Finite Element Analysis for the Engineering Sciences: A Web-Based, Video-Streamed Education Environment at a Distance

A.J. Baker, Z. Chambers and M.B. Taylor
University of Tennessee
Knoxville, TN 37996-2030

Abstract

Finite element theory, and associated codes, forms the backbone of most computer-based simulation methods for analysis and design of engineered systems, ranging from structures to fluid mechanics, heat transfer, and coupled systems. Herein is described the organization and content of the Internet offering of this pertinent first-level graduate course. It presents full details on the pedagogical and technical innovations and investments required created, or reduced to practice, to enable the necessary functionalities. The local and remote hardware environment requirements are detailed, each constituted of no more than respectable PCs with adequate soundcard and free software. The website at http://cfdlab.engr.utk.edu contains full information.

Introduction

Finite element theory constitutes the fundamental support for the wide range of computational theories applicable to analysis and design of engineered systems, ranging from structures to fluid mechanics, heat transfer, electromagnetics, i.e., *computational continuum mechanics*. The Engineering Science program at UTK has developed and taught the first level graduate course in this area, specifically tailored for students majoring in computational mechanics. It has proven highly useful as well in addressing students across engineering disciplines, and the natural sciences, with an interest in using scientific simulation in thesis or dissertation projects.

Developing a hands-on practical computing environment has been a course focus, with software system growth leading to ever broader applications capability. One outcome of this process was the introductory textbook *Finite Elements* 1-2-3[1], published in 1991 and containing a PC code on a 5.25" floppy disc (how ancient!). Developments since then have led to utilization of matrix manipulation packages, e.g., MATLAB[2], to convert theory to practice in a much more transparent venue. Reporting course computational lab results has similarly transcended from paper to html, admitting full results documentation in color and on-line.

The emergence of the Internet, and in particular high performance communications, has opened the opportunity to move this instruction process into the web venue, with appropriately developed, specifically designed courseware (replacing the traditional textbook) and computing software. For the first time, in fall semester 1998, *Finite Elements for the Engineering Sciences* was offered as a live, video-streamed graduate level lecture course over the Web, complete with the full compliment of supporting lecture/laboratory materials. The web site (http://cfdlab.engr.utk.edu/551w) was specifically designed and developed to support functionality requirements for distance and off-campus local students, as well as "resident" students located in the Internet teaching laboratory at UTK.

This paper details the pedagogical and technical innovations created to enable this functionality. The remote (and local) environment requires no more than a "respectable" PC with adequate sound card and some additional (inexpensive and free) software. Two way live communication is enabled via a chat room[3], and networked email connects all students, support staff and faculty. The website contains all pertinent general information, e.g., registration, hardware requirements, e-mail, technical help, etc., as well as the complete course syllabus and problem and computer lab assignments.

The site also contains the *courseware* textual material, which is organized as a combination of conventional mathematical descriptions with supporting "vu-graphs". This precludes the requirement for extensive whiteboard writing, via directed referencing, and is enabled using Adobe Acrobat Reader[4]. The live video-streaming of each hour and 20 minute lecture uses cutting edge compression technology[5], amenable to modem rates from 28.8Kbps to a direct Internet connection. The streaming process induces about a 7-second delay at the receiving end. No passage of large files results, even though the video recorded lecture (for post-processing) amounts to ~14 gigabytes of data. After recording, the lecture is "cleaned up" for voice and clarity, compressed and loaded onto the web site for viewing by participants anytime thereafter, via video-streaming, which again precludes large file downloading time delays.

Discussion and Results

The creation of the introductory graduate FE analysis web course required the imagination and services of a diverse group of people, ranging from website artistic development to the monumental word-processing tasks associated with creation of the courseware. The many colleagues and associates of the authors involved in this process are acknowledged at the end of this paper. This discussion section takes the reader through the website, highlighting the issues associated with the design and implementation of the concept.

The website front page (first attachment) contains a brief description of the course, its history, and the current offering while providing all necessary detailed information about timing, scheduling for the class and grading policy. The key function of the front page is the nest of a dozen hot words in the upper left-hand corner, which supports *navigation* for accessing all material pertinent to the course. This section briefly discusses the functions accessed at the various hot button sites.

Touching the *Instructor* hot word brings up the page describing the academic interests, background and experience of the instructor, see second attachment. The next left column hot word is the *Course Calendar*, presenting the summary of the lecture topic for every class meeting, along with citations for the appropriate courseware material.

A key course compliment is the design of classwork *Problems* and computer *Lab Assignment* experiences. On the *Course Calendar*, the date of assignment of problems and when they are due are hot words. The student is thus immediately led to the appropriate locations in correlation with the current subject material. A printout of the first page in the course calendar, problem and computer lab assignment areas follows.

The second column of navigation panel hot words leads to items of specific support to the online lecture process. The *FEm.PSE Tutorial* courseware is consists of textual and vu-graph material specifically organized for lecturing detailed technical material on the Internet. The front page of the *Tutorial*, attached, gives an introduction to the concept of the "problem-solving environment" that is a key conceptualization in design and presentation of this course.

The *Tutorial* table of contents follows, and therein each *Chapter* heading is a hot-word. The entire document is password protected after the first two sessions, which limits access to only those individuals who are registered. Page samples from the Tutorial are appended, illustrating the organization of text and vu-graph material, which in the predecessor hard copy form occurred on facing pages. This organization will again be employed, for functionality, when the new material is made available in hard copy.

Regarding the computer lab experiments, an extensive archival lab report database exists. Generating computer results can be frustrating, and the archive has proven highly useful in transcending the tendency of computer experiences to be unreasonably time consuming. The *Lab Archives* is a hot word on the *Assignments* page, which leads to an index of archived lab reports. Students are encouraged to read these reports in the process of generating and reporting their data. They are further required to archive their lab reports at the website, which thereby makes them accessible to all other students as well as faculty and staff.

The second key lecture support function is the *MATLAB Primer*, written as a “just-in-time” document to define MATLAB "lingo" in support of the generation of the computational experiment data. The *Primer* front page is appended, and following the guidance and hot words thereon, the students are led through the essential language constructs of MATLAB on a need-to-know basis.

As with all material on the website, the *Primer* can be downloaded and printed if a class participant so desires. The site also gives access to all FE algorithm template scripts, which have been prepared for support of the computational experiences. These scripts, being essential course content, are password protected.

The third item in the second hot word column is *Video*, leading to the location where the remote individual logs into the live video stream for each lecture day. Additionally, all previous lectures are archived at this site, such that a participant can review, at their leisure, any of the predecessor lectures.

Archived lectures have been electronically “cleaned up” for both audio and video and reside on the website server. In the longer term, the entire course, with all supporting material, can be archived on two CDs. When completed, this will constitute the complete Web-supplement (replacement) for the correspondence or video-taped distance education experience. It promises to make inroads into the classic "lecture-textbook" experience as well.

The last hot word in the central column is *Grades* which is password protected. Students have immediate access to the status of their individual material submissions, such that no confusion can exist on material that has gone through the grading process.

The right-hand hot word column leads to information of general utility. First is *Communication*, which links to the chat-room in use during the lecture period, see attachment. The selected software is I-Chat, and the chat-room operates during each lecture such that any remote student can, at any time, post a question. It is then immediately picked up at the lecture site and answered within a matter of moments. There is also a forum discussion area, whereby students doing assignments can communicate to their colleagues, and the faculty and staff, regarding any questions. These are broadcast to the entire class, and any student is encouraged to answer should they have the appropriate knowledge.

The second right column hot word gives instruction on course *Registration*. Non-UTK students may take UT graduate courses for audit/credit by registering as a transient student for a modest fee. All participants pay the regular in-state or out-of-state tuition. The registration process is entirely electronic, including payment which may employ a credit card.

The third hot word topic in the right column provides access to *Technical Help*, see attachment. This site gives full information on both minimal and optimal hardware specifications for receiving the signals, as well as software requirements. The hardware required is truly nominal, and no paralyzing technical detraction to the Web presentation of the course has become apparent to date. The last hot word in this column returns to the front page from anywhere in the site.

The Investments

The investments required to put together this course are substantial, from the standpoint of personnel time involved in creation of the courseware and software supporting materials, but only modest from the viewpoint of hardware and supporting technology acquisition. The companion paper [6] details in completeness the hardware and video acquisitions required for live streaming of the course. Starting with an operational PC laboratory in the UT *College Center for Computer Integrated Engineering*, roughly $12,000 of additional investment was required to complete the Internet teaching laboratory. Key investments were a high-quality digital camcorder ($1,500) with quality video capture card ($200). The selected capture machine is a Pentium 333 PC with 384 MB Ram ($3,500) with two external 18 gigabyte hard drives ($1,200 each) to handle the 10gigabyte/hour lecture data rate. Cost of the video editing system was approximately $400, with the CD burner for archiving the material costing another $400. There were numerous other modest software acquisitions, a suitable lighting system was built for the "stage," and a high fidelity lapel mike was found necessary. Complete information and details on the selected brands are given in the companion paper[6].

Personnel effort required for creation of the courseware benefited from initiation of the design of the system based on several years of organizing industrial and short course presentations. Starting with the traditional vu-graphs that support an oral presentation, requests from participants to have back-up material led to the creation and design of the companion text material organized on a page-by-page basis. A rather complete rough draft of this material was present at the beginning of the course.

However, to tune content to a truly comprehensive graduate course presentation required a substantial update and editing process to be carried on while the lecture series evolved. The time commitment by the author (Baker) was roughly half a week per week, plus weekends, which was supported by an equal effort by a word processing specialist. A similar weekly effort by a Ph.D. student was required to convert all material to pdf files, add graphics and load it into the website. The pdf format was selected as truly superior to alternatives, e.g., html, due to the significant content of differential equation forms and tabular data presentations.

A companion personnel investment was required in organizing the MATLAB constructs for converting presented theory into practice. Again, this process benefited from several years of developing the *template* instruction procedure, as well as a move to MATLAB in the previous two regular offerings of this course. The *MATLAB Primer* had to be substantially updated, and loaded onto the website along with the specific instruction sets for each computational laboratory exercise. This also required approximately twenty hours per week by a Ph.D. student .

As expected, numerous refinements to the courseware process and course organization became obvious as the material was presented. Therefore, updates and corrections to the material online at the webpage were continually made, such that students accessing the archived material would have the most current (correct) form available for review. This is truly an outstanding feature of the electronic form for the courseware, in distinction to the traditional hard copy textbook/PC code that originally supported this graduate course offering.

Summary and Conclusions

The first graduate level course in finite element analysis for the engineering sciences has been developed for Internet presentation using real-time video streaming. All required hardware, software and courseware functionalities are created to support the pedagogically professional organization of this distance learning experience. A key attraction is that the in-class student environment is identical to that of the remote students, i.e., at a computer with windows open for the *Tutorial* and various other functionalities used during the lecture.

An absolutely key attribute of this Internet course organization is that only a minimal amount of whiteboard writing is required, even though the technical content is quite detailed. This significantly eases the video load, such that students can focus on absorbing knowledge in a multi-media presentation framework. The longer-term plans are to extend this development to our graduate course compliment in computational mechanics. Accomplishing this will not only serve the local graduate student population, but also will readily support on-site professional training appropriately piped to remote industrial locations on an as-needed basis. The opportunity for true international collaboration in preparation of cutting edge lecture courses will also become enabled via this technology.

Acknowledgments

The authors have benefited from the innovation and services of many people in designing and organizing the Website for this distance education experience. We are particularly indebted to Dr. Julie Little and Ms. Jean Derco, of the UTK *Innovative Technology Center*, for website artistic design. Our thanks to Mr. Mark Spurlock and Mr. Alexy Kolesnikov, who debugged the systems leading to pdf logging of all courseware onto the website. Finally, our sincere appreciation goes to Ms. Marva Anderson, who contributed greatly to the project in the timely word processing with continual editing of all courseware material, always with minimal leadtime.

Bibliography

1. A. J. Baker and D.W. Pepper, *Finite Elements* 1-2-3, McGraw-Hill, NY, l991.
2. MATLAB, The Math Works, Inc., Prentice-Hall, New Jersey.
3. I-Chat, http://www.ichat.com
4. Adobe Acrobat Reader, http://www.adobe.com
5. RealPlayer, http://www.real.com
6. Z. Chambers, M.B. Taylor, J. Iannelli and A.J. Baker, “Production of Digital Internet Video Material for Streaming Applications," Proceedings, ASEE National Convention,June 1999.

A.J. BAKER
A.J. Baker, Ph.D., PE, is Professor, Engineering Science, and Director of the CFD Laboratory at the University of Tennessee/Knoxville. He joined the faculty in 1975, following a research stint in aerospace industry, with the specific goal to develop the graduate curriculum in computational fluid dynamics and heat transfer. He has authored more than 240 technical papers on the subject, including 60 achival journal articles, and has published two textbooks, each with international editions and one Japanese translation. The CFD program matriculates an average of one each Ph.D.and M.Sc.degree per year, and currently has six graduate students at various stages of degree completion.

Z. CHAMBERS
Zachariah Chambers is a Ph.D. student in the Engineering Science CFD curriculum. He holds B.S. and M.Sc. degrees in Mechanical Engineering from Rose-Hulman Institute of Technology, Terre Haute, Indiana. With the collegial help of graduate student colleagues, Mr. Chambers selected, organized and put together the entire complement of computer hardware/software systems required for the Internet course.

M.B. TAYLOR
Mike Taylor is a Ph.D. student in the Engineering Science CFD curriculum. He holds a Bachelor of Mechanical Engineering from the Georgia Institute of Technology, and an M.Sc. degree from the University of Tennessee Space Institute. He was a commissioned officer in the United States Air Force for twelve years, with the last assignment as an Assistant Professor of Aeronautics at the Air Force Academy. Mr. Taylor created the implementation of finite element theory template script files, and is principal author of the just-in-time *MATLAB Primer.*

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Instructor: Prof. A. J. Baker
Office:Perkins Hall 316A
Office phone: (423) 974-7674
e-mail: ajbaker@cfdlab.engr.utk.edu
Office hours: daily 11-12 noon

Meeting: Tuesday & Thursday, 5:05 - 6:20pm

Text: *FEm.PSE Tutorial*, A.J. Baker

Reference: *Finite Elements 1-2-3*, A.J. Baker/D.W.Pepper, McGraw-Hill, 1991

Additional References: W.F. Ames, *Num. Mtd. for PDE, Academic* J.H. Ferziger, *Num.Mtd fot Engr. Appl.*, Wiley

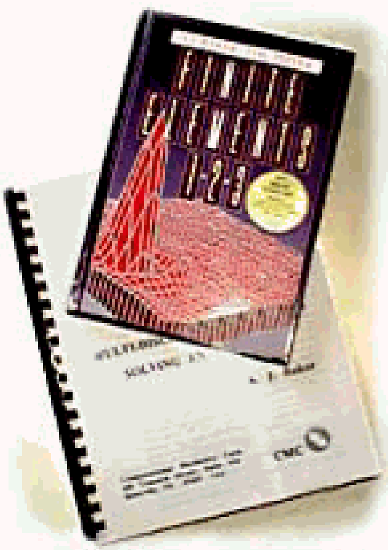
Courseware: *MatLab Tutorial*, online

PSE Laboratory: Totally flexible, reporting via html on Internet

Course Grading
Problem Assignments 1/4
Lab Reports 1/4
Hour Exam 1/6
Final Exam 1/3

This first-level graduate course (MAES 551) has been the backbone introduction to weak statement (finite element) theory for scientific computer simulation for ES graduate students majoring in computational mechanics. It has attracted, as well, graduate students from diverse departments and colleges within UT, with an interest in using scientific computing for dissertation projects. Examples include meteorite accretion and radioactive waste disposal models (Geology), fractured media porous flow (Civil Engr.), several bioremediation reacting system models (Chemical, Agricultural Engineering, Microbiology), and rheology (Materials Science).

Hands-on *practical* computing experience has been a focus, with software system developments leading to broader applications capability. The academic course led to writing of the introductory text *Finite Elements 1-2-3* (McGraw-Hill,) published in 1991 with a PC code. This code is now replaced by *problem solving environments* which utilize component-based software systems to convert theory to practice, e.g., MatLab, FEm.PSE. Reporting of the computational experiment results has transcended from paper to html, admitting full archival data *in color*, c.f., http://cfdlab.engr.utk.edu/551w/Archives.



The software system/problem solving environment concept has led to preparation of the *FEmPSE Tutorial* text supplement/replacement. With recent advances in *high performance communications*, this combination enables going online with this thoroughly practical course to reach the larger audience with diverse interests in engineering and the sciences. Thereby, MAES 551w will employ the full complement of courseware and software in a real-time Internet video streaming environment.

MAES 551w may be taken for transfer credit (3 hrs) or for audit. Your home site need have only a respectable PC loaded with free software for receiving of the video signal. Additional real-time communication will be enabled via a chat room and interactive email. The course lectures will also be digitally archived, hence those missed may be reviewed at any time.

For those interested, this Fall course will be followed in Spring by MAES 552w, *Computational Fluid Dynamics, Heat, and Mass Transfer*, the Web-based successor to the current MAES 552, Computational Fluid-Thermal Systems. Planned for the next year are MAES 554w, *Computational Aerodynamics* and MAES 553w, *Computational Structural Mechanics*. Each will build on the introductory FE course MAES 552w.

instructor

teaching
Computational mechanics | Fluid mechanics/heat transfer | Numerical methods, CFD

education
BME, Union College | MS, PhD SUNY/Buffalo

research
Computational mechanics | Applied computational simulation in engineering | Distance learning/multi-media

professional experience

1975 - Present
Professor, Engineering Science, and Director (since 1983), UT CFD Laboratory,
University of Tennessee, Knoxville, TN.

1975 - 1995
Chief Scientist, Computational Mechanics Corp., Knoxville, TN.

September 1995
Visiting Professor, Civil Engineering, Chuo University, Tokyo, Japan.

1974 - 1975
Visiting Associate Professor, Mechanical Engineering/Mechanics, Old Dominion University, and NASA Research Scientist, Hampton, VA.

1971 - 1973
Visiting Scientist (summers), ICASE, NASA Langley, Hampton, VA.

1970 - 1974
Principal Research Scientist and Manager, Computational Fluid Mechanics Group, Research Dept, Textron/Bell Aerospace, Buffalo, NY.

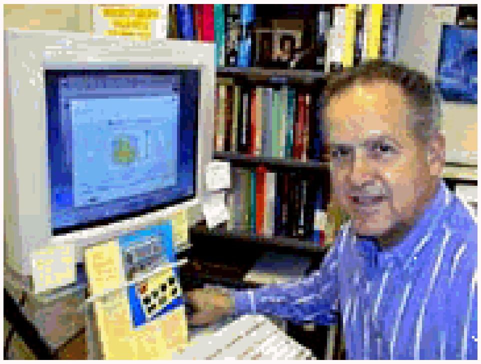
A.J. Baker, PhD, PE
Professor, Engineering Science and Director,
UT CFD Laboratory

316A Perkins Hall
University of Tennessee
Knoxville, TN 37966-2030

Office phone:
(423) 974-7674

Email:
ajbaker@cfdlab.engr.utk.edu

Fax:(423) 974-6372



1970 - 1974
Principal Research Scientist and Manager, Computational Fluid Mechanics Group, Research Dept, Textron/Bell Aerospace, Buffalo, NY.

1965 - 1970
Instructor, Engineering Faculty, State University of New York/Buffalo, and Digital Analyst (summers), Textron/Bell Aerospace, Buffalo, NY.

1958 - 1964
Mechanical Engineer, Development Laboratory, Linde Division, Union Carbide Corp., Buffalo, NY.

professional activities

Assoc. Fellow, Amer. Inst. Aero. & Astro. (AIAA) Member, Amer. Academy of Mechanics (AAM), Amer. Soc. Heating, Refrig, Air Cond. Engineers (ASHRAE), and N.Y. Academy of Science. Licensed Professional Engineer (New York and Tennessee), Editorial Board Member of five technical journals, Listed in Who's Who in Science & Technology.

selected publications

Archival Journal Articles: (55 manuscripts, 1969-1996, "A Weak Statement Perturbation CFD Algorithm with High Order Phase Accuracy for Hyperbolic Problems," with S. Roy, *Comp. Mtd. App. Mech. & Engr.*, V. 131, p.209, 1996.*(*=available online)

"Incompressible Computational Fluid Dynamics and the Continuity Constraint Method for the 3-D Navier-Stokes Equations," with P.T. Williams, *J. Num. Heat Transfer, Part B Fundamentals*, V. 29, p. 137-273 (entire issue), 1996.

"A Non-linear Sub-Grid Embedded Finite Element Basis for Steady Monotone CFD Solutions," with S. Roy, *J. Num. Heat Transfer, Part B. Fundamentals*, v., 1996.*

"On Taylor Weak Statement Finite Element Methods for Computational Fluid Dynamics," with D.ÊJ. Chaffin, *Int. J. Num. Mtd Fluids*, V. 21, p.273-294, 1995.*

Books: (2 textbooks, 9 monograph chapters, 1975-1997)
"The Finite Element Method for Numerical Solution of the Equations of Fluid Mechanics," Ch. IV.4 in R. W. Johnson (Ed in Chief), *The Handbook of Fluid Mechanics*, CRC Press, FL, 1998.

Finite Elements 1-2-3, with D. W. Pepper, McGraw-Hill, New York, NY (1991). Int1l Student Edition, Singapore (1992), Japanese translation, Tokyo (1997).

Conferences and Proceedings (109 papers, l970-1996)
"Finite Element Weak Statement Solution for the ASME Thermal Cavity Benchmark," with M.B. Taylor, D. J. Chaffin and S. Roy, presented at ASME WAM, Dec. l995.*

"On Development of a Software Platform for Rapid Implementation of Finite Element Weak Statement CFD Algorithms," with S. Roy, P.D. Manhardt and E.G. Schaub, in M. Cecchi, et al (ed), 3Proc. IX Int1l Conf Finite Elements in Fluids,2 Univ. Padua Press, p. 115-124, 1995.

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course calendar

class	date	topics	text/ref.	prob	due	lab	due
1	AUG 27	Content,requirements; Intro to FE analysis, weak statements	FE.1-10			L-1	
2	SEP 1	Problem statements in Engr. Sciences, PDEs, BCs, examples	PS.1-11 IM.1-2	P-1			
3	3	Solution processes, 1,2,3-D, analytical, approx., FD, WS	IM.3-18	P-2			L-1
4	8	WS tutorial: approximation, error, FE basis, element matrices, assembly, solution, accuracy, convergence	HC1-12 Ref. Ch.3	P-3	P-1		
5	10	Steady heat transfer, convection BC FE lagrange bases; FE WS^h completion for k=1, n=1, example	HT1.1-6	P-4	P-2		
6	15	Steady cond, data handling, template, convergence, k=1	HT1.6-10		P-3	L-2	
7	17	Steady conduction, k=2,3 FE bases, matrices, assembly, examples, accuracy	HT1.11-14 Ref. 4.6				
8	22	Steady conduction, k=1,2,3, convergence, error est.	HT1.14-20			L-3	L-2
9	24	Non-uniform data, accuracy, error estimation	HT1.21-22			L-4	
10	29	Non-linear conduction, Newton template, convergences	HT1.23-24, 28			L-5	L-3
11	OCT 1	Euler-Bernoulli beam, cubic hermite FE, WS^h + BCs	CM1.1-8 Ref 4.8	P-5	P-4		
12	6	Euler-Bernoulli beam, derived variables, WSs, k=1	CM1.9-111			L-6	
13	8	Timoshenko beam, WS, under-integration, art. diffusion; finned tube heat exchanger, insights	CM1.12-14, 19-22				L-4
14	13	Steady conduction, n=2,3, triangles, tetrahedra, quads, hexahedra, FE bases, nodes	HTn. 1-6	P-6			
	15	**Fall Break**					
15	20	**Hour Exam - Covers Classes 4-13**			P-5		L-5

Problem sets may be transmitted via fax, email or snail mail.
One point (out of six - nine) will be deducted for each day submission is late.

1.1 Complete the lecture heat conduction example ODE solutions for BCs, for each of the given heat source forms.

.2 Solve the 1D unsteady heat conduction PDE to determine the temperature distribution in a rod initially at uniform temperature T_1, with the "right" end increased to T_2 at time t_0. (Hint: cast the solution on the difference between the steady state and the time-evolution of temperature.)

.3 (Optional): Solve the 2D laplacian for Φ on the rectangular domain $0<x<a$, $0<y<b$ for the BCs $\Phi(0,y)=0$, grad$\Phi(x,0)$.**n** = 0 = grad$\Phi(x,b)$.**n** and $\Phi(a,y) = \cos(3\pi y/b)$ **Due Class 4**

2.1 Confirm the second order accurate FD approximation for a first derivative.

.2 Establish the modification to the answer for 2.1 for a non-uniform mesh, hence determine the truncation error.

.3 Derive the uniform mesh FD stencil for the laplacian in 2D and 3D.

.4 Work through, hence verify the derivation of the Lagrange interpolation polynomial of degree J. **Due Class 5**

3.1 Verify the analytical solution (3.4) to the tutorial model problem (3.1)-(3.3).

.2 Verify that the Ψ^{α} and Q^{α} cited on HC.2 for T^N agree with (3.4).

.3 Verify the integrated-by-parts WS form (3.13).

.4 For the linear basis, verify the matrix terms on HC.8 for WS^h, (3.21).

.5 Verify the assembly of components in (3.26) to form (3.30).

.6 Verify the approximate solution (3.34).

.7 Verify the boundary flux solution from (3.32).

.8 Compute the FE WS^h solution for a 3-element uniform discretization of the span L of problem (3.1)-(3.3). Comment on nodal and flux accuracy.

.9 Repeat 3.8 for a non-uniform 3-element mesh. **Due Class 6**

lab assignments

Assignments are noted on the MAES 551W schedule. Labs employ provided MatLab template scripts, and are to be completed by the class indicated. Limit narrative to a *single page* with tabular data and plots appended as appropriate. Archival verification data and extensive lab reports are available at
http://cfdlab.engr.utk.edu/551w/Archives.
Student reports can be accessed from
http://cfdlab.engr.utk.edu/lab_front.html
Notify instructor of completion by e-mail. One point deducted for each class period late.

1. State an *n*-dimensional PDE, with appropriate BCs, describing an *engineering analysis* problem of *your interest*. Briefly describe features of its solution prompting your interest, and anything you know about available solution processes (for the simplified or real problem). Prepare your report using word, LaTex, etc., and submit via fax or e-mail for review. Then translate it to *html* using available utilities, and place in your lab directory.
   Due at class 3.

2. Complete the 1-D heat transfer linear basis convergence study, summarized in VuG HT1.10 and detailed in the on-line *MatLab Primer*. Verify template construction forming the [DIFF] matrix, hence modifications for HBC and Dirichlet BCs. Realizing T_{exact}=1000.00, verify the error estimate (4.91). Prepare the *html* report with tabulated data and appropriate graphics.
   Due at class 8.

3. Extend the GWS^h template for the 1-D heat conduction convergence study to $1 \leq k \leq 3$ FE bases, as summarized on VuG HT1.14, for appropriate uniform discretizations Ω^h. Insert MatLab command "FLOPS," hence compare floating point operation counts for *k*. Verify the asymptotic error estimate (4.91) using the energy semi-norm, and in T_{max} *not using* the exact solution.
   Due at class 10.

4. Execute a convergence study for the conduction with distributed source problem, for a single material, then for two dissimilar materials with double sine source, VuG HT1.20, for $1 \leq k \leq 2$

FEm.PSE Tutorial:

*F*INITE *E*LE*m*ENTS
for *P*ROBLEM *S*TATEMENTS
in *E*NGINEERING

A.J. Baker

Price: $59 US

FEm.PSE - Problem Solving Environment

Following two-plus decades of cutting edge research on NASA, DoD, DOE & NSF funded computational mechanics theory/code contractual projects, the inescapable conclusion has emerged that the *root detraction* to real-time utilization of multi-disciplinary computational mechanics simulation is the *absence* of computer code *versatility*.

To now, any "given code" (commercial, "free," or self-generated) is the software imple-mentation of a *specific* discrete model, narrowly focussed to the problem class for which derived. Such "hard-wired" codes are not very amenable to varying the embedded intricate details (*nuances*) that distinguish *your problem* from those for which the code is validated. Hence, *problem-adapting* invariably involves significant *recoding*, and only a few syntax changes can make it stop running! This leads to time and personal effort applied to debugging, rather than executing *today's* simulation today!

The replacement for such a "code" is emergent as *component-based software platforms* operating in today's *high performance computing and communications* (HPCC) Web environment. The computational theory generalization employs the *weak statement* (WS), with implementation via a *finite element* (FE) discretization. As the prototype, *FEm.PSE* is the first to break the entrenched approach of direct theory embedding, by *totally separating* the issue of theory/application (hence advances) from implementation. WS algorithm instructions are word-processed into a *template* construction, which with *hooks* imprints every *nuance* in *English* rather than Fortran, C, or some other "foreign language." Since *you* write the source (template), you know (!) what is running. But you cannot insert bugs into the "real" code since it functions beyond your reach. It represents an entirely *new* level of *software versatility/reliability* for widely diverse engineering/science analysis applications.

This *Tutorial* develops the essence of modern WS discrete modeling, with applications aimed to the emergent *problem solving environment*. Elementary problem templates employ the **Matlab** environment, which transparently leads to ***FEm.PSE*** implementations for *genuine* problems. The theory presentation parallels that in the McGraw-Hill text ***Finite Elements*** **1-2-3**, with major extensions for dimensionality and application diversity.

FE*m*.PSE, the Tutorial
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a weak statement FE tutorial

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n=1 FEs in multiple disciplines

HT*n* STEADY HEAT TRANSFER:
n=2,3 FE, BCs, accuracy, error control

FDVE. FINITE DIFFERENCES of OPINION:
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n=2,3 FEs in multiple disciplines

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n=1 FE for steady/unsteady convective transport, accuracy, convergence

CD1 Solution Examples

Problem	Java Viewer *Slow to Download*	RealPlayer *Small Window*	RealPlayer *Big Window*
Unsteady Axisymetric Pipe		100 kbps	

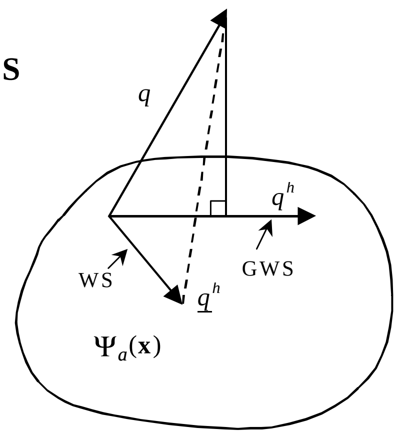
CD*n* CONVECTION-DIFFUSION:
n=2,3 FE for unsteady transport, BCs, error estimation/control

CDn Solution Examples

Problem	Java Viewer *Slow to Download*	RealPlayer *Small Window*	RealPlayer *Big Window*
Rotating Cone - k=1,C=0.5	Java Script	100 kbps	200 kbps
Rotating Cone - CN, C=0.5	Java Script	100 kbps	200 kbps
Rotating Cone - k=1, C=0.5, Pe=1000	Java Script	100 kbps	200 kbps
Rotating Cone - k=1, C=0.5, theta=1	Java Script	100 kbps	200 kbps
Gaussian Plume - k=1, Pe=10	Java Script	100 kbps	200 kbps

FE.9 OPTIMAL WEAK STATEMENT

Many choices exist for implementing WS



- *does an optimal selection for $\Psi_a(\mathbf{x})$ and $\Phi_a(\mathbf{x})$ discretized trial and test space basis sets exist?*

Engineer's choice is e^N minimum!

mathematicians can prove that

- *the discrete approximation error is extremized when the test and trial space (basis functions) are identical.*

The corresponding FE implementation is *Galerkin* WS^h

GWS^h error is *orthogonal* to trial space $\Psi_a(\mathbf{x})$

FE.10 SUMMARY, FE WEAK STATEMENT

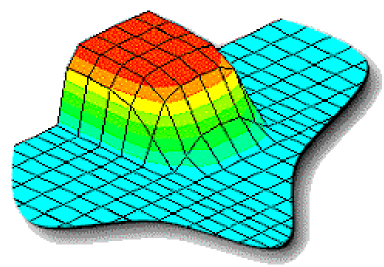
For arbitrary geometries and non-linearity:

problem statement: $\mathrm{L}(q) = 0 \quad on \quad \Omega \subset \Re^n \; + \;$ BCs

approximation: $q(\mathbf{x}) \approx q^N(\mathbf{x}) \equiv \sum_a \Psi_a(\mathbf{x})\, Q_a$

discretization: $\Omega \approx \Omega^h = \cup_e \Omega_e$

$q^N \equiv q^h = \cup_e \{N\}^T \{Q\}_e$



error extremization: $\mathrm{GWS}^h = \sum_e \mathrm{WS}_e \equiv \{0\}$

$\mathrm{WS}_e = \int_{\Omega_e} \{N\}\, \mathrm{L}(q^h)\, d\tau$

linear algebra: $[\text{ Matrix }]\{Q\} = \{b\}$

error quantization: Ω^h refinement

FE.9 The fact that all these choices exist, and have been made, immediately raises the *fundamental* question

- *does an optimal selection for* $\Psi_\alpha(\mathbf{x})$ *and* $\Phi_\beta(\mathbf{x})$ *exist, hence their discretized trial and test space basis sets?*

One has to define "optimal" to answer this question, and the mathematicians will work this issue to the point of distraction!

Engineers are not so burdened, and their (obvious) definition would be the selection that produces the absolutely *minimum* discrete equivalent to the error $e^N(\mathbf{x})$, associated with the discrete approximate solution

$$q^N(\mathbf{x}) \quad q^h(\mathbf{x})$$

In this instance, and for the linear PDEs describing introductory problem statements in Engineering Science, the mathematicians directly provide this answer as

- *the discrete approximation error is extremized when the test and trial space basis functions are defined to be identical.*

The *Galerkin* FE implementation GWS^h *is* this choice, hence is *optimal!*

FE.10 In summary then, the FE discrete implementation guarantees the evaluability of the weak statement WS for problem domains Ω with arbitrarily non-regular boundary $\partial\Omega$.

The key theoretical issue is the *trial space basis set spanning FE domains* Ω_e. Symbolically, the resultant FE solution process is

approximation: $q(\mathbf{x}) \quad q^N(\mathbf{x}) \equiv \sum_\alpha \Psi_\alpha(\mathbf{x}) Q_\alpha$

discretization:

$$\Omega \approx \Omega^h = {}_e\,\Omega_e$$

$$q^N \equiv q^h = {}_e\{N\}^T\{Q\}_e$$

error extremization:

$$\mathrm{GWS}^h = \sum_e \mathrm{WS}_e$$

$$\mathrm{WS}_e = \int_{\Omega_e} \{N\} L\left(q^h\right) d\tau$$

linear algebra: $[\mathrm{Matrix}]\{Q\} = \{\mathrm{b}\}$

error quantization: Ω^h refinement

We now fill in some details about problem statement formulations in the Engineering Sciences.

MatLab REFERENCE MATERIAL*

A Matlab Primer for FEm.PSE Users - Acrobat pdf form
Due to the LaTex input source, this file will not print

A Matlab Primer for FEm.PSE Users - PostScript form
This form is printable but must be downloaded to your hard drive

Mathworks Homepage (http://www.mathworks.com)

***Be sure to read the Primer *before* starting on the computational experiments.**

Access to the following MatLab template scripts requires course registration

MatLab TEMPLATE SCRIPTS

Computational Experiment	MatLab Template Scripts	
Experiment 2	lab2.m	lab2conv.m
Experiment 4	lab4a.m	lab4b.m
Experiment 5	lab5a.m	lab5b.m
Experiment 6	lab6a.m	lab6b.m
Experiment 7	fun_problem.m	
Experiment 8	axi_pipe.m	
Experiment 9	Lshape_quad.m	do_Lshape2D_dlist.m
Experiment 10	same as above	same as above

MatLab FEm.PSE TOOLBOX

Make sure your MatLab startup file points to the current FEm.PSE toolbox:

/cfd3/utcfdlab/matlab/fempse

Place the downloadable startup.m file in the root of your matlab directory for access to the most recent toolbox edition.

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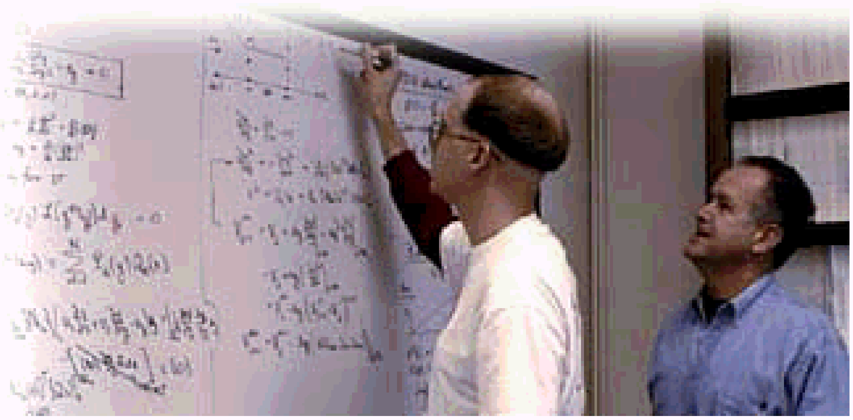
VIDEO LECTURE EXAMPLES

Date	28.8k modem	56k modem	112k ISDN
Aug 27 Lecture Website Tour	28	56	112
Aug 27 Lecture Overview	28	56	112
Sep 1 Lecture Overview	28	56	112



Problems? E-mail Zac Chambers for technical assistance.

Access to the following video material requires course registration

ARCHIVES

Date	28.8k modem	56k modem	112k ISDN
Aug 27 Lecture	28	56	112
Sep 1 Lecture	28	56	112
Sep 3 Lecture	28	56	112
Sep 8 Lecture	28	56	112
Sep 10 Lecture	28	56	112
Sep 15 Lecture	28	56	112
Sep 17 Lecture	28	56	112
Sep 22 Lecture	28	56	112
Sep 24 Lecture	28	56	112
Sep 29 Lecture	28	56	112

TODAY'S STREAMING LECTURE

SEMESTER COMPLETE!

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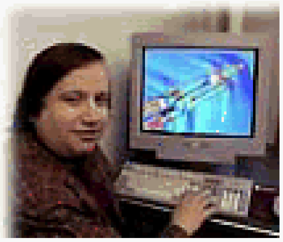
communication

Chat and Forum: maes551w



Chat Room
Forum Discussion Area
Note: *These links will open in a new window.*

Email Links to Professor and GTAs

Dr. A.J. Baker
ajbaker@cfdlab.engr.utk.edu

Zac Chambers - *video guru*
chambers@cfdlab.engr.utk.edu

Mike Taylor - *MatLab guru*
mtaylor@cfdlab.engr.utk.edu

Email the Entire Group

maes551w@cfdlab.engr.utk.edu

Email Links to Individual Students

Mohan Ball	bmohan@gumbo.bae.lsu.edu
Dan Martin	dmartin@agctr.lsu.edu
Chang Kim	cskim@gumbo.bae.lsu.edu
Derrick Baird	Roknrol13@aol.com
Bo Chen	bochen@cfdlab.engr.utk.edu
Kislaya Gautam	gautam@verdi.engr.utk.edu
Liang Jiang	ljiang@utk.edu
Atish Mitra	mitra@cfdlab.engr.utk.edu
Bryant Seals	bseals@math.utk.edu
Dan Sherman	labrat@utk.edu
Hank Wayland	waylanh@baico.com
Wei Zhao	wzhao@nestor.engr.utk.edu

registration

1. A non-UT student taking a UTK Internet course for graduate credit must apply to the UT graduate school as a "transient student." This should be done at least ten days in advance of the final registration for the term. This is easily done online at http://marge.cas.utk.edu/gradschool/. Transcripts and letters of recommendation are not required for students already admitted at the major university level in the USA.

2. Once the online application is completed, a "Signature and Payment" form will be printed automatically.

3. Another form, "Transient Student Certification form," must be acquired from UTK and signed by the dean of the Graduate School at the University receiving the UTK Internet graduate course. Also, the Graduate School dean will likely want either a department head or faculty signature from the student's department. Both of these forms and the transient student fee of $35 must be sent to Graduate Admissions and Records at UTK before processing can take place.

> Address:
> Graduate Admissions and Records
> 218 Student Services Bldg.
> Knoxville, TN 37996-0220

A good contact is Linda Sisk at Graduate Admissions and Records, phone: 423.974.1338, to check if all forms have been received and processed. She can be very helpful.

4. Once the forms are processed, Internet graduate course fee payment is handled through the UTK Evening School. The contact point is Dr. Dulcie Peccolo, 423.974.5200, who will handle tuition determination. The course will count towards the degree program at your university but likely will not show up on that transcript. The grade and credit hours will be recorded on the UTK transcript.

5. Upon receipt of the information sheet, you will be congratulated on your acceptance as a transient student. You will also be informed to send (fax) a picture ID with SSN and a statement asking for the PSC (personal security code), which UTK, in turn, will mail to you.

6. Any individual wishing to audit a UTK Internet course need only contact Dr. Peccolo to complete the registration process

TOP

technical help

To be able to participate fully in this class and receive the video lectures, you will need an active internet connection and a computer that meets the following hardware and software specifications:

HARDWARE REQUIREMENTS (minimum)

IBM compatible computer

- 133 MHz Pentium Processor
- 16 MB ram (Windows 95) or 32 MB ram (Windows 98)
- 8 MB hard drive space
- Sound Card
- 28.8 modem or faster

Macintosh Power PC

- 100 MHz Processor
- 16 MB ram
- 8 MB hard drive space
- Sound Card
- 28.8 modem or faster

HARDWARE REQUIREMENTS (optimal)

IBM-compatible computer

- 166 MHz Pentium Processor
- 32MB ram (Windows95) or 48 MB ram (Windows 98)
- 8 MB hard drive space
- Sound Card
- 56K modem or faster

Macintosh Power PC

- 133 MHz Processor
- 32 MB ram
- 8 MB hard drive space
- Sound Card
- 56K modem or faster

SOFTWARE REQUIREMENTS

To download the required software to your computer's hard drive, just click on the appropriate link(s) and follow the manufacturer's instructions. *Note: These links will spawn a new window.*

- Netscape 4.0 or Internet Explorer 4.01
- An active email account (see below)
- RealPlayer Plugin (G2 or 5.0)
  http://www.real.com
- ICHAT plugin
  http://www.ichat.com
- Adobe Acroread 3.0
  http://www.adobe.com

To open a UTK email account and for any other technical questions, contact:
Zachariah Chambers
E-mail: chambers@cfdlab.engr.utk.edu