Learning the Methods of Engineering Analysis Using Case Studies, Excel and VBA - Course Design

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Abstract

Methods of Engineering Analysis, EAS 112, is a first year course in which engineering and applied science students learn how to apply a variety of computer analysis methods. The course uses a "problem-driven" approach in which case studies of typical engineering and science problems become the arena in which these analytical methods must be applied. A common spreadsheet program, such as Microsoft Excel, is the starting point to teach such topics as descriptive statistics, regression, interpolation, integration and solving sets of algebraic, differential and finite difference equations. Students are also introduced to programming fundamentals in the Visual Basic for Applications environment as they create the algorithms needed for the analysis. In this programming environment students gain an understanding of basic programming concepts, such as data types, assignment and conditional statements, logical and numerical functions, program flow control, passing parameters/returning values with functions and working with arrays.

EAS 112 is a stop along the *Multidisciplinary Engineering Foundation Spiral*[1] in the engineering programs at the University of New Haven. A typical student will take the course in the second semester of the first year. Certain engineering foundation topics will appear in the assigned problems and case studies, contributing to students' understanding of areas such as electrical circuits, mass balances, and structural mechanics. At this point along the spiral curriculum students are given most of the equations needed to analyze the case study problems, but they are responsible for development of the algorithms and implementing these in the spreadsheet and/or programming environment.

This paper will provide a detailed discussion of the course design along with several examples of the case studies used. Results of an initial pilot offering of the course will be discussed, including an assessment of student's progress and their opinion of the course.

Introduction

Faculty of the School of Engineering and Applied Science (SEAS) at the University of New Haven (UNH) have developed a comprehensive curriculum for the first two years of our engineering programs. This program includes four new Engineering & Applied Science (EAS) courses in the first year. The course of interest in this paper, Methods of Engineering Analysis (EAS 112), is required of all engineering students in the second semester of the freshman year. At that point students should have completed two EAS courses in the previous semester: EAS

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107, Introduction to Engineering and EAS 109, Project Planning and Development, as well as one semester of General Chemistry, Calculus I (or precalculus) and English Composition.

For most students, EAS112 replaces a combination of spreadsheet applications (1 credit) and C programming (2 or 3 credits). Engineering students in several majors at UNH have had difficulty with the C programming courses, and very few have chosen to use C when solving problems in subsequent engineering courses . Our experience in this regard is consistent with what has been reported by others in the literature, as discussed later in this paper.

Broadly stated, the goal of EAS112 is to help students develop skill in using computer programming tools to solve problems from a variety of engineering disciplines. This can be broken down into four primary objectives:

> To develop proficiency in the design of spreadsheets and related programming tools, such as Visual Basic for Applications
>
> To provide an understanding of programming fundamentals
>
> To gain experience in solving engineering problems using spreadsheets & programming
>
> To enhance the understanding of basic engineering concepts in a variety of areas

The engineering concepts indicated in the fourth objective above are basic principles from areas such as statics, electric circuits, material balances, thermodynamics and fluid mechanics. These will appear in the examples, homework and projects used in the course to provide applications of various solution methods and programming concepts. Related concepts were introduced during the previous semester in the Introduction to Engineering course (EAS107) thus providing a basic level of understanding of these concepts on which to build. This is part of the *Multi-Disciplinary Engineering Foundation Spiral* that forms the backbone of our first two years.

Previous Work

Many engineering programs are struggling to determine the best choice of a computer course for their students. While traditional programming courses in languages such as C, Fortran and Pascal are still widely used, a number of schools are turning to spreadsheets and mathematical packages, such as Mathcad and Matlab. In considering how to prepare our students, consideration of industrial trends is important. Recent surveys of practicing engineers indicate very heavy use of spreadsheets by engineers in industry. A recent survey by the CACHE (Computers and Chemical Engineering) organization [2] indicates that 98% of respondents use spreadsheets, while only 38% reported that they write programs at work. A majority of those surveyed, however, indicated that their employer expected them to be competent in a programming language (73%). When asked about which language they recommended, Visual Basic garnered 33%, "does not matter" was selected by 28% and C++ by 21%. The remaining 17% was spread among 6 other choices (Java, C, Fortran 77, Pascal, Fortran 90 and "others"). Thomas[3] reports similar findings for Mechanical Engineers in industry.

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In the academic arena, Jones[4] reports on a lack of use of computers in engineering science courses. While computers are probably used more extensively in upper-level courses, this is often in the form of specialized design packages in various disciplines. Thus there is a gap in academic computer usage for generalize solution of engineering problems. In many cases, students learn a programming language as freshmen, but do not use their programming skills routinely to solve problems in their early engineering courses.

A number of authors have proposed the use of spreadsheets or mathematical packages rather than a programming language. Bjedov and Andersen[5] propose the use of Matlab to teach basic computer programming logic as well as to provide students with a way to develop computer solutions for engineering problems. The authors claim that it takes considerably less time for a student to learn enough to be able to write a useful computer program with Matlab, compared to using Fortran. Herniter, et. al.[6] also suggest the use of Matlab to teach basic programming concepts. Martin[7] suggests the use of a Excel with Visual Basic in a freshman Operations Research course for teaching basic programming topics (labels, values, formula) through advanced topics (eg., structured programming). He points out that use of a spreadsheet makes the abstract nature of computer data storage and handling less "invisible" to students, and thus easier to comprehend.

For many engineering disciplines, is should be possible to prepare students for industrial practice while meeting academic expectations for an understanding of programming concepts by using a spreadsheet in combination with Visual Basic. This software combination allows students to quickly develop the ability to create practical computer models, as required in industry. In addition, EAS 112 should provide a strong background for students who will go on to study another programming language.

Course Structure and Content

Methods of Engineering Analysis was developed to provide engineering students with a significant exposure to spreadsheets and programming concepts in the context of engineering problems drawn from a variety of disciplines. Members of the multidisciplinary development team as listed in Table 1.

Table 1
EAS 112 Development Team

Faculty Member	Discipline
Michael Collura (team leader)	Chemical Engineering
Bouzid Aliane	Electrical Engineering
Steve Ross	Mechanical Engineering
Greg Gibson	Computer Science

The course negotiated the UNH academic approval process in the Fall of 2003 and was adopted

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by all the engineering programs. A pilot offering of the course is scheduled for the Spring 2004 semester.

The catalog description is given below:

> Prerequisite Courses: M 115 (precalculus), a laboratory science course; co-requisite: M 117 (Calculus I). Students will be introduced to typical problems encountered in various branches of engineering and will gain experience using computer tools to solve these problems numerically. This course will require extensive use of a spreadsheet program and the development of programming fundamentals. Topics include simple statistical methods, logical and numerical functions, solving sets of algebraic, differential and difference equations, regression, interpolation, integration, data types, assignment and conditional statements, program flow control, passing parameters, returning values with functions, arrays. 2 meetings per week of 2 hours each, 3 credits.

Prerequisite and co-requisite courses are listed in the catalog description , however, of more interest here are the topical prerequisites expected of students taking the course. These are listed in Table 2.

Table 2
Topical Prerequisites for EAS 112

Math	algebraic techniques, such as solving sets of linear equations, graphing of data, functions, including linear, polynomial, logarithmic, exponential, sinusoidal.
	Co-requisite topics include familiarity with derivatives and the concept of integration
Science	accuracy, precision, significant figures, units and dimensions, basic principles of matter and energy

Students completing the course are expected to demonstrate the following abilities:

- to use computer tools and programming to solve engineering problems which include systems of linear and non-linear equations, simple differential equations, finding roots of equations and finite difference methods.

- to represent and analyze data sets using appropriate graphical methods, descriptive statistics, linear and non-linear regression and interpolation techniques.

- to demonstrate an understanding of common computer data types, such as character, integer, floating point & boolean.

- to write and use stand-alone functions which accept parameters and return data.

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- to develop and implement computer algorithms which include features such as arrays, mathematical and logical operators, built-in and user-defined functions, assignments and conditional statements.

- to apply iterative methods to solve engineering problems, including the development of programs which use loops and program other flow control features.

Course Strategy and Modality:

The course will use a problem-driven approach employing case-studies to set the stage for applying particular computer analysis techniques. An engineering or scientific situation will be presented, the mathematical description of this situation will be provided in the form of a set of equations, data tables or similar information. The computational method will then be introduced and applied to the problem. Students will be asked to consider variations on the application which use the techniques of interest and to apply the techniques to other, unrelated applications.

Students will maintain a notebook or portfolio throughout the course to compile their own reference manual on the techniques used. This will be evaluated periodically. This portfolio will be part of the Student Handbook of Engineering Practice that they will compile as they move through the set of freshman and sophomore EAS courses. In addition to the techniques recorded in the handbook, students will add to the sections on engineering science topics, such as statics, circuits, mass balances, thermodynamics and fluid mechanics. Entries will include terminology, basic equations and major concepts. The handbook provides continuity across the set of EAS courses to better prepare the students for further study of these topics.

The course will meet for 2 periods per week of 2 hours each (1 hr, 50 min). Meeting will be a combination of interactive lecture, recitation, occasional lab work. Some team projects will be used (extended homework problems). Students will submit a short memo with each homework assignment and will be asked to give a couple of oral presentations. The classroom used for this course should be equipped with student computers (2 students per computer) as well as with a projection system for the instructor's computer. Some provision for simple laboratory work would be an asset, but not a necessity as long as other lab facilities could be used occasionally.

Content Outline

Table 3 lists the topics planned for a pilot offering of EAS 112 during the Spring 2004 semester. This will be the initial offering of the course.

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Table 3 Topical Matrix for EAS 112			
Analysis methods	Programming Topics	Specific to Excel & VBA	Engineering Examples
Generate meaningful plots from data sets, including linear and logarithmic axes	Data types and data storage, binary system, bits, etc	Plot types, formatting and labeling, grids, axes, trend lines, relative / absolute addresses, defined variables	Calibration of a flowmeter,
Use descriptive statistics to analyze data, such as mean, median, variance, standard deviation, statistical tests		Excel statistical functions	Quality control data - are specifications met? Analysis of marketing data.
Use regression to obtain correlations between variables (linear, polynomial, etc.)	mathematical and logical operators and common built-in functions, loops in VBA	Excel regression routines, single and multiple independent variables, error analysis	Correlation of vapor pressure data, chemcial reaction rate data analysis
Table look-up methods and interpolation, including non-linear methods	Functions, parameters, return values		Use of steam tables, estimation of physical properties from tables
Solve systems of equations with multiple unknown variables, both linear and non-linear, including solvability		Excel functions, including solver, lookup, statistical	Set of material balance equations, RC circuit equations, control valve & pump sizing
Find roots of equations	program flow (logic) & iteration (and recursion)	Excel Solver, with buttons	Stability analysis of a control system
Optimization methods, engineering economics	Assignment and conditional statements	Excel Macros	Minimizing capital cost for pipeline with pump,
Finite difference equations	Arrays		heat conduction problem
Solve simple differential equations			filling/emptying a bathtub, charging a capacitor, heat loss from hot tile
Numerical integration	More iteration		Determining the height of a packed gas absorption column,

Case Study Examples

A set of case studies are being developed to provide a variety of problems and examples for use in EAS112. At present the intent is to develop material in two areas for the initial course offering: the design of an energy storage system using solar energy and fuel cells and the design of a bridge.

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Examples of topical areas for problems from the case studies include:

Fuel Cell Case Study:

power and electric circuits
- power, voltage current models for the fuel cell
- analysis of a resistive network
- modeling of a energy storage capacitor

material balances and reactions
- relationship between gas flows and electric power production
- consideration of hydrogen generation by solar-powered electrolysis
- humidity considerations of gases entering and leaving the fuel cell

heat transfer and energy considerations
- modeling fuel cell temperature

quality control (probability & statistics)
- consideration of properties of solar cells or membranes

economic optimization
- comparison of battery storage to the fuel cell system
- evaluation of solar alternatives

Bridge Design Case Study:

statics
- force balances on a truss bridge design

strength of materials
- analysis of stress test data to determine Young's Modulus for bolt materials

quality control (probability & statistics)
- sampling bolt lots to determine risk of bolt failure
- applying probability models to assess risk of selecting 2 faulty bolts in sets of 4 bolts

An early assignment based on the fuel cell theme involved calculating hydrogen gas requirements for a fuel cell system sized to power a typical home. The students were given a copy of the expected results and had to create a spreadsheet which looked the same. The objectives of this assignment included spreadsheet organization, entering formulas, relative and absolute addressing and other basic spreadsheet principles. Figure 1 shows the expected result.

Several assignments and class exercises were structured around the bridge design theme. In the discussion of statistics with the spreadsheet, the following situation was used as a motivating scenario:

> In the construction of a steel truss bridge thousands of bolts may be required. We are considering the situation in which groupings of 4 bolts will be used to attach structural members to each other or to foundation supports. The strength of the bolts will vary somewhat due to differences in material micro structure as well as in fabrication (casting, machining, heat treatment, etc.). Past experience leads us to believe that some very small

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EAS 112 Methods of Engineering Analysis
FuelCell Case Study: Gas Flowrates and Volumes

ClassPlan1.xls **28-Jan-04**

Hydrogen usage is related to power produced by the following equation:

$$N_{H2} = Pe / (2 * Vc * F)$$

N_{H2} = moles H_2/sec, P_e = electric power, watts, Vc = voltage per cell, volts
F = Faraday's Constant, $9.65 * 10^4$ Coulombs/mole of electrons

Volume is given by V (liters) = n * R * T / P = (ideal gas), where P = pressure, atm.,
R = universal gas constant = 0.08206 liter-atm/gmol-°K, T = absolute temperature, °K

Flowrates: M (mass flowrate in kg/s) = N * w = , where w = molecular wt in grams/gmol
standard volumetric flowrate (std liters/s) = N * 22.4
[note: standard volume is the volume for this number of gmoles at 0oC, 1.0 atm]
V (actual volumetric flowrate in liters/s) = N * R * T / P

v (velocity in meters/sec) = 0.001 * V / area,
where area = inside area of tube or pipe in m2, area = pi $D^2/4$

INPUT DATA

Constants			
constant	**value**	**units**	**name**
R	0.08206	liter - atm	rcon
		gmol °K	
F	9.65E+04	Coulomb	fcon
		gmol elec	
std vol	22.4	liter/gmol	volstp

Parameters				
	value	**units**	**name**	**comment**
V	120	volts		system voltage
I	100	amperes		system current
Pe	12000	watts		system power
Vc	0.65	volts		cell voltage
P	5	atm	pcell	cell pressure
T	298	deg K	tcell	cell temperature
T	298	deg K	ttank	storage tank temp

name refers to the name assigned to the cell containing the value

RESULTS

Flowrates	
gmol H_2/s	0.0957
std L/min	129
act L/min	28.1

Pipe Diam	area	velocity
cm	m^2	m/s
0.5	1.96E-05	23.8
1	7.85E-05	6.0
2	3.14E-04	1.5
4	1.26E-03	0.4

Storage Volume Needed, m^3			
time, hours	pressure of storage tank, atm		
	5	10	100
24	40	20	2
48	81	40	4
72	121	61	6

time is hours of operation using stored gas

Figure 1

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percentage of the bolts have a strength property (yield strength) which is below the acceptable limit. The design compensates for this by using the 4 bolt pattern for critical attachments, in which the integrity will be maintained even if one of the 4 bolts fails. However, there is some very small probability that 2 bolts may fail, which could lead to serious problems requiring expensive repair work. The following questions are raised by this situation:

> Can we predict the number of "bad" bolts in a large batch of bolts?
> How is risk quantified and what is the level of risk that a failure might occur?
> What is an acceptable level of risk?
> How likely is it that a "bad" bolt will be selected in a group of 4 bolts?
> How likely is it that 2 "bad" bolts will be selected?
> How can we determine whether or not to accept a batch of bolts from a manufacturer?
> Is there a significant difference in the properties of two batches of bolts which came from different manufacturers?

A class exercise was developed using 200 small Lego parts of different colors to represent bolts of various quality. Each student randomly picked samples and the data for the whole class was collectively analyzed to apply statistical methods to analyze the bolt quality and other issues raised in the above discussion.

When plotting data and regression was discussed, the class was taken to a mechanics lab to witness a tensile stress test. Actual test data was then assigned to the class for analysis to determine the Modulus of Elasticity, yield stress and related properties.

As an application of the spreadsheet's built-in functions students developed a spreadsheet model for analyzing a seven-member truss. The student assignment was as follows:

> A bridge is needed to cross a small stream. The span between supports must be 32 meters. The maximum load on the bridge can be estimated by considering the case of a line of vehicles stretching across the span and using an average mass for the vehicles. The proposed design uses a 7-member truss with cylindrical members. Structure height and member diameter are to be determined. The support on the left is a "pin", rigid in both vertical and horizontal planes. The support on the right is a "roller", providing only vertical support to allow for bridge expansion in the horizontal dimension.
>
> Your assignment is to develop a spreadsheet model which includes the following features:
>
> INPUTS: number and mass of vehicles supported
> truss length and height and diameter
> material properties: density, yield stress, cost per unit mass
> safety factor to be used in the design
>
> OUTPUTS length of each member
> force exerted at the supports
> type of force in each member (tension or compression)
> magnitude of stress in each member for any given diameter
> maximum tensile stress in any member
> total amount of material needed and estimated cost of material

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Figure 2 is from a mini-lecture on force balances as applied to the truss structure. Figure 3 is the solution to the problem. Students were given a template worksheet which already contained the figure and several defined areas. They needed to fill in the formulas to do the indicated calculations, including determination of lengths and angles, calculation of stresses, determination of costs and set up of the summary section. In addition to trigonometric and other mathematical functions, the assignment included look-up, if, max functions and conditional formatting.

Student Portfolios

To help students develop an organized approach to learning, each student is required to assemble a portfolio or journal which documents the material covered in this course. The portfolio is also useful for helping the students carry this knowledge forward to other courses and to professional practice. Students were given the following instructions for setting up and maintaining their portfolios:

> Content: Each of these sections should contain material you generate, as well as class materials provided to you. For example, your own glossary of terms, with definitions, your own list of concepts, with explanation, your own list of tips for using Excel, etc.

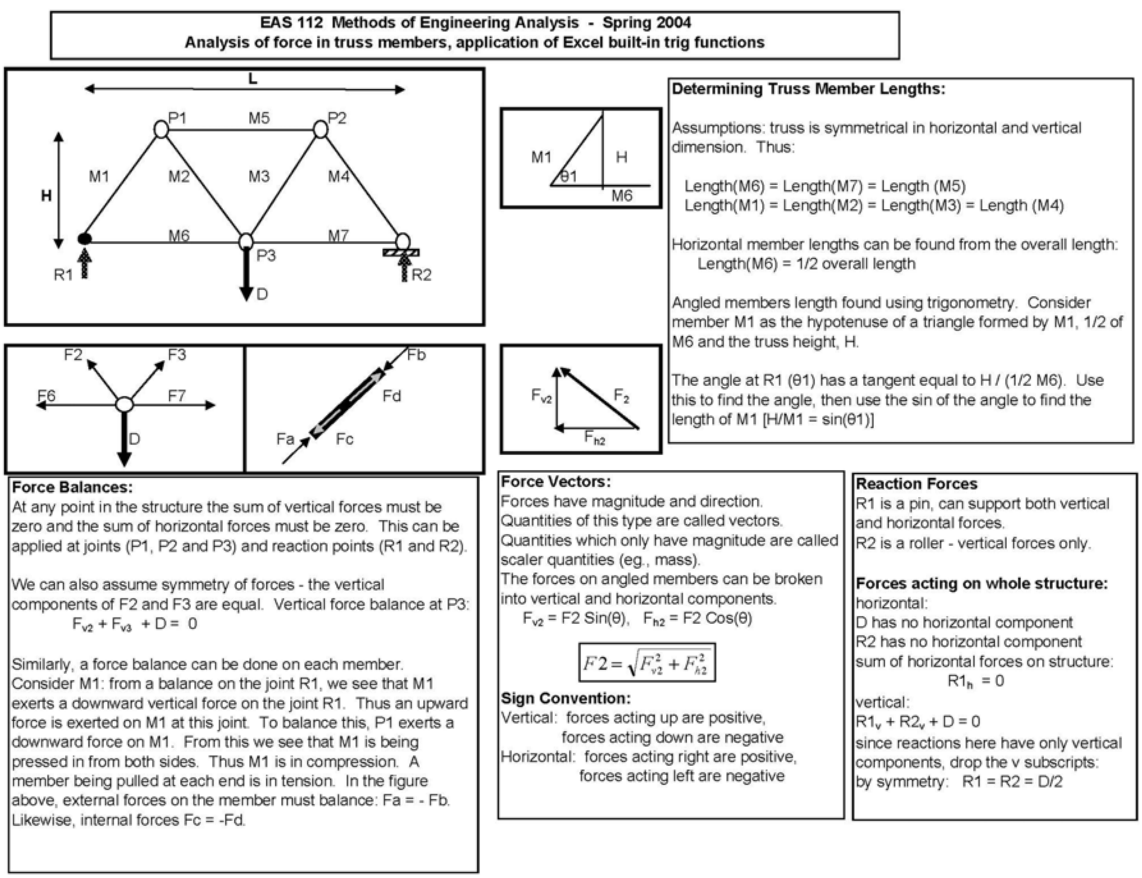

Figure 2

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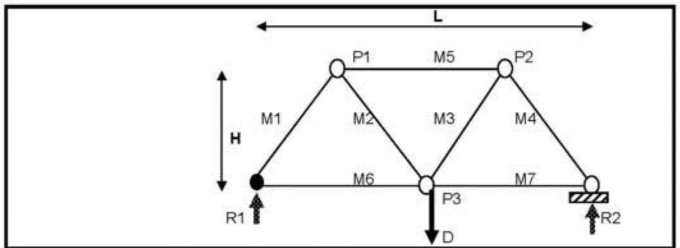
Analysis of truss bridge - determine stress type and size in members as a function of load, truss length, truss height and member diameter



Input Specifications			
N =	10		number of vehicles
m =	1500	kg	mass per vehicle
g =	9.8	m/s^2	graviational acceleration
W =	147000	N	total weight of vehicles

Design Features			
H =	6	m	truss height
L =	32	m	truss length
d =	5	cm	member diameter
A =	0.00196	m^2	cross-sectional area
D =	-147	kN	load on truss
R1 =	73.5	kN	Reaction Force at R1
R2 =	73.5	kN	Reaction Force at R2

Results	
length, m	88.00
volume, m^3	0.173
mass, kg	1358
cost, thousands of dollars	$0.7
maximum stress, M-Pa	0

Design Evaluation
Safety
Cost

Material Properties			
Steel =	1025		material, steel number
Sy	221	M-Pa	Yield Stress
ρ =	7860	kg/m^3	Material density
$C =	0.52	$/kg	cost
f	5		Safety Factor

direction of forces from members acting on each joint (vertical/horizontal)									
Joint	M1	M2	M3	M4	M5	M6	M7	direction legend	
R1	D/L					N/R		R	right
R2				D/R			N/L	L	left
P1	U/R	D/R			N/L			U	up
P2			D/L	U/R	N/R			D	down
P2		U/L	U/R			N/L	N/R	N	none
tension or compression	compress	tension	tension	compress	compress	tension	tension		

Member	M1	M2	M3	M4	M5	M6	M7
Member Type	angled	angled	angled	angled	horizontal	horizontal	horizontal
length, meters	10.00	10.00	10.00	10.00	16	16	16
angle to horizontal, radians	0.64	0.64	0.64	0.64	0	0	0
angle to horizontal, degrees	36.9	36.87	36.87	36.87	0	0	0
Vertical Force, kN (up is +)	-73.5	73.5	73.5	-73.5	0.0	0.0	0.0
Horizontal Force, kN (right is +)	-98.0	-98.0	98.0	98.0	-196.0	-98.0	98.0
Total Force, kN	-122.5	122.5	122.5	-122.5	196.0	98.0	98.0
stress, M Pa	**-62**	**62**	**62**	**-62**	**100**	**50**	**50**

Figure 3

Class materials

handouts and assignments, including student work and any miscellaneous materials

Spreadsheet topics

A summary of spreadsheet features as they are uncovered by the student, with notes on usage, dated weekly entries.

Programming concepts

A summary of programming topics, similar to the spreadsheet topics section

Engineering concepts

A summary of engineering principles encountered in the class through examples, assignments and case study discussions. Engineering topics will be categorized into the following subject areas: mass balance, electrical, mechanics, thermo-fluids and systems. Each engineering subject area should contain information of 3 types: glossary of terms, common equations and summary of concepts.

Analysis topics

summary of the mathematical and other analysis methods used

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Grading Rubric:

First Evaluation	70%	Organization / 30% Content
Second Evaluation	50%	Organization / 50% Content
Third Evaluation	30%	Organization / 70% Content

Conclusion

At the time of submitting this paper, we are about halfway through the first offering of the course. The amount of preparation time is very high - on the order of a full day for each 2-hour class. Much of this time is used in preparing the class activities and creating the handouts, such as shown in Figure 2 for the force balance discussion. There are 16 students in the class, mostly second semester freshmen, all engineering majors. The class is taught in a computer classroom with desktop computers for each student. One of the pitfalls of such a classroom environment is that a few students can be easily distracted by the computers when there is not a more compelling activity. Variations in student proficiency with computers presents a challenge for classroom activities that require intensive computer work. Since there are no teaching assistants in the class, it is sometimes useful to have the more advanced students help their neighbors who are having difficulty.

At this point it is much too soon to judge the extent to which the students grasp the engineering topics which appear in the case studies. It is clear from recent class discussions that some students can effectively manipulate equations, such as calculation of forces, with little actual understanding of the concepts they are applying. It is hoped that their understanding will develop as they encounter similar concepts at several points in the course in the process of learning spreadsheet, programming and engineering analysis techniques. Further assessment of the students and the course will continue and will be reported at a future forum.

The faculty of the School of Engineering and Applied Science would like to acknowledge the National Science Foundation for their support of the offering of several pilot courses in our *Multidisciplinary Engineering Foundation Spiral* curriculum[8].

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Appendix I - Possible Textbooks and References

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