



BioMEMS and Biomedical Nanotechnology Education:

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BioMEMS Education at Louisiana Tech University

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Abstract. A course in BioMEMS was recently taught at the senior undergraduate and graduate level at Louisiana Tech University and the Institute for Micromanufacturing. The course focused on the basic principles and applications of MEMS technology in the area of biomedical microsystems. The course was well received and had an enrollment well above that expected. Student feedback and a review of the course evaluations indicated that the course was effective in achieving its aims. A poster session involving the presentation of student design projects at the end of the course proved to be a highlight and a valuable experience for all involved. While the course proved successful, suggestions for improvement of the course are outlined and a summary of student responses is presented. An overview of a BioMEMS short course based on the University course is also presented.

Key Words. BioMEMS, education, curriculum, micro-total-analysis-systems

University: Louisiana Tech University

Department: Biomedical Engineering (College of Engineering and Science)

Instructor: Dr. Bruce K. Gale

Class Title: Biomedical Applications of Microsystems (three semester credits)

Quarter Offered: Winter 2000–2001

Number of Students: 18

Level and Enrollment: Senior Undergraduates (3) and Graduate Students (15)

Introduction

Biomedical applications of microelectromechanical systems, or BioMEMS, is a rapidly growing field with an increasing number of companies investing in the area. Accordingly, demand for skilled and educated workers in this field is rapidly expanding and universities need to develop educational plans to address the specialized needs in the BioMEMS area. BioMEMS education

provides a number of unique challenges when considered from an educational perspective. Traditional MEMS applications which focus on mechanical and electrical applications are highly interdisciplinary in nature even though they grew out of the highly specialized integrated circuit industry. BioMEMS calls for an even greater level of interdisciplinary work, education, and research. While general MEMS curriculum development relies heavily on traditional materials science, electrical engineering, and mechanical engineering classes, BioMEMS requires additional background in physiology, molecular and cell biology, biomedical engineering, biology, chemistry, and other related fields. Because of this interdisciplinary nature and the significant background required to work and study in this area, courses taught in BioMEMS must be at the graduate level or very advanced undergraduate level, and may require a number of prerequisites that are not normally included in a typical electrical or mechanical engineering curriculum. Thus, a complete BioMEMS curriculum would likely include classes from mechanical, electrical, and biomedical engineering, biology, chemistry, and other disciplines.

At Louisiana Tech University, an extensive series of courses in MEMS has been developed and taught for the last several years as part of the Institute for Micromanufacturing (IfM). Figure 1 shows the titles and course numbers of these classes as well as their relationship to each other. The only prerequisites for the first class in the series, Vacuum Science and Technology, is graduate standing in engineering or approval of the instructor. Each of the courses in this sequence is highly focused on the topic area and provides significant depth in both theoretical and practical topics. The majority of the courses include labs and laboratory exercises. The program is specifically designed for Ph.D. students and provides an in depth education in MEMS that we feel rivals any in the world (Lin, 2001). Typical enrollments in these courses range from 30 to 50 students.

Since the complete series is rather long and involved, in the past year the IfM has developed a survey course more geared toward MS students and senior-standing

undergraduates. This class is similar to those offered at many other universities and will be taught by the author in the Fall of 2001. The current enrollment in this course is more than 80 students. To complement this survey course, and to teach specific application and design concepts to both PhD and MS students, a cluster of focused application classes have also been developed over the last year related to the various thrust areas at the IfM, which include BioMEMS, EnviroMEMS (chemical and environmental engineering applications), and nanotechnology (including self assembly and ultra thin films). Accordingly, classes focused on biomedical and chemical applications, as well as nanotechnology methods, have been developed and taught during the past year. The BioMEMS class was also recently compressed into a short course that was presented to over 100 registered attendees at the Precision Instrument Development Center (PIDC) in Hsinchu, Taiwan (ROC). This paper will focus on the details associated with the class Biomedical Applications of MEMS, which was taught during the 2000–2001 school year and the BioMEMS short course, which was presented in March of 2001.

Syllabus and Course Outline

A major challenge associated with the course was to determine the prerequisites required for students to take the class. For the first offering of the class, the prerequisites were limited to allow as many students access to the class as possible. Prerequisites were only senior standing as an undergraduate or graduate standing in engineering. This allowed for a fairly diverse class makeup that presented a few challenges during the course of the class. No micromanufacturing experience or courses were required for the class.

The first question associated with developing a class on the subject of BioMEMS revolves around the still debated question: What exactly is BioMEMS? An even more general question to answer that may help with this question is: What is MEMS? For the purposes of our curriculum and this class, we chose to focus on microscale devices that use photolithography or beam machining as a primary fabrication method. This definition of MEMS eliminates many traditional techniques, such as glass pulling, that can be used to develop structures or devices on the microscale, but that are not considered novel. We chose to examine a few devices that used micromachining equipment, such as a microlathe or micromill, but these were the exception rather than the rule.

With these basic guidelines in place, we broke BioMEMS down based on two categories of BioMEMS. The first category of BioMEMS devices included any MEMS device that had a biological application. This definition could include such things as microfabricated pressure sensors used to measure blood pressure or even accelerometers that are used in a variety of biomechanics experiments. Most MEMS devices that have general applications, with only slight potential modification for use in a biological environment, were not discussed or addressed since it was assumed they would be well covered in a general MEMS course. Some other multi-purpose devices, such as microanalysis systems, which could also be used in general chemistry, environmental analysis, or process monitoring, were closely covered in the class since a primary application of those devices would be related to medicine or biology. These devices often required specific properties or modifications to be used in biologically based applications.

The second category of BioMEMS was much more biologically oriented in that it included only devices that

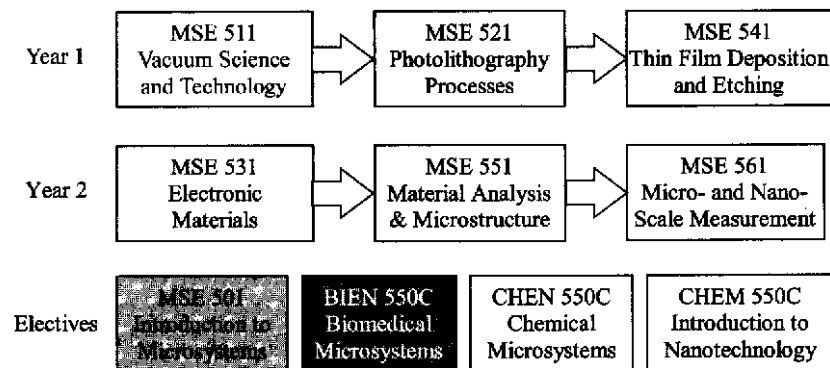


Fig. 1. Chart showing the various MEMS classes available at Louisiana Tech University. The two-year sequence of classes is designed for PhD students and they can take the elective application classes as appropriate. The light gray course is an introductory course that has just been developed for Masters and senior undergraduate students and will serve as a prerequisite for the other elective application and design oriented classes.

were specifically designed to operate in the presence of biological media or incorporated a biological component into the operation of the device. An example of the first case would be microneedle arrays, which do not include any biological components in their design, but are specifically designed to interact with biological tissues and fluids. An example of the second case would include an enzyme-loaded bioreactor. While the bioreactor may be based on "normal" chemical reactors, the enzyme component would require some unique design methods and would make the device an example of BioMEMS.

Two more important questions to be addressed were: Where does the class begin? and What knowledge does it assume? As mentioned previously, no background in microfabrication was required for the course, so the first several lectures in the course went over a brief review of the various microfabrication techniques available and their application toward miniaturized devices. These techniques were general microfabrication techniques and are not specifically or primarily geared towards BioMEMS applications. After a review of the general microfabrication techniques (first four lectures), techniques specifically important to biomedical applications were discussed and analyzed. Topics that fell into this category included micromolding and hot embossing of plastics, soft lithography, and direct writing in polymers. These polymer techniques were considered especially important and relevant due to the increased focus on these types of materials in BioMEMS applications and research.

Since not every student in the class was conversant in

Table 1. Course topics covered each lecture period of the class

Lecture	Topic
1	Introduction; Photolithography; Crystallography, Mask Design
2	Wet and Dry Etching
3	Thin Film Deposition and Growth
4	Electroplating, Molding, LIGA, Bonding and Sacrificial Processes
5	Polymer Processing and Rapid Prototyping; Packaging
6	Exam I
7	Biomaterial Basics
8	Biocompatibility Issues
9	μ -TAS: Fluid Control Components
10	μ -TAS: Sample Handling
11	μ -TAS: Separation Components
12	μ -TAS: Detection
13	Cell Handling and Characterization Systems
14	Systems for Biotechnology and PCR
15	Polynucleotide Arrays and Genetic Screening
16	Miniature Biosensors and Biosensor Arrays
17	Neural Interfaces and Implantable Devices
18	Microsurgical Tools, Microneedles, and Drug Delivery
19	Miniature Bioreactors and Microsystems for Tissue Engineering
20	Final Exam
21	Poster Session

biomedical principles, a brief review of biology, biocompatibility, and biomaterials was presented. This review of biological principles focused on the impact that traditional micromanufacturing materials and processes might have on the function of a BioMEMS device and the host organisms (if any). After this point in the class, specific application areas, operational principles, design concepts, and unique considerations were examined for a variety of BioMEMS devices. Table 1 is a summary of the topics included in the class along with the relative amount of time spent in the class on the subject. It should be noted that Louisiana Tech has a unique quarter system that awards semester hours for classes taken. For this particular class, which was a 3 credit class, we met twice weekly for 2 hours at a time, so each lecture corresponds to two hours of material. Course notes and additional information on the class are available on the course website at http://www.latech.edu/tech/engr/bme/gale_classes/biomems.htm.

The first exam for the class covered the basic micromanufacturing methods and consisted of a design problem in which the student was required to develop a design for a basic MEMS pressure sensor and explain all of the fabrication steps. This exam was a take-home test that allowed the students to consult published works on the subject and to give in-depth information regarding fabrication and the processes used. The second 2/3 of the class included weekly quizzes that covered the preceding two lectures. The final exam was taken in class and was comprehensive in coverage, but focused on the application areas discussed in the 2nd portion of the class. It included a BioMEMS design problem that required the students to examine the issues related to the design and fabrication of a microdevice used to perform a polymerase chain reaction (PCR).

In addition to the lectures presented by the instructor, a number of other educational activities were included. First, each student was required to present orally to the class a current journal paper related to the topic discussed that day in class. Students typically had anywhere from 3 to 5 weeks to prepare for this presentation. Thus, there was usually at least one and sometimes two 15 minute presentations by students during each lecture period in the second "half" of the class. These presentations allowed the students to develop some experience in an area of their choice, develop presentation skills, and break up the long class period. Fifty percent of each student's presentation grade was determined by the scores received from the other students in the class. The peer review provided important incentives to both the presenting and observing students.

The second additional educational activity was a quarter long design project. Each of the graduate students chose a topic to research and was required to develop a

design for a viable BioMEMS device during the quarter. The three undergraduates in the class worked together as a team on their project. The project was approved by the instructor and was expected to include the following sections in the final report: problem definition, motivation or rationale, implementation methods considered (brainstorming), "customer" requirements, functional specifications, modeling and scaling effects, fabrication methodology, mask or CAD layout, packaging, testing methodology/plan, and conformance to specifications. On the last day of class, a poster session was held where each individual/group presented their work to the public. The posters were graded as part of the design project along with the final report turned in to the instructor. The various components of the design project were required to be reviewed by the instructor during the course of the class to ensure that proper progress was being made on the projects during the quarter, and therefore served as milestones.

Textbook and Additional Bibliography

The list of potential textbooks for a class in biomedical applications of MEMS is currently quite short, and none are specifically designed for the purpose. We chose the book *Microsystems in Chemistry and the Life Sciences*, edited by Manz and Becker (1999). The book was chosen specifically for its broad ranging coverage of both manufacturing methods in BioMEMS (soft lithography), design principles, and clear application examples. The subjects covered in the book helped to guide the selection of topics for the class, as well as the proceedings of several relevant conferences available at the time the class was prepared (Knowledge Foundation, 2000; Harrison and Van Den Berg, 1998; Van Den Berg and Bergveld, 2000). As support texts, several books on microfabrication principles and methods were used with the primary one being *Fundamentals of Microfabrication* by Mark Madou (1997). Several other books and proceedings were used as regular references by the instructor including: *Micromachined Transducers Sourcebook* by G.T.A. Kovacs (1998), *Semiconductor Sensors* by S.M. Sze (1994), the conference proceedings from MicroTAS in both Harrison and Van Den Berg (1998) and Van Den Berg and Bergveld (2000), the proceedings of the 1st International IEEE-EMBS Conference on Microfabrication in Medicine and Biology (Dittmar and Beebe, 2000), the CRC *Handbook on Biosensors and Electronic Noses* (Kress-Rogers, 1997), and journals such as *Biomedical Microdevices*.

BioMEMS and Biomedical Optics Short Course

As mentioned previously, the author of this paper along with Dr. Michael McShane also presented a three-day short course on the subject of BioMEMS and biomedical optics that combined the material discussed here in the BioMEMS class with material prepared by Dr. McShane related to biomedical optics. The BioMEMS portion of the course condensed the material covered in the class down to 12 hours of lecture. The biomedical optics portion also included 2 hours devoted to optical biomedical microsystems. Participants in the short course were provided with lecture notes and a CD of the presentations.

Discussion

A main objective of the course, in addition to the normal educational objectives, was to rapidly prepare and train students at Louisiana Tech to perform basic research in the area of BioMEMS. Several professors at LTU have a significant interest in MEMS, so there was a natural constituency for this course. The course was designed to allow each student to progress rapidly in their chosen area of specialization (journal paper presentation and design project) while giving each student a broad background in BioMEMS and an understanding of the core issues in most biomedical MEMS applications. In general, the interested faculty and students responded favorably to the course and felt that the course had met its objectives, but there was still significant room for improvement. These areas of improvement will be discussed in the following sections.

Course enrollment

When the course was advertised there was a significant number of students that expressed interest in the course. Nearly 30 students originally enrolled in the course, but due to conflicts with required courses (involving mostly the number of credit hours per quarter), the enrollment dropped to a final number of 18, which is a healthy number when compared to the typical biomedical engineering graduate class enrollment at Louisiana Tech of about 12 students. One option that would likely increase enrollment in the future is to hold the course in the Spring, when the number of required courses for students (both graduate and undergraduate) is significantly reduced and there is generally more flexibility. This approach, though, reduces some of the effectiveness of the course in preparing students new to the university to participate in research efforts. The recent addition of

the Introduction to Microsystems course at the IFM, though will significantly help in preparing students to perform MEMS type research, so there may be more flexibility in scheduling for the future.

Course materials

The textbook for the course was determined to be a good reference work for the students with up to date information and was generally well written, but it lacked many of the valuable additions that help to make it a good textbook. For example, there are no problems or examples designed for students in the text, or any sort of instructor aids. Thus, the instructor was required to develop homework, quizzes, tests, handouts, and other classroom materials. Many of these materials are available at the previously mentioned class website. Considering that there are no textbooks designed specifically for classroom instruction in BioMEMS, the instructor decided that a good reference and review book for the students was preferable to having no textbook at all. Student reaction to the textbook was mixed, with more advanced students tending to appreciate the book more than students who were only recently introduced to BioMEMS. A fundamentally sound, yet application oriented textbook on BioMEMS would be a great addition to the field and the educational endeavors of universities interested in this field.

Lecture notes and other course materials were distributed in PDF format to students via the Internet. Comments and remarks from the students regarding the notes were highly positive, especially considering that in many cases they were available before class so that students could come prepared and could focus their attention on comprehending concepts rather than making detailed notes. The lecture notes were also designed to supplement the textbook and to focus student attention on important concepts and applications. All lectures were delivered using presentation software and a computer projector, which allowed for significant graphics and animations to be incorporated into the lecture presentations. These electronic resources were extremely valuable in demonstrating and explaining difficult concepts and designs. For example, complicated processes could be displayed using simple animations that focused on the important concepts and demonstrated the phenomenon in easy to understand graphics. These graphics are clearly difficult to implement effectively using customary teach tools.

Course content

In general, the course content was well received and appreciated, but there was a consensus opinion that the material was covered quite quickly. In addition, the students who had not had any significant MEMS

experience felt at a significant disadvantage. Accordingly, in future versions of the course, we have determined to eliminate the background lectures on microfabrication principles and to require a basic microfabrication course that is just beginning to be taught at Louisiana Tech. This modification to the course content would allow for a higher level of instruction and would allow more time to be spent on the details of the material.

Another general comment revolved around the need for labs associated with the course. Many of the students wanted to be able to physically perform some of the experiments and fabrication procedures discussed in class. Thus, in future renditions of this course, a lab component will be added, and the course may be modified to be two credits of lecture and one credit of lab to allow for a significant laboratory experience. While reducing the lecture time may significantly reduce the areas that can be covered, the practical training for the students would be invaluable to both them and their research advisors.

Each lecture that discussed an application area of BioMEMS also included at least one student presentation of a recent publication in that area. The presentations allowed students to gain additional depth of knowledge in at least one area of BioMEMS. The presentations also allowed for a greater breadth of material to be covered, as some of the papers were for more obscure application areas. Student presenters were required to critically evaluate the work presented in the paper and give their assessment of both the current and future value of the work. As part of the process, they were also asked to defend the paper under questioning and to show a deep understanding of both the fabrication of the biomedical microsystem and its operation. Overall the presentations were well prepared and well received, and provided an additional forum for discussion of BioMEMS principles.

The first exam, which consisted of a MEMS design problem, was a significant challenge for those without any MEMS experience, and a substantial time investment was required for those students. For students with greater experience, the exam proved to be a good test of basic microsystem design principles and microfabrication processes. Since there was not one "correct" answer, grading of the exam required a significant effort on the part of the instructor to understand the approach taken by each student. From a grading standpoint, the exam also clearly indicated who understood the material, and who did not. The exam results proved valuable in another way in that a wide variety of designs were developed, so review of the exams in class provided an excellent catalyst for discussion of MEMS design and what types of designs might be "best."

The final exam was given in class and included a wide variety of question types designed to test the students' understanding of the basic principles of the various BioMEMS applications discussed in class. The exam also included a specific BioMEMS design question related to a microfabricated PCR system. The students were required to discuss the issues they felt would be most important in the development and operation of the system (as well as demonstrate a basic understanding of PCR). Each student again presented a simple design for a microfabricated PCR system, which gave the instructor the opportunity to evaluate the students' understanding of microfabrication processes, mask design, biocompatibility, system integration, packaging, and testing of the device. As with the first exam, a wide variety of designs were suggested, and some were of very high quality. Overall, the instructor felt that the course material was well learned and that the students were prepared to function in the BioMEMS environment.

The quarter long design projects were selected by the student and approved by the instructor with the intent that they would be able to fit in directly with the student's ongoing research efforts. The project content, which was described earlier, provided an opportunity, if used correctly, to jump-start a research effort by students who had only been at the University for a few months in most cases. Projects covered the full range of the course material and provided an in-depth experience to each student in their chosen area. The written reports were generally of high quality, and a number of them could have easily been converted into research proposals with a reasonable effort. As with all long-term projects, some of the students fell behind in the schedule and needed a major effort as the deadline approached to submit a quality report. As such, the instructor is considering requiring not a "complete" final report, but high quality intermediate reports that would be assembled into the final report and graded as a whole. The student response to the projects was good and many felt the experience was valuable. In general, the students who chose projects closely aligned with their research, or who used it for their thesis research, had a better experience and progressed more quickly both in the class and in their external research activities.

The poster session at the conclusion of the course was the highlight of the class and received praise from not only the students, but also from the professors and broader campus community that attended. The posters consisted of the students design project and allowed them the opportunity to publicly explain and defend their work. In general, the professors that attended the poster session were impressed by the high quality of work that was presented and the innovative ideas generated by the students. The students benefited significantly by

receiving feedback not just from the instructor and other students in the class, but the professors who attended. Several new ideas for research projects were generated by the session and new collaborations were forged during the activity. The experience for the students was very similar to that at major conferences and gave them all the opportunity to develop a greater understanding of the interactions and activities that go on in the research arena.

Assessment of Course

From the instructor's perspective, the main goal of the course was to provide sufficient background and training to students so that they might rapidly advance their individual research goals in the area of BioMEMS. In reviewing the course, this goal would seem to have been met. From a thesis selection point of view, of the 17 graduate students who took the class, 16 have chosen thesis topics in the area of BioMEMS or bionanotechnology. The one student who did not select a BioMEMS topic graduated the quarter the class was administered. Whether the time to graduation or the graduation rate of the students in the class was affected, remains to be seen, since the majority of students in the class had just recently begun the graduate educations. The three undergraduates in the class have all chosen to continue in graduate school and are currently working on thesis topics in the BioMEMS area.

The course also appeared to meet its goals related to education and training of students. The instructor felt that the test and exam results were generally excellent and the work and ideas generated by students showed a sufficient depth and breadth of knowledge related to BioMEMS. Several papers and proposals are expected to come from work that was initiated as research projects in this course.

The student's perspective on the course is also critical. Standard Louisiana Tech evaluations of the course revealed high levels of support for the class and the instructor. In all areas, the course was rated above average when compared to other graduate and undergraduate courses in the college and the biomedical engineering program. Student comments were generally positive and the negatives fit into one of three categories. First, the course covered too much material and needed some additional depth. Second, a lab was needed to make some of the examples more concrete. Third, modifications to the student presentations (include more than one paper) or the exams (include more of them so the amount of material was more manageable) were suggested. Responses to these student suggestions are included in

the next section. Overall, the reviews were highly positive and encouraging with regard to holding the course on a regular basis in the future.

Future Plans

While the course was well received and proved a success, there is still significant room for improvement. First, since enrollment in the course does not appear to be a problem, and Louisiana Tech is developing a new introductory course in MEMS, the introductory microfabrication component of the course will be dropped and a basic understanding of microfabrication principles will be established as a prerequisite for the course. This will allow for more in-depth coverage of the basic BioMEMS components of the course, while reducing the overall breadth of the course. Second, lab sessions will be added to the course to allow for a hands-on, immersive learning environment. The lab will also allow for instruction on more practical matters and fabrication details that are often glossed over in courses. Third, with the modification of the course curriculum, the exam schedule will be modified and an additional exam will be added to focus the exams in more specific areas. Fourth, part of the design project will be to fabricate at least a basic part of the project and demonstrate its function. This laboratory exercise may need to be modified depending on the projects chosen and the facilities available at the time, but the goal will be to begin some basic BioMEMS fabrication in the lab relevant to each student's research goals. Depending on demand, the course may also be offered on an annual basis, rather than a biannual basis.

A follow up course to this introductory course is also being developed by the author. The class would focus on design issues in BioMEMS and would explore more deeply the important phenomena related to this area of study. The course would explore the most recent publications and findings related to BioMEMS and examine their potential impact, and the future direction of this research. A lab session would also be included in the course in which these advanced students would be required to fully design and implement a BioMEMS project and characterize the fabrication and design of the system using appropriate analysis tools. Thus, the laboratory experience would be more self-guided than for the lab proposed for the introductory course.

The author would also like to integrate the class with the current design projects carried out by graduating seniors that span a full year. By using the course to prepare undergraduates to do design in this area and to generate ideas for senior design projects, the course

could in effect be extended far beyond the boundaries of a normal class. Funding has been made available by NSF to further pursue this course of action.

Short Course

The three-day short course made up of the BioMEMS material discussed earlier and a day of biomedical optics was very well received by researchers in Taiwan. The course was the first ever to sell out at PIDC and allowed for a transformative interaction between the attendees and the presenters. While the material of necessity was presented with broad strokes and in a summary manner, the material provided a strong foundation for researchers and students in Taiwan interested in moving into the area of BioMEMS and Biomedical Optics. The response to the course was overwhelmingly positive from both the attendees and the administrators of the session. The attendees seemed to appreciate the topics chosen by the instructors, and so provided little feedback with regard to which information was most relevant. It should be noted that the introductory microfabrication material that was included in the University course was not included in the short course, since most of the attendees were expected to have a strong grounding in basic MEMS principles. The main advantage of this short course that may be of interest to the reader is that the short course provided a synergistic opportunity to improve the teaching materials available for the university course. Thus, since the two courses were very similar in nature, extra high quality materials could be produced to present the material, providing a better experience for all.

Conclusions

Overall, the course provided a strong fundamental base in biomedical microsystems to the students who participated in the class. The student response to the course was highly favorable, and the public response was excellent at the end of term poster session. Thus, the course was able not only to fulfill the basic university mission of educating students, but was also able to contribute to the greater university mission. These contributions included: improving the research atmosphere through collaboration and dialog, involving and educating the public, and disseminating the knowledge acquired by the students and instructor during the

duration of the course. The course will be taught again in the Winter of 2002–2003 and any recommendations or inquiries are welcome.

Acknowledgments

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