"Design-Based" Instruction in Engineering and ABET 2000 Criteria

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Abstract

What is "design-based" instruction? Engineering design is often presented as a number of steps beginning with a problem statement and ending with the validation of a design. The author presents a 5 step iterative scheme for the design process that serves as a framework for design-based instruction. Successful design also involves the use of three types of literacy: conceptual literacy (knowledge of theory and concepts), mechanical literacy (knowledge of tools, machines, and components), and cultural literacy (knowledge of how to communicate and how to properly place a design into a social framework). Design-based instruction includes aspects of all 5 steps in design and also includes the supporting types of literacy for those steps. A planning matrix that enables the instructor to plan the mix and balance of design steps and types of literacy is presented. This approach can also be used to clearly document how ABET 2000 criteria are met in a given project or course presentation. Specific projects used by the author are presented to illustrate the planning matrix and also the ABET 2000 documentation.

Introduction

Imagine having a major design project that is so popular that students enter your classroom on the first day and ask when they will be able to begin the project. Imagine having to hold students back a little so that they can fully appreciate the lessons of today in preparation for the tomorrow they are eager to reach. An impossible dream? Not at all! The understanding and development of the "design based" approach described in this paper came as a result of my search for an approach that would more clearly meet the needs of my students and that would also better reflect current engineering practice. In retrospect this approach also fits the requirements of ABET 2000 remarkably well.

The formal approach described in this paper was developed after a very successful experience with a project titled *The Wooden Shoe Regatta* – a design, build, test, and race project involving a 1/12 scale model sailboat. And in the beginning, the boat project was developed as an almost desperate measure….

We had an excellent textbook. At the United States Naval Academy we had far better laboratory equipment than most undergraduate schools. Lab handouts were prepared for all of the lab exercises and the exercises were related to the classroom presentation…but there was no real excitement, no sense that this new knowledge was meaningful to the students. There was no sense that the student was being transformed by the academic experience to more fully identify him/herself as an engineer with knowledge of fluid mechanics.

Building a wooden boat model would involve “hands on” skills in the shop at a level possible for most students to attain. Each student would have a tangible end product that he/she could keep. The engineering analysis would involve many of the concepts covered in class such as: buoyancy and stability, external flows, boundary layers, separation, and dimensional analysis, as well as an understanding a sailboat as a system subject to many fluid forces. Students would be forced to work within limits (single hull and carved from the 2”x4”x10” wood block provided) while leaving plenty of room for creativity and a sense of aesthetic design.

The project was received with great enthusiasm that was repeated for 5 more years at the Naval Academy. The same level of enthusiasm exists at Grand Valley where the tenth annual *Wooden Shoe Regatta* was held last summer. The interest and excitement generated by this projects lasts long after the class is finished. Naval officers who were once in my fluids class tell me that they still have their boats. At GVSU one summer a few years ago a student was walking around with a completed model shortly after the project started. When I commented about his swift completion of the build phase, he informed me that this was the boat that his boss had built when his boss was in my class. His boss thought that it would be useful for inspiration.

Based on this long-term level of enthusiasm, I can only conclude that this project meets the needs and expectations of students on many levels. The next task is to understand how and why this occurs. My search to understand led to a structured approach that I call “design-based” instruction. Although labs are an important part of “design-based” instruction, it involves more than just the labs; it places all instruction within the meaningful context of engineering practice.

Beginning with Design

Design is a complex activity which lies at the heart of engineering practice. ABET(1996 criteria) defines it as *“ the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective....The engineering design component of a curriculum must include most of the following features: development of student creativity, use of open-ended problems, development and use of modern design theory and methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations, production processes, concurrent engineering design, and detailed system descriptions. Further it is essential to include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impact.”* In retrospect it was easy to see that the Wooden Shoe Regatta project – including the speed and style competitions – met this definition of design quite well. It met those requirements in a junior level class normally taken before the senior design project, and the project took (and still takes) at least 5 weeks to complete. Was there a way to meet the ABET design criteria within a much smaller project and was there a simpler way to articulate the ABET criteria?

The generic 5 step model shown in figure 1 is one way to view the design process. It provides us with some structure for thinking about teaching design: our teaching should involve a balance of all 5 steps, where the balance reflects engineering practice. Note that homework assignments, lectures, and labs often involve mainly aspects of steps 2 and 3. In fact, often in lab we verify a particular model – concentrating on step 2 almost exclusively. We miss an opportunity here because the other steps of design are most easily included in the less formal environment of the lab.

Literacy

Figure 1. also shows 3 types of "literacy" often required to complete each design step. I have found the concept of literacy a useful one as I think about design. *Conceptual literacy* is a knowledge and understanding of scientific and mathematical concepts or ideas that form the basis for engineering analysis. *Mechanical literacy* is an understanding of tools and machines as well as a working knowledge of how to use them. *Cultural literacy* is an understanding of various groups within a culture and how to communicate effectively with them. Engineering design practice involves a roughly equal balance of these 3 types of literacy. Note that our usual approach in the classroom and in lab concentrates on conceptual literacy and in a very limited way (via written reports and homework) on cultural literacy.

In summary, our normal approach to instruction emphasizes only 2 of the 5 steps of design and only 1 of the 3 types of literacy. As will be evident in the discussion of the project worksheet, the *Wooden Shoe Regatta* project reflects a balance in the steps of design and also the types of literacy required to complete the tasks assigned. This is why the project is received with so much enthusiasm. If the rest of the curriculum could be similarly balanced, one result might be that engineering students might be far more enthusiastic about their studies.

What are the possible consequences of an unbalanced approach – one that favors one particular design step, or one particular type of literacy? In his book, Cultural Literacy (1987), Dr. E.D. Hirsch discussed mental schemata or structures as related to literacy and understanding. "*We know that schemata perform two essential functions that are relevant to literacy. The first is storing knowledge in retrievable form; the second is organizing knowledge in more and more efficient ways, so that it can be applied rapidly and efficiently. Without appropriate background knowledge, people cannot adequately understand written or spoken language. And unless that knowledge is organized for rapid and efficient deployment, people cannot perform reading tasks of any complexity. Although there are sizable variations in reading rates among good readers, no good reader is a very slow reader. Slowness of reading beyond a certain point makes assimilation of complex meaning impossible. The limits of short-term memory do not allow the integration of "unchunked" material, and so crucial parts of meaning are lost to memory while other parts are being painstakingly worked out."*

Instead of reading, we are talking about the complex task of design. The 3 types of literacy: conceptual, mechanical, and cultural, form the mental structure or the schemata into which our students must place new knowledge and from which they must deploy knowledge. If that structure is incomplete or weak, students will find it difficult to assimilate what they see as “unchunked” material. They will lose critical parts of meaning as they painstakingly work out those weaknesses in an attempt at design. Even worse, they may sense that their preparation is not complete and, on their own, they may not see how to complete it. If nothing in the curriculum addresses it, this can lead to uneasiness and discouragement – even fear, and students may decide to leave an engineering program because of it. (Although this could be another paper, it is worth noting that this could be why women and minorities often leave engineering after they have invested a year or more in a program.)

For example, how can mechanical engineering students design a pumping system if they do not know what various pump designs look like? How can they design a piping system if they do not know about plumbing components? A piping system is more than a theoretical concept; it is a practical reality in design practice. This is an example of mechanical literacy - an area in which many of our students are very weak. The typical high school preparation of college-bound students does not include even one shop class and most students have little experience (beyond Lego’s) with building components of any kind. Unlike many faculty members, most students have not had experience with taking things apart and building things as they were growing up. Most of my fluids students have no idea what the difference between a gate valve and a globe valve is…or what a sweat fitting is, yet these are the components which they must specify in a system design. Many students also do not know where to go to find these things out. Their level of mechanical literacy is very low, yet this is the type of information that can be easily incorporated in a very informal way into a well designed laboratory experiment by simply requiring that students select and install the component that is to be tested. This will provide the students with the opportunity to examine the valves closely and it also provides the instructor with an opportunity to discuss why loss factors might be different based on the valve geometry.

When you provide a well balanced curriculum which recognizes the weaknesses of students and provides opportunities to build the necessary schemata, the effect is the same as the effect of well balanced diet on health. Students make the new knowledge their own and are able to build on it and use it. Their class activities become essential to a transforming experience. They begin to *feel like engineers*.

Project Worksheet

Table 1. shows the project worksheet for the *Wooden Shoe Regatta*. This worksheet is a very helpful tool in assessing the balance in a particular project. The purpose statement is given at the heading of the worksheet. The 5 steps of problem solving are listed in column 1. The specific tasks that the student is expected to complete for each problem-solving step are listed in column 2. In column 3, the types of literacy required to complete this problem-solving step and the assigned tasks are listed.

Once this worksheet has been completed it is readily apparent if the project is well balanced or not. For example, the *Wooden Shoe Regatta* is balanced in the problem-solving steps and also in the types of literacy required.

Since this is a complex project with a 5 to 8 week duration, it can be expected to be well balanced. Individual weekly lab experiments or homework exercises might not reflect the same balance. However, just as a parent might balance a child's diet over the period of a day or a week without balancing each meal, an instructor can balance student practice in the problem solving steps and types of literacy over a longer period of time (such as an entire semester).

It is also important to note that it is not always necessary to have student activity fill in the entire worksheet. Neither is it necessary to make every part of a project a graded activity. For example, the *Wooden Shoe Regatta* always involves the development of a press release. This is something that I do and submit for student review. At the time that I show it to them, we discuss the importance of a press release when dealing with the media and when it is important to tell the story correctly. We also talk about how to work with the public relations people who are part of the staff of most companies and organizations. The students gain the benefit of an exposure to this aspect of cultural literacy within the presentation step of problem-solving. They gain it within the context of engineering practice and without involving a lot of their time or my time in grading 30+ press releases.

The worksheet is a valuable aid in documenting the design content of curriculum elements. This same overall structure can provide guidance in setting up an approach to an entire course. For example, the first step in the design process is problem identification. This involves asking the right questions. While students have a wealth of practical experience with fluids from everyday life, they are generally not adept at recognizing that certain phenomena are related to their studies of fluids. For that reason the first lab in fluid mechanics is an observation lab in which a series of 10 to 15 stations is presented to the students. They are asked to sample at least 7 of the stations and to articulate questions as well as to advance theories about answers related to those questions. The stations are selected to pose specific questions that will be answered as the course progresses. For example, at one station students are asked to drink milkshakes and water through a variety of straws. They are asked to view their mouths as pumps and the straws as piping systems. They are then asked what factors affect the required pumping power for a given flowrate. This is a very simple and common experience but most likely the student has not viewed it as related to the study of fluids. A series of such simple experiences provides a set of questions that can be answered as the course progresses. It also raises the student's expectation that this area of study will have practical application. Because the lab is enjoyable, the students begin to expect to enjoy lab and some of the questions are posed in order to initiate or enhance that "aha" reaction when it is explained in lecture. The students present their results for this lab in the form of a journal that might be appropriate for a general audience.

This first lab does have elements of all 5 steps of problem-solving, but it is strongest in steps 1 and 5 - problem identification and presentation. Knowing this, later labs, classroom exercises, and homework can be stronger in the other steps. The types of literacy can be balanced in a similar way. This may seem to be complicated and it may seem to require a lot of extra time on the part of the instructor, however it is important to recall a point made earlier in this paper. Not all activities need to be graded in order to give students the full benefit of the activity. For example, simply suggesting that the plumbing section of a local hardware store might be a good place to see the types of plumbing components gives the motivated student the information he/she needs to be able to fill in a gap in literacy. Another example: students generally need practice in giving short, impromptu oral presentations. I have required students to give one short (less than 5 minutes) oral explanation of the experiment completed in lab during the last week. The presentations are given at the beginning of the lab period and one or two are scheduled per week. Each student must present once during the semester. I provide immediate oral feedback with good and bad points (as appropriate), but there is no letter grade and I simply note that the student has completed this requirement. All of the students benefit from the feedback, and by the end of the semester the presentations are far more professional.

Enter ABET 2000

Design-based instruction involves carefully balancing student activity and student exposure to the 5 steps of problem solving and all aspects of the 3 types of literacy required for the practice of engineering design. The project worksheet presented in this paper is a valuable aid to quickly assess this balance. Students sense that a balanced curriculum does meet their needs. They learn more and they learn it with far more interest and enthusiasm. In the end, this is essential if our students are to become and also remain proficient in design. The ABET 2000 criteria have also been designed to make design practice part of the entire engineering curriculum. Figure 2 shows the a-k criteria as well as an analysis matrix filled out for a fluids lab. For each of the criteria the predominant types of literacy involved are included in parentheses. This serves as an initial screen for criteria that have been met by a particular assigned question or task. For example, if a particular question ranks high (H) in cultural literacy, potentially criteria c, d, f, g, h, j and also criteria e, i, and k could be satisfied. Initally 3 types of literacy are easier to identify than 11 criteria. In the matrix each design question posed or each task assigned is assessed to identify high (H), medium (M), low (L), or no content in each type of literacy and each of the a-k criteria. The balance for that particular exercise is immediately apparent and the matrix can be used to decide which questions to assign if time does not permit the assignment of all the questions in a given exercise.

Not Just for Fluid Mechanics!

Design-based instruction is rooted in the design process and uses design problems as the context for teaching the skills, concepts, and other special knowledge required to solve the problem posed. While the examples given in this paper are from a fluids class, the method is widely applicable. In fact, this approach was greatly refined when I first came to Grand Valley State University. I was assigned to a project that was to develop curriculum materials to teach environmentally responsible design to all engineering students. Environmental problems are often very complex and involve a mix of technical, legal, social, and regulatory expertise. They provide a wonderful way to meet the ABET 2000 criteria but the problems can quickly become overwhelming. There is simply no way that one class or even an entire 4 year curriculum can provide everything that a student will need for good environmentally responsible design. Instead of lecturing at length, for example, on environmental regulation, the team chose to pose an environmental problem that involved a limited amount of regulation. The exercise was posed as a hands on laboratory exercise and the pertinent regulation could be introduced as part of a much larger body of regulation. A student who would need more detailed information at a later date was made aware of that extended information and also how to find it. For the project at hand, the exposure could be carefully limited to allow us to properly balance the exercise. In this, I have found that the project planning chart and the ABET matrix are very useful as I chose which activities to assign, which areas I will provide detailed information for, and which areas I will provide general information for. Environmental projects using a design-based approach were developed for and used in freshman through senior level classes. (The collection is available to interested faculty in the form of a volume titled "Teaching Environmentally Responsible Design"– reference 3.) The student response to these projects has been very enthusiastic. In many cases the students do considerable research on their own and have been able to add to the body of supplemental project information made available to students the next time the project is assigned. The balance that can be achieved with a design-based approach definitely builds enthusiasm and prepares the student for life-long learning.

Grading

Design-based instruction often emphasizes the design process even more than end results. When we grade student work, we are accustomed to grading end results and not paying too much attention to process. In design there is seldom one correct answer. Instead there are many answers possible – all meeting the design requirements in a different but equally legitimate way. Fair and effective grading can be difficult in this case, but feedback is absolutely essential. Figure 3 shows a grading form used for fluid mechanics labs. The form is made available to students when the work is assigned so that they know how their work will be assessed. It is worth pointing out to students that this form is essentially a set of specifications – something that is often done in the design process. The form is different for different types of projects but in every case the form is divided into "technical issues" and "presentation mechanics". I often require an outline because that forces students to organize information – another design skill. Finally every form includes a section for comments. Here I am able to give feedback about the process that students show in their reported work and I am able to give encouragement. The form enables me to be much more fair as I grade reports that can vary widely in their overall appearance and style. The form also provides the flexibility that I need as I attempt to provide students with meaningful feedback

Conclusion

An engineering education involves much more than simply mastering a set of skills and techniques. While such mastery is essential it is also important that students are transformed by their education; that their interests, their attitudes, their sense of compassion are shaped by the education experience. An engineer is, in a very real sense, a type of person that you *become.* Building an identity as an engineer is essential to this process of *becoming.* Design-based instruction can be used together with the ABET 2000 guidelines to provide students with a curriculum that is meaningful to them and that builds their identity as engineers.

Bibliography
1. ABET Criteria for the Assessment of BSE Programs, current in 1996
2. Dr. E.D. Hirsch, 1987, Cultural Literacy, Houghton Mifflin Company, Boston, MA, pp. 56 – 57
3. Teaching Environmentally Responsible Design, self published and available from Padnos School of Engineering, GVSU, 301 West Fulton Street, Grand Rapids, MI 49504, (616) 771-6750.

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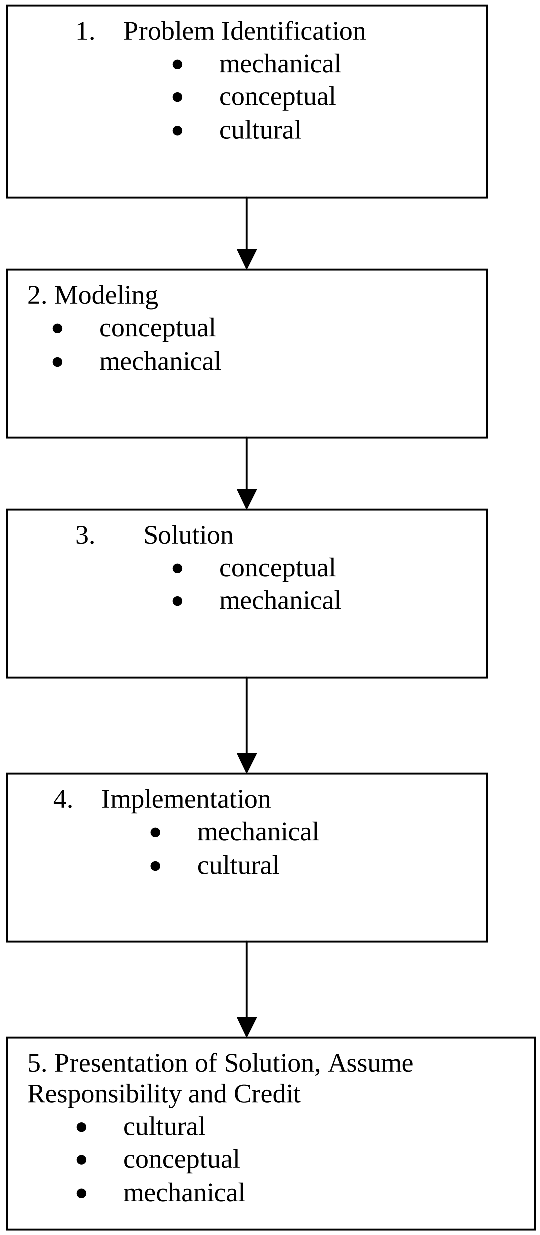

Figure 1. The problem solving (Design) process in five steps

Engineering Criteria 2000

Criterion 3: Program Outcomes and Assessment

Engineering programs must demonstrate that their graduates have:

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

Q#	mech.	concept	cultural		a	b	c	d	e	f	g	h	I	j	k
1		H			H				H		M				H
2	M	H			H	M	H		H		M				H
3	M	M			M	M	M		M						M
4	H	H			H	H	H		H		M				H
5	H	H			H	H	H	L	H		M				H
RW	H	H	M		H	H	H		H		H		L		H

Comments:
RW = Report writing

Figure 2. ABET 2000 Criteria and the analysis matrix for a lab experiment with 5 design questions and a required lab report.

Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition

EGR 365 Fluid Mechanics
Lab Grading Form

Student:____

Lab:____

Technical Content: Collection and presentation of data:______/2

Data interpretation:_______/4

Error assessment:_______/2

Theory development:_______/3

Effective information exchange:_______/2

Demonstrated grasp of material:________/2

Total:_________/15

"Mechanics" Professional appearance:________/1

Spelling, grammar, punctuation:________/1

Outline:_________/2

Completion of design questions:_________/1

Total:_______/5

Overall Total:__________/20

Comments:

Figure 3. Lab grading form for Fluid Mechanics. Note that cross reference to ABET 2000 Criteria can also be easily done.

Project: Design, build, and test a 1/12 scale model of a single hull sailboat. Write a technical report that includes the model hull and sail force tests to predict full scale performance. Use the single block of wood provided to make the hull. Be finished in 5 weeks.

Steps	Tasks	Required type of Literacy
1. Problem Identification	1. Identify forces/moments acting on sailboat system 2. Identify geometrical factors that might affect forces 3. Model must be stable 4. Hull to be carved from a single 2"x4"x10" block provided	1. Mechanical- what does a sailboat look like? Why proportioned as it is? 2. Conceptual- knowledge of fluid forces, direction of action, factors affecting forces
2. modeling	1. Model test equations a.) Froude scaling for hull b.) Reynolds scaling for sails 2. Decide on test velocities for realistic prototype speeds 3. Decide on hull shape and sail configuration	1. Mechanical – test equipment, operation and limitations a. How fast do sailboats sail? b. How to trip a turbulent boundary layer on model 2. Conceptual – understand test results a. skin friction drag b. form drag c. wave-making resistance d. Froude's hypothesis e. Definition of hull speed f. Vector analysis
3. Solution	1. Resolve trade-offs in hull design- example: length for speed vs. width for stability and limited material to use.	1. Conceptual – same list as for modeling plus stability principles
4. Implementation	1. Shape and finish hull 2. Add mast, weights for trim adjustment if needed 3. Design and build sail 4. Add keel and rudder 5. Perform hull resistance and sail force tests on model hull, sails 6. Test model to sail on a beam reach for race (wind from side)	1. Mechanical a. Use of various power & hand tools b. Finishing techniques i.e. painting, wetsanding, etc. c. Use & calibration of lab test equipment 2. Conceptual a. Inadequacies of modeling b. Error propogation c. Visualize force balances d. Effect of appendages on hull drag 3. Cultural a. Work as "apprentice" with skilled craftsmen b. Time management – deadline to meet c. Getting along with technical staff
5. Presentation-take responsibility and credit	1. Write technical report 2. Competitions – Style&Speed a. not graded b. trophies awarded 3. Publicity: a. posters and announcements b. invitations to special guests c. media-press release 4. Official logo, stationary 5. Thank you to technical staff 6. Announcement of results 7. 3-6 above instructor responsibility, also trophies	1. Cultural a. presentation of work to public and tech. report b. dealing with news media c. importance of recognition of support staff to support morale 2. Conceptual : evidence in report, mastery of all concepts listed above 3. Mechanical : Sail, rudder adjustments to sail desired path

Table 1. Project planning matrix