Teaching Transmission Line Transients Using Computer Animation

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Abstract - Transmission line theory in electromagnetics comes alive when the travelling waves are animated on a computer screen, using program "BOUNCE". Fundamental concepts such as "travelling wave", "reflected wave", and "load matching" are forcefully demonstrated in the classroom. Problems using series connections of dissimilar line, shunt loads, and branches can be readily examined. Transmission line theory is applied to problems in the design of tri-state logic circuits that cannot be solved readily by hand, using animation to show how the voltage waveforms arise. Animation is used with a sinusoidal generator to illustrate the evolution to the sinusoidal steady state, as an introduction to solving transmission line circuits with phasors. Students are encouraged to run BOUNCE at home as a computational laboratory to verify their solutions to homework problems. This paper presents the BOUNCE program, and some of the demonstrations with BOUNCE that are used in the classroom.

Introduction

Transmission line theory is usually taught to undergraduates as part of an E.M. waves course using textbooks such as Refs. [1], [2] and [3]. Transients on transmission lines using steps, ramps and pulses illustrate reflection, transmission and matching. Students are taught to track interactions using a "bounce diagram". Then the transition is made to the sinusoidal steady state, solved using phasors and impedance. For computer engineering students transmission line transients are so important that a recent textbook[3] presents this topic at the outset of the course, and includes material not part of the customary presentation in [1] or [2].

This paper describes the teaching of transmission line theory in electromagnetics with the aid of computer animation, using a program called "BOUNCE". The program is run in the classroom on a Pentium laptop computer with a projector. The first classroom session demonstrates fundamental concepts. The second deals with more complex problems of matching of the source and the load in the context of tri-state logic. The third is concerned with a sinusoidal generator and the transition to the sinusoidal steady-state. Watching the instructor run the program "live" convinces students that BOUNCE is easy to use and encourages them download it from the site in Ref. [4] and to try it at home. As the skill of the students increases, more sophisticated problems are solved and assigned for homework. This paper presents the BOUNCE
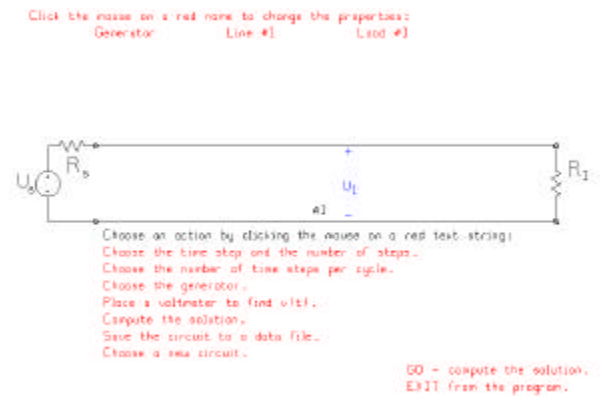

Figure 1. BOUNCE's main menu for the simplest circuit template.

program and some of the demonstrations used with it in the classroom.

Running BOUNCE

When BOUNCE is started it presents the user with a menu of circuit templates, including the very simple circuit of Fig. 1, series connections of several lines, and circuits with branches. Built-in circuit templates obviate the need to describe circuits in an input file, or construct circuits with a graphical user interface. In BOUNCE's main menu, Fig. 1, the circuit diagram appears across the center, with buttons at the top to define the generator, the transmission line parameters, and the load values. In BOUNCE, character strings shown in red are menu items that can be selected with mouse. Click the mouse on the generator button to choose a step function, a pulse, a square wave, a triangle wave, or a sinusoidal generator, and to set the internal resistance. Similarly, use the mouse to fill in the length, characteristic resistance and phase velocity of the transmission line and the value of the load resistor. The circuit including the values of these parameters can be saved to a data file with the extension "bnc".

The button labeled "Place a voltmeter" is used to position observers called "voltmeters" anywhere on the transmission line circuit. Fig. 1 shows a voltmeter near the center of the line. BOUNCE will display the voltage at this position as a function of time. As many as four voltmeters can be defined on any circuit.
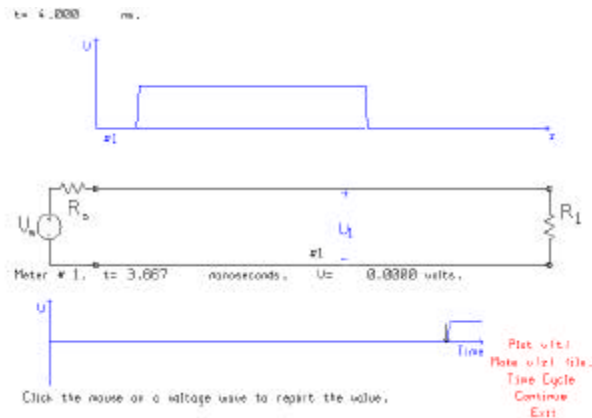
Figure 2. A pulse voltage travelling from left to right across the screen demonstrates basic wave propagation.

Wave Propagation

After the lectures have developed the transmission line equations, their general solution, and reflection from a load, the BOUNCE program can be used in the classroom to illustrate these fundamental concepts[5]. When a pulse generator is selected and we click the "GO" button in Fig. 1, we see the display in Fig. 2, animated with the pulse moving from left to right across the top of the screen, on the voltage-as-a-function of distance axes. Seeing the pulse move along the transmission line conveys the idea of "travelling wave" quite forcefully. In Fig. 2 the leading edge of the pulse has just passed the location of the voltmeter, and so the voltage vs. time graph at the bottom of the screen shows that the voltage has stepped up at this location. Similarly, a triangle wave and a sine wave can propagate across the screen, illustrating the principal that any function $f(t - z/u)$ is a solution to the lossless transmission line equations.

The BOUNCE program runs for a fixed number of time steps, called a "cycle", and then pauses. Set the number of steps in each cycle with the "Time Cycle" button. When the program pauses, click the mouse on the voltage vs. distance graph, or on the voltage vs. time graph, to read back values. The program draws an arrow at the location of the mouse click, seen at bottom right in Fig. 2 at the rising edge of the pulse, and reports the time and voltage value just below the circuit schematic. After each pause, click "Continue" to extend the solution for another time cycle, or "Exit" to return to the main menu.

The demonstration is run first with a matched load; the leading edge of the pulse disappears at right with no reflection and the voltage at the observer steps down as the trailing edge of the pulse passes the voltmeter location. Terminating our 50 ohm line with a 25 ohm load permits the animation to be used to demonstrate reflection. When the pulse reaches the load, the reflection coefficient is $\Gamma = (R_L - R_0)/(R_L + R_0) = -1/3$, and our 5 volt pulse
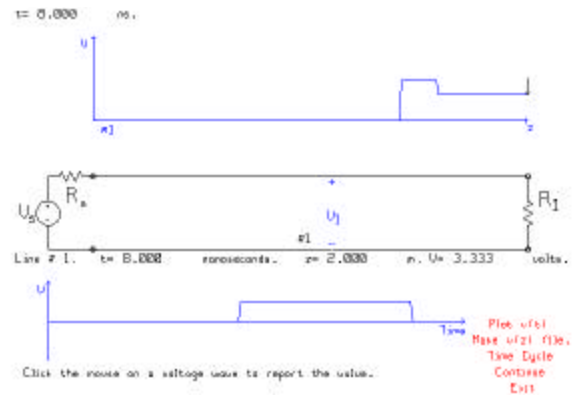

Figure 3. The reflection from a 25 ohm load.

generates a reflected pulse is of amplitude –1.667 volts. We see the leading edge of the reflected pulse travelling from right to left across the screen, combining with the incident pulse as it goes. Fig. 3 shows an instant of time where the reflected pulse has traveled back towards the trailing edge of the incident pulse. The mouse has been clicked at the right side of the voltage vs. distance graph, and the program has drawn an arrow at that location, and reports that the voltage there is 3.333 volts. We expect the load voltage to be the sum of the incident plus the reflected pulse, 5 plus –1.667 equals 3.333 volts.

BOUNCE is used to explore various simple transmission line circuits[5]. Propagation from a 50 ohm line onto a 73 ohm line is demonstrated. Reflections from and transmission past a shunt resistor is examined. A branching transmission line is an introduction to both a power splitter in an A.C. context and to logic devices at the end of branches on a computer bus.

Mismatched Lines in Series

Fig. 4 shows a 1 ohm step-function generator driving a 120 ohm line, in series with a 50 ohm line, terminated by a 20 ohm load, with equal transit times on the two transmission lines. This problem was assigned as homework and proved challenging for students to solve. The class reported that the BOUNCE program obtained wrong answers! The step from the source propagates to the junction and is partially reflected back towards the source and partially transmitted towards the load. Then the reflections from the load and from the source arrive at the junction at the same instant of time. In Fig. 4, time has advanced to the point where these reflections are about to meet at the junction. Students had difficulty solving this interaction with a bounce diagram. The display in Fig. 4 can be used to verify that the student has computed the magnitude of the step-up arriving from the left and the step-down coming from the right correctly. By advancing the time in small steps from the instant shown in Fig. 4 until after the reflected pulses leave the junction, the
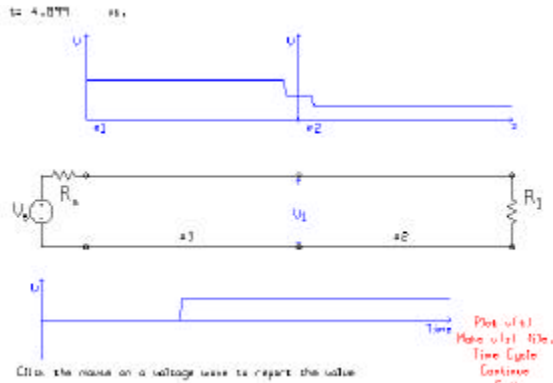
Figure 4. A step voltage propagating on two unmatched transmission lines of equal length.

class was able to see the interaction happen. The amplitudes of the reflected pulses were readily verified on the blackboard using the bounce diagram as a guide. The BOUNCE program reinforces the pencil-and-paper homework and indeed provides a "laboratory" for students to simulate the circuit and verify their solution.

Tri-State Logic Problems with BOUNCE

The second classroom demonstration, to a class of computer engineering students, deals with the need for matching in designing logic circuits[3]. We will define a "tri-state logic" device as one that can be either a "listener" or a "talker". As a talker the tri-state device drives the line "high" to +5 volts nominally, or it drives the line "low", to zero volts nominally. The internal resistance of the device in the talker mode varies with the design from a few ohms up to a few hundred ohms. As a "listener" the input resistance of the tri-state logic device is very high, much, much larger than the characteristic resistance of our transmission lines. The listener accepts a voltage >3.6 volts as a logical "1" and <1.4 volts for logical "0". Also, the listener expects the voltage to stabilize rapidly, or else a logical-0 might be misinterpreted as a 1 or vice-versa.

Fig. 5 shows a simple transmission line circuit with a low-impedance talker at the left side, a high-impedance listener in the middle and a high-impedance listener terminating the line at right. Many students expect that if the talker drives the line with a step up to five volts, then the voltage at the listener will simply rise to 5 volts after a delay equal to the length of the line divided by the speed of propagation. Fig. 5 shows that something quite different happens, namely that the leading edge of the step function becomes trapped on the transmission line as it reflects back and forth between the open circuit at right and the 1 ohm talker at left. It takes many trips back and forth on the line before the minimum voltage rises above the 3.6 volt threshold for a logical-1. The response of Fig. 5 is very
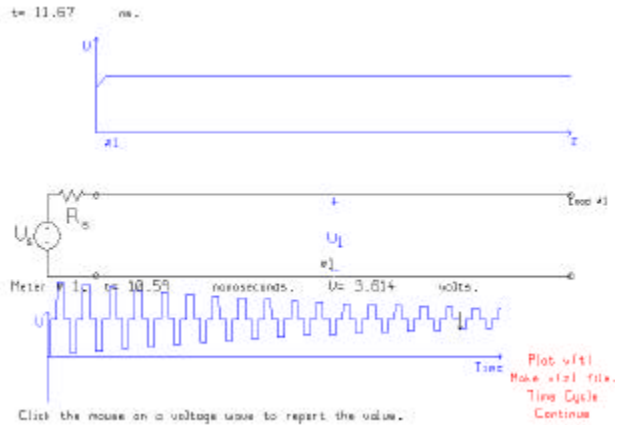

Figure 5. A low-impedance source and a high-impedance load give rise to ringing on a transmission line.

tedious to obtain by hand calculation but is simple and quick using BOUNCE.

Seeing the pulse bounce back and forth on the line graphically illustrates the need for matching. Adding a 40 ohm resistor in parallel with the high-impedance listener terminating the 50-ohm line at right provides an approximate match, and the voltage at the listener in the middle of the transmission line settles rapidly, as shown in Fig.6.
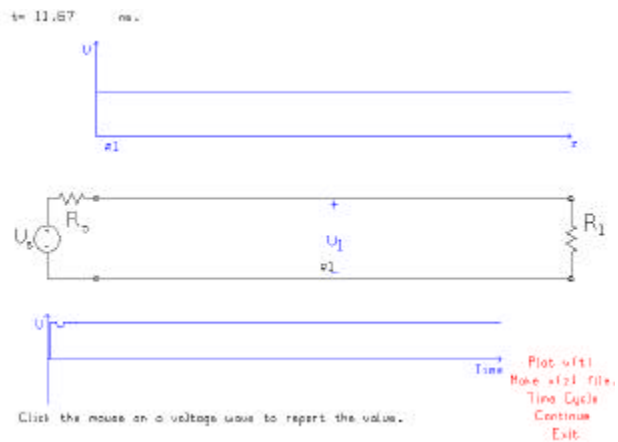

Figure 6. An approximate match at the load solves the ringing problem.

Short Branch to the Listener

It is common for a device to be connected at the end of a short branch in the transmission line, as shown in Fig. 7. A one ohm generator drives a 50 ohm line that branches into a pair of 50 ohm lines, one terminated with a high-impedance "listener", and the other terminated with a 50 ohm load resistor. The circuit can be used to demonstrate the need for
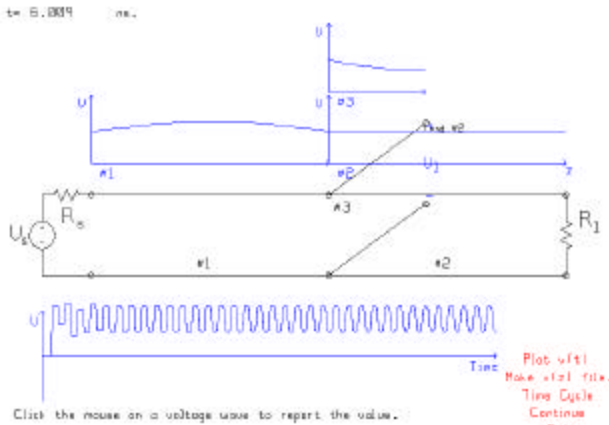
Figure 7. A listener at the end of a short branch, with an unmatched generator.

source matching. The leading edge of the step generator sees mismatch at the connection point of the branch. The parallel combination of the two 50 ohm impedance is 25 ohms; the reflection coefficient is –1/3 and so there is a substantial reflection at the junction. Because the source resistance is only one ohm, energy coupled between the source and the junction bounces back and forth causing the extended ringing seen in Fig. 7 for the listener at the end of the branch. Further, the wave transmitted onto the "stub" line is fully reflected from the end of the line, because the load is a high-impedance listener, and then transmitted back onto the transmission line via the junction. The voltage waveforms seen on lines #1 and #3 may surprise even an experience instructor. The number of interactions used to compute Fig. 7 is impossible by hand calculation. BOUNCE extends very considerably the sophistication of problems that can be presented in the classroom.

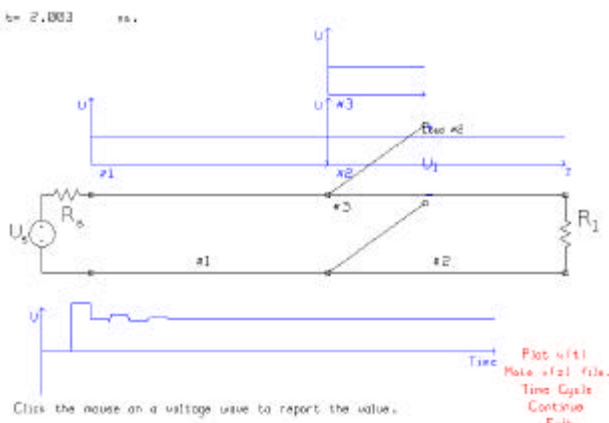The solution to the ringing is to approximately match

Figure 8. When the generator is approximately matched to the line the voltage at the listener settles rapidly.

the generator. Thus if the internal resistance is 40 ohms and the source voltage is raised to 9 volts to provide a 5 volt step

onto a 50 ohm line, the voltage at the listener is as shown in Fig. 8. The voltage at the listener at the end of the branch settles rapidly, in spite of the fact that the branch is terminated with a high impedance and there is some ringing of the voltage on the branch itself. The conclusion that we can draw is that both the source and the load need to provide an approximate match. Listeners at the end of short branches see a satisfactory voltage with a delay associated with the length of the transmission line from talker to listener.

In BOUNCE the circuit schematic is first seen on the main menu, as in Fig. 1. When the user clicks the mouse on "GO" to run the simulation, the circuit schematic is deliberately allowed to overlap the voltage vs. distance axes. Visual separation is maintained by drawing the circuit in black and the axes in blue.

BOUNCE provides a circuit template with two branches and one with three branches, in addition to the one-branch circuit of Fig. 7. These more complex templates can be used to explore matching considerations on a bus with several listeners.

Transition to the Sinusoidal Steady State

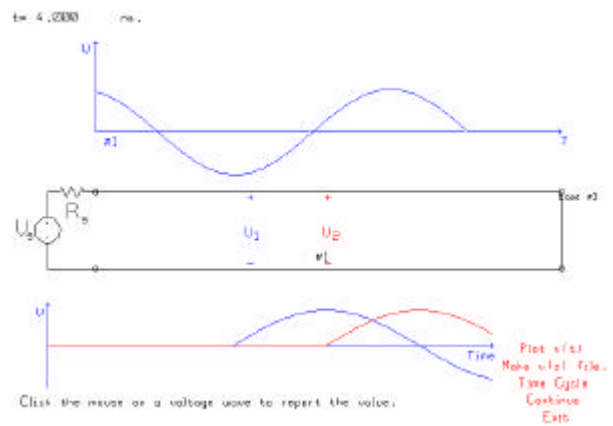The final classroom demonstration is done at the end of the

Figure 9. A sinusoidal waveform propagating past two "voltmeters" illustrates phase difference due to time delay.

course segment on transmission line transients, just before introducing phasors to solve the transmission line equations in the sinusoidal steady state. BOUNCE's animation is used to show a wave emerging from a sinusoidal generator, travelling along the line to the load, as in Fig. 9. Two observers are positioned on the line a quarter-wavelength apart. The animation clearly shows the delay between the arrival of the wave at observer #1 and at observer #2, and associates the delay with the 90 degree phase shift. With a matched load, there is no reflection and the wave simply
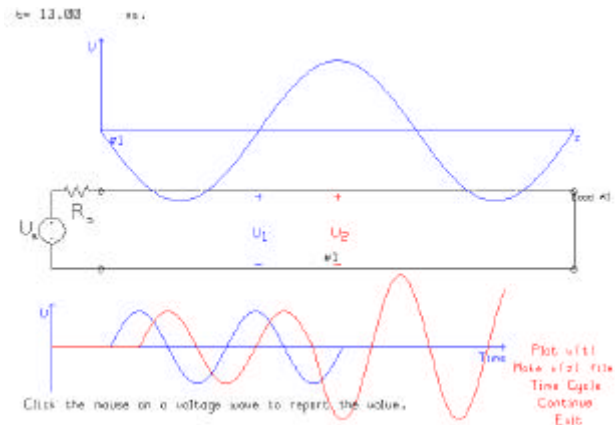
Figure 10. Observer #1 is positioned at a minimum in the standing-wave pattern, and #2 at a maximum.

disappears into the load. The steady-state solution is simply a "pure" travelling wave on the line. In Fig. 9, color-coding is used to associate each waveform on the voltage vs. time graph with the associated voltmeter on the circuit schematic.

With an open-circuit or a short-circuit load, the change from incident-wave-only to a standing wave is of considerable interest and relevance. As time advances the "travelling wave" picture in Fig. 9 evolves into the "standing wave" of Fig. 10. At observer #1, the incident and the reflected wave are precisely out of phase and the result is zero voltage.   But at observer #2, a quarter-wavelength away, the two waves are in phase and add. The dynamics of the standing wave throughout the AC cycle give students insight into the standing-wave pattern that is derived using phasors in the following lectures. These transitions can also be demonstrated effectively with one-dimensional FDTD programs such as that of Ref. [6].

Power Splitter

Fig. 11 shows a power splitter made of a 50 ohm line, a quarter-wave transformer, and two parallel 50 ohm lines with matched loads.   The leading edge of the sinusoid is initially reflected from the input of the quarter-wave transformer. Watching the animation carefully, this reflected wave can be seen clearly. The match is built up only after the reflection from the junction of the two output lines has propagated back to the input of the transformer, and indeed several trips back and forth are needed for the match to be perfect.   In Fig. 11 time has advanced to steady state and it is clear that the incident voltage has been split into two equal sine waves at observers #2 and #3. Also, as time advances, it is clear that there is no standing wave on the input line, that is, that the transformer provides a perfect match. It is instructive to watch the wave progress through the transformer as time advances.   BOUNCE's time-domain

solution can be compared with the sinusoidal steady state solution obtained with BOUNCE's companion program, TRLINE[7].

For more advanced students, stub matching circuits can be examined in a similar way to discover how the match is built up. The matching circuit can be designed and verified in the frequency domain using TRLINE, and then the voltages on the lines and stubs examined throughout the AC cycle with BOUNCE. Similarly, a bandpass filter can be built from three stubs, and the voltages on the lines and stubs can be examined throughout the AC cycle, both for frequencies in the pass band and for those in the stop band.

How It Works

BOUNCE subdivides each transmission line into an integer number of cells such that the wave on each line propagates a distance of exactly one cell in each time step. Transmission line lengths are approximated with integer number of cells. A trade-off exists between fast simulation and good spatial resolution. On the one hand, a large time step leads to snappy animation, but with poor approximation of line lengths. On the other hand, a fine time step slows the animation but provides fine distance resolution. This is a good lesson in the compromises associated with time domain methods in computational electromagnetics.

The program maintains two vectors for the voltage on each transmission line: one for the value of the positive-going travelling wave in each cell and one for the negative. At each time step the program shifts the entries in the positive-going vector one step forward, and the entries for the negative-going wave one step back. The vectors are then summed and the result displayed on the computer screen. In each shift, one entry pops out of the end of the positive-going vector. It is multiplied by the reflection coefficient for the load or junction connected to the end of that transmission line. The result is entered into the end of the vector for the negative wave. Similarly, multiplication by the transmission coefficient provides a value to enter into the first position for the positive-going wave vector for the next transmission line in series. This provides a simple, fast algorithm for handing interactions at loads and junctions in the transmission line circuit.

The author was intrigued that the class of computer engineering students showed no curiosity whatever concerning how the BOUNCE program computes the voltages on the lines as a function of time. The class seemed content to use the program as a black box.

The present version of BOUNCE has some limitations. The program does not display the current on the transmission lines.   The positive-going wave and the negative-going wave cannot be displayed separately, only the net voltage on each transmission line. Loads are resistive only.   These are not fundamental limitations. Removing them is a small matter of programming. Lossy
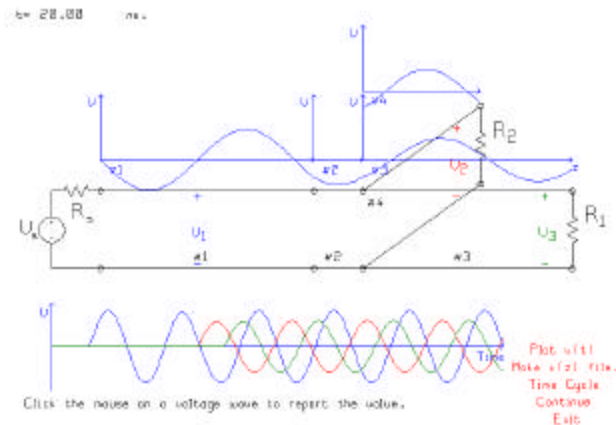
Fig. 11 A power splitter using a quarter-wave transformer to match to parallel transmission lines to the generator.

lines are more difficult to implement and FDTD may provide a better algorithm in that case.

Conclusion

The instructor should plan classroom demonstrations carefully and run BOUNCE to rehearse them. For each problem a "bnc" data file should be created with the source and transmission line parameters, and an appropriate time step and time cycle. Each demonstration needs to be repeated in the classroom at least twice. It is imperative that the instructor be fluent in operating the program and comfortable using it. Then students see that the program is easy to use and are encouraged to try it themselves.

BOUNCE was received enthusiastically by the class and the instructor was pleasantly surprised at the extent to which students used the program. Students are asked to write their comments on the course as part of the anonymous "course evaluation". Of 61 students registered, 48 filled out course evaluation questionnaires, and 31 wrote comments. Of these 22 mention the BOUNCE program, all favorably. One student commented "the computer programs (BOUNCE and TRLINE) were very useful to understand the transmission lines part and to visualize the travelling waves". Another commented "The BOUNCE and TRLINE programs are useful in seeing what actually happens on transmission lines." Another student wrote "The programs … are extremely useful and fun and helped (me to) understand the material a great deal", and another, "The computer programs were very good. I was able to see graphically what was happening." These comments encourage the author to consider writing demonstration programs for other parts of the course.

The transmission line segment represents about 4 lectures in a 26 lecture sequence. The final exam had 6 questions, of which one customarily deals with transients on transmission lines. Although no statistics were compiled, the instructor got the impression that this questions was answered much better by the class this year than in previous years when BOUNCE was not used.

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