



“Hands-On” Approach to Teaching Undergraduate Heat Transfer

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Over the last eight years we have converted our undergraduate heat transfer course from a traditional lecture-based format to a “hands-on” environment taught in a room equipped with a computer for each pair of students. For nearly each major topic covered in this third-year survey course we have developed either a “canned” module or a student-implemented project illustrating that topic. The modules are written in Visual Basic and are graphically rich and highly interactive, while modern, research-based algorithms run behind the scenes. Many of these nine modules grew out of demonstrations and student projects developed for use in graduate level courses taught through our outreach program, which for many years has provided a highly supportive environment for instructional innovation. In addition, the student clientele, working engineers who already know and use computation and visualization extensively in their own careers, provides ample incentive for curriculum modernization.

INTRODUCTION

In the last quarter century or so, modeling, simulation and visualization have evolved from a curiosity practiced mostly by Ph.D.s in certain “high-tech” pockets of research and industry to a routine activity involving just about any engineer involved with research, design and manufacturing. A typical issue of *Mechanical Engineering* includes dozens of advertisements for various modeling and analysis packages. Although some engineering professors act as if computers haven’t been invented yet, B.S.-trained engineers do use most of these software products.

To address this change in industry practice, we have tried to integrate as much modeling, simulation and visualization as possible into all the courses we teach, both undergraduate and graduate. Some of the instructional modules under discussion here assumed nearly their current form as early as 1987 when they were first used in a televised, graduate course in Computational Fluid Dynamics (CFD). In a course oriented toward algorithms like CFD, a simple, but graphically-rich demonstration can often make a point much more vividly than the corresponding and often obtuse differential equation or worse, a table of numbers. Unlike traditional students, working adults have few qualms with respect to complaining about out-of-date instruction. Thus those instructors who teach distance learners are forced to constantly update materials and delivery paradigms, an experience that cannot help but change his or her approach to on-campus instruction as well [Young, 2002].

This project got a big boost during the 1995-96 academic year when, with intensive help from the University’s faculty development program [T+TI, 2002], Visual Basic interfaces were developed. Finally after that year of intense development, the programs could be used

not just by the instructor for in-class demonstrations as before, but also by the students themselves. As a result we switched our undergraduate heat transfer survey course to a two-lecture-a-week format plus a two-hour-long “studio session.” These hands-on sessions are held in a room equipped with a computer for each pair of students and are run very much as one would a real physical lab [Wilson, 1996]. In the eight years of running the studio sessions, we have continued to enhance and improve this software greatly. This ongoing work includes not only correcting actual errors, but also enhancing the input and display of the results.

Since many very powerful commercial CFD packages can be used on several of the problems these modules were developed to handle [Stern, et al., 2004] one might wonder why we do not just use one. Many educators who have tried that option, especially in a survey course already packed with a wide variety of topics, report having to divert too much class time to “learning the software.” That drawback was exactly the reason we developed a custom interface for each unit. Learning this software is synonymous with learning the heat transfer. If the user doesn’t know the significance of a Fourier number in transient conduction or can’t do a simple energy balance on a control volume and isn’t willing to learn (from the lecture, the textbook or the help files), then this software will not help much. The best student comment at the end of the course, in fact, has been, “After using the software, I go back and read the book – and now it all really makes sense!”

Nearly all the nine “canned” modules we have completed involve research-based numerical algorithms operating behind the scenes to solve the governing ordinary and partial-differential equations in real time. Then with the solution available for the entire domain, we use modern visualization methods to display the underlying physics on a



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desktop computer. Several of the modules may be considered “virtual laboratories,” that is, they allow students to take data from a computer screen for post-processing — much as if they were working in a real, extremely well equipped, laboratory. Indeed, since these programs will operate over an essentially infinite parameter space, designing illustrative “experiments” for these virtual laboratories can be more difficult than in a real laboratory. Others, e.g., the two modules for heat exchangers, give the option of performing dozens of “what if” calculations rapidly. While in the past a heat exchanger problem would involve one set of parameters and a single “correct” solution, with this new software one cannot help but ask the question, “What makes a good design?”

In the past, since we were so busy developing and debugging the software itself, we used many problems directly from textbooks. Creating new exercises, especially design projects, which more thoroughly exploit the speed and visualization capabilities of this software, continues. Indeed, once one sees how several of these modules eliminate much of the tedium of conventional problem solving, one soon recognizes that much more of the available class time can and should be devoted to understanding concepts [Jacobi et al., 2003] and to engineering design.

In addition to the nine “canned” modules, close to a dozen other projects that are likely to be implemented on a spreadsheet have been developed. In the language of instructional technologists, these projects would be dubbed “Low Threshold Applications,” that is, they do not involve much in the way of I.T. skills on the part of either the developer or the student. In some cases we use macros, e.g., for fluid properties, written in Visual Basic for Applications [Ribando, 1998] and supplied to the students.

Currently our modules and the student projects cover nearly all the major, fundamental topics discussed in a heat transfer survey course, including steady-state and transient conduction, external and internal flows, radiation view factors, heat exchangers, etc. A “screen shot” of the user interface and thorough description of the modules may be found at: <http://www.people.virginia.edu/~rjr/modules>.

Many, though not all [Benvenuto, 1999], of the students taking our course recognize and appreciate that while learning heat transfer in a much more interesting way than is conventional, they are being introduced to the kinds of computational, simulation and visualization procedures that they will routinely use in their working careers — even though many will never work directly in heat transfer again. Indeed, the concepts, techniques and skills to which they are introduced in this course are those very much in demand in our high tech, global economy. With nearly all of the existing modules representing simulations of real, fundamental physical problems, it should in theory be possible to “discover” virtually everything discussed in the corresponding section of a typical textbook [Sonwalker, 2001]. While using this software, mature students do in fact wind up in the discovery mode, we must say that getting the majority from the mindset of getting the single

“right number” to hypothesizing, testing, observing, conceptualizing, synthesizing and developing insight on their own using the power sitting in front of them is challenging.

WHY THIS COURSE?

In Mechanical Engineering we must continually strive to convince potential students and those we have managed to attract into our program that we are just as “high tech” and glamorous as “hotter” fields like computer engineering and computer science. In fact, most of us in the traditional areas (and some less traditional ones like biomedical engineering) would say that our computer applications are more exciting and challenging than what CS people do and as equally transferable later into applications we haven’t even dreamed of yet.

In the traditional undergraduate mechanical engineering curriculum, heat transfer sits at the peak of the engineering sciences and bridges the gap to the application of those sciences in design. Students may have had an “introduction to design” course in their first year, but those courses must necessarily be quite generic. In contrast, by the time students are taking heat transfer, they have already taken their math and physics courses, thermodynamics, fluid mechanics, differential equations and programming. They are anxious to use this knowledge in the design of real hardware, and through applications to such devices as heat sinks and heat exchangers, can see the value of the disciplines they have already studied. Thus, a heat transfer survey course provides an excellent transition between the engineering sciences and the design courses that will occupy more of their last year of studies.

A recent ASME panel discussion on the state of heat transfer education in the US [Khounsary, et al., 1998] focused extensively on the large amount of class time and textbook space spent teaching classical analytical techniques versus the application of heat transfer principles in design, the latter much preferred by most practitioners in industry. Our modules attempt to address that problem. In many cases a simple First Law heat balance is applied on a small, representative control volume, and then we let the computer solve the resulting set of algebraic equations. Extensive use of graphics for display of the solution means that students can see, and hopefully understand the physics involved and then are ready to move on to design applications. We skip some of the classical solutions and traditional design methodologies, but actually gain valuable class time.

Because of its maturity as a discipline, heat transfer is an ideal candidate for the infusion of technology use [Kulacki, et al., 2002]. Many of the topics we must cover in an undergraduate survey course were topics of research in the first half of the 20th century, while only in the late 1940’s were digital computers available to anyone. As such many of the useful results were recorded in tables, graphs, correlations, etc. Though convenient and necessary at the time, these pre-computer analysis and design procedures often serve mainly to obfuscate the underlying physics. In contrast to the subject matter, the possibilities for teaching and learning heat transfer concepts have



expanded dramatically since the advent of the personal computer. Virtually everything we study in heat transfer can be presented visually and dynamically. Even a simple analytical solution, for example for steady-state volumetric heating in a plane wall, can be plotted up readily so that it becomes a physical problem and no longer just a mathematical exercise. One can “see” what an adiabatic boundary means and can test, for instance, the effect of the volumetric heating rate. With commonly available packages, it is simple to plot not just the obvious, i.e., the temperature profile, but the heat flux as well. Then the reason the temperature profile takes the shape it does becomes apparent. Students can “discover” on their own that while temperature is a scalar, heat flux has both magnitude and direction.

Other topics we cover in heat transfer are much too complicated for the student him or herself to “build” a model, but using well designed, graphically-rich software such as we have created allows the student to explore the physics by complete immersion. Dramatic differences between the behaviors of oils and liquid metals, for instance, are readily evident in contour plots on the screen.

One of the issues always brought up by those who may be computer-leery is verification of the computed solution. Again, fortunately in heat transfer there are analytical solutions, correlations, etc. that can and should be used for validating and verifying numerical solutions. In addition the problems that we work on are simple and fundamental enough that intuition is still useful. In other words, with some prompting perhaps, students should be able to explain any trends observed on their screen.

On the downside, our young and most research-oriented faculty members are often anxious to teach heat transfer (and a number of the other engineering science courses) because these have been taught in a “chalk-and-talk” mode traditionally, and thus, once developed, require less ongoing investment of faculty time.

MAJOR OBSERVATIONS

Issues in Visualization

Today’s engineering students are able and anxious to use any of the powerful commercial packages to render objects in three dimensions on a computer screen; similarly they can put together a glitzy (and often silly [Tufte, 2003]) PowerPoint presentation in short order. In general, however, neither activity necessarily takes much deep analytical thinking. What we try to do is expose and reinforce in engineering students the concept of using graphics as a tool throughout their analytical and design work and not just something to be used for a final presentation [Card, et al. 1999]. Among other things, this includes checking of input, testing hypotheses and verifying, validating, interpreting and reporting of final conclusions and recommendations. Included also are using the readily available tools to learn new concepts or to make sense out of the massive amounts of data a computer can easily collect or generate. In addition we stress using computer graphics to help debug and understand

computer models, both the ones we have already canned and the simple ones we design for student implementation, and as to question and test their predictions.

Anyone from outside engineering education reading the previous paragraph would say incredulously, “Are you saying that you aren’t already doing all those things? Personal computers have been around since before your students were born! Packages that can be used to create graphs and charts become easier to use and still more powerful every month!” The sad fact is that many engineering students are hardly exposed to such uses of the computers sitting on their desks [Jones, 1998].

Given the attitudes among many of the faculty, it is hardly surprising that students are also reluctant to use their computers for anything that requires much conceptual thinking. Many are quite comfortable with end-of-chapter problems similar to worked examples in the text and having a single correct answer (which is probably available somewhere on the Internet.). Getting all students to recognize the value of computer “experimentation” and visualization as a means of reinforcing and extending what they are exposed to in lecture and in the textbook presentation and not an additional burden has been a major goal. In all our development so far, we have been careful to ensure that we use terminology identical to that used in every textbook in the field, thus making the transition to our software-oriented approach as easy as possible.

Learning Styles, Gender and Diversity Issues

Our own anecdotal evidence appears to indicate that women students respond better to the use of visualization and computers in heat transfer instruction. That observation has also been made with the similar studio approach at RPI [Farrell, 2002]. Is this behavior related to their not being spoiled as girls by excessive computer gaming [Scott, 2002], and can this observation be quantified and exploited? The results of our informal survey do reveal differences due to gender in rating various aspects of our course.

In a recent article in the Washington Post [Fletcher, 2002], Christina Hoff Sommers observed: “Girls have been getting stronger and stronger and boys weaker, in almost all ways that count academically,” “... men are more likely than women to spend large amounts of time watching television, partying and exercising during their senior year of high school. Women, meanwhile, report spending more time than men studying or doing homework, talking with teachers outside of class and doing volunteer work.” Linda Sax, a UCLA education professor, said “I hesitate to say this, but it seems that women have an orientation, not only toward achievement, but also toward being good and pleasing others.”

At ASEE 2002, Sue Rosser described how ABET’s EC 2000 can help make engineering more female friendly. She proposed adjusting engineering education to appeal to different learning styles. Female-friendly pedagogy includes active, cooperative learning; providing relevance, meaning and context for the material; and inquiry-based learning including experimentation and discovery. The majority of students, including the traditional white, male engineering



student, do not learn well from passive participation in a chalk-and-talk lecture class. The studio experience can "...enrich undergraduate education with expanded opportunities for student and faculty interaction, including an emphasis on *hands-on learning*,"- this being one of Cornell Dean John E. Hopcroft's four specific goals given in his welcome to the Engineering Class of 2004 [Hopcroft, 2004].

Assessment

The authors conducted an informal short survey (13 questions and space for comments) to obtain student reactions to the studio sessions of MAE 314 (Heat and Mass Transfer) at the end of the Spring 2002 semester. The responses for each item consisted of rated level of agreement or disagreement with each item. Of 63 possible respondents, we received surveys from 51 (response rate = 81%): 13 women and 33 men (5 respondents did not report their gender). There was no significant difference in reported overall GPA for men vs. women. These students expressed general agreement with the following items:

"Most of the major topics of the course were covered adequately by the studio activities."

"I feel more confident in implementing something myself on a spreadsheet as a result of the several experiences I have had using Excel in 314 studio." This is the only item for which responses are meaningfully related to GPA: all students with high reported GPAs agreed with this item. Those with average or low GPAs were distributed across all levels of rated agreement.

"... I would feel more confident in using (canned programs) intelligently as a result of my experience in 314 studio."

"... For the most part the studio sessions helped me understand and appreciate the physics underlying the heat transfer topic we were studying."

Only one item met with strong disagreement: both men and women objected to the idea of randomly assigned (studio) partners; women expressed stronger opposition.

Statistically significant gender differences were apparent on 3 items:

"I learned more working in collaboration with my partner than I would have if I had to do the assignment alone." Mean rating for women = 4.54; mean rating for men = 3.47, difference significant at a p-value of .001. The test for equality of variances rejected that assumption; the men's ratings were far more variable than the women's were. About $\frac{3}{4}$ of the women voluntarily partnered with other women.

"For the most part the studio sessions reinforced what we were talking about in lecture and reading about in the textbook." Mean rating for women = 3.85; mean for men = 3.26, difference significant at p-value of .031.

"The on-line quizzes helped me recognize what I should be noticing while working with the software in studio." Mean rating for women = 3.62; mean rating for men = 2.88; difference significant at p-value of .034.

As far as assessment of student understanding of the material is concerned, self-tests are already in place for the upgraded modules; each has a set of some 40 concept questions available. Since these are intended for students to work on and discuss with their peers, answers are not provided. As time permits we are developing a collection of potential test items that may be used to generate self-assessments on-demand. The hope is that a particular set of items will be selected anew each time a given student requests a self-test. Short answer and multiple-choice conceptual items will be included to assess understanding and require interpretation of outcomes.

Faculty Issues and Teaching Resources

No one who has tried introducing computer use into his or her own engineering instruction will argue that it saves faculty time; in fact, using the computer generally turns out to be such a time sink that many faculty somehow manage to avoid it [Geoghegan, 1994; Jones, 1998]. Because of the studio sessions we initiated, student contact hours alone over the last seven years have been double what they would have been with the conventional lecture-based paradigm. There are a number of things, however, that can be done to make the concept more palatable to faculty.

One overwhelming advantage of the traditional lecture-based/weekly problem set paradigm over ours is the literally hundreds of end-of-chapter homework problems and more importantly, the exhaustive answer books provided along with the major textbooks in the field. In any case considering the potential of this software-based approach for (1) developing physical insight and (2) for ready application in design, the end-of-chapter homework problems with a single correct answer seem to be in many instances just not appropriate.

We have also worked to cut down the paper generated. We have run the existing studios much like a real physical laboratory and create too much paper in the form of lab reports for someone to grade. Our own enrollments in mechanical engineering have doubled in the last few years, and we have to deal with that rising workload without additional TA's or graders. That situation is becoming more common at all universities. Part of the solution is in using the computer itself more for the assessment of student learning. We have moved to more and more multiple-choice conceptual questions and on-line quizzing over the last two years [Ribando et al., 2002] and intend to push that approach still further as time is available.

SUMMARY

By now it is evident that a paradigm shift will eventually take place in engineering education [Smerdon, 2001; Wulf and Fisher, 2002], and that using technology as an integral part of instruction is here to stay [Felder, 2000]. Our industrial customers, acting through the new ABET 2000 process, are demanding change. In addition, while some academics continue in the "business as usual" mode, the whole nature of engineering practice itself has changed in the last several decades. Computers routinely do

mundane calculations that in the past were done manually by ‘green’ or less-talented engineers under the tutelage of an experienced mentor. Thus the expectations placed on the new practicing engineer are higher than ever. We cannot continue to “train” our students to do things that a computer can do better than them anyway. Instead we must educate them to observe, hypothesize, test, verify, design and synthesize – skills a well-educated engineer can beat a computer at any day!

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