Using Software with Visualization to Teach Heat Transfer Concepts

Robert J. Ribando, Timothy C. Scott, Larry G. Richards, Gerald W. O'Leary
University of Virginia

Abstract

Over the past six years we have transformed our undergraduate heat transfer course from a strictly lecture format by adding a two-hour "studio" session held in a classroom equipped with a computer for each pair of students. Much of the studio work revolves around a set of locally developed, research-based numerical algorithms that solve in real time the ordinary and partial-differential equations describing heat and fluid flow. With the complete field solution available from the numerical routines, the software can provide a visually rich and highly interactive learning experience. This encourages the user to better investigate and understand the underlying physics. Additional studio exercises involving student-developed spreadsheets allow them to explore a wide range of input parameters - as a practicing engineer would in any good design study.

Anecdotal evidence suggests that practicing engineers support this approach since they are accustomed to using graphically-rich, commercial software and recognize that computers and software have taken over much of the mundane "number-crunching" that used to occupy many of an engineer's working hours. Many undergraduate engineering students, especially the weaker ones, are oriented toward the routine solving of problems – particularly problems that are very similar to worked examples in the textbook and have a single "correct" answer (and exactly what computers can be trained to do better than they!). At the graduate level those students who study computational fluid dynamics (CFD) quickly learn "the purpose of computing is insight, not numbers," but inculcating that idea in undergraduates takes much effort. The software we have developed and use in this course encourages all students to take a second look, to run cases and to notice the effects of parameters. The course instructor must be willing to change his or her mode of operation, by developing and assigning more open-ended and design problems and especially by including "concept" questions along with conventional problem solving in assessing student performance.

Introduction

In recent years we have transformed our undergraduate heat transfer course from a typical "chalk-and-talk" lecture course to include what we call a "studio" session. The latter, a two-hour "hands-on" session held in a room provided with a computer for each pair of students, supplements the two lectures each week that are held in a room having a computer and projection system just for the instructor. Unlike the two other "hands-on" computer classrooms in our building, the one we use for the heat transfer studio sessions was deliberately designed with two seats per workstation so as to encourage cooperative work among small teams of students [1,2]. During these sessions the course instructor and GTA circulate around the classroom answering and asking classes of the teams as they work on their assignments.

Much of the studio session centers on a set of modules that we have developed locally for use in our undergraduate and graduate heat transfer courses (See Ref. 3, which includes a screen shot and description of each of the interfaces and a dozen published references describing this software and our experience in using it. Reference 4 includes a CD of the entire software suite.) We note that each of these modules was custom-tailored to the heat transfer topic at hand and stress to anyone who will listen that "Learning the software is learning the heat transfer" - because the topics chosen plus all inputs and outputs, are covered in every textbook in the field! This avoids the steep learning curve that often accompanies using a much-more-powerful (and expensive) commercial CFD package. While it would probably be possible for us to take the next step and teach this entire course in the "studio" mode, as pioneered especially in physics instruction at RPI [5,6] and several other universities [7,8], we have not taken that drastic (and counter cultural) a step as yet. Experience with applying the studio/workshop concept to another fundamental course (thermodynamics) in our own school is recounted in Reference 9.

Much of the developers' efforts during the first several years of this project were taken up in debugging and making the software more robust, adding more features including "Help" files and redesigning the interfaces, including the graphics, to be more intuitive, etc. Even now we continue to add new features. Also much current effort is going into converting the original modules to Visual Basic 6, which allows much more interactivity for the user. The eight original modules involved mixed-language programming: VB-3 for the interfaces and Fortran DLL's for the number crunching and graphical displays. VB6 is compiled; VB3 was not and thus far too slow for the computations we do in these modules. Besides greatly enhancing the interactivity, the transition to VB6 will ensure that these modules remain sustainable over time. Capable staffers who can do mixed-language programming and interface design, plus know the discipline and pedagogy are few and far between!

Figure 1 shows one of the recently completed VB-6 interfaces. One might note that in accordance with good interface design practices learned during this effort, user text input to the module has been minimized in favor of sliders (with which the designer can limit the range of inputs). Pop-up "tool tips" plus extensive hypertext help files make this module a nearly complete lesson in transient, one-dimensional conduction. This particular module is intended to replicate (and animate) the data normally taken from the well-known Heisler charts, which were first published in 1947 - before there were more than a handful of computers in the world – and are still the primarily means of solving such problems.

Of the engineering sciences taught in the Mechanical Engineering curriculum, heat transfer is a particularly fruitful area in which to apply modern computational and visualization methods. At least in the thermal sciences stem of M.E., heat transfer is the last of the basic science courses and thus provides a good venue in which to illustrate how the fundamentals our students have learned thus far including differential equations, thermodynamics, fluid mechanics, computational techniques and graphics all can be applied in the design of thermal systems. Unfortunately, other than simple one-dimensional, steady-state conduction problems, many topics, which we must cover in heat transfer, involve mathematics that is too advanced for the undergraduate student or would be too time-consuming to cover in a survey course even if they did have the necessary background. In other cases there are no analytical solutions, and complicated correlations of empirical data are applied instead. The result is that the typical textbook includes a plethora of graphs, tables and equations to be used with techniques that were developed specifically because there was not a computer sitting at each person's workplace at the time. Generally speaking the techniques conventionally taught and used do very little to develop physical insight; thus nearly anything an instructor can do is an improvement over the status quo.

Assessment and Outcomes

In a previous ASEE paper [10], we listed among our goals and outcomes of this studio approach to teaching heat transfer:

1. Using modern numerical methods.
2. Understanding the physics behind the correlations.
3. Comparing with experiments.
4. Emphasizing fundamentals.
5. Testing parameters and using spreadsheet macros.
6. Verifying output and input.

On one level we have accomplished these goals. Using modern research-based numerical methods along with full-color graphics of the field solutions we can show students immediately, for instance, the drastic differences between the behavior of ordinary fluids and that of extreme-Prandtl-number fluids. Having seen the effects visually, students can process the numerically generated data and compare it with the standard correlations. For some modules we have built simple desktop experiments so our students can compare the results with computer predictions. We have demonstrated how our students can eschew the standard "cookbook" methods for heat exchanger design and analysis using modern software based on simple First Law energy balances. We introduce more advanced uses of spreadsheets, including the use of Visual Basic for Applications (VBA) macros. In some cases we show how effective software interface design can be used to verify both user input and the desired computer-generated output.

Feedback from practicing engineers who have seen the software and our approach has been very supportive: "How I wish something like this had been available __ years ago when I took heat transfer! … Now I can see why the Prandtl number changes the convective heat transfer coefficient so drastically … I wish I had been able to use computational software on fundamental problems where I understand the physics before having to use (a particular commercial CFD code) on a problem involving horribly complicated physics and geometry." Working engineers appreciate that it is only with experience that an engineer learns when a simple back-of-the-envelope calculation is more appropriate than a complete CFD solution of the Navier-Stokes equations, how to choose and apply software and how to display, validate and interpret computed results, etc.

Feedback from our own students has been largely anecdotal and mixed. We do not have enough students or the faculty resources to offer more than one section of this course each academic year, thus we have had no control group. Furthermore each year we have continued to improve the quality of the software and the supporting assignments, so even a year-to-year comparison might not be valid. Thus there has really been no systematic assessment of the approach.

In any case, feedback, especially from the better students, has been supportive. Several students in the most recent class said that the studio session was “where they learned almost everything in the course.” We did notice that student interest was even better during exercises in which they had to develop a spreadsheet to solve a particular problem (with fairly close faculty guidance), and many students were particularly appreciative of the VBA macro programming we introduced. (These “light-duty” exercises were developed originally because the goal of having a “canned” module for nearly each major topic proved too ambitious.) Verbal feedback from the women students (who make up about ¼ of the class) has seemed to be more supportive than that from males; this finding is consistent with reports from RPI that hands-on learning appeals to and attracts female students [11].

Up to this point our assessment of student learning of the material they could learn from working with the modules has been fairly primitive. Instead of having three problems each counting 33 points on a typical exam, we have instead substituted 10 or so multiple-choice questions for one of the problems. In many cases we have clipped and included the results section of the interface, e.g., the bar chart seen in Figure 1 below. Then we can ask questions like: Is this plane wall being heated or cooled (which they should be able to figure out from the curvature), does this graph correspond to a high Biot number or a low Biot number (which they should be able to figure out by comparing the magnitude of the temperature difference between the surface and the fluid relative to that between the surface and the centerline.)

Student reaction to this kind of testing has been mixed. Many students would rather a 33-point number-crunching problem where the instructor/grader struggles to give partial credit – even when perhaps they went off in the wrong direction almost immediately – than a number of concept problems each having a single correct answer. Our students have experienced concept-oriented, multiple-choice exams in the physics classes they have already taken. In such exams the problems may take a few calculations to get a numerical value. Overall scores on these exams tend to be fairly low on a 100-point scale, and thus they may harbor a sour attitude toward this assessment approach.

A recent article [12] (which actually addresses online learning more than the synchronous learning we discuss here) sheds some light on the issue of learning concepts rather than routine problem solving skills by postulating a “pedagogical learning cube.” Much traditional classroom instruction in engineering ("sage on the stage") tends to fall toward the bottom back left corner of the cube (Figure 2). Certainly a dynamic lecturer will occasionally venture up the (vertical) media axis by including graphics, video and even animations and simulations in his or her classroom presentation, but often the student learning style still hovers toward the left end of the horizontal axis (apprenticeship). With the modern, graphically rich simulations we use, it really should be possible to move the level of student involvement well toward the right. Indeed it is possible to "discover" a very high proportion of what is presented in the standard textbooks and in classroom lectures. Creating the hands-on exercises to promote that mode of learning clearly takes thought, time and experience and assessment tools that will encourage students to use the software to its fullest. Perhaps the most appreciated verbal comment from a student taking the course the last time (a good one) was: "After working with the software in the studio session, I can go back and everything I read in the textbook makes sense!"

While our assessment efforts so far have focused mainly on the interpretation of the graphical output from our own modules, it is gratifying to see that the latest edition of one time-honored textbook [13] and one fairly new textbook [14] have each included a section of "concept" questions along with their traditional end-of-chapter problems. Also the inclusion of testing modules in various commercial classroom management software packages (and in the locally-developed package used at our university) makes the grading of additional assessment instruments less of issue than in the past.

Conclusions

The use of graphically rich, well-designed interactive simulations shows real promise for teaching fundamental concepts in heat transfer. In order to make that mode of instruction successful, assessments must include objective questions in addition to the usual problem solving. In addition to formal assessments (those that "count") the instructor must be willing to create frequent, informal assessments so that students understand that they are expected to act as thinking individuals rather than merely formula-following number crunchers. Well-crafted objective questions can get the students into the mode of thinking critically about the course materials while providing valuable feedback for the instructor.

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Biographies

ROBERT J. RIBANDO

Robert J. Ribando is an Associate Professor in the Mechanical and Aerospace Engineering Department at the University of Virginia. He formerly served as Director for Academic Outreach Programs in the School of Engineering and Applied Science, where he was in charge of our off-grounds master of engineering degree program. Over the last 15 years he has played a very active role in the development of the infrastructure for making use of technology in instruction at the University. The work reported here was begun under the University of Virginia's Teaching + Technology Initiative faculty fellowship program.

TIMOTHY C. SCOTT

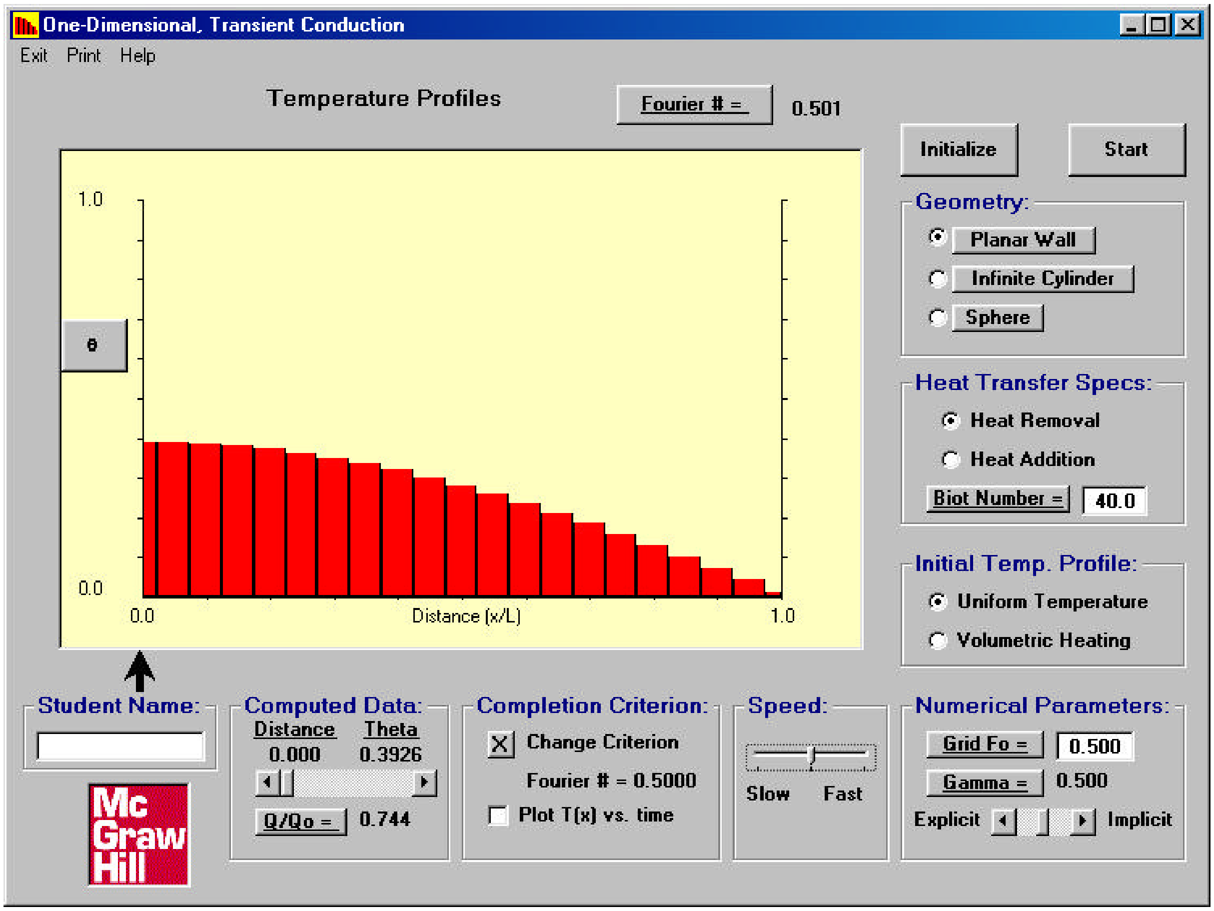
Timothy C. Scott is Instructional Laboratory Director and an Associate Professor in the Mechanical and Aerospace Engineering Department at the University of Virginia, where his primary interests are in the thermal sciences area. All three degrees are from the University of Michigan. Dr. Scott has 15 years experience in the automotive industry and continues to consult with his former employer.

LARRY G. RICHARDS

Larry G. Richards is an Associate Professor in the Department of Mechanical and Aerospace Engineering at the University of Virginia. He has degrees in Psychology from Michigan State University and the University of Illinois. He has used technology in instruction for over 30 years and participated in UVa's Distance Learning Program since 1987. His current interests include invention and design, creativity and new product development, and assessing the effectivenes of technology in education. He was a UVa Teaching + Technology Initiative fellow several years ago.

GERALD W. O'LEARY

Gerald W. O'Leary is a Computer Systems Engineer in the Mechanical and Aerospace Engineering Department and the developer of all our Visual Basic interfaces. His degrees include a BS from the University of Notre Dame and an ME degree from U.Va. He has worked as a field engineer in the aerospace industry and as a systems engineer in the defense industry.



Fourier # = 0.501

Geometry:
● Planar Wall
○ Infinite Cylinder
○ Sphere

Heat Transfer Specs:
● Heat Removal
○ Heat Addition
Biot Number = 40.0

Initial Temp. Profile:
● Uniform Temperature
○ Volumetric Heating

Computed Data:

Distance	Theta
0.000	0.3926

Q/Qo = 0.744

Completion Criterion:
☒ Change Criterion
Fourier # = 0.5000
☐ Plot T(x) vs. time

Numerical Parameters:
Grid Fo = 0.500
Gamma = 0.500

Figure 1. Visual Basic 6 Interface for One-dimensional, Transient Conduction Module.

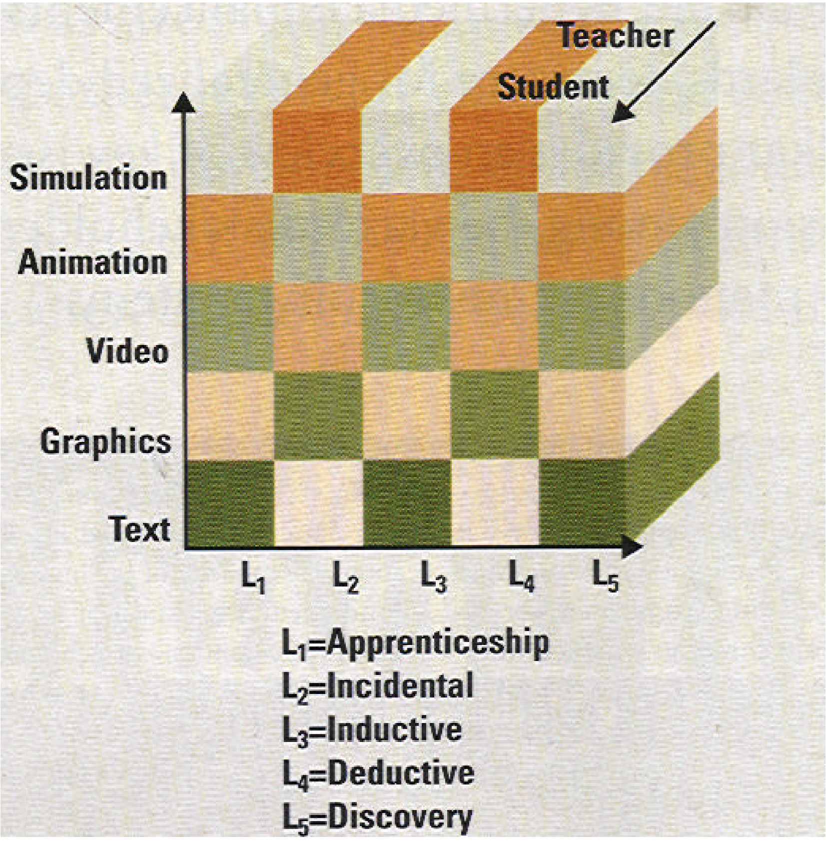


Figure 2. The Pedagogical Learning Cube [Reproduced from Reference 11]