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Mechanics in the *Engineering First* Curriculum at Northwestern University*

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A new core curriculum, Engineering First, *has been developed at Northwestern University which integrates a subset of mathematics and science with engineering. The topics chosen for integration in the course are those which most closely relate mathematics to the computer solution of engineering problems: linear algebra and ordinary differential equations. The science of mechanics is emphasized, although other areas such as circuits and communication networks are also considered. The analytical topics are taught in a four course sequence called Engineering Analysis, which begins with the first quarter of the freshman year. The familiarization of students with computer methods in these courses enables us to introduce them in the freshman year to design analysis: the selection of design parameters by analysis. The sequence is currently being taught in a pilot version to 80 students; pre-pilots were taught last year. A program of evaluation has been developed and early results are very favorable. Next year the sequence will be taught to all freshmen.*

INTRODUCTION

ENGINEERING First represents a major revision in the engineering core curriculum at Northwestern University aimed at increasing the student's competence in design and modern engineering methods. Subsets of the traditional mathematics and science curriculum have been integrated with engineering to provide a sequence of courses which introduces the students to problem solving in engineering and spans the gap between theory and application. In addition, these courses provide an opportunity to pose problems in design analysis, which, combined with a two-course freshman sequence in design and communication, give the students an early grounding in design and an understanding of engineering.

As in many other engineering schools, the core curriculum at Northwestern has been almost unchanged for the past three decades. The structure of the curriculum was largely driven by the engineering science thrust which evolved after World War II [1]. In the current curriculum, the first two years consists primarily of courses in mathematics, science, communications and electives. Only a few scattered and disconnected engineering courses are taken by the students in the first two years (see Table 1).

This has several disadvantages:

1. It is difficult to start teaching design early in the curriculum, because a context in which design can be taught is not available.
2. A degree of student dissatisfaction was apparent due to the absence of engineering in the first two years.
3. Skills in computer methods cannot be developed in the first two years.

Many students felt that the heavily mathematics/science-based curriculum provided no understanding of engineering in the beginning and stifled motivation. Thus, students who were uncertain of their selection of an engineering career had little experience in their first two years on which to base their choice.

A highly innovative, fully integrated core curriculum of mathematics, science and engineering was developed at Northwestern in the 1970s. This *Block Program* was jointly taught by faculty in engineering, science and mathematics. The *Block Program* combined all of the core science and mathematics courses and featured sequential, concentrated time blocks on each science and mathematics topic, motivated by the idea that students enjoy focusing on one subject at a time. However, the co-ordination of this program required a level of effort which was not sustainable in a major research university and it was discontinued after a period of 8 years.

Our recent re-examination of the curriculum was motivated by the urgent need to improve our teaching of design and to adapt the curriculum to the dramatically altered work environment of today's engineers. There have recently been many calls by national organizations to improve the undergraduate engineering curriculum [2, 3]. Traditional curricula, including that at Northwestern, provide few opportunities for teaching design until the last two years. Furthermore, the content of the

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Table 1. Current curriculum

	Freshman Year			Sophomore Year		
	Fall	Winter	Spring	Fall	Winter	Spring
Math	Calculus 1	Calculus 2	Calculus 3	Vector Calculus	Series, Linear Algebra	Differential Equations
Physics			Mechanics	Electricity & Magnetism	Waves, Optics, Quantum Mech.	
Chemistry	General Chem.	Inorganic Chem.				
Engineering	Computer Programming		Freshman Seminar	Statics	Major	Major
Other	Elective	Speech, Elective	Writing, Elective	Elective	Elective	Electives

core courses in engineering topics does not reflect the changes in the engineering workplace that have taken place. The *Engineering First* revision has the following objectives:

- introduce design in the freshman year so that a familiarity with the approaches and issues in design can be developed to a higher state of maturity;
- integrate certain parts of mathematics, science and engineering in order to improve the student's understanding of these topics and their motivation;
- improve computer literacy and problem solving on computers by exposing the students to a continuous series of exercises in design analysis beginning in the first quarter of the first year.

To meet these objectives, two sequences of courses were developed: a four-quarter sequence of courses called Engineering Analysis (EA) and a two-quarter sequence called Engineering Design and Communication. The engineering design and communication courses are a novel coordination between the engineering and communications faculty in which the basics of engineering design are taught in conjunction with writing; the description of this course sequence can be found elsewhere [4].

The engineering analysis sequence

Engineering Analysis is a four-quarter sequence which integrates engineering with linear algebra, ordinary differential equations, programming, and mechanics as taught in Physics. Thus it is an integration of selected fields in mathematics and science with engineering. The topics in mathematics which have been integrated are those most closely related to computational applications. The integration of these fields serves several purposes. First, by combining mathematics and science with its applications, the student's understanding and motivation is improved. Secondly, computer applications of these methods are given throughout the courses so that the linkage between computer methods and the basic principles becomes more apparent. Computer applications not only aid in teaching the student how engineering problems are formulated and solved, but provide a means of teaching design analysis: the selection of parameters for a design by means of analysis. Although this is only one aspect of design, it is a critical bridge between the analytical methods which are taught throughout the engineering curriculum and design.

While schools like Drexel University [5, 6], Rose-Hulman Institute of Technology [7, 8] have had considerable success with almost complete integration of engineering with science and mathematics, it was felt that a complete integration was not possible at Northwestern. The additional teaching load in the Engineering School which would result from complete integration would be very burdensome for a faculty heavily involved in research, and our previous experiences at Northwestern with integration based on cross-disciplinary teaching indicated that it was not sustainable. Moreover, there was a strong consensus that all engineering students should be exposed to the intellectual style of science and mathematics.

Some schools, such as Carnegie-Mellon and University of Pittsburgh have instituted year-long freshman courses in the major engineering area. While this is quite appealing, the number of students at Northwestern who are undecided as to their major even towards the middle of the sophomore year made this option unworkable. Furthermore, since a course in a discipline typically does not cover basic material, the number of core courses or advanced courses would have to be reduced to accommodate such major courses.

Therefore in the *Engineering First* curriculum, we elected to integrate the subset of the mathematics courses which is most closely associated with computing and engineering analysis: linear algebra and ordinary differential equations. The science and engineering content of *Engineering First* focuses on mechanics. Mechanics is generally taught in two to three courses in an undergraduate engineering curriculum: the first course in physics and subsequent engineering courses in statics and dynamics (Northwestern had an unusual arrangement whereby statics and dynamics were combined into a single course for most disciplines). Mechanics is an attractive setting in which to teach engineering analysis because it is readily comprehensible to freshmen and many of the methods apply to other fields. Moreover, to give a student an appreciation of the similarities of the mathematical fundamentals of various fields, examples in other fields, such as circuits and telephone networks are included in the EA courses.

This paper describes the four-course EA sequence in the *Engineering First* program. The overall structure of the program is described and then each of the courses is described in detail. The courses which have been eliminated from the curriculum and the topics which have been de-emphasized or removed are discussed. Finally, we describe our experiences with these courses. Two of these courses have been taught in pre-pilot and pilot versions and our experiences with those are described, including feedback from the students. In the coming years, these courses will be required for all freshmen.

CURRICULUM CHANGES

The old and new curricula for the first two years of engineering are shown in Tables 1 and 2. As can be seen, in our old curriculum, engineering was limited in the first two years to three disconnected courses (with one or two courses taught in the chosen major at the end of the sophomore year, depending on the department). The first course is electrical and computer engineering ECE A01, which is a course in FORTRAN programming combined with some numerical methods, such as numerical integration (a C programming course was also an option). Students usually took no engineering courses in the second quarter. In the third quarter, students had the option of taking a seminar related to a major, although only 30% took this option. In the first quarter of the sophomore year, students took a combined course in statics and dynamics, but this course usually involved no computer applications nor any design analysis and was quite unrelated to the course content of the previous two engineering courses.

In the new curriculum, students take a continuous sequence of engineering analysis courses from the first quarter in the freshman year. Skills developed in the first course are used and further developed in the subsequent courses, and the course material is highly interrelated. Computer implementation of methods developed in the courses play a central role, so the students can quickly appreciate how the concepts taught in the courses are used in engineering analysis. Furthermore, to develop an appreciation for design, problems in design analysis are assigned in each course.

In contrast to the original curriculum, computer programming in FORTRAN or C is no longer a requirement. Instead, the emphasis in the EA sequence is on solving problems with computers. For this purpose, programming is taught with MATLAB [9], a higher level language and computationally oriented software package, in the EA1 course and used for all subsequent courses in the sequence. Use of a higher level language dramatically reduces the workload of developing a computer solution, so that more problems can be assigned without overloading the student. In addition, higher level languages include convenient graphical display capabilities which aid the student in understanding the results.

Our decision to eliminate programming in a standard language, such as FORTRAN or C, as a requirement in the curriculum was based on changes in the engineering workplace. Whereas a decade ago, many engineers in industry often programmed in one of the standard languages, this is not the case today. Engineers today use primarily general-purpose software and higher

Table 2. *Engineering First* curriculum

	Freshman Year			Sophomore Year		
	Fall	Winter	Spring	Fall	Winter	Spring
Math	Calculus 1	Calculus 2	Calculus 3	Vector Calculus		
Physics				Electricity & Magnetism	Waves, Optics, Quantum Mech.	
Chemistry	General Chem.	Inorganic Chem.				
Engineering	EA1: Linear Algebra & Programming	EA2: Linear Algebra and Mechanics	EA3: Dynamic System Modeling	EA4: Differential Equations	Major	Major
Engineering		ED&C-1	ED&C-2			
Other	Elective		Elective	Elective	Elective	Elective

level languages. Programming in the standard languages is done almost exclusively by software engineers today and requires many skills which cannot be taught in a single course. Therefore we felt that programming in standard languages should be an elective for students with a special interest in software. Teaching computer applications in a sequence of courses using a language like C or FORTRAN would be prohibitively burdensome to the students.

The first course in the sequence is EA1, which replaces the course ECE A01. The EA1 course also covers the majority of the material from our introductory level course in linear algebra. However, whereas linear algebra is usually taught without many illustrations or applications, in EA1 the applications are an essential ingredient of the course. The concepts taught are developed to the point of engineering applications, so that students can immediately grasp their significance and usefulness.

EA2 partially replaces the first physics course in mechanics and the combined statics and dynamics course. Statics and dynamics are taught in both EA2 and EA3. An important consideration in the design of the EA2 course was to build on the material taught in EA1. Therefore, emphasis is placed on posing problems as linear systems of equations, solving them using MATLAB and visualizing results obtained by varying parameters. To provide a vehicle for the integration of linear algebra and mechanics, matrix methods of structural analysis are presented for simple cases. Students are thus introduced to finite element methods, a tool widely used in engineering. Several design analysis problems are assigned in which design parameters are evaluated by these methods.

EA3 focuses on dynamics, but expands the purview of a typical dynamics course by considering other dynamical systems, such as simple circuits and hydraulic models. In this course, eigenvectors are introduced and immediately illustrated and applied through the evaluation of natural modes and frequencies of a system. The concept of a differential equation is also introduced, although only numerical methods for their solution are used. The analytical solution and the description of the theory of linear differential equations is taught subsequently in EA4.

EA4 is quite similar to a classical introductory course in differential equations except for the addition of substantial material on numerical solutions and many applications to engineering problems. The objective is to immediately give the student an appreciation of the central role of ordinary differential equations in simulation and to illustrate the powers of simulation in understanding the behavior of systems and in design.

The four courses are taken in sequence, so the student completes the sequence by the second quarter of the sophomore year. However, the courses are offered in two rotations to accommodate students that get off sequence. In addition to the EA sequence, in the new curriculum the students take a design and communication sequence in the second and third quarters of the freshman year.

The list of the new courses and the ones which are replaced are given in Fig. 1. It can be seen that the new curriculum, even with the addition of the two-quarter design and communication sequence, does not increase the number of courses, and for those students who took the Freshman Seminar, the number of courses is decreased. A large part of this benefit was generated by the integration of the mathematics with the engineering sciences.

DESCRIPTION OF ENGINEERING ANALYSIS COURSES

EA1: Linear algebra and programming

The goals of EA1 are two-fold:

1. Teach basic linear algebra of square and rectangular systems with an emphasis on applications and computations.
2. Teach computer programming using MATLAB.

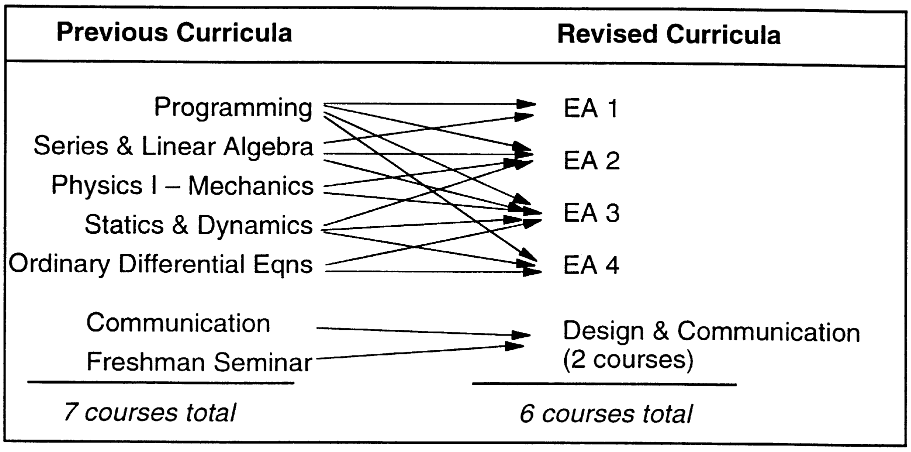


Fig. 1. Replacement of courses by new curricula.

Specifically the course is designed to teach basic linear algebra (not including eigenvalues) with applications and programming methods using MATLAB. The linear algebra material includes matrix notation, the solution of square systems using the LU decomposition, matrix inverses, rectangular systems, subspaces, spanning sets, linear independence and dependence, dimension and rank, projections and least squares. The material is first taught mathematically, and then illustrated by applications. These applications include circuits, heat transfer and fluid flow. Overdetermined systems are illustrated by applications from communication networks.

Concurrently with the mathematics the students are taught and expected to use computation. Students are first taught the concept of computer arithmetic (i.e., words of memory, storage of real numbers using exponents and mantissas and round-off errors). After this background students are taught the basics of MATLAB (scalars, vectors and matrices), arithmetic operations in MATLAB and basic MATLAB functions. They are then able to use MATLAB to compute some of the linear algebra concepts (e.g. matrix products, dot products and transposes). As the course progresses more complicated concepts such as decision and loop structures are stressed. Finally, the importance of modularization (in MATLAB through M-files) is emphasized both in classroom presentations and through the assignments.

The linear algebra and computational material are illustrated by computational exercises chosen from different disciplines, including circuits, heat transfer, fluid flow and communication networks. In addition to the lecture material, a standard linear algebra text and a MATLAB text are used in this course [10, 11], although we will replace Strang with a more introductory linear algebra text next year. As the course progresses, students are expected to do more than just solve specific problems. For example, computational problems involving determining parameters to satisfy certain criteria or determining sensitivity of solutions to different parameters, are given.

We now list specific goals associated with the course. The overall goal of the course is to give the students an understanding of the following topics in the theory of linear algebra:

- matrix and vector notation and operations and recognize equivalence between systems of equations and matrix notation;
- singular and nonsingular systems;
- the mathematics underlying row operations;
- the ideas behind the LU decomposition and the importance of this decomposition in solving systems of linear equations;
- the concepts of inverses;
- the differences between rectangular systems and square systems in particular to illustrate both in general and by example, differences between square, overdetermined and undetermined systems;
- the concept of vector space and subspaces;
- spanning sets, linear independence and concept of basis and dimension;
- the concept and meaning of subspaces associated with a matrix namely, column space, null space, row space and left null space;
- the circumstances for which solutions do not exist and circumstances where solutions are not unique students should understand this both mathematically and in terms of applications (e.g. least squares for overdetermined systems and communication networks for underdetermined systems);
- the concepts of orthogonality and orthogonal decomposition;
- projections and overdetermined systems in the context of least squares;
- how to obtain orthonormal sets (Gram-Schmidt) and why these sets are important.

In teaching the applications of linear algebra, the goal is to develop an understanding in the following basic concepts and ideas:

- the diversity of applications of linear systems of equations;
- round-off error as a general phenomenon associated with computation in general (i.e. not necessarily just for computation of linear systems of equations);
- round-off error and ill-conditioned linear systems, via specific numerical examples (e.g. Hilbert matrix);
- specific applications from circuits (Kirchhoff's laws), heat transfer, fluid flow and communication networks.

Our goal in the programming aspect of the course is to teach:

- decision (i.e. logic) and repetition (i.e. for loops) structures in the context of both formal syntax and applications where these structures have to be used;
- the importance of modularization for both program development and debugging, in particular, both the formal syntax of M-functions and techniques to break up programming projects into small modules which can be developed and debugged individually;
- how to generate graphs and plots in both one and two dimensions, show how they interact with MATLAB code and stress the importance of graphics in interpreting the results of computations;
- students to combine their programming and linear algebra knowledge by working through specific programming projects in computational linear algebra.

An example of a homework problem from this class is given in Fig. 2 and the complete assignment will be available on our website. This figure

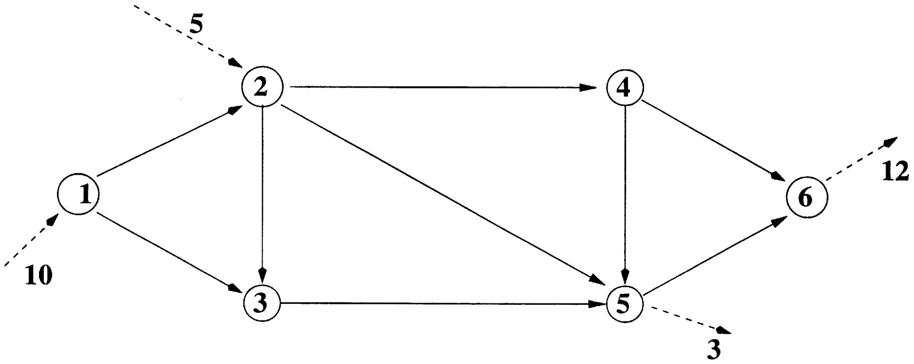


Fig. 2. Example homework problem from EA1: a communications network.

represents a very simplified telephone network where calls originating at city 1 and city 2 need to be routed to city 5 and city 6. The inputs to nodes 1 and 2 (i.e. 10 and 5) represent the number of calls (in thousands) generated in each of these cities. The outputs from nodes 5 and 6 represent the number of calls with these destinations. The problem is how to route the calls between these two pairs of cities. The students analyze the network and reduce it to a system of equations that can be manipulated via linear algebra concepts. The model is then programmed in MATLAB with a cost function to obtain an optimal solution.

EA2: Linear algebra and mechanics

EA2 is the second course in the Engineering First freshman engineering sequence. This course integrates mathematics, mechanics and design analysis and makes extensive use of computer analysis as a tool for exploring problems in mechanics. It also reinforces the methods of linear algebra taught in EA1. A course outline is given in Table 3.

As can be seen from Table 3, the first part of the course starts with vectors, particle dynamics and equilibrium, but also includes programming and numerical solutions of problems not amenable to closed form analytical solutions. Students see how numerical integration of the equations of motion of a particle can be used to solve complex problems readily. It should be noted that students have not had a course in differential equations (this is now covered in EA4) and the exploration of particle motion by numerical methods proves attractive at this early stage (finite-difference techniques for integration of the equations of motion were covered).

In the first design analysis problem, the flight path of a vehicle in the presence of air drag, the students are introduced to several ideas: namely, that analytical solutions of idealized problems (neglecting air drag) can form the starting point for a real problem (including air drag); that numerical solutions are indispensable in real situations but at the same time not too difficult to obtain; that such solutions might have to be obtained through an iterative analysis (the problem requires numerical integration using the so-called shooting method since restrictions on the position and velocity are imposed on the far end of the trajectory).

In the second part of the course, EA2 departs from traditional courses both in content and philosophy. The typical material covered in physics courses at this point include work and energy principles; these however are deferred to EA3 in our sequence. Instead, Newton's laws of equilibrium are extended to rigid bodies of finite dimensions, i.e. the particle idealization is relaxed.

Table 3. Topics Covered in EA2

- Vectors
- Scalars and vectors
- Vector operations: addition, scalar multiplication, dot and cross products; mixed triple products
- MATLAB programming of vector operations
- Kinematics and Dynamics of Particles:
- Displacement, velocity, and acceleration
- Newton's laws of motion for a particle
- Analytical integration of simple motions; rectilinear, circular and projectile motions
- Numerical integration of the equations of motion (forward Euler method):
  - Motion of an electron in an electromagnetic field
  - Projectile motion with air drag
  - Orbital motions
- Design analysis: Determination of launch positions and velocities such that pellets can be shot through air (taking into account air drag) into a slot at a specified height with specified restrictions on the entry velocity.
- Mechanics (Statics) of Rigid Bodies:
- Concept of force and moment equilibrium
- Analysis of rigid trusses, frames and machines
- Numerical solutions: graphical solutions to problems that lead to transcendental equations
- Design Analysis:
  - Device to raise a refrigerator using cables and pulleys
  - Design of simple weight balances
- Mechanics of Deformable Bodies:
- Springs and deformable rods - Hooke's experiment: stress and strain
- Stretching of rods of uniform and varying cross-section
- Systems of rods and springs: statically indeterminate 1D and truss systems
- Matrix methods of analysis of systems of rods and springs
  - Element stiffness matrix for rods and springs
  - Assembly of global stiffness matrix of unconstrained systems
  - Imposition of constraints and applied forces
- Numerical Solutions: Determination of the stresses and displacements of a tapered observation tower under the action of its own weight.

Figure 3: Homework for EA2

Write a MATLAB program to calculate the motion of a charged particle of mass m and charge q that is in an electric field **E** and magnetic field **B** (in later courses you will learn more about electromagnetic fields and the forces they produce) given that the force on such a particle is:

$$\mathbf{F} = q\{\mathbf{E} + \mathbf{v} \times \mathbf{B}\}$$

Plot the trajectories of an electron:

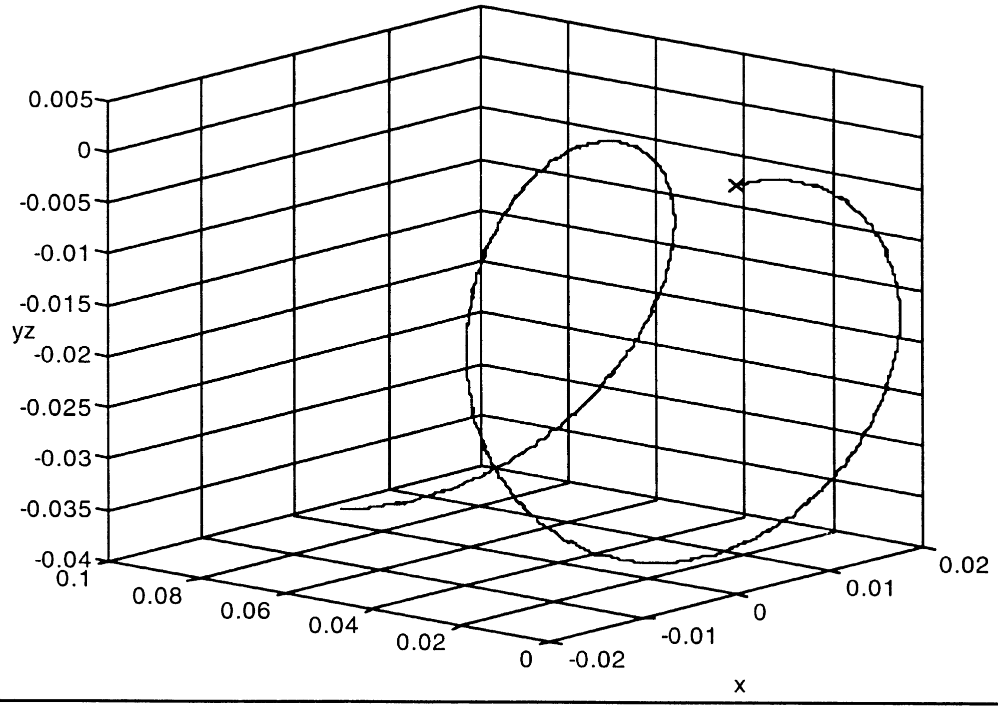
mass m = 9.11×10^{-31} kg;
charge q = -1.6×10^{-19} Coulombs)
that is introduced at $\mathbf{r}(t=0) = 0\mathbf{i}+0\mathbf{j}+0\mathbf{k}$
with an initial velocity $\mathbf{v}(t=0) = 2.2\times10^{7}\,\mathbf{i}\ \mathrm{ms}^{-1}$

for the following cases:

(a) a constant electric field $\mathbf{E} = 15\mathbf{j}$ kN/Coulomb, and no magnetic field $\mathbf{B}=\mathbf{0}$.
(b) a time varying electric field $\mathbf{E} = 15\sin(\omega t)\,\mathbf{j}$ kN/Coulomb where $\omega = 2\times10^{9}\mathrm{s}^{-1}$, and no magnetic field $\mathbf{B}=\mathbf{0}$.
(c) no electric field $\mathbf{E} = \mathbf{0}$, and a magnetic field $\mathbf{B} = 6.8\times10^{-3}\,\mathbf{j}$ kg/Coulomb.sec.
(d) no electric field $\mathbf{E} = \mathbf{0}$, and a magnetic field $\mathbf{B} = 6.8\times10^{-3}\,\mathbf{i}$ kg/Coulomb.sec. Comment on this trajectory obtained (no numerical computation needed for this part)
(e) an electric field $\mathbf{E} = -15\mathbf{j}$ kN/Coulomb, and a magnetic field $\mathbf{B} = 6.8\times10^{-3}\,\mathbf{k}$ kg/Coulomb.sec.
(f) an electric field $\mathbf{E} = -15\mathbf{j}$ kN/Coulomb, and a magnetic field $\mathbf{B} = 6.8\times10^{-3}\,\mathbf{j}$ kg/Coulomb.sec.

Use a time-step of $\Delta t = 1\times10^{-11}$s and a runtime (total duration of each test) of 8×10^{-9}s
Drop your m-files in the electronic drop box. Hand in hardcopy results for (a-f).

Sample Results from Part f:



Motion of an electron in an electromagnetic field

The concept of moment equilibrium is introduced, and analysis of simple rigid trusses, frames and machines is presented, as is typically done in a sophomore engineering mechanics course. Once again, numerical methods are emphasized, including determination of the roots of transcendental equations using the bisection method and/or graphically. The students are assigned simple design analysis problems which involve computer solutions and introduce them to the design of simple mechanical systems.

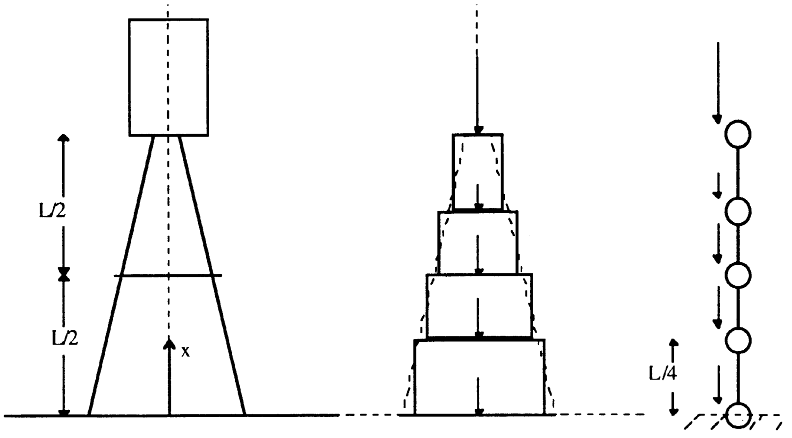
The last part of the course introduces the students to statically indeterminate problems, and forces the students to re-evaluate the limitations of the rigid body assumption. This naturally leads to an introduction to the mechanics of deformable bodies, a topic typically covered in a sophomore course on strength of materials. Analysis of rod/spring systems and simple deformable trusses leads to matrix/finite element analysis (in one dimension) of such systems. The students are shown how this leads to a system of linear equations, and how the method can be implemented in a MATLAB program. A final problem is assigned which requires the students to model a structure of varying geometry and varying loads as a one-dimensional system of rod elements.

In summary, the content of the course is drawn vertically from material typically offered in freshman physics and sophomore engineering mechanics and strength of materials courses. Newton's equations of motion (and equilibrium) form the thread that logically connects the entire material. Within this contextual framework, the course:

- provides the students opportunities for tackling open-ended design analysis problems;
- introduces several powerful methods of mathematical and numerical analyses that have applications outside of mechanics;
- integrates computer programming at every level.

Sample problems.

A typical computer homework problem is given in Fig. 3 as an example of the integration of mathematics, vector mechanics and computer programming. Students were previously required to write a program to determine cross products. (The



The observation tower shown in figure consists of a tapered base of length L=100m whose area varies as $A(x) = A_0 \{1\text{-}0.5x/L\}$ where $A_0 = 1\text{m}^2$. Atop the base sits the observation room. The first half of the tower ($0 < x < 0.5L$) is made of steel of Young's modulus $E_{st} = 2.1\text{x}10^{11}\ \text{Nm}^{-2}$ and density $\rho_{st} = 8100\text{kg/m}^3$ and the rest of the tower is made of aluminum of Young's modulus $E_{al} = 0.7\text{x}10^{11}\ \text{Nm}^{-2}$ and density $\rho_{al} = 2700\text{kg/m}^3$. The obervation room and its contents weigh 50,000N.

Model the tower (without the observation room) as being made of 4 elements of equal length. Let the areas of these elements be the average area of the corresponding tapered section. Model the weights of each segment as being lumped at the corresponding nodes below. The observation room is removed and its weight is assumed to act as shown on the top element. Using this finite element model of the tower, obtain the displacements and the stresses in the tower.

Remark: You can get even better results by *refining* the mesh, that is by using say 8 elements rather than 4. This way, you will be modeling the taper of the tower a little better. Try this if you are adventurous, but you do not have to hand this in.

- This assignment should take you no more than 3 hours. If you find yourself spending more time than this, take a deep breath, relax, talk to your classmates, and call us for help.
- Hand in a hardcopy of your worksheets and results.

Fig. 4. EA2 homework problem: matrix analysis of a tapered tower.

MATLAB code has a built-in cross-product function but this exercise is nonetheless useful in reinforcing students' understanding of programming and the use of determinants.) The problem in Fig. 3 involves particle motion in three dimensions and illustrates some interesting aspects of the motion of an electron in an electromagnetic field. The students are asked to visualize the results graphically. The solution to part (f) of the problem is also shown. Other related homework problems consisted of explorations of orbital mechanics. Here, the students were required to explore the use of time-steps and to comment on their attempts to obtain a convergent solution. The students were also asked to identify various types of orbits (circular, elliptic, parabolic and hyperbolic).

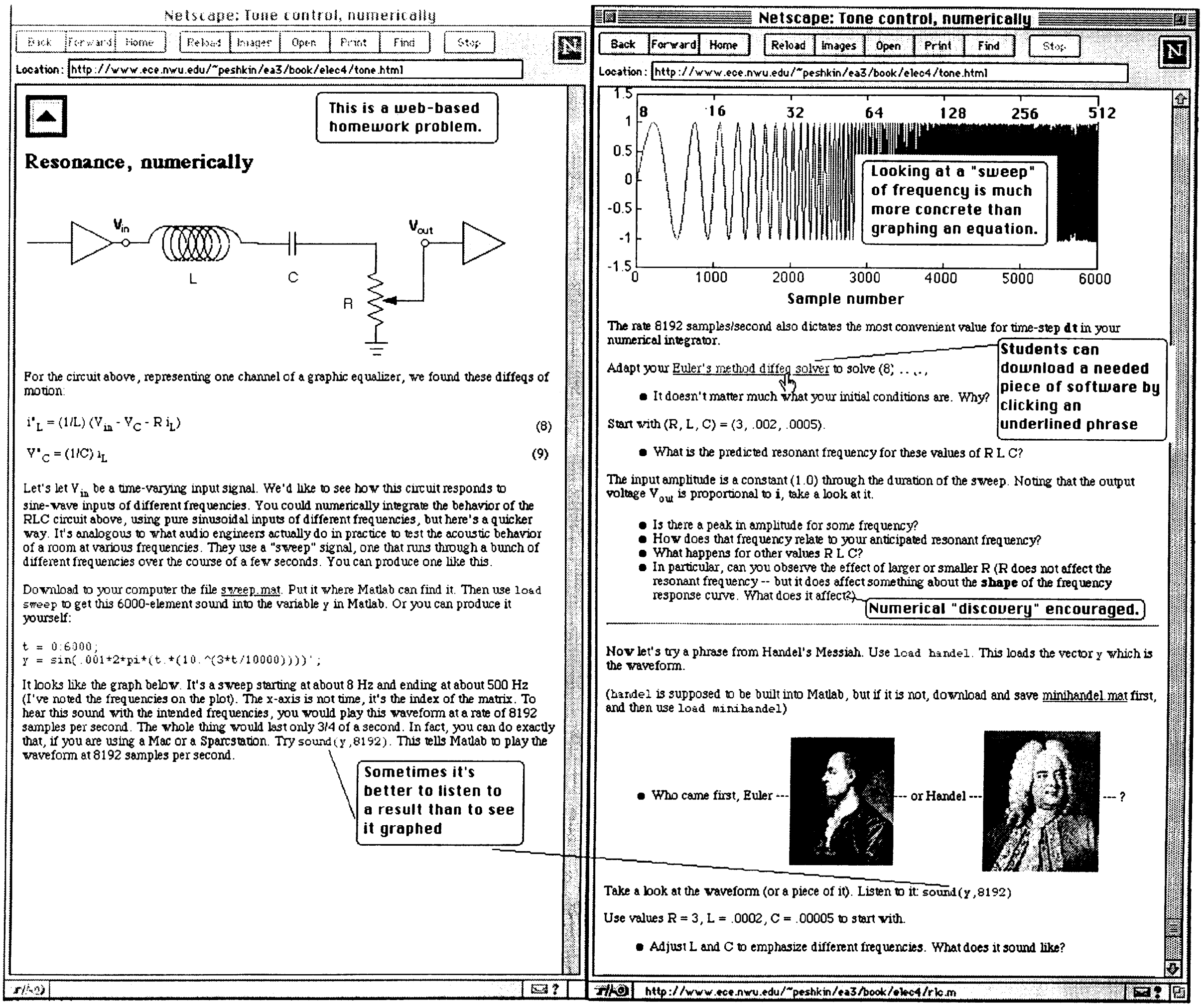
Another computer homework problem involving mechanics, linear algebra and MATLAB programming is given in Fig. 4. Here, the students are asked to suitably modify a MATLAB code to solve problems involving one-dimensional systems of rods and springs. The students gain an appreciation of approximating a complex geometry (essentially a rod with tapered cross-section) as N-segments of uniform cross-section, and they learn how to approximate distributed loads (the weight) as 'lumped' loads at discrete points. Once they cast a real engineering structure into an approximate model, they are required to obtain the stress and displacements through the structure. They are then encouraged to improve upon this solution by refining their model.

Text.

The text used for the first part of the course is *Statics and Dynamics* by Bedford and Fowler [12]. It was chosen on the basis of its readability and its use of numerical methods, which fit in nicely with the philosophy of this course. Supplemental material [13] covering the latter parts of the course was made available to students.

EA3: Dynamic System Modeling

EA3 focuses on the modeling of dynamic systems, the reduction of models to differential equations of motion, and some exploration of the behavior of the solution of those equations. Numerical methods of solution are emphasized by using MATLAB to solve differential equations and visualizing the results.



This is a web-based homework problem.

Resonance, numerically

For the circuit above, representing one channel of a graphic equalizer, we found these diffeqs of motion:

$$i'_L = (1/L)\,(V_{in} - V_C - R\,i_L) \quad (8)$$

$$V'_C = (1/C)\,i_L \quad (9)$$

Let's let V_{in} be a time-varying input signal. We'd like to see how this circuit responds to sine-wave inputs of different frequencies. You could numerically integrate the behavior of the RLC circuit above, using pure sinusoidal inputs of different frequencies, but here's a quicker way. It's analogous to what audio engineers actually do in practice to test the acoustic behavior of a room at various frequencies. They use a "sweep" signal, one that runs through a bunch of different frequencies over the course of a few seconds. You can produce one like this.

Download to your computer the file sweep.mat. Put it where Matlab can find it. Then use `load sweep` to get this 6000-element sound into the variable y in Matlab. Or you can produce it yourself:

```
t = 0:6000;
y = sin(.001*2*pi*(t.*(10.^(3*t/10000))))';
```

It looks like the graph below. It's a sweep starting at about 8 Hz and ending at about 500 Hz (I've noted the frequencies on the plot). The x-axis is not time, it's the index of the matrix. To hear this sound with the intended frequencies, you would play this waveform at a rate of 8192 samples per second. The whole thing would last only 3/4 of a second. In fact, you can do exactly that, if you are using a Mac or a Sparcstation. Try `sound(y,8192)`. This tells Matlab to play the waveform at 8192 samples per second.

Sometimes it's better to listen to a result than to see it graphed

Looking at a "sweep" of frequency is much more concrete than graphing an equation.

The rate 8192 samples/second also dictates the most convenient value for time-step **dt** in your numerical integrator.

Adapt your Euler's method diffeq solver to solve (8) .. ..,

- It doesn't matter much what your initial conditions are. Why?

Students can download a needed piece of software by clicking an underlined phrase

Start with (R, L, C) = (3, .002, .0005).

- What is the predicted resonant frequency for these values of R L C?

The input amplitude is a constant (1.0) through the duration of the sweep. Noting that the output voltage V_{out} is proportional to **i**, take a look at it.

- Is there a peak in amplitude for some frequency?
- How does that frequency relate to your anticipated resonant frequency?
- What happens for other values R L C?
- In particular, can you observe the effect of larger or smaller R (R does not affect the resonant frequency -- but it does affect something about the **shape** of the frequency response curve. What does it affect?)

Numerical "discovery" encouraged.

Now let's try a phrase from Handel's Messiah. Use `load handel`. This loads the vector y which is the waveform.

(`handel` is supposed to be built into Matlab, but if it is not, download and save minihandel.mat first, and then use `load minihandel`)

- Who came first, Euler --- --- or Handel --- --- ?

Take a look at the waveform (or a piece of it). Listen to it: `sound(y,8192)`

Use values R = 3, L = .0002, C = .00005 to start with.

- Adjust L and C to emphasize different frequencies. What does it sound like?

Fig. 5. An example of web-based homework problem for EA3.

EA3 is a heavily computer-based course. The text itself, as well as the homework problems, are on the web. This makes possible a highly interactive text, in which students can download program 'shells', adapt them for their simulated system, and explore system behavior. An example of such a web-based exercise is shown in Fig. 5. In this exercise, students apply what they have learned about electrical components and systems to the circuit shown, which is representative of a graphic equalizer channel; they solve the system numerically via a MATLAB differential equation solver and can then listen to the effect of the circuit applied to a frequency sweep and to an excerpt of Handel's Messiah.

The goal is to learn system modeling across several physical domains (mechanical, hydraulic, electrical), and in each:

- to understand the elements of each domain (e.g. spring, capacitor; or voltage, pressure, force);
- to recognize the elements in real life, so that real systems can be abstracted into ideal systems composed of familiar elements;
- to express precisely the way in which the elements interact (e.g. circuit diagrams, free-body diagrams);
- to reduce the idealized systems to equations, which describe their behavior quantitatively.

The topics covered are:

1. Behavior of the elements; modeling systems of elements; free-body diagrams; masses, springs, and dampers; mechanical rotation; absolute and relative pressure; flow rate; Kirchoff's laws; capacitors, inductors, resistors, batteries.
2. Multiple degrees of freedom; simple harmonic oscillators (example: mechanical and electrical domain); matrix formulation (example: transmission line treated as a 32-element lumped parameter model); numerical solutions to matrix equations; eigenvalues, normal modes.
3. Constants of the motion; energy/work in mechanical systems; elastic and inelastic collisions; energy/power in electrical systems; energy in hydraulic systems; linear momentum, collisions and angular momentum in mechanical systems.

EA4: Differential equations

EA4 is a one-quarter course on ordinary differential equations (ODEs) and the final course in the Engineering Analysis sequence. In many ways, a course on ODEs is the perfect setting in which to summarize and solidify the concepts that have been developed throughout the previous three courses because of the many examples of engineering systems that can be described using differential equations. This has already been recognized at many universities, of course, since a large number of ODE courses are heavily populated with engineering students and the accompanying textbooks are filled with numerous applications from science and engineering.

Nevertheless, ODE courses are often considered by students to be 'cookbook' in that much of the curriculum appears to be driven by solution of equations for which exact, analytic answers can be found. As a result, the course material often comes across as a recipe: for one type of equation, use this method; for another type, use this one, and so on.

Analytic solutions are extremely important, of course, but in practice it is no longer true that an analytic solution is always the best answer. Often, a good numerical solution will be more illustrative than a complicated analytic answer. To verify computed solutions, however, it is important to have some qualitative idea beforehand as to how a solution is expected to behave, and this is increasingly the role of analytic solutions.

EA4 is designed around a three-tiered approach combining:

- Exact (analytic methods): classification of ODEs; separable equations; integrating factors; second-order linear equations; constant coefficient equations; forced equations; boundary value problems; first-order systems; nonlinear systems.
- Qualitative and approximate methods: direction fields; critical points and stability; linearized stability; phase plane methods; perturbation methods; bifurcation theory.
- Numerical solutions: Euler, improved Euler and Runge-Kutta methods; stiff equations; implicit methods; graphical representation.

Students will be taught to understand the advantages and disadvantages of each solution method and when each is likely to be appropriate. In addition, students will learn how to combine solution techniques to gain a better understanding of a solution's behavior. A differential equation textbook will be used for this course [14], with several other texts as reference sources [15, 16].

Analytic solutions, for example, will be used to elucidate the basic theory and to explain what one should expect for more complicated problems when numerical solutions are used. Time will be devoted to non-dimensionalizing or scaling equations and how to identify terms which are small and easily neglected, or are large and which might cause problems when numerical solutions are attempted (i.e. stiff equations). The concept of perturbation methods will be introduced as a method for finding corrections when small parameters are present. For nonlinear equations, critical points and their stability, and qualitative techniques such as phase line and phase plane methods will be discussed. Bifurcation concepts will be introduced to explain how solutions change as parameters are varied.

MATLAB will be used to provide the numerical solutions and the graphical representation of results. In addition, various numerical solution methods (i.e. forward Euler, improved Euler, Runge-Kutta, etc.) will be explained. Implicit schemes for handling stiff equations (e.g. those arising in chemical reactions) will also be discussed.

Throughout EA4 problems examples from real-world applications will be used to illustrate the concepts. Considerable discussion will be included regarding the principles behind the design of the ODE models of physical systems and the usefulness of differential equations. Some of the topics which can be included are:

- heating and cooling
- growth and decay
- birth and death processes (elementary queuing theory)
- mechanical vibrations and damped oscillations
- forced vibrations and resonance
- electrical circuits
- nonlinear mechanical systems
- chemical reactions.

As a specific example, a simple model of the oscillations produced in a multistory building by an earthquake can be constructed by connecting masses using springs, as shown in Fig. 6. Students will first discuss the pros and cons of such models. (How good is the mass-spring model likely to be? Is it reasonable to consider only horizontal displacements? What effects have been left out?) Students will then solve the problems using different methods, and will discuss the advantages and disadvantages of each method (e.g., expanding in the natural eigenmodes of the system gives better conceptual information but looking for periodic solutions directly is more practical). These problems will be followed by open-ended design analysis questions (e.g. how one would build an earthquake damping system to protect the building).

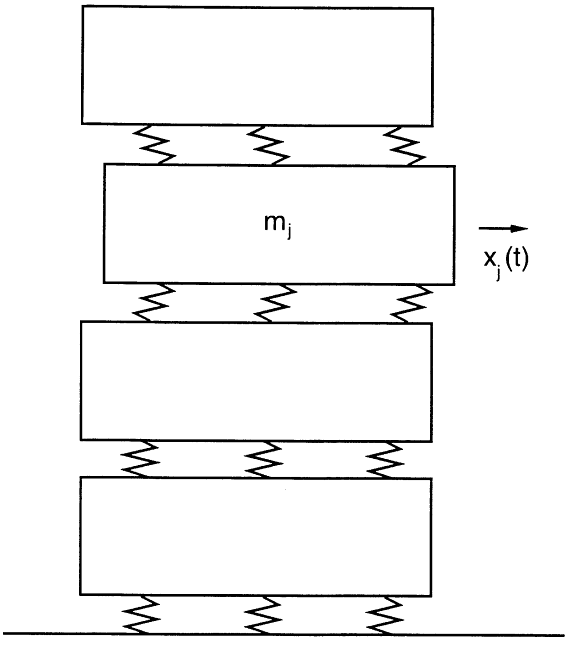


Fig. 6. Homework from EA4, modeling oscillations in a building due to an earthquake.

Web and network use

Teaching *Engineering First* has been helped immensely by use of the Web throughout the courses. In addition to homework problems and textual material on the Web for several of the EA sequence, an electronic conference system dedicated to the engineering analysis sequence has been set up and used to communicate with the students. Faculty and teaching assistants involved in the course (as well as some faculty interested in seeing this resource in action) and all students in the course have access to the conference. Areas (or channels) for general class discussion are provided and specialized areas for discussion of homeworks are also available. Participants can post messages, comments and questions to the group in e-mail style formats, or alternatively can chat in real time with other participants who are logged on. Group discussion can be held and private communication (messages or chat) with individuals can be held. An especially useful feature of the conference is that documents (such as a sample Matlab program for direct use or modification by students) can be posted for the students to download and a special folder (drop-box) is provided for students to turn in their completed programming assignments. These programs can be accessed and tested by the teaching assistants.

The general consensus on this type of conference facility is that it is extremely useful and will likely be increasingly used in other courses not part of the present curriculum development. The conference provides a valuable means of obtaining timely feedback from students as the course progresses (as the they give vent to their thoughts on the difficulty or otherwise of an assignment, for example) and, consequently, problems can often be nipped in the bud.

The *Engineering First* website, www.engfirst.nwu.edu has been used in the pilot courses and will be further developed and even more heavily used in the full implementation of *Engineering First* next year. The website contains both general information on the curriculum (of interest to prospective students, parents, colleagues at other universities) as well as course material for use of the students in the classes. Use of the website for supplementary text material, homework problems, and examples has proven extremely useful, both for the faculty and the students.

IMPLEMENTATION AND EVALUATION

The first two EA courses were first taught as pre-pilots in the academic year 1995–6. These pre-pilot classes were taught as special sections of the corresponding engineering courses in the original curriculum. The classes were designated as 'special sections with computer enrichment'. The students were self-selected and there was considerable interest in participating in this experiment. These classes enabled the instructors to develop and refine the computer assignments which are a key part of the EA courses and to test the pedagogical soundness of the material. The response of the students was strikingly favorable, which provided a major impetus for proceeding with the development of the new courses.

In 1996–97, the entire sequence of EA courses is being offered as pilots to a group of 80 students. These students were selected by a lottery after indicating an interest in taking this curriculum; we did not have enough slots to accommodate all students who were interested. The students were subdivided into two sections of 40 taught by different instructors. The two instructors collaborated closely to organize the syllabi and develop additional new material.

In 1997–98 all incoming freshmen will take the new curriculum. The Northwestern freshman engineering class typically consists of about 320 students, so eight sections of the engineering analysis courses will be offered. Although going to a full-scale implementation immediately after the pilots limits the time and iterations to tune these courses, a continuation of the pilots phase was deemed undesirable because of the resulting inability of advanced courses to take advantage of the new material and the difficulties of managing a dual-track curriculum. Revisions of the courses will be carried out in the summer quarter by teams led by the instructors of the pilot courses.

The implementation of these courses will require substantial additional resources. While the number of courses taken by freshmen has not been changed, two courses have been shifted from the College of Arts and Sciences. Since all freshmen will be taking these courses, the combined effect of the engineering analysis and engineering design & communications courses has been to add markedly to the teaching load of the engineering faculty.

In addition, the shift of part of the freshman training to the engineering school requires a significant increase in physical resources. While Northwestern requires that students have access to a personal computer and most students meet this requirement by purchasing their own computer, a series of computer-intensive courses requires substantial computer laboratories where students can be instructed and where they can go with questions. Although we have primarily invested in workstation laboratories in the past, it has become clear that PCs are now more appropriate in these laboratories. Since students do most of their work on their own PCs, laboratories using workstations are quite awkward. The operating system and the look and feel of many software packages differs between PCs and workstations, which hampers the students' learning. Furthermore, the speed and software availability for PCs is now on a par with workstations. In view of the much lower costs of the hardware and software associated with PCs, their advantages look overwhelming. We believe a similar shift will gradually occur in the engineering workplace, so familiarity with workstations will be of decreasing importance. Some of the advanced courses will continue to use workstations.

For purposes of evaluating and tuning these courses, an extensive program of concurrent evaluation has been instituted. The program consists of questionnaires filled out by students, discussion sessions with the students, and testing administered to students in both the pilot courses and a control group in the traditional curriculum.

Prior to beginning the freshman year, all students were given a questionnaire dealing with general expectations and attitudes. At the end of the freshman year, a more comprehensive questionnaire to examine student satisfaction, their perceptions of course difficulty and workload and their evaluations of the courses they have taken will be administered. By comparing feedback from students who took the pilot courses with those who took the regular curriculum, we hope to measure how the new curriculum meets the student's perceived needs.

As part of the evaluation program, at the midpoint of each course, a meeting is held with the students in which the instructors are not present. The objective is to find out whether the level of the material matches the abilities of the students, the intellectual challenge and interest of these courses, and the suitability of the workload. Such dialogues are very useful in ascertaining weaknesses in a course. For example, we found out quite early that the original text in EA1 was felt to be too difficult. Weaknesses in organization and motivation are also intensely discussed in such sessions. These meetings with the students are also very useful in determining the merits and shortcomings of these courses. In general, students have been very receptive to the integration of mathematics with engineering applications by computer. For the majority of engineering students, this approach increases their interest in the mathematics, for they can appreciate its importance when they see it applied.

The evaluation of the impact of the new courses on learning poses a difficult challenge. One important skill which is stressed by the new curriculum, the ability to develop computer models for design analysis and relate mathematical tools to computer methods, cannot be readily assessed by a test. However, one of our key goals was not to overlook the objective of the core courses: to provide a firm understanding of fundamentals. Therefore, we intend to administer similar test questions to the students taking the pilot version and the old curriculum at several points in the first two years. These questions will be administered as part of regular examinations, since the use of tests which do not count towards a grade is often misleading because of the diminished motivation and the burden on the students.

In addition to this, a standard questionnaire is administered at the end of each course which measures the student's perception of the quality of the course, its organization and the instruction. These surveys were designed and given to the students at the end of the courses along with the usual teaching evaluation questionnaires. In the pre-pilot and pilot EA classes taught thus far, the responses from students have been overwhelmingly positive. The students had friends enrolled in the 'standard' curricula, yet the response to the key question 'I would still register for this special section if I could start the quarter all over again,' was a 3.4/4.0 for EA2 pre-pilot. For the EA1 pilot class, students agreed that the 'course provided a good integration of linear algebra and computing' 4.6/6.0. The students also found the design portions of the computer assignments useful and interesting and perceived learning MATLAB as useful with rankings of 3.1/4.0 and 3.2/4.0 in EA2. There were many helpful comments from students in the written portion of the forms for all the pre-pilot and pilot courses taught thus far. A few selected student responses are:

- 'I ... liked the MATLAB homework as an alternative to the other more mundane homework.'
- 'I learned the most from the design projects.'
- 'The course helped me learn, however ... a lot of extra effort was put into this class the programming was especially difficult as I had no experience.'
- '... helped me learn how linear algebra can be used in engineering.'
- 'I learned how to think systematically and how to solve real life problems. This class was highly beneficial. It was most excellent.'
- 'I learned a lot, but in my mind it took too much effort. Strang [textbook] was too vague and obscure.'
- 'I learned a lot—a great crash course into the future!'

The most important effects of the program will become apparent as the students take their courses in the junior and senior years and go on to positions in engineering and other fields. When the current class enters the last two years of the engineering program, instructors will be able to evaluate the adequacy of the preparation and the problem-solving and design skills of the students. While we do not plan to formally measure these changes, meetings will be set up with faculty to share their experiences and to determine any shortcomings or drawbacks of the program.

Evaluation after graduation is largely anecdotal, although it is often very revealing. Unfortunately, this feedback is only available many years after the start of a new program. The Engineering School polls all graduates three years after graduation. Questions aim to identify the strengths and the weaknesses of the engineering curriculum. Graduates are asked which courses and material they have found most useful in their work environment and what skills are inadequately developed. They are also asked to rate the usefulness and the intellectual challenge of courses they have taken in their undergraduate program.

Thus, while our evaluation is primarily qualitative, we should have substantial material by which to evaluate this program. Our attitude towards this program is that it is a continuous experiment. If feedback from the students and faculty indicates that something is not working, the preparation is not adequate, or new material is desirable, we will revise the courses accordingly.

DISCUSSION AND CONCLUSIONS

The *Engineering First* program at Northwestern University has been developed to effect a partial integration of mathematics and science with engineering and to facilitate the development of design skills early in the curriculum. A series of courses have been designed that integrate linear algebra and ordinary differential equations with mechanics and engineering. These courses enable the applications in engineering to be combined with the mathematics; thus the application of mathematics to engineering problems can be illustrated at the same time it is taught. In addition, a two-course sequence for freshmen that combines design with communication has been developed; this is described elsewhere [4]. These courses should provide students with a better foundation in modern engineering methods and design, starting from the freshman year.

The curriculum is currently in a pilot stage in which it is being taken by a group of 80 students, but it will be taken by all freshmen in the coming year. We have organized an intensive program of student feedback and a moderate program of testing to evaluate these courses. In particular, we have carefully watched the tendency of faculty to overreach in designing new courses by adding too much material or overburdening the freshmen. Nevertheless, we have not avoided this problem completely and will have to tune the courses further.

While a substantial part of the content of these courses is computer-oriented, many important concepts in mathematics and science have to be taught as part of these courses. While the computer implementation gives the opportunity to show the link between theory and application, there is a persistent danger that insufficient stress will be placed on the theory. By carefully evaluating the students' competence at various stages of this program and by stressing to the faculty the need to thoroughly teach and drill the fundamentals, we believe that this integrated program will improve the students' understanding and knowledge of the fundamentals.

It should be pointed out that while these courses look markedly different from existing core courses, in a sense the changes have been evolutionary rather than revolutionary. Three of these course are built on traditional core courses and standard texts are available for teaching the bulk of the material. The supplementary material is provided to the student through notes which are posted on the Web. Thus the course content did not need to be developed from scratch. Instead the new courses represent mostly the rearrangement and enrichment of existing core courses.

We hope that the impact of these courses will echo throughout the entire curriculum: the midpoint of the sophomore year, students will have a solid background in use of mathematical and numerical models for engineering problems. In addition, the design analysis aspect of the courses will start the students on the learning process of how to reduce a complex real-world problem to its essential elements necessary for a model and solution. Since they have learned material in an integrated fashion, they should be ready to integrate advanced subjects such as fluids and heat transfer, where they can tackle interesting design problems. Other upper level courses will be able to benefit from this preparation: for example, the Strength of Materials class can now incorporate introductory material on finite elements, since matrix methods in one dimension were introduced in EA2 [17]; in the junior chemical engineering course, Kinetics and Reactor Engineering, a project for reactor design involving solution of differential equations will be readily understood and tackled by the students. Moreover, individual departments may be able to begin some of their major courses earlier than is now possible.

A rewarding part of this experience is the enthusiasm that has been rekindled among faculty when challenged to develop new courses and teach students with new approaches. The faculty have devoted substantial time to this effort. Furthermore, their enthusiasm has spread to the students. The students' ratings of these courses have been very high and the entire process has been invigorating.

Engineering education is now at a crossroads: while the workplace changed dramatically, engineering education was almost static for the past three decades. It is clear that the content of our core courses must be changed to better prepare our students. In particular, with the increasing emphasis of employers and ABET on design, a foundation for design must be built beginning in the very first year. The engineering analysis courses described here are part of a two-pronged effort at Northwestern for meeting these needs. The students' response to our initial effort has been very favorable. Although we realize that adjustments will have to be made, the needs of students and employers will be better met by a program which teaches engineering skills from the first year.

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REFERENCES

1. L. E. Grinter, 'Report on Evaluation of Engineering Education,' *Int. J. Engr. Educ.*, (1995) pp. 25–60.
2. J. Harris, E. M. DeLoatch, W. R. Grogan, I. C. Peden, and , J. R. Whinnery, 'Journal of Engineering Education Round Table: Reflections on the Grinter Report,' *J. Engr. Educ.*, **83** (1994), pp. 69–94.
3. K. S. Pister, *Engineering Education: Designing an Adaptive System*, National Academy Press, pp. 79.
4. P. Hirsch, J. E. Colgate, B. Shwom, D. Kelso, J. Anderson and G. Olson, *Engineering Design and Communication: Jump-starting the Engineering Curriculum*, Proceedings of the 1998 ASEE Annual Conference, Seattle, WA.
5. R. Carr, D. H. Thomas, T. S. Venkataraman, A. L. Smith, M. A., Gealt, R. Quinn and M. Tangel, Mathematical and scientific foundations for an integrated engineering curriculum, *J. Engr. Educ.* **84** (1995), pp. 137–150.
6. Drexel University, *E4: Enhanced Educational Experience for Engineers—Summary Report*, Philadelphia, PA, Drexel University Press.
7. Rose-Hulman Institute of Technology; http://foundation.ua.edu/http://www.rose-hulman.edu/Users/groups/Assessment/Public/html/IRA/index.html, 1997).
8. G. J. Rogers, and B. J. Winkel, Integrated, First-Year Curriculum in Science, Engineering, and Mathematics at Rose-Hulman Institute of Technology: Nature, Evolution, and Evaluation, *Proceedings of the 1993 Conference of the American Society for Engineering Education*, (1993).
9. The Mathworks Inc., (http://www.mathworks.com, Natick, Mass., 1995).
10. D. Etter, *Engineering Problem Solving with MATLAB*, Simon & Schuster, Upper Saddle River, NJ (1997).
11. G. Strang, *Linear Algebra and Its Applications*, Harcourt Brace Jovanovich, New York. 3rd ed. (1988).
12. A. Bedford and W. L. Fowler, *Statics and Dynamics*, Addison Wesley, New York (1995).
13. T. Belytschko, C. Brinson, B. Moran and S. Krishnaswamy, *Introduction to Finite Elements (Matrix Methods),* for EA2, Evanston, IL, supplementary notes (1997).
14. C. H. Edwards, and D. E. Penney, *Differential Equations: Computing and Modeling*, (1995).

15. M. Braun, *Differential Equations and their Applications*, Springer-Verlag, New York. 3rd ed. (1983).
16. J. C. Polking, *Ordinary Differential Equations Using Matlab*, (1993).
17. L.C. Brinson, T. Belytshko, B. Moran and T. Black, Design and computational methods in basic mechanics courses, *J. Engr. Educ.*, April, pp. 159–166 (1997).

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