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Categories and Levels for Defining Engineering Design Program Outcomes

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ABSTRACT

Recent trends in engineering education have shifted from course-based to outcomes-based degree programs. An outcomes-based engineering degree program requires clear definition of student learning targets, planning to ensure that they will be achieved, and assessment to determine how well these targeted outcomes have been achieved. Because engineering degree programs encompass science and design dimensions, engineering educators must be able to define both the science-related and the design-related achievements by their students. The design-related outcomes are more elusive in their definition and assessment, so they are addressed in this paper.

This paper summarizes the competencies required for effective performance of engineering design and provides a basis for delineating four different levels of achievement within eight categories of design competencies. Categories of design competencies include: information gathering, problem definition, idea generation, evaluation and decision making, implementation, communication, teamwork, and process improvement. Levels include: basic knowledge, application of knowledge, critical analysis, and extension of knowledge. Together, the categories and levels encompass the practice-related characteristics of engineering graduates listed as part of the ABET Engineering Criteria 2000.

This paper also shows how knowledge of competency categories and levels can be used to achieve specific design learning (educational) objectives. Creation of student design exercises based on this approach provides a direct link between the steps students follow in their learning activity and the competencies identified as learning objectives. The paper gives examples that can serve as models for other engineering educators to use in their creation of new design education materials.

The competency categories and levels also serve as a structure for designation of entering-junior competencies and graduating-senior competencies, important steps in development of outcomes-based engineering education programs.

INTRODUCTION

Educational reform across the United States has dramatically shifted educators' attention—changing from coverage of topics to achievement of educational outcomes. Beginning first at the K-12 educational level, this re-focusing has now reached higher education, where concepts of educational outcomes and assessment of outcomes achievement are unfamiliar concepts. Interestingly, continuous improvement methods—defining product quality and controlling processes to achieve continuous improvement in this quality—are found in many engineering-

related industries and can serve as models for an educational-outcomes-based approach. However, the slow adoption of continuous improvement methods among engineering faculty, faculty's general resistance to educational reform, and their unfamiliarity with educational assessment have been serious obstacles to adoption of outcomes-based education in engineering education.

This manuscript provides a model for defining outcomes and for structuring assessment that is appropriate for individual courses or for an entire curriculum. First, a foundation is laid for outcomes-based engineering design education. Next, this foundation is used to direct the creation of learning exercises that achieve desired educational outcomes with specific measures for achievement. Finally, the concept is expanded to illustrate how it is used for establishing targeted outcomes for an engineering degree program.

A BASIS FOR DESIGN OUTCOMES

Educational outcomes must be defined completely enough to guide student learning and to support assessment of outcomes achievement. This requires both qualitative and quantitative descriptions of educational outcomes. Typically, engineering educators have defined outcomes based on students' knowledge of topics listed in a course outline. Seldom have they defined a full set of desired outcomes at the point of graduation or job entry. Recent approval of Engineering Criteria 2000 by the Accreditation Board for Engineering and Technology (ABET, 1995) has provided a set of abilities or characteristics that graduates should exhibit when they complete accreditable engineering degrees. This list defines a direction for engineering curricula, but it is not a set of outcomes that can be assessed easily.

The following two sections present elements of a categories-and-levels structure for defining engineering design outcomes.

Categories of Design Competencies

Eight categories of engineering design competencies are defined in Table 1. The first five identify five major repeatedly-used steps employed in engineering design. The next three identify three over-arching competencies required to manage and support the design process. These categories, when fully elaborated, encompass the set of competencies required by engineers to perform engineering design as required in engineering practice.

Table 1. Definitions of Categories for Design Competencies.

Information Gathering	Use various sources and techniques to identify, obtain, and determine relevance of information needed at different stages of the design process
Problem Definition	For a given problem situation, prepare a goal statement with specific technical and nontechnical, measurable, criteria to be satisfied in a successful design solution
Idea Generation	Select and employ appropriate techniques effectively for creating numerous innovative yet relevant ideas at various stages throughout the design process
Evaluation and Decision Making	Select and utilize appropriate methods for evaluating ideas and making design decisions based on established criteria
Implementation	Define, interpret, and follow instructions for advancing a design to a stage of usefulness to prospective clientele
Communication	Accurately and efficiently exchange technical and nontechnical information among individuals with widely varying backgrounds, using appropriate methods and forms
Teamwork	Work with others of diverse backgrounds in informal groups or structured teams to produce collective achievements beyond those which could be accomplished individually
Process Improvement	Utilize appropriate processes and employ methods to facilitate continuous improvement and efficient resource management toward optimal achievement of design objectives

Levels of Competencies

The four rows presented in Table 2 identify levels of achievement for any category of competency. They delineate progressive sophistication of knowledge, its use, and its development as students gain expertise within a given category of competence. Students need some preparation at the lowest level (basic knowledge) before they can properly apply this knowledge (application of knowledge level). Additionally, they need both basic knowledge and some experience in its application before being able to judge and critique the knowledge (critical analysis). The highest level (extension of knowledge) requires the ability to critique in order to discern valid extensions.

Table 2. Levels of Achievement for Competencies.

Level	Description
Basic Knowledge	Recognition and understanding of facts, terms, definitions, descriptions, relationships
Application of Knowledge	Use of knowledge in ways that demonstrate understanding of concepts or terms, their proper use, and limitations of their applicability
Critical Analysis	Examination and evaluation of information as required to judge its value to a design solution and to make decisions
Extension of Knowledge	Extending knowledge beyond what was received, creating new knowledge, making inferences, transferring knowledge to usefulness in new areas of application

This structure provides a means for distinguishing levels of understanding as well as a guide for sequencing instruction so that essential prerequisite preparation is provided prior to students' advancing to the next level. Even as students learn at the higher levels, they continue developing greater depth within the lower levels of competencies.

EDUCATING TOWARD OUTCOMES

Specifying Educational Outcomes

This categories-levels structure also provides a basis for integrating design across a curriculum, as required for accreditation of engineering degree programs (ABET, 1995). Design integration frequently means integrating learning from multiple instructors, degree programs, and institutions. This can be achieved more widely if design education outcomes rather than specific courses become the basis for integration. This approach allows different institutions and instructors to employ methods and courses that meet their needs while also ensuring that required educational outcomes are achieved. However, for an outcomes-based approach to exist, target levels of achievement must be identified at intermediate and end points in an engineering curriculum.

An outcomes-based approach to design education has been adopted in the state of Washington through a recent endorsement of design education for the first two years of students' engineering curricula (WCERTE, 1996). Rather than requiring specific design courses in the first two years, institutions have agreed that students need to be introduced to the engineering design process and to supporting competencies, such as teamwork and communication used in engineering design. Through faculty workshops across the state, faculty have developed agreement on engineering design competency categories and have identified levels of achievement suitable for entering juniors. Figure 1 shows the consensus levels defined after two different faculty workshops.

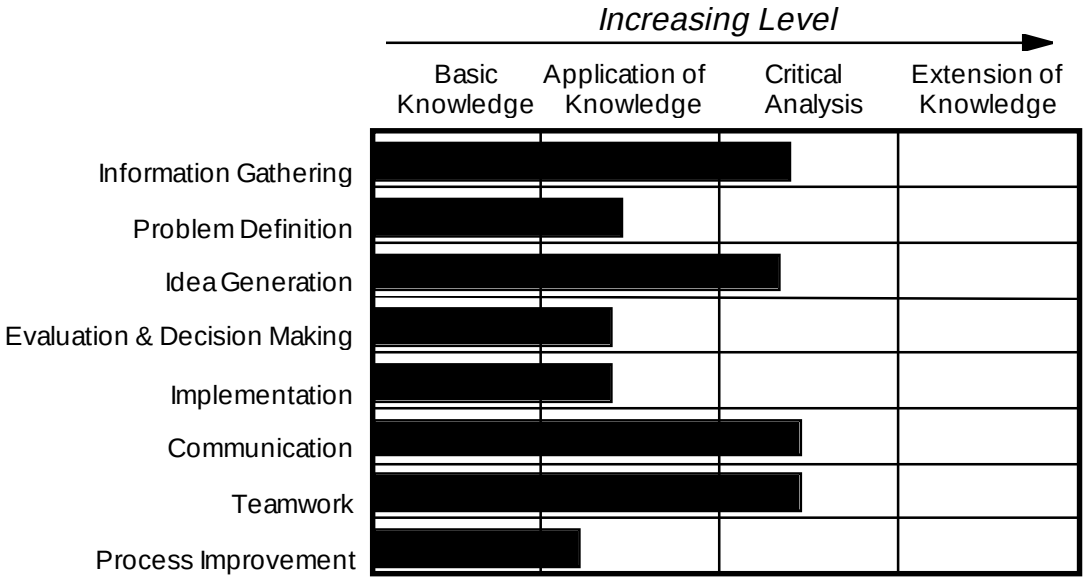

Figure 1. Target Levels of Engineering Design Competencies for Entering Juniors.

Targeting specific educational outcomes that can be assessed requires that outcomes be defined in terms that are observable and measurable. Thus, outcomes should be defined as student knowledge, student skills, or the products of student effort, as indicated in Table 3. Examinations, discussions, observations, and evaluation of products will provide information useful for assessing the achievement of these outcomes.

Table 3. Types of Observable Outcomes.

Type	Definition of Type	Measures for Achievement
Knowledge	Cognitive information or understanding	Correctness of answers or explanations to questions
Process Skills	Steps defined and performed to accomplish tasks or to create requested products	Proper definition and execution of appropriate steps
Products	Objects or deliverables created upon request	Extent to which deliverables meet requirements

Educational outcomes can be defined using the following collection of elements: the appropriate type of outcome within the selected category and at the desired level of achievement. An example is presented below to illustrate the usefulness of this approach.

Outcomes for First-Year Students

Based on the WCERTE endorsement referenced above, three categories of competencies appear relevant for first-year engineering students: process improvement, communication, and teamwork. (Note: The process improvement category of competencies includes definition of processes, performing them, and improving them.) Levels of competencies appropriate for these students likely will be limited to basic knowledge and elementary applications of this knowledge. Seven specific outcomes are defined below to fit within these categories and levels.

Category: Process Improvement

Level: Basic Knowledge

1. Students are able to define major steps required to complete a specific design.

Level: Application of Knowledge

2. Students can perform defined design steps adequately to produce the required deliverable on time.

Category: Communication

Level: Basic Knowledge

3. Students are able to list types of information transfer required among internal and external clients involved in a design process.

4. Students can define suitable communication forms (e.g., memos, posters, reports) for specified exchanges of information.

Level: Application of Knowledge

5. Students can prepare simple memos, reports, and posters that exchange information effectively.

Category: Teamwork

Level: Basic Knowledge

6. Students are able to define a team structure that is useful for a given engineering design project.

Level: Application of Knowledge

7. Students can perform satisfactorily each of the identified team roles when working on a team design project.

Measuring Achievement

Table 4 defines measurables for each of the seven stated design outcomes. For their measurement, students will be required to answer questions to show basic knowledge, perform specific tasks to show process skills, or to deliver a product for its evaluation. For first-year students, who are at the lower levels of achievement, learning emphasis is placed on the knowledge and process skills development; thus, most assessment focuses on how well they can define what needs to be done and how well they perform these processes, not on the quality of their products.

Table 4. Typical Measurables for Seven Design Education Outcomes for First-Year Students.

Outcome	Measurables for Assessing Outcomes
1. Students are able to define major steps required to complete a specific design.	• Set of steps listed includes defining the problem, generating ideas, evaluating ideas. • Evaluation of ideas is based on problem definition.
2. Students can perform defined design steps adequately to produce the required deliverable on time.	• Students allocate time to steps. • Students define the problem using specific requirements. • Students generate ideas. • Students evaluate ideas against their solution requirements. • Students finish within their allotted time.
3. Students are able to list types of information transfer required among internal and external clients involved in a design process.	• Primary internal and external clients are identified. • Most important information is identified for each client.
4. Students can define suitable communication forms (e.g., memos, posters, reports) for specified exchanges of information.	• An appropriate communication form is selected for each client and situation.
5. Students can prepare simple memos, reports, and posters that exchange information effectively.	• Students use proper format and include appropriate content for memos, reports, and posters. • Information presented is readable, organized, and free from grammatical and spelling errors.
6. Students are able to define a team structure that is useful for a given engineering design project.	• Students identify team member roles relevant to the requirements of the project. • Responsibilities of each role are defined.
7. Students can perform satisfactorily each of the identified team roles when working on a team design project.	• Each student performs each of the roles. • Every student performs assigned roles adequately to support the team's progress toward its completion on time.

Developing Student Competencies

Once targeted educational outcomes have been defined, faculty need to develop learning experiences for students that will produce these desired outcomes. Because the desired outcomes include knowledge, process skills, and products, learning exercises must address each of these types at the appropriate times. Also, because teamwork and capability for design are desired outcomes, students must be engaged in team-based design activities. Thus, development of student design capabilities can not be achieved solely by lectures of engineers about their design experiences. Students must be guided in realistic practice of engineering design.

Factors important to achieving design educational outcomes include formation and management of student design teams, evaluation/grading, and keeping students properly focused. The following suggestions are offered to enhance achievement of design education outcomes.

- Use teams to help students learn content as well as methods.
- Define team roles and responsibilities that engage all students as contributing team members.
- For extended team projects, begin their assignment with team building exercises.
- For any team exercise, provide written instructions that include stated expectations and learning objectives.
- Define for students the design process and design competencies necessary for performing design effectively.
- Explain evaluation/grading criteria for students before the assignment begins, and align evaluation with desired learning and performance.
- Minimize the weight given to quality of a design product when grading first- or second-year engineering students; focus on their knowledge and application of knowledge in using the design process.
- For students approaching graduation, determine a significant part of their grade from the quality of their design product; this prepares them for engineering practice.
- Include practical considerations (e.g., performance, producability, social impact, life-cycle costs) in design projects assigned juniors and seniors in engineering programs.
- Use varied instructional methods in design education so that students with different learning styles benefit from their learning exercises (Felder, 1996).

Student design activities and design projects can be created to engage students strategically in steps that build desired design competencies. Davis et al. (1996) describe a method useful for designing effective design projects.

ESTABLISHING PROGRAM OUTCOMES

Program-Level Outcomes

Educational outcomes targeted for graduating engineers will span a wide range of categories (including mathematics, physical sciences, liberal arts, engineering sciences, and engineering design) and will stretch into the upper levels of achievement. Although some targeted categories and levels will be common to many degree programs, others depending upon specialization within a discipline will differ from one program to another.

Figure 2 shows a set of categories and levels targeted by a group of faculty for graduating seniors from a food engineering degree program. Some categories include design competencies, others address basic sciences; some target disciplinary strengths, and others cover topics in other engineering disciplines. For every category shown in this chart, faculty expect graduates to display some competence at the critical analysis level, and for some categories they expect graduates to be prepared to extend their knowledge to higher levels and to new applications. (Note that competencies at levels lower than indicated by the bars are also assumed to be present.)

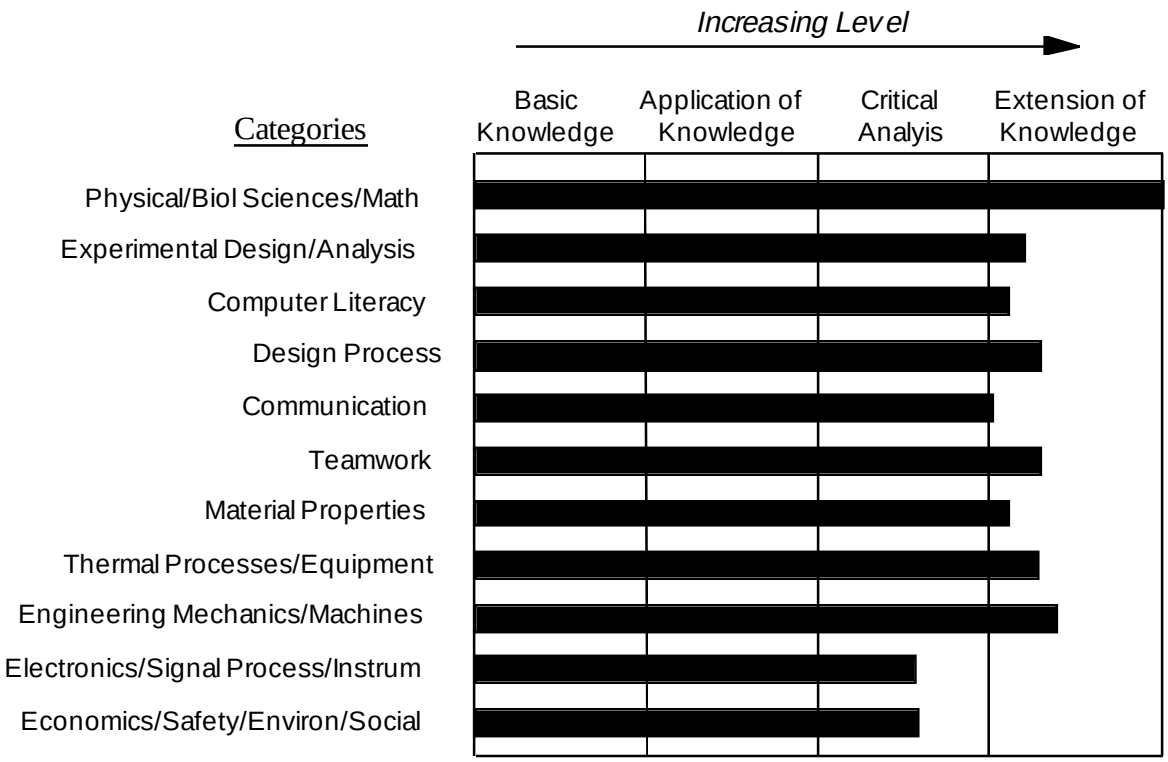

Figure 2. Outcome Categories and Levels Targeted for Food Engineering Program Graduates.

Design Outcomes for Graduating Engineers

Because this manuscript focuses on design education, only the categories listed in Figure 2 relating to design competencies (design process, communication, and teamwork) will be addressed here. (In fact, these three categories are encompassed by the original eight engineering design categories defined earlier.) These three categories will be used to define educational outcomes suitable for graduating engineers. Other categories not addressed here can be addressed in the same way.

Category: Design Process

1. Graduates are able to define steps required to complete a specific design, allocate resources, monitor the design process, make process changes for improvement, and complete the project within allocated time and other resources.
2. Graduates are able to identify appropriate sources of information, retrieve information, judge its relevance to a specific situation or design project, and synthesize it to improve its usefulness.
3. Graduates are able to define (a) clear statements of goals for a design project, (b) specific customer requirements for a successful design, and (c) constraints to be observed in the process, and to refine these requirements as improved information becomes available.
4. Graduates are able to select methods appropriate for idea generation, effectively employ these methods alone or in groups, and improve creativity by modifying processes or environments as appropriate.

5. Graduates are able to identify assumptions and principles relevant to decision making, select appropriate decision making tools, perform analysis and comparisons competently to make decisions, and check and defend their design decisions.
6. Graduates are able to follow through on design decisions to produce the deliverables (reports, models, specifications, drawings, parts, processes, etc.) required by other team members or by clients of their design products.

Category: Communication

7. Graduates are able to receive and deliver design information in appropriate oral, written, and graphic forms so that essential content and meaning are communicated effectively among individuals of varied backgrounds and interests.

Category: Teamwork

8. Graduates are able to structure effective multi-disciplinary teams, manage and perform team roles, and assess and improve team performance so that the productivity and quality of team contributions to design activities exceed that which could be accomplished by the same individuals working independently.

This set of design outcomes may be used as a starting point for defining program outcomes for other engineering degree programs. Once defined, achievement of these outcomes can be assessed by writing measurables (as defined in an earlier section) and by gathering the data necessary to make these assessments.

CONCLUSIONS

The categories-levels structure for design education outcomes offers a way to define specific outcomes for intermediate points in a curriculum or at degree completion. Outcomes need to be written so they are measurable, and data needs to be collected to make the necessary assessments. Although this requires significant effort, the results will provide documentation of student learning and will provide feedback for program improvement. Both are required elements of the ABET Engineering Criteria 2000.

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