Teaching Computational Electromagnetics at Northeastern University: From PCs to Supercomputers

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Abstract

As supercomputers become more accessible and as inexpensive personal computers become more powerful, the numerical modeling of electromagnetic fields in non-idealized geometries becomes increasingly practical. To enable graduate students to solve useful real-world problems, Northeastern University's course ECE 3347: *Computational Methods of Electromagnetics* teaches the important techniques of field and wave simulation, making use of a variety of programming languages, graphics packages, and computer systems which range from home computers to the most powerful supercomputers. Strong emphasis on algorithm design and computer testing helped motivate students to develop an understanding of the major issues involved in using computers to simulate electromagnetics problems.

Introduction: Computational EM at Northeastern University

Electromagnetics is a major research area in the Electrical and Computer Engineering Department at Northeastern University in Boston Massachusetts. The department consists of about 50 faculty and 100 full-time graduate students, and maintains the second largest funded research budget in New England. The Center for Electromagnetics Research is an NSF Industry/University Center of Excellence which is the focus of much of the EM graduate research at the university.

Although the computational electromagnetics course ECE 3347 has been offered for some time, it has only been during the 1991-92 academic year that instruction and assignments on supercomputers have become part of the academic curriculum. Both the massively-parallel Thinking Machines CM-2 and the Cray Y-MP platforms were used in computation problem sets. With the increasing interest in solving large, practical EM propagation and

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scattering problems – many of which cannot be solved without resorting to numerical computation methods – students' familiarity with state-of-the-art supercomputing is becoming essential.

Many of the graduate classes are taught in studio classrooms and broadcast to local area industrial sites as part of the Network Northeastern Program, or across the United States as part of the National Technological University. The studio classroom offers the option of using both a board and an overhead camera. Conventional blackboard lecture presentation is often supplemented with multi-color video displays from texts, journal papers, and presentation graphics.

It has been observed that students taking the course find it enjoyable and interesting, and quite useful for their own research. As such they worked very hard, commenting in evaluation forms that the work load was much greater than other classes, but that it was worth the effort.

NU Course ECE 3347: Computational Methods of Electromagnetics

The syllabus for the Winter 1992 quarter of ECE 3347 is shown in Figure 1. The topics covered include standard EM computational methods, such as Moment Methods, but also more modern techniques: FDTD, conjugate gradient methods, stimulated over-relaxation (SOR), and multi-step Lax-Wendroff methods, to name a few. This syllabus is similar to that of other universities, in particular, one reported by Iskander [1]. The prerequisites for the course include graduate electromagnetic field theory and mathematics, as well as a fair amount of programming experience.

The major complaint of the 17 students who took ECE 3347 was the lack of a unified textbook specifically dealing with *electromagnetic* numerical computation. *Numerical Recipes*, by Press, et. al. [2] is an excellent all-round reference, and Lapidus and Pinder [3] is useful for pure mathematical theory, but no book deals with both finite methods and moment methods for electromagnetics. This problem has been recently alleviated with the publishing of several new texts [4,5].

Two important aspects of ECE 3347 are the development of scientific computing expertise and the understanding of engineering design in numerical electromagnetics. Half the student's grade is based on a term project of his or her own choosing. The project was not intended to represent original research, but rather more of an independent replication of results published in the literature. One-third of the projects did involve original research, which may be incorporated into the students' ongoing theses. Five problem sets determine the remaining 50% of the grade: three computational assignments and two assignments which derive mathematical bases for several methods.

Although all students were offered accounts on the university's VAX 6420 mainframe, most used computers they were already working with. These included Sun 3 and Sparc 440 workstations, Macintosh IIsi and IBM compatible 80286, 80386, and 80486 desktops, and a Convex 210 computer. Arrangements were also made through the NSF- and NIH-sponsored Pittsburgh Supercomputer Center for computer time on their CM-2 and Cray Y-MP supercomputers as part of their Educational Coursework Grant program. One major point observed in teaching the class is that to be useful in general research, the numerical methods must be transportable to a wide variety of computational platforms.

Allowing students to use any computer they felt comfortable with, along with their favorite high-level programming language and graphics software, provides flexibility and avoids the steep initial learning curve accompanying learning a new programming language. No software, except for the SAS-Graphics package [6], was made available to the students. Everything used for simulation was completely written by each student for his/her own computer system. For some students, the first few weeks were somewhat aggravating, but most were constructing their first iterative Laplace's Equation solver by the second lecture.

The most popular programming language was MATLAB, and FORTRAN was the compiled language of choice. However, software was also written in Mathematica, HP-Basic, Pascal and C. Separate graphics packages included: SAS-Graphics, BBN RS-1, Trimetrix Axum, Microsoft Excel, Autocad, and Lotus 123. One lecture was devoted to teaching CM-FORTRAN, and one student independently (and successfully) learned C*, so students could program that massively parallel Single Instruction Multiple Data CM-2 computer. The single 100 minute lecture certainly could not develop fluency with a new language, but it was enough to establish an appreciation of parallel architecture and programming.

Each of the students who chose to use the CM-2 to solve matrix equation problems using the conjugate gradient method got the correct answer and demonstrated a 1 to 2 order of magnitude performance improvement over conventional computers. Several subtle lessons were learned in working with the supercomputer. First, although FORTRAN is considered by many computer scientists to be antiquated and inefficient, it is the language of choice for scientific computing, both with the massively parallel CM-2 and the powerful Cray Y-MP. The more modern C programming language is supported on the CM-2, but because of its unique hardware/compiler architecture, floating point calculations can only be performed 1/32 times as often as with CM-FORTRAN. A second lesson is that computer performance comparisons can be misleading. For example, students found that it takes about the same amount of time to invert a 100 by 100 double precision element dense matrix on a conventional computer or the CM-2 using the conjugate gradient method, or using a 80486 desktop using MATLAB. However, to invert a 1000 by 1000 matrix takes roughly the same amount of time as for the smaller case on the CM-2, 40 times longer on a VAX and so long on the desktop (because of repetitive data swapping to disk) that it could not be measured.

One problem set in ECE 3347 is based on one-dimensional FDTD modeling of reflection from a lossy dielectric half-space. Issues such as the Courant number, differentiability of the incidence pulse (Gaussian versus truncated sinusoid), loss behavior in the time domain, and absorbing boundary conditions were examined. Many students were surprised when they specified the electric field pulse with zero magnetic field, and watched as two waves—a left as well as a right propagating wave—were generated. An example of graphical output, showing a single Gaussian electric field pulse, computed using the FDTD algorithm, as a function space and time approaching and reflecting off the boundary at $SPACE = 491$; and also attenuating into the lossy medium with a different velocity (as seen by the space/time slope) is shown in Figure 2. The effect of not using an absorbing boundary on the left lattice termination is clearly exhibited with another reflection. The time domain analysis and display is instructive since although the wave pulse propagates, reflects, and attenuates as one might expect, the usual reflection and transmission coefficients are formulated in the frequency domain, making the mathematics of a Gaussian pulse interaction quite complicated.

An electrostatic computer problem uses iterative relaxation methods to solve for the total potential between and surrounding a pair of capacitor plates. The electric field lines must also be displayed. This non-trivial plotting task is accomplished by using analytic function theory to find the stream function orthogonal to the potential function, and then realizing that the electric field lines coincide with its level contours. Students also are exposed to boundary effects from the lattice termination in this problem.

The final computational exercise, offered as an alternative to the conjugate gradient problem, is to solve for the currents on a variety of dipole antennas using the Method of Moments.

Reading the term papers for ECE 3347 was informative and satisfying. Some of the more original project titles are: "Novel Absorbing Boundary Conditions", "Moment Methods in Polygonal Wire Antennas", "Electroquasistatic Solution of Laplace's Equations for a Field Emission Microtip Structure" which was later used as part of a Master's thesis on vacuum microelectronic device design (with equi-potential contours around a field emitter shown in Figure 3), "Scattering from Inhomogeneous Dielectric Cylinders Using the Unimoment Method", "The Numerical Solution of the Time-Dependent Schroedinger Equation" (with a sample interaction of a wave with a square potential well clearly displayed in Figure 4), and "U.S. Coast Guard WHEC 378 Hamilton Class Cutter High Frequency Antenna Model" (which makes use of the Numerical Electromagnetics Code EFIE and MFIE simulation). The typical term paper was 35 pages long and was of sufficient quality to be considered a professional technical report.

Conclusions

It appears that ECE 3347 has been an important part of the graduate electromagnetics education at Northeastern University. Many students use the methods learned in their current research to simulate effects with detail that is otherwise impossible. The areas of student research aided by this knowledge range from microwave magnetics to quantum physics, and antenna design to microelectronics.

Teaching students Connection Machine FORTRAN was less difficult than was expected. Once the parallel architecture is discussed, highlighting the major new constructs and syntactic differences in the context of a particular problem gives the students enough to have them experiment and program efficiently.

The design-oriented format of the class was found to be a strong motivating force. The appeal of using software to perform real-world engineering analysis and application design is universal among the students. The students perceived the computer problems as an engineering challenge, and gave high priority to solving them. In addition, the practical aspect code writing, with emphasis on the engineering problem solution rather than the finer points of the code, is good preparation for future electrical engineering work.

Exposing students to many computational platforms helps illustrate the nature of available resources. By encouraging students to discuss the benefits and disadvantages of one system over another among themselves lets them come to their own conclusions about the best approaches to computational problem solving.

Acknowledgements

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References

1. Iskander, M., Morrison, M., Datwyler, W., and Hamilton, M., "A New Course on Computational Methods in Electromagnetics," *IEEE Transactions on Education*, vol. 31, No. 2, May 1988, pp.101-114.

2. Press, W.H., et. al., *Numerical Recipes*, Cambridge, 1986.

3. Lapidus, L. and Pinder, G., *Numerical Solution of Partial Differential Equations in Science and Engineering*, Wiley, 1982.

4. Sadiku, M., *Numerical Techniques in Electromagnetics*, CRC Press, Boca Raton, 1992.

5. Umashankar, K., and Taflove, A., *Computational Electromagnetics*, Artech House, Norwood, 1993.

6. Council, K. and Helwig, J. (ed.), *SAS/Graph User's Guide*, SAS Institute, Inc., Cary, NC, 1981.

NORTHEASTERN UNIVERSITY

ECE–3347 Computational Methods in Electromagnetics

Winter 1992

INSTRUCTOR:
Prof. Carey Rappaport
235 Forsyth Building
Work phone (617) 437–2043

OFFICE HOURS: Tuesday 1:00–3:00 and Thursday 1:00–3:00 or by appointment

CLASS TIME: Monday and Wednesday 9:50–11:30. (EST)

TEXT:

Required:

Lapidus, L. and Pinder, G., *Numerical Solution of Partial Differential Equations in Science and Engineering*, Wiley, 1982.

Suggested:

Hall, C.A. and Porsching, T.A, *Numerical Analysis of Partial Differential Equations*, Prentice Hall, 1990.

Press, W.H., et. al., *Numerical Recipes*, Cambridge, 1986.

Harrington, R., *Field Computation by Moment Methods.*

Recommended (on reserve):

Hoole, R., *Computer Aided Analysis of EM Devices.*

Burnet, *Finite Element Analysis.*

Strikwerda, *Finite Difference Schemes and PDE's.*

Segerlind, *Appl. Finite Element Analysis.*

GRADING:
Homework (3 two-week and 2 one-week assignments): 50%
Term Paper: 50%

OBJECTIVES: To develop an understanding and appreciation of the approximations, mechanisms, and mathematics of numerical computation, with emphasis in electromagnetics. Using rigorous and complete development of topics starting from first principles, the course will provide the student with the background to attack and solve complex problems which cannot be solved using standard modal or ray optics methods.

SYLLABUS

Topic 1 7 lectures	**Finite Differences.** Introduction to difference approximations of continuous functions: one dimensional integration, first order ODE's, Laplace's equation, wave equation, non-uniform grids, FDFD/FDTD.
Topic 2 3 lectures	**Matrix Manipulation.** Technique for working with large matrices: review of LU decomposition and Gaussian reduction, sparse matrix techniques, the conjugate gradient method.
Topic 3 4 lectures	**Finite Elements.** Variational theory of finite elements, element specification and connectivity, spurious modes.
Topic 4 3 lectures	**Moment Methods.** Specialization of finite elements to Galerkin and other moment methods for solving antenna and waveguide problems in terms of the impedance matrix.
Topic 5 2 lectures	**Radiation Boundary Conditions.** Approaches to terminating the computational boundary for exterior (radiation) problems.

Figure 1: Syllabus for ECE 3347

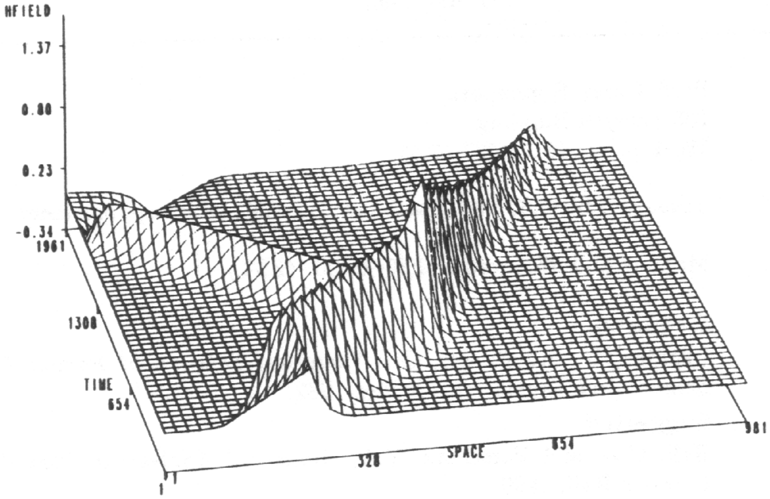

Figure 2: Problem set 3 solutions: FDTD analysis of a Gaussian electric field pulse reflecting off, and transmitting into a lossy dielectric half-space, $\epsilon = 4\epsilon_0$, $\sigma = \frac{1}{50\eta_0 \Delta\tau}$, $\Delta\tau = c\Delta t = .5$.

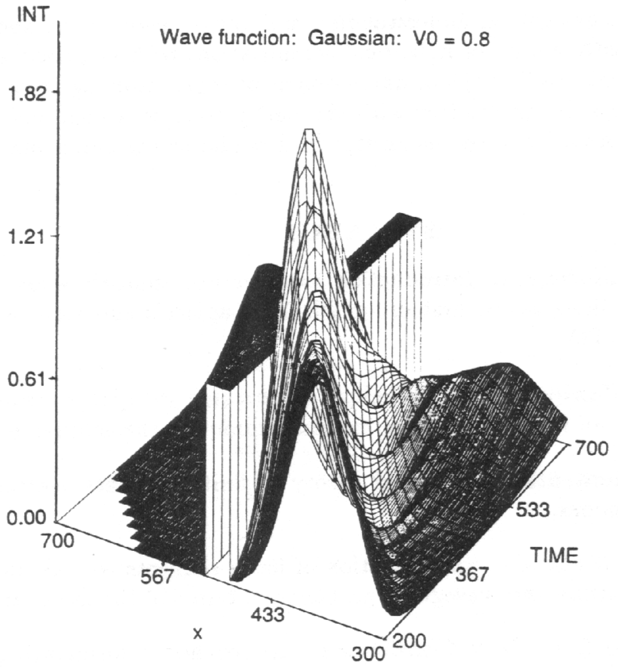

Figure 3: Equi-potential contours around the emitter tip of a vacuum microelectronic amplifier model.

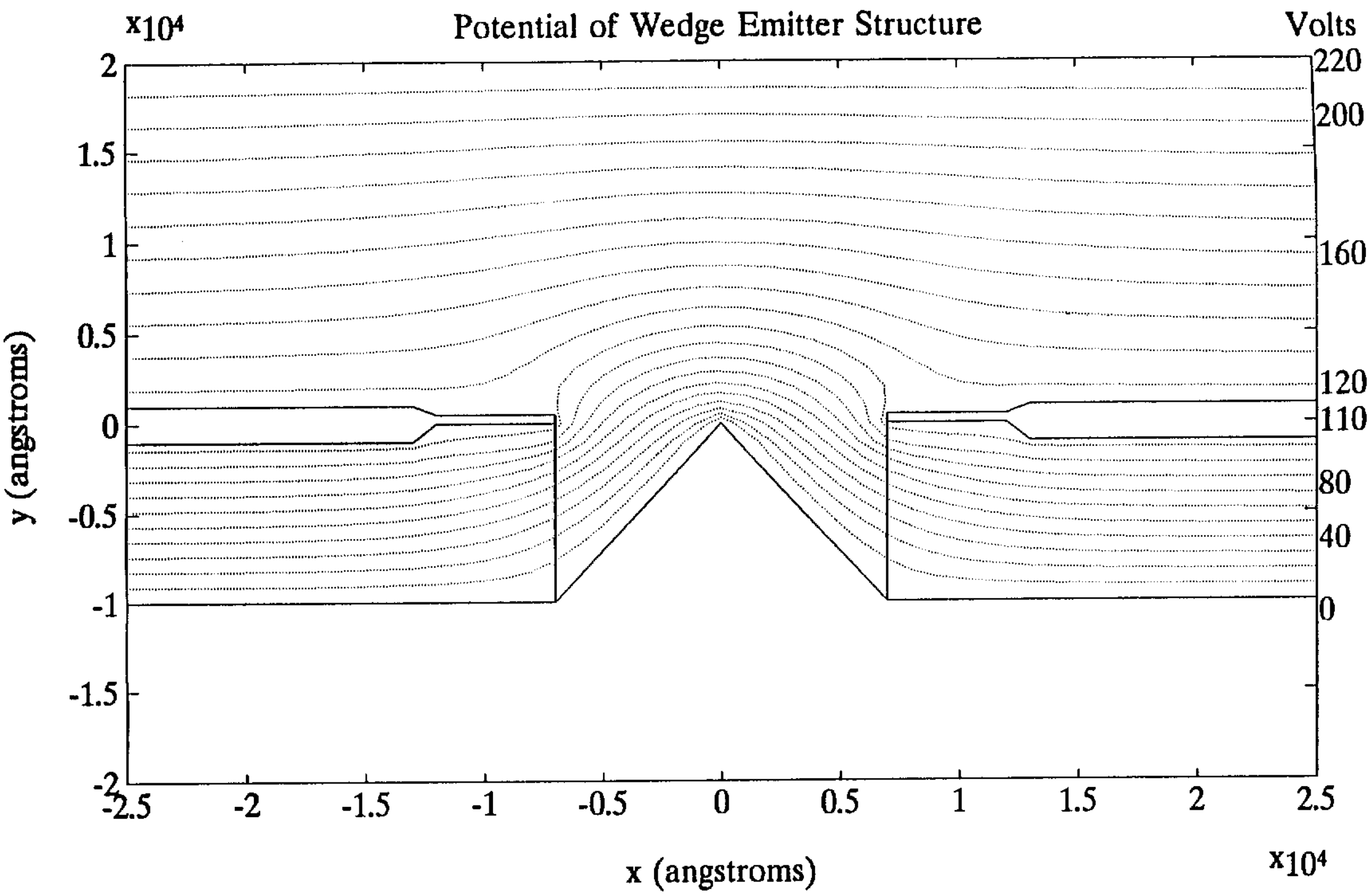

Figure 4: A Gaussian wave packet incident on a potential barrier of fixed width and small height.