BOUNCE User's Guide

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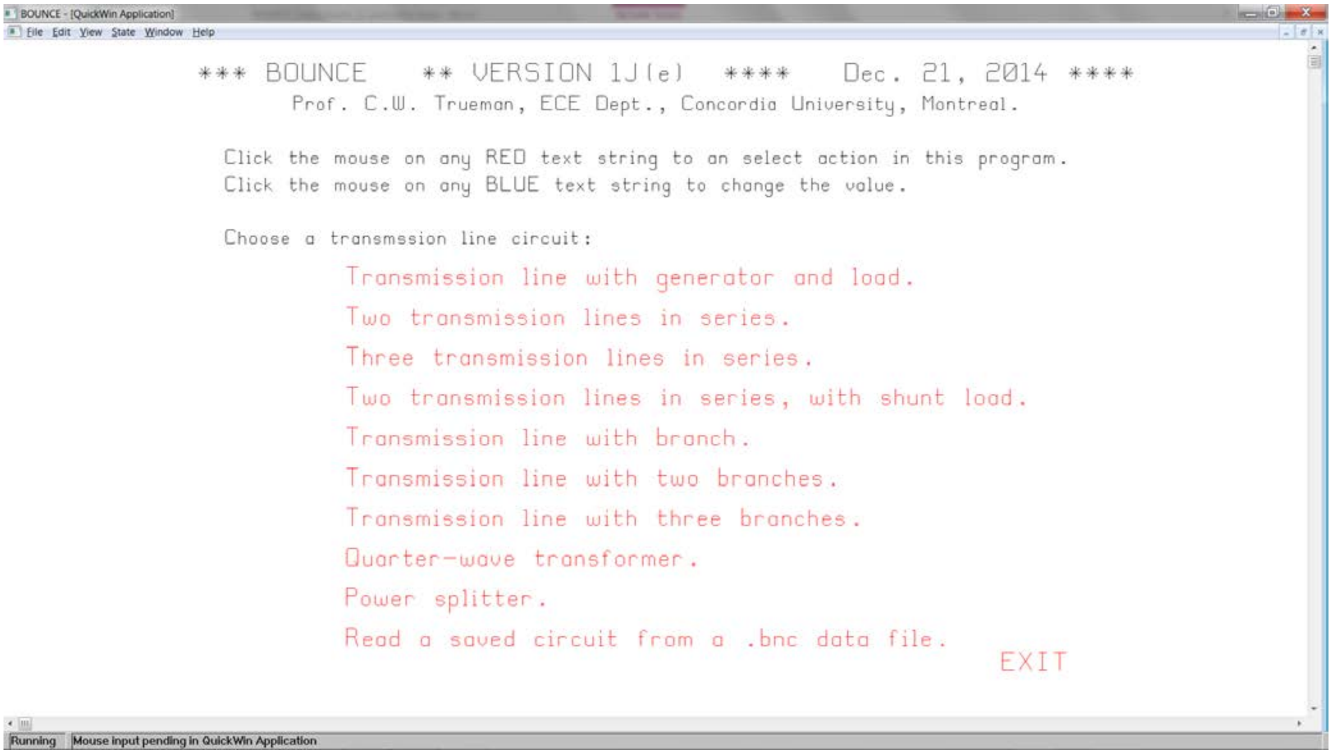
Introduction

Program BOUNCE uses animation to show waves traveling on transmission lines. BOUNCE is designed to be very easy to use: a few mouse clicks and a wave is traveling across the screen. The program uses built-in circuit templates for various series and branching transmission line circuits. Transmission line parameter values and load values are entered using interactive menus. The generator can be a step, a square pulse, a triangular pulse, a square wave at a given frequency, or a sine wave. Loads terminating transmission lines can be resistors, or RC or RL circuits in series or in parallel. BOUNCE under Windows 7.

Program BOUNCE has been described in "Teaching Transmission Line Transients Using Computer Animation" [1] at the Frontiers in Education Conference in the fall of 1999, and in "Animating Transmission Line Transients with BOUNCE" [2] in the IEEE Transactions on Education.

Starting BOUNCE

Create a directory for your project and copy the "bounce.exe" file into the directory. Then run BOUNCE either by double-clicking on "bounce" in the directory window, or by opening a DOS window and changing to the directory, and then typing the command "bounce". The entry menu is shows in Fig. 1. BOUNCE uses menus in which text strings printed in RED are menu buttons. Click the mouse on a red text string to select that menu item. The lower right corner of the screen usually has a button labelled "back" to return to the previous menu, or "Exit" in the main menu to terminate the program.



```
*** BOUNCE    ** VERSION 1J(e)   ****   Dec. 21, 2014 ****
      Prof. C.W. Trueman, ECE Dept., Concordia University, Montreal.

 Click the mouse on any RED text string to an select action in this program.
 Click the mouse on any BLUE text string to change the value.

 Choose a transmssion line circuit:
          Transmission line with generator and load.
          Two transmission lines in series.
          Three transmission lines in series.
          Two transmission lines in series, with shunt load.
          Transmission line with branch.
          Transmission line with two branches.
          Transmission line with three branches.
          Quarter-wave transformer.
          Power splitter.
          Read a saved circuit from a .bnc data file.
                                                        EXIT
```

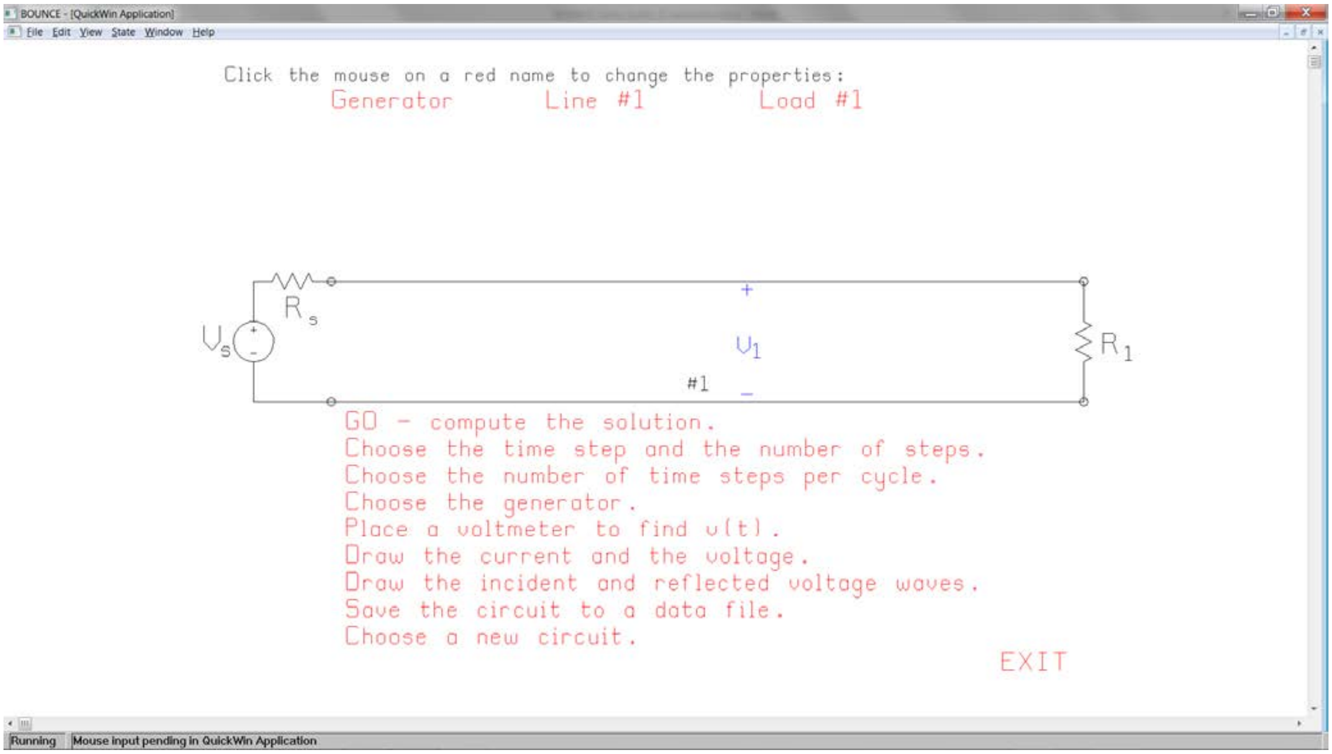
Running   Mouse input pending in QuickWin Application

Fig. 1 The entry menu lets the user choose a circuit template.

BOUNCE has a variety of built-in "circuit templates" of increasing complexity, from a simple transmission line to a line with three branches. Choose a circuit template by clicking the mouse on the name of the circuit. Or you can recall a previously saved circuit by choosing “Read a saved circuit…” which reads a circuit saved as a “bnc” file or “bounce” file.

BOUNCE’s Main Menu

Choose a circuit template in the entry menu, and BOUNCE sets up the circuit and then shows the main menu. For example, choosing "transmission line with generator and load" by clicking the mouse on the red text string obtains the main menu shown in Fig. 2.



Click the mouse on a red name to change the properties:

Generator Line #1 Load #1

GO – compute the solution.
Choose the time step and the number of steps.
Choose the number of time steps per cycle.
Choose the generator.
Place a voltmeter to find v(t).
Draw the current and the voltage.
Draw the incident and reflected voltage waves.
Save the circuit to a data file.
Choose a new circuit.

EXIT

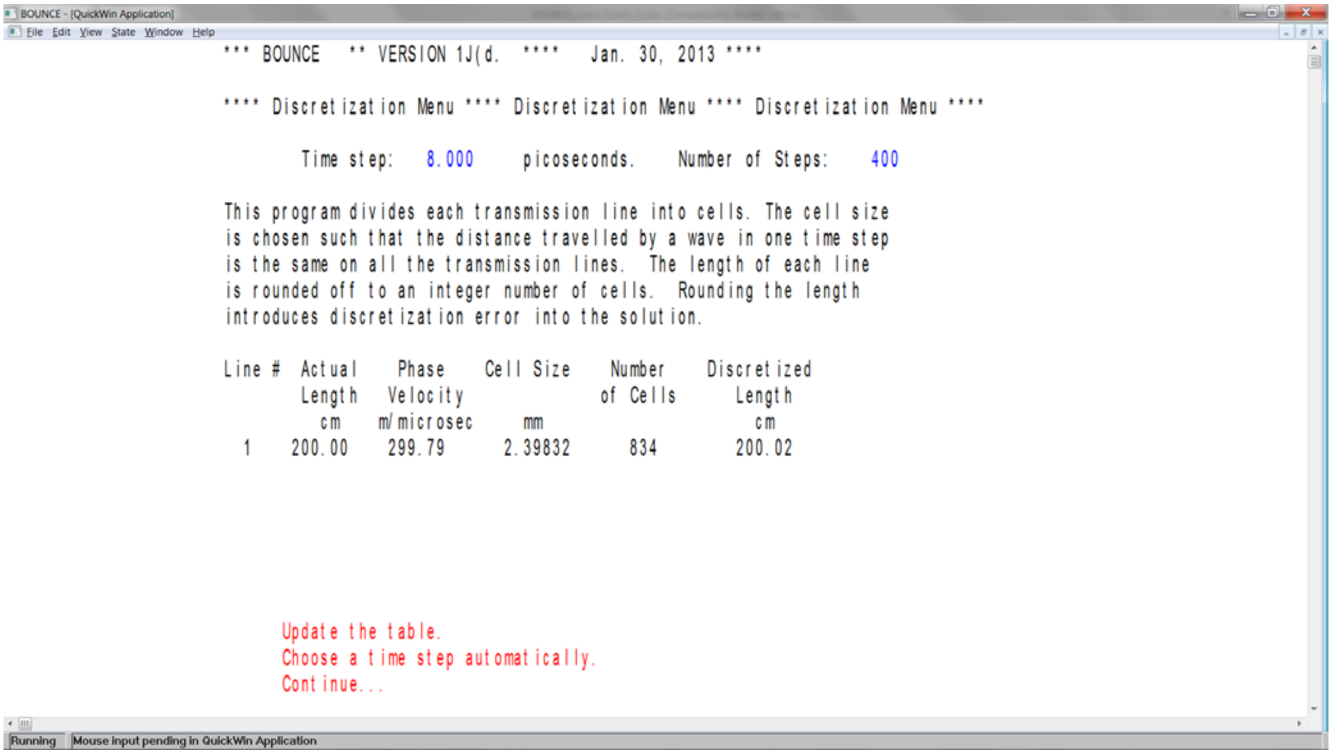
Fig. 2 The main menu in BOUNCE shows the circuit schematic and lets the user choose the generator, line properties and load properties, then run the simulation.

The main menu in BOUNCE has four parts. The center of the screen shows a schematic of the circuit. Here we see a voltage generator V_s, with internal resistance R_s, a transmission line labeled "#1" at the bottom center, and a load R_1. BOUNCE uses "voltmeters" to measure the voltage as a function of time at selected points on the transmission line. In this circuit, there is a "voltmeter" V_1 near the center of the transmission line. You can move this voltmeter and add more with the voltmeters menu, which is described below. In the lower right-hand corner, there is an “EXIT” button to terminate the BOUNCE program.

Below the circuit there is a button labelled “GO – compute the solution”. Click the mouse on “GO” runs the simulation and BOUNCE shows the voltage wave traveling along the transmission line. The top area of the main menu has buttons that you can click to modify the properties of the generator, of each transmission line in the circuit, and of each load in the circuit. These are described more fully below. The area below the circuit diagram offers menu items to modify the time step and the length of the time cycle; to change the generator; to move the voltmeters; to view the current or the positive-going and negative-going traveling wave components; to save the circuit as a “bnc” file; and to change to a new circuit.

Program Control Buttons

Below the circuit diagram on the main menu, there are seven “program control buttons”: choose the time step; Choose the number of time steps per cycle; Choose the generator; Place a voltmeter; Draw the current and the voltage; Draw the incident and reflected voltage waves; Save the circuit; and Choose a new circuit.

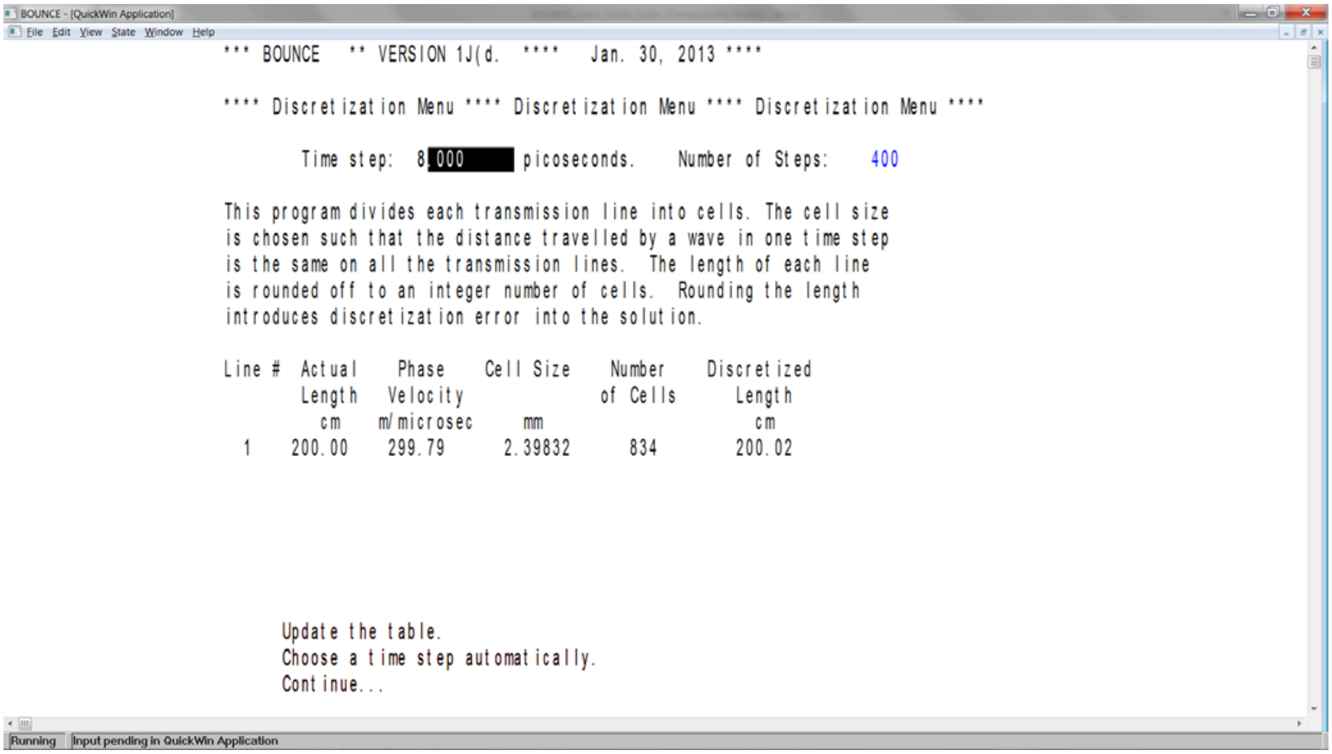


```
*** BOUNCE   ** VERSION 1J(d.   ****   Jan. 30, 2013 ****

**** Discretization Menu **** Discretization Menu **** Discretization Menu ****

        Time step:   8.000     picoseconds.    Number of Steps:    400

This program divides each transmission line into cells. The cell size
is chosen such that the distance travelled by a wave in one time step
is the same on all the transmission lines.  The length of each line
is rounded off to an integer number of cells.  Rounding the length
introduces discretization error  into the solution.

Line #  Actual     Phase     Cell Size    Number     Discretized
        Length    Velocity               of Cells      Length
          cm     m/microsec     mm                       cm
  1     200.00    299.79     2.39832      834         200.02




      Update the table.
      Choose a time step automatically.
      Continue...
```

Fig. 3(a) The time step menu.

Choose the Time Step

Click the mouse on “Choose the time step” in the main menu of Fig. 2 to obtain the time step menu of Fig. 3(a). Blue character strings are numerical values that you can change. Click the mouse on a blue character string such as “8.000” in Fig. 3 to change its value, to get the menu of Fig. 3(b). The number to be changed appears in inverse video, and the red menu buttons turn black because they are not active. Type a new value, and then push the “enter” key on the keyboard to return to the time step menu of Fig. 3(a). The menu buttons become active and are shown in red.



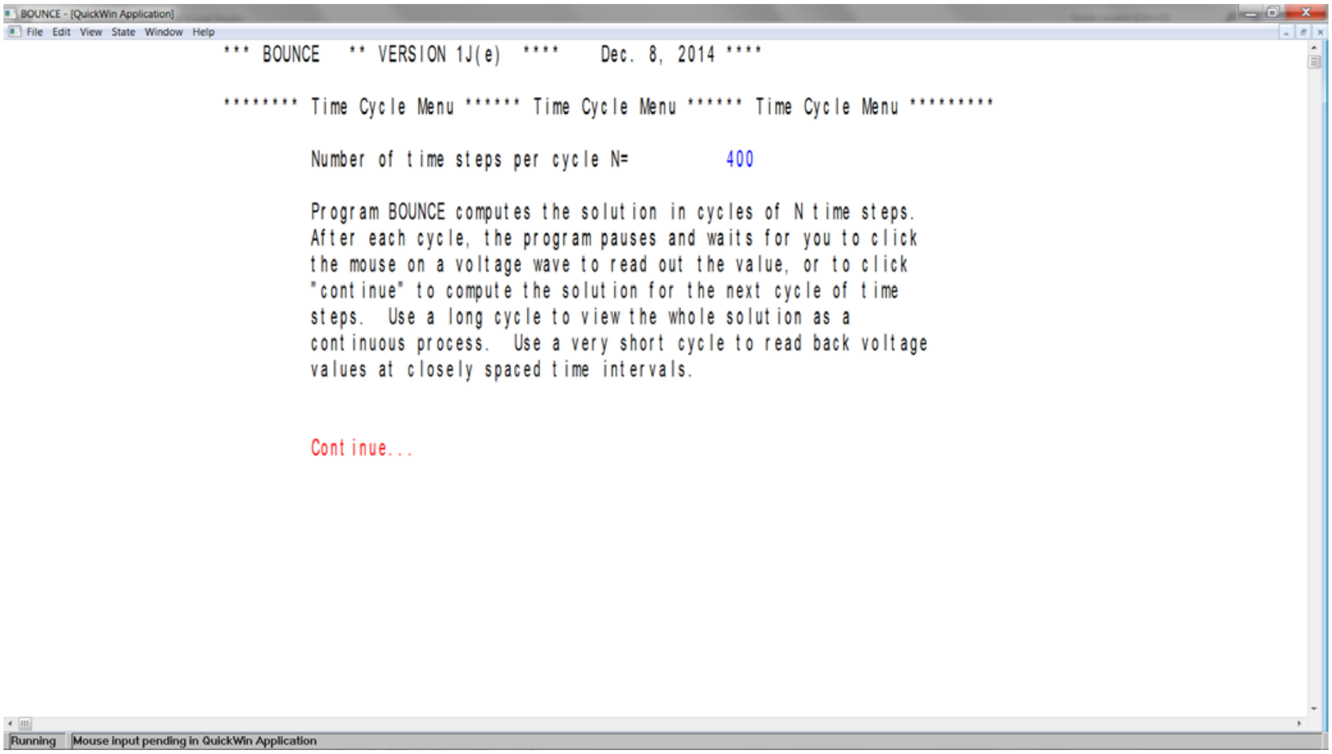
```
*** BOUNCE  ** VERSION 1J(d.  ****  Jan. 30, 2013 ****

**** Discretization Menu **** Discretization Menu **** Discretization Menu ****

        Time step:  8.000     picoseconds.   Number of Steps:   400

This program divides each transmission line into cells. The cell size
is chosen such that the distance travelled by a wave in one time step
is the same on all the transmission lines.  The length of each line
is rounded off to an integer number of cells.  Rounding the length
introduces discretization error into the solution.

Line #  Actual    Phase    Cell Size   Number    Discretized
        Length   Velocity              of Cells    Length
          cm    m/microsec     mm                    cm
  1     200.00    299.79    2.39832      834       200.02




      Update the table.
      Choose a time step automatically.
      Continue...
```

Fig. 3(b) Change the value of the time step by clicking on the blue character string.

BOUNCE solves the circuit in the time domain by dividing time into “time steps” of duration Δt. BOUNCE finds the voltages and currents on the transmission lines at the current time step, updates the display, then advances time by one step, and solves the circuit again. BOUNCE "runs" the simulation for a period of time equal to the number of time steps in a “time cycle”, and then pauses to let you examine the waveforms on the screen and to use the mouse to “read back” values. This menu lets you chose the time step and number of steps in the time cycle.

In BOUNCE, at each time step, the wave travels a distance step of $\Delta z = u\Delta t$ on the transmission line, where u is the wave speed. BOUNCE approximates the length of the transmission line as an integer number of distance steps Δz, so that the wave reaches the end of the transmission line in an integer number of steps. BOUNCE does not obtain the exact solution to the problem because the length of each line is approximated as an integer number of distance steps. The table at the bottom of the menu show the actual length of each transmission line, the number of distance steps Δz used to approximate the length, and then the approximate length that BOUNCE uses. With a time step of 8 ps, the 200 cm transmission line is approximated with 834 “cells” or distance steps, and the length is approximated as 200.02 cm. If you use a coarse time step, the lengths of the lines are more approximate but the simulation proceeds rapidly. If you use a fine time step, the length approximation is more accurate but the simulation goes more slowly. If the total number of transmission line cells is about 500, we get a reasonable tradeoff between accuracy and speed.

There are three menu buttons at the bottom of the screen in Fig. 3(a). If you change the time step, then the program is not smart enough to update the table automatically. Click “Update the table” to see the new values. If you are not sure of what time step to choose, click “Choose a time step” and the program will make a choice for you. This is based on the rule of thumb that the total number of cells in the problem should be about 500. Click “Continue” to return to the main menu.



```
*** BOUNCE   ** VERSION 1J(e)  ****    Dec. 8, 2014 ****

******** Time Cycle Menu ****** Time Cycle Menu ****** Time Cycle Menu *********

         Number of time steps per cycle N=          400

         Program BOUNCE computes the solution in cycles of N time steps.
         After each cycle, the program pauses and waits for you to click
         the mouse on a voltage wave to read out the value, or to click
         "continue" to compute the solution for the next cycle of time
         steps.  Use a long cycle to view the whole solution as a
         continuous process.  Use a very short cycle to read back voltage
         values at closely spaced time intervals.


         Continue...
```

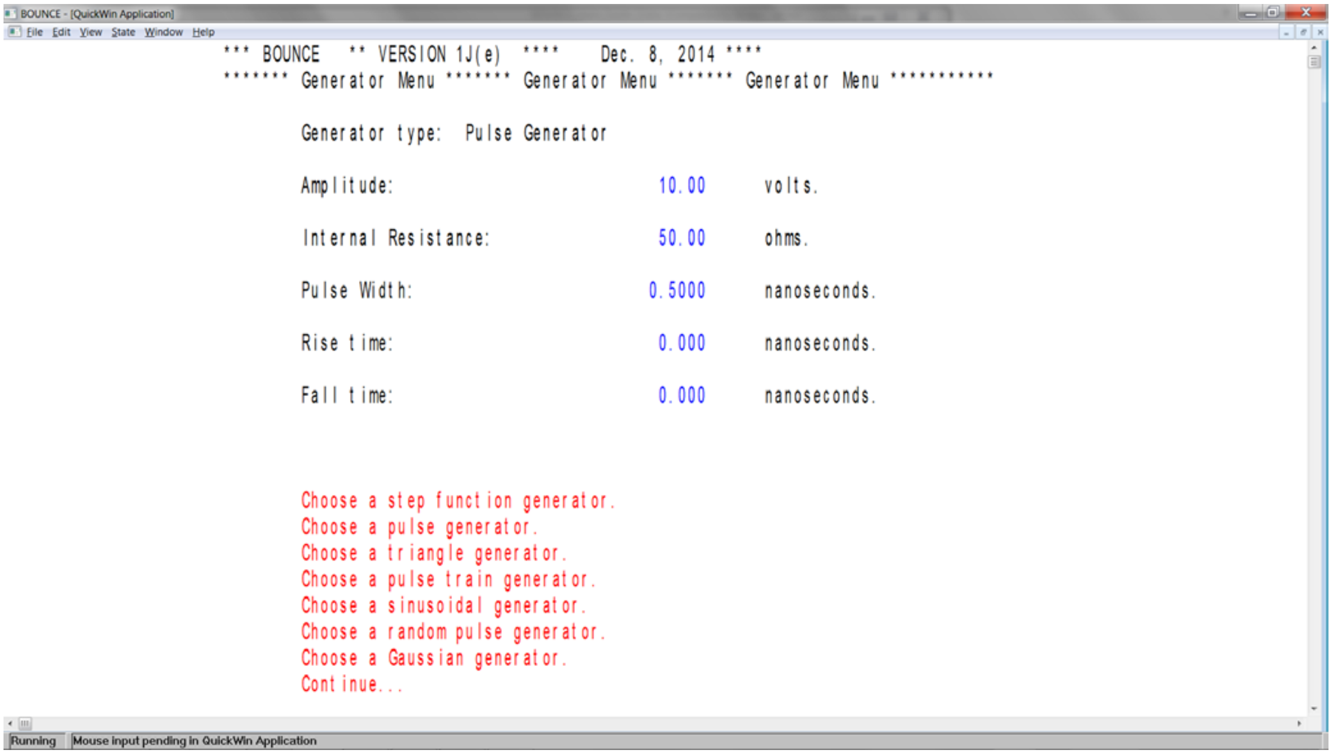
Running

Mouse input pending in QuickWin Application

Fig. 4 Choose the number of time steps per cycle.

Choose the Number of Time Steps per Cycle

From the main menu of Fig. 2, click “Choose the number of time steps per cycle” to get the cycle menu of Fig. 4. Click on the blue string and type the new value, then type the “Enter” key to return to the menu. Click the red string “Continue” to return to the main menu.

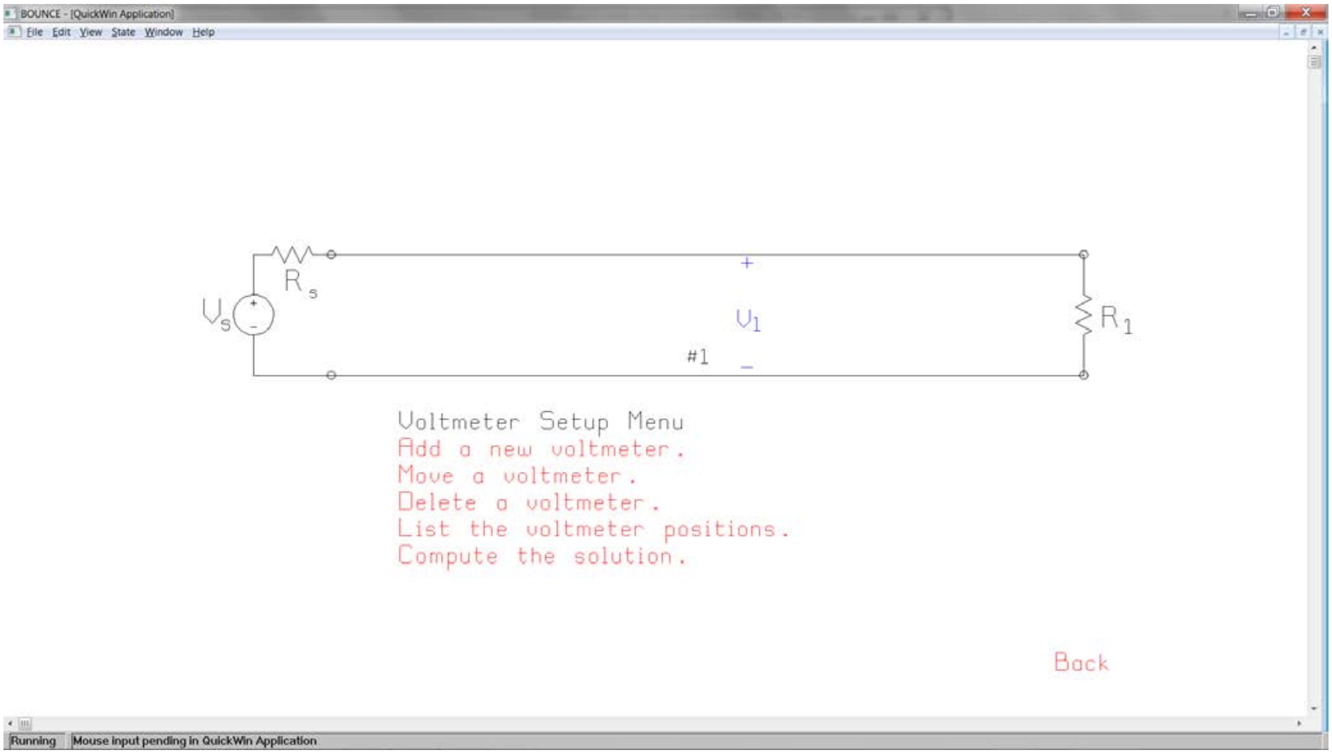


```
*** BOUNCE   ** VERSION 1J(e)   ****    Dec. 8, 2014 ****
******* Generator Menu ******* Generator Menu ******* Generator Menu ***********

        Generator type:  Pulse Generator

        Amplitude:                         10.00      volts.

        Internal Resistance:               50.00      ohms.

        Pulse Width:                      0.5000      nanoseconds.

        Rise time:                         0.000      nanoseconds.

        Fall time:                         0.000      nanoseconds.



        Choose a step function generator.
        Choose a pulse generator.
        Choose a triangle generator.
        Choose a pulse train generator.
        Choose a sinusoidal generator.
        Choose a random pulse generator.
        Choose a Gaussian generator.
        Continue...
```

Fig. 5 Define the voltage generator with this menu.

Choose the Generator

The menu of Fig. 5 lets you choose the waveform of generator or source, and gets the same menu as the "Generator" button at the top of the screen. Choose the type of source: step, pulse, triangle, square wave or "pulse train", sinusoid, random pulse sequence, or Gaussian pulse. Note that you must be careful that your pulse length makes sense compared to the delay times of your transmission lines, and to the time step that you have chosen. As in any computer simulation, it is easy to compute nonsense!



Mouse input pending in QuickWin Application

Fig. 6 Place a voltmeter.

Place a Voltmeter

In BOUNCE, you place “voltmeters” on the transmission lines to observe the voltage waveform at a desired location. You can have up to four voltmeters. The menu lets you create a new voltmeter, move a voltmeter, delete one, or list the positions of the voltmeters and adjust them. Use the “Back” button at the lower right to return to the main menu. More information about voltmeters can be found below.

Draw the Current and the Voltage on each Transmission Line

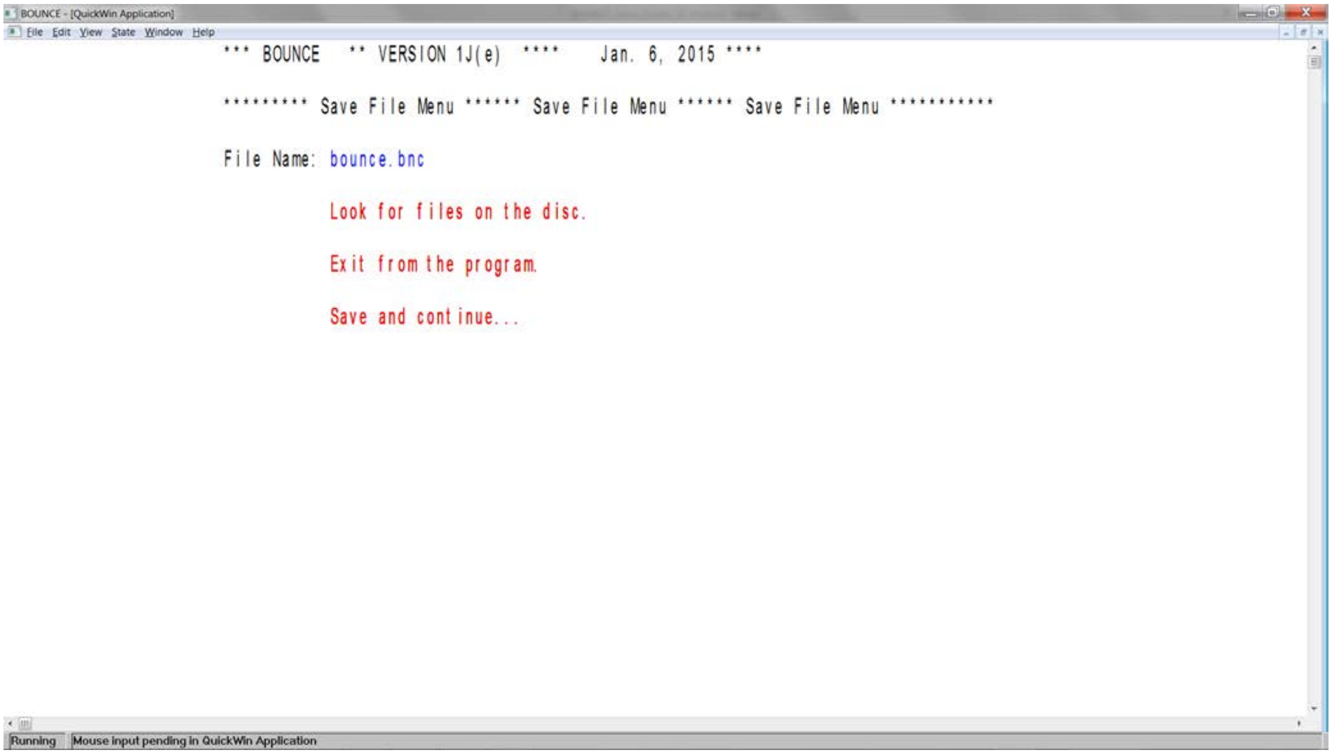
When the simulation is run by clicking the mouse on the "GO" button at the lower right, BOUNCE draws the voltage on each transmission line as a function of the position on the line, at each time step. As time advances the voltage wave progresses across the screen and is reflected from junctions and loads. To see the current wave on the transmission lines as well, click the “Draw the current” button. The voltage wave is drawn in blue, and the current in red.

Draw the Incident and Reflected Voltage Waves

Clicking the "GO" button shows the voltage on the transmission lines as a function of distance and time. The voltage can be written as the superposition of a positive-going traveling wave $V^+(z,t)$ plus a negative-going traveling wave, $V^-(z,t)$ according to

$$V(z,t) = V^+(z,t) + V^-(z,t)$$

Sometimes it is instructive to see the positive-going wave and the negative-going wave individually. Clicking the “Draw the incident…” button and the program draws the incident wave $V^{+}(z,t)$ and the reflected wave $V^{-}(z,t)$ individually, as well as their sum.



```
*** BOUNCE  ** VERSION 1J(e)  ****   Jan. 6, 2015 ****

********* Save File Menu ****** Save File Menu ****** Save File Menu ***********

File Name: bounce.bnc

           Look for files on the disc.

           Exit from the program.

           Save and continue...
```

Fig. 7 Give a file name and click Continue or Exit to save the circuit to a “bnc” file.

Save the Circuit

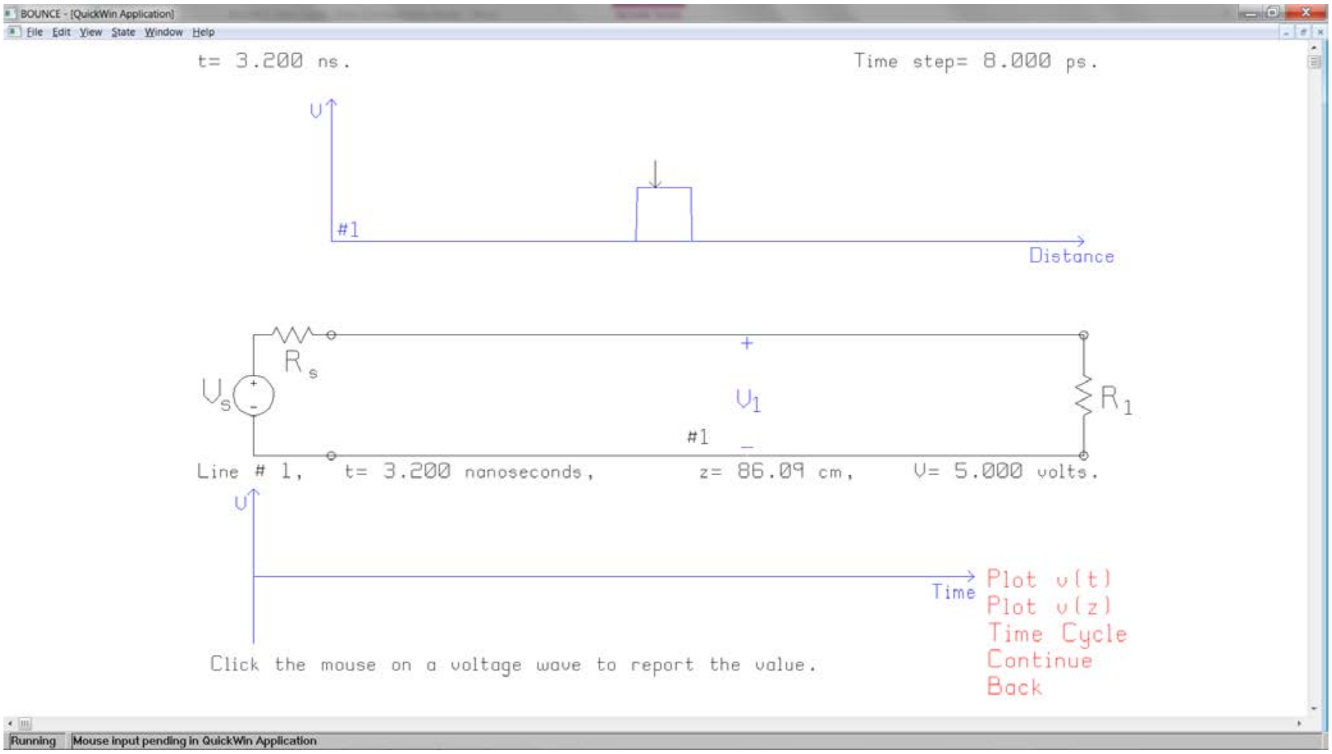
If you have entered values for the generator, the line lengths, speeds and characteristic resistances, and values for the loads, then you may want to save all these values to a "bnc" data file. Then you can recall the circuit later and you won’t have to re-enter all the numbers. You can do this using the “Save the circuit” menu button to get the menu of Fig. 7. Click the mouse on the blue file name character string and type a file name. The standard file extension for this program is "bnc".

Choose a New Circuit

This button gets back the entry menu, which lists the circuit templates, and also lets you read a circuit from a "bnc" file that you saved on a previous run of the program.

Running the Simulation

The “default” values for the simple circuit of Fig. 1 are as follows. The generator is has internal resistance 50 ohms and the open-circuit voltage is a 10-volt, 0.5-ns pulse, and are shown in the menu of Fig 5. The transmission line has length 2 m, propagation velocity 29.797 cm/ns, and characteristic resistance 50 ohms. The load is 50 ohms, matched to the transmission line.



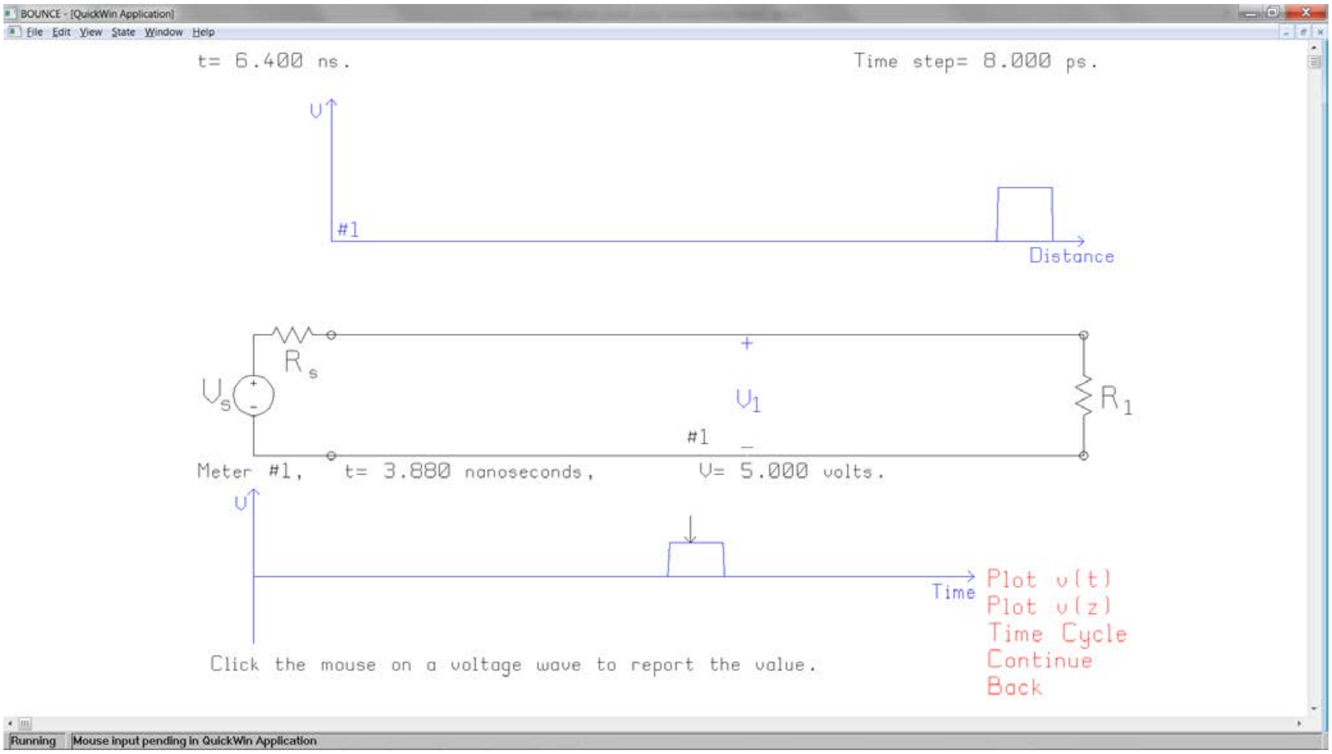
```
t= 3.200 ns.                                        Time step= 8.000 ps.
Line # 1,   t= 3.200 nanoseconds,       z= 86.09 cm,      V= 5.000 volts.
Click the mouse on a voltage wave to report the value.
Mouse input pending in QuickWin Application
```

Fig. 8 The simulation pauses after one time cycle.

Click the mouse on the “GO” button in the main menu to run the simulation and start time advancing. We see the pulse emerge from the generator and then move out onto the transmission line. With the time step set to 8 ps and the time cycle set to 400 steps, the program pauses after 3.2 ns and the display is shown in Fig. 8. The pulse from the generator advances onto the transmission line and propagates about a half of the distance to the load. Click the mouse on the pulse and the program reports the mouse location as z=86.09 cm, and the voltage as 5.000 volts. The small arrow above the pulse shows where the mouse was clicked, and the data for the voltage is shown below the circuit schematic.

The simulation menu shown in Fig. 8 has three parts. The graph at the top of the screen in Fig. 8 shows voltage as a function of *distance* along the transmission line. The generator launches a wave onto the transmission line, and as time advances, you see the wave traveling along on the transmission line. The graph across the bottom of the screen shows voltage as a function of *time* at the voltmeter location on the transmission line. In Fig. 8, the pulse has not yet reached the voltmeter so the voltage there is zero. The simulation menu of Fig. 8 shows the time step in the upper right corner to remind the user that BOUNCE advances time in discrete steps, and the results obtained can be dependent on the time step because of the approximation of the length of the transmission lines.

Click the mouse on the voltage pulse at the top of the screen to “read back” the voltage and position. Fig. 8 shows that the BOUNCE program draws a small arrow on the waveform at the location where the mouse was clicked, and reports the value of the time, position and voltage below the circuit schematic. Thus, in Fig. 8, at time 3.2 ns and 86.09 cm distance, the voltage is 5.000 volts.



BOUNCE - [QuickWin Application]

t= 6.400 ns.

Time step= 8.000 ps.

Meter #1, t= 3.880 nanoseconds, V= 5.000 volts.

Click the mouse on a voltage wave to report the value.

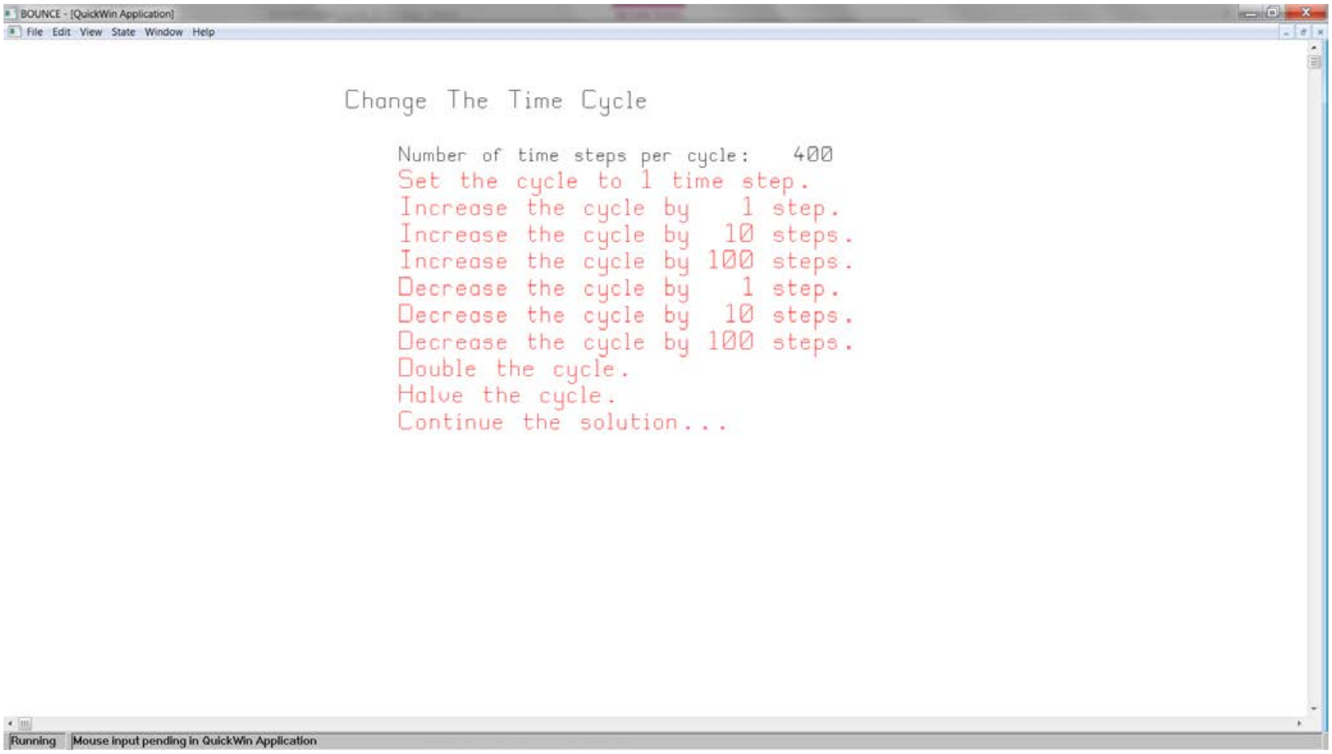
Running

Mouse input pending in QuickWin Application

Fig. 9 The simulation after one more time cycle.

Click “Continue” in the lower right corner of the simulation menu and time starts to advance once again. When the leading edge of the pulse reaches the position of the voltmeter the voltage as a function of time at the bottom of the screen pops up to 5 volts, and then when the trailing edge passes the voltmeter the voltage drops back down to zero. After a second time cycle has passed, BOUNCE once again pauses, with the pulse approaching the load, with the waveforms shown in in Fig. 9. Click the mouse on the voltage-as-a-function of time to read back the time as 3.8 ns with voltage 5.000 volts. The “read back” feature is very handy for checking answers to homework problems worked out by hand calculation!

By choosing a *short* time cycle we can watch the voltage wave advance with frequent pauses. During each pause, we can use the mouse to “read back” values from the curves. Advancing time in short cycles permits the amplitude of reflected waves to be read back after each individual reflection. Conversely, choosing a *long* time cycle shows the overall picture of what happens in the circuit, with many reflections leading to steady state. Both a short and a long time cycle are useful ways of studying the behavior of the circuit.



```
Change The Time Cycle

    Number of time steps per cycle:   400
    Set the cycle to 1 time step.
    Increase the cycle by   1 step.
    Increase the cycle by  10 steps.
    Increase the cycle by 100 steps.
    Decrease the cycle by   1 step.
    Decrease the cycle by  10 steps.
    Decrease the cycle by 100 steps.
    Double the cycle.
    Halve the cycle.
    Continue the solution...
```

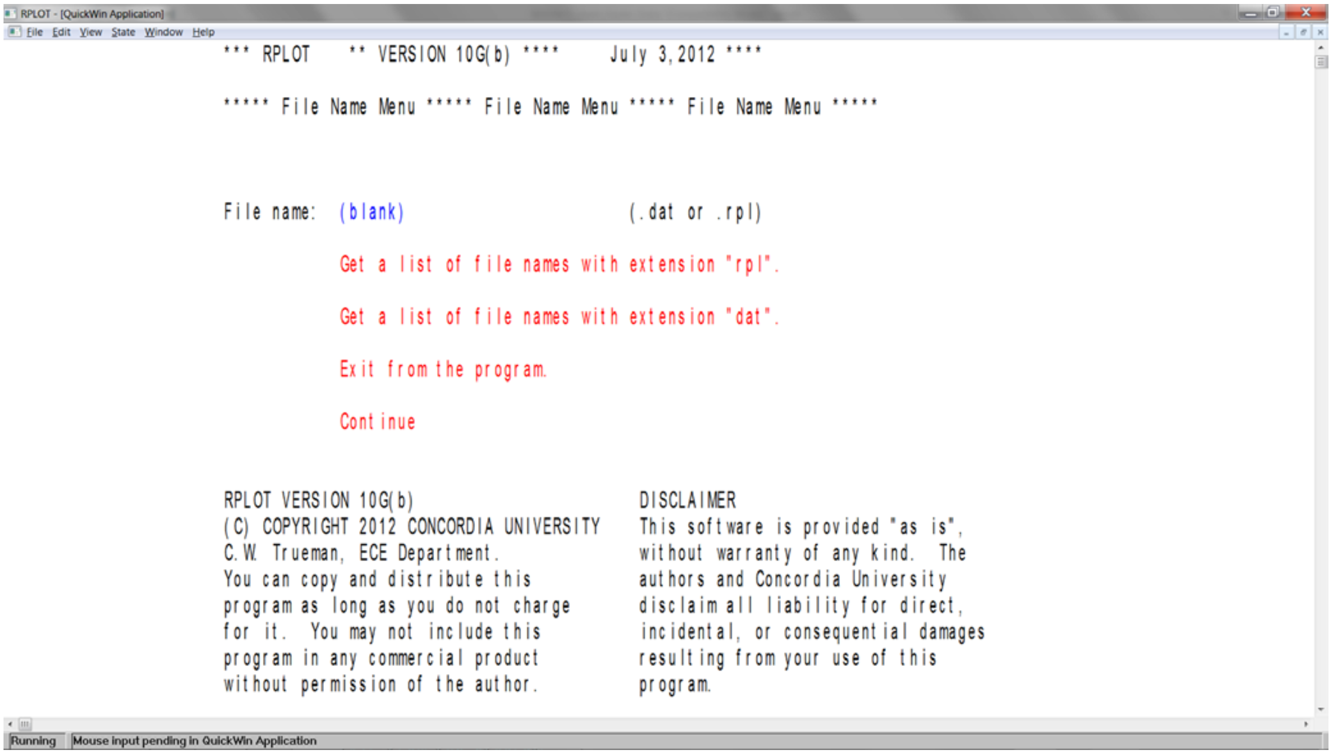
Fig. 10 The time cycle menu is available when the simulation pauses at the end of a time cycle.

The simulation menu of Fig. 8 has some buttons at the lower right to determine what the program will do next. **"Time Cycle"** gets the menu of Fig 10 that lets you increase or decrease the number of steps in each time cycle, and continue the simulation for another time cycle. This can be handy to use a long time cycle to bring the leading edge of a step close to, say, a junction of transmission lines, then change the time to a few steps or even one step to let the simulation proceed very slowly to observe the interaction at the junction in detail. **"Continue"** tells the program to continue the simulation for another time cycle, then pause once again.

Graphing the Transmission Line Voltage as a Function of Distance or Time

The simulation menu of Fig. 8 has buttons labeled **“Plot v(z)”** and **“Plot v(t)”** to graph the voltage on each transmission line as a function of distance and of time, respectively. The graphs are more formal and better labeled than those on the simulation menu. The BOUNCE program uses the general-purpose program RPLOT to graph the waveforms. You need to have “rplot.exe” in the same directory as “bounce.exe”: Get rplot.

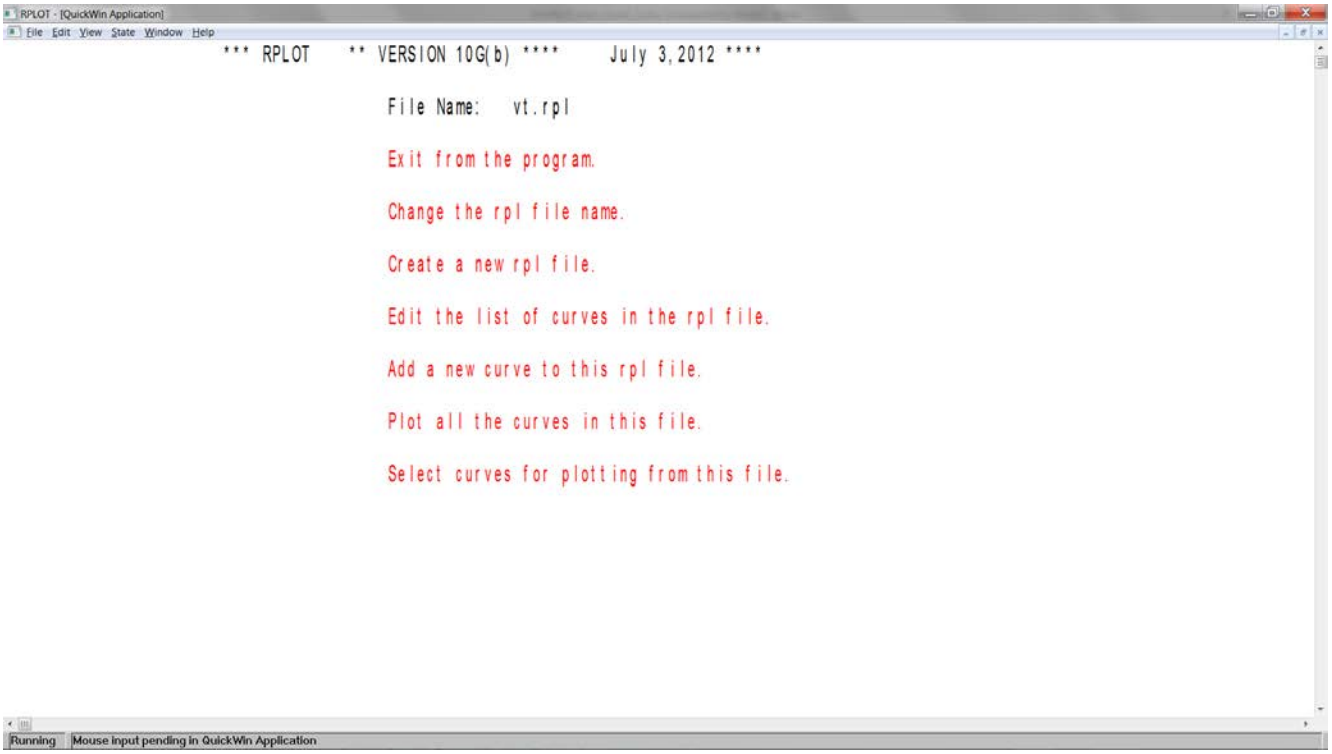
Run the simulation for the simple circuit of Fig. 2 for two time cycles to get the display of Fig. 9. Then click “Plot v(t)”. BOUNCE creates a data file for RPLOT called VT.RPL and then starts the RPLOT program. The execution of BOUNCE is suspended until you exit from RPLOT.



```
*** RPLOT    ** VERSION 10G(b) ****     July 3,2012 ****

***** File Name Menu ***** File Name Menu ***** File Name Menu *****



File name:  (blank)                      (.dat or .rpl)

            Get a list of file names with extension "rpl".

            Get a list of file names with extension "dat".

            Exit from the program.

            Continue


RPLOT VERSION 10G(b)                  DISCLAIMER
(C) COPYRIGHT 2012 CONCORDIA UNIVERSITY  This software is provided "as is",
C.W. Trueman, ECE Department.          without warranty of any kind.  The
You can copy and distribute this      authors and Concordia University
program as long as you do not charge  disclaim all liability for direct,
for it.  You may not include this     incidental, or consequential damages
program in any commercial product     resulting from your use of this
without permission of the author.     program.
```

Fig. 11 The RPLOT entry menu.

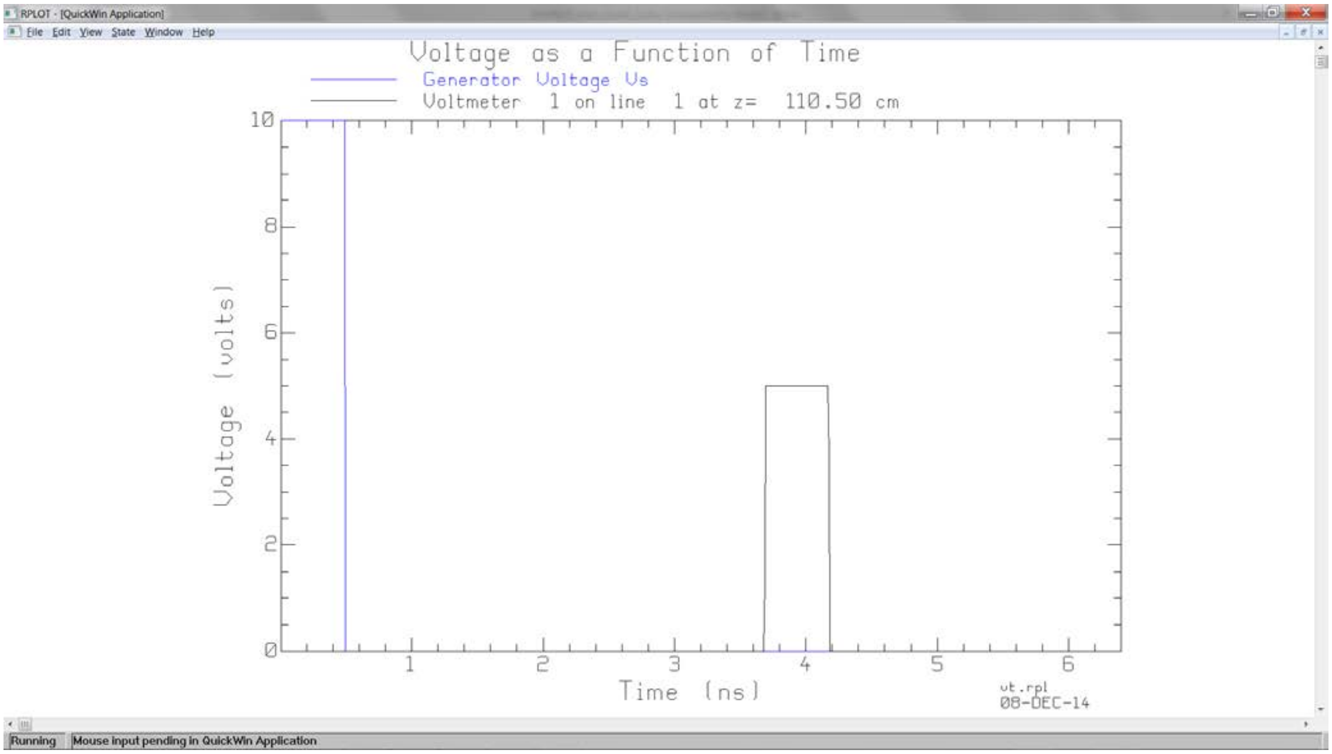
When you click “plot v(t)”, the RPLOT program starts and you see the RPLOT entry menu in Fig. 11. Click the mouse on “(blank)” which is a place-holder for the file name, and type the file name “vt.rpl”, or click the mouse on “Get a list of file names with extension rpl” and choose “vt.rpl” with the mouse. Then click the mouse on “Continue” to get the intermediate menu of Fig. 12.



```
*** RPLOT    ** VERSION 10G(b) ****     July 3,2012 ****

                  File Name:   vt.rpl

                  Exit from the program.

                  Change the rpl file name.

                  Create a new rpl file.

                  Edit the list of curves in the rpl file.

                  Add a new curve to this rpl file.

                  Plot all the curves in this file.

                  Select curves for plotting from this file.
```

Fig. 12 The RPLOT intermediate menu.

Fig. 12 shows RPLOT’s intermediate menu which offers various useful choices for expert RPLOT users. Click the mouse on “Plot all the curves”.



Mouse input pending in QuickWin Application

Fig. 13 The RPLOT display of the voltage as a function of time.

RPLOT graphs the voltage as a function of time as showin in Fig. 13. The blue curve is the generator voltage V_s, and the black curve is the voltage at the location of the voltmeter. In RPLOT you can click the mouse on the curve and the program will “read back” the value and report it in the lower left corner of the screen. If there are several voltmeters RPLOT will display all the curves on the same graph.

```
*** RPLOT    ** VERSION 10G(b) ****     July 3,2012 ****       vt.rpl
 0.8000E-02<= x-data <=  6.400    ,       0.000     <= y-data <= 10.00

x-axis          Linear scale from 0.8000E-02 to  6.400
                Labels every  1.000     units starting at    0.000
                Minor pips between labels:  4
                Multiply x data by factor:  1.000

y-axis          Linear scale from  0.000     to  10.00
                Labels every  2.000     units starting at    0.000
                Minor pips between labels:  3
                Multiply y data by factor:  1.000

x-axis title:               Time (ns)
y-axis title:             Voltage (volts)

       --- Flags ---                       --- Flags ---
       Draw the legend block?   Yes        Write the file name?     Yes
       Draw zero axes?           No        Draw the grid?           No
       Draw the EMC logo?        No        Sort the data?           No
       Write the graph titles?  Yes
```

Fig. 14 The RPLOT main menu.

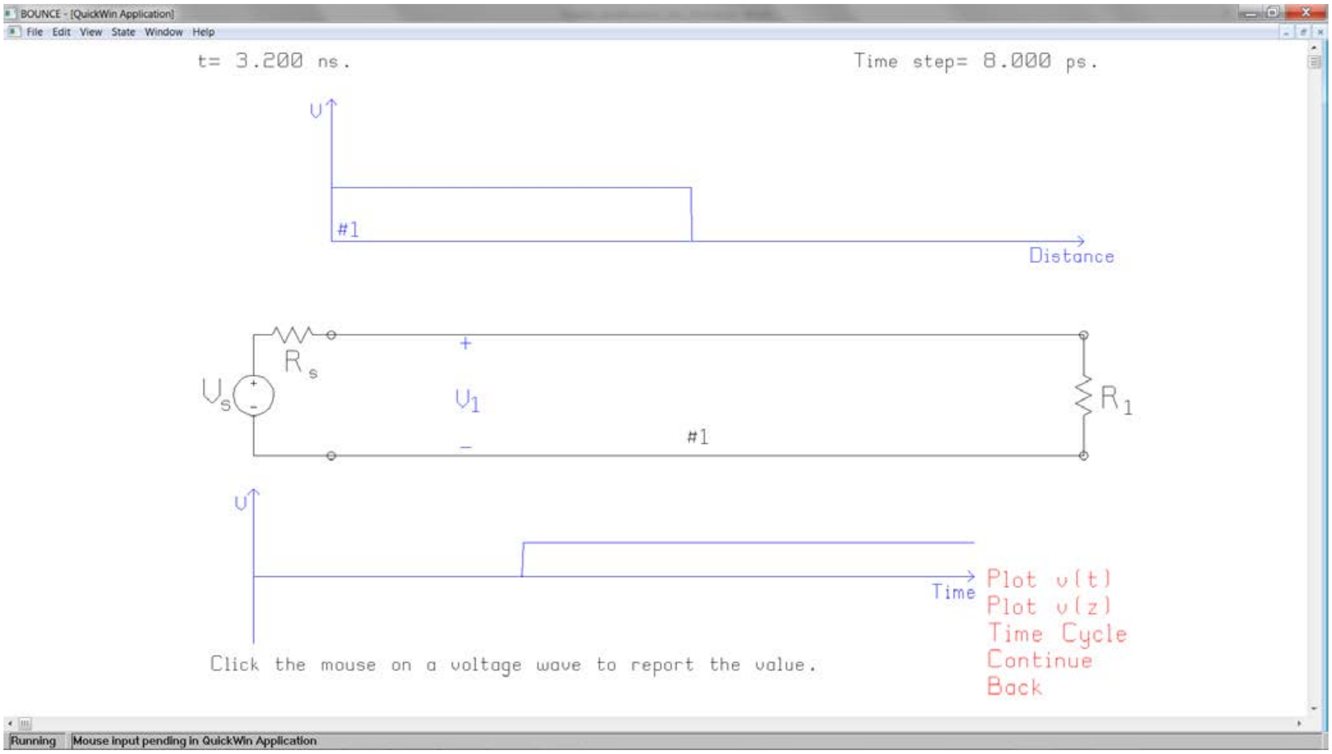
Type the "Enter" key to get the RPLOT main menu of Fig. 14. The RPLOT main menu lets you change the axis ranges, the labels, and the legends for the axes. The "Legends" menu at the bottom right lets you choose colors for the curves, solid or dashed lines, symbols such as crosses, and so forth. Experiment with the sub-menus to discover other features! When you are done click Exit to terminate the RPLOT program. The vt.rpl file remains on the directory in case you want to graph it again. But you should rename it or BOUNCE will overwrite the file next time you run RPLOT to plot a new curve. When RPLOT terminates, execution of BOUNCE resumes.

Generator, Line and Load Menus

The main menu of Fig. 2 offers sub-menus across the top of the screen for the "Generator", for each "Line" and for each "Load". This section describes these menus for choosing the generator, the properties of the transmission lines, and the load properties.

Generator Menu

The "generator menu" lets the user change the properties of the generator, and is obtained by clicking the mouse on "Generator" at the top of the main menu. The generator menu of Fig. 5 offers seven types of generator: a step function, a pulse function, a triangle function, a pulse train, a sinusoid, a string of random zeros and ones, and a Gaussian pulse. The following describes the parameters of each type of generator.



t= 3.200 ns.

Time step= 8.000 ps.

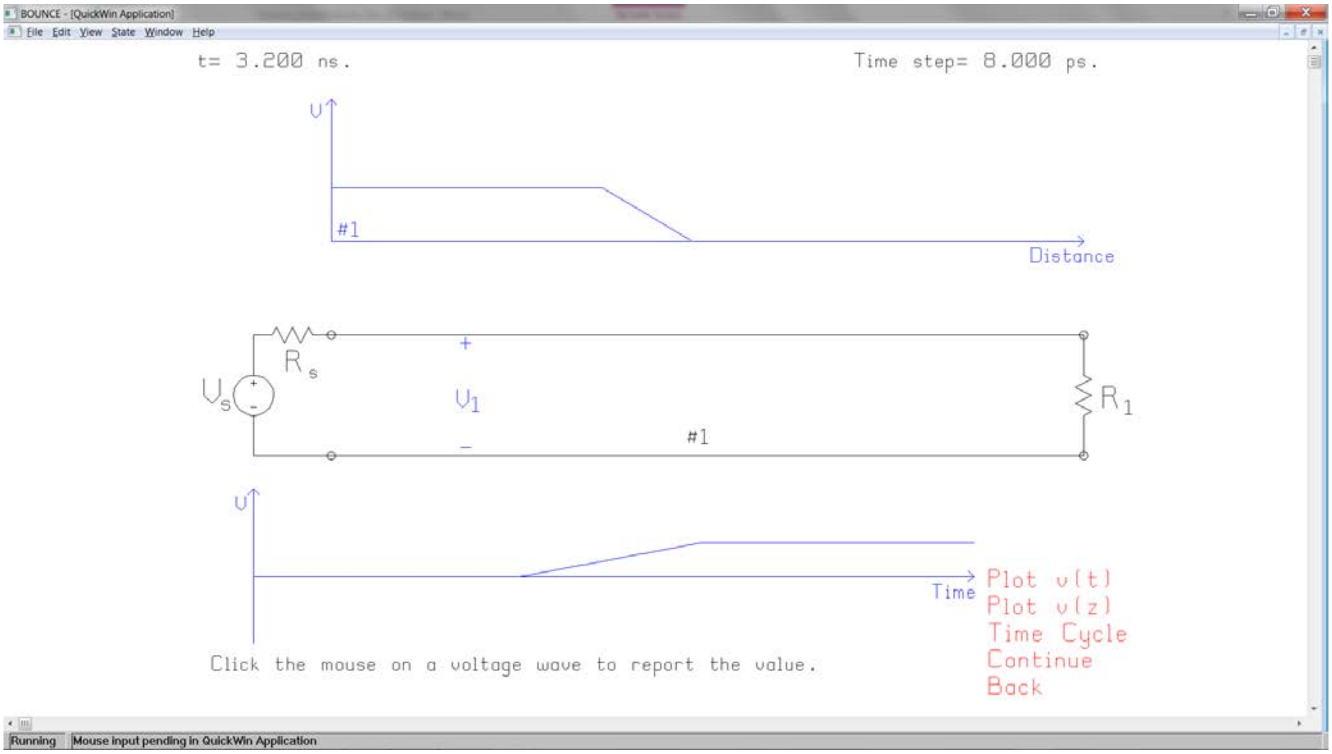
Click the mouse on a voltage wave to report the value.

Fig. 15 The voltage waveform of the step generator.

Step Function Generator

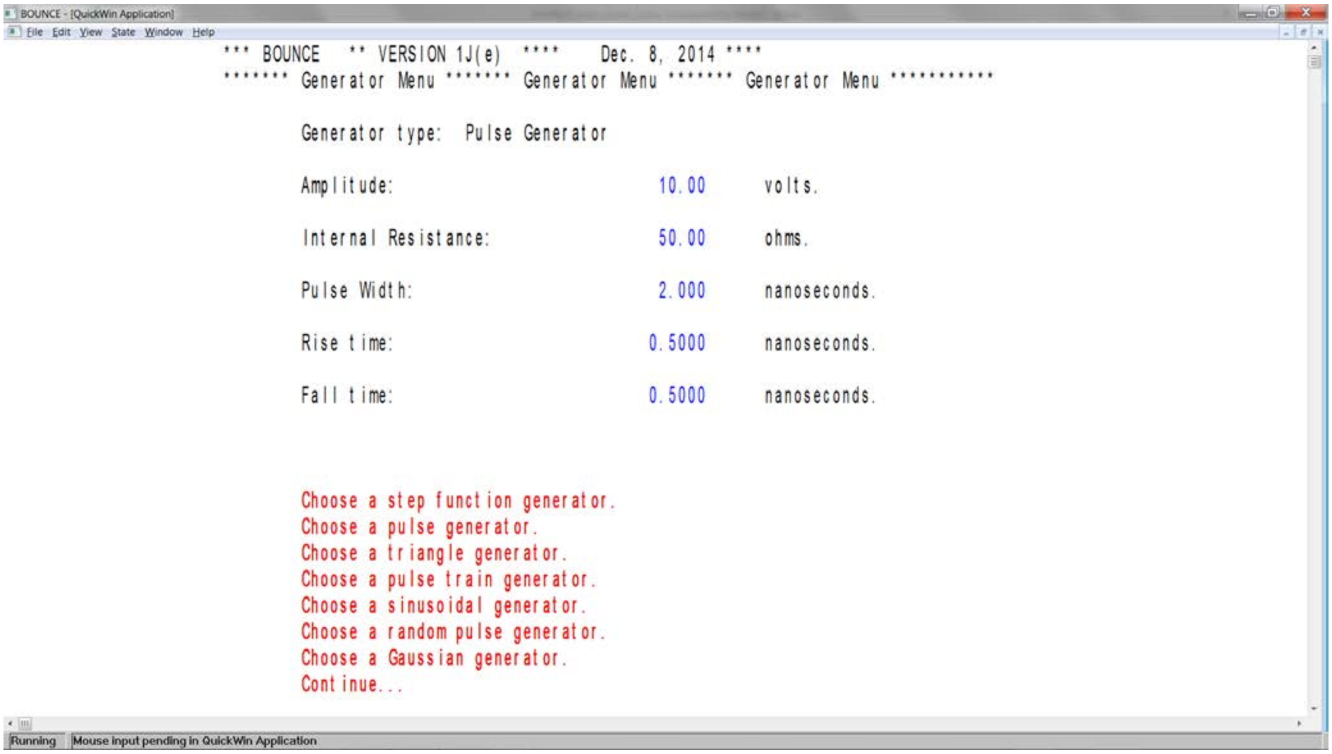
Click on “Choose a step function generator”, and then enter the amplitude or open-circuit voltage, the internal resistance, and the rise time in the menu boxes of Fig. 8. The step function generator’s waveform is shown in Fig. 15. Even if the rise time is zero, the step generator takes one time step to rise linearly from zero to its full amplitude so is not a true mathematical “step function”. A longer “rise time” can be specified. Fig. 16 shows the “step generator” function when the rise time is set to 800 ps and a time step of 8 ps. The “step” is actually a ramp function that increases linearly from 0 to 5 volts in 800 ps. Click on “Continue” to return to the main menu.

Note that if the generator has a 50 ohm internal resistance and a 10 volt open-circuit voltage, and the transmission line has a 50 ohm characteristic resistance, then the voltage divider relation at the generator terminals determines that the pulse launched onto the transmission line will have an amplitude of 5 volts.



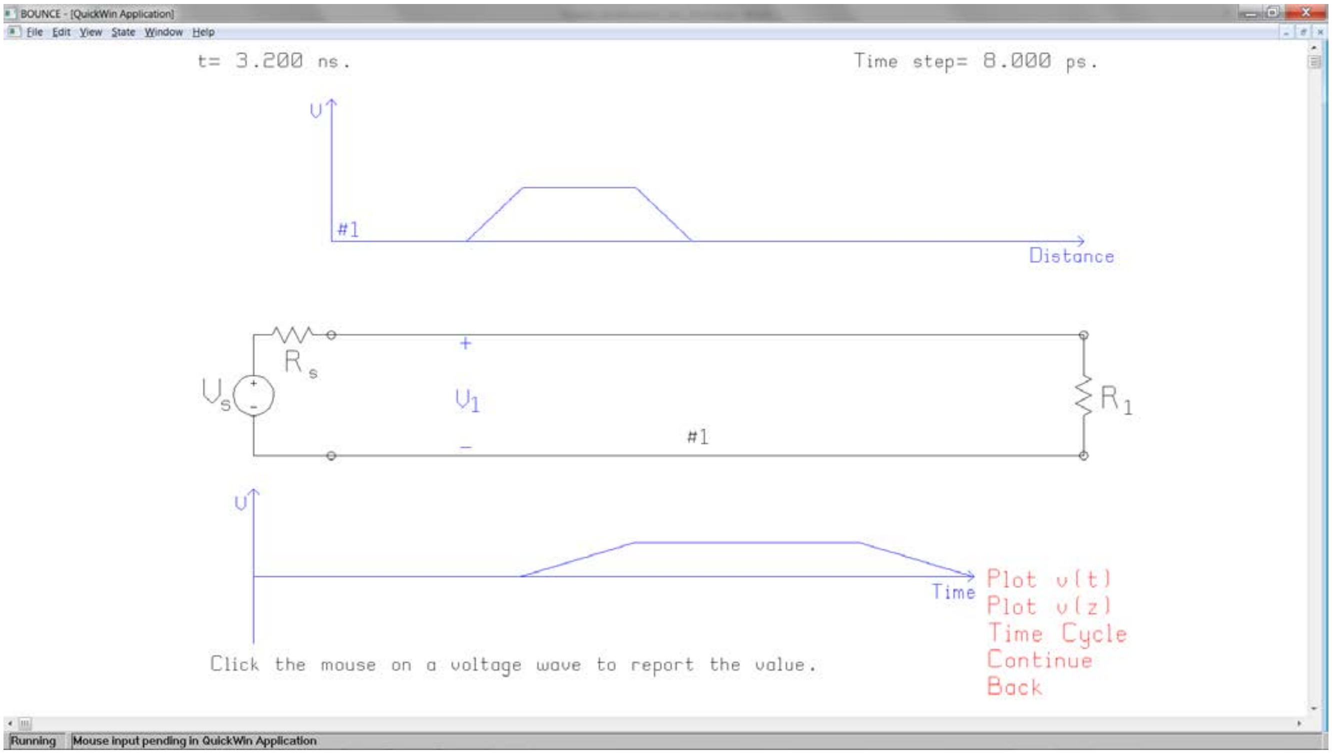
```
t= 3.200 ns.                              Time step= 8.000 ps.

Click the mouse on a voltage wave to report the value.
```

Fig. 16 A “step” generator with an 800 ps rise time is a ramp function.



```
*** BOUNCE  ** VERSION 1J(e)  ****   Dec. 8, 2014 ****
******* Generator Menu ******* Generator Menu ******* Generator Menu ***********

        Generator type:  Pulse Generator

        Amplitude:                        10.00      volts.

        Internal Resistance:              50.00      ohms.

        Pulse Width:                      2.000      nanoseconds.

        Rise time:                        0.5000     nanoseconds.

        Fall time:                        0.5000     nanoseconds.
```

Fig. 17 The pulse generator menu set to a pulse width of 2 ns with a rise time of 0.5 ns and a fall time of 0.5 ns.



t= 3.200 ns.

Time step= 8.000 ps.

Click the mouse on a voltage wave to report the value.

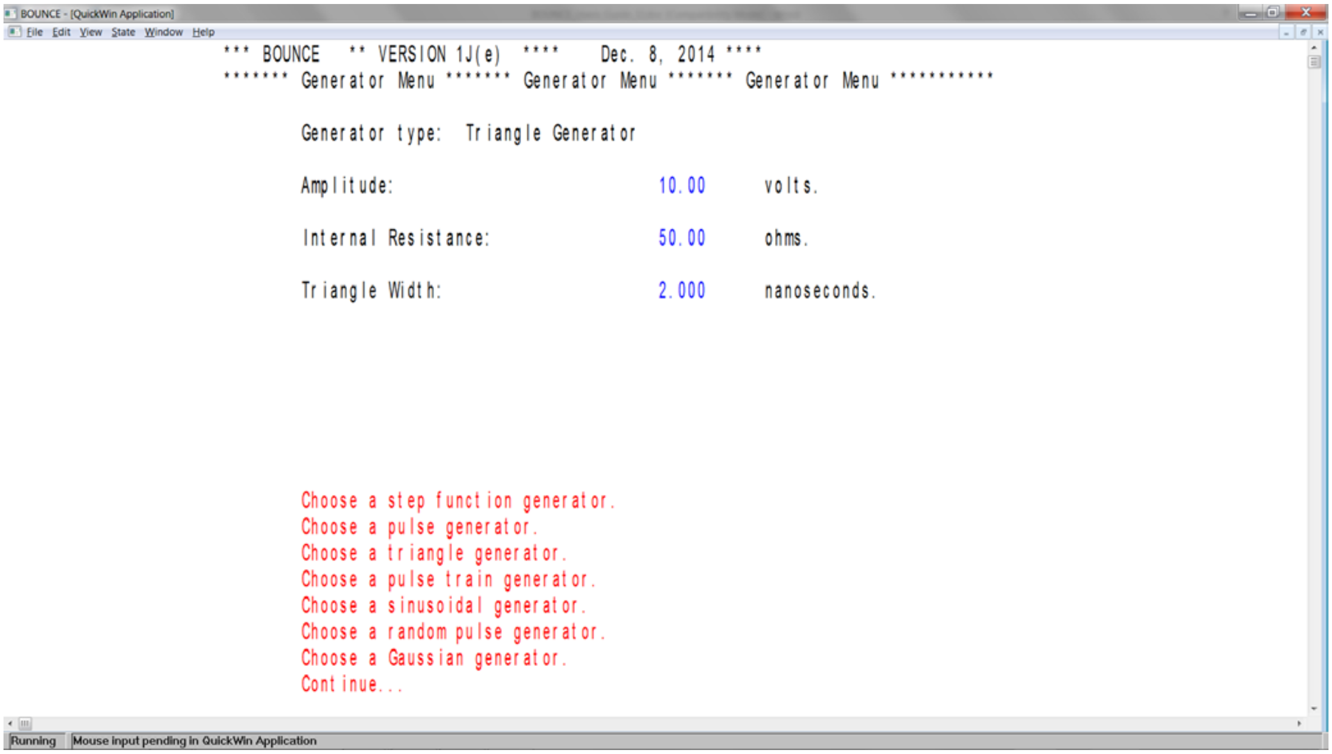
Running

Mouse input pending in QuickWin Application

Fig. 18 A pulse of length 2 ns with a rise time of 0.5 ns and a fall time of 0.5 ns.

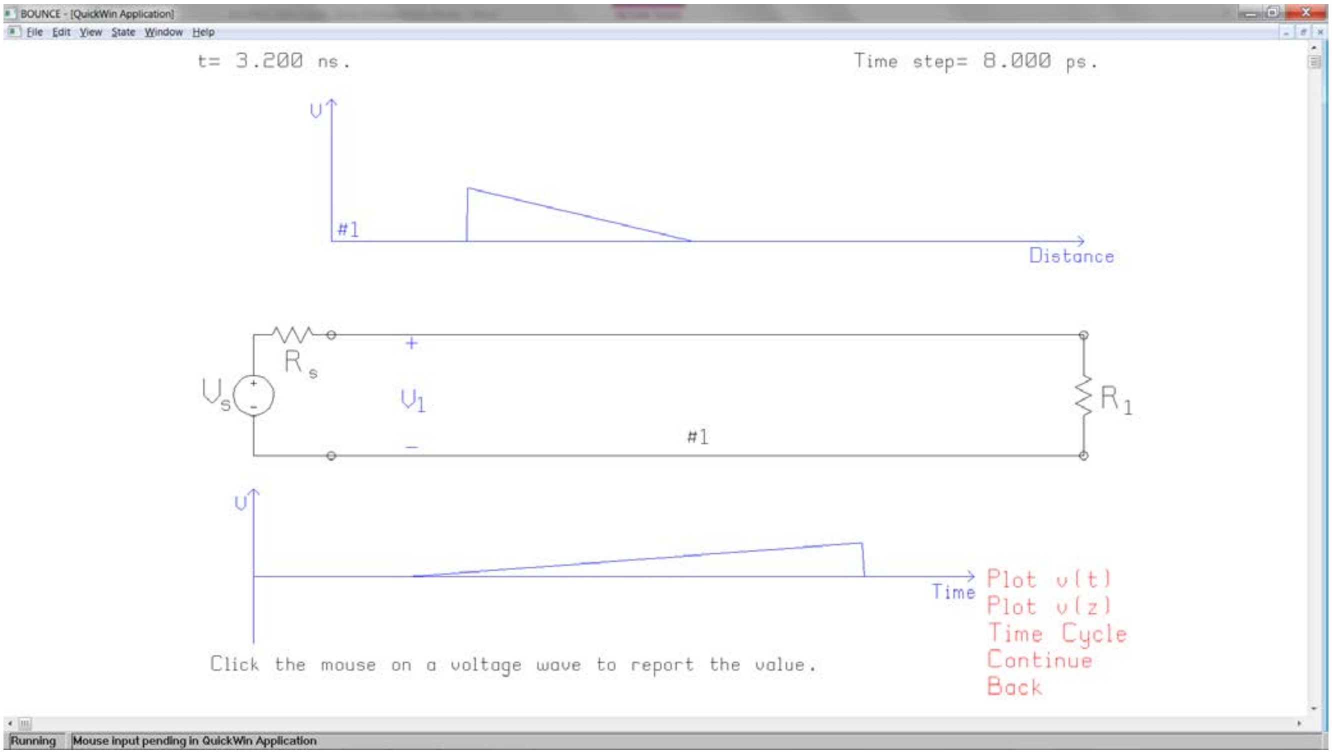
Pulse Generator

Fig. 17 shows the pulse generator menu. In addition to the amplitude of the pulse and the internal resistance of the generator, the user must specify the length of the pulse, the rise time and the fall time. Fig. 18 shows a pulse of overall length 2 ns, from the start of the rise time to the end of the fall time. The rise time is 0.5 ns and the fall time is 0.5 ns. Fig. 18 shows that the pulse on the 50-ohm transmission line rises linearly from zero to five volts in 0.5 ns, stays at 5 volts for 1 ns, and then falls linearly from 5 to 0 volts in 0.5 ns, for an overall length of 2 ns. The minimum rise time and fall time can be entered as zero to get the sharpest possible pulse. The actual minimum is one time step for the rise time and one time step for the fall time.



```
*** BOUNCE   ** VERSION 1J(e)   ****    Dec. 8, 2014 ****
******* Generator Menu ******* Generator Menu ******* Generator Menu ***********

          Generator type:  Triangle Generator

          Amplitude:                      10.00      volts.

          Internal Resistance:            50.00      ohms.

          Triangle Width:                 2.000      nanoseconds.




          Choose a step function generator.
          Choose a pulse generator.
          Choose a triangle generator.
          Choose a pulse train generator.
          Choose a sinusoidal generator.
          Choose a random pulse generator.
          Choose a Gaussian generator.
          Continue...
```

Fig. 19 The triangle generator menu.

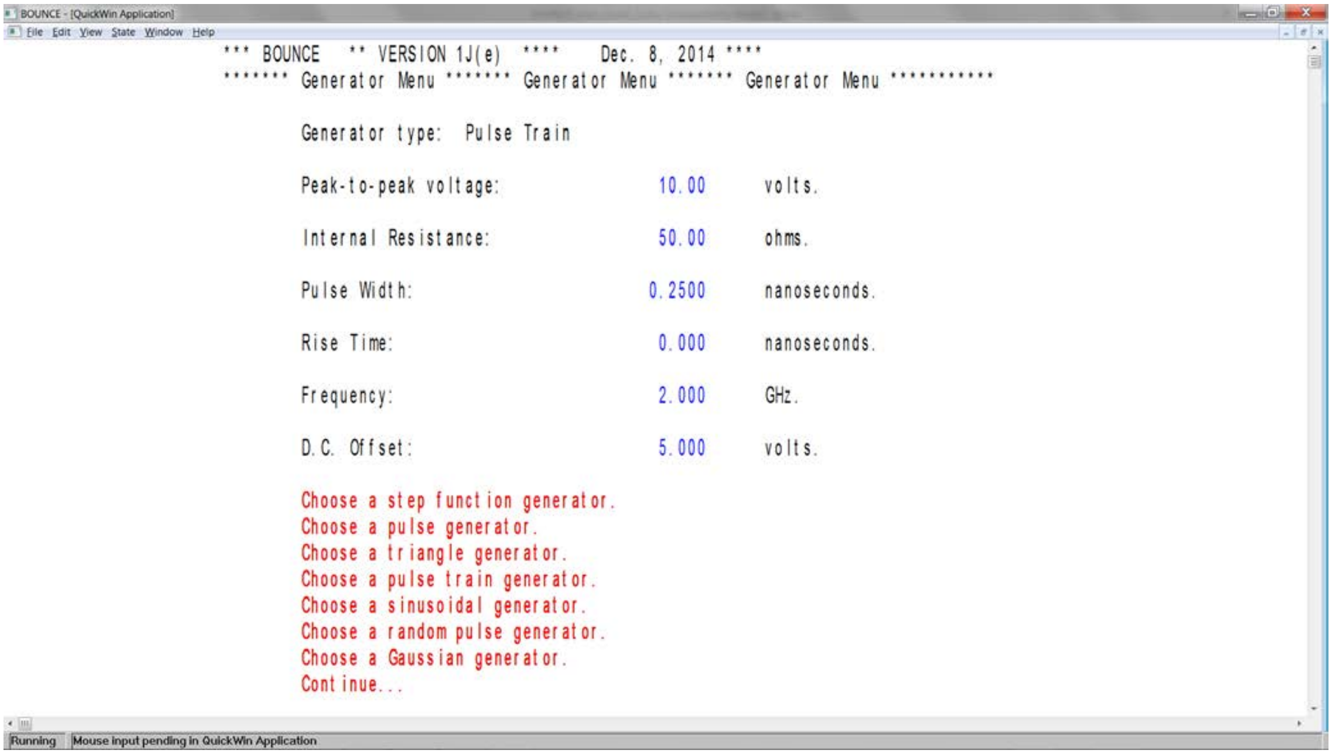


```
t= 3.200 ns.                               Time step= 8.000 ps.

Click the mouse on a voltage wave to report the value.
```

Fig. 20 The triangle generator's waveform.

Triangle Generator

The third generator choice is the triangle function, with the menu in Fig. 19. Fig. 20 shows that the triangle rises linearly from zero to the overall amplitude, then falls back to zero in one time step. The pulse is useful for demonstrating that the voltage as a function of distance on the transmission line is reversed compared to the voltage as a function of time, as Fig. 20 shows. This triangle function could be obtained using the rise time and fall time parameters for the pulse described above. It is convenient to have the triangle available as a separate “built-in” function.

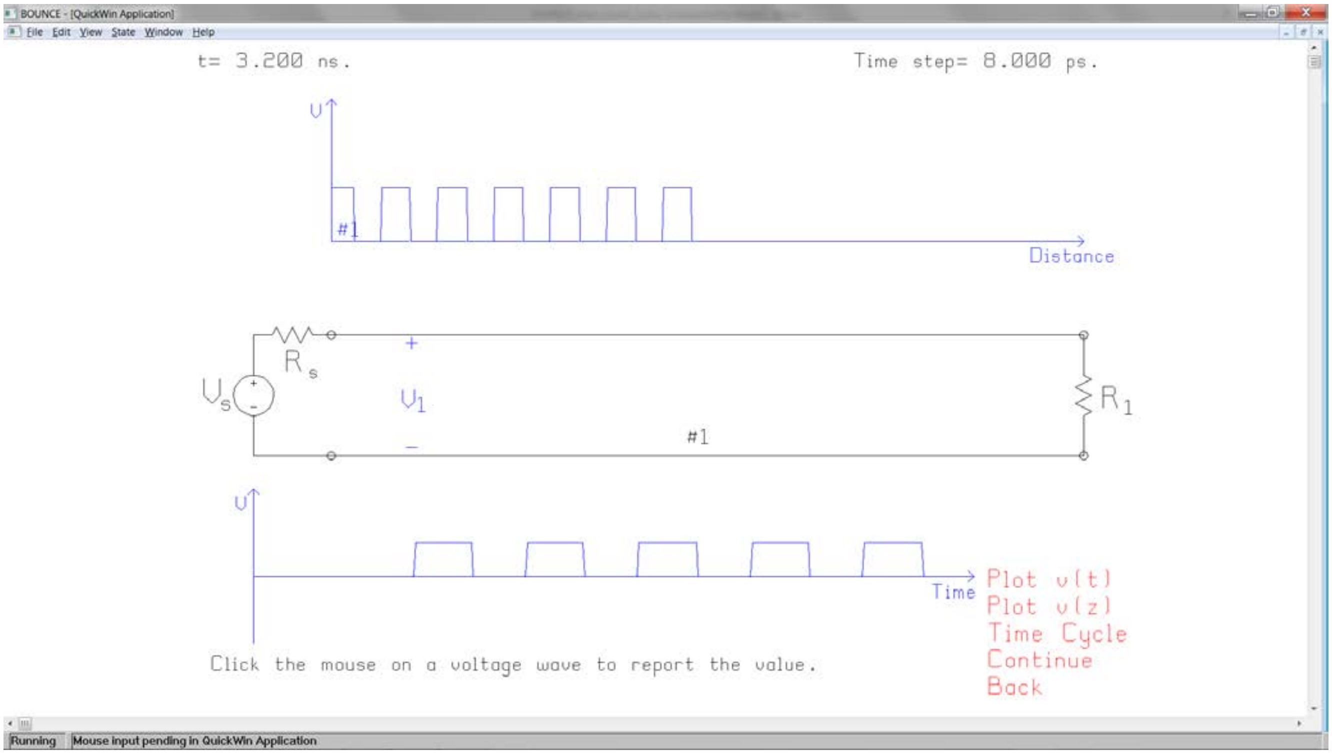


```
*** BOUNCE   ** VERSION 1J(e)  ****    Dec. 8, 2014 ****
******* Generator Menu ******* Generator Menu ******* Generator Menu ***********

        Generator type:  Pulse Train

        Peak-to-peak voltage:             10.00      volts.

        Internal Resistance:              50.00      ohms.

        Pulse Width:                      0.2500     nanoseconds.

        Rise Time:                        0.000      nanoseconds.

        Frequency:                        2.000      GHz.

        D.C. Offset:                      5.000      volts.

        Choose a step function generator.
        Choose a pulse generator.
        Choose a triangle generator.
        Choose a pulse train generator.
        Choose a sinusoidal generator.
        Choose a random pulse generator.
        Choose a Gaussian generator.
        Continue...
```

Fig. 21 The pulse train menu.

Pulse Train Generator

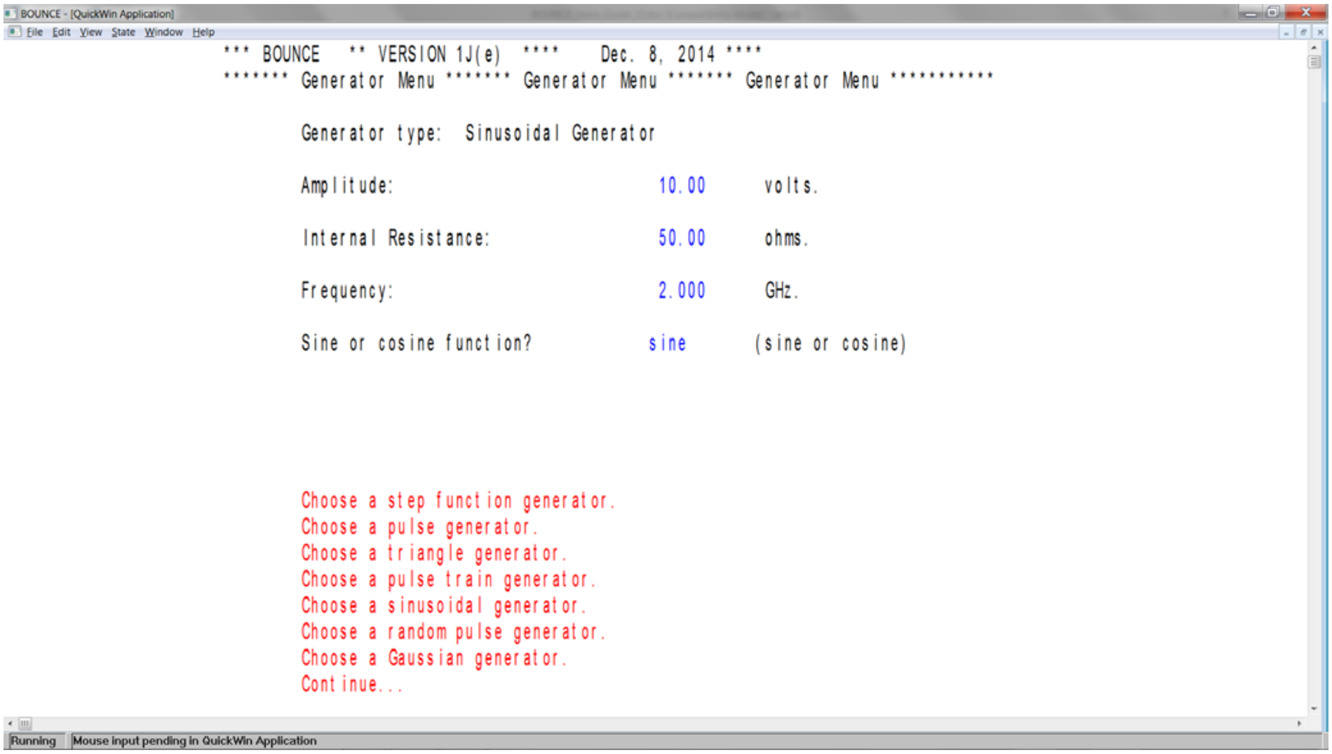
Fig. 21 shows the pulse train menu. Suppose we want a pulse train at 2 GHz, where V_s varies from 0 to 10 volts, and is “on” and “off” for equal periods of time. The period of a 2 GHz square wave is $T = 1/(2\ \text{GHz})$ = 0.5 ns, so the pulse is “on” for 0.25 ns and “off” for 0.25 ns. With no D.C. offset setting V_s to 10 volts gets a square wave symmetric about 0 volts of peak-to-peak value 10 volts. Specify a D.C. offset of 5 volts to make V_s vary from 0 to 10 volts. If the generator has internal resistance 50 ohms and the transmission line has characteristic impedance 50 ohms, then the voltage-divider at the source makes the square wave on the transmission line have amplitude 5 volts. The menu allows you to specify a rise time for the square wave, and the rise and fall times will be the same. In Fig. 20 the rise time is 0 ns, meaning that the square wave will rise in one time step in the BOUNCE approximation.



```
t= 3.200 ns.                                    Time step= 8.000 ps.

Click the mouse on a voltage wave to report the value.
```

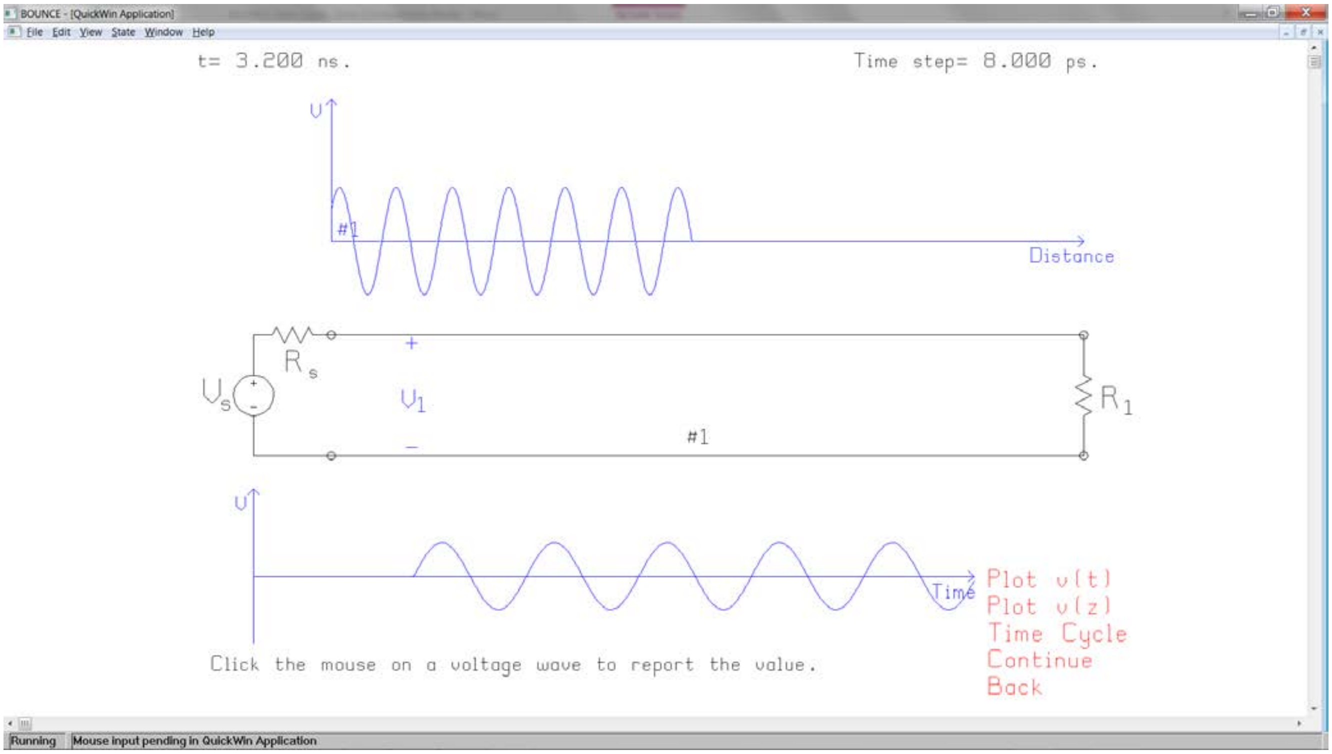
Fig. 22 The voltage waveform for the pulse train.

Fig. 22 shows the pulse train after 3.2 ns. The pulse train has propagated along about half the length of the transmission line. We see a square wave at the voltmeter, varying from 0 to 5 volts, at a frequency of 2 GHz.



```
*** BOUNCE  ** VERSION 1J(e)  ****    Dec. 8, 2014 ****
******* Generator Menu ******* Generator Menu ******* Generator Menu ***********

        Generator type:  Sinusoidal Generator

        Amplitude:                          10.00      volts.

        Internal Resistance:                50.00      ohms.

        Frequency:                          2.000      GHz.

        Sine or cosine function?           sine       (sine or cosine)
```

Fig. 23 The menu for the sinusoidal generator.

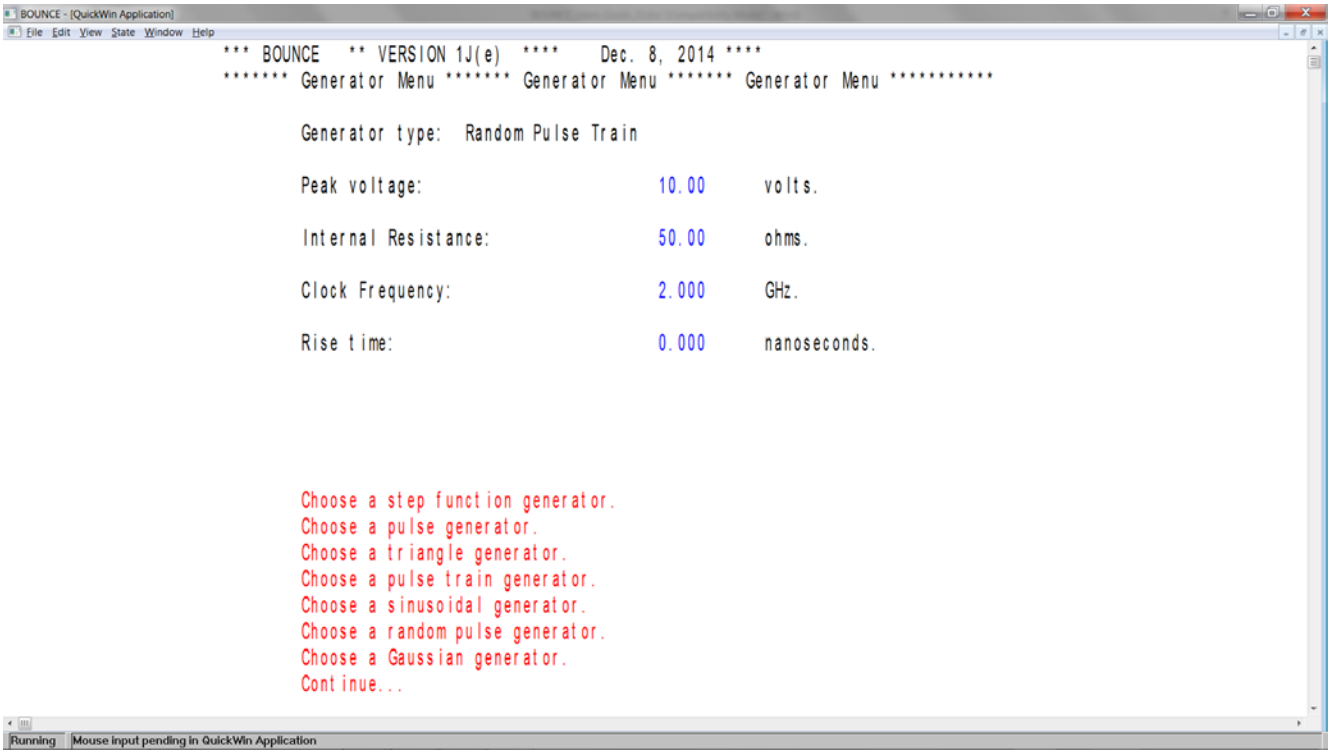


```
t= 3.200 ns.                                Time step= 8.000 ps.

Click the mouse on a voltage wave to report the value.

Running    Mouse input pending in QuickWin Application
```

Fig. 24 The sinusoidal generator's waveform.

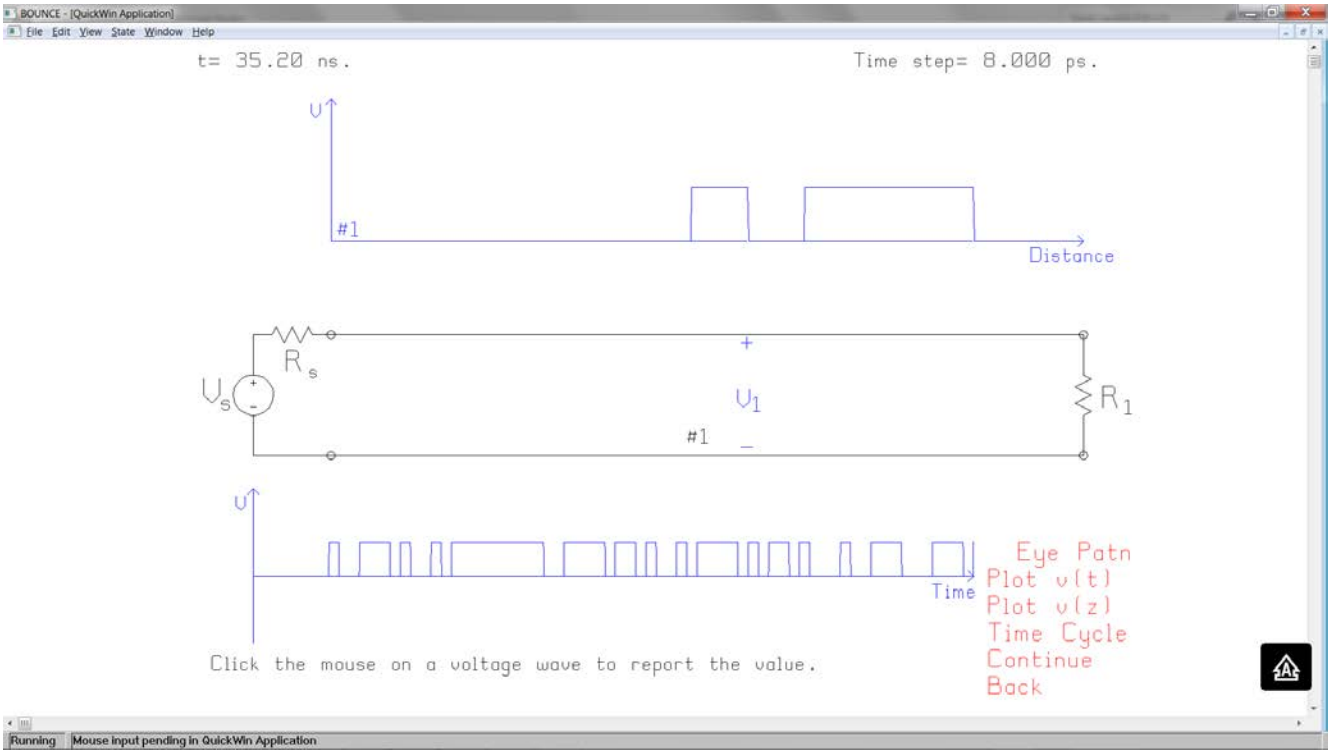
Sinusoidal Generator

Fig. 23 shows the menu for specifying the amplitude, internal resistance, and frequency of a sine wave generator, and Fig. 24 shows the waveform. A cosine wave can also be chosen, which turns on abruptly at t=0. The sine wave generator can be used to demonstrate the transients when the generator turns on, and the gradual change to the sinusoidal steady state. With a matched load the sine wave propagates smoothly along the transmission line and is absorbed by the load, and demonstrates the fundamental concept of "travelling wave". With an open circuit or short circuit load the sine wave is fully reflected by the load, and at steady state demonstrates the concept of "standing wave".



```
*** BOUNCE   ** VERSION 1J(e)   ****    Dec. 8, 2014 ****
******* Generator Menu ******* Generator Menu ******* Generator Menu ***********

          Generator type:  Random Pulse Train

          Peak voltage:                10.00      volts.

          Internal Resistance:         50.00      ohms.

          Clock Frequency:             2.000      GHz.

          Rise time:                   0.000      nanoseconds.



          Choose a step function generator.
          Choose a pulse generator.
          Choose a triangle generator.
          Choose a pulse train generator.
          Choose a sinusoidal generator.
          Choose a random pulse generator.
          Choose a Gaussian generator.
          Continue...
```

Fig. 25 The random pulse train menu.

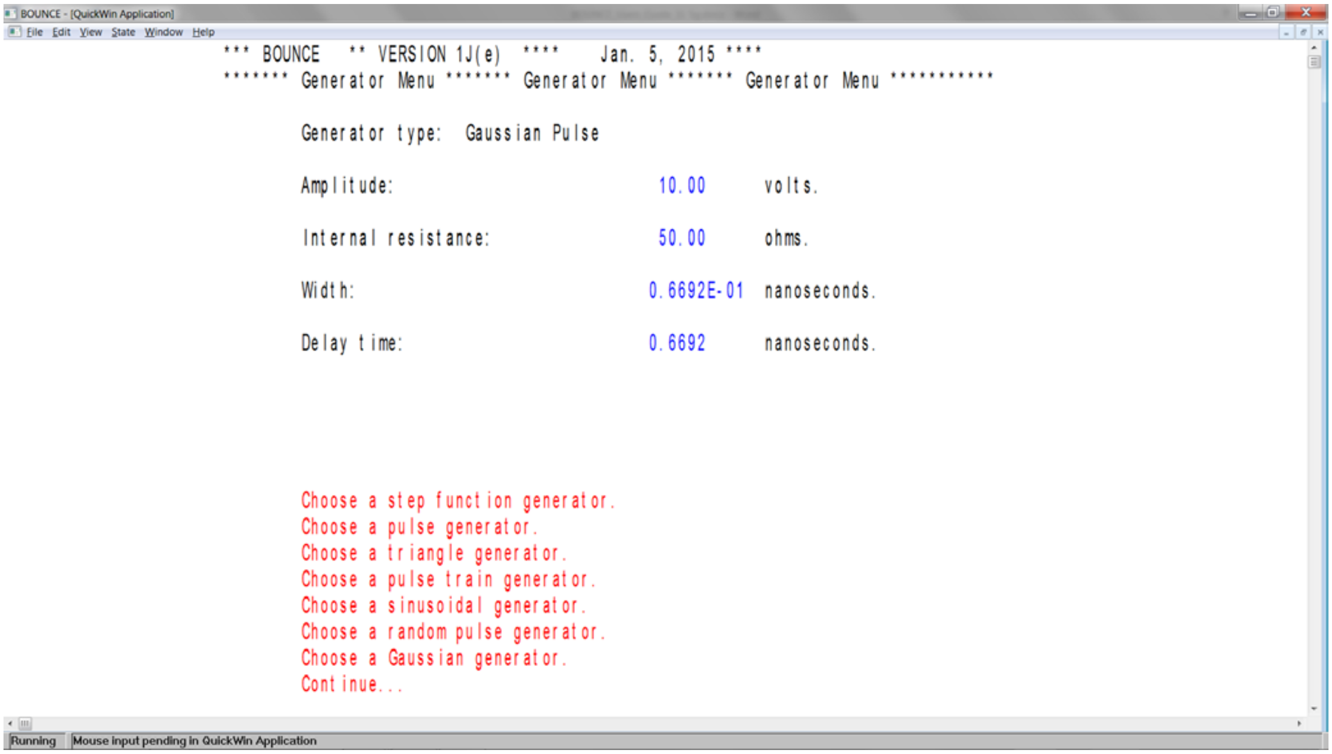


```
t= 35.20 ns.                          Time step= 8.000 ps.

Click the mouse on a voltage wave to report the value.
```

Fig. 26 A random pulse train at 2 GHz.

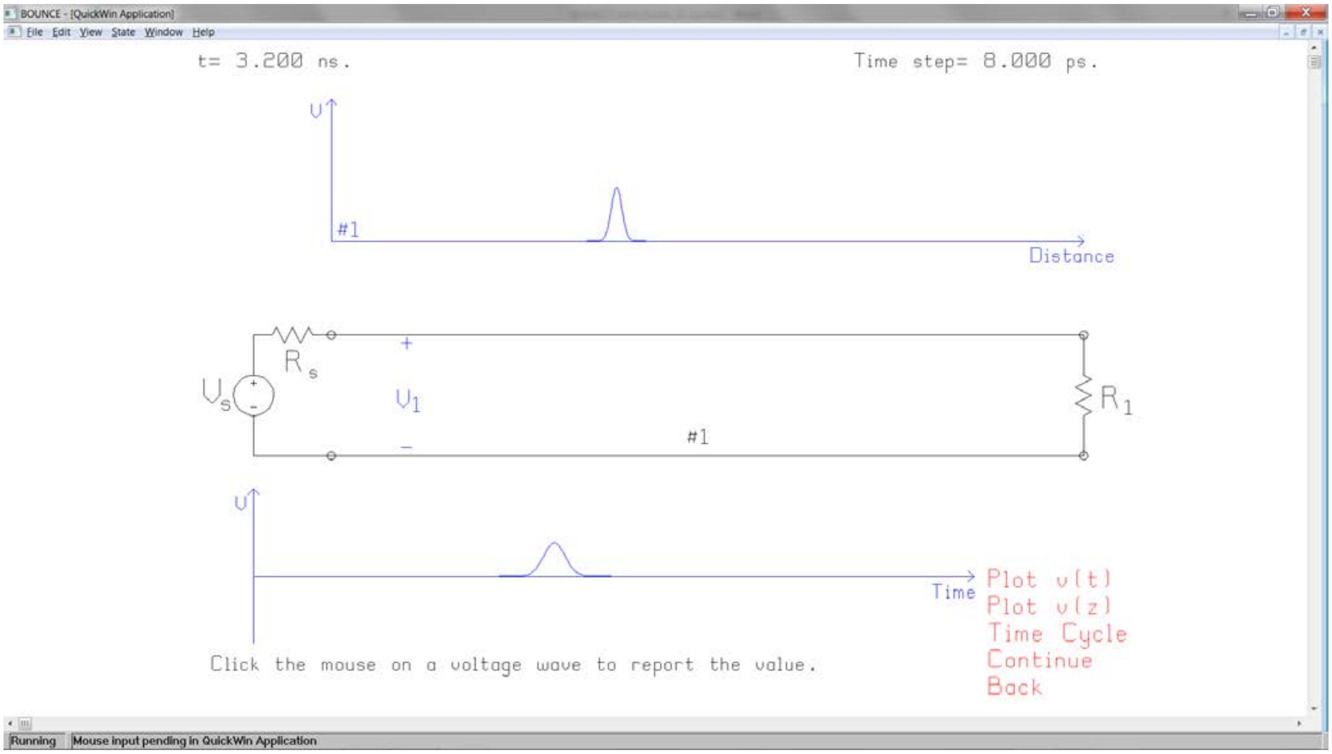
Random Pulse Train Generator

Fig. 25 shows the generator menu for the random pulse train. This source produces a random sequence of 0s and 1s and is used to test digital circuits and to draw an eye pattern. Specify the amplitude of the pulses, the internal resistance of the generator, and the clock frequency. Each pulse lasts for one-half the period of the clock. The rise time can also be specified. Fig. 26 shows a random pulse train at 2 GHz. After the time delay required for the first pulse to reach the observer at V_1, the voltage switches randomly between 0 and the amplitude of the pulse, accounting for the voltage-divider at the generator terminals. Each time you run the simulation, the generator will produce a different series of 0s and 1s.



```
*** BOUNCE   ** VERSION 1J(e)  ****   Jan. 5, 2015 ****
******* Generator Menu ******* Generator Menu ******* Generator Menu ***********

        Generator type:  Gaussian Pulse

        Amplitude:                        10.00      volts.

        Internal resistance:              50.00      ohms.

        Width:                           0.6692E-01  nanoseconds.

        Delay time:                      0.6692      nanoseconds.




        Choose a step function generator.
        Choose a pulse generator.
        Choose a triangle generator.
        Choose a pulse train generator.
        Choose a sinusoidal generator.
        Choose a random pulse generator.
        Choose a Gaussian generator.
        Continue...
```

Fig. 27 The Gaussian Pulse Generator



t= 3.200 ns.

Time step= 8.000 ps.

Click the mouse on a voltage wave to report the value.

Mouse input pending in QuickWin Application

Fig. 28 A Gaussian Pulse.

Gaussian Pulse Generator

It is useful to find the impulse response of a circuit because the Fourier transform of the impulse response is the frequency response. Numerical algorithms such as that used by BOUNCE have a limited bandwidth over which their approximate solution is accurate. Since a true impulse has infinite bandwidth, BOUNCE can't solve for the true impulse response. Instead of exiting the circuit with an impulse, circuits are often excited with a Gaussian Pulse, such as that shown in Fig. 28. As the width of the pulse gets narrow, it approximates an impulse.

A Gaussian pulse is given by

$$v(t) = V_s e^{-((t-t_s)/T_w)^2}$$

where V_s is the amplitude of the pulse, t_d is the time delay or the time value at which the pulse reaches its maximum value, and T_w controls the width of the pulse. At $t = t_d \pm T_w$ the value of the pulse is

$$v(t_d \pm T_w) = V_s e^{-((t_d \pm T_w - t_s)/T_w)^2} = V_s e^{-((\pm T_w)/T_w)^2} = V_s e^{-1} = 0.3679\, V_s$$

At $t = t_d \pm T_w$, the pulse is reduced by 20log(0.3679)=-8.7 dB from its maximum value. A Gaussian pulse is often used to probe the response of a circuit and find an approximation of the transfer function. Thus. the Fourier transform of the response of the circuit divided by the Fourier transform of the input Gaussian pules is approximately equal to the transfer function of the circuit. The approximation is limited to the bandwidth over which the Gaussian pulse has significant energy, which is turn is chosen to match the bandwidth over which the numerical simulation of the circuit is valid. Choose the width of the pulse according to

$$T_w = \sqrt{\frac{3}{\pi^2 \log(e) f_{\max}^2}}$$

so that the spectral density of the Gaussian pulse at frequency $f_{\max}$ is 60 dB below its value at D.C.

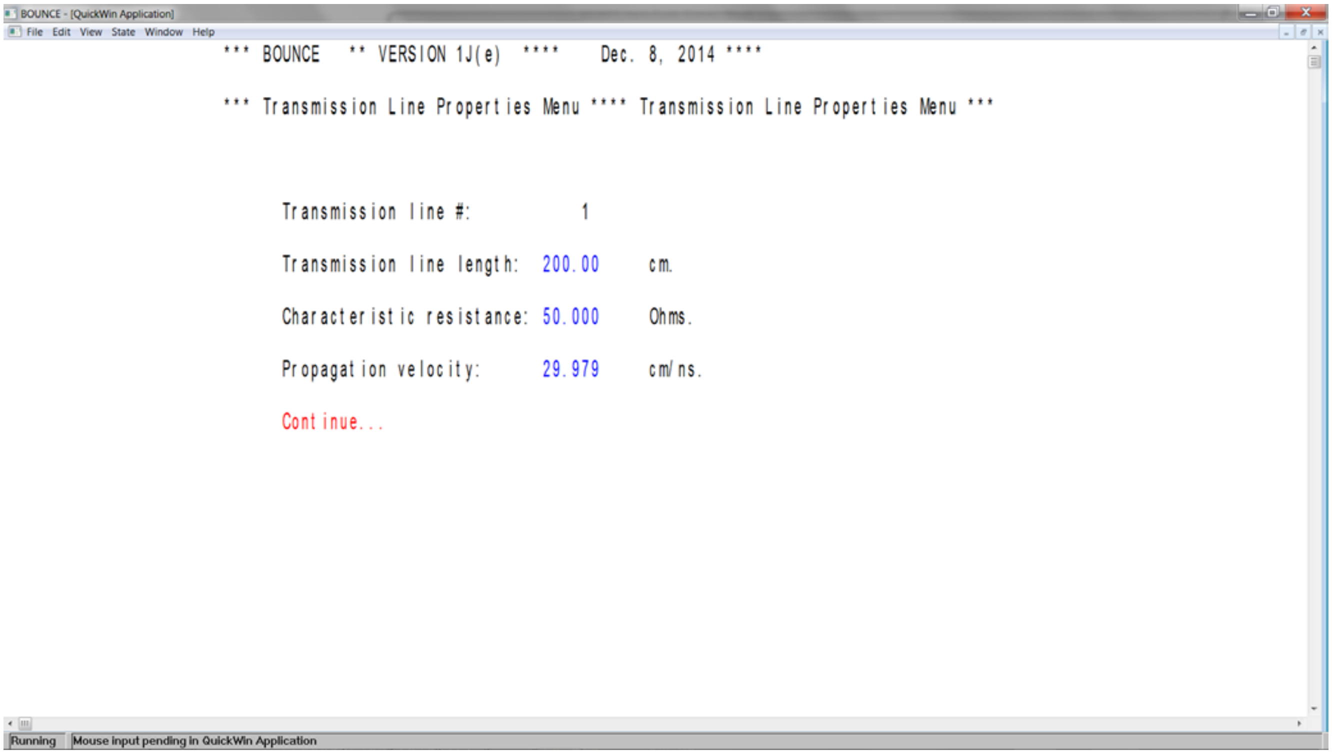
With a time step of Δt sec the cell size is $\Delta x = u\Delta t$ where u is the propagation velocity. The frequency limit of the BOUNCE algorithm is about 10 cells per wavelength, so at the limiting frequency $\lambda_{\min} = 10\Delta x$ so $f_{\max} = \frac{u}{\lambda_{\min}} = \frac{u}{10\Delta x} = \frac{1}{10\Delta t}$. The width parameter of the pulse should then be chosen as

$$T_w = \sqrt{\frac{3x(10\Delta t)^2}{\pi^2 \log(e)}} = 8.366\Delta t$$

For Fig. 27, the time step is 8 ps and the formula evaluates to a width parameter of $T_w = 0.06692$ ns. The delay time for the pulse is set to ten times this value, 0.6692 ns, to allow the whole pulse to emerge from the generator. Fig. 28 shows the Gaussian pulse on a 200 cm, 50 ohm transmission line. The pulse comes out of the generator and travels along the transmission line. There is a voltmeter at 20 cm distance from the generator and at the voltmeter we see the Gaussian pulse as it passes the voltmeter's position. Choosing the width of the Gaussian pulse according to the bandwidth over which the BOUNCE simulation is valid leads to a good approximation of the transfer function over this bandwidth.

Transmission Line Menu

The transmission line menu lets you set the parameters of one of the transmission lines in the circuit. In the main menu in Fig. 2, click the mouse on "Line #1" to set the properties of transmission line number one.



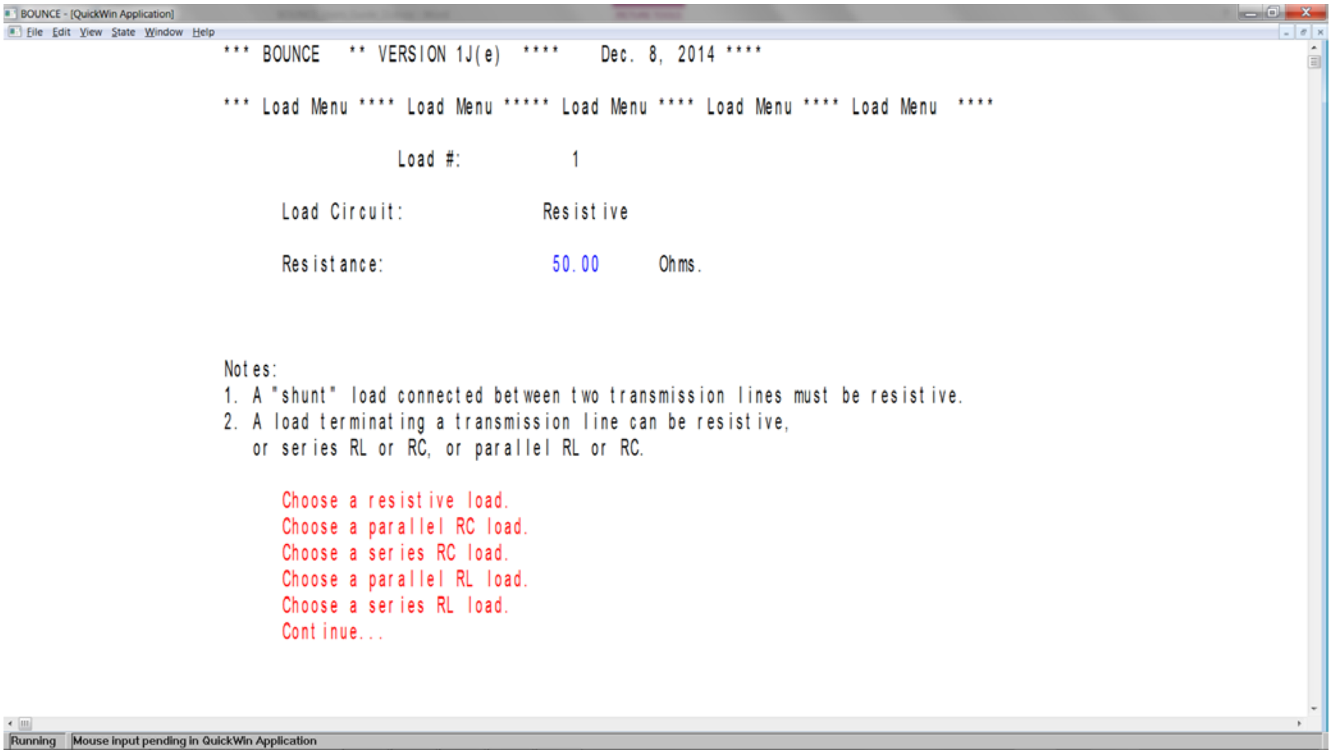
```
*** BOUNCE    ** VERSION 1J(e)   ****    Dec. 8, 2014 ****

*** Transmission Line Properties Menu **** Transmission Line Properties Menu ***


   Transmission line #:          1

   Transmission line length:  200.00     cm.

   Characteristic resistance: 50.000     Ohms.

   Propagation velocity:      29.979     cm/ns.

   Continue...
```

Fig. 29 The transmission line menu.

The transmission line menu of Fig. 29 has three blue number fields, for the transmission line length, the characteristic resistance, and the propagation velocity. Click the mouse on a blue field to change its value. The field switches to inverse video and you can type the new value. Finish by typing the Enter key. You can change from one field to the next with the tab key. To finish click the mouse on the red Continue button. Note that in BOUNCE the transmission lines are lossless.

Load Menu

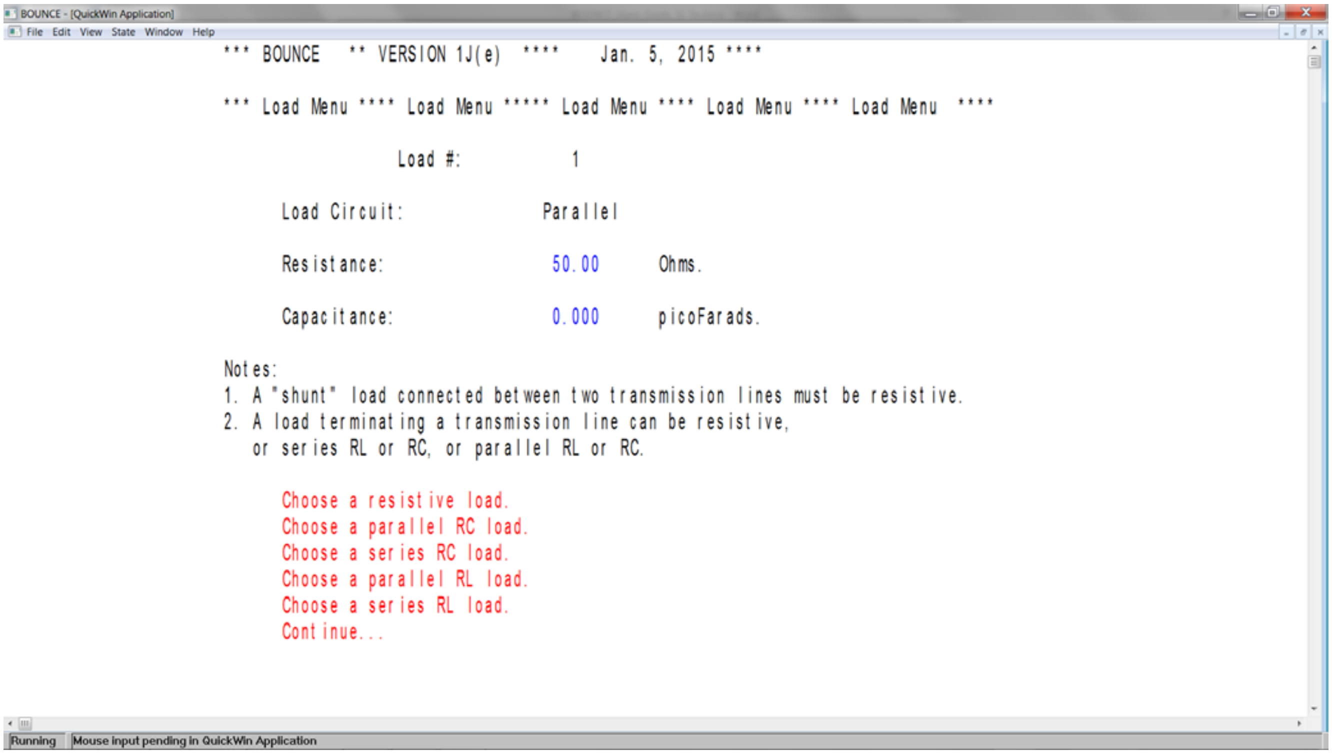
The load menu lets you choose the circuit for each load on the transmission line, and specify the values of the components. There are two kinds of loads. The first kind is a “shunt load” connected at the junction of two transmission lines. This kind of load must be a resistor, with no inductance or capacitance. BOUNCE calls this a “resistive” load. The second kind is a load that terminates a transmission line. This can be a simple resistor, or a series connection of a resistor and a capacitor, or a resistor and an inductor. The load can also be a parallel connection of a resistor and capacitor, or a resistor and an inductor. Thus there are five configurations for the load terminating any transmission line.



```
*** BOUNCE  ** VERSION 1J(e)  ****   Dec. 8, 2014 ****

*** Load Menu **** Load Menu ***** Load Menu **** Load Menu **** Load Menu  ****

               Load #:          1

     Load Circuit:              Resistive

     Resistance:                50.00     Ohms.



Notes:
1. A "shunt" load connected between two transmission lines must be resistive.
2. A load terminating a transmission line can be resistive,
   or series RL or RC, or parallel RL or RC.

     Choose a resistive load.
     Choose a parallel RC load.
     Choose a series RC load.
     Choose a parallel RL load.
     Choose a series RL load.
     Continue...
```

Fig. 30 The load menu.

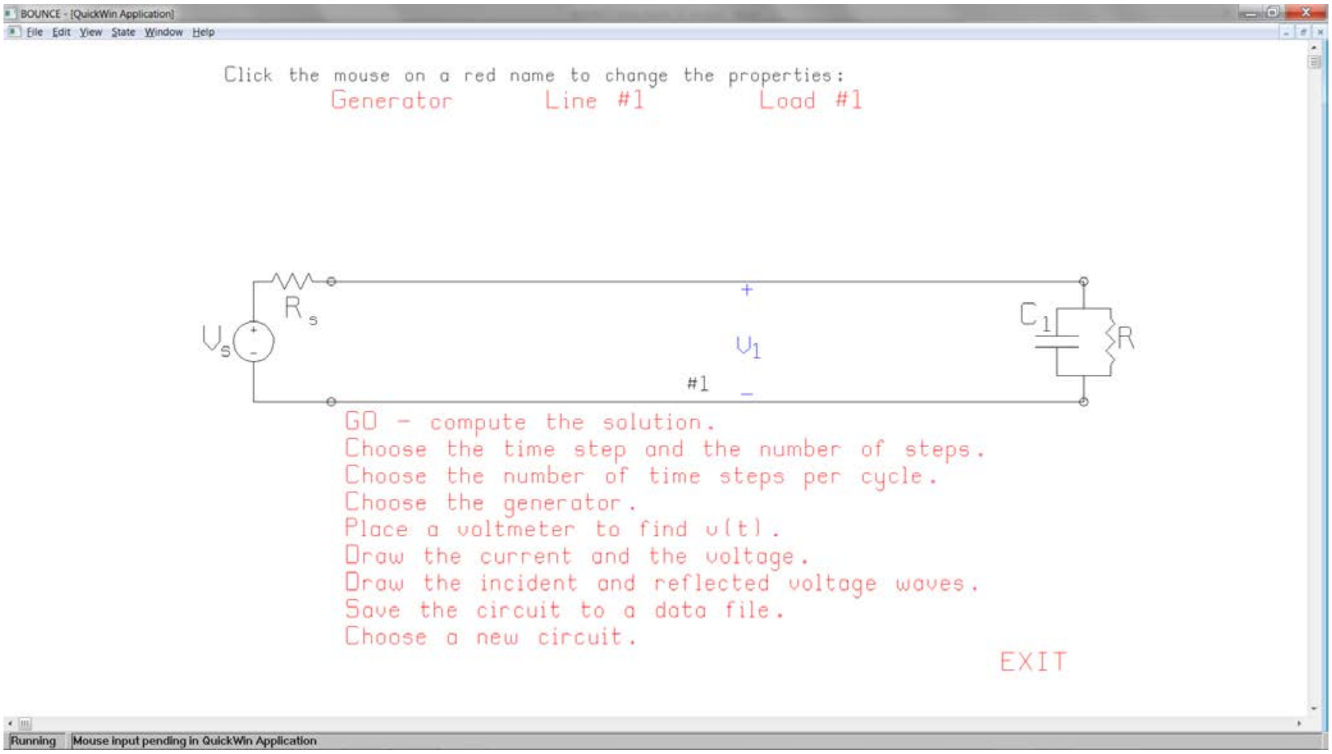
Fig. 30 shows the load menu. Use the red menu buttons at the bottom to choose the type of load. In Fig. 30 the simple resistor has been chosen and the blue number field lets you enter the value of the load. Click on the number field to change it to inverse video and type your new value. Finish by typing the Enter key. Click on Continue to return to the main menu.



```
*** BOUNCE   ** VERSION 1J(e)  ****    Jan. 5, 2015 ****

*** Load Menu **** Load Menu ***** Load Menu **** Load Menu **** Load Menu  ****

                    Load #:          1

       Load Circuit:               Parallel

       Resistance:                 50.00     Ohms.

       Capacitance:                0.000     picoFarads.

Notes:
1. A "shunt" load connected between two transmission lines must be resistive.
2. A load terminating a transmission line can be resistive,
   or series RL or RC, or parallel RL or RC.

       Choose a resistive load.
       Choose a parallel RC load.
       Choose a series RC load.
       Choose a parallel RL load.
       Choose a series RL load.
       Continue...
```

Fig. 31 The load menu for a parallel RC load circuit.

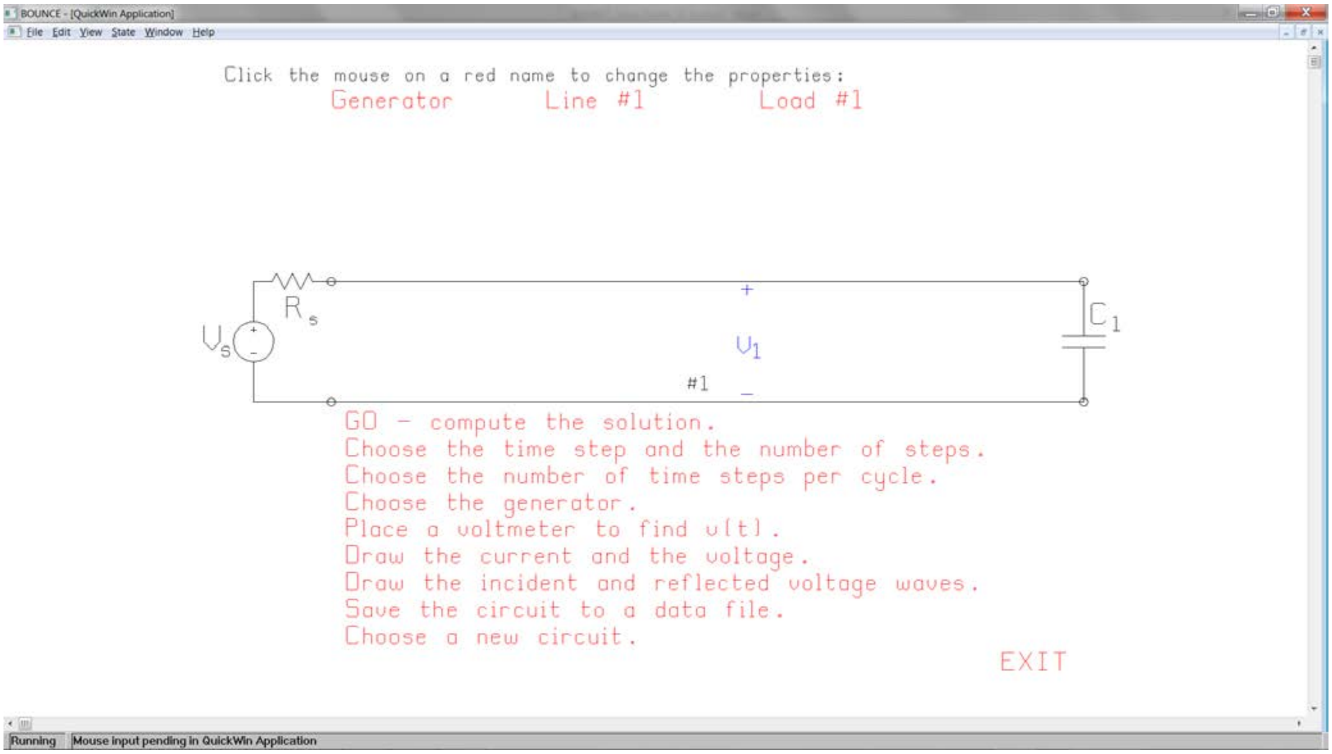
Fig. 31 is the menu for the parallel RC load. This menu has blue number fields for the resistance and the capacitance. There are similar menus for all the load types.



```
Click the mouse on a red name to change the properties:
```

Fig. 32 The parallel RC load circuit.

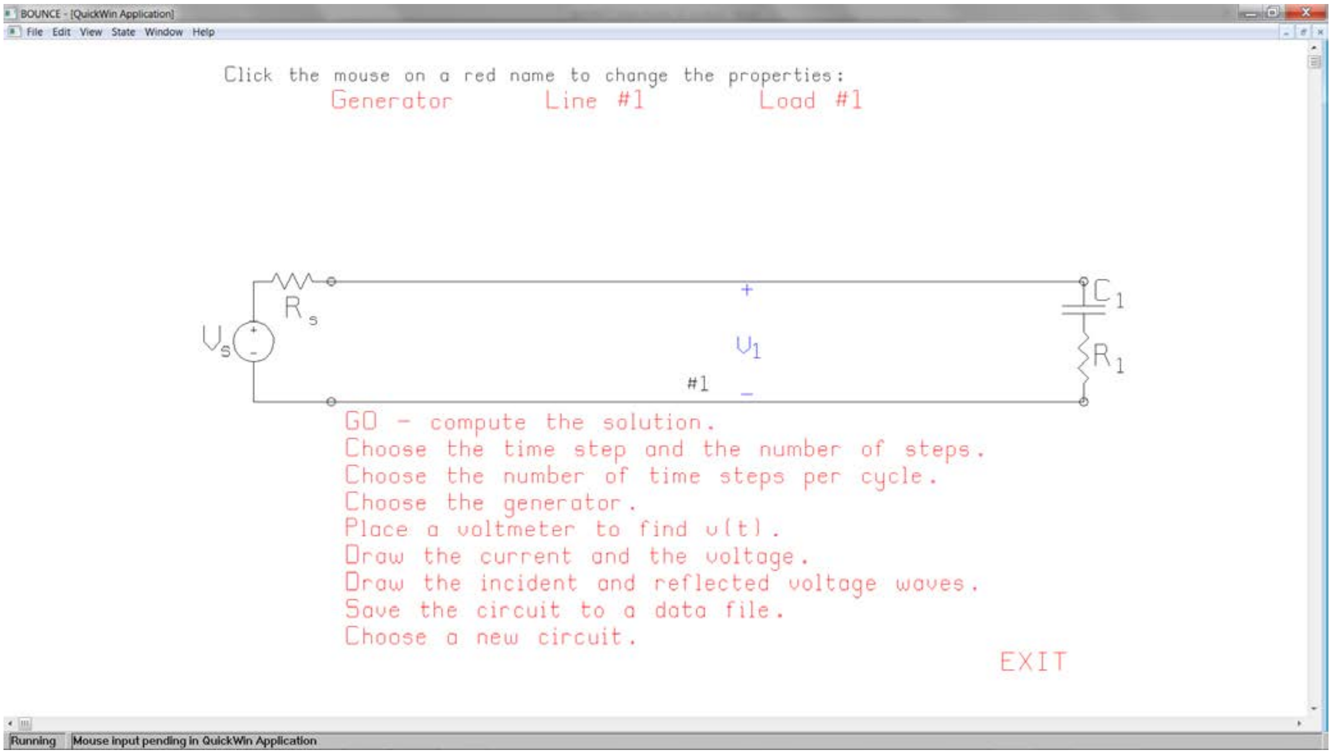
Fig. 32 shows a transmission line circuit with a parallel RC load. Enter the value of the resistor and the capacitor in the menu of Fig. 31. The initial voltage across the capacitor is zero volts. For a simple capacitive load, make the value of the resistor very large, say 1 million ohms. Then the graphics in the program omits the resistor and draws the load as capacitive, Fig. 32. Parallel RC loads are used to model the input of CMOS gates in switching circuits.



Click the mouse on a red name to change the properties:

Mouse input pending in QuickWin Application

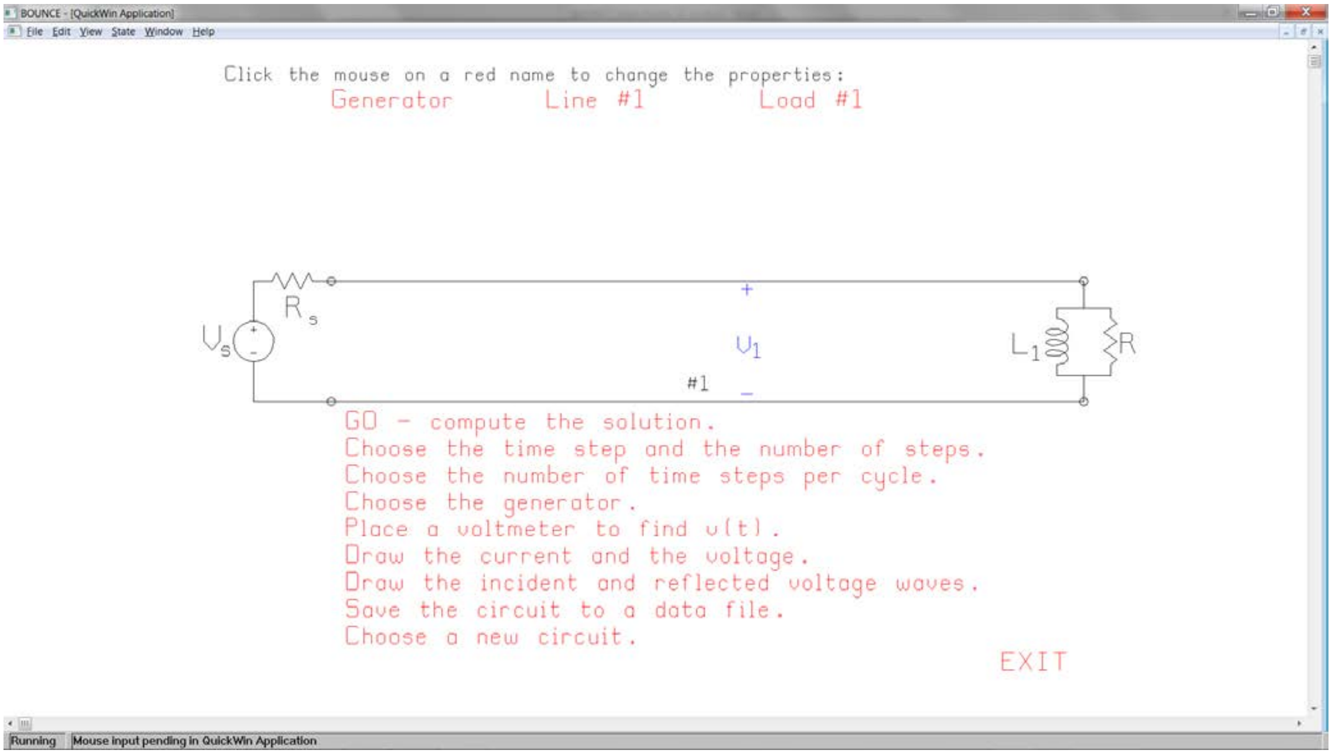
Fig. 33 A simple capacitive load can be obtained with the parallel RC load circuit by setting the value of the resistor to 1,000,000 ohms.



```
Click the mouse on a red name to change the properties:
      Generator        Line #1        Load #1

GO - compute the solution.
Choose the time step and the number of steps.
Choose the number of time steps per cycle.
Choose the generator.
Place a voltmeter to find v(t).
Draw the current and the voltage.
Draw the incident and reflected voltage waves.
Save the circuit to a data file.
Choose a new circuit.
                                              EXIT
Running   Mouse input pending in QuickWin Application
```

Fig. 34 The series RC load circuit.

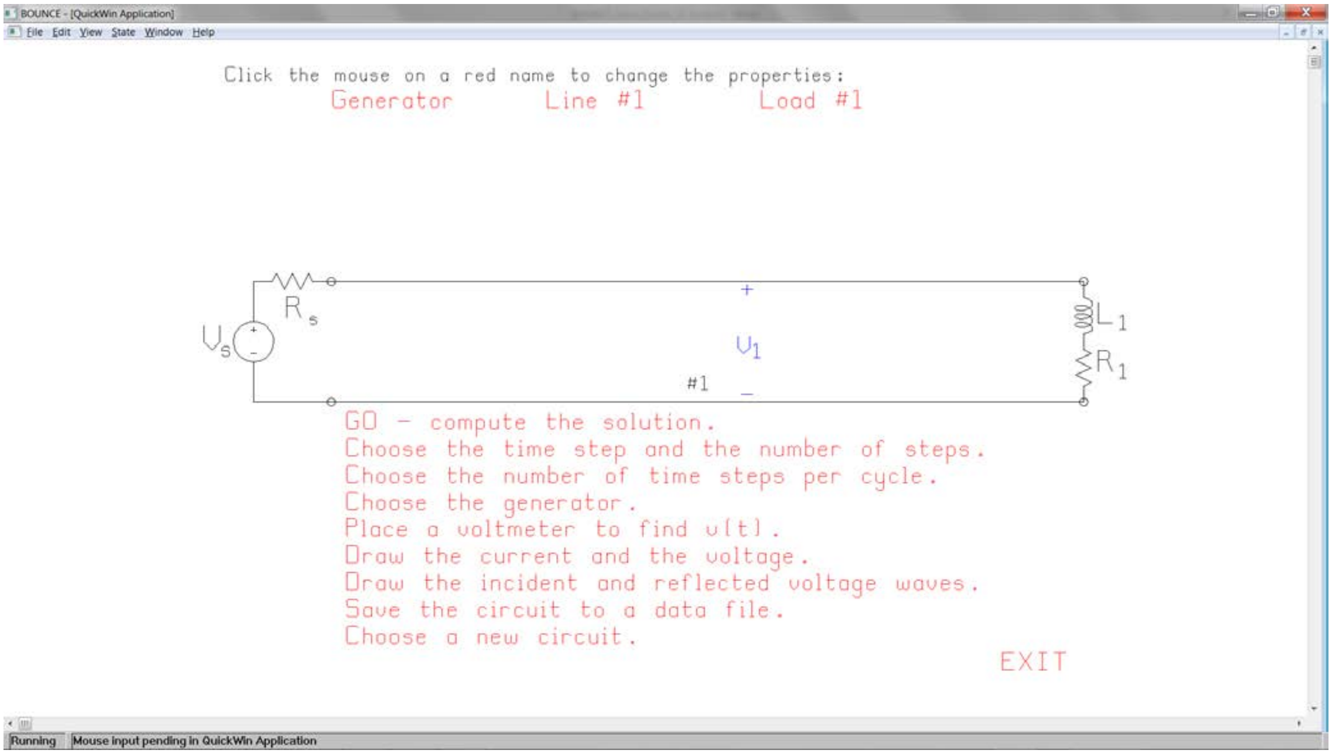
Fig. 34 shows the series RC load circuit. The initial voltage across the capacitor is zero volts. Specify the value of the resistor and the capacitor in the load menu. For a simple capacitive load, make the value of the resistor equal to zero ohms.



```
Click the mouse on a red name to change the properties:
      Generator        Line #1        Load #1

GO - compute the solution.
Choose the time step and the number of steps.
Choose the number of time steps per cycle.
Choose the generator.
Place a voltmeter to find v(t).
Draw the current and the voltage.
Draw the incident and reflected voltage waves.
Save the circuit to a data file.
Choose a new circuit.
                                              EXIT
Running   Mouse input pending in QuickWin Application
```

Fig. 35 The parallel RL load circuit.

Fig. 35 shows the parallel RL load circuit. The load menu provides boxes for entering the value of the resistor and the inductor. The initial current through the inductor is zero amps. For a simple inductive load, with no resistor, make the value of the resistor very large, say 1 million ohms.

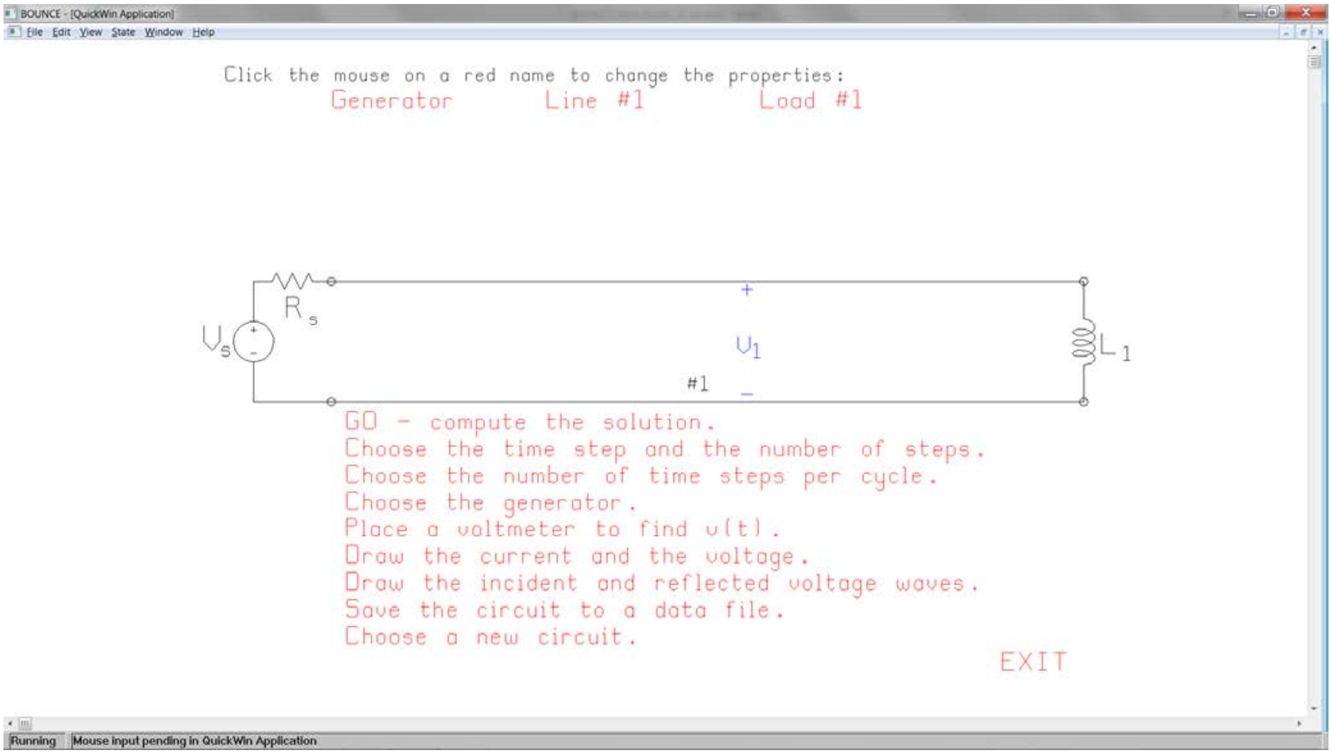


Click the mouse on a red name to change the properties:

GO - compute the solution.
Choose the time step and the number of steps.
Choose the number of time steps per cycle.
Choose the generator.
Place a voltmeter to find v(t).
Draw the current and the voltage.
Draw the incident and reflected voltage waves.
Save the circuit to a data file.
Choose a new circuit.

Fig. 36 The series RL load circuit.

Finally, the last load type is the series RL load of Fig. 36. Enter the value of the resistor and the inductor in the load menu. The initial current through the inductor is zero amps. For a simple inductor, make the value of the resistor zero, to obtain the load of Fig. 37.



Click the mouse on a red name to change the properties:

GO - compute the solution.
Choose the time step and the number of steps.
Choose the number of time steps per cycle.
Choose the generator.
Place a voltmeter to find v(t).
Draw the current and the voltage.
Draw the incident and reflected voltage waves.
Save the circuit to a data file.
Choose a new circuit.

Fig. 37 A circuit with a simple inductive load, consisting of the series RL load circuit with the resistor set to zero.

The Voltmeters

In BOUNCE, placing a “voltmeter” on a transmission line is like connecting an oscilloscope across the circuit at that location. The program reports the voltage as a function of time at the voltmeter’s location.

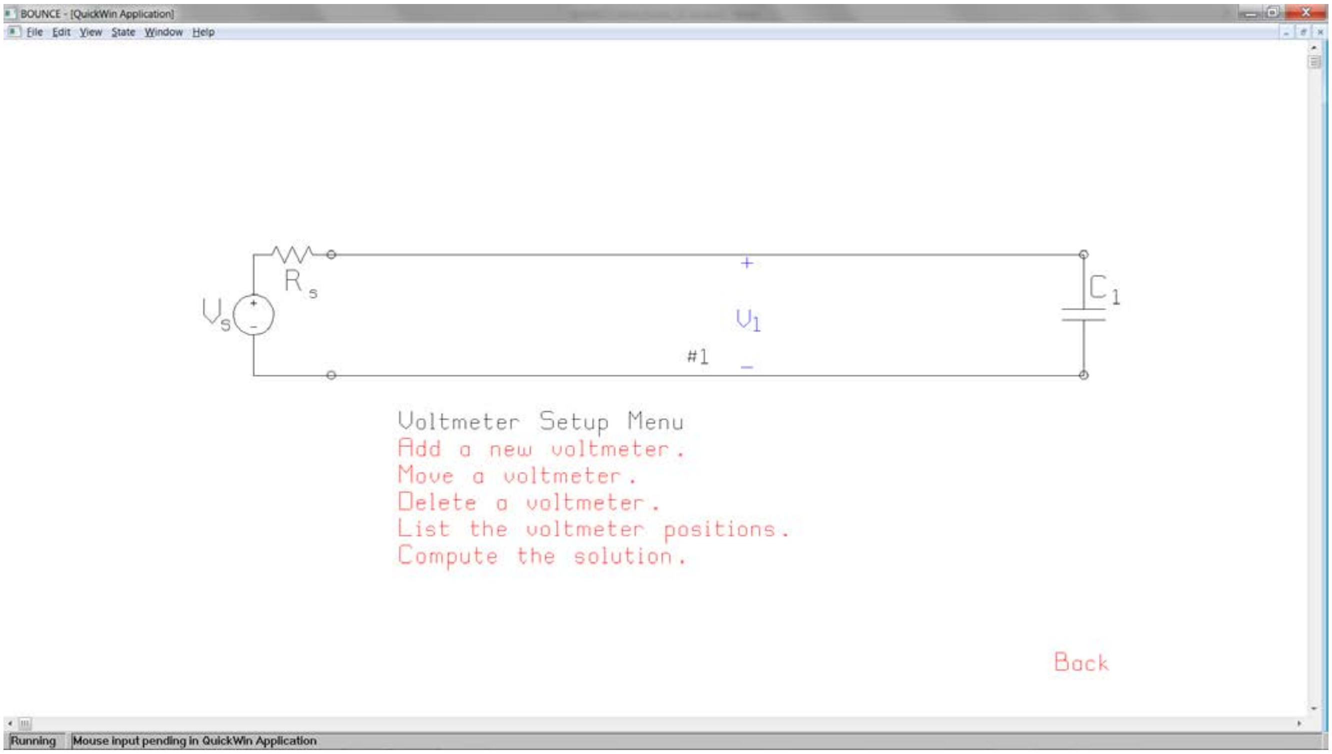
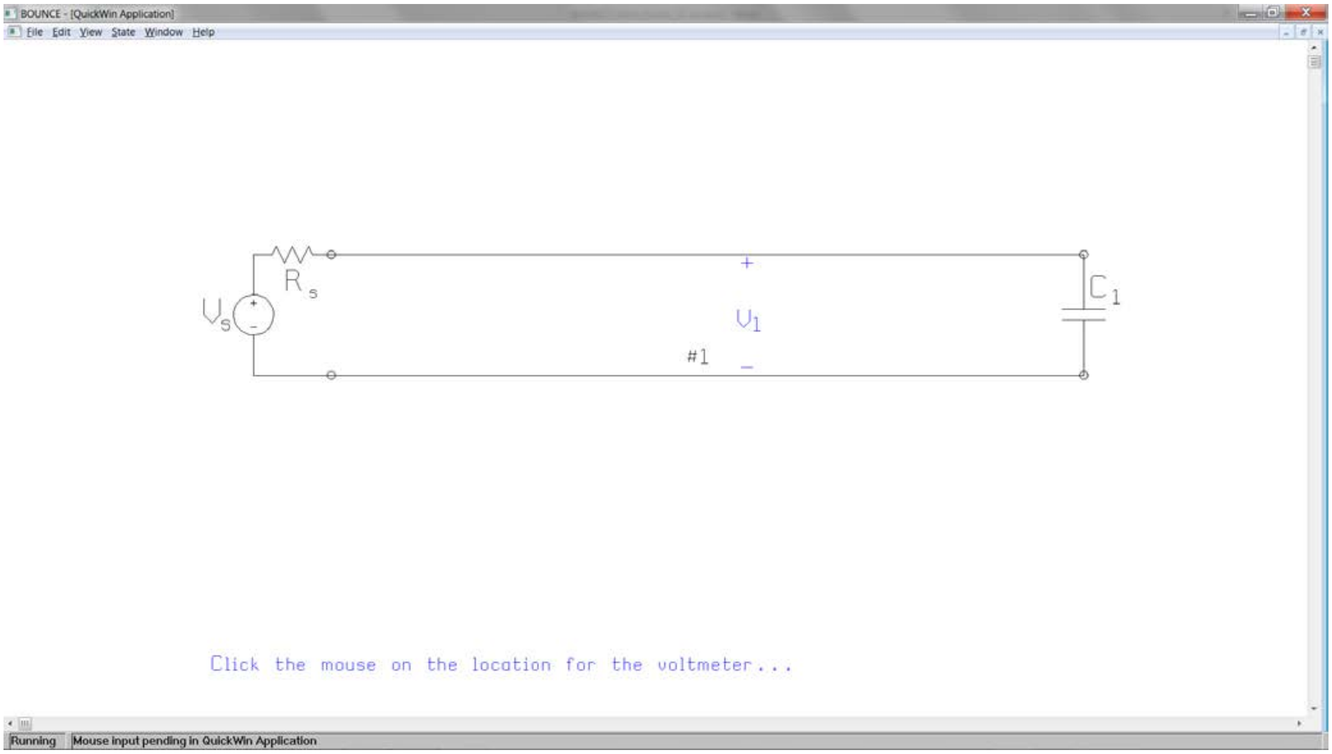


Fig. 38 The voltmeter setup menu.

The voltmeters setup menu, Fig. 37, lets you position a "voltmeter" anywhere in the circuit, so you can find the voltage as a function of time anywhere in the circuit. You can have as many as four voltmeters. These are color-coded so that you can see which curve corresponds to each voltmeter location. A larger, clearer graph of the voltage at each voltmeter as a function of time is obtained by clicking the mouse on the "Plot v(t)" button in the simulation menu of Fig. 3. Clicking “make a v(t) file” creates an “rpl” file, which can be graphed with the rectangular-plotter program “RPLOT”.

The voltmeter setup menu of Fig. 38 has five buttons for adding a voltmeter, moving a voltmeter, deleting one, listing their locations, and then starting the simulation, as follows.

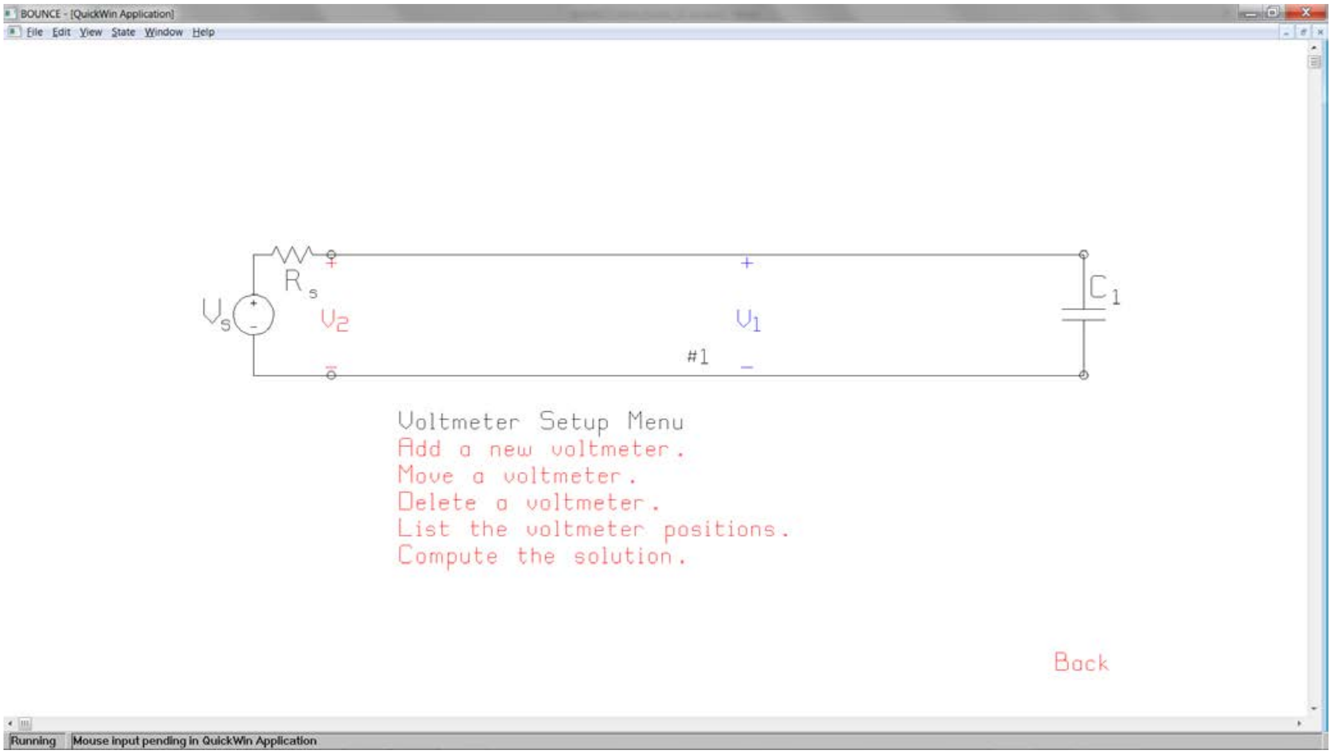


```
Click the mouse on the location for the voltmeter...
```

```
Mouse input pending in QuickWin Application
```

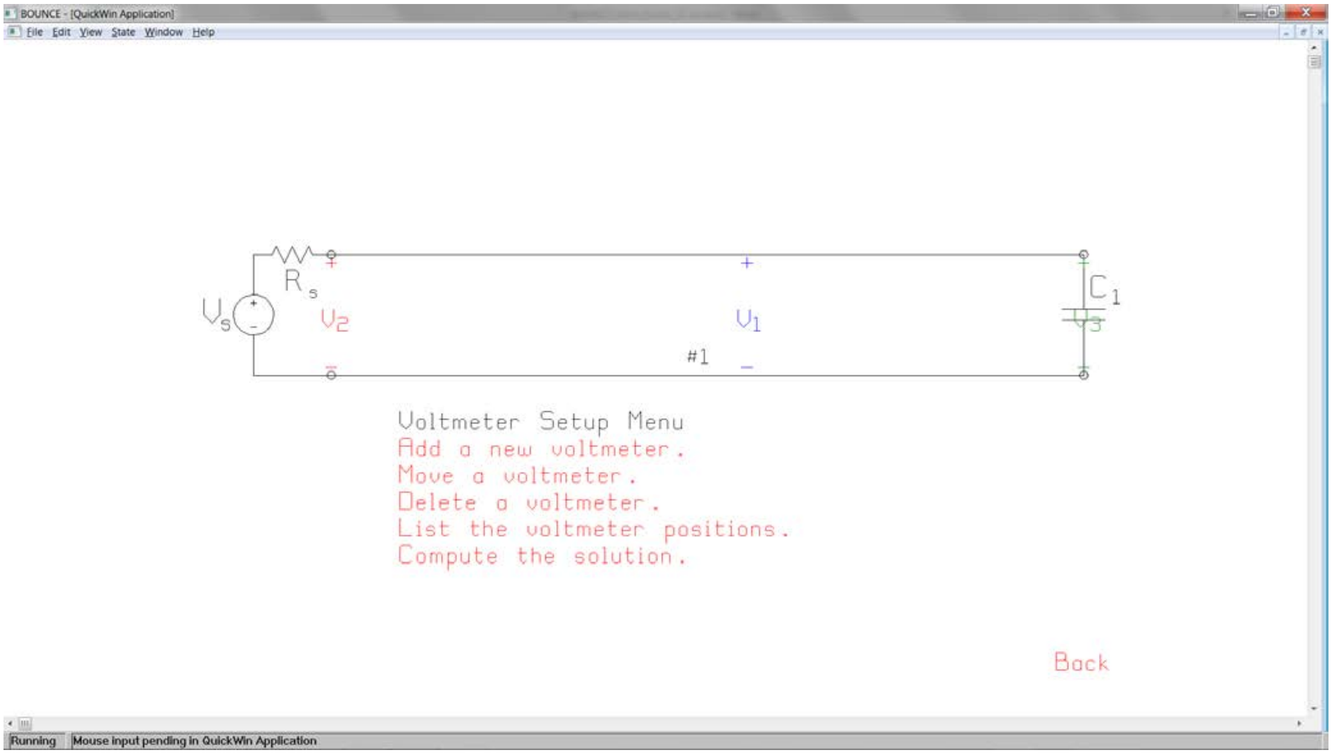
Fig 39 Click on "add a voltmeter" and the BOUNCE program responds by asking you to click on the location for the new voltmeter.

"Add a new voltmeter" is used to put another voltmeter into the circuit. Click the mouse on "Add a new voltmeter" and the program asks you to click on the location for the new voltmeter, Fig. 39. Then click the mouse on the place in the circuit where you want to put the voltmeter, say at the generator terminals. A new voltmeter simulation appears. You can have up to four voltmeters. Fig. 40 shows the circuit with voltmeter V_2 at the generator terminals, and V_1 near the middle of the transmission line.



Mouse input pending in QuickWin Application

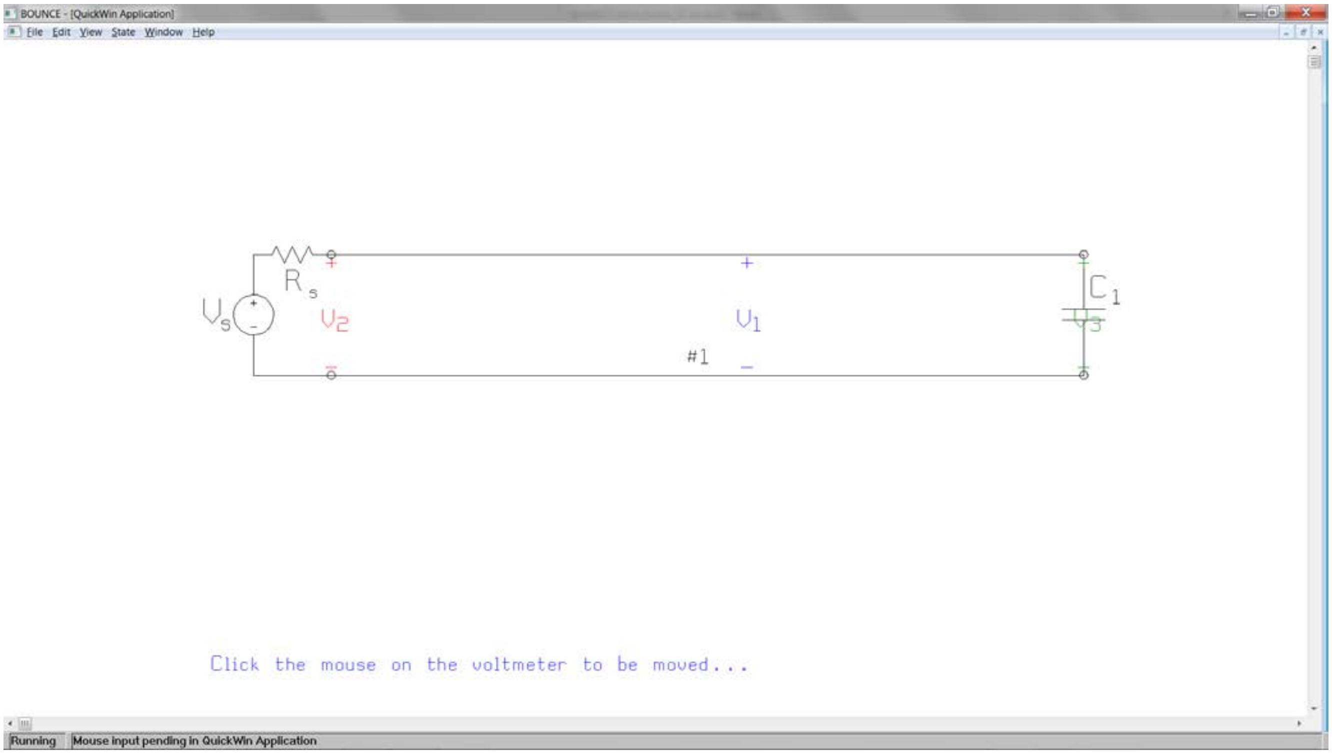
Fig. 40 A second voltmeter has been added at the generator terminals.



Mouse input pending in QuickWin Application

Fig. 41 A circuit with three voltmeters.

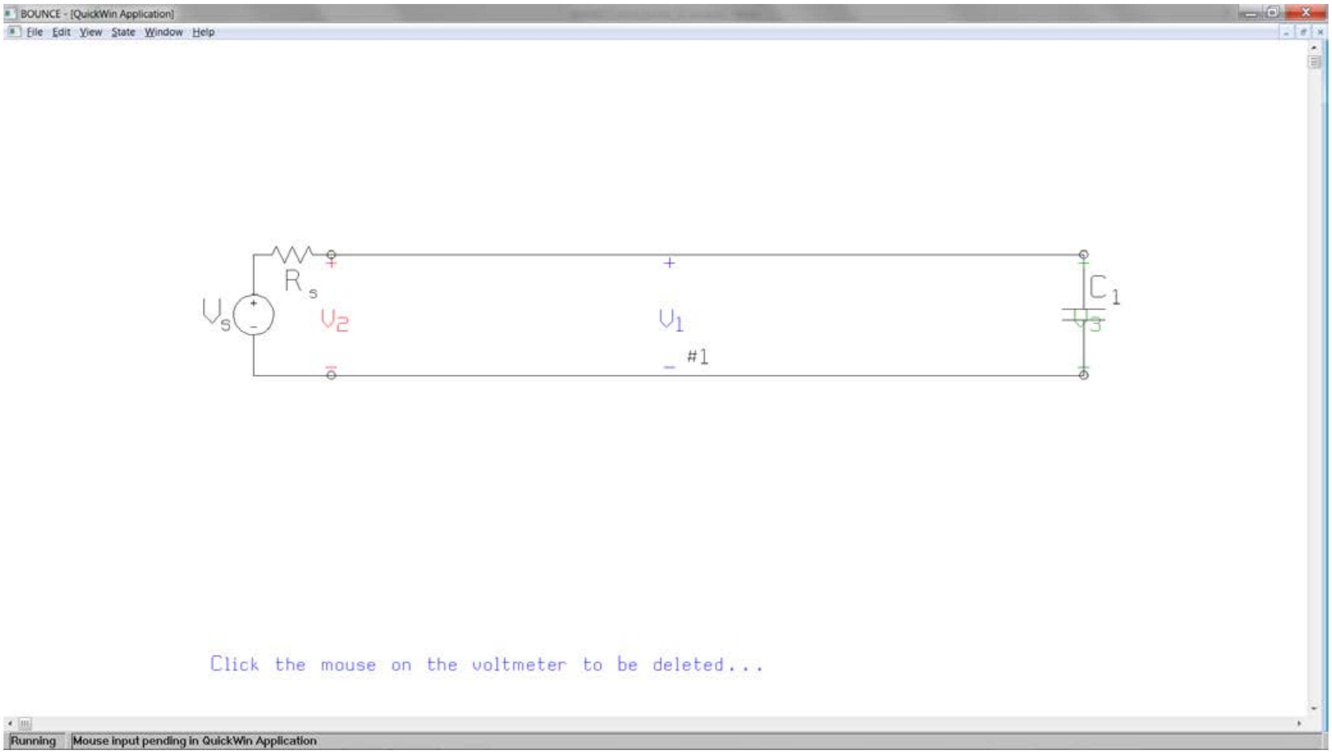
In the circuit of Fig. 41, the user has add a third voltmeters. V_3 measures the voltage at the load. Note that the “V3” label on the schematic overlaps the symbol for the load capacitor, an unavoidable problem if the voltmeter is to be drawn at its true location on the transmission line.



Click the mouse on the voltmeter to be moved...

Fig. 42 Click “move a voltmeter” and the program first asks you to click the mouse on the voltmeter to be moved, and then on the new location for the voltmeter.

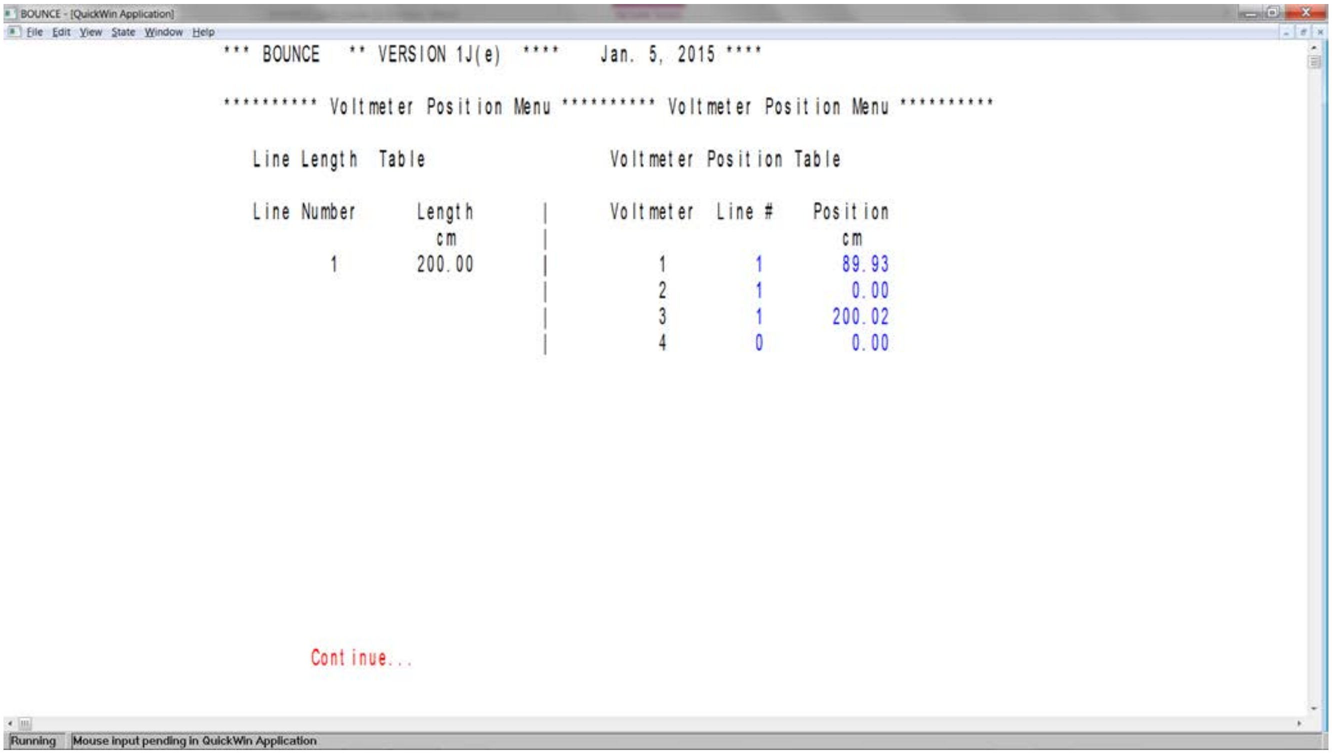
“Move a voltmeter” lets you change the position of any voltmeter. Click the mouse on “Move a voltmeter”. If there is only one voltmeter, click on the new location for the voltmeter, Fig. 42. If there are two or more, the program asks you to click the mouse on the voltmeter to be moved, and then to click the mouse on the new location.



Click the mouse on the voltmeter to be deleted...

Fig. 43 Click on “delete a voltmeter” and the program responds by asking you to click the mouse on the voltmeter to be deleted.

“Delete a voltmeter” lets you remove a voltmeter from the circuit. Click “Delete a voltmeter” and the program asks which voltmeter is to be deleted, Fig. 43. Then click on the voltmeter you wish to remove.



```
*** BOUNCE  ** VERSION 1J(e)  ****    Jan. 5, 2015 ****

********** Voltmeter Position Menu ********** Voltmeter Position Menu **********

   Line Length  Table                Voltmeter Position Table

   Line Number      Length      |         Voltmeter  Line #    Position
                      cm        |                                 cm
        1           200.00      |             1        1        89.93
                                |             2        1         0.00
                                |             3        1       200.02
                                |             4        0         0.00




         Continue...
```

Running   Mouse input pending in QuickWin Application

Fig. 44 Click on “List the voltmeter positions” to get a table of voltmeter locations. This menu permits you to precisely position the voltmeters on the transmission lines.

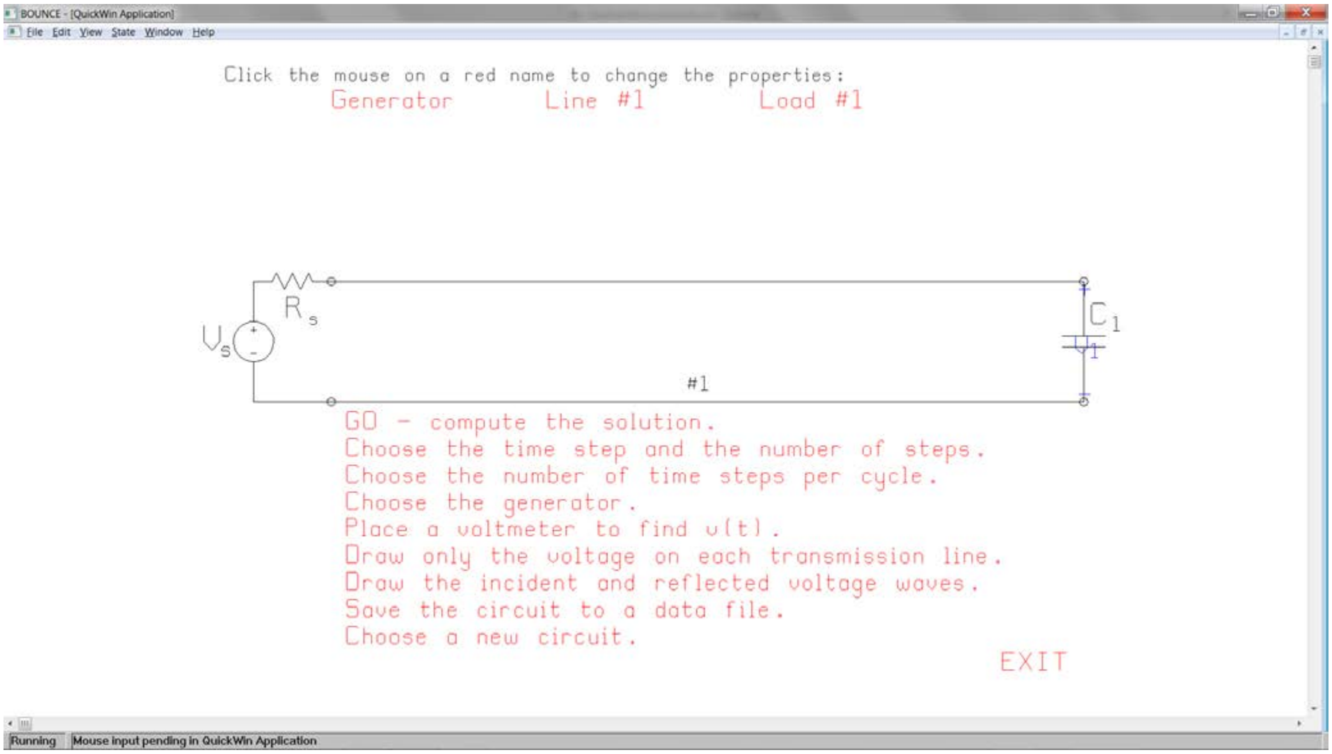
“List the voltmeter positions” in the voltmeters menu of Fig. 40 gets the table of voltmeter positions shown in Fig. 44. At left there is a list of the transmission lines and their overall lengths. At right, there is a list of the voltmeters, the line on which each voltmeter is positioned, and the location on that line. Voltmeter #1 is at location 89.93 cm on line #1, which is 200 cm long. Voltmeter #2 is at 0 cm on the line, corresponding to the input terminals where the generator is connected. Voltmeter #3 is at 200.02 cm, at the load terminals. Although the line is nominally 200 cm long, it is modelled with a line precisely 200.02 cm in length, which reflects the approximation of the line lengths with an integer number of cells, discussed previously.

You can change the locations by typing new values into the fields of the menu. This is good for precisely positioning voltmeters in the circuit. In Fig. 4, the position of voltmeter #1 can be changed to 100 cm to put this voltmeter exactly at the center of the 200 cm transmission line. Click the mouse on the blue string 89.93 and it changes to inverse video, then type 100, and Enter. This changes the location to the center of 200 cm line. Note that you can add a 4th voltmeter to the circuit by entering the line number and position for the 4th meter into the boxes at the lower right of this menu. You can also delete a voltmeter by entering “0” for the transmission line on which it is located.

The last two buttons in the menu of Fig. 44 are "Compute the solution", which runs the simulation, and "Back", which returns to the main menu.

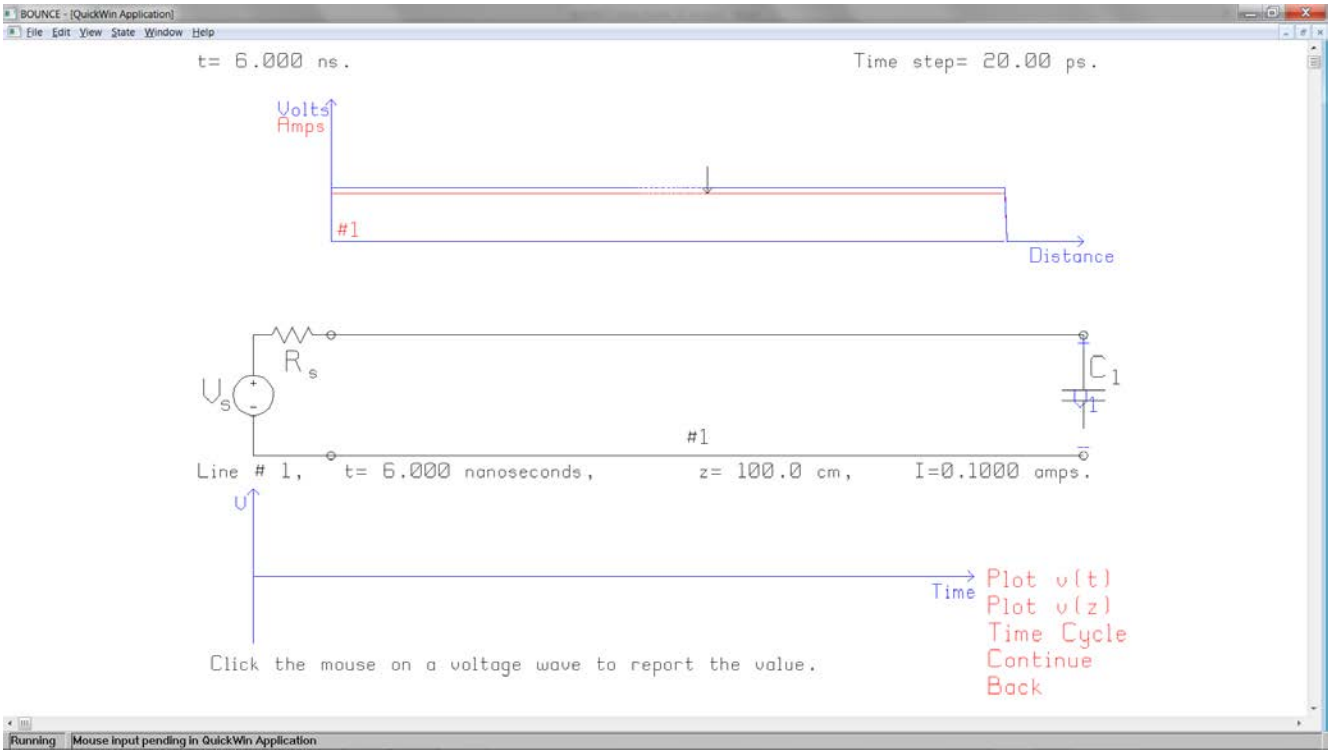
Drawing the Current Waveform

Sometimes the current on the transmission line is of interest in understanding the behavior. To see the current on each transmission line as a function of distance, as well as the voltage, click the mouse on the button “Draw the current and the voltage” in the main menu of Fig. 2. For example, consider a transmission line driven with a step generator of height 10 volts and internal resistance 50 ohms. The transmission line is 200 cm in length and has characteristic resistance 50 ohms. The speed of propagation is equal to the free-space speed of light, 29.979 cm/ns. The load is a 10 pF capacitor. Position a voltmeter in the middle of the transmission line, as shown in Fig. 45.



Click the mouse on a red name to change the properties:

Fig. 45 A circuit with a 10 pF capacitor as a load, and a voltmeter across the load.



```
t= 6.000 ns.                                   Time step= 20.00 ps.
Line # 1,   t= 6.000 nanoseconds,       z= 100.0 cm,     I=0.1000 amps.
Click the mouse on a voltage wave to report the value.
Running    Mouse input pending in QuickWin Application
```

Fig. 46 The voltage and current on the transmission line as a function of distance at t=6 ns.

Running the simulation until t=6.00 ns obtains the voltages and currents shown in Fig. 46. At the top of the figure we have the voltage on the transmission line as a function of distance, blue curve, and the current as a function of distance, red curve. The leading edge of the step function has progressed almost as far as the load. The voltage has not reached the V1 voltmeter connected across the load.

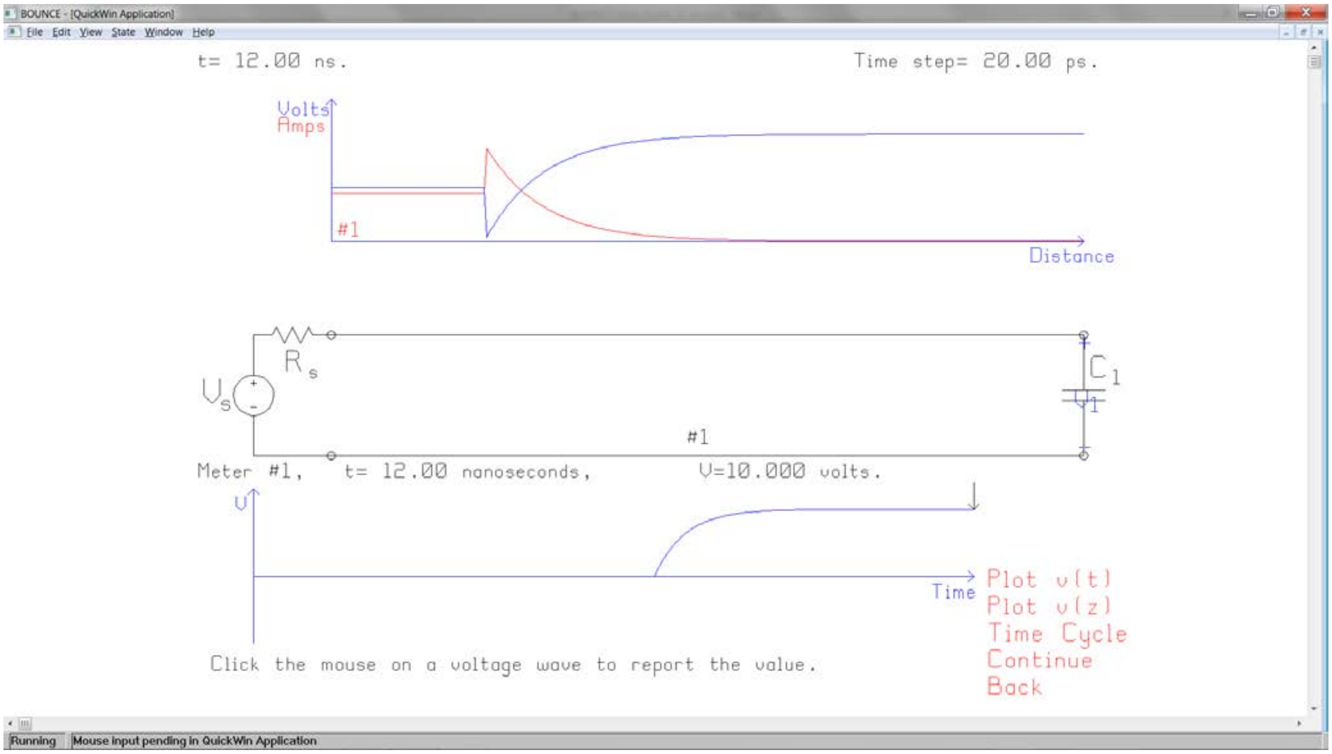
In general the voltage on the transmission line is

$$V(z,t) = V^{+}(z,t) + V^{-}(z,t)$$

where $V^{+}(z,t)$ is the positive-going or incident voltage wave and $V^{-}(z,t)$is the negative-going or reflected wave. In general the current is

$$I(z,t) = \frac{1}{R_c}V^{+}(z,t) - \frac{1}{R_c}V^{-}(z,t)$$

where R_c is the characteristic resistance of the transmission line. The incident current wave is V^{+}/R_c and the reflected current wave is $-V^{-}/R_c$, where the minus sign accounts for the fact that the reflected wave carries power towards the generator. For the problem of Fig. 46, V^{+} is a five-volt step function, and $V^{-}=0$ since the incident wave has not yet reached the load and so there is no reflected wave. The current is $V^{+}/R_c = 5/50 = 0.1$ amps. The user has clicked the mouse at 100 cm distance at the top of Fig. 46, and the program draws a small arrow pointing to the current graph, and reports that the distance is 100 cm and the current there is 0.1 amps.



t= 12.00 ns. Time step= 20.00 ps.

Meter #1, t= 12.00 nanoseconds, V=10.000 volts.

Click the mouse on a voltage wave to report the value.

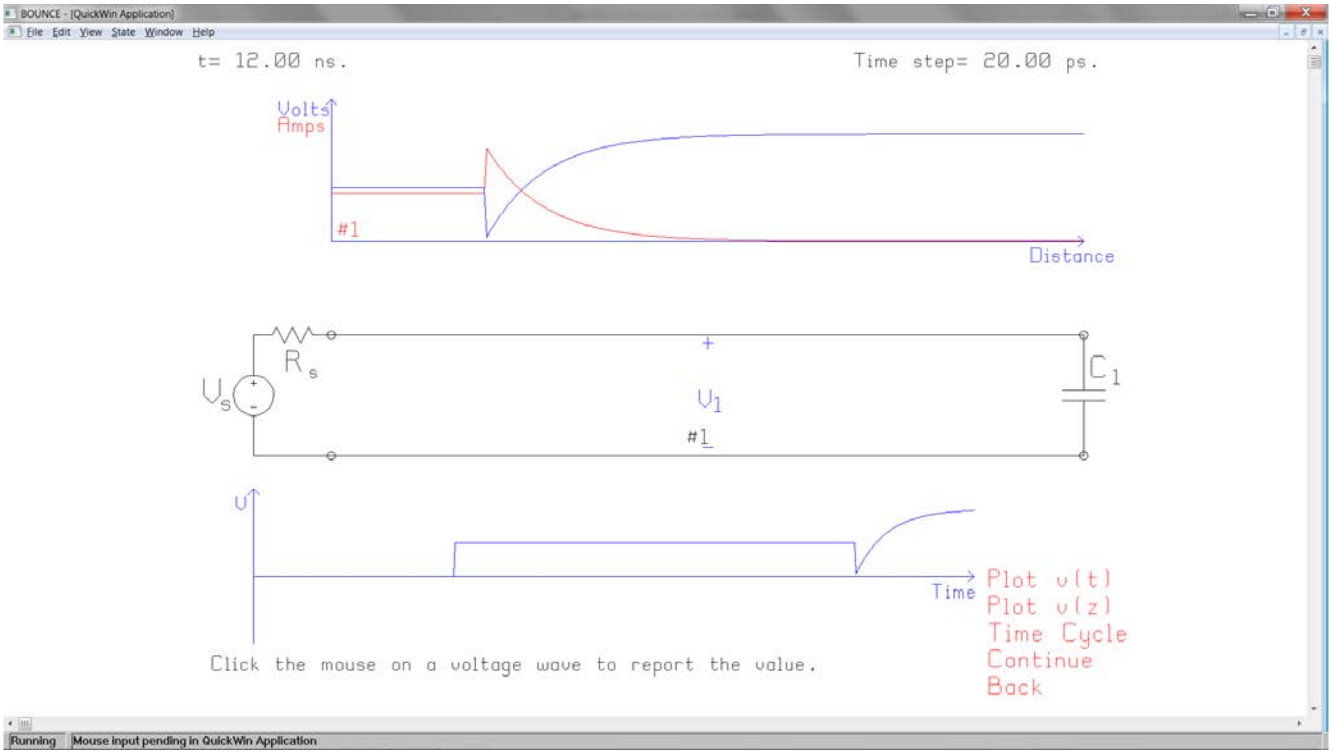
Fig. 47 The voltage and current at 12 ns.

Letting the time advance to 12 ns obtains the response in Fig. 47. The top graph shows the voltage in blue and the current in red, and the wave reflected from the load has travelled almost all the way back to the generator. The bottom graph shows the voltage at voltmeter V1 at the load, as a function of time. The capacitor is initially uncharged and so V1=0. The capacitor cannot charge instantaneously, so it pulls the transmission line voltage down to zero when the leading edge of the step first arrives. Then the capacitor gradually charges, and the voltage rising exponentially towards the final value of 10 volts, because the capacitor behaves as an open circuit as time gets large. The exponentially-rising waveform is reflected from the capacitive load towards the generator, and so in the voltage-vs.-distance graph at the top, we see the blue curve stepping down to almost 0 volts and then charging exponentially to 10 volts. Conversely, the current jumps up to a large initial value and then declines exponentially towards zero amps. The time constant of the exponential changes is $\tau = RC =$ 50 ohms x 10 pF = 50 ps. After about five time constants, the capacitor is fully charged and behaves as an open circuit. The final value of the voltage across the capacitor is then 10 volts.

When the step function first reaches the load, the capacitor is uncharged and behaves as a short circuit, with a reflection coefficient of minus one. The voltage across the load is

$$V(L) = V^+ + V^-$$

where $V^+ = 5$ and $V^- = \Gamma_L V^+ = (-1)x5 = -5$ volts, so that at the instant when the step reaches the load, $V(L) = 5 - 5 = 0$ volts. When the capacitor is fully charged, it draws zero current and so behaves as an open circuit, with a reflection coefficient of plus one. Then $V^- = \Gamma_L V^+ = (+1)x5 = +5$ volts and $V(L) = 5 + 5 = 10$ volts.



t= 12.00 ns.

Time step= 20.00 ps.

Click the mouse on a voltage wave to report the value.

Mouse input pending in QuickWin Application

Fig. 48 The voltage and current waveforms after 12.8 ns.

It is instructive to move the voltmeter to the center of the transmission line, to obtain the voltage curve in Fig. 48. We see the step function arrive at the voltmeter location, so that the voltage steps up to 5 volts. Then the reflection from the capacitor arrives at the voltmeter location and the voltage drops down to (almost) zero volts, and then rises exponentially to a final value of 10 volts.

Viewing the Incident and Reflected Voltage Waveforms

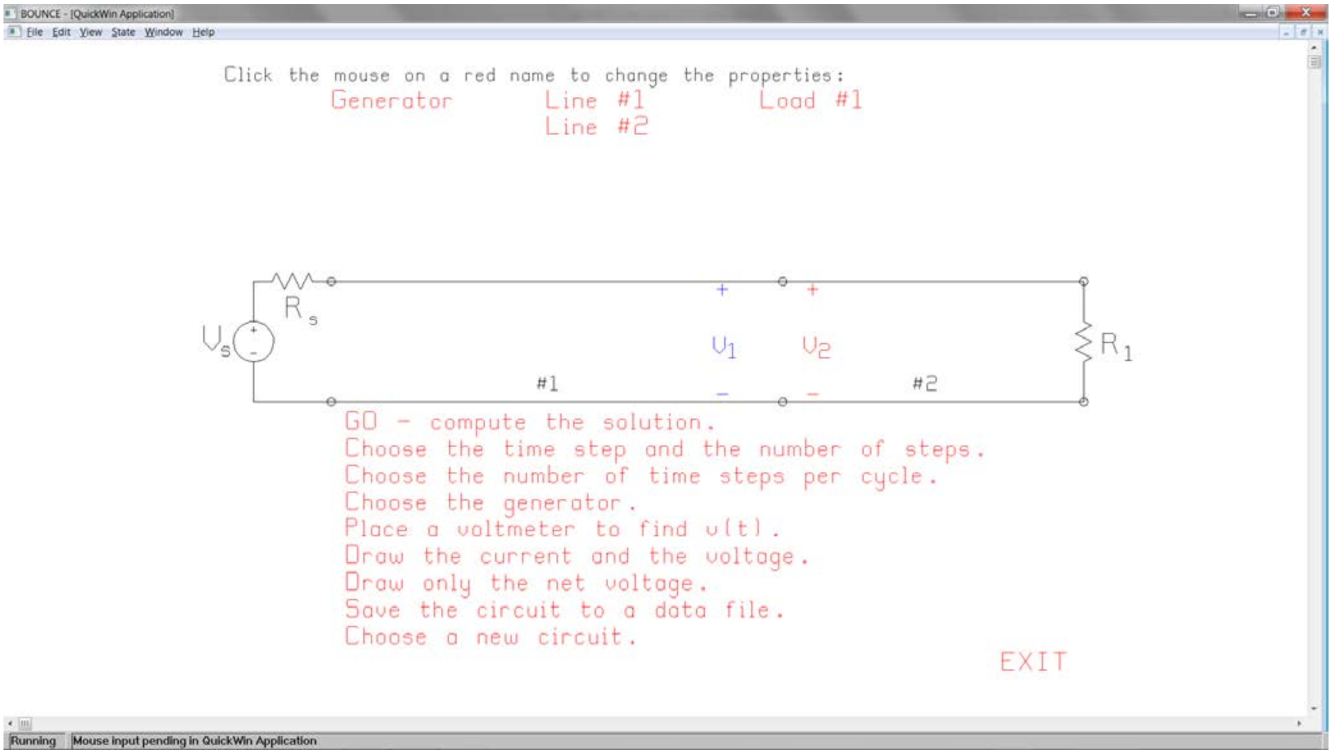
Sometimes it is useful to decompose the voltage on the transmission line into the “incident” or positive-going voltage wave and the “reflected” or negative-going voltage wave. Thus the voltage on the transmission line can be decomposed as

$$V(z,t) = V^{+}(z,t) + V^{-}(z,t)$$

where the incident wave is $V^{+}(z,t)$ and the reflected wave is $V^{-}(z,t)$. Click the mouse on “Draw the incident and reflected voltage waves”, and the program will draw the functions for the incident wave $V^{+}(z,t)$ and the reflected wave $V^{-}(z,t)$ individually, as well as their sum, $V(z,t)$. Two examples will be presented. In the first a pulse is partially reflected from a junction and partially transmitted. The second example will be the reflection of a sinusoidal voltage from an unmatched load.

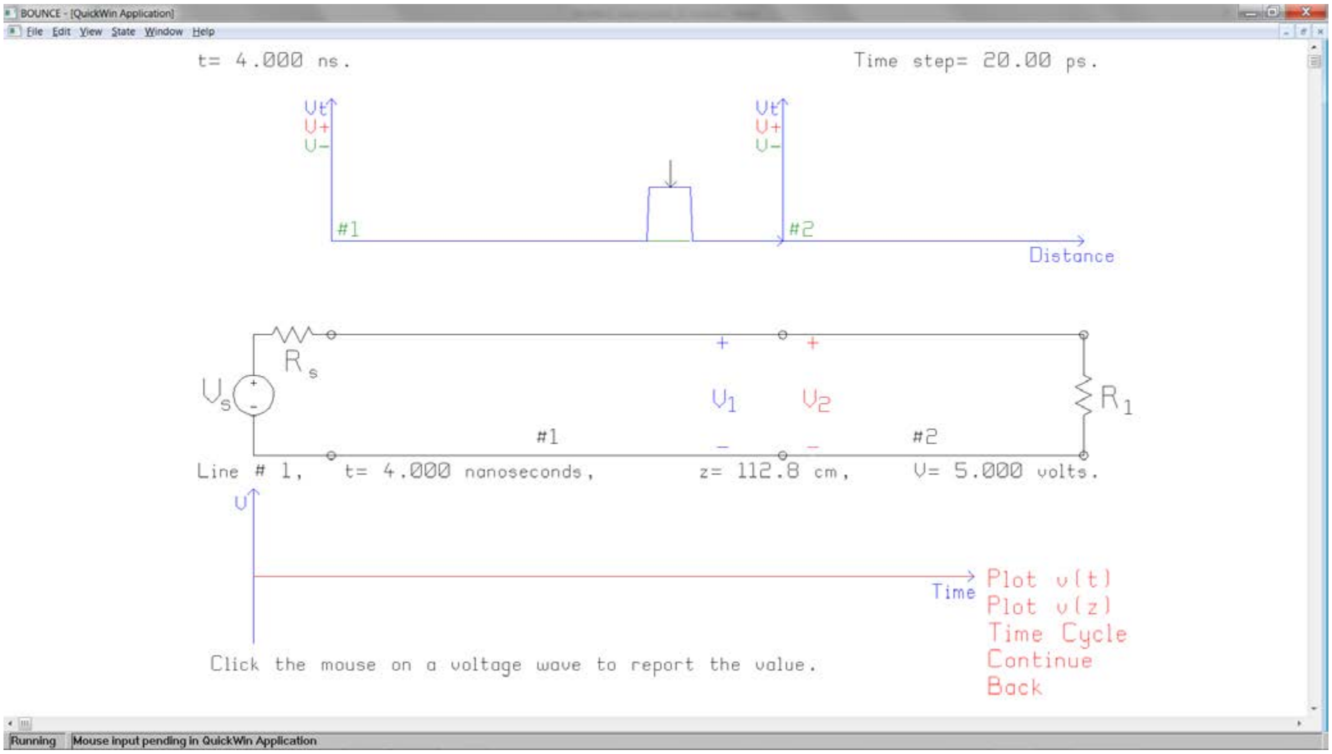
Reflection and Transmission at a Junction

Consider a circuit with two transmission lines in series, shown in Fig. 49. The generator is a pulse of 10 volts amplitude (open-circuit) and duration 0.5 ns. The internal resistance is 50 ohms. Line #1 is 150 cm in length, with characteristic resistance 50 ohms, and speed of propagation 30 cm/ns. Line #2 is 100 cm in length with characteristic resistance 100 ohms, and speed of propagation 30 cm/ns. The load is 100 ohms. Choose a time step of 20 ps. Position voltmeter #1 at 130 cm on line #1, 20 cm from the junction. Position voltmeter #2 at 10 cm on line #2. The voltmeters will be used to observer the reflected pulse from the junction and the transmitted pulse through the junction. Also, to separate the incident pulse and the reflected pulse on line #1, click the mouse on “Draw the incident and reflected voltage waves”.



Click the mouse on a red name to change the properties:

Fig. 49 A transmission line circuit with two lines in series.



t= 4.000 ns.

Time step= 20.00 ps.

Line # 1, t= 4.000 nanoseconds, z= 112.8 cm, V= 5.000 volts.

Click the mouse on a voltage wave to report the value.

Fig. 50 The pulse has almost reached the junction.

Fig. 50 shows the transmission line circuit. Time has been advanced to 4 ns. The incident pulse amplitude is V_1^+=5 volts, determined by the voltage divider between the internal resistance of the generator of $R_s = 50$ ohms and the characteristic resistance of transmission line #1 of $R_c = 50$ ohms. The incident pulse has not yet reached the junction so the reflected voltage is zero in Fig. 50.

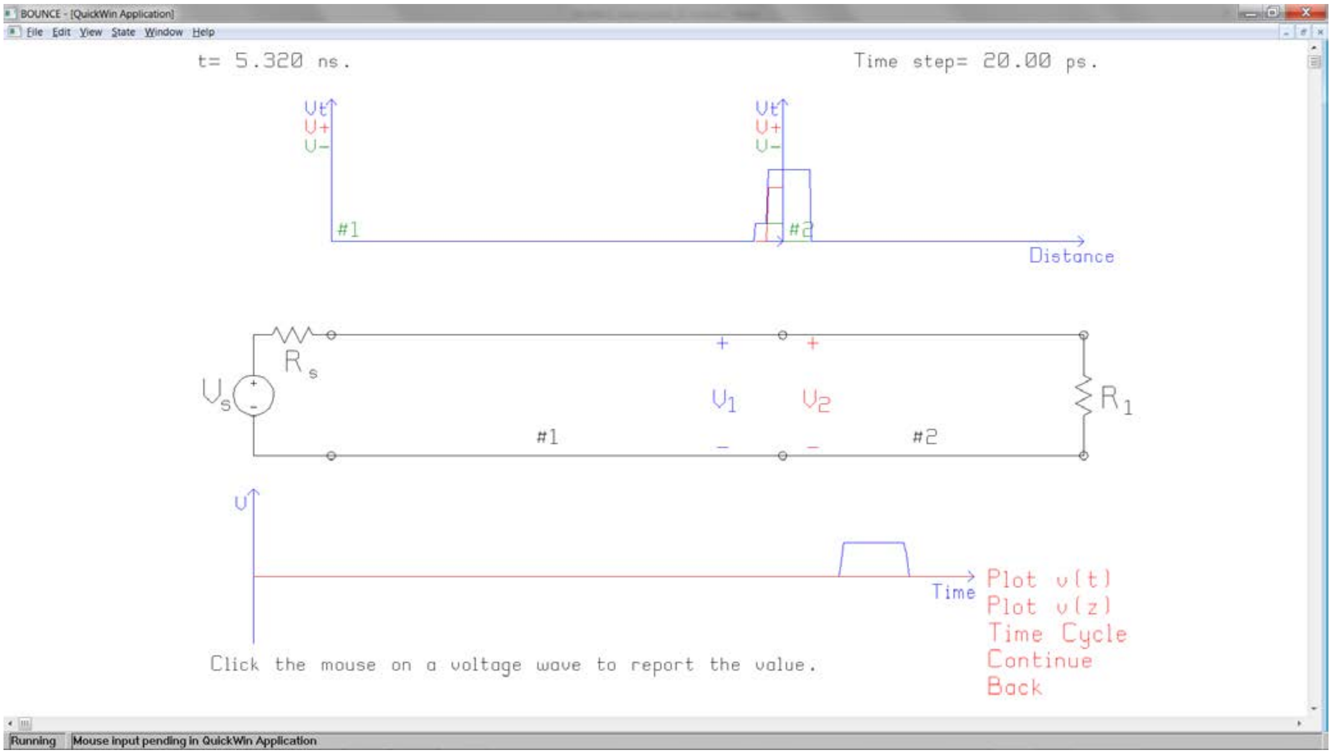
The junction is characterized by a reflection coefficient of

$$\Gamma_L = \frac{R_{c2} - R_{c1}}{R_{c2} + R_{c1}} = \frac{100 - 50}{100 + 50} = 0.333$$

and a transmission coefficient of

$$T_{21} = \frac{2R_{c2}}{R_{c2} + R_{c1}} = \frac{2x100}{100 + 50} = 1.333$$

We expect the incident pulse of V_1^+=5 volts amplitude to reflected as a pulse of amplitude $V_1^- = \Gamma_L V_1^+ = 5x0.333 = 1.667$ volts, and that there will be a transmitted pulse of amplitude $V_2^+ = T_{21} V_1^+ = 5x1.333 = 6.667$ volts.



t= 5.320 ns.

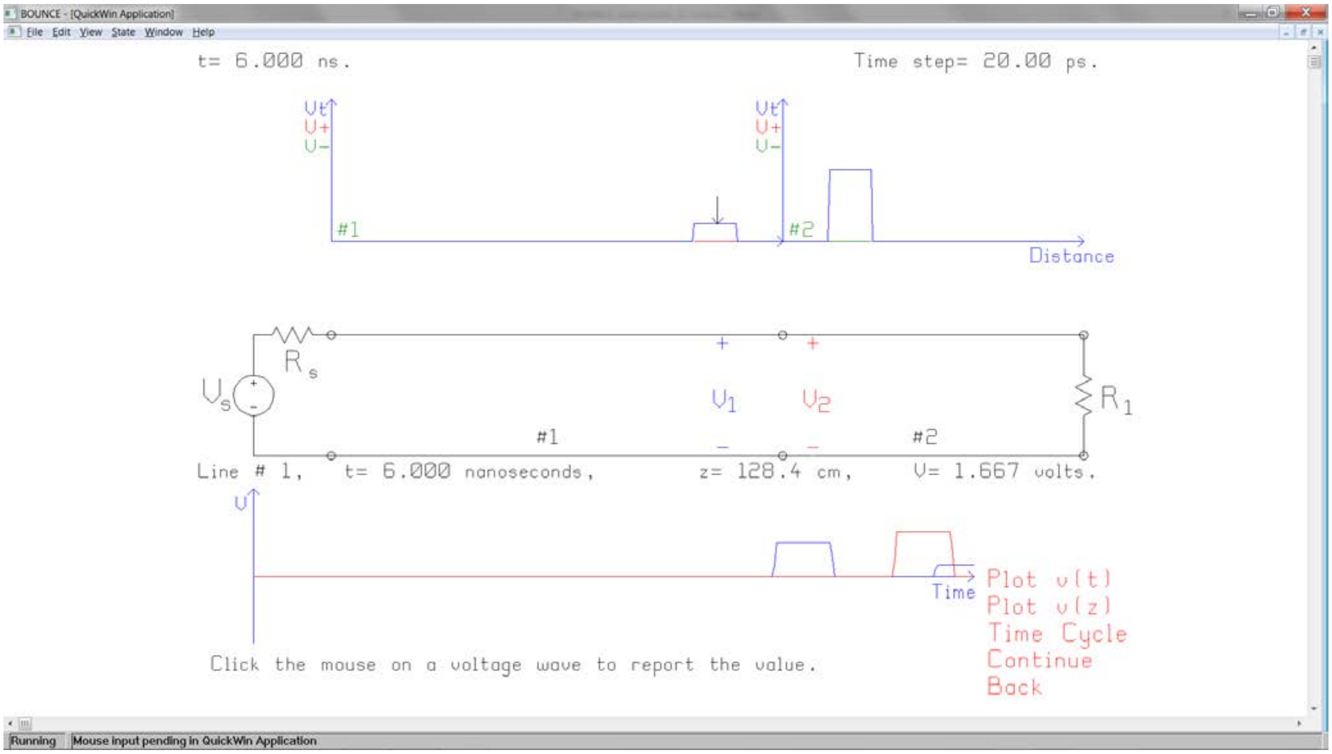
Time step= 20.00 ps.

Click the mouse on a voltage wave to report the value.

Mouse input pending in QuickWin Application

Fig. 51 The reflection is in progress at 5.32 ns.

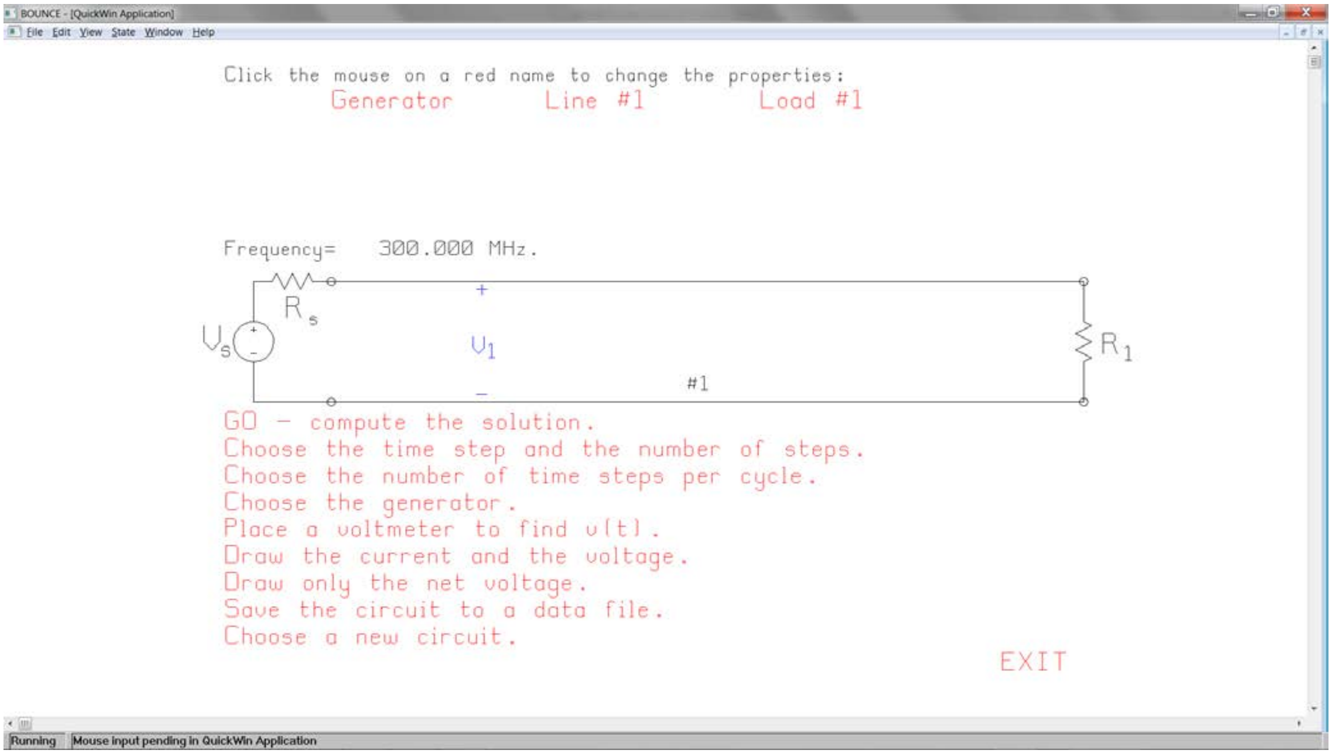
Fig. 51 shows the voltages at t=5.32 ns, when the interaction with the junction is in progress. On line #1 just to the left of the junction, we see the 5 volt incident pulse in red, and the 1.667 volt reflected pulse in green, and they add up to the 6.667 volt net voltage shown in blue. On line #2 we see the 1.667 volt transmitted pulse, shown in blue because this is also the net voltage on transmission line #2. Note that Kirchoff’s Voltage Law is satisfied at the junction. The net voltage on the left side and the net voltage on the right side are the same.



```
t= 6.000 ns.                                   Time step= 20.00 ps.

Line # 1,   t= 6.000 nanoseconds,        z= 128.4 cm,     V= 1.667 volts.

Click the mouse on a voltage wave to report the value.
```

Fig. 52 Time has advanced to 6 ns and we see the reflected and the transmitted pulse.

Allow time to advance to 6 ns, to get the voltages in Fig. 52. Line #1 has a reflected pulse of amplitude 1.667 volts travelling back towards the generator, and line #2 has a pulse of amplitude 6.667 volts travelling towards the load.

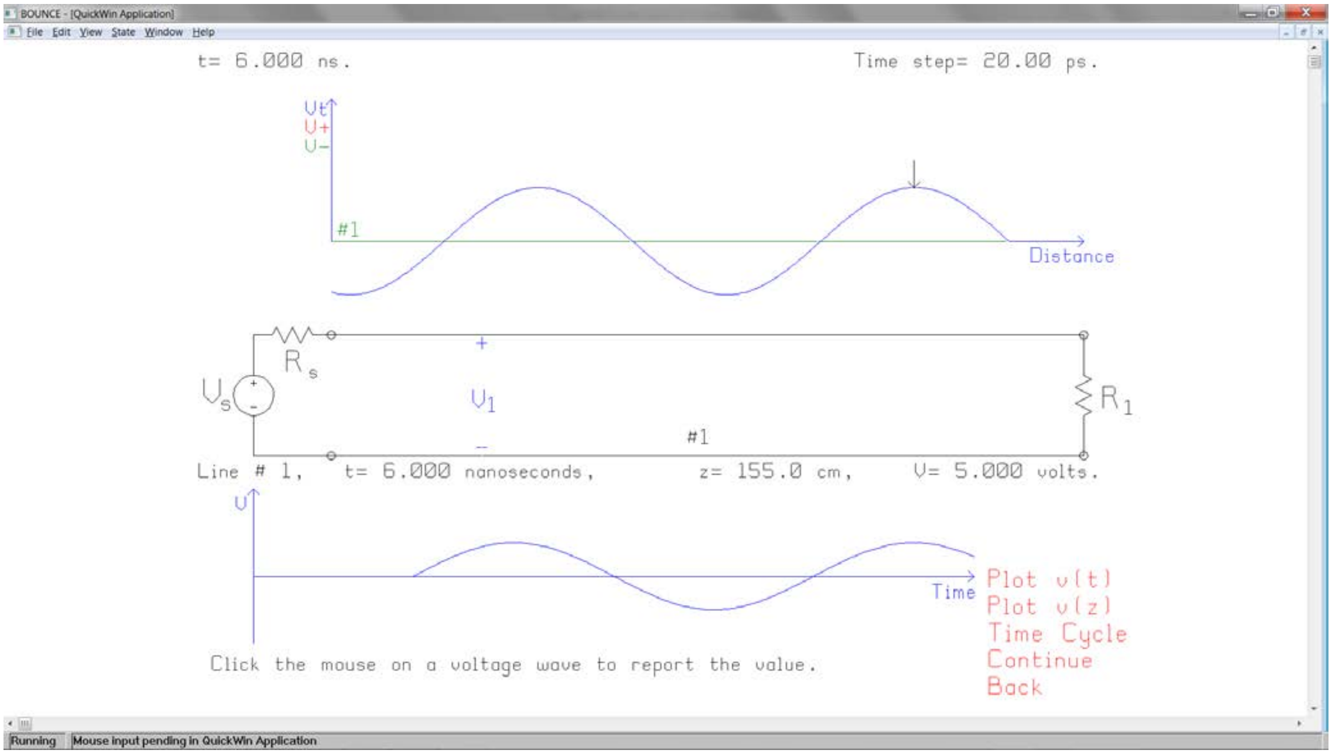


```
Click the mouse on a red name to change the properties:

Frequency=   300.000 MHz.
```

Fig. 53 A transmission line driven by a sinusoidal generator. Note that with a sinusoidal generator, the program reports the frequency, in this case 300 MHz.

Reflection of a Sinusoid at an Unmatched Load

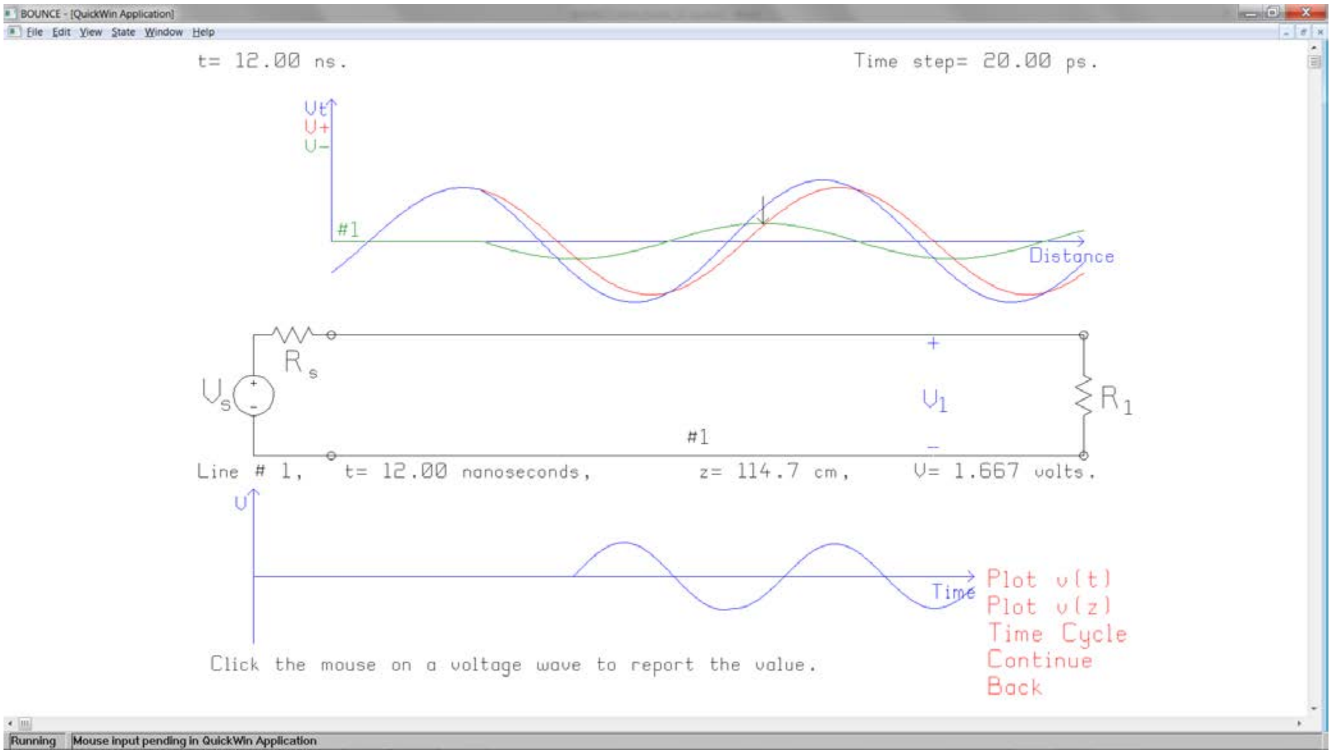
The second example using decomposition into the positive-going and negative-going traveling waves concerns the reflection of a sinusoid at an unmatched load. Choose the simple transmission line circuit in the entry menu of Fig. 1. Set the generator to a 10-volt, 300 MHz sine wave with internal resistance 50 ohms. Use a 200 cm, 50 ohm transmission line with propagation velocity 30 cm/ns. Set the load to 25 ohms. The voltmeter is at position 40 cm. The circuit is shown in Fig. 53. Set the time step to 20 ps.



```
t= 6.000 ns.                                   Time step= 20.00 ps.
Line # 1,   t= 6.000 nanoseconds,      z= 155.0 cm,     V= 5.000 volts.
Click the mouse on a voltage wave to report the value.
Running    Mouse input pending in QuickWin Application
```

Fig. 54 The voltage waveforms at 6 ns.

In Fig. 54, time has advanced to 6 ns, and the leading edge of the generator's sine wave has almost reached the load. The voltage at the voltmeter V1, located at 40 cm from the generator, has about one and a half cycles of the incident sine wave. The amplitude of the incident wave is $V^{+} = 5$ volts. There is no reflected wave. The animation of the sine wave moving along the transmission line illustrates the fundamental concept of travelling wave.



t= 12.00 ns.

Time step= 20.00 ps.

Line # 1, t= 12.00 nanoseconds, z= 114.7 cm, V= 1.667 volts.

Click the mouse on a voltage wave to report the value.

Running

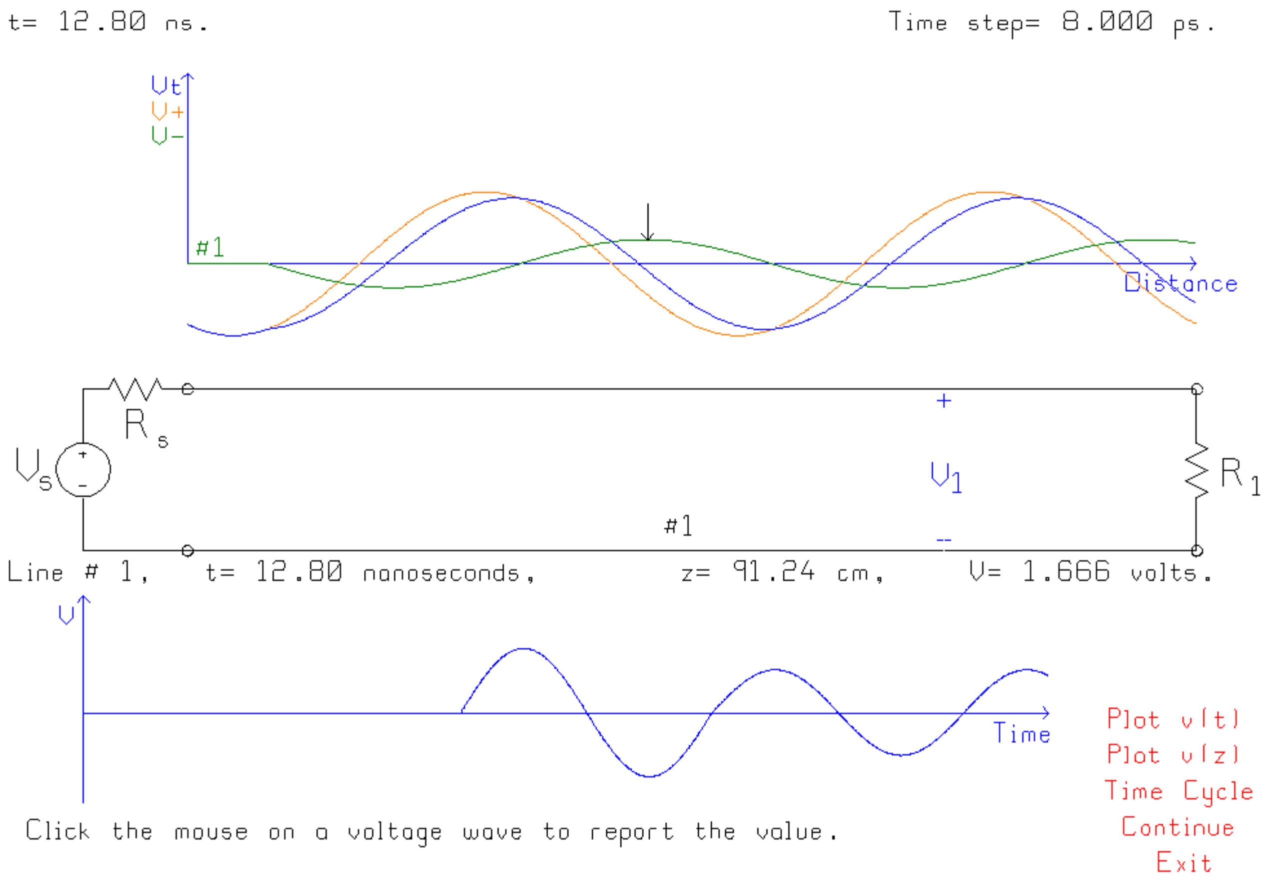
Mouse input pending in QuickWin Application

Fig.55 The voltage waveforms at 12 ns.

The reflection coefficient at the load is

$$\Gamma_L = \frac{R_L - R_c}{R_L + R_c} = \frac{25-50}{25+50} = -0.333$$

We expect the reflected sine wave to have amplitude 5x0.333=1.667 volts. The amplitude is by definition a positive number. The minus sign represents a phase change of 180 degrees.



t= 12.80 ns.

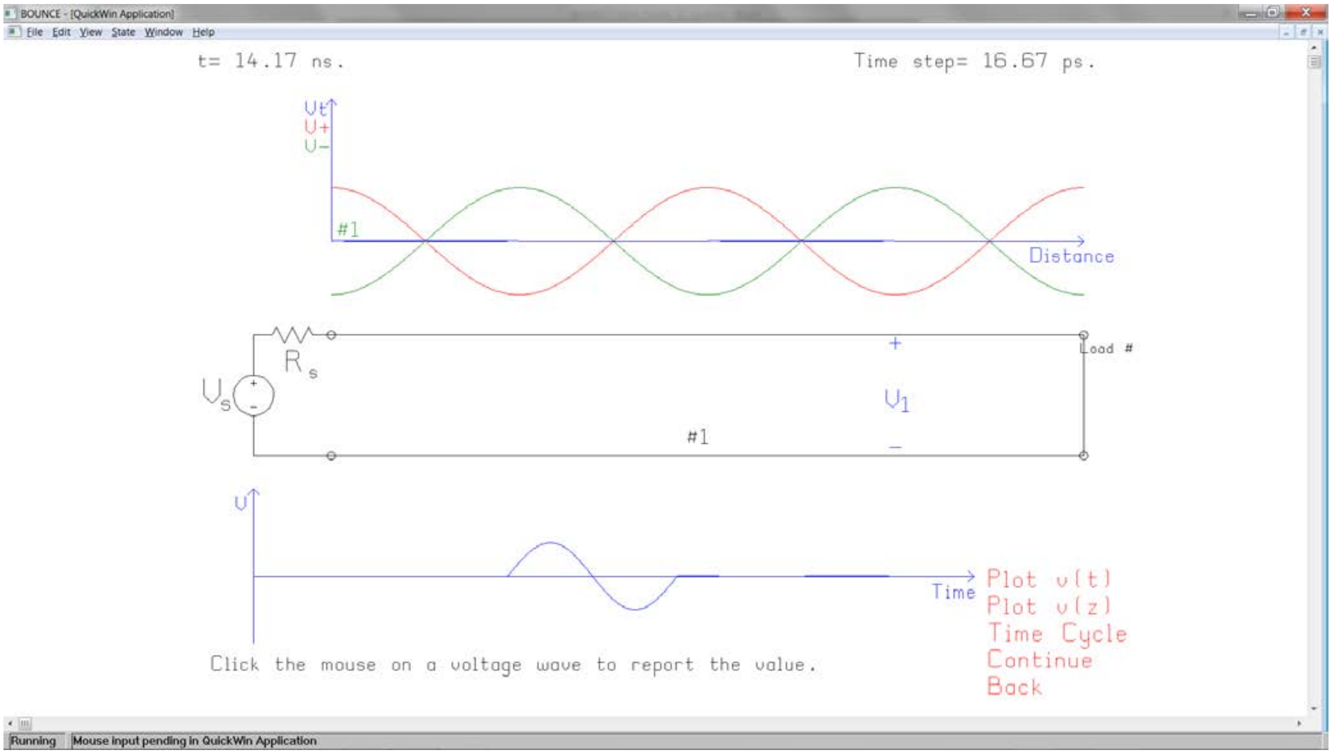
Time step= 8.000 ps.

Line # 1, t= 12.80 nanoseconds, z= 91.24 cm, V= 1.666 volts.

Click the mouse on a voltage wave to report the value.

Fig. 56 The incident, reflected and total voltages on the transmission line.

By decomposing the voltage on the transmission line into the positive-going or incident wave V^{+} and the negative-going or reflected wave V^{-}, we can observe how the incident wave and the reflected wave, add up to the net voltage at each point on the transmission line. Letting time advance to 12.8 ns is enough for the reflected wave to travel almost all the way back to the generator as shown in Fig. 56. The voltage-vs.-distance graph at the top of Fig. 46 show the incident or positive-going traveling wave in red, with an amplitude of $V^{+}=5$ volts. The reflected or negative-going traveling wave is shown in green, and has amplitude $V^{-}=1.666$ volts as expected. The blue curve is the total voltage, which is the sum of the incident and the reflected wave. At the bottom of Fig. 46 we see the voltage at the voltmeter location, half a wavelength from the load. After once cycle of the five-volt incident wave, the reflected wave reaches the voltmeter, and the amplitude changes to 5-1.666=3.334 volts.

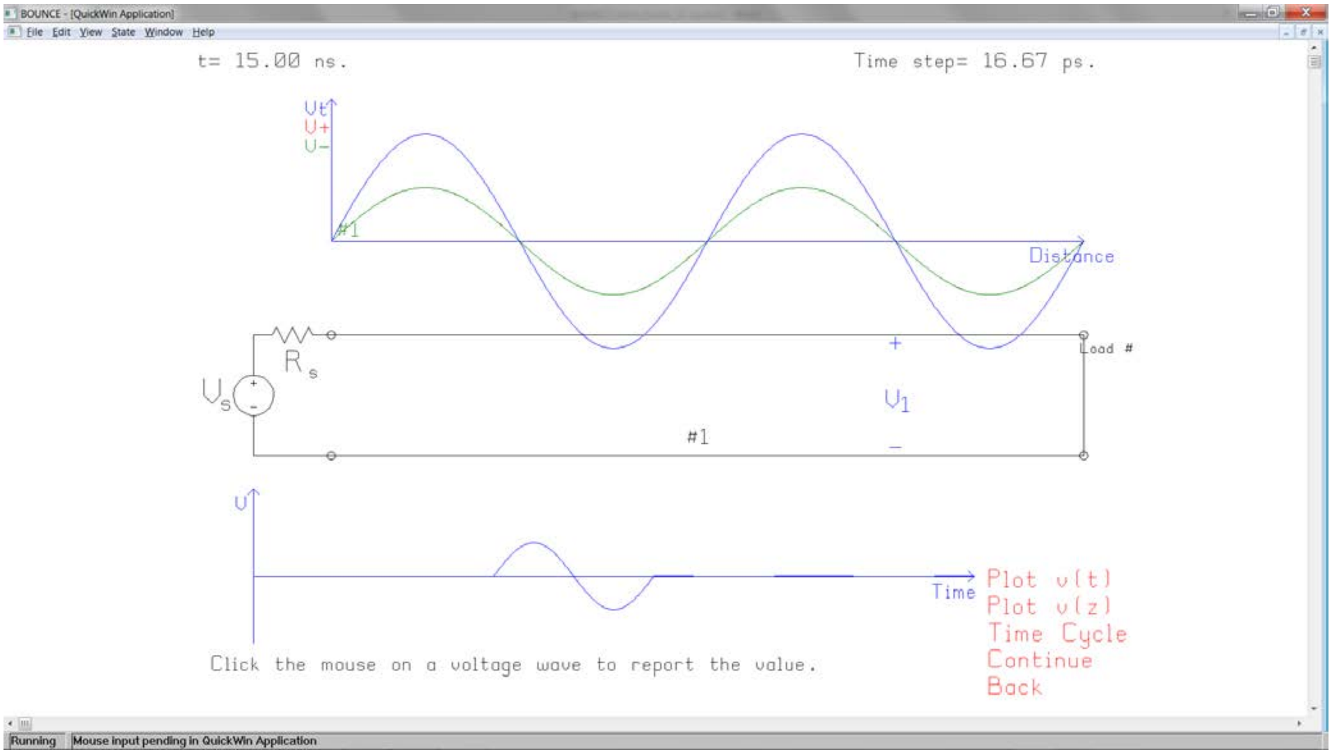


Click the mouse on a voltage wave to report the value.

Fig. 57 The voltage at 14.17 ns.

We can demonstrate a standing wave by changing the load to a short circuit. With a propagation velocity of 30 cm/ns and a frequency of 300 MHz, the wavelength is $\lambda = u / f = 30/0.3 = 100$ cm. Move the voltmeter to position 150 cm, which is one half a wavelength from the load. With a short circuit load, the reflection coefficient is minus one. The phase of the incident wave at $z = 150$ cm is $-\beta z$, where $\beta = 360/\lambda = 360/1 = 360$ degrees per meter, so the phase of the incident wave is $-\beta z = 360 x 1.5 = -540$ degrees. The incident wave travels a further 50 cm to the load, undergoes a phase change of 180 degrees, and then travels an addition 50 cm from the load back to the observer. So the phase of the reflected wave is -540-360-180=-1080 degrees, and the phase difference between the incident wave and the reflected wave is -1080-(-540)=540 degrees. Subtracting a full cycle of 360 degrees, the phase difference is 180 degrees and the reflected wave at z=150 cm is out-of-phase with the incident wave by 180 degrees. We expect the incident wave and the reflected wave to cancel at z=150 degrees, and so the voltage at this location should be zero.

The period of the 300 MHz sine wave is $T = 1/ f = 3.333$ ns. Set the time step to 16.667 ps, and run the simulation. The sine wave travels out from the generator to the load, is reflected, and then travels back to the source. Let time advance to 14.17 ns as shown in Fig. 57. The incident wave (red) and the reflected wave (green) are out-of-phase at this instant of time, and add up to zero voltage everywhere on the transmission line (blue). At the voltmeter, we see once cycle of the incident wave, and then the reflected wave arrives, and as explained above, is 180 degrees out of phase with the incident wave, and so the incident and reflected waves cancel, and the voltage at z=150 cm is zero for all time.



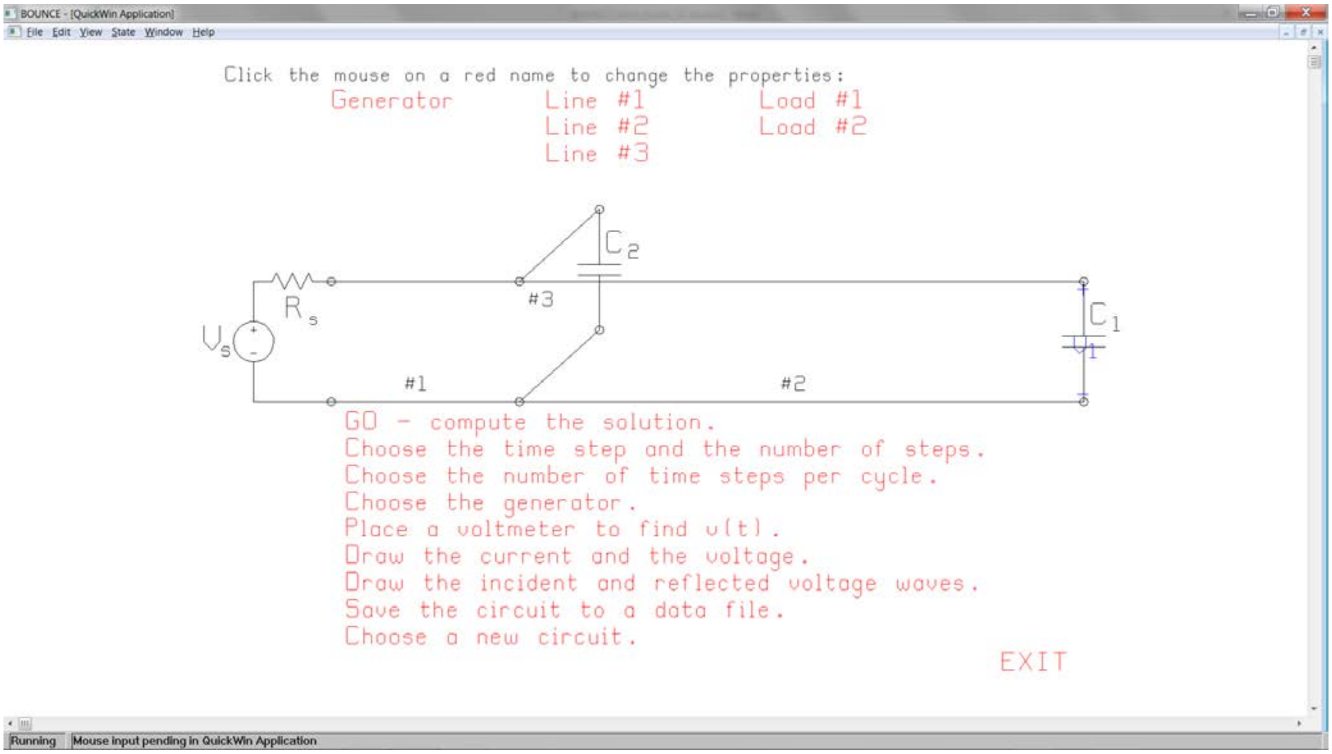
t= 15.00 ns.

Time step= 16.67 ps.

Click the mouse on a voltage wave to report the value.

Fig. 58 the voltage at t=15 ns.

Fig. 58 shows the voltage on the transmission line one-quarter of a period later at 15 ns. Now the incident and reflected waves are identical and the red curve and the green curve superimpose. They add up, point by point, to the blue curve which is the net voltage on the transmission line. At some locations, the voltage is a maximum of 10 volts, but at other locations such as the voltmeter position at z=150 cm, the incident and reflected waves have zero crossings and the voltage is zero. Run the simulation and let time advance. The voltage on the transmission line "marches in place" rather than advancing along the transmission line, and is called a "standing wave".



Click the mouse on a red name to change the properties:

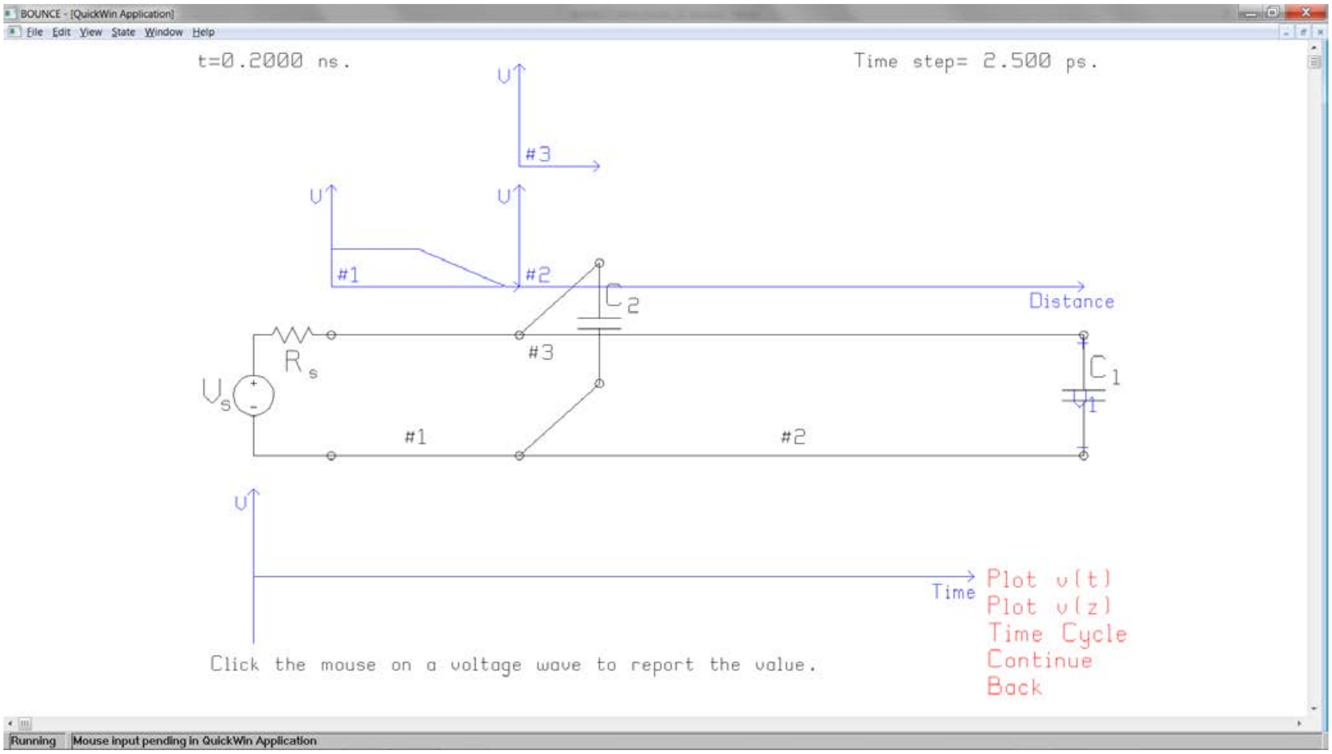
Generator
Line #1
Line #2
Line #3
Load #1
Load #2

GO - compute the solution.
Choose the time step and the number of steps.
Choose the number of time steps per cycle.
Choose the generator.
Place a voltmeter to find v(t).
Draw the current and the voltage.
Draw the incident and reflected voltage waves.
Save the circuit to a data file.
Choose a new circuit.
EXIT

Fig. 59 In this circuit a pulse generator drives two CMOS logic gates with a branching circuit.

Transmission Line Branching to two Gates

Fig. 59 shows the circuit template for two transmission lines in series with a short branch. This circuit can be used to simulate a “talker” chip (the generator) that drives two “listener” chips through a branching circuit. The listeners have high-resistance inputs, but are capacitive with a capacitance of 1 pf. The talker produces a step function voltage with a rise time of 0.1 ns and a step amplitude of 5 volts. The generator has internal resistance 100 ohms so is not matched to the transmission line. All the transmission lines have propagation velocity 14 cm/ns and all have characteristic resistance 50 ohms. The lengths are: line #1, 3 cm; line #2, 9 cm, and line #3, 2 cm. The logic family considers a voltage of 4 volts sufficient for a logical one. How long does it take the voltage at the listener chip at the end of line #2 to stabilize to a voltage of 4 volts or more?



t=0.2000 ns.

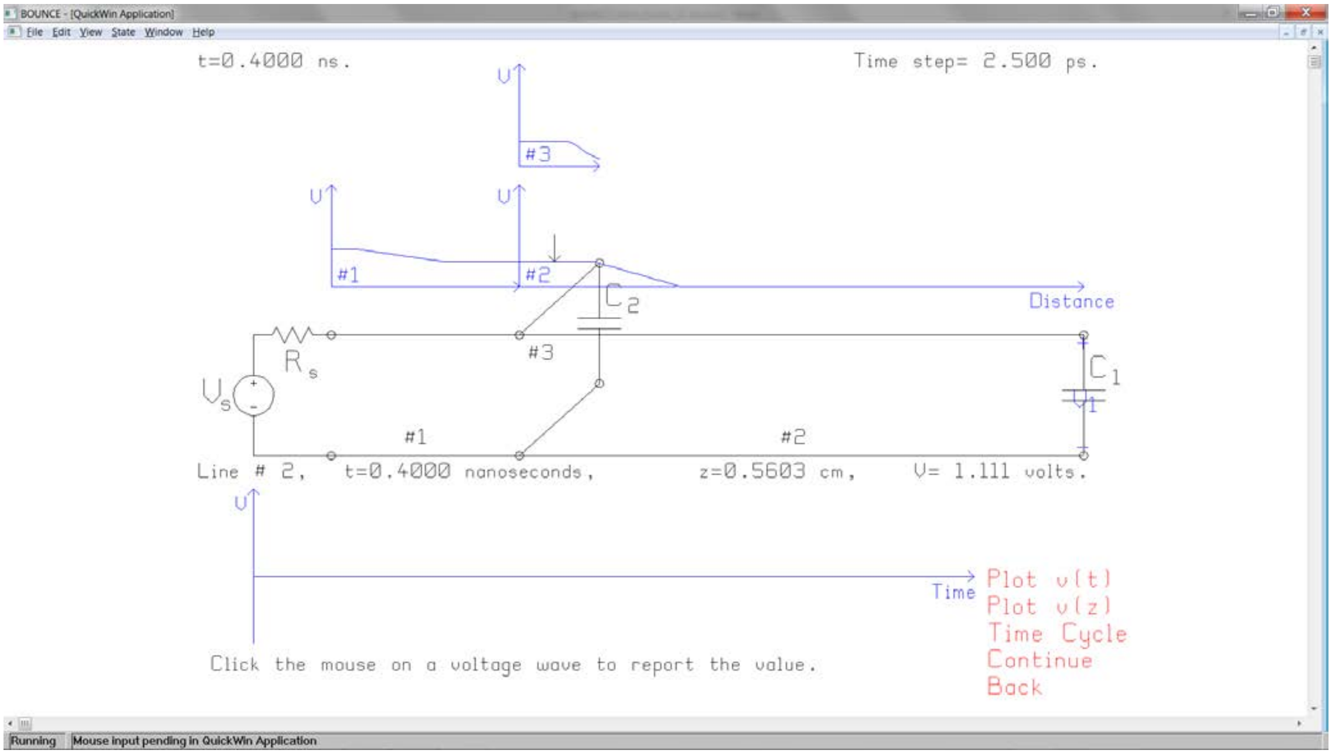
Time step= 2.500 ps.

Click the mouse on a voltage wave to report the value.

Mouse input pending in QuickWin Application

Fig. 60 The step function emerges from the generator.

Fig. 60 shows the voltages on the transmission lines after 0.2 ns. The leading edge of the step function has just arrived at the junction. We see the 0.1 ns rise time of the step generator, and then the generator voltage stabilizes at 1.667 volts, which is the voltage-divider between the generator's internal resistance of 100 ohms and the transmission line characteristic resistance of 50 ohms.



t=0.4000 ns.

Time step= 2.500 ps.

Line # 2, t=0.4000 nanoseconds, z=0.5603 cm, V= 1.111 volts.

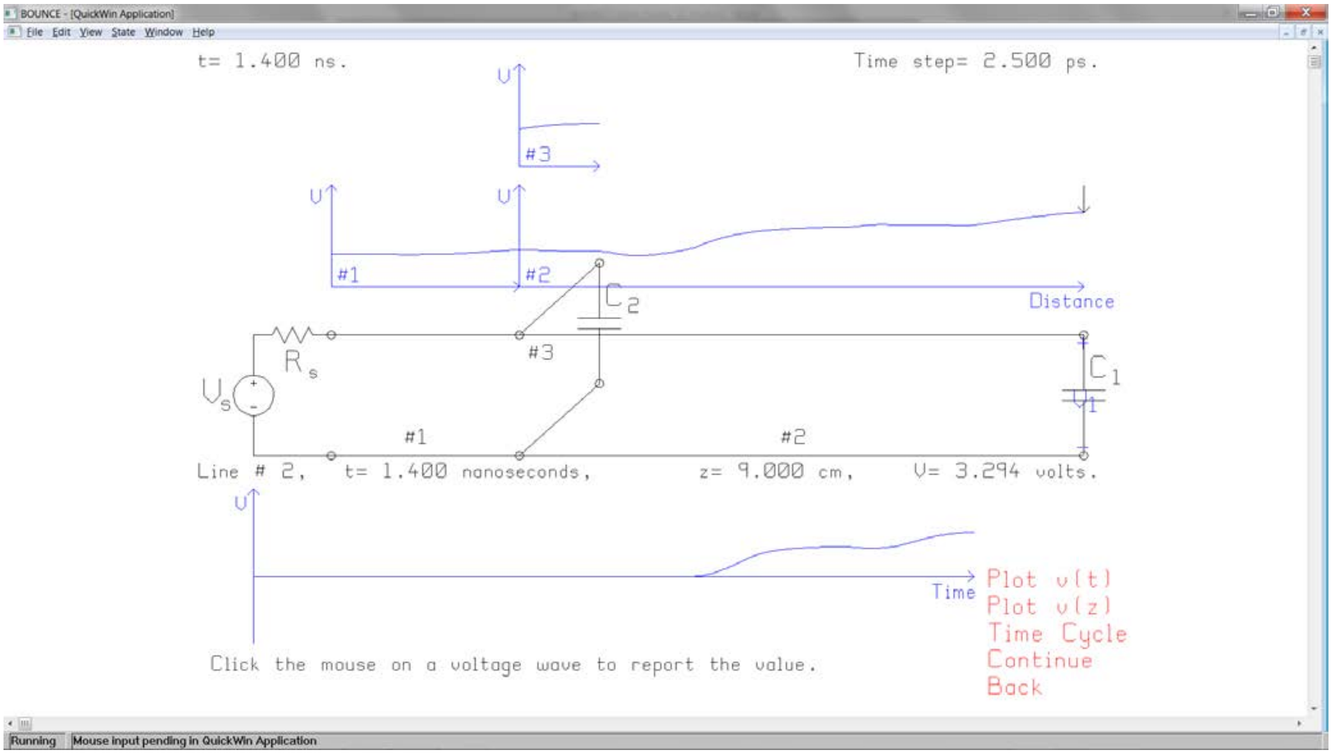
Click the mouse on a voltage wave to report the value.

Fig. 61 The step propagates through the junction.

Fig. 61 shows the voltages on the transmission lines at 0.4 ns. The transmission coefficient for the junction is

$$T = \frac{2R_p}{R_c + R_p}$$

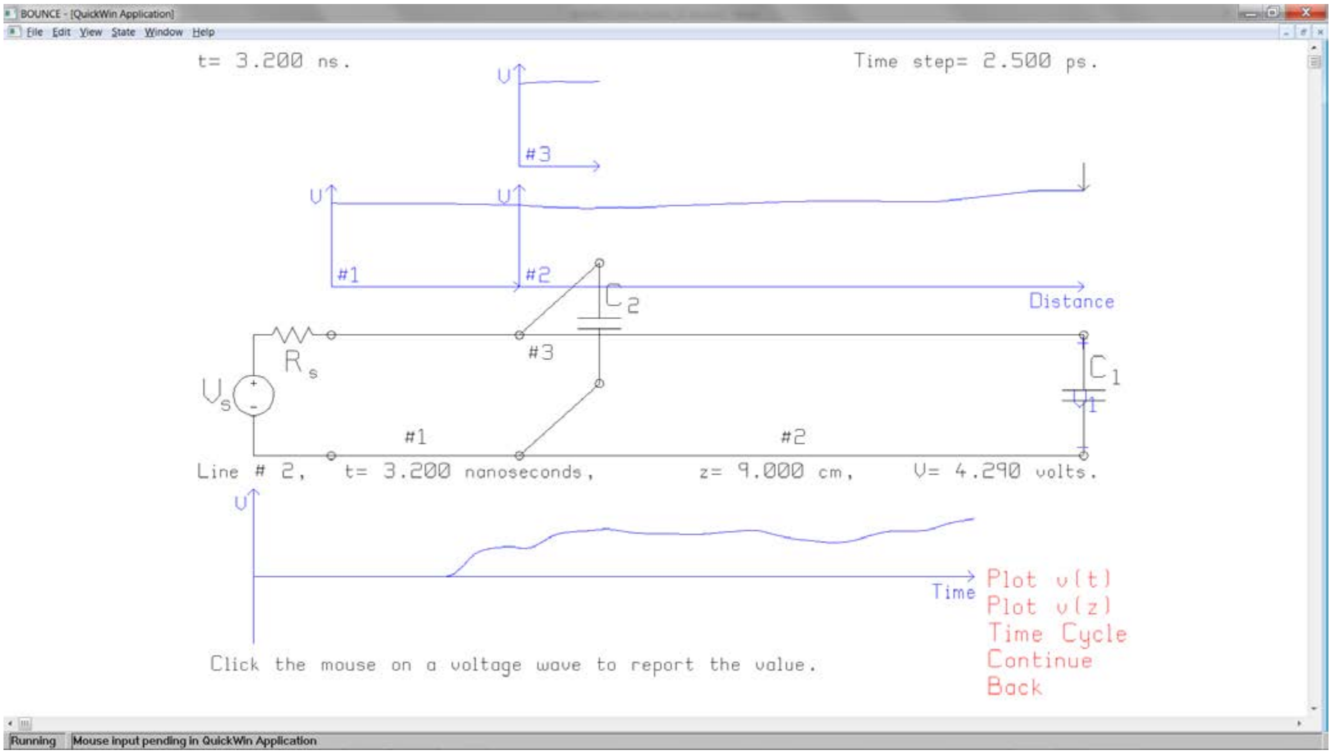
where $R_p = R_c \parallel R_c = 25$ ohms, so $T = 2x25/(50+25) = 50/75 = 0.6667$. The incident step amplitude is 1.667 volts, so the transmitted step has height 0.6667x1.6667=1.111 volts. We see a step of height 1.111 volts transmitted onto line #2. Also, on line #3, the short branch, the leading edge of the step has reached the capacitive load, and is starting to be reflected.



```
t= 1.400 ns.                                  Time step= 2.500 ps.
Line # 2,   t= 1.400 nanoseconds,        z= 9.000 cm,    V= 3.294 volts.
Click the mouse on a voltage wave to report the value.
```

Fig. 62 The step reaches the load on line #2.

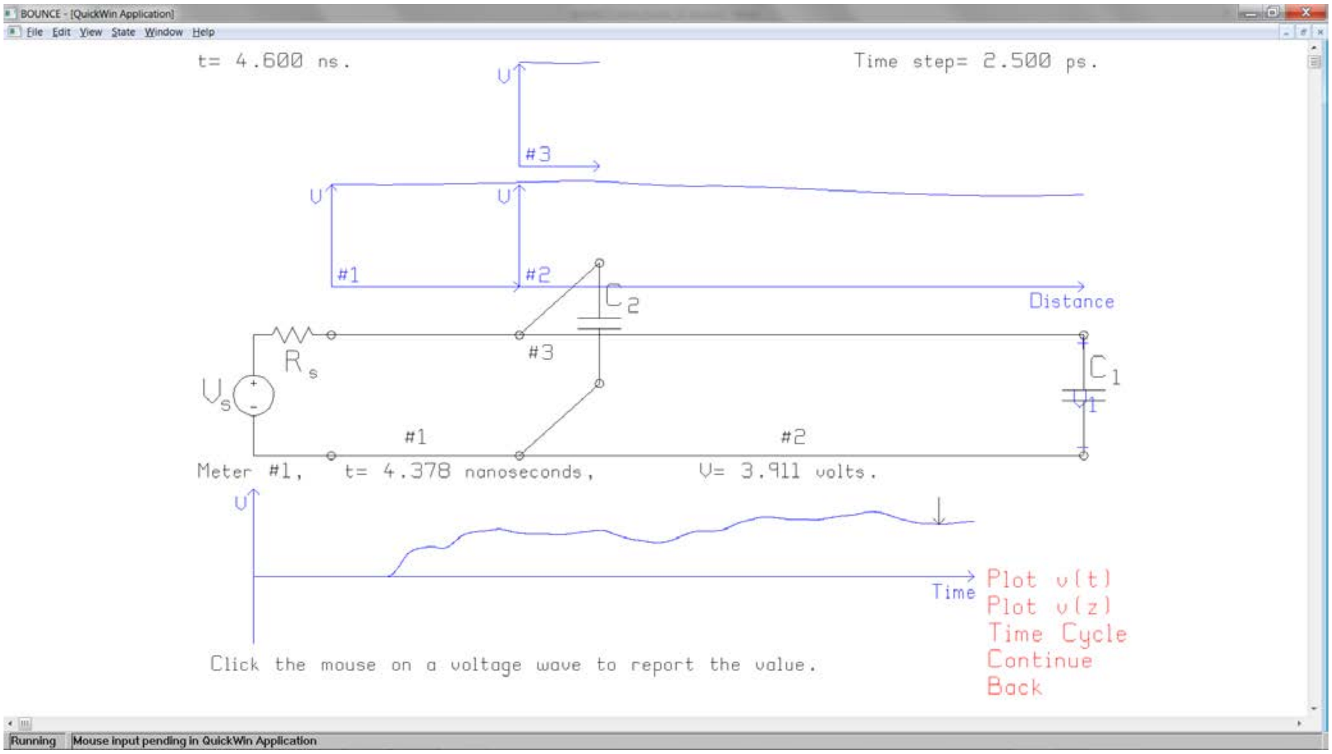
Allow time to advance to 1.4 ns. The step on line #2 reaches the load and is reflected from the capacitor. As the capacitor charges, the voltage rises, and in Fig. 52 is 3.294 volts, not yet enough for a logical one. Also, the process on line #1 and on the short branch is quite complex, with many reflections back and forth between the unmatched generator, the junction, and the capacitive load on the short branch.



```
t= 3.200 ns.                                    Time step= 2.500 ps.
Line # 2,   t= 3.200 nanoseconds,        z= 9.000 cm,     V= 4.290 volts.
Click the mouse on a voltage wave to report the value.
```

Fig. 63 At 3.2 ns, the voltage at the load has risen to 4.29 volts.

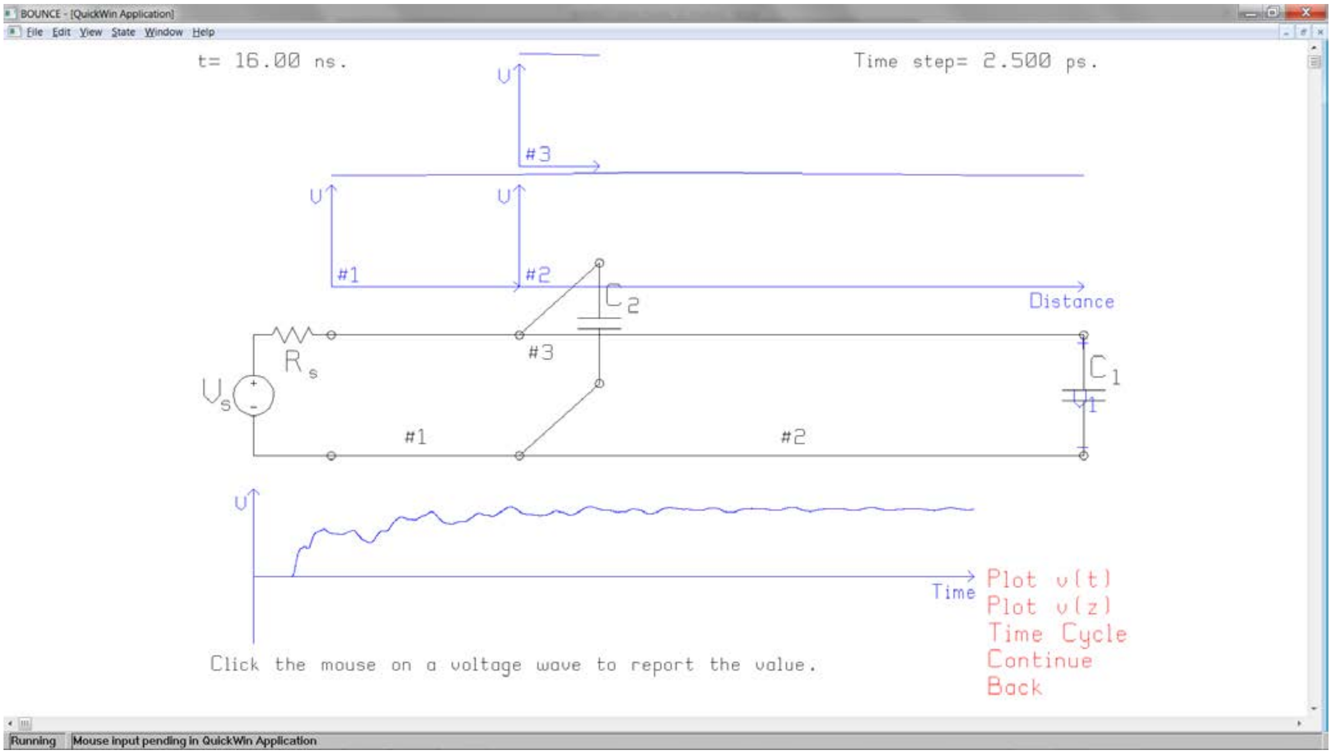
Allowing time to advance to 3.2 ns as in Fig. 63, we note that the voltage at the voltmeter across C_1 falls, then rises, then falls to a minimum, then rises towards 4 volts, and is 4.29 volts at 3.2 ns.



```
t= 4.600 ns.                                    Time step= 2.500 ps.
Meter #1,   t= 4.378 nanoseconds,        V= 3.911 volts.
Click the mouse on a voltage wave to report the value.
```

Fig. 64 The voltage across the load falls to 3.911 volts at 4.387 ns.

If we follow the waveform further, Fig 64, we see that the voltage across C_1 drops to 3.911 volts at 4.387 ns, not large enough for a logical-1. The voltage rises above 4 volts at 4.493 ns and then remains above 4 volts.



t= 16.00 ns.

Time step= 2.500 ps.

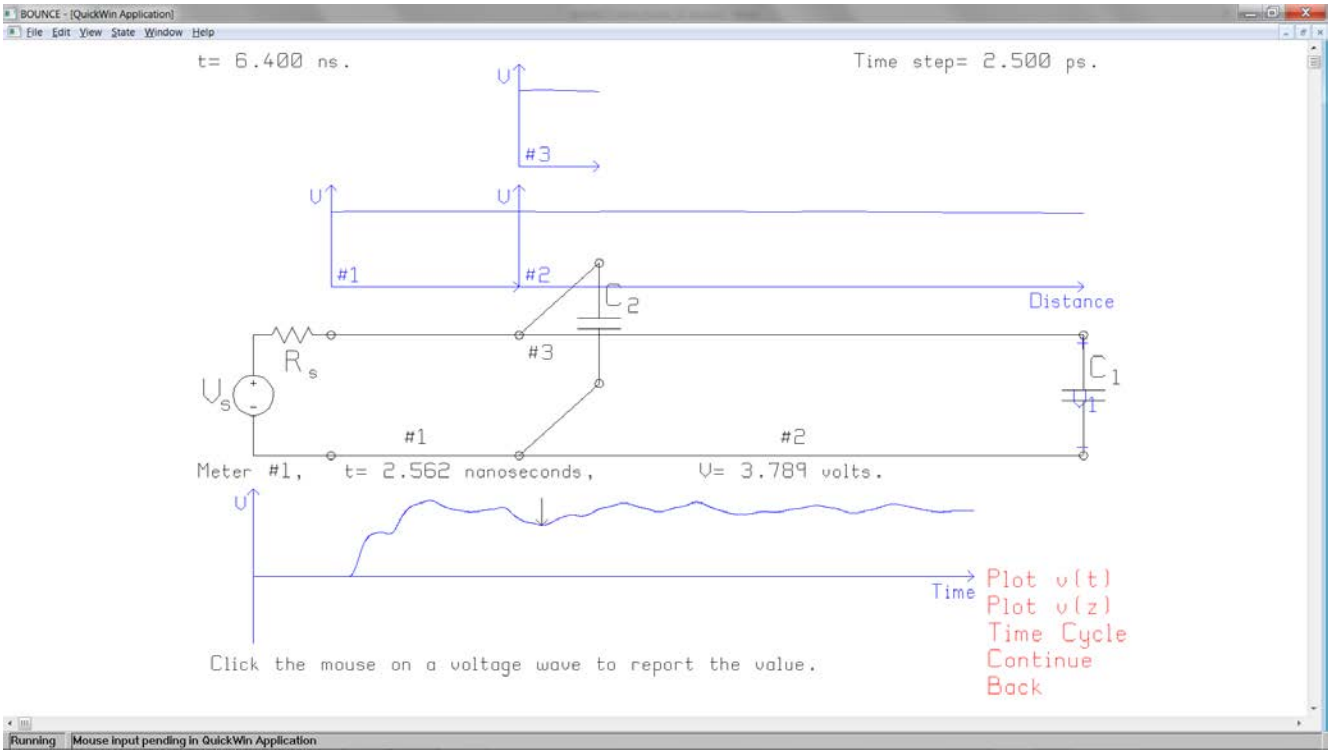
Click the mouse on a voltage wave to report the value.

Running

Mouse input pending in QuickWin Application

Fig. 65 At 16 ns, the voltage at the load is gradually stabilizing at 5 volts.

Fig. 65 show that the voltage at the load gradually settles towards five volts, after a long time has gone by. The problem with this circuit is that the generator is not matched to the transmission line, and line #1 between the generator and the junction behaves as a resonator, reflecting waves back and forth many times. Also, line #3, the short branch, behaves as a resonator, trapping energy between the junction and the capacitive termination. Eliminating these resonators can improve the response of the circuit.



t= 6.400 ns.

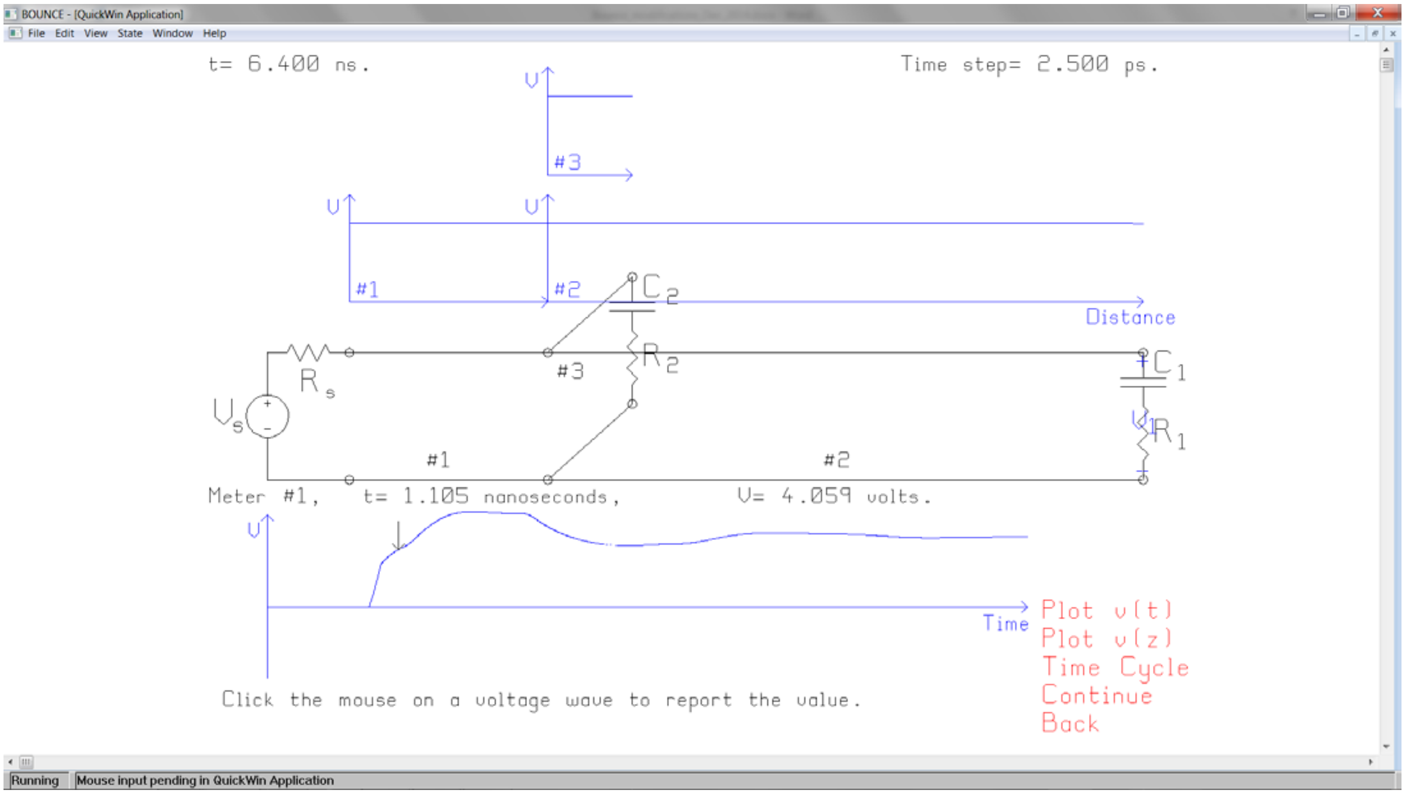
Time step= 2.500 ps.

Meter #1, t= 2.562 nanoseconds, V= 3.789 volts.

Click the mouse on a voltage wave to report the value.

Fig. 66 The circuit settles much more quickly with a matched generator.

In Fig. 66, the generator impedance has been changed to 50 ohms, to match line #1. Then any wave on line #1 propagating from the junction towards the generator is absorbed by the generator, and line #1 no longer traps energy like a resonator. Fig. 66 shows the response. The voltage across C_1 rises rapidly but then declines to below 4 volts at 2.562 ns. At 2.645 ns, the voltage rises above 4 volts and stays above 4 volts. The circuit presents a logical-1 at the load terminals after 2.645 ns, faster than the 4.493 ns of Fig.64 with an unmatched generator.



```
t= 6.400 ns.                                Time step= 2.500 ps.
Meter #1,  t= 1.105 nanoseconds,         V= 4.059 volts.
Click the mouse on a voltage wave to report the value.
Running   Mouse input pending in QuickWin Application
```

Fig. 67 Matching resistors in series with the load capacitors further improves the circuit's response.

We can further improve the performance of this circuit by inserting a resistor in series with each capacitive load. The capacitor is initially uncharged so behaves as a short circuit, and a 50-ohm resistor in series with the capacitor matches the load to the transmission line. Fig. 67 shows the response. The voltage rises rapidly, reaching 4 volts at 1.105 ns. The voltage rises to a maximum of 5.288 volts at 1.53 ns, then declines to a minimum of 4.048 volts at 2.513 ns. This is above the minimum of 4 volts for a logical 1, and so this version of the circuit reaches logical 1 in only 1.105 ns. This is a substantial improvement over the unmatched circuit of Fig. 64 at 4.493 ns.

Conclusion

BOUNCE is intended as a learning tool for students taking a first course in "electromagnetic fields and waves". Reference [2] describes various demonstrations of wave phenomena using BOUNCE. The animation helps in visualizing how the waves travel on transmission line circuits and how they interact with junctions and loads. Ref. [2] also describes some demonstrations that are relevant for computer engineering students, to make them aware of the importance of matching considerations in digital circuits. BOUNCE is particularly useful for students as a "software laboratory" to verify pencil-and-paper solutions to transmission line problems solved with a "bounce diagram" or "lattice diagram".

References

[1] C.W. Trueman, “Teaching Transmission Line Transients Using Computer Animation," Frontiers in Education Conference, San Juan, Puerto Rico, Nov. 10-13, 1999.

[2] C.W. Trueman, “Animating Transmission Line Transients with BOUNCE”, IEEE Transactions on Education, Vol. 43, No. 1, pp. 1-14, February 2000.