

Spreadsheets in Electromagnetics Education: Coupled Problems with Graphical Post-processing*

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This paper revives the use of spreadsheets and demonstrates that with the new graphical capabilities built into spreadsheets, they can present extensive views of the abstract field. The methodology couples the graphing and cell-coloring capabilities of modern spreadsheets to show how graphs of potentials and color maps of scalar and vector fields can be produced. Further, the ability to link one spreadsheet to another, permits the exploitation of coupled field problems. These abilities are combined with some rudimentary Visual Basic programming to produce the required graphical depictions of the field. The problem of making the use of these spreadsheets less difficult remains because of the need to program the spreadsheets. This is somewhat ameliorated by the instructor giving the required program to students. Alternatively the electromagnetics class may be used in an integrated curriculum to reinforce programming concepts from other classes.

INTRODUCTION

CLASSICAL SUBJECT topics in electrical engineering such as field computation, traveling waves, waveguides, etc. have traditionally been taught using closed-form explicit mathematics. These solutions are exact. But because the mathematical methods apply to simplified models like squares and circles, real devices are approximated by models that we can handle mathematically. In a sense therefore these exact solutions are not very helpful. For they are exact solutions to inexact models.

On the other hand, numerical methods are very powerful. They can handle any shape and although the solution is approximate, its accuracy can be increased by using finer approximations. Thus we have the strange paradigm of approximation methods being more exact. These methods are now an industry standard.

Computer Aided Instruction (CAI) is increasingly seen as an effective way of teaching mathematically tough and physically abstract topics like classical electromagnetics using graphics. But the difficulty in using these CAI programs has held back the progress of, if not impeded, the wide acceptance of CAI techniques. Simpler programs like spreadsheets have been historically seen as a via media, where easy to use spreadsheet packages are used, buying ease of use at the cost of flexibility and even control over the program. But as formal professional computational packages developed into easy-to-use and powerful tools, spreadsheets

fell behind. A huge factor in this was the inability to present fields graphically with spreadsheets. Spreadsheets therefore seemed to have lost the battle to the alternative classroom use of programs developed for professional design.

The origins of CAI can be traced to the development of the computer. The earliest use of CAI in electrical engineering was in the teaching of electromagnetics—a subject that is mathematically difficult and involves the abstract concept of the field. The graphics capabilities of the computer vividly present equipotential and flux density maps that seem to give life to the field. The book by Hammond [1] was one of the earliest to teach electromagnetics with the analysis tending to be numerical. Other attempts by Silvester [2] followed. Hoole with co-authors showed how the finite element method could be used in CAI effectively [3–5] and developed a book substantively devoted to teaching electromagnetics numerically [6].

Today, CAI techniques in electrical engineering and electromagnetics in particular [7] are widely accepted and have special issues of journals devoted to them, as is the case with this issue.

Nonetheless, the classroom continues to be dominated by the old methods and the sophisticated numerical methods developed remain largely unused except as project assignments. The reason is that the new numerical methods involve sophisticated programming. Often a vendor who has developed a very capable program for industrial quality design, sells it off as a CAI package by simply limiting the size of problem that can be solved with it. Thus when classical subjects are taught through numerical methods, strong

* Accepted 14 July 2004.

programming skills are called for from the student. To overcome this, general-purpose software packages have been used but James Hoburg of Carnegie-Mellon University, an experienced instructor who devoted several years of his professional life developing CAI packages, poignantly asks in a surprise paper whether the CAI exploiting class is dominated by learning the tools for teaching the subject rather than the subject itself [8].

Spreadsheets are an intermediate solution to these two opposite approaches [9, 10]. They allow the use of numerical methods but do not require the sophisticated programming expertise that is required with advanced numerical methods. But they have been limited on two fronts: they can handle only limited methods like the finite difference method [9] and lack the sophisticated post-processing tools of advanced packages. To be sure, the post-processing capabilities are one of the strongest points about numerical methods since they give students a feeling for the intangible field and a physical appreciation for its presence.

In this paper we exploit the fact that today, close to 20 years after one of these authors began introducing numerical methods in his electromagnetic classes and ten years after James Hoburg's indictment, typical electrical students are far more sophisticated in their programming skills with easier access to computers. Rather than using simple iterations on a spreadsheet, these students can be asked to use some basic programming when assigned work with spreadsheets to give good post-processing capabilities. Further, as educators we see the role of the teacher as very wide. We see an electromagnetics class as not only for teaching electromagnetics but also a place where we emphasize the integrated nature of engineering and its curriculum by showing students how what they learnt in their programming class is applied across the curriculum.

Thus, in this paper, we show how Visual Basic programming is used to employ spreadsheets in a pedagogically powerful way. We show that the facility to link one sheet to another can help us to do coupled problems such as in a current flow problem coupled to a joule heating problem which in turn affects conductivity and therefore the current flow problem. We also show that by linking a spreadsheet of temperature or electric field intensity values to another sheet of cells whose colors are based on this intensity, a color map of fields may be rather trivially obtained. In contrast, specifying a path through cells on a spreadsheet, graphs of fields (potential and field intensity) may be obtained with almost no programming using the graphing facilities of the spreadsheet.

EXAMPLE PROBLEM STATEMENT

Electro-heat problem

Here we analyze a coupled electro-heat problem and to this end we consider the example of a fuse

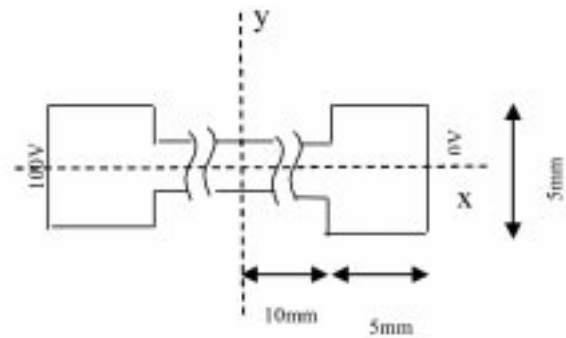


Fig. 1. Symmetric shape of fuse about x and y axes.

problem for demonstration purposes (Fig. 1). As the current flows and heats up the fuse through Joule heating, to demonstrate the effects, we need color plots of temperature distribution and thermal power distribution. For that, we have to first find the voltage distribution, then the electric field intensity and the electrical power at each grid point. Then, we have to find the temperature distribution by solving another finite difference problem (this time for temperature) and thermal energy distribution and then obtain color plots of those distributions.

Defining geometrical shape of a device using spreadsheet

The domain of the device is defined and it is divided into $0.25 \times 0.25 \text{ mm}^2$ grids. And each node value is referred to a cell in the spreadsheet. The solution domain is confined to the device. The calculation in a cell in the spreadsheet gives the calculation at a node. And the shape of the combination of filled cells takes the exact shape of the fuse where many cells are used. Too small a number of cells would result in non-smooth contours as we will see. There is no general rule for the number of cells. Even if many cells are used, a close-up view would show discontinuities whereas any view where the cells look small would give a graphics output that looks smooth.

CALCULATIONS USING SPREADSHEETS

Voltage difference

The computation of the voltage distribution governed by the Laplace equation derived from current continuity principles is well known but we review it briefly for completeness and continuity with subsequent sections dealing with coupled problems. In the first spreadsheet, the voltage at each node is calculated knowing only the boundary conditions, using the finite difference method [9, 10]. Actually, here we consider only the left-upper quarter of the fuse since we need the field potential to find electric power and the distribution of the field potential is symmetric about both the axes (Fig. 1). The known values here are 100 V and 50 V at the left and right sides of the considered

portion (the right end being the middle of the fuse), respectively. The 100 V potential difference from end to end drives the current. We first put these values in the corresponding cells. If v_1, v_2, v_3 and v_4 are the voltages at the four neighboring finite difference nodes 1, 2, 3, and 4 of a node 0 (if 0 is at (x,y) , then 1 is at $(x+h,y)$, 2 at $(x,y+h)$, 3 at $(x-h,y)$ and 4 at $(x,y-h)$) with voltage v_0 , the 5-point finite difference approximation formula from the Laplace equation for a square mesh is given by:

$$v_0 = (v_1 + v_2 + v_3 + v_4)/4 \quad (1)$$

In the Microsoft Excel™ spreadsheet which is widely available and will be used throughout the rest of this paper, the cells are divided into a grid going by alphabetical letters one way (left to right) and numeric letters the other (top to bottom). Thus say you have v_0 in cell C4, the 5-point formula applying to a square grid will be:

$$C4 = (B4 + C3 + D4 + C5)/4 \quad (2)$$

To be sure, in a professional setting we would use a far more flexible finite-element method and not the finite difference method to solve the field problem. Even if we did use finite differences, we would use matrix solvers that are more efficient than successive over-relaxation as indicated by Equation (2) where we improve the value of cell C4 using the latest approximations of cells B4, C3, D4 and C5. This is effectively the application of the SOR or

Successive Over-Relaxation algorithm to the equation corresponding to node 0. We do this because the purpose here is to teach electromagnetics and not to bog the students down with matrix algorithms in an electromagnetics class. The SOR scheme is naturally put into the iterative schemes of spreadsheets as shown in Fig. 2. This formula is put in cells according to the nodes in the problem. For this also one can first type in one cell and then paste it down in other cells so that time will be saved and accuracy of entry ensured; the spreadsheet will automatically adjust the cell reference when the formula is pasted in other cells.

To do this, from the *Tools* menu one can open the *Options* dialog box. There the *Iterations* check box in *Calculations* tab should be checked and one can set the maximum number of iterations and the maximum change (Fig. 2). If one selects the *Manual* radio button under *Calculation* one may press the *F9* function key, after typing all the formulas, to start the iterative calculations based on the SOR scheme. Up to this is well known methodology in finite differences for CAI.

This formula involves cyclic reference of cells since each node value is found using the four neighboring nodes. This process is possible since spreadsheets naturally have the inbuilt facility for iterative schemes as already mentioned.

Electric field intensity

Once the voltage distribution is computed, using the computed potential values, we calculate the

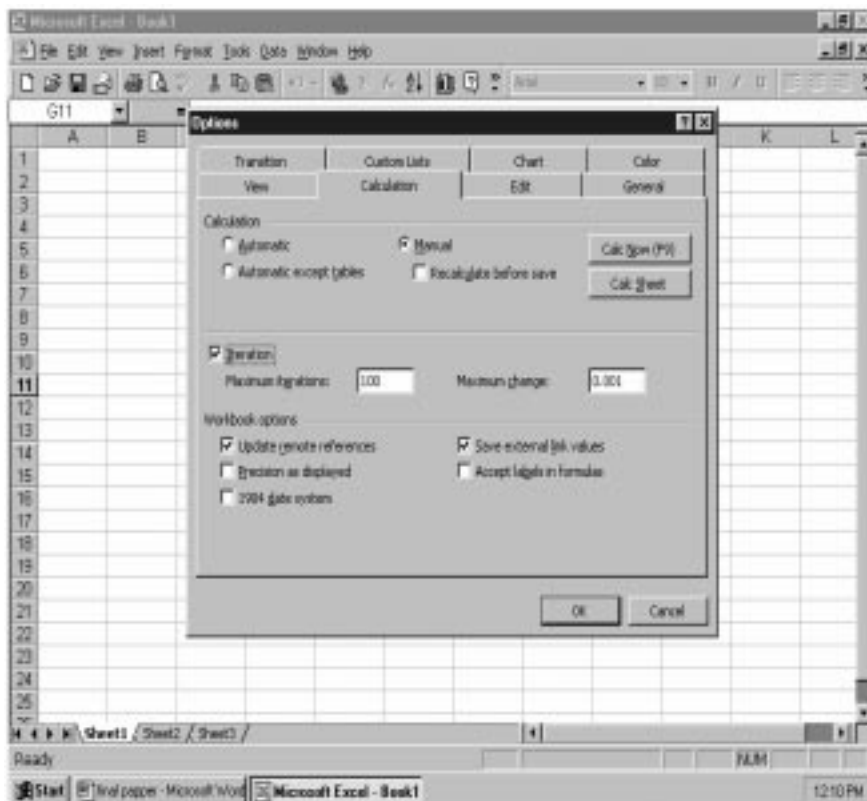


Fig. 2. Options dialog box for iterating the cell-values until convergence.

field intensity at each node using the fact that the negative gradient of the potential field is the electric field:

$$|E_0| = \sqrt{\left(\frac{v_1 - v_3}{2h}\right)^2 + \left(\frac{v_4 - v_2}{2h}\right)^2} \quad (3)$$

where h is the square mesh size, E_0 is the scalar magnitude of electric field intensity at the node 0 considered and v values of the potential are as computed from sheet 1. Because of the linking facility of the spreadsheets, we could calculate field intensity E using the values in sheet 1 and put that in sheet 2. Therefore, say, E_0 is in cell C4 in sheet 2 the formula to be typed there will look like:

$$C4 = \sqrt{\left(\frac{\text{Sheet 1!D4} - \text{Sheet 1!B4}}{2h}\right)^2 + \left(\frac{\text{Sheet 1!C3} - \text{Sheet 1!C5}}{2h}\right)^2} \quad (4)$$

Actually we calculated the square of field potential in sheet 2 and then took the square root of it in sheet 3. This facilitates error checking.

Electric power

The filled cells corresponding to the upper-left quarter of the fuse in sheet 2 are mapped to the cells corresponding to the lower-left quarter using a simple macro-function coded in Visual Basic. It follows a Pascal-like structure. The function is as given in Fig. 3. This may be given to students or they may be asked to program it themselves using the exercise as a means of making them more computer-literate. Our experience is that students can be taught to develop the code in a pre-lab session with due instruction. Then, in sheet 4 using these $|E|^2$ values the electrical power of each node is calculated using:

$$q = \sigma_e |E|^2 n \quad (5)$$

```

Sub map ()
  Dim i, j As Integer
  For i = 2 To 12
    For j = 2 To 62
      Worksheets ("Sheet2").
      Cells (11 + i, j) = Cells (13
      - i, j). Value
      Worksheets ("Sheet2").
      Cells (11 + i, j) = Cells (13
      - i, j). Formula
    Next j
  Next i
End Sub
    
```

Fig. 3. The 'map' macro-function for mapping the cells.

where σ_e is the conductivity and the factor n will take the values 1, $\frac{3}{4}$, $\frac{1}{2}$, or $\frac{1}{4}$ depending whether the node is surrounded by conductive material in all 4 quarters or 3 quarters or 2 quarters or 1 quarter, respectively [6]. A factor $\frac{1}{2}$ will appear in Equation (5) for AC problems but does not exist for DC problems. Where AC currents are employed, Equations (1) and (2) will require minor changes to incorporate the diffusion term [6] and additional macros will be required to support complex arithmetic. The mathematical formulation will become more complex and therefore an AC-excited fuse is not recommended for an undergraduate class.

Temperature and thermal energy

In sheet 4, only the left half of the fuse is analyzed. Note that it is symmetric about the y-axis. The temperature distribution is calculated in sheet 5. The calculation is similar to that in sheet 1 since the governing equation is now the Poisson equation in place of the Laplace equation. But unlike with the current problem where there is no flow outside the metal of the fuse, there is now heat flow outside the material of the fuse. Therefore the solution domain extends outside the fuse to a distant Dirichlet boundary at room temperature, with its simplifying assumptions as suitable for an undergraduate electrical and computer engineering class. Thus the region to be analyzed extends to air since the known boundary value is the room temperature near the fuse. The governing equation in finite difference form is:

$$T_o = \left((T_1 + T_2 + T_3 + T_4) + \left(\frac{q_o h^2}{\sigma_T} \right) \right) / 4 \quad (6)$$

where σ_T = thermal conductivity and q_o = electric power deposited through Joule heating for the particular node. $q_o = 0$ if the node considered is in air and it will take the value in sheet 4 when the node is in the fuse. So we inserted some cells with 0 values in sheet 4 to fill the air area and used the common formula for all the cells in sheet 5.

In sheet 6, the thermal power distribution (Q_t) is found using the temperature distribution in sheet 5 and using:

$$|q_0| = \left(\sqrt{\left(\frac{T_1 - T_3}{2h}\right)^2 + \left(\frac{T_2 - T_4}{2h}\right)^2} \right) \times \sigma_t \quad (7)$$

which is based on the gradient of temperature according to Newton's law.

COLOR PLOTS

Simple conversion and color plots using macro functions

For the purpose of visual representation of the results we select the colors Violet, Indigo, Blue, Green, Yellow, Orange and Red and assigned them to integers 1 to 7 respectively. To do this,

the maximum (max) and the minimum (min) values of the plotting scalar variable are found by searching through the cells. That is, if we are plotting potential, then we would search through sheet 1 for the lowest and highest values of potential to be plotted. Now if we assumed that the plot-variable e corresponded to the color c according to $c = ae + k$, then:

$$7 = a \times \min + k \tag{8}$$

$$1 = a \times \max + k \tag{9}$$

Equations (8) and (9) are used to find the constants k and a for the mapping of the variable being plotted to its color. If e is the value to be converted, to the range between 1 and 7, the converted value c can now be calculated using (10);

$$c = a \times e + k \tag{10}$$

Colour plots

We used macro-functions to obtain color plots of field intensity (Fig. 5), temperature (Fig. 6) and power deposition (Fig. 7) distributions. This is accomplished by filling corresponding cells in a separate spreadsheet with the appropriate color. We have put the color plots in three separate sheets, each linked to the corresponding data sheet; that is sheets 3, 5 and 6. When many cells are used, the color plots are smooth. But when few cells are involved, the plots are misleading. This necessarily means a lot more computation. What is acceptable depends on whether we are looking at a close-up view or not and students must play with these ideas and experiment.

Plots from spreadsheets

For the visual representation of results we first used the facilities available in the spreadsheets. Here we obtained line plots of row data of voltage distribution (Fig. 8) and surface plot of temperature distribution (Fig 9). For this you can select *Chart* from *Insert* menu. When the *Chart wizard* opens, one has the option of selecting which type of plot one is going to use.

For line plots, by default, it will take the lowest data row as the series 1. For convenience of observation one can change the plotting order of data series. Also in Fig. 4 the series of values for each row is scaled so that the variation along all the columns is clearly visible.

CONCLUSIONS

In this paper we exploit the color and post-processing capabilities of modern spreadsheets to extend traditional spreadsheet solutions of field problems to coupled problems. The use of multiple linked sheets makes such use pedagogically effective since a student can switch from one view of a variable to another easily and from viewing one variable to another.

Tackling coupled problems with color post-processing capabilities comes close to the effectiveness of modern design packages that are far more costly and, in the context of CAI, difficult for students to use. Numerical calculations are easier

```

Sub color_()
Dim RINDEX, COLINDEX As Integer

For RINDEX = 1 To row_no

For COLINDEX = 1 To col_no

With Worksheets ("Sheet_no"). Cells (RINDEX, COLINDEX)

If. Value = 1 Then
.Font. Bold = True
.Interior. Color = RGB (128, 0, 255)
End If
If. Value = 2 Then
.Font. Bold = True
.Interior.color = RGB (50, 0, 255)
End If
If. Value = 3 Then
.Font. Bold = True
.Interior.color = RGB (0, 0, 255)
End If
If. Value = 4 Then
.Font. Bold = True
.Interior.color = RGB (0, 255, 0)
End If
If. Value = 5 Then
.Font. Bold = True
.Interior.color = RGB (255, 255, 0)
End If
If. Value = 6 Then
.Font. Bold = True
.Interior.color = RGB (255, 60, 0)
End If
If. Value = 7 Then
.Font. Bold = True
.Interior.color = RGB (249, 0, 0)
End If

End With

Next COLINDEX

Next RINDEX

End Sub
    
```

Fig. 4. Principal Macro-function for Color Plots.

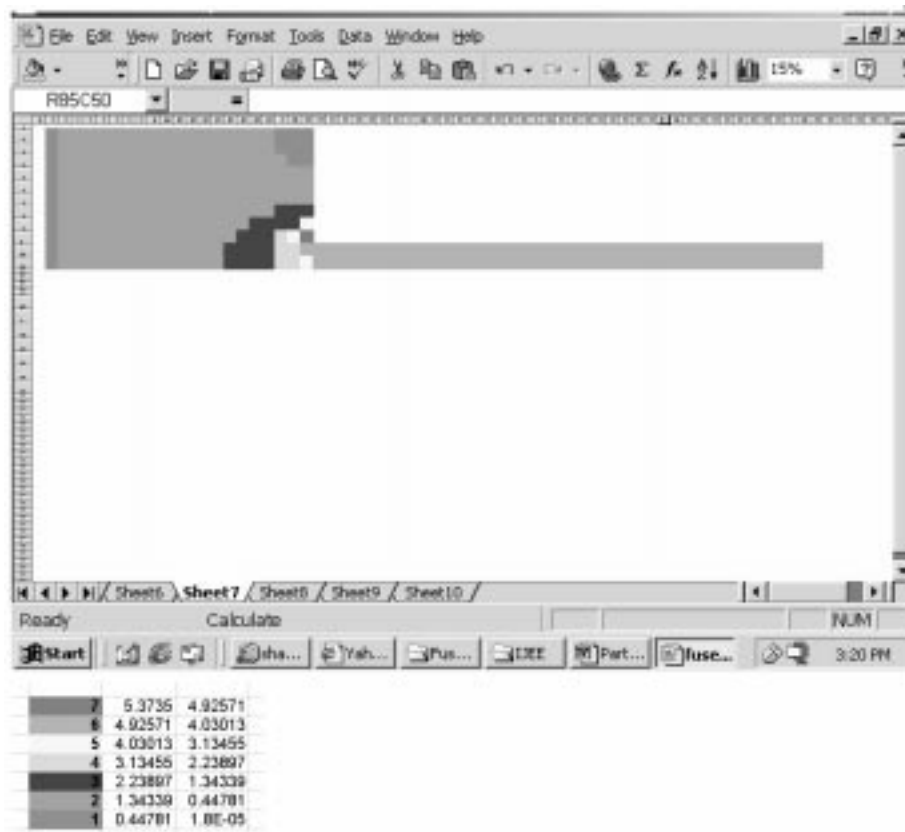


Fig. 5. Color plot of electric field intensity.

in spreadsheets since we need to consider the boundary and type the equation in one cell and then just by select-and-drag we can copy the equation used for the calculations in all the other cells. It automatically allows for the cell referencing. Since the linking facility is there we could do different calculations in different sheets without any confusion.

In problems where symmetry is used to reduce the field computation, we may wish to see a plot of the entire region rather than only of the symmetric half where the field was computed. For such mapping, taking the mirror image, we need to develop a little coding. Since no sophisticated post-processing tools exist in spreadsheets, we have to write a little extra code to obtain the

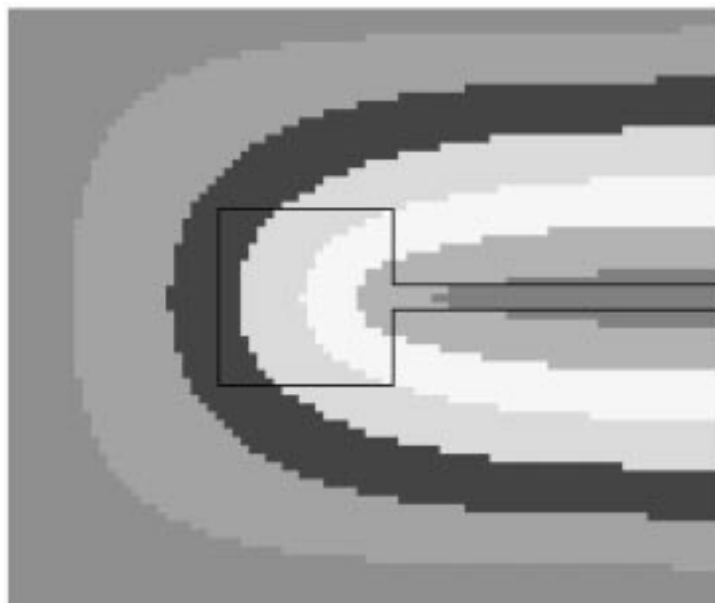


Fig. 6. Color plot of temperature.

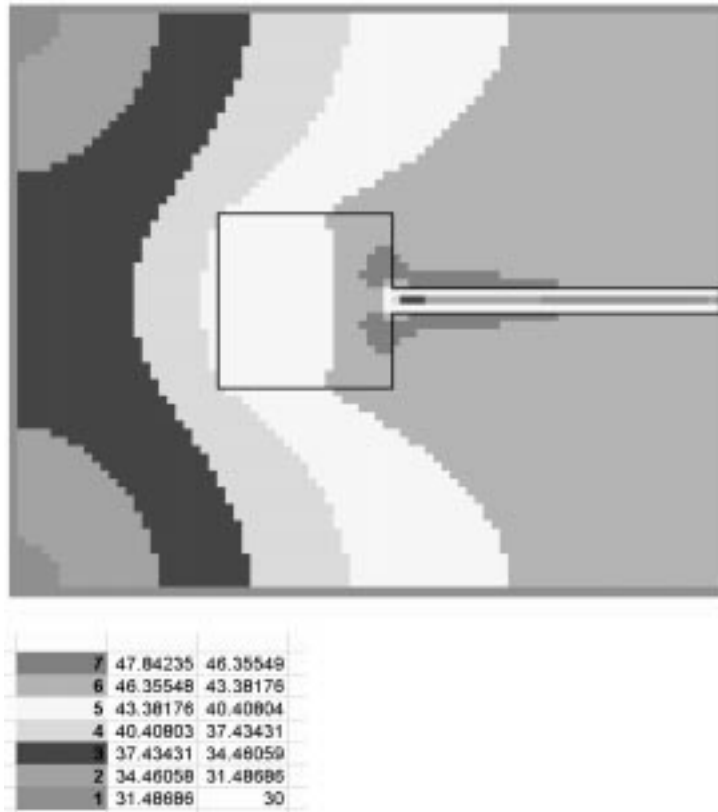


Fig. 7. Color plot of thermal power.

color plot of the various distributions. And the same copy of the code with nominal changes (that is, with changes only to the reference number of the sheet containing the data) could be used to plot the different distributions. This has been demonstrated for a heating problem involving electric potential, the electric field intensity and the temperature field.

User reactions to the method of teaching were positive. Post-processing methods, where easy

visual solutions are obtained by a student who is not too much of an expert in programming, are a powerful means of enhancing the learning experience. However, the visual effects are not as powerful as with professional programs written for design but these can only be purchased at high prices making spreadsheets an attractive option based on price.

In the context of developing countries, this cost is an important factor. Further, many of our

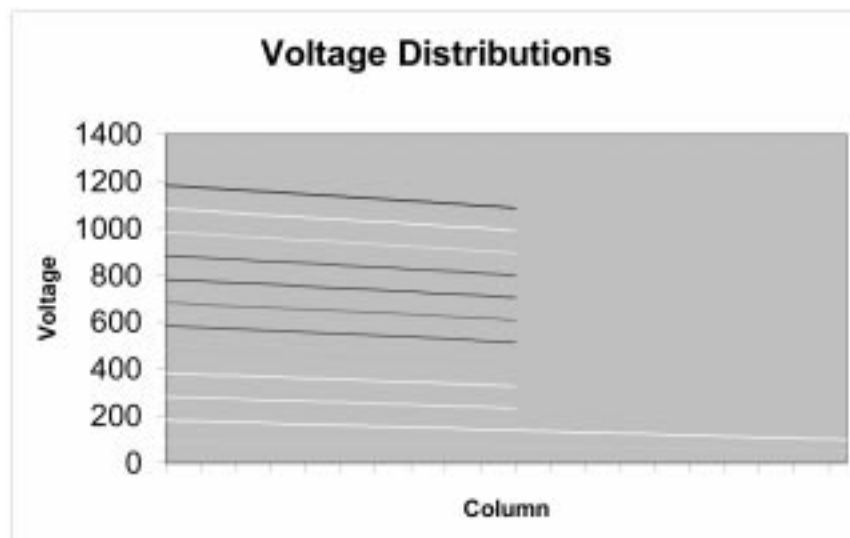


Fig 8. The 'line plots of voltage distribution along rows from the left to the right of the fuse.

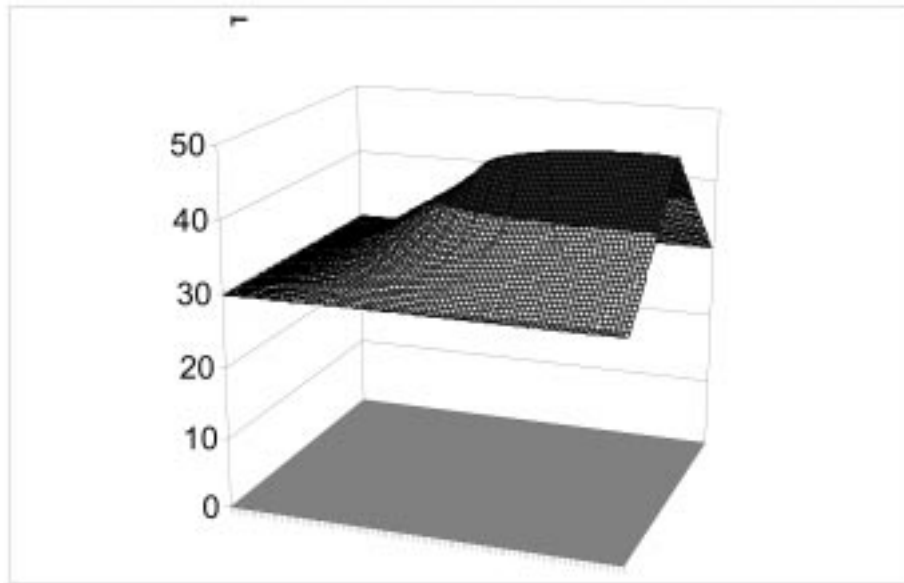


Fig. 9. The surface plot of temperature distribution (from thick end to thin middle of fuse).

students use a computer only after entering the university. Exposure to computing has to be accelerated if they are to be trained to accepted standards of engineering competency. In this sense, exposure to computing through these methods is also found to be useful and effective

and enhances the integrated nature of the curriculum.

Acknowledgements—The National Science Foundation of Sri Lanka kindly supported this project under Grant Nos.RG/2000/BG/12, RG/2001/E/04, NSF/RSP/UOP/E/01, and NSF/RSP/UOP/E/02.

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