Competency Matrix Assessment for First-Year Curricula in Science, Engineering, and Mathematics and ABET Criteria 2000

Dr. Jeffrey E. Froyd
Department of Electrical and Computer Engineering
Rose-Hulman Institute of Technology
5500 Wabash Avenue
Terre Haute, Indiana 47803

Abstract - *ABET Engineering Criteria 2000 will encourage institutions, departments and individual faculty to rethink their approaches to assessment and grading. A competency matrix approach is offered as an alternative to more commonly used points and percentages schemes. The competency matrix approach combines goals, objectives, and topics with the levels of learning as described in Bloom's taxonomy to create a two-dimensional matrix which summarizes performances expected from students. The interdisciplinary faculty team which offered the Integrated, First-Year Curriculum in Science, Engineering and Mathematics used a competency matrix assessment process for assigning grades in the 1995-96 academic year. Their experience was described in a paper for the 1996 FIE Conference. In general students were very positive about the competency matrix approach and faculty thought the many positive aspects outweighed possible drawbacks. Based on positive student response and faculty experience, the faculty team voted to use the competency matrix approach in 1996-97. For 1996-97 two major student concerns were addressed. First, students were concerned about how they stood during the quarter with respect to grades. Second, students were concerned about students intentionally misrepresenting their portfolio and competency matrix. Approaches for addressing these concerns will be described. This paper will summarize the process through which the competency matrix was developed, modified, and applied. Improvements to the approach which were adopted for 1996-97, student response and faculty experience will be described. The possible role of a competency matrix approach in satisfying the ABET 2000 accreditation criteria will be described.*

Introduction

ABET Engineering Criteria 2000 attempts to shift the focus of accreditation from education process to student outcomes. In the past ABET accreditation criteria focused on the education process which each engineering program provided. For example, programs documented the number of credits required by their curricula, categories to which these credits were assigned, quality of courses, and quality of laboratory experiences. Under the ABET 2000 criteria, programs are expected to document their assessment plan, their processes for assessing and improving student outcomes, and student performance in terms of specified outcomes. This shift in focus will require substantially different approaches to preparing for ABET accreditation.

For the past two years, an interdisciplinary team of faculty at Rose-Hulman Institute of Technology has been using a competency matrix assessment approach [1] to acquire the data upon which grades will be based. The competency matrix approach illustrates, in miniature, an approach through which a program could document the degree to which its graduates satisfy the ABET 2000 student outcomes. The competency matrix approach has been used by the faculty team which offers the Integrated, First-Year Curriculum in Science, Engineering and Mathematics (IFYCSEM) [2, 3] which integrates topics in calculus, physics, computer science, chemistry, engineering statics, engineering design, and engineering graphics. Although IFYCSEM is not nearly as broad as an engineering curriculum, it includes material from approximately seventy-five percent of the first-year curriculum. Therefore, it demonstrates applicability of a competency matrix approach to a sizable chunk of an engineering curriculum.

Typically, an eight-member faculty team offers IFYCSEM to 90 students in three sections as two-thirds of their teaching load. Since IFYCSEM requires 18 contact hours for each IFYCSEM student, the total student contact hour load is 1620 student contact hours. When this number is divided by eight faculty, the student contact load per faculty member is 202. Since the standard teaching load for a Rose-Hulman faculty member is 300 student contact hours, IFYCSEM represents approximately two-thirds of a typical teaching load.

The following sections describe the competency matrix approach, changes incorporated into the approach for 1996-97, and suggestions through which the competency matrix approach could be extended to an entire engineering program.

Competency Matrix Assessment Approach

The rows of a competency matrix are the topics in the course. The columns of the matrix are the levels of learning as described in the Bloom taxonomy [4]. IFYCSEM faculty have used the first four levels of Bloom's taxonomy since they believe these are the most appropriate for first-year students [8].

1. **Knowledge**: Knowledge is (here) defined as the remembering of previously learned materials. Recalling appropriate information.
   - defines; enumerates; identifies; labels; lists; matches; names; reads; reproduces; restates; selects; states; views;
2. **Comprehension**: Grasping the meaning of material
   - classifies; cites; converts; describes; discusses; estimates; explains; generalizes; gives examples; paraphrases; summarizes; understands;
3. **Application**: The use of learned material in new and concrete situations
   - acts; administers; articulates; assesses; charts; collects; computes; constructs; contributes; controls; determines; develops; discovers; establishes; extends; implements; includes; informs; instructs; operationalizes; participates; predicts; prepares; preserves; produces; projects; provides; records; relates; reports; shows; solves; takes; teaches; transfers; uses; utilizes;
4. **Analysis**: The breaking down of material into its component parts so that its organizational structure may be understood.
   - breaks down; correlates; diagrams; differentiates; discriminates; distinguishes; focuses; illustrates; infers; limits; outlines; points out; prioritizes; recognizes; separates; subdivides;.

Typically, faculty develop topics by starting with a broad goals such as “acquiring the fundamentals of thermodynamics” or “learning to set up integrals for various applications.” The broad goals are broken down into more specific objectives which, in turn, are further refined until a faculty member has reached a level of detail at which specific assessment activities can be developed. Simultaneously, the faculty member is deciding appropriate levels of learning for each row. Deciding the appropriate level of learning requires that a faculty member answer questions such as “Do I want a student to recall the specified topic?” “Do I want a student to demonstrate understanding of a topic when the context of the topic is clearly specified?”, or “Do I want a student to be able to apply the topic without the context being supplied?” If the answer to the first question is yes, then at least knowledge level of learning is required. If the answer to the second question is yes, then at least comprehension level of learning is required. If the answer to the third question is yes, then at least application level of learning is required. In this way, a faculty member builds a matrix which indicates that desired performance for the goal on which the faculty member is working. Shown in Figure 1 is a portion of the matrix used in the SE102, the second in the three course sequence which forms IFYCSEM.

				Information	Understanding	Thinking	
				Knowledge Recall	Comprehension Know-How	Application	Analysis
Thermo-chemistry	Terminology	Physical processes		CBA	CBA		
		Thermodynamic		CBA	CBA		
	Internal energy	Energy storage methods		CBA	BA		
		First law calculation		CBA	CBA	BA	
	Work	Pressure-Volume	Isobaric	CBA	CBA	BA	
			Isothermal	CBA	BA		
	Heat	Phase changes		CBA	CBA		
		Heat capacity	Constant pressure	CBA	CBA	BA	
			Constant volume	CBA	CBA		
	Enthalpy	Definition	H = E + P*V	CBA	CBA	BA	
		Processes	Standard state, formation	CBA	BA		
			Reaction	CBA	CBA	BA	
			Combustion	CBA	CBA		
	Calorimetry	Heating curve	Graphical interpretation	CBA	CBA		
			Heat required	CBA	CBA	BA	
		Adiabatic	Multiple component	CBA	CBA	BA	
			Calorimeter constant	CBA	CBA	BA	
		Bomb		CBA	BA		

Figure 1 Portion of the Competency Matrix for SE102

Note how the goal of “knowing thermochemistry” is broken down into objectives such as “terminology”, “work”, “heat”, etc. These objectives are successfully refined into topics until activities such as homework problems, laboratory experiments, and exam problems can be designed to assess specific levels of learning for one or more selected topics. For the Winter Quarter, the entire competency matrix is a Microsoft Excel spreadsheet which is thirteen pages long.

Each box in the matrix contains one or more letters. If a box contains “CBA,” the all students would be expected to have demonstrated competency in this topic at this level of learning. If a box contains “BA,” then students expecting to earn either an “A” or “B” would be expected to have demonstrated competency in this topic at this level of learning. Finally, if a box contains “A,” then students expecting to earn an “A” would be expected to have demonstrated competency in this topic at this level of learning. Also, the shaded blocks in the matrix show the blocks which students had opportunities to earn. Therefore, the competency matrix also illustrates both the topics which were intended to be covered and exactly which topics were covered during the quarter.

When completed, a competency matrix specifies the learning outcomes expected in the course. As the course is offered, students demonstrate competency in selected topics on homework problems, laboratory reports, examination problems, competency recovery sessions, K-level competency recovery, and design projects. Competency recovery sessions are offered in which students can “make up” or “recover” blocks by working problems correctly. If students failed to demonstrate knowledge level competency blocks on exam problems, then they may “recover” knowledge level blocks by submitting correct answers to the exam problems to the faculty member who graded the problem. This K-level recovery process encourages students to rework exam problems to improve their understanding of the selected topics and increase their preparation for future opportunities.

Each student kept in a portfolio his or her own competency matrix and the associated documentation which faculty returned to students. For each block which students earned, they filled in an appropriate reference to the appropriate page in their portfolios. Each quarter, a student portfolio would fill a three-inch ring binder. Faculty would audit their advisee’s portfolios one or two times during a quarter to make sure students were recording blocks correctly, that they hadn’t missed any blocks which they had earned, and that they didn’t claim any blocks for which they did not have documentation in their portfolio. Faculty believe that requiring students to maintain their portfolios encourages them to accept more responsibility for their own learning.

Changes in the 1996-97 Academic Year

Student feedback offered during the 1995-96 academic year indicated three areas which required improvement. First, faculty need to hand out the entire competency matrix near the beginning of the quarter instead of distributing pieces of the matrix throughout the quarter. Students indicated that they were more comfortable if the expectations were clear. Receiving pieces of the competency matrix throughout the quarter muddied expectations as the students perceived that they were be required to learn an increasingly larger body of material. In 1996-97, faculty prepared and distributed almost the entire matrix by the second week of the quarter. Feedback to date indicates that students are more comfortable with this approach.

The second area of improvement is helping students clarify where they stand during the quarter with respect to a letter grade. Although students could keep their matrix current and see areas in which they had demonstrated strength and areas in which further work was necessary, it was difficult for them to understand their position with respect to a letter grade. To address this challenge faculty indicated that if students earned ninety percent or more of the available blocks, they would earn an “A” for the course. If students earned eighty percent or more of the available blocks, they would earn a “B” for the course and so on. Faculty then attempted to keep the on-line matrix current to show which blocks had been made available and the total number of blocks which had been made available. It was difficult for the faculty team to keep the on-line matrix and the available block count current. Further work is required to meet this challenge.

The third challenge was student concern about cheating by falsifying a matrix. Since each student kept his or her own matrix, students expressed concern that one or more students could falsify competency matrices in an attempt to receive a higher grade. To date, faculty on the IFYCSEM team have expressed confidence in the process of each student maintaining his or her own competency matrix accurately. Faculty audits have revealed no documented attempts to falsify the count. Where errors were found, it appeared that students did not correctly implement specified processes for recording competencies.

Several team members have expressed reservations about the processing of translating the data contained in a competency matrix into a single letter grade. Currently, faculty use percentages of available blocks as markers to help assign letter grades. There is some concern, for example, that seventy percent of the available blocks sets the bar too low for earning a “C.” One way to explore this question is to examine how well students who complete IFYCSEM perform in subsequent classes. Data is already being accumulated to address this issue. For example, students who completed IFYCSEM in the 1995-96 academic year received in the Fall Quarter of their sophomore year a higher grade point average than a carefully matched comparison group. The process of translating a properly maintained matrix into a letter grade needs to be examined and improved in the future.

Competency Matrix Assessment and the ABET 2000 Criteria

Criterion 3, Program Outcomes and Assessment, in ABET 2000 Criteria describes the desired student outcomes. "Engineering programs must demonstrate that their graduates have

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs
(d) an ability to function on multi-disciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice."

Theoretically, a competency matrix assessment scheme could be used to document achievement of ABET 2000 student outcomes. Faculty members could start with the eleven student outcomes. A faculty team could then start with each desired outcome and ask a question such as "How would we recognize students who meet our implicit, subjective requirements for this outcome?" Selected answers to the question would then become objectives. Objectives would be further refined until specific topics were defined. These topics would become the rows of the matrix. Simultaneously, the same faculty team could define levels of performance. Faculty could start with the levels of learning as defined in the Bloom taxonomy, use another existing model, or create their own definitions for levels of performance. Graduation requirements could be expressed by specifying a required level of performance for each topic or row in the matrix. Students could check off elements in the matrix by taking courses, working on projects, performance undergraduate research, or other possibilities. Students would graduate upon completion of the specified matrix.

For example, start with the first student outcome, "an ability to apply knowledge of mathematics, science, and engineering." Now, how will faculty recognize students who achieve this outcome? One answer could be: Pass the Fundamentals of Engineering Examination. If this is the only requirement, then passing this examination will demonstrate that students have achieved the first student outcome. However, some institutions may interpret the first student outcome more specifically. For example they may break down the first student outcome in more detail. The following table shows a somewhat traditional breakdown of the knowledge of mathematics, science and engineering.

Table 1 ABET Student Outcome (a)

(a) an ability to apply knowledge of mathematics, science, and engineering		
Mathematics	Differential calculus	Symbolic differentiation
		Graphical interpretation
		Related rates
		Optimization
	Integral calculus	Methods of integration
		Applications of integration
	Multivariable calculus	Partial derivatives
		Vector calculus: gradient, divergence, curl
		Multivariable optimization
		Multiple integrals
	Differential Equations	

	Statistics	
	Mathematical Modeling	
Physics	Mechanics	Translational kinematics
		Conservation of linear momentum
		Conservation of energy
		Rotational kinematics
		Conservation of angular momentum
	Electricity	
	Magnetism	
	Waves	
Chemistry	Stoichiometry	
	Dynamic Equilibrium	
	Reaction Kinetics	
	Thermochemistry	
	Electrochemistry	
	Solid State	
	Orbital Structure	
	Descriptive Chemistry	
	Material Properties	
Engineering Science	Statics	
	Dynamics	
	Thermodynamics	
	Fluids	
	Circuits	

Next, an institution may then specify the different levels of learning at which students are expected to demonstrate these topics. Once the matrix showing expected levels of performance for the designate topics has been assembled, the task of demonstrating that students have achieved these expectations must be outlined. For example, an institution could state that knowledge and comprehension levels of learning for differential calculus will have been demonstrated upon successful completion of the first calculus course. It is often the higher levels of learning which present a challenge. Normally, faculty are not satisfied with comprehension of the topics listed in the table above. They want students to be able to apply these topics in new ways and synthesize them together in innovative ways. In short, they expect students to be able to perform at the application and synthesis levels of learning. However, it is not clear where students will be able to demonstrate these higher levels of learning for the topics listed in this table. Is a synthesis level of learning for mechanics topics required in the first physics course? Usually not, and appropriately so. If not the physics course, then where will students demonstrate the higher levels of learning? If a competency matrix is developed for each student outcome, then the challenge may be to find processes through which student performance, especially at the higher levels of learning can be demonstrated.

This type of approach is being used to develop transferable requirements for the first two years of engineering design in the state of Washington. The Transferable Integrated Design Engineering Education (TIDEE) project [5-7] is developing a Design Competency Category-Level Matrix. The rows of the matrix are categories of design competencies while the columns of the matrix are levels of performance.

Other teams of faculty could develop competency matrices for the other student outcomes in the ABET 2000 criteria. These would illuminate what is implied by these student outcomes and allow faculty to assess whether graduates are meeting the implied requirements in these outcomes.

References

1. Anderson, C., K. Bryan, J. Froyd, D. Hatten, C. Kiaer, N. Moore, M. Mueller, E. Mottel, and J. Wagner, "Competency Matrix Assessment in an Integrated, First-Year Curriculum in Science, Engineering, and Mathematics," *Proceedings of the 1996 Frontiers in Education Conference*, Salt Lake City, Utah, November 1996.
2. Winkel, B. and J. Froyd, "A New Integrated First-Year Core Curriculum in Engineering, Mathematics and Science: A Proposal", *Proceedings of the 1988*

Frontiers in Education Conference, Santa Barbara, California, October 1988.
3. Rogers, G. and B. Winkel, "Integrated, First-Year Curriculum in Science, Engineering, and Mathematics at Rose-Hulman Institute of Technology: Nature, Evolution, and Evaluation," *Proceedings of the 1993 Conference of the American Society for Engineering Education*, Champaign, Illinois, June 1993.
4. Bloom, B., *Taxonomy of Educational Objectives, Handbook I: Cognitive Domain*. Longmans, Green and Co., 1956.
5. Crain, Jr., R., D. Davis, D. Calkins, and K Gentili, "Establishing Engineering Design Competencies for Freshman/Sophomore Students," *Proceedings of the 1995 Frontiers in Education Conference*, Atlanta, Georgia, November 1995.
6. Calkins, D., D. Davis, R. Crain, Jr., M. Trevisan, and K Gentili, "TIDEE: The First Year of a Design Educational Partnership for Washington State," *Proceedings of the 1996 Frontiers in Education Conference, Salt Lake City, Utah, November 1996*.
7. Davis, D., R. Crain, Jr., D. Calkins, K Gentili, and M. Trevisan, "Competency-Based Engineering Design Projects," *Proceedings of the 1996 Conference of the American Society for Engineering Education*, Washington, DC, June 1996.
8. World Wide Web URL, http://weber.u.washington.edu/~krumme/guides/bloom.html (Günter Krumme, 416B Smith, Department of Geography Box 353550,University of Washington, Seattle, WA 98195-3550, URL: http://weber.u.washington.edu/~krumme/, e-mail: krumme@u.washington.edu)