

**AC 2008-1695: A TWO-PROJECT SEQUENCE FOR LEARNING FEM, CAD AND
MANUFACTURING SKILLS**

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Introduction

For biomedical engineering (BME) graduates to be effective contributors to the field, BME students should be introduced to the use of a variety of modern engineering tools in their undergraduate curriculum. ABET establishes that expectation through criterion 3k, which states that a biomedical engineering graduate from an accredited program should be able to demonstrate “an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice”. These tools may take on a variety of forms, including both engineering software (e.g. LabVIEW, SolidWorks, COMSOL, MatLAB) and engineering instrumentation (e.g. DAQ, oscilloscopes, multimeters, rapid prototype machines, and machine shop tools). In our BME curriculum, we aim to introduce students to a broad range of engineering tools through direct hands on experiences. While some tools are incorporated into standard 2 hour instructional laboratories, others are introduced through student-selected, open-ended, multiweek or semester long projects.

In this paper, we present a two-project sequence spanning two semesters that was designed to introduce students to several engineering tools through open-ended, student-selected projects. This project sequence is based on investigation of physiological fluid flow phenomena using 2D computational modeling and 3D flow chamber fabrication and testing. The engineering tools that students learn to use to complete their fluid flow projects are computational modeling software (COMSOL), computer-aided design software (SolidWorks), and manufacturing tools (rapid prototype machine, mill, saw, and drill). However, a similar two-project sequence could be developed in a variety of biomedical emphases and to include a variety of engineering tools.

In this paper we will provide an overview of each of the courses and projects involved in the sequence, including project objectives. We will share examples of the final results for both projects, and summarize the feedback received from student evaluations for the two years the project sequence has been taught. Finally, we will summarize the advantages, challenges, and broader applications of this approach in the conclusion.

Course and Project Sequence

This two-project sequence spans two required courses offered in two consecutive semesters. BMEG 300, Biotransport I, is taught in spring of the junior year. This course introduces students to the principles of biomedical fluid mechanics and culminates in the first project: a 2D computational model of a physiological fluid flow phenomenon. The second course in the sequence, BMEG 409, Fabrication & Experimental Design, is taught in fall of the senior year. The first half of this course introduces students to fabrication tools, and culminates in the second project: the design and fabrication of a 3D fluid flow chamber. Both courses and projects will be described in more detail below.

BMEG 300: Biotransport I

BMEG 300 is designed to provide students with instruction and hands-on experience with a range of biomedical fluid flow topics including blood rheology, liquid pumps, blood flow and biomedical applications of momentum balances. In addition to homeworks, tests and laboratory exercises, each student is required to complete a finite element modeling project utilizing COMSOL software. The primary project objective given to the students is:

To identify, set up and solve a two-dimensional, steady, biomedically relevant fluid mechanics problem and interpret the results with regards to the physiological phenomenon.

The primary deliverables for this project are periodic progress memos and a final conference style poster to be displayed in a public poster session. While an assessment of these deliverables is factored into each student's grade for the project, the detailed modeling results and associated physical interpretations are weighted the most. In designing this project, we anticipated and addressed a number of student concerns that could arise throughout the project including:

- How can I do this since I do not know the software package?
- With no partner in the project, how can I be sure my model is correct?
- How am I going to manage my own time when I have always been in teams for projects?
- It is not fair that my project is harder than those of other students
- I've never had to make a technical poster before.

As this is the students' initial exposure to finite element modeling, they are not only challenged by identifying the motivation for the project and executing the project, but also with learning the software package. In order to assist the students in the learning process, a series of classes and labs are dedicated to allowing the students to work in groups on solving predefined computational models in the first part of the course and to work on their own projects in the latter half of the course. In addition to assisting them in making progress on their projects, the use of lab time for the projects also reduces the amount of out of class time the instructor needs to dedicate to the projects. Beyond these sessions, each student needs to independently learn more of the software's capabilities depending upon his/her project topic.

To address the anticipated concerns, we assured all students that the degree of difficulty in each project would be taken into consideration. For example, a student with a simpler model would be expected to provide more in-depth results analysis while a student with a more complicated model might only have basic results analysis. Additionally, we provided sufficient poster preparation guidance for each student as some had made conference posters before and others had not. Overall, we attempted to provide each student with the opportunity to succeed. Examples of student projects include: 1) analysis of flow through bypass vessels, 2) analysis of the fluid mechanics in aneurysms, 3) analysis of the effects of plaque build up on blood flow.

After implementing this project for the first time in spring 2006, we determined that the combination of the open-endedness of the projects and the requirement that students work individually can create various valuable challenges for the students. First, while all of the projects have some basic characteristics in common, each possessed unique qualities requiring each student to learn slightly different modeling approaches and software capabilities. Due to this, each student had to become self dependent and become the 'expert' in that area of the modeling as there were no partners to consult. This exercise was a direct example of students independently learning technical information on their own and implementing it into a technical project. The second challenge experienced by the students was the physical interpretation of the simulation results which represented a significant portion of the project grade. As each model was different, each produced results that had different physical meaning and required students to consult a wide range of books and journal articles.

At the end of the projects, the students repeatedly expressed how they valued the opportunity to choose the topics for their projects. While each student experienced some of the frustrations of carrying out independent, open-ended projects, each of them also displayed a strong sense of pride at the final poster presentation that was attended by numerous engineering and science faculty.

BMEG 409: Fabrication & Experimental Design

The goal of BMEG 409 is to expose students to a variety of laboratory skills and engineering tools that are both useful for professional engineers and potentially valuable for their senior design projects. While not all of the topics introduced in this course will be applicable to all senior design projects, this course was designed to provide students with exposure to both engineering and biological tools that are not covered elsewhere in the curriculum. The course is broken into two units, the CAD/fabrication unit and the cell culture/biostatistics unit. The CAD/fabrication portion of the course is focused on device fabrication through developing skills in computer-aided design (CAD), machine shop tools, and rapid prototyping. The cell culture/biostatistics unit of the course is focused on basic mammalian cell culture techniques and statistical analysis of biological data. Due to the hands-on nature of the skills to be taught in this course, both units culminate in group projects. The project for the CAD/fabrication unit of this course is linked with the BMEG 300 project.

The CAD/fabrication unit of the course culminates in the fabrication of a physiological flow chamber. The project description given to the students begins with:

Project Goal:

The overall goal of this project is for each student to complete an engineering design project that utilizes SolidWorks computer-aided design (CAD) software, machine shop tools and the rapid prototyping machine to create a functional prototype device. Through this project, students will demonstrate their proficiency with SolidWorks and gain an appreciation for the tools used for prototype design. These skills will be valuable as they pursue their senior design projects.

Project Description:

In BMEG 300, you used FEMLAB to model flow in a variety of biomedically relevant flow channels. In this course, you will have the opportunity to design and build a flow chamber that will allow you to visualize the flow in one of those models. Choose a flow pattern investigated by one member of your group. You will use SolidWorks to design the flow chamber. The different parts of the flow chamber will be built using a combination of rapid prototyping and machine shop tools. You may use the same geometry you used in BMEG 300, or you may refine the geometry based on the outcome of your FEMLAB models (while still addressing the same flow condition). Note: these models do not need to be truly 3-D; you may use rectangular or hemispherical channels.

As indicated in the project description, the students work in groups of 2 or 3 to design, fabricate, and test a flow chamber designed to simulate flow in a physiologically relevant geometry. The physiological motivation and base geometry are drawn from the finite element modeling studies completed in BMEG 300. This decreases the ramp-up time required for them to identify and research a physiological motivation, while still providing them with a project driven by their own interests. To complete these projects, the students use the SolidWorks computer aided design (CAD) software to design the chamber, and then the flow chambers are fabricated using a combination of tools in the machine shop and the rapid prototyping machine. Thus, students gain experience using CAD software, instruments in the machine shop, and the rapid prototyping machine. The steps involved in the project, from learning the CAD software through flow visualization, are presented in more detail below.

Similar to the BMEG 300 projects, students need to gain experience with the engineering tools before applying them to their projects. In the first few weeks of the course, students individually complete a series of software tutorials and assignments aimed at introducing them to the basic functionalities of the SolidWorks computer-aided design software package. At the same time, they are learning in class about how to make effective engineering drawings and different types of fabrication methods, including rapid prototyping, the use of machine shop tools, and injection molding. In addition, they observe demonstrations of the different types of rapid prototype machines and machine shop tools (mill, lathe, drill, and saw). Together, the software exercises and the fabrication tool demonstrations provide them with the tools they will need to complete their projects.

The physiological flow chamber project is introduced in the first week of class, and is used to motivate the various assignments and activities that must be completed during the fabrication unit of the course. By the time they have completed the SolidWorks tutorials, the students have picked teams of 2 or 3 (the teams are self-picked), and selected a project to pursue. Because the BMEG 300 projects are individual and the BMEG 409 projects are done in groups of 2 or 3, each team of students faces the challenge of selecting one of their 2D models and adapting it to a 3D model for fabrication. The selection process is based on the ability to translate the 2D model to a 3D model and whether interesting stream lines were observed in the 2D model. Often in the 2D models the students varied a particular parameter, such as the diameter or placement of an aneurysm. For their 3D model, they must select a single condition to fabricate. They must also scale their designs to ensure that flow lines will be visible and that the entire chamber can fit

within the build size of the rapid prototype machine (12" by 12" by 10" for our system). Hence, this project teaches them some aspects of designing with constraints.

Once a project topic has been selected and a base geometry identified, the team works together to design their 3D model in SolidWorks. The students are required to complete models of both the base and the lid, with the aim of fabricating the base using the rapid prototyping machine and the lid using machine shop tools. They are also required to create engineering drawings of each part. During the design process, they are required to consult with the manager of the rapid prototype machine to ensure compliance with the instrument and get advice on their designs. When the design of the base is approved, the students export the file in .STL format and work with the manager of the rapid prototype machine to have the bases built. They then use their engineering drawings of the lid to work with the machine shop technicians to machine the lid to the proper geometry and drill holes in the appropriate places. Each team is provided with a 12" by 12" sheet of 1/8" thick acrylic from which to machine the lid.

Finally, the students must construct their chambers and test them, videotaping the observed streamlines under different conditions. The project culminates with an oral presentation and demonstration of their flow chamber, and a written report documenting the construction of the flow chamber and evaluating the results of the experiments with respect to their previous COMSOL simulations. The students are required to compare the results of their experiments to the results expected based on their previous COMSOL simulations, and explain any discrepancies. This often led students to identify some limitations of 2D modeling. The final paper and presentations also provide students with experience in oral presentations and written report writing in a scientific discipline, in contrast to the graphical presentation methods used in BMEG 300.

Project Comparison

The two projects have some key similarities and differences which we feel enhances the learning experience. For example, the projects share a similar format in that to introduce each engineering software tool (COMSOL and SolidWorks) students are assigned tutorials and structured problems to be solved with the tool before applying them to their chosen project topic. In addition, the project is used as the motivator for the whole unit in each case. However, the group/individual nature of the projects and assignments varies for each course. In the transport course, which has an independent project, students do some of the tutorials and assignments in groups to build skills and gain confidence in their abilities. In the fabrication course, which has a group project, the tutorials and assignments are individual until work begins on the project, to ensure that all students have sufficient exposure to the tool. So through each project, the students receive a mix of team and individual assignments, although the balance is different in each case.

The presentation format for each course also varies. Each unit culminates in the interpretation and presentation of their project results. In the transport course, the final presentation is in the form of a research poster, while in the fabrication course the final presentation is an oral presentation including a demonstration of their flow chamber. The fabrication course also requires a written engineering report. Hence, through the two projects students gain experience in professional oral, written, and graphical communication skills.

The two projects also share the challenge of requiring the students to teach themselves additional skills beyond what they learn in class. While the tutorials and structured exercises leading up to each project provide an understanding of the basic functionalities of each computer program, each student (or group of students) has to learn additional features to successfully complete their projects. These projects therefore both provide students with lifelong learning experience, and using their self-selected projects helps to motivate this independent learning experience.

While the primary goal of this two-project sequence is to introduce students to engineering tools (ABET 3k), the design of the projects does allow for the assessment of numerous ABET Program Outcomes. In our program, we use these projects as means for assessing communication skills (300 and 409), lifelong learning (300), and engineering tools (300 and 409). However, due to the various characteristics of the projects, several additional assessment areas could also be addressed. First, based on the mixture of team and individual assignments, students' abilities to function on teams (3d) could be assessed. Second, contemporary issues (3j) could be addressed since students work with state-of-the-art rapid prototyping equipment and focus their projects on current medical challenges. Next, since the project sequence is based on the analysis of a physiological flow system, assessment for ABET criterion 9 (problem solving at the interface of engineering and biology) could be implemented. Finally, the COMSOL modeling is an example of identifying, formulating and solving a biomedical engineering problem (3e, 9), while the flow chamber fabrication project could be used to assess design with constraints (3c). Overall, the structure of the two-project sequence provides a great deal of assessment flexibility.

Example Projects

Below are two sample projects from BMEG 300 and BMEG 409, showing the progression in each case from a 2D theoretical finite element model to a 3D fabricated flow chamber.

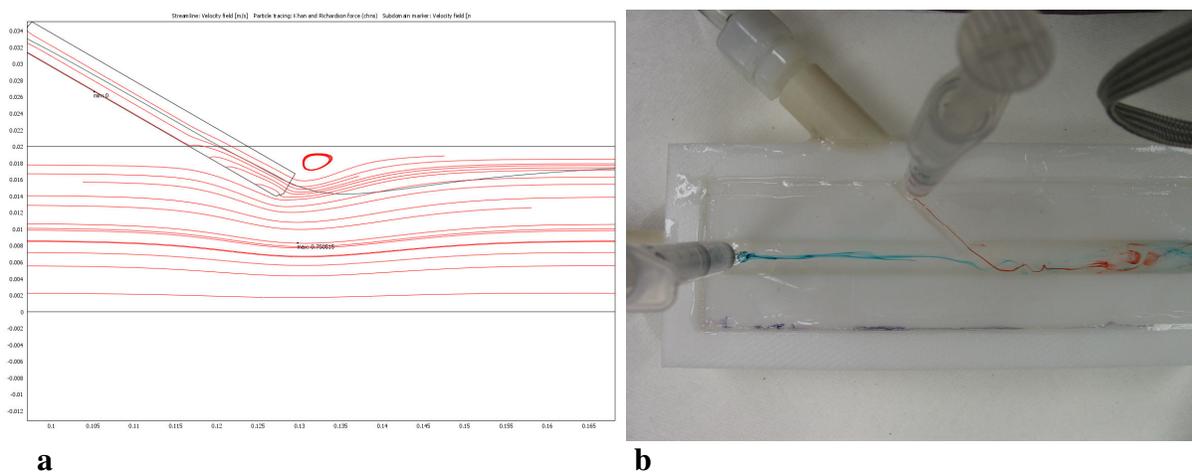


Figure 1: (a) COMSOL plot of 45° injection with velocity streamlines, particle tracing, and observed recirculating flow near tip of injection device. (b) Image of flow patterns in the 3D fabricated flow model of the same geometry.

The first example is a model of a needle injection into the brachial artery. In the COMSOL model, the student varied the angle of implantation of the needle and the relative velocities of the injected fluid and the fluid flowing through the primary channel. For the 3D flow chamber, the students picked a single injection angle (45°), but still investigated flow patterns for two different flow conditions. Different dye colors were injected through each syringe to visualize the interaction of the flow through the “needle” with the flow in the “artery”. They found that the observed streamline patterns were similar the behavior predicted by the COMSOL model for each flow condition tested. Sample COMSOL plots and stream line images for the 45° injection angle are shown in Figure 1.

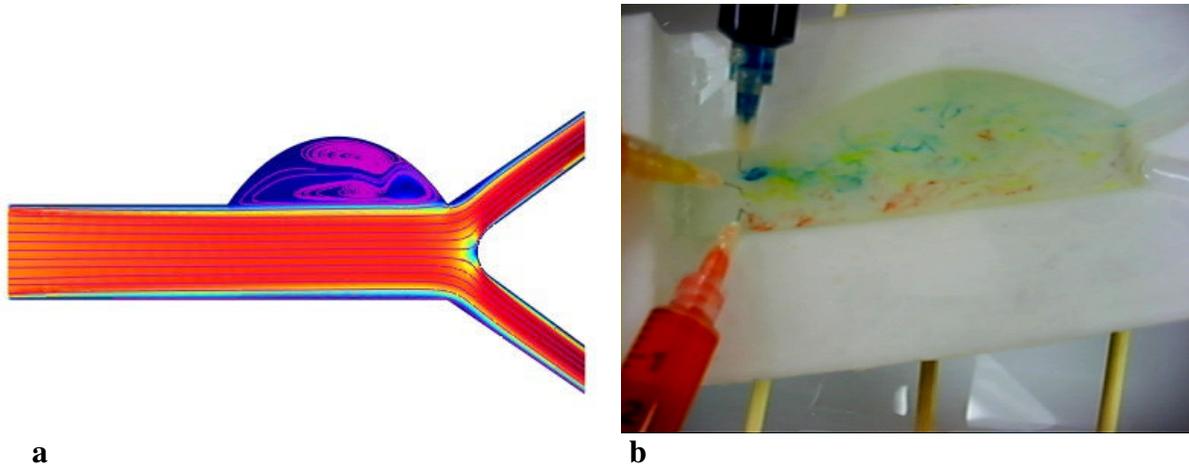


Figure 2: (a) Streamlines and velocity results from COMSOL analysis. (b) Turbulent flow through the aneurysm in the 3D flow chamber.

The second example is a model of an abdominal aortic aneurysm. Figure 2 shows streamlines and vorticity mapping in the 2D COMSOL model (Figure 2a) and the flow patterns in the 3D fabricated model (Figure 2b). Note that the COMSOL model shows smooth flow down the primary vessel, with recirculation in the aneurysm. The stream lines in the flow chamber, however, show a great deal of turbulence throughout the model. Some of this turbulence is likely due to the fact that the students did not leave enough straight vessel before the aneurysm to allow the flow to stabilize between the inlet and the aneurysm. But some was likely due to the 3D shape of the aneurysm in the flow chamber. In the 2D model, the student modeled the aneurysm as a bulge on the wall of the aorta. In the 3D model, the students made the cut for the aneurysm revolve around the whole vessel, so there was also an increased depth to the aorta in the region of the aneurysm. The students speculated that this may have had a large impact on the flow patterns observed.

Assessment

BMEG 300

BMEG 300 has now been taught twice with each offering including the finite element modeling project. When asked at the end of the semester if the finite element modeling projects were a valuable part of the class, the students expressed their positive opinion through an average score

(on a 5-point Likert scale) of 4.77 in 2006 (13 students) and 4.47 in 2007 (15 students). Furthermore, in the written course comments over the two years, 14 of the 28 students indicated that the finite element project was the course component they liked the most. Overall, we have received little negative feedback from the students regarding the project. From the instructor's perspective, the students' abilities to analyze complex flow problems have been positively affected by the finite element projects. Their abilities to understand the physical meaning of the governing Navier-Stokes equations and successfully interpret the modeling results are reinforced through the individual projects. Student quotes from course evaluations include:

“Comsol project allowed practical application of knowledge”

“I really enjoyed the Comsol project. It was very challenging but I learned a lot from it.”

“Comsol provided a way to visualize detailed problems.”

BMEG 409

BMEG 409 has also been taught twice with each offering incorporating the 3D flow chamber fabrication project, and the student evaluations indicate that it is their favorite part of the course, on average. In the written course comments, 9 of the 13 students in 2006 and 10 of the 15 students in 2007 indicated that the SolidWorks and prototyping flow chamber project was the course component they liked the most. When asked if the hands-on projects were a valuable part of the course, the average score (on a 5-point Likert scale) was 4.23 in 2006 and 4.33 in 2007. Students were only queried specifically about the flow chamber fabrication project and its connection to BMEG 300 in 2007. When asked if the SolidWorks and rapid prototyping was a valuable part of the course, the score was 4.07, with 13 of the 15 students giving the unit a positive score of 4 or 5. Overall, the reaction to the flow chamber project has been very positive. Student quotes from course evaluations include:

“I really enjoyed practicing and learning SolidWorks. I felt that the tutorials were extremely helpful in grasping the main commands of the problem so we could construct the chamber.”

“The flow chamber prototype project was very interesting and educational.”

“I liked that we learned some hard skills that will be useful to know, especially SolidWorks.”

While the overall response to the project was positive, some students (0 in 2006, 3 in 2007) did indicate that they would have liked more instruction in SolidWorks.

Project Sequence

In 2007, the students were also specifically queried about the project sequence. When asked specifically if exploring the same physiological flow phenomenon using two different methods, COMSOL modeling and flow chamber fabrication, was a valuable experience, the score was 3.93. There were 11 positive scores of 4 or 5 for this question, associated with comments such as:

“It was interesting to see the differences between the 2D and the 3D model.”

“I liked the transformation from computer to 3D with the flow chamber.”

“I think it was good to make the COMSOL model into a chamber but comparing our two methods was pointless because the addition of the 3rd dimension completely changed the problem but that was interesting to investigate.”

The course evaluations also provided some constructive feedback that will aid in improving the project sequence, as illustrated in the following quotes:

“For most COMSOL models, the measured parameters (shear, pressure, etc.) could not be measured in the prototyped models. Streamlines were not always interesting.”

“Would be better if last year I knew more about this (scope) project so that my COMSOL model could be done instead of the COMSOL model I made which could not easily be done.”

Such comments raise an interesting point about the need to introduce the entire project sequence in the first course in order to ensure maximum benefit in the second course. Since the students did not know that they would be using flow chambers to visualize streamlines when they performed their simulations, many did not investigate flow patterns in their COMSOL models, but rather focused on parameters like shear and pressure distributions. Another way to solve this problem would be to require an analysis of flow patterns as part of the modeling project, rather than leaving the selection of parameters to analyze completely open to the students.

Discussion and Conclusions

After conducting this sequence two times, we have found that incorporating the learning of engineering tools into open-ended, self-defined projects has many advantages. For example, letting the students pick the underlying motivations for their projects enhances their desire to learn and apply the techniques under less guidance. In addition, because the students are all working on different projects, each student or team may need to become experts in different aspects of the software packages used, and they can then advise other students in their area of expertise. Linking the two projects together also provides some continuity between otherwise disparate courses and provides a self-selected biomedical motivation for the CAD and fabrication project that does not require research time as part of the course. Linking the two projects also allows students to examine the same problem using multiple methods that may initially seem unrelated and provides students with exposure to both 2D and 3D models of the same physiological flow system.

Of course, using open-ended, self-defined projects to introduce engineering tools also has some challenges associated with it. For example, the instructors likely do not know what the outcome should be for each project and may not be experts in the specific skills each student or group needs for their project. To offset this challenge, students are encouraged and expected to use other provided resources (such as books, tutorials, technicians and each other) to overcome obstacles. Success in these projects is very dependent upon students being able to learn new material on their own. A second challenge is finding an appropriate balance of structured assignments and time spent on the open-ended project. For example, spending too much time on structured assignments reduces the level of progress students can make on their projects. Third, some of the 2D projects do not have interesting flow patterns associated with them. If students go on to fabricate 3D models for those projects, they do not observe interesting streamlines. Other 2D projects do not translate well to the 3D models within the limits of the fabrication techniques available and the students' skills. Because students work in teams on the 3D modeling projects, they do not need to fabricate 3D models of each 2D project. This allows for more freedom in the 2D models while still making it likely that each group of 3 students will have a viable fabrication project to pursue. However, groups may need coaching to select which

of team members' 2D projects would be the most appropriate to translate into a 3D model so that they will have the most satisfying 3D project.

In conclusion, we feel that this two-project sequence provides students experience with several engineering tools while simultaneously enhancing their "buy in" in the projects by allowing them to select the biomedical motivation. Furthermore, the interdependence of the projects provides students with an opportunity to examine the same problem with multiple methods. We have presented student feedback and evaluations that support the effectiveness of this instructional method, while also highlighting some areas for improvement. Finally, while the focus of our project sequence is physiological flows, we feel that this technique could be applied to many areas in biomedical engineering and be tailored to introduce different modern engineering tools. The key concepts to consider in designing a sequence are: self-motivation for the project, analyzing a single BME problem using multiple methods and engineering tools, and providing sufficient background in the tools needed to approach the problem using each method. The implementation of the project sequence could also be varied by including both versions of the project in a single course, depending on the tools being taught and the objectives of the course.