program to meet the requirements for accreditation, each of Outcomes 3a–3k must map onto one or more program outcomes in this manner, from which it follows that the core courses in the program curriculum must collectively include learning objectives that address each of Outcomes 3a–3k. (There is no need for any individual course to address all 11 outcomes, however, and it would be a rare course indeed that does so.)

It takes little skill to write learning objectives for some of the Criterion 3 outcomes. Almost any objective that could be written for an engineering course, for example, could be plausibly claimed to address Outcome 3a (apply knowledge of mathematics, science, and engineering), and it would also not be difficult to write objectives that address Outcome 3k (use modern engineering techniques, skills, and tools). Other outcomes pose somewhat greater challenges. For example, Outcome 3e (identify, formulate, and solve engineering problems) requires some thought. Solving engineering problems is not a problem—most traditional course objectives involve problem-solving of one type or another—but objectives that clearly define the skills involved in problem identification and formulation are not obvious.

Having to write objectives for some of the other outcomes throws most engineering professors into completely unfamiliar territory. Little in their background or experience provides a basis for knowing how students might show an ability to work effectively in multidisciplinary teams (3d) or to engage in lifelong learning (3i), or how they might demonstrate an understanding of professional or ethical responsibility (3f) or of the impact of engineering solutions in a global and societal context (3h).

Outcome indicators & core courses	**Outcome 1**	**Outcome 2**	**Outcome 3**	**Outcome 4**	**Outcome 5**	**Outcome 6**	**Outcome 7**
Portfolio	3	3	3	3	3	3	2
FE Exam	3						
GPA	1						
GPA in CHE	2						
Design course: Project report	2		3		3	1	2
Design course: Oral presentation	2		3		3	2	2
Exit interviews with seniors	2	2	2	2	2	2	2
Alumni interviews	2	2	2	2	2	2	2
ENGR 101 (Freshman engineering)			1	1	1	1	2
CS 110		1					
ENGL 112 (Freshman composition)					1		
ENGL 365 (Technical writing)					3		
CHE 205	3				2	2	
CHE 311	3		1				
CHE 312	3		1				
CHE 315	3						
CHE 316	3						
CHE 330 (Engineering laboratory)	2	3			2	3	2
CHE 410 (Engineering & society)				3	2		2
CHE 446	3		1				
CHE 425	3		2				
CHE 450	3		2				
CHE 451 (Capstone design course)	3		3		3	3	2

1 = objective addresses outcome slightly, 2 = moderately, 3 = substantively

Outcome 1:	**Ability to apply mathematical, scientific, and engineering principles to the identification, formulation, and solution of engineering problems**
Outcome 2:	**Ability to design and conduct experiments & to analyze and interpret data using modern engineering tools and techniques**
Outcome 3:	**Ability to design engineering processes and products to meet desired needs**
Outcome 4:	**Ability to analyze important social and environmental problems and identify and discuss ways that engineers might contribute to solutions, including technological, economic, and ethical considerations in the analysis**
Outcome 5:	**Ability to communicate effectively in both writing and speaking in a variety of professional contexts**
Outcome 6:	**Ability to function effectively in both single-discipline and multidisciplinary teams**
Outcome 7:	**Recognition of need for and ability to engage in lifelong learning**

Table 3. Program outcome assessment matrix.

A monumental resource for writing outcome-related learning objectives is being assembled by a team of some of the top assessment experts in engineering education in the country [9]. For each of Outcomes 3a–3k, they define *outcome elements*—different abilities implied by the outcome statement that would generally require different assessment measures, and for each element they define *outcome attributes*—actions that explicitly demonstrate mastery of the specified abilities. Separate attributes are defined for each of the six levels of Bloom's taxonomy of cognitive objectives [11] and for the valuation level of Krathwohl's taxonomy of affective objectives [45]. For some outcomes, the elements are literally extracted from the outcome statement, as in the following case:

Outcome 3b—ability to design and conduct experiments, as well as analyze and interpret data ⇒ *designing experiments, conducting experiments, analyzing data, interpreting data.*

For other outcomes, the elements are formulated by inference:

Outcome 3e—ability to identify, formulate, and solve engineering problems ⇒ *problem identification, problem statement construction and system definition, problem formulation and abstraction, information and data collection, model translation, validation, experimental design, solution development or experimentation, interpretation of results, implementation, documentation, feedback* and *improvement.*

Attributes defined by Besterfield-Sacre et al. [9] for the element "Problem statement construction and system definition" of Outcome 3e include:

- *describes the engineering problem to be solved;*
- *visualizes the problem through sketch or diagram;*
- *outlines problem variables, constraints, resources, and information given to construct a problem statement*;
- appraises the problem statement for objectivity, completeness, relevance, and validity

Each of these attributes specifies an observable student action and so could be included in a course learning objective, which could then be cited to demonstrate that the course addresses Outcome 3e.

Illustrative learning objectives for each of Outcomes 3a–3k are given in Appendix B, and an exhaustive list of attributes for each element of each outcome is provided in Reference 9. Instructors seeking to formulate outcome-related learning objectives for their courses may begin by adapting items from either of these sources. If the attributes in the second list are not directly expressed in measurable terms (e.g., if they begin with words like "know" or "understand" or "appreciate,"), the instructors may recast them using appropriate action words, many of which are also suggested in Reference 9.

IV. ASSESSING LEARNING

Once program outcomes have been formulated and outcome indicators and performance targets specified, outcome-related learning objectives should be drafted for all core courses and a plan should be made for assessing the degree to which the objectives are being met. The assessment plan should also specify who is responsible for each part of the assessment, when the assessment will be performed, and who will receive the results [74].

Triangulation (using multiple methods to obtain and verify a result) is an important feature of effective assessment [10]. The more tools used to assess a specific program outcome or course learning objective, the greater the likelihood that the assessment will be both *valid* (meaning that what the chosen method is actually assessing matches what is supposedly being assessed) and *reliable* (the conclusion would be the same if the assessment were conducted by other assessors or again by the same assessor). Following are some possible program-level (P) and course-level (C) assessment tools:

1. Exit surveys, exit interviews (P)
2. Alumni surveys and interviews (P)
3. Employer surveys and interviews (P)
4. Job offers, starting salaries (relative to national benchmarks) (P)
5. Admissions to graduate school (P)
6. Performance in co-op and internship assignments and in problem-based learning situations (P,C)
7. Assignments, reports, and tests in the capstone design course (P,C)
8. Standardized tests—e.g., the FE Examination (the value of which is discussed by Watson [87]), the GRE, and the Force Concept Inventory in physics (P,C)
9. Student surveys, individual and focus group interviews (P,C)
10. Self-analyses, learning logs, journals (P,C)
11. Peer evaluations, self-evaluations (P,C)
12. Student portfolios (P,C)
13. Behavioral observation, ethnographic and verbal protocol analysis (analyzing transcripts of student interviews or working sessions to extract patterns of problem-solving, thinking, or communication) (P,C)
14. Written tests or test items clearly linked to learning objectives (C)
15. Written project reports (C)
16. Oral presentations (live or on videotape) (C)
17. Research proposals, student-formulated problems (C)
18. Abstracts, executive summaries, papers (C)
19. Letters, memos (C)
20. Written critiques of documents or oral presentations (C)
21. Classroom assessment techniques [5, 60, 77] (C)

Nichols [61] and Prus and Johnson [69] summarize the strengths and weakness of many of these assessment tools.

The reliability of objective tests such as standardized multiple-choice and (setting aside questions related to partial credit) quantitative problem-solving tests may be demonstrated with relatively little difficulty. On the other hand, ratings of such student products as portfolios and project reports are necessarily matters of opinion, and designing reliable rating methods can be difficult. An effective approach is to identify aspects of the product or presentation to be rated (e.g., for grading project or laboratory reports, the aspects might be technical soundness, organization, thoroughness of discussion, and quality of writing), select a weighting factor for each aspect, and construct a *rubric*—a form on which the evaluator assigns numerical ratings to each specified aspect and then uses the specified weighting factors to compute an overall rating. Trevisan et al. [85] offer suggestions regarding the effective design and use of rubrics, including a recommendation that the characteristics of the highest and lowest ratings and the midpoint rating for each feature be spelled out fairly explicitly. If several raters complete forms independently and then reconcile their ratings, the result should be very reliable, and the reliability can be increased even further by giving raters preliminary training on sample products or videotaped presentations.

Considerable expertise is required to design valid questionnaires and interviews [20, 33, 82], so unless an already validated instrument is available, assistance from a knowledgeable consultant should be sought when using these assessment tools. Similarly, assembling and evaluating student portfolios is a complex and time-consuming task that can become completely unmanageable without careful planning. Several resources are available to assist in this planning for portfolios in general [7, 18, 62, 64] and for electronic portfolios [6, 73, 89].

More detailed discussions of assessment in the context of engineering program accreditation are given by Besterfield-Sacre et al. [9, 10], McGourty et al. [55], Olds and Miller [62], Rogers [71], Rogers and Sando [72], and Scales et al. [75]. Deek et al. [19] discuss the assessment of problem-solving skills.

V. TEACHING TO ADDRESS OUTCOMES 3A–3K

The ABET engineering criteria have been discussed extensively in articles and presentations since they were first announced, but most of the discussion has focused on assessing Outcomes 3a–3k, with relatively little being said about what must be done to achieve those outcomes. The tacit assumption seems to be that determining whether or not students have specific skills is much harder than equipping them with those skills. In fact, the opposite is closer to the truth. We know a great deal about how to assess communication skills, for example, but judging from the common complaints that most engineering graduates cannot write a coherent report or give a comprehensible talk, we clearly have not yet worked out how to raise those skills to satisfactory levels.

In Section A we outline instructional methods that address each of the Criterion 3 outcomes and cite references on how to implement them and on the research that supports their effectiveness. Sections B and C discuss cooperative learning and problem-based learning, two instructional approaches that have the potential to address all eleven Criterion 3 outcomes effectively. For additional descriptive details and research findings about the methods to be described, see Bransford et al. [13], McKeachie [57] and Wankat [86].

A. General Instructional Methods

The more explicitly students know what they are expected to do and the more practice they get in doing it, the greater the likelihood that they will acquire the desired skills [28, 34, 49]. An effective approach to achieving any desired learning outcome is therefore to show the students the course learning objectives that address that outcome, either on the first day of the course or (better) in study guides for the course tests. Other instructional techniques that address specific Criterion 3 outcomes are suggested in Appendix C. While a full discussion of all of the outcomes is beyond the scope of this paper, we briefly discuss two of them as illustrations.

Let us first examine Outcome 3b (ability to design and conduct experiments, analyze and interpret data). In the traditional engineering laboratory course, the students work through a series of fairly rigidly prescribed experiments in which they follow instructions on equipment operation, collect the prescribed data, shut down, do the prescribed data analysis, and write and submit a report. In terms of the four elements of Outcome 3b, they can certainly be said to have conducted experiments, but whether they can claim to have done anything meaningful by way of analyzing and interpreting data is a matter of opinion, and experimental design has clearly not entered the picture.

Alternative ways to conduct the laboratory course offer much better prospects of satisfying Outcome 3b and greatly improving the learning experience. Perhaps the most promising approach would be to run fewer but more open-ended experiments. For a given experiment, the students would be given an objective (determine a physical property, establish an empirical correlation, validate or refute a theoretical prediction,…), provided with enough training to keep them from destroying the equipment or injuring themselves, and turned loose. It would be up to them to design the experiment (choose experimental conditions, specify how many runs to carry out at each condition and the data to be collected, plan the data analysis to be carried out), run it and collect the data, perform the data analysis and interpretation, draw conclusions, and prepare and submit the report. A lab course conducted in this manner could legitimately claim to be addressing all of the elements of Outcome 3b.

Addressing an outcome and satisfying it are not synonymous, however. If students are to perform well on the Outcome 3b indicators built into the program assessment plan, they must be helped to develop the skills in question. A general educational principle is, *don't assess skills that have not been taught*. Starting in the first week of the course, instruction should be provided in experimental design and statistical data analysis and any other topics that have not been solidly addressed earlier in the curriculum. The instruction may take the form of mini-lectures, supplementary readings, or best of all, interactive multimedia tutorials if good ones can be found or prepared. Another effective technique is to provide real or hypothetical reports that illustrate both good and bad approaches to experimental design, data analysis and representation, interpretation and discussion, and report preparation; have the students critique the reports in teams; and then give them feedback on their critiques.

Another well-known educational principle is that *the assessment drives the learning*. If students know they are going to be held individually accountable for course material, most will make a serious attempt to learn it; without the individual accountability, many overburdened engineering students will choose to spend their time in more productive ways. For example, if an experiment is carried out by a team and team member A is responsible for the statistical data analysis, members B, C, and D may not try to understand or even read that section of the final report. However, if individual tests that cover statistical analysis are built into the course and study guides containing related objectives are handed out beforehand, the chances that all four students will make the effort to learn the material increase dramatically. Another instructional strategy is to randomly select team members to report on different sections, making the designation a short time before the reports are due, and have the team grade depend in part on the quality of the reports. The students will then be forced to learn the entire report content and not just the parts for which they were responsible. Most of the learning that takes place may occur in the tutoring sessions that precede the reports. Since the expert in, say, statistical analysis knows that her grade depends in part on how well her teammates can explain what she did, she will make it her business to see that they understand it.

Laboratories are not the only places experimental skills can be acquired, and no outcome should be addressed in only a single course in the curriculum. In lecture courses, real or simulated experimental data may be provided in classroom exercises or in homework problems and the students can be asked to perform the appropriate data analysis and interpretation. Particular care should be taken to build experimental error or discrepant results into the data to emphasize the idea that in the laboratory (as opposed to textbooks) things don't always go the way they're supposed to. In other class activities and assignments, the students can be asked to design an experiment to measure a variable or property or validate a theory or empirical correlation being discussed in the lectures. As before, if this part of the course content is to be taken seriously, it should be included in study guides and on tests.

Let us move now to Outcome 3i (recognize the need for and be able to engage in lifelong learning). Candy [16] defines lifelong learning skill as the ability to "continue one's own self education beyond the end of formal schooling." Drawing on work of McCombs [53], Marra et al. [51] suggest that if students are to be motivated and equipped to continue teaching themselves, their formal education must go beyond presentation of subject content to address four objectives: (1) helping them to understand their own learning processes, (2) requiring them to take responsibility for their own learning, (3) creating an atmosphere that promotes confidence in their ability to succeed, and (4) helping them see schooling and education as personally relevant to their interests and goals.

The instructional methods suggested in Appendix C for addressing Outcome 3i are consistent with these goals (as are the learning objectives suggested for this outcome in Appendix B). Acquainting students with their learning styles is a direct and effective way to help them understand their learning process [25]. Assignments that require independent literature and Web searches promote a sense of individual responsibility for learning and also help develop the skill to find and organize information in the absence of texts and course notes. Presenting realistic and interesting technological and socially relevant problems and asking the students to contemplate approaches to solving them (*problem-based learning*, discussed in greater detail in the next section)—and assuring them that they're going to have to do that all the time as engineers—may be the best way to impress on them the need for lifelong learning. Giving them repeated practice in formulating solution approaches will help equip them to engage in lifelong learning after they graduate. Finally, any student-centered instructional approach such as cooperative learning (discussed in Section C) that moves the locus of responsibility for learning from the instructor to the student obviously prepares students to learn in environments where there are no instructors, lecture notes, textbooks, or any of the other trappings of formal schooling.

B. Problem-Based Learning

The instructional method known as *problem-based learning* (PBL) can easily be adapted to address all eleven outcomes of Criterion 3. In PBL, entire courses and individual topics within courses are introduced with complex open-ended focus problems whose solutions will require the knowledge and skills set forth in the course learning objectives [21, 50, 58, 90]. The students (generally working in groups) carry out the following steps.

1. Attempt to write a clear problem definition statement.
2. Hypothesize ways to obtain a solution.
3. Identify (a) what they know, (b) what they need to know (both information and methods), and (c) what they need to do. These lists are regularly updated as the students proceed through the solution process.
4. Prioritize learning needs, set learning goals and objectives, and allocate resources and (if teams are used) responsibilities.
5. Carry out the necessary research and analysis and generate possible solutions (first seeing if the problem can be solved with currently known information), examine their "fit," choose the most appropriate one, and defend the choice.
6. Reflect critically on the new knowledge, the problem solution, and the effectiveness of the solution process used.

The instructor serves as a resource in all stages of this process, but does not provide formal instruction until the students (possibly with some guidance) have generated a need for it in the context of the problem. Any teaching method may be used to provide the instruction, ranging from lecturing to full-scale cooperative learning. Relative to students taught conventionally, students taught using PBL acquire greater mastery of problem-solving, interpersonal, and lifelong learning skills and are more likely to adopt a deep (as opposed to surface or rote) approach to learning [90, 91].

PBL was developed in the early 1970s in the McMaster University Medical School and has achieved widespread adoption in medical education. Its strongest proponent in engineering has been Donald Woods of the McMaster University Department of Chemical Engineering, who has developed resources for both instructors and students engaged in PBL [58, 91]. Other implementations in engineering have been undertaken at Lafayette College, Dartmouth College, and MIT [37]. A problem-based program has been developed at Virginia Commonwealth University in which multidisciplinary teams of students run an engineering consulting firm, finding solutions to real industrial problems and in some cases generating millions of dollars in savings for their clients [40].

Once problem-based learning has been adopted in a course, very little additional work must be done to address all of Outcomes 3a–3k. Focus problems may be chosen to involve any experimental or analytical technique, tool, technical or interpersonal skill, or professional or contemporary societal issue that the instructor chooses to address. Appendix D outlines possible approaches to using PBL to address Outcomes 3a–3k, and Maskell [52] discusses issues of assessment in a PBL environment.

C. Cooperative Learning

Cooperative learning (CL) is instruction that involves students working in teams to accomplish a common goal, under conditions that include the following elements [42]:

1. *Positive interdependence*. Team members are obliged to rely on one another to achieve the goal.

2. *Individual accountability*. All students in a group are held accountable for doing their share of the work and for mastery of all of the material to be learned.

3. *Face-to-face promotive interaction*. Although some of the group work may be parceled out and done individually, some must be done interactively, with group members providing one another with feedback, challenging one another's conclusions and reasoning, and perhaps most importantly, teaching and encouraging one another.

4. *Appropriate use of collaborative skills*. Students are encouraged and helped to develop and practice skills in communication, leadership, decision-making, conflict management, and other important aspects of effective teamwork.

5. *Regular self-assessment of group functioning*. Team members periodically assess what they are doing well as a team and what they need to work on, and they identify changes they will make to function more effectively in the future.

A large and rapidly growing body of research confirms the effectiveness of cooperative learning in higher education [43, 80, 83]. Relative to students taught traditionally—i.e., with instructor-centered lectures, individual assignments, and competitive grading—cooperatively taught students tend to exhibit higher academic achievement, greater persistence through graduation, better high-level reasoning and critical thinking skills, deeper understanding of learned material, lower levels of anxiety and stress, more positive and supportive relationships with peers, more positive attitudes toward subject areas, and higher self-esteem. A number of references outline steps that can be taken to satisfy the five defining criteria of cooperative learning and achieving the learning benefits just enumerated [26, 29, 42, 59]. Appendix E outlines cooperative learning methods that address Outcomes 3a–3k in the context of an engineering course.

VI. SUMMARY: AN INTEGRATED APPROACH TO CRITERION 3

Suppose an engineering program seeking accreditation has defined its educational objectives and program outcomes, and that each educational objective and each of Outcomes 3a–3k maps onto one or more of the program outcomes. We propose the following approach to meeting the requirements of Criterion 3.

1. [*Program level*] Select outcome indicators (assessment measures) for each program outcome and define performance targets for each indicator. (See Appendix A for examples.) One approach is to break each outcome into elements (abilities specified or implied in the outcome that would require separate assessments), select attributes of each element (student activities that demonstrate mastery of the designated abilities), and then select appropriate assessment measures for each attribute. Besterfield-Sacre et al. [9] provide an excellent guide to this process.

2. [*Program level*] Identify the program core—the required courses in the program curriculum that will collectively be designated to address the knowledge, skills, and attitudes enumerated in the program outcomes.

3. [*Course level*] For every course in the core, define observable outcome-related learning objectives that are guaranteed to be in place regardless of who happens to teach the course (Section III-B and Appendix B) and define assessment methods for each core objective (Section IV and Besterfield-Sacre et al. [9]). Each of these learning objectives should map onto one or more program outcomes, and all program outcomes should be addressed by objectives in several core courses—the more, the better. Some programs have found it helpful to formulate *course outcomes* for each required course that include some program outcomes or outcome elements, and then formulate the course learning objectives to address the course outcomes.

4. [*Course level*] Prepare a course assessment matrix with columns for program outcomes and rows for outcome-related course learning objectives (Table 2). Place a 1, 2, or 3 in the matrix to indicate that an objective addresses an outcome marginally, moderately, or substantively. The entries should reflect a consensus of all faculty members who are likely to teach the course before the next accreditation visit.

5. [*Program level*] Prepare a program outcome assessment matrix with columns for program outcomes and rows for outcome indicators and core courses (Table 3). Place a 1, 2, or 3 in the matrix to indicate that an outcome indicator or core course addresses an outcome marginally, moderately, or substantively, basing the entries for each course on an examination of course materials and the course assessment matrix by a faculty review committee.

6. [*Course level*] Teach each course in a manner that addresses all of the targeted program outcomes (Appendices C–E). Implement the assessment methods selected in Step 2 and place asterisks next to the 1's, 2's, and 3's in the course assessment matrix when a learning objective is judged to have been met.

7. [*Program level*] Implement the program outcome assessment methods selected in Step 1 and evaluate the performance targets. Insert asterisks next to the 1's, 2's, and 3's for an outcome indicator to indicate that the corresponding performance target has been met. If the assessment for a particular outcome indicates shortcomings or room for improvement, initiate appropriate actions to improve instruction in the relevant courses. The program outcome assessment matrix should indicate which courses might be modified, and the course assessment matrix for each of those courses should suggest areas that need strengthening. Possible instructional modifications may be found in Section V and Appendices C–E.

We make no claim that this procedure is the only way or the optimal way to prepare for an ABET visit; we simply suggest that it is rational and consistent with both the letter and spirit of the engineering criteria, and we propose that engineering programs consider adapting it to their own needs and resources.

Regardless of the programmatic approach adopted, however, individual faculty members must take responsibility for assuring that the program outcomes are met and that program outcome assessment results are used for continuous program improvement. Fulfilling this responsibility entails defining outcome-related course learning objectives, selecting and implementing assessment methods that address all the objectives, and teaching the courses in a way that promotes positive assessment results. Our hope is that the suggestions and examples presented in the body and Appendices B–E of this paper will provide a useful resource to professors engaged in this process.

ACKNOWLEDGMENTS

The preparation of this work was supported by the SUCCEED Engineering Education Coalition (NSF Cooperative Agreement EEC-9727411). The authors are indebted to Lisa Bullard of North Carolina State University, Gary Huvard of Virginia Commonwealth University, and George Peterson of ABET for their insightful critiques of an early draft.

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AUTHOR BIOGRAPHIES

Richard M. Felder is Hoechst Celanese Professor Emeritus of Chemical Engineering at North Carolina State University. He is coauthor of the text *Elementary Principles of Chemical Processes* (3rd Edn., Wiley, 2000), co-director of the ASEE National Effective Teaching Institute, and a Fellow of the ASEE.

Address: Department of Chemical Engineering, North Carolina State University, Raleigh, NC, 27695-7905; e-mail: rmfelder@mindspring.com.

Rebecca Brent is president of Education Designs, Inc., a consulting firm specializing in faculty development and assessment of pre-college and college teaching. She is co-director of the ASEE National Effective Teaching Institute, and an adjunct associate professor of education at East Carolina University.

Address: Education Designs, Inc., 101 Lochside Drive, Cary, NC, 27511; e-mail: rbrent@mindspring.com.

APPENDIX A

Glossary Of Accreditation Terminology

1. *Program educational objectives*—"broad, general statements that communicate how an engineering program intends to fulfill its educational mission and meet its constituencies' needs [4]."

Example: Provide students with a solid grounding in the basic sciences and mathematics, an understanding and appreciation of the arts, humanities, and social sciences, and proficiency in both engineering science and design.

2. *Program outcomes*—more specific statements of program graduates' knowledge, skills, and attitudes that serve as evidence of achievement of the program's educational objectives.

Example: The program graduates will be able to analyze important social and environmental problems and identify and discuss ways that engineers might contribute to solutions, including technological, economic, and ethical considerations in their analysis.

In Criterion 3, ABET specifies eleven outcomes (Outcomes 3a–3k, listed in Table 1). Program outcomes must encompass Outcomes 3a–3k but should not be verbatim copies of them. To meet the requirements of the engineering criteria, the program outcomes should clearly have been formulated to address all of the program educational objectives.

3. *Outcome indicators*—the instruments and methods that will be used to assess the students' attainment of the program outcomes [75].

Examples: Alumni, employer, and industrial advisory board surveys, exit interviews with graduating seniors, student portfolios, capstone design course performance ratings, performance on standardized tests like the FE Examination and the GRE, and job placement data of graduates.

4. *Performance targets*—the target criteria for the outcome indicators.

Examples:

- The [average score, score earned by at least 80%] of the program graduates on the [standardized test, standardized test item, capstone design report, portfolio evaluation] must be at least 75/100.
- The [median rating for, rating earned by at least 80% of] the program graduates on the [self-rating sheet, peer rating sheet, senior survey, alumni survey, employer survey, final oral presentation] must be at least [75/100, 4.0 on a 1–5 Likert scale, "Very good"].

5. *Outcome elements*—different abilities specified in a single outcome that would generally require different assessment measures. Besterfield-Sacre et al. [9] break each of Outcomes 3a–3k into separate elements. For some outcomes, such as Outcome 3b, the elements are literally extracted from the outcome statement:

Outcome 3b—ability to design and conduct experiments, as well as analyze and interpret data ⇒ designing experiments, conducting experiments, analyzing data, interpreting data.

For others, such as Outcome 3e, the elements are derived from an analysis of the specified abilities:

Outcome 3e—ability to identify, formulate, and solve engineering problems ⇒ problem identification, problem statement construction and system definition, problem formulation and abstraction, information and data collection, model translation, validation, experimental design, solution development or experimentation, interpretation of results, implementation, documentation, feedback and improvement.

6. *Outcome attributes*—actions that explicitly demonstrate mastery of the abilities specified in an outcome or outcome element. The main thrust of the work of Besterfield-Sacre et al. [9] is to define attributes at the six levels of Bloom's taxonomy of cognitive objectives [11] and at the valuation level of Krathwohl's taxonomy of affective objectives [45] for each of Outcomes 3a–3k.

Examples: Attributes proposed by Besterfield-Sacre et al. [9] for the element "Problem statement construction and system definition" of Outcome 3e include:

- describes the engineering problem to be solved,
- visualizes the problem through sketch or diagram,
- outlines problem variables, constraints, resources, and information given to construct a problem statement, and
- appraises the problem statement for objectivity, completeness, relevance, and validity.

7. *Program core*—a set of courses designated to address some or all of the program outcomes. Required courses in the major field of study would be obvious candidates for the core. Required courses given in other programs, such as mathematics, physics, chemistry, and English—might be included as long as they consistently address outcomes. Elective courses or courses whose content varies from one offering to another (so that the outcomes might not be addressed in a particular offering) would not be included.

8. *Course outcomes*—knowledge, skills, and attitudes that the students who complete a course are expected to acquire. Some of the outcomes in program core courses should map onto or be identical with one or more program outcomes.

9. *Course learning objectives* (aka *instructional objectives*)—statements of observable student actions that serve as evidence of the knowledge, skills, and attitudes acquired in a course.

Examples: The students will be able to

- explain in terms a high school student could understand the concepts of specific gravity, vapor pressure, and dew point
- solve a second-order ordinary differential equation with specified initial conditions using Matlab
- design and carry out an experiment to measure a tensile strength and determine a 95% confidence interval for its true value
- define the four stages of team functioning and outline the responsibilities of a team coordinator, recorder, checker, and process monitor

Learning objectives should begin with observable action words (such as *explain, outline, calculate, model, design*, and *evaluate*) and should be as specific as possible, so that an observer would have no trouble determining whether and how well students have accomplished the specified task. Words like "know," "learn," "understand," and "appreciate" may be suitable for use in educational objectives or program or course outcomes but not learning objectives. To know whether or not students understand, say, the impact of engineering solutions in a global/societal context (Outcome 3h), one must ask them to do something to demonstrate that understanding, such as *identify* an important problem and discuss ways engineers might help solve it.

10. *Outcome-related course learning objectives*—learning objectives for a core course that specifically address one or more program outcomes. These objectives would normally be cited in the self-study to establish where and how the program is addressing

the outcomes in its curriculum, and they must be guaranteed to be in place whenever the course is given. Core courses would also generally include other learning objectives unrelated to program outcomes.

We have defined these terms because they or variants of them appear in the accreditation literature and in published self-study reports, but there is no requirement that any individual self-study make use of all of them. The only ones mentioned by ABET are the first two (program educational objectives and program outcomes) and the ninth one (course learning objectives); the other terms might or might not be included in a self-study, depending on how the program chooses to approach the engineering criteria.

APPENDIX B

Illustrative Learning Objectives for Outcomes 3a–3k

Outcome 3a (apply knowledge of mathematics, science, and engineering) and Outcome 3k (use modern engineering techniques, skills, and tools)

The student will be able to (insert the usual engineering course objectives).

Outcome 3b (design and conduct experiments, analyze and interpret data)

The student will be able to

- design an experiment to (insert one or more goals or functions) and report the results (insert specifications regarding the required scope and structure of the report). Variants of this objective could be used in traditional lecture courses as well as laboratory courses.
- conduct (or simulate) an experiment to (insert specifications about the goals of the experiment) and report the results (insert specifications regarding the scope and structure of the report).
- develop a mathematical model or computer simulation to correlate or interpret experimental results (insert specifications regarding the experiment and the data). The results may be real data from a laboratory experiment or simulated data given to students in a lecture course.
- list and discuss several possible reasons for deviations between predicted and measured results from an experiment, choose the most likely reason and justify the choice, and formulate a method to validate the explanation.

Outcome 3c (design a system, component, or process)

The student will be able to

- design a system (or component or process) to (insert one or more goals or functions) and report the results (insert specifications regarding the required scope and structure of the report). Variants of this objective could be included in traditional lecture courses (including the freshman engineering course) as well as the capstone design course.
- use engineering laboratory data to design or scale up a system (or component or process).
- build a prototype of a design and demonstrate that it meets performance specifications.
- list and discuss several possible reasons for deviations between predicted and measured results from an experiment or design, choose the most likely reason and justify the choice, and formulate a method to validate the explanation.

Outcome 3d (function on multi-disciplinary teams)

The student will be able to

- identify the stages of team development and give examples of team behaviors that are characteristic of each stage.
- summarize effective strategies for dealing with a variety of interpersonal and communication problems that commonly arise in teamwork, choose the best of several given strategies for a specified problem, and justify the choice.
- function effectively on a team, with effectiveness being determined by instructor observation, peer ratings, and self-assessment.
- explain aspects of a project, process, or product related to specified engineering and non-engineering disciplines.

Outcome 3e (identify, formulate, and solve engineering problems)

The student will be able to

- troubleshoot a faulty process or product (insert specifications regarding the nature of the process or product) and identify the most likely sources of the faults.
- create and solve problems and identify their levels on Bloom's Taxonomy.
- examine a description of a problematic technology-related situation and identify ways that engineers might contribute to a solution.

Outcome 3f (understand professional and ethical responsibility)

Given a job-related scenario that requires a decision with ethical implications, the student will be able to

- identify possible courses of action and discuss the pros and cons of each one.
- decide on the best course of action and justify the decision.

Outcome 3g (communicate effectively)

The student will be able to

- critique writing samples and identify both strong points and points that could be improved in grammar, clarity, and organization.
- critique oral presentations and identify both strengths and areas for improvement.
- write an effective memo (or letter, abstract, executive summary, project report) or give an effective oral presentation… (insert specifications regarding the length and purpose of the communication and the intended audience).

Outcome 3h (understand the global/societal impact of engineering solutions)

The student will be able to

- discuss historical situations in which technology had a major impact on society, either positively or negatively or both, and speculate on ways that negative results might have been avoided.
- propose a solution or critique a proposed solution to an engineering problem, identifying possible negative global or

societal consequences and recommending ways to minimize or avoid them

Outcome 3i (recognize the need for life-long learning and be able to engage in it)

The student will be able to

- find relevant sources of information about a specified topic in the library and on the World Wide Web (or perform a full literature search).
- identify his or her learning style and describe its strengths and weaknesses. Develop strategies for overcoming the weaknesses.
- participate effectively in a team project and assess the strengths and weaknesses of the individual team members (including himself or herself) and the team as a unit.

Outcome 3j (know contemporary issues)

The student will be able to

- identify important contemporary regional, national, or global problems that involve engineering.
- propose and discuss ways engineers are contributing or might contribute to the solution of specified regional, national, and global problems.

APPENDIX C

Instructional Methods that Address Outcomes 3a–3k

The ideas that follow are offered as illustrations, since the possibilities are limitless. The references cited in Table 1 amplify many of the ideas related to the individual outcomes.

Outcome 3a (apply knowledge of mathematics, science, and engineering)

All teaching methods customarily used in engineering education address this outcome.

Outcome 3b (design and conduct experiments, analyze and interpret data)

- Run several open-ended experiments in engineering laboratory courses that call on the students to design and carry out experiments to achieve specified goals. Prescribe a lab report format that includes sections on experimental design, experimental procedures, instrument calibration and data analysis (including error estimation): and interpretation of results in light of theory. Provide instruction in each of the given topics in the form of lectures, readings, or interactive Web-based self-study modules, and have students critique good and bad examples taken from real or hypothetical reports. Provide study guides with learning objectives that cover each section and give individual tests consistent with the study guides. If student teams give oral reports, randomly select which team member presents each section rather than allowing the students to report on the sections for which they were primarily responsible.
- Give students in lecture courses real or simulated experimental data to analyze and interpret. Build realistic experimental error into the data and sometimes give experimental results that contradict theoretical expectations. Include problems of this type in classroom exercises, study guides, and tests.
- Assign students in lecture courses to design experiments to measure specified variables and have them provide examples of the data they would expect to collect and how they would analyze it. Include problems of this type in classroom exercises, study guides, and tests.

Outcome 3c (design a system, component, or process)

- Include design methods in lectures and design problems in courses throughout the curriculum (including the freshman engineering course). Early in the curriculum, provide constructive feedback and models of good responses to these problems but give them relatively little weight in grading, and increase their importance in grading as the students progress toward the senior year.
- In all courses in which design problems are assigned (including the capstone design course), provide study guides with learning objectives that deal with every aspect of the process used to solve the problems. Give individual tests consistent with the study guides.
- Bring experienced design engineers into engineering classes to talk about and give examples of what they do.
- Use structured cooperative learning if designs are to be done by teams (see Section V-C and Appendix E).

Outcome 3d (function on multidisciplinary teams)

- In courses throughout the curriculum (starting with the freshman engineering course and including the capstone design course), assign projects that involve material and methods from different disciplines—e.g., different branches of engineering and physical sciences, biological sciences, mathematical sciences, computer science, economics, and management science. Form teams and assign team members to be responsible for the portions of the project associated with the different disciplines. (If the students actually come from different disciplines, so much the better.)
- Provide training in effective team functioning.
- Provide study guides with learning objectives that cover elements of effective multidisciplinary team functioning (including strategies for cross-disciplinary communication and ways of dealing with common team dysfunctionalities), and give individual tests consistent with the guides.
- Use structured cooperative learning, especially jigsaw (see Section V-C and Appendix E).

Outcome 3e (identify, formulate, and solve engineering problems)

- Include problem identification and formulation in course learning objectives.
- In design or analysis problems in class, on assignments, and on tests, hypothesize situations in which the equipment or process in question is operated as stated in the problem but does not meet specifications and ask the students to brainstorm possible reasons for the discrepancy between predicted and measured performance. For example, after the students in a fluid dynamics course have determined that a __-hp centrifugal pump should be adequate to deliver ___ gal/min of a coolant from a storage tank through a system of pipe segments and fittings that span a specified vertical rise, tell them that the pump was

installed and failed to achieve the specified delivery rate and ask for possible reasons. (Responses to such questions might include computational errors, measurement errors, instrument calibration errors, violations of assumptions or inappropriate approximations or failure to account for important factors in the design calculation, flaws in the purchased equipment, incorrect choice of model, algorithm, or formula, equipment failure of one type or another, sabotage, etc.)
- As part of a homework assignment, ask students to make up a problem having to do with the material taught in class that week. Tell them that they will get a minimal passing grade for a completely straightforward formula substitution problem and to get a higher grade their problem must call for deep understanding or critical or creative thinking on the part of the problem solver. Provide constructive feedback and examples of good responses. In a subsequent assignment, ask them to make up *and solve* a problem having to do with that week's material, and later ask them to make up and solve a problem having to do with what they covered that week in this class and in some other class in the curriculum (multidisciplinary thinking), or a problem that involves an ethical dilemma (Outcome 3f) or a contemporary issue (Outcome 3h or 3j). Make copies of some or all student-generated problems for assessment purposes and consider including good ones on course tests. (Announce your intention of doing so when the assignment is given.) [23]

Outcome 3f (understand professional and ethical responsibility)

- Include elements of ethical and professional responsibility in course learning objectives and on tests in at least one core engineering course in each year of the curriculum, including the capstone design course. Provide instruction in engineering ethics in the form of lectures or supplementary handouts. (A less effective alternative is to offer an elective course on professional and ethical responsibility.)
- Include several course-related professional/ethical dilemmas in each engineering course that has professional and ethical issues in its learning objectives. Have students formulate responses and justifications individually, then reach consensus in pairs or teams of three. Provide constructive feedback and several alternative models of good responses, being sure to convey the idea that there is not one "correct" response and that what matters is the clarity and logical consistency of the justification [67]. Have the students reformulate their initial responses to the dilemmas in light of the feedback.

Outcome 3g (communicate effectively)

- Incorporate "writing across the curriculum" or "writing to learn" methods into engineering courses [14, 39].
- Include some qualitative descriptive problems ("Explain in terms a high school senior could understand the concept of ___") in course learning objectives, in-class exercises and homework, and study guides and tests. Grade both technical correctness and clarity of expression.
- In courses that require technical report writing or oral presentation, provide preliminary instruction. Offer bad examples for students to critique and good and bad examples for them to compare and contrast.
- Have students (or student teams) critique first drafts or presentations of other students' (teams') reports, considering both technical accuracy and presentation quality in the critiques. For written reports, collect but do not grade the first drafts; for written and oral reports, grade both the critiques and the revised draft or final presentation.

Outcome 3h (understand impact of engineering solutions in a global/societal context) and Outcome 3j (know contemporary issues)

Incorporate some in-class exercises, homework problems, and/or case studies that involve current global/societal issues in several engineering courses, including freshman engineering and capstone design courses. (Recent newspaper articles and science and society texts are good sources of topics.) Include such issues as environmental/economic tradeoffs, health and safety/economic tradeoffs, problems related to globalization such as movement of production facilities to other countries, total quality management, and pros and cons of government regulation of private industry. Ask students to generate potential solutions and evaluate them. Require such discussions as part of all major design projects. (A less effective approach is to include a "Science and Society" course in the curriculum.)

Outcome 3i (recognize need for and be able to engage in lifelong learning)

- Teach students about learning styles, help them identify the strengths and weaknesses of their style, and give them strategies to improve their study and learning skills [25].
- Require library and Web searches and documentation of references. Grade on the thoroughness of the searches and the quality of the documentation.
- Occasionally introduce case studies of realistic industrial problems and have the students identify what they would need to know to solve them and how they would go about obtaining the needed information. (In other words, use problem-based learning.)
- Use active and cooperative learning (see Section V-C and Appendix E), both approaches that move students away from relying on professors as the sole source of information and accustom them to relying on themselves and one another.
- In general, anything done to meet Criteria 3e (identify and formulate engineering problems), 3f (understand professional and ethical responsibility), and 3h (understanding of global/societal context of engineering solutions) automatically addresses Criterion 3i.

Outcome 3k (Use modern engineering techniques, skills, and tools)

- Have students use state-of-the-art technology for engineering system design, control, and analysis, mathematical analysis, Web-based research, writing, and communication.
- Use computer simulations to conduct extensive parametric studies, process optimization, and "what-if" explorations.
- Use modern equipment and instrumentation in undergraduate laboratories.
- Include plant visits and presentations by practicing engineers in required engineering courses to make students aware of modern engineering tools and practices.

APPENDIX D

Problem-Based Learning Methods that Address Outcomes 3a–3k

Outcome 3a (apply knowledge of mathematics, science, and engineering)

The traditional instructional approach in science, mathematics, engineering and technology that presents "fundamentals" and then (as much as three years later) presents the applications that make use of the fundamentals has repeatedly been associated with low motivation, poor learning, negative attitudes toward the subject, and high student attrition [84]. Virtually all modern research-based references on effective teaching and learning agree that students have greater motivation to learn and learn more effectively when they perceive a need to know the material being taught [30, 70]. Establishing a need to know material before teaching it is almost by definition what problem-based learning does.

Outcome 3b (design and conduct experiments, analyze and interpret data)

Rather than having student teams work through a large number of pre-designed experiments in the engineering laboratory course, assign a small number of problems that require experimentation to solve (choosing problems that can be solved with existing or readily obtainable resources) and have the student teams devise and implement experiments to solve them. Provide instruction or resources for self-study in experimental design, statistical data analysis, instrument calibration, equipment operation, etc., only after the teams have encountered a need to know the material.

Outcome 3c (design a system, component, or process)

In the capstone design course, do not provide instruction or resources for self-study in the elements of the design process—conceptual design, cost and profitability analysis, CAD, optimization, etc.—until the student teams encounter a need for instruction in those topics in the course of developing their designs.

Outcome 3d (function on multidisciplinary teams)

Assign problems whose solutions require material from several disciplines. (It would be difficult to find problems with the complexity and open-endedness needed to be suitable for problem-based learning that fail to satisfy this condition.) Assign different team members to take primary responsibility for each discipline, making sure to hold all team members accountable for the work done by each of them. (For suggestions about how to achieve this individual accountability, see Appendix E.)

Outcome 3e (identify, formulate, and solve engineering problems)

Problem-based learning is an ideal instructional approach for helping students develop skills in problem identification, formulation, and solution, in that it explicitly requires students to do all three in the course of analyzing complex problems. Simply using PBL is therefore a major step toward addressing this outcome. To further facilitate development of problem formulation skills, have students formulate their own focus problems once they have acquired some experience with instructor-formulated problems.

Outcome 3f (understand professional and ethical responsibility)

Incorporate professional and ethical dilemmas in focus problems. To impart a unique understanding of professional responsibilities, use a variant of the Virginia Commonwealth University student consulting team experience [40].

Outcome 3g (communicate effectively)

Development of communication skills occurs automatically in problem-based learning as long as written or oral reporting is part of the implementation, especially if students work on the problems in structured teams. The greatest benefit is obtained if the implementation adheres to the principles of cooperative learning delineated in Appendix E.

Outcome 3h (understand impact of engineering solutions in a global/societal context)

Choosing PBL focus problems that have global or societal implications may be the most effective way of addressing this outcome. For example, assign the students to design a small, inexpensive, easily portable solar-powered water purification system for use in rural areas in developing countries and to explore its potential technical and economic benefits.

Outcome 3i (recognize need for and be able to engage in lifelong learning)

Any instructional method that transfers some of the burden of learning from the instructor to the students gives students an awareness of the need to assume this burden and helps them develop their skills at doing so. Problem-based learning is a quintessentially student-centered instructional approach, and the complex open-ended problems that provide the basis of the approach are exactly the types of problems the curriculum should be preparing the students to address throughout their careers.

Outcome 3j (know contemporary issues)

If focus problems involve contemporary issues, the students will end by knowing the issues to an extent that no other educational experience could provide.

Outcome 3k (use modern engineering techniques, skills, and tools)

As stated previously, focus problems can be chosen to address any technique, skill, or tool that the instructor wishes to address.

APPENDIX E

Cooperative Learning Methods that Address Outcomes 3a–3k

To use cooperative learning, the instructor should have some or all course assignments (problem sets, laboratory experiments, design projects) done by teams of students that remain together for at least one month and as much as the entire semester. Roles should be defined for team members that rotate from one problem set, lab experiment, or phase of the project to the next. Possible roles are listed below:

- (All settings) *Coordinator* (schedules meetings, makes sure all team members know what they are supposed to be doing and deadlines for doing it, *recorder* (coordinates preparation of the final solution set, lab report, or project report to be graded and of any required intermediate drafts), *checker* (verifies correctness of the final product), and *group process monitor* (verifies that each team member understands each part of the final product, not just the part for which he or she was primarily responsible).

- (Laboratory course) *Experimental designer* (coordinates determination of the data to be collected in each run, the number of runs to be carried out, the conditions of each run, and the required data analysis), *operations supervisor and safety monitor* (coordinates instrument calibration and operation and data recording), *data analyst/statistician* (coordinates data analysis, including estimation of error, and statistical quality control), and *theorist* (coordinates interpretation of results in light of existing theory and/or material in related lecture courses).
- (Design course) *Process or product designer* (coordinates conceptual design), *process analyst* (coordinates determination of process equipment and product specifications), *process engineer* (coordinates design of instrumentation, process control, and quality control systems and production planning and scheduling), and *economic analyst* (coordinates cost and profitability analysis and process optimization).

Two sets of roles may be assigned simultaneously, e.g., (a) and (b) in laboratory courses and (a) and (c) in design courses.

The principal method of assuring individual accountability in cooperative learning is to give individual examinations covering every aspect of the assignment or project, something routinely done in lecture courses but rarely in laboratory or design courses. Another method applicable to courses involving oral project reports is to arbitrarily designate which team member presents which part of the report a short time before the reports are to be presented. The team members who were principally responsible for particular aspects of the project (for example, the occupants of the roles specified in Items (b) and (c) of the list given above) then have the added responsibility of making sure that all of their teammates understand what they did, and their project grade depends in part on their ability to provide that instruction.

A third method is to collect peer ratings of team citizenship, construct weighting factors from the ratings, and apply them to team assignment grades to determine individual grades for each assignment [44]. This procedure addresses many of the commonly expressed concerns about team members who do not pull their weight on the team (and perhaps don't participate at all) but receive the same grade as their more responsible teammates. Standard references on cooperative learning suggest other methods of achieving individual accountability and satisfying the other defining criteria for cooperative learning [26, 29, 42, 59].

When technical roles are assigned as in (b) and (c), the *jigsaw* technique can be used to further enhance the effectiveness of cooperative learning. Once the teams have been formed and the roles assigned, "expert groups" consisting of all of the students in a specific role are given supplementary training in their areas of expertise by a faculty member or graduate teaching assistant. In a laboratory course, for example, the operations supervisors (and no other team members) would be given instruction on operation of the experimental equipment, the data analysts would be given instruction on elements of error analysis and/or statistical quality control, and so on. Each team member has the responsibility of applying his or her expert knowledge to completion of the team assignment, thus assuring positive interdependence (if an expert does a poor job, everyone's grade is diminished).

Following are cooperative learning methods that specifically address Outcomes 3a–3k.

Outcome 3a (apply knowledge of mathematics, science, and engineering)

A large body of research data indicates that using cooperative learning in a course with mathematics, science, and engineering content increases the likelihood that this content will be mastered [42, 80, 83]. No specific technique is required to achieve this outcome as long as the five defining criteria of cooperative learning are met.

Outcome 3b (design and conduct experiments, analyze and interpret data), Outcome 3c (design a system, component, or process), and Outcome 3d (function on multidisciplinary teams)

Assign roles to laboratory team members that involve experimental design, analysis, and interpretation (3b), to design team members that involve all principal aspects of the design process (3c), and to team members in any project-based course that involve tasks commonly associated with different disciplines (3d). Implement jigsaw. Take measures to hold all team members individually accountable for every part of the final project report.

Outcome 3e (identify, formulate, and solve engineering problems)

At the beginning of a course, give a diagnostic assignment to assess skill in problem identification and formulation and include on each homework team at least one individual who scores well on this assignment. Give team assignments that call for problem identification, formulation, and solution, followed by individual assignments and/or examinations that do the same.

Outcome 3f (understand professional and ethical responsibility)

Give assignments in which individuals analyze professional or ethical dilemmas (ideally imbedded within technical assignments) and then work in teams to reach consensus on how to respond to the dilemmas. Later in the course, include dilemmas in individual assignments and/or examinations.

Outcome 3g (communicate effectively)

Cooperative learning requires communication, and all of the techniques suggested in the cooperative learning literature to promote the success of the method automatically promote the improvement of communication skills. When assignments involve written or oral communication, an effective technique is to have pairs of teams critique each other's first drafts of written reports or rehearsals of oral reports. The critiquing team members individually fill out copies of the rating sheet to be used for the actual evaluations and then reconcile their ratings and discuss them with the presenting team, which makes revisions taking the feedback into account.

A communication technique for helping students resolve the serious disagreements and conflicts that sometimes arise in teamwork is *active listening* [29]. Have one side make its case, and then have someone on the other side repeat the case verbatim without attempting to refute it, with people on the first side making corrections as needed until the party of the second part gets it right. Then the second side makes its case, and the first side has to repeat it without editorial comment. Finally, both sides try to work out an agreement that addresses everyone's issues and feelings.

Outcome 3h (understand impact of engineering solutions in a global/societal context)

Use *structured controversy* [41] to analyze case studies of controversial engineering solutions that have had a global or societal impact. Give each team member or pair of team members a position or possible alternative solution to advocate and material to help them develop arguments for their position (or have them do their own research, which will also address Outcome 3i), and then have them argue their positions in an intra-team debate. After each side has made its case, have them work as a team to formulate and justify a consensus position.

Outcome 3i (recognize need for and be able to engage in lifelong learning)

Using cooperative learning in any way at all moves students away from depending on teachers as resources and toward relying on themselves and their peers, the principal resources for lifelong learning. Having to work in CL teams promotes recognition of the need for independent and interdependent work, and the experience of doing so promotes the ability to do so successfully.

Outcome 3j (know contemporary issues)

Require teams to make up problems that place course content in the context of contemporary issues (which also addresses Outcome 3e). The issues may relate to professional or ethical dilemmas (Outcome 3f) and/or global or societal issues (Outcome 3h). In subsequent assignments, have teams solve other teams' problems.

Outcome 3k (use modern engineering techniques, skills, and tools)

In any group, some students are likely to have greater computing skills than their teammates have. If computer applications are included in course assignments done by cooperative learning teams, the novices will benefit from one-on-one tutoring from their more experienced colleagues and the latter students will receive the depth of learning that results from teaching others. The same argument can be made for any engineering technique, skill, or tool.