A Series of Design Courses in Biomedical Engineering

Frank J. Fronczak, John G. Webster
University of Wisconsin-Madison

Abstract

The curriculum for the BSBME degree at the University of Wisconsin-Madison requires a series of six design courses. Students begin in their third semester with prerequisites of calculus, physics and chemistry. We solicit real projects from faculty in biomedical engineering and the life sciences. Groups of two or three students interact with these clients to define the specifications for their projects. Instructors teach them design principles and guide them to seek information from the web, a course web page (http://www.engr.wisc.edu/coebin/courses98/get/bme/200/webster/) and other sources, brainstorm for a variety of solutions, select the best solution, and develop it. Students e-mail weekly reports to their clients and instructors. A mid-semester oral presentation is videotaped to provide feedback to the students. An end-of-semester report and public poster session enhances presentation skills. The succeeding five design courses build on other biomedical engineering courses and include exercises to meet the ABET requirements. We report on the first students experiencing this novel curriculum designed to prepare them for careers in Biomedical Engineering.

I. Introduction

In the Fall of 1998 a new Biomedical Engineering undergraduate degree program was launched at the University of Wisconsin-Madison. The inaugural class of 17 students was enrolled in the first of a sequence of required Biomedical Engineering Design courses. The BSBME degree curriculum includes a substantial design component. The students are required to take the interdepartmental Introduction to Engineering Design course in their first semester, and then, starting their sophomore year, begin a sequence of 5 one credit design courses. This is culminated with a three credit capstone design course. More detailed information about the curriculum requirements can be found at http://www.engr.wisc.edu/interd/bme/undergrad/handbook.pdf, however a few salient characteristics are repeated here for convenience.

It is anticipated that most students enrolling in the undergraduate BME program at the UW-Madison will pursue either an MD or an MSBME degree upon completion of their undergraduate work. The undergraduate program allows the students to pursue a concentration in one of the following areas:

- Bioinstrumentation
- Biocomputing
- Biosignals
- Biomechanics
- Biomaterials and Biochemotechnology
- Health Care Systems and Medical Information

Within the Biomedical Engineering Department, all students take courses in Bioinstrumentation, Biomechanics, Biomaterials, Physiology for Engineers, and Modeling of Physological Systems. The sequence of Biomedical Engineering Design courses should provide a unifying theme throughout the program and the enable students to gain an appreciation for the interdisciplinary nature of Biomedical Engineering. The attention placed on design experience in the curriculum reflects recognition of the importance of developing skills and cultivating attitudes that are a critical part of engineering success. While the students certainly acquire a substantial amount of engineering knowledge to supplement the knowledge learned in their technical specialty courses while working on their projects, the design course sequence is intended to provide the students a sustained opportunity to develop their creativity and judgement. As the students progress through the curriculum, they will be expected to tackle ever more challenging design problems involving an increasingly greater breadth and depth of knowledge and skill.

II. Course Objectives

Some specific objectives that the design sequence is intended to meet are:

- Develop engineering design skills
- Cultivate an innovative attitude
- Develop teamwork skills
- Promote a sense of engineering professionalism
- Provide exposure to a wide range of biomedical engineering technology
- Develop communication skills
- Motivate and excite the students to achieve a standard of excellence

It is noteworthy to point out that these objectives are, like design itself, fundamentally open-ended. They are quite unlike bits and pieces of knowledge or techniques that can be clearly marked out as being mastered or not. If we want to be sure that a student knows how to determine the frequency response of an electronic circuit or a mechanical system for example, we can devise a series of questions, which have a correct answer. If a student can answer the questions correctly, we can be confident that they have successfully learned the knowledge being taught and they are ready to learn different material. However, when we are talking about developing skills, or cultivating attitudes, the situation is not nearly so clear cut. There certainly is a body of knowledge that is particularly relevant to the design activity, and it is important to have the students become familiar with the various design principles and tools that are utilized. However, it is also essential to keep in mind that the development of skills is never ending. Just as the last step in the design process is to start over again by identifying the shortcomings of our current design and what opportunities for improvement exist, so too is it the case with development of skills. Design requires the continual exercise of judgement, and we are faced with dealing with the reality that good judgement comes from experience – and experience comes from bad judgement. By working with our students on design projects that require them to exercise judgement, and then having them deal with the consequences, we can work to continuously improve their judgement throughout their time at the university. We certainly recognize that when they graduate they are nowhere near their ultimate skill level but they hopefully have reached a point where they have a solid foundation which they can build upon. An appreciation of this led to the incorporation of the five design courses in the BME curriculum.

III. Project Selection

The students worked in two or three person teams on projects that were provided by biomedical researchers and medical practitioners. Projects were solicited from the University and local communities. At the beginning of the semester the students were presented with a selection of projects that had been prescreened for suitability by the course instructors. Thirteen potential problems that were consistent with the course objectives were submitted. Brief descriptions of these projects are provided at http://www.engr.wisc.edu/coebin/courses98/get/bme/200/fronczak/projects/ . This selection provided the students with an opportunity to form teams and select a project that they were most interested in, and consequently the project that they were most likely to be excited about.

Because the first design course is scheduled to be taken at the beginning of the sophomore year, most students have had few technical engineering courses, therefore the first project is intended to be one which does not require extensive technical knowledge. Because the students have had physics and thus have some familiarity with rudimentary mechanical systems, most of the first semester course projects involved relatively straightforward physical principles based on mechanics. However, because the students have a wide variety of interests, and one of the objectives of the course is to have the students be exposed to a wide variety of technologies, not all the projects fit the ideal mold. The projects which the students worked on were:

- Fluid Tissue Dissection Stabilizer
- Microdissection Device for Blood Vessels
- Forearm Prosthesis
- Mouth-Based Electrotactile Information Display
- Development of a Vaporized Substance Delivery Device for an MRI Machine (two groups)
- Knee Ligament Injury Simulator
- Mini-Mental Status Data Acquisition Program

One particular point about the faculty who taught the course bears mentioning here. The two instructors assigned to the course were from very different backgrounds, with one being an Electrical Bioinstrumentation engineer and the other a Mechanical Machine and Product Design engineer. This very diverse technical background provided the students with an immediate resource for quite a variety of technical expertise. Each student group had one instructor to whom they reported directly, but all the groups took advantage of the different backgrounds of the two instructors and frequently met with both instructors. Furthermore, most students were able to gain considerable technical advice from the individuals who had provided the projects as well as shop personal and several graduate students. While the students were certainly expected to gain experience in gathering information from a variety of sources such as the internet, catalogs, trade journals, and catalogs, for example, the availability of sources of immediate information proved very helpful, particularly in light of the students' relative inexperience level.

IV. Methods Utilized

The project nature of the course was the primary force that drove the methods used in the course. While most of the class time was devoted to the faculty working with the individual groups, a limited amount of time was devoted to activities involving the entire class. While a thoroughly active learning environment is implicit in a project course of this nature, and emphasis was placed on learning by doing, it was found beneficial to have a few formal lectures interspersed throughout the semester. These lectures were intended to provide the students with information that would give them some guidance in pursuing their projects. It is certainly recognized that there is a large body of knowledge relevant to the design process that has been codified, and that this could serve as the basis for any number of formal lectures. However, we chose to limit the number of these lectures in order to be sure that the students recognized that the emphasis of the course was their work on the project. The lecture material that was covered was selected to provide the students with a structure to guide them through the process. The topics that were covered included:

- Overview of the design process
- Development of design specifications
- Generating solutions
- Intellectual property
- Project planning and scheduling techniques
- Giving a presentation
- Types of drawings and their uses

These topics were selected for presentation to the entire class because they were considered to be of importance to all the groups, and this provided a more efficient use of time. The material was introduced in a timely fashion, that is, just as the students were dealing with the issues covered.

For background reading on some of these topics, the students were referred to a textbook being developed by one of the instructors and made available to the students at http://www.engr.wisc.edu/coebin/courses98/get/bme/200/webster/textbookch/ . While a couple of assignments were drawn from this book and the material in the book provided a valuable source of information for the students, the text served primarily as a reference source for the students.

The limited time spent on formal class activity such as lectures left the bulk of the time for the students to work in their groups and for the instructors to work with the individual groups. The role of the instructor was seen to be akin to that of a chief engineer. It is our job to provide some guidance (mostly by reviewing the students' work and by asking probing questions), to offer suggestions, and to evaluate the work. It has been found necessary to emphasize that suggestions are just that, *suggestions*, and they are not to be construed as mandates. Very often students will take off-the-cuff comments as gospel and respond accordingly.

In addition to helping guide the students through the process, the instructors also served as a source of some specific technical knowledge. This is also consistent with the faculty serving the role of a supervisory engineer. While the students were able to expect that they could consult with us on particular technical issues, they understood that our primary job responsibility was to provide them with guidance in the *process*, not to solve their problems. We reminded the students that we were *not* members of their design team. We would give advice, but certainly not do their work.

While the different backgrounds of the instructors enabled the students to have immediate access to a fairly wide body of technical knowledge, it was important for them to also become more skilled in acquiring new knowledge from a variety of sources. In all cases the students had a client that had initially proposed the project. In most case, these clients maintained a continuing interest in the progress of the projects and were able to provide advice as well as specific information in a timely manner. The students also made wide use of the Internet in obtaining information as well as more traditional sources such as manufacturers' catalogs and data sheets.

In addition to developing design skills and familiarity with a wide body of biomedical related technical knowledge, an important goal of the course was to develop the communication skills of the students. The activities directed towards these activities included weekly progress reports to the instructors and clients, a midterm oral presentation along with a written status assessment, and a final poster session with oral presentation, and a written final report.

The weekly reports were intended to provide an update of the team's progress, identify any particular difficulties (technical, group dynamics, gathering information, facilities, etc.) that the group was having, provide an updated schedule, and identify plans for the coming week. Each report was to include a concise statement of each team member's contributions to the project during the week. These reports were e-mailed to the instructors and the client and thus kept the lines of communication open among the team members, the instructors, and the client. They also were a convenient means of providing the basis for the discussions between the instructors and the students during the regularly scheduled class time. Problems that were identified could be addressed before they became insurmountable. The format for the report that the students were provided is available at http://www.engr.wisc.edu/coebin/courses98/get/bme/200/webster/designproc/. Completion of the conceptual design stage of the design process provided an opportune time for the students to give a formal oral presentation to the entire class. To help the students know what was expected of them, one of the instructors made a sample presentation in the week preceding the students' presentations. The students' presentations were videotaped to allow them the opportunity to review them; however, most students opted not to review their tapes.

Upon completion of the conceptual design stage, all groups began developing the details of their designs. Each group was required to actually construct a suitable representation of their design. This requirement was seen as an essential element of the project for several reasons. Certainly this forced the students to come to grips with the practicalities of their design concepts. It also required them to attend to details that are so important in a successful design. Rather than just waving their hands and dancing around the details, they had to confront them head-on and develop suitable solutions to the myriad problems that they faced. This required them to become more familiar with a variety of existing technologies that were needed for their designs. They also came to recognize that they had to often make important decisions with less than adequate knowledge and thus learn to better cope with uncertainty and ambiguity. By requiring something to be actually built, they were forced to deal with a whole host of issues not readily apparent while they are developing their designs. Certainly they learn a lesson related to scheduling issues and the realities of the time needed to acquire material and actually build things. By working with the shop personal, they quickly learned the truth in the old adage "Your failure to plan does not constitute an emergency for me." They also gain valuable firsthand experience that teaches them that design work done early and appropriately pays dividends and helps the project be completed more smoothly. Most importantly, perhaps, they learned that things don't always work as well in hardware as they do on paper. They must come to grips with the fact that the things that they considered and dealt with in the design stage are only a part of the problem; inevitably there are problems that they did not anticipate and these must be effectively dealt with before a project can be considered successful. In short, they learn the powerful lessons that come only from actually doing something, rather than just theorizing about it.

The final presentations were combined with a poster session in the lobby of the main engineering building. This provided the students with an opportunity to publicly display the results of their efforts. The teams that had made working models of their designs were able to use this opportunity to demonstrate them as well. This approach also served to publicize the new Biomedical Engineering undergraduate program among the students and faculty. The final oral presentations were made to the faculty and any interested bystanders at this time. This public display of the students' work certainly lent an air of excitement to the final presentations that is not typically seen in more traditional in-class final presentations. The written reports were placed on the web and can be viewed at http://www.engr.wisc.edu/coebin/courses98/get/bme/200/webster/finalrepor/ .

Assigning an appropriate grade to the students presented a rather formidable challenge. Several difficulties arose that should be considered. Certainly it is important to consider that the admissions policy to the Biomedical Engineering program is highly selective. These students are bright, energetic, and highly motivated. Consequently, it should be expected that they would do better than the average student; the grades should be reflective of this. The fact that this is a one-credit course also creates some additional consternation. At the University of Wisconsin-Madison, the academic culture has generally been such that the students tend to think of one credit courses as blow-off courses and they do not expect to have to devote substantial effort towards them. This is further compounded by the faculty culture generally having a higher expectation of student time commitment for design project courses than for more conventionally structured courses. These factors combined to form a situation in which students' expectations did not meet very squarely with the faculty's reality. Consequently, the students generally felt that the amount of work expected from them was more than that warranted by the credit allotment. Interestingly, however, they typically enjoyed the course and were willing to do the requisite work because they felt it was worthwhile. Their main complaint seemed to be with the system that allocated only one credit for the course and that their workload expectations were significantly exceeded.

A further complication is due to the fundamentally subjective nature of evaluating both designs and design engineers, especially ones with as little experience as these students have had. The grading scheme that was utilized in the course was based on the instructors' overall evaluation of the students and their work product. The grades were assigned to the team and all members of the team received the same grade. Because the nature of the work and the nature of students typically result in an inordinate amount of the work being accomplished in the final weeks of the semester, it was not felt useful to assign intermediate grades to the teams. Feedback was provided throughout the semester during the weekly discussions, but these generally just confirmed that the projects were behind schedule and that a lot of work needed to be done in order to accomplish the teams' goals. This approach, while it may appear somewhat harsh, was consistent with the belief that you learn more from your mistakes that you make than from your successes (especially when your successes come about because you have been led by the hand).

The grade ultimately reflected the instructors' overall impression of the student's effectiveness as a young design engineer. The grading involved several different elements with both objective and subjective components. While the actual level of performance was an important element that was taken into account when assigning a grade, it was certainly not the only factor. Improvement over the course of the semester also played a significant factor in the grading. Furthermore, an indication of future anticipated growth, or potential as a design engineer played a role as well. In this way, the grade was seen to be reflective of the knowledge, skill, and attitude exhibited by the students. Put another way, the grade was based on how strongly we would recommend the student, or how strongly we would feel about hiring the student for an appropriate, entry level position doing design engineering.

Some of the key items that were considered important were:

- Regular attendance and participation
- Creativity in approaching and solving problems encountered when working on the project
- Completeness and thoroughness in keeping a design notebook and in the final design drawings
- Attention to detail
- Ability to communicate effectively (written, verbal, and visual communication skills are all important, but special emphasis is placed on visual communication, e.g. sketching)
- Sustained effort throughout the semester
- Overall professionalism

The grading was done on a conventional A-F scale; however, the qualitative nature of the evaluation required a different approach than that typically used. The grading scale that was used was:

- A - Really on top of things, knows what to do, how to do it, and actually gets it done. Someone we would really go after to hire. They stand out as someone who will be an asset to the organization, who will make independent contributions above and beyond the norm.
- B - Can be counted on to do a thorough, dependable, (although perhaps unimaginative) job. Someone who we would be comfortable in hiring, who will make some contributions to the organization with relatively little guidance.
- C - Can be expected to do a passable job with a considerable amount of guidance. Can do less demanding tasks (such as looking up information) within the general job description adequately, but even with these tasks requires a substantial amount of guidance. We would hire this person only if we couldn't get someone that we really would want.
- D - Really can't be counted on to do a good job. Probably hinders progress more than helps it. We really wouldn't want to hire this person. We would do so only in a severe pinch, and we would immediately begin looking for a replacement.
- F - Completely ineffectual. Either minimal contributions, or actually an impediment to progress. We wouldn't hire this person even if we needed help desperately, and they were the only one available, because they would just cause our ship to go down even faster than it already was sinking.

A related issue that bears mentioning is that several of the students intend to apply to medical school upon completion of their BSBME program. Because of the extreme competition for admission to medical school, and the accompanying emphasis on high grades, the students have a particularly acute sensitivity to the grade that they receive. They are faced with the challenge of being enrolled in a program, which presumably develops particularly valuable skills, but at the cost of a more demanding and subjective grading policy. While this issue is not unique to the Biomedical Engineering program, it appears to be particularly acute.

V. Evaluation

At the end of the semester, the students were asked to evaluate the course with respect to the criteria that ABET has established for accrediting engineering programs and to offer comments on how the course could be improved. While this course is not expected to contribute towards satisfying all of the elements that ABET considers, it is interesting to note that 14 or more of the 16 students responded positively concerning 7 of 11 of the ABET goals. In particular, the students felt that the course met the ABET goals in the following areas (Numbers in parenthesis refer to the number of students responding positively):

a) an ability to apply knowledge of mathematics, science, and engineering (15)
b) an ability to design and conduct experiments, as well as to analyze and interpret data (14)
c) an ability to design a system, component, or process to meet desired needs (15)
d) an ability to identify, formulate, and solve engineering problems (16)
e) an ability to communicate effectively (16)
f) a recognition of the need for, and an ability to engage in life-long learning (15)
g) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice (15)

These evaluations gave a clear indication that the students felt that the course was meeting the established goals. One area in which the course fell somewhat short was developing an understanding of professional and ethical responsibilities. Only 11 of the 16 students responded positively on this item. Somewhat related areas where the students did not overwhelmingly feel that the course contributed towards meeting the ABET goals were:

a) an ability to function in multi-disciplinary teams (9)
b) the broad education necessary to understand the impact of engineering solutions in a global and societal context (4)
c) a knowledge of contemporary issues (9)

This information was used to help guide the topics to be considered in more detail in subsequent courses.

One clear theme emerged from the students' comments on how to improve the course. There clearly was some frustration concerning the somewhat ambiguous nature of the expectations that we had for the students. Of the 11 students that provided comments, 5 felt that more clearly defined expectations would be preferred. This reaction is probably to be expected given the open-ended nature of design and the prospects for continually improving on designs. Furthermore, while the students were reasonably conscientious in working throughout the semester, it is clear that they were not completely immune from the almost universally common (student) practice of putting forth a heroic effort during crunch time. These factors, along with the subjective nature of the grading as already discussed create some uneasiness on the part of the students. While it may be out of vogue to argue that this is actually a desirable state of affairs, it nonetheless may be. Furthermore, consistent with the course objective of promoting a sense of engineering professionalism, it can be reasonably argued that one mark of professionalism is be able to accurately assess the quality of one's own work. The ambiguity and subjectivity inherent in the grading forces the students to develop a sense of responsibility for evaluating their own effort and the quality of their own work. They then can compare this to the standards held by the instructors and see if they are in agreement or not.

An additional theme that showed up dealt with the relative inexperience of the students. Two students made specific comments that conveyed a sense that they felt that they did not have sufficient technical background to face the challenges presented by the projects. Once again, this is to be expected since the nature of engineering design calls for design engineers to continually extend the limits of their knowledge.

Subsequent discussions with the students in the second course in the sequence confirmed the sense expressed in their written comments. These discussions also established that the students, while feeling that they had to work harder than the one credit would indicate, generally enjoyed the experience and felt that it was very worthwhile.

VI. Closure

The first of a sequence of 6 Biomedical Engineering Design courses was launched last fall with 16 sophomore level students completing the course. The course had an auspicious first run, with both the students and the faculty generally satisfied with the process and the outcome. The goals of the course were ambitious. They were geared towards beginning the process of developing the skills and cultivating the attitude needed to be a good design engineer. The students were given a choice of challenging projects requiring them to acquire technical knowledge in a variety of fields. Without exception, they performed well and, to varying degrees, successfully completed representative models of their designs. Furthermore, they exhibited enthusiasm and energy in completing their projects. Certainly a single one-credit course cannot create accomplished design engineers. It can, however, provide a welcome opportunity for the students to acquire some worthwhile technical knowledge and develop some useful professional skills. In addition, and perhaps most importantly, the students had an opportunity to learn first hand the value in embracing a positive, resolute attitude, for as Thomas Jefferson noted, “ Nothing can stop the man with the right mental attitude from achieving his goal; Nothing on earth can help the man with the wrong mental attitude.”

Bibliography

A compilation of titles drawn from lists generated by Paul King http://www.bme.vanderbilt.edu/ tnbme2/ and Frank Fronczak

Adams, J.L., 1979, *Conceptual Blockbusting: A Guide to Better Ideas*, W.W. Norton & Co., New York, New York.

Burgess, J. 1986. *Designing for Humans: The Human Factor in Engineering*, Princeton, Petrocelli Books. (Any of you needing ergonomics)

Carper, K. L. 1989. *Forensic Engineering*, New York, Elsevier. (interesting case studies)

Foltz, R., Penn, T. 1989. *Protecting Engineering Ideas & Inventions*, Cleveland OH, Penn Institute. (In-depth coverage of the titled topic, of value in your professional activities)

French, M.J., *Conceptual Design for Engineers*, London, The Design Council

French, M.J., 1994, *Invention and Evolution: Design in Nature and Engineering, 2nd Ed.*, Cambridge, England, Cambridge University Press

Goldberg, P., 1983, *The Intuitive Edge*, Los Angeles, California, Jeremy B. Tarcher, Inc.

Hanks, Belliston, *Draw! A Visual Approach to Thinking, Learning and Communicating,* Los Altos, California, William Kaufmann, Inc.
Hollins, B., and Pugh, S., *Successful Product Design*, Kent, England, Butterworths Press
Ingle, K. A. 1994. *Reverse Engineering,* New York, McGraw-Hill Inc. (excellent ME/EE reverse engineering examples)
Koberg, D., and Bagnall, J., 1976, *The Universal Traveler,* Los Altos, California, William Kaufmann, Inc.
Laithwaite, E., 1994, *An Inventor in the Garden of Eden*, Cambridge, England, Cambridge University Press
McKim, R.H., *Thinking Visually; A Strategy for Problem Solving*, Belmont, California, Lifetime Learning Publications, Division of Wadsworth, Inc.
McKim, R.H., *Experiences in Visual Thinking, 2nd Ed*., Monterey, California, Brooks/Cole Publishing Co.
Ferguson, E.S., *Engineering and the Mind's Eye*, Cambridge, Massachusetts, MIT Press.
Middendorf, W. H. 1990. *Design of Devices and Systems*, New York, Marcel Dekker, (Good overview, good coverage of Human Factors)
Pahl, G., Beitz, W. 1988. *Engineering Design, A Systematic Approach*, London, Springer-Verlag. (Good, but hard to read)
Petroski, H., 1994, *Design Paradigms: Case Histories of Error and Judgement in Engineering,* Cambridge, England, Cambridge University Press
Sunar, D. G., 1989. *The Expert Witness Handbook*, Belmont CA, Professional Publications. (overview of expert witness responsibilities)
Von Oech, R., *A Whack on the Side of the Head*, Warner Books
Wilcox, A. 1990. *Engineering Design For Electrical Engineers*, Englewood Cliffs N.J., Prentice- Hall. (Easy)

FRANK J. FRONCZAK
Frank J. Fronczak is a Professor of Mechanical and Biomedical Engineering at the University of Wisconsin-Madison. He teaches in the areas of machine and product design, dynamic systems analysis, and fluid power. Dr. Fronczak's research includes work involving the design of hydraulic hybrid vehicles, hydraulic-mechanical-electrical systems, and rehabilitative equipment. He has also consulted with industry on dozens of design projects. He received a BS degree in General Engineering and an MS in Theoretical and Applied Mechanics from the University of Illinois, and a DE (Doctor of Engineering) degree in engineering design from the University of Kansas in 1977.

JOHN G. WEBSTER
John G. Webster received the B.E.E. degree from Cornell University, Ithaca, NY, in 1953, and the M.S.E.E. and Ph.D. degrees from the University of Rochester, Rochester, NY, in 1965 and 1967, respectively. He is Professor of Electrical and Computer Engineering at the University of Wisconsin-Madison. In the field of medical instrumentation he teaches undergraduate and graduate courses, and does research on RF cardiac ablation and measurement of vigilance. He has authored, co-authored, and edited 18 books in the field of the field of medical instrumentation. Dr. Webster has been a member of the IEEE-EMBS Administrative Committee and the NIH Surgery and Bioengineering Study Section. He is a fellow of the IEEE, Instrument Society of America and the American Institute of Medical and Biological Engineering. He is the recipient of the AAMI Foundation Laufman-Greatbatch Prize and the ASEE/Biomedical Engineering Division, Theo C. Pilkington Outstanding Educator Award.