ELEC353 Lecture Notes Set 5

The homework assignments are posted on the course web site.
http://users.encs.concordia.ca/~trueman/web_page_353.htm

Homework #3: Do homework #3 by February 1, 2019.
Homework #4: Do homework #4 by February 8, 2019.
Homework #5: Do homework #5 by February 14, 2019.

Mid-term test: Thursday February 14, 2019.

- Includes Homework #5!

- See the course web site for sample mid-term tests with solutions.
- Study tip:
    - Download the question paper for a mid-term from a previous year.
    - Spend one hour 15 minutes solving the test with your calculator and the formula sheet, but no textbook or notes.
    - Grade your answer against the solution to the test!

Transmission Line Topics:

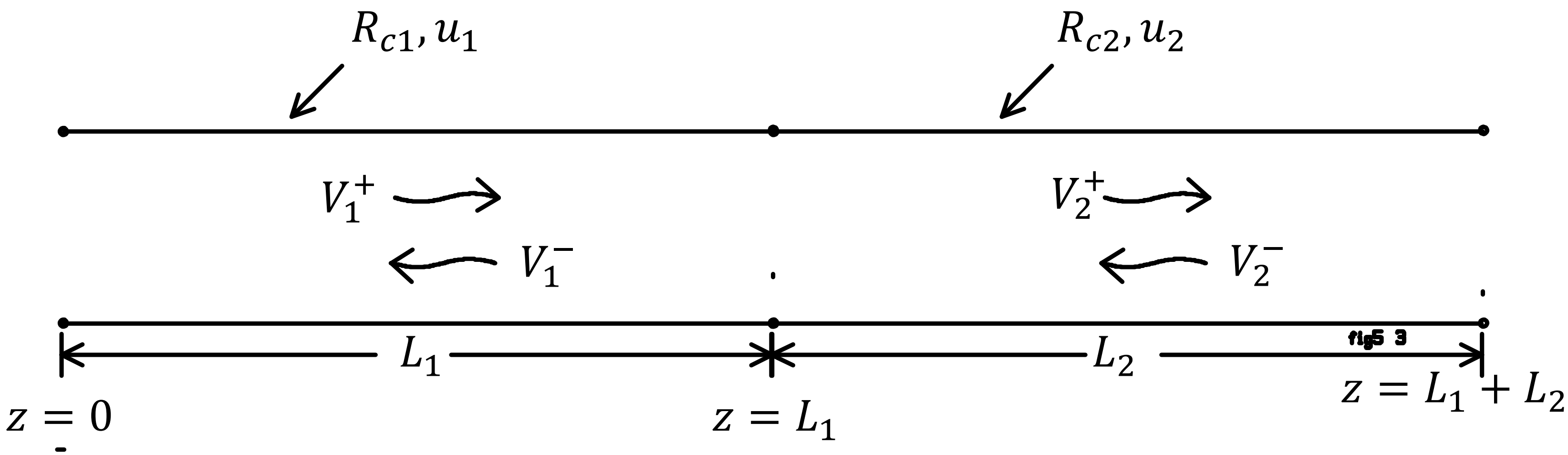
1. Junctions Between Transmission Lines
2. Transmission Line with Shunt Load
3. Branching Transmission Lines
4. Inductive and Capacitive Terminations
5. Time Domain Reflectometry

(Class Test)

6. The Sinusoidal Steady State

Junctions between Transmission-Lines

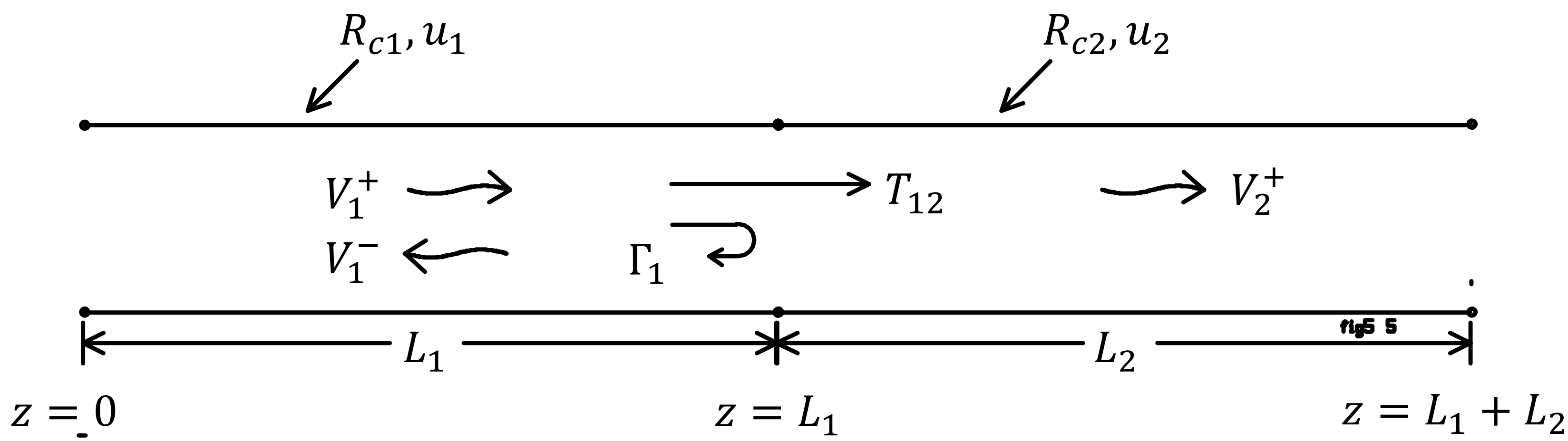
Inan and Inan Section 2.4.2



$$V_1(z,t) = V_1^+(z,t) + V_1^-(z,t) \qquad V_2(z,t) = V_2^+(z,t) + V_2^-(z,t)$$

$$I_1(z,t) = \frac{V_1^+(z,t)}{R_{c1}} - \frac{V_1^-(z,t)}{R_{c1}} \qquad I_2(z,t) = \frac{V_2^+(z,t)}{R_{c2}} - \frac{V_2^-(z,t)}{R_{c2}}$$

Incidence from the Left

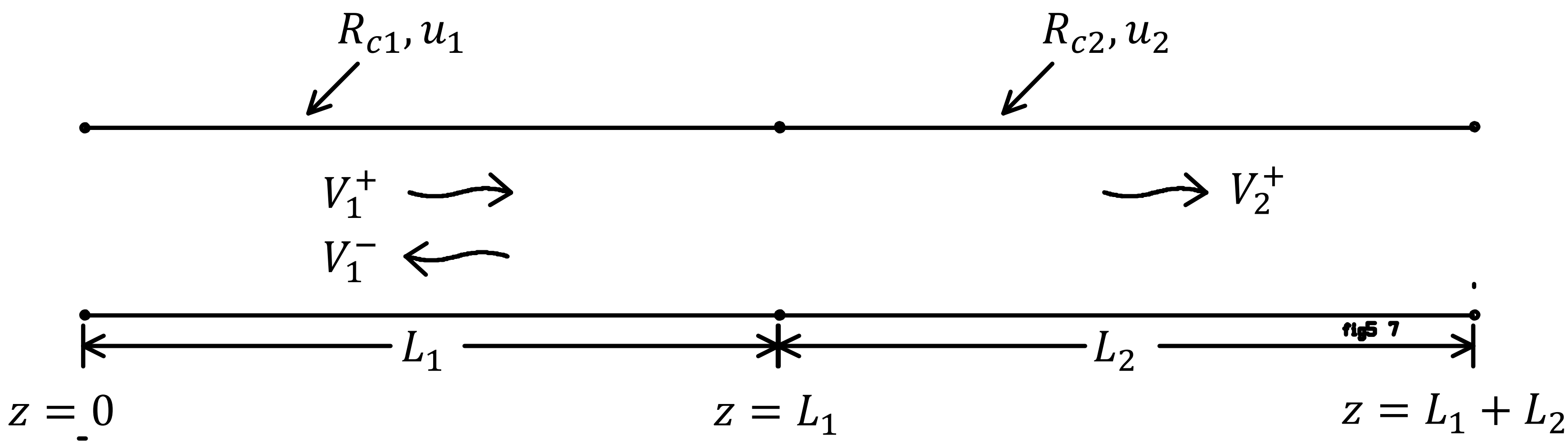


For incidence from the left: ($V_2^- = 0$)

$$\Gamma_1 = \frac{V_1^-}{V_1^+}$$

$$T_{12} = \frac{V_2^+}{V_1^+}$$

Find the Reflection and Transmission Coefficients for incidence from the left, with $V_2^- = 0$:



Incidence from the left, given V_1^+ with $V_2^- = 0$

$$V_1(z,t) = V_1^+(z,t) + V_1^-(z,t) \qquad V_2(z,t) = V_2^+(z,t)$$

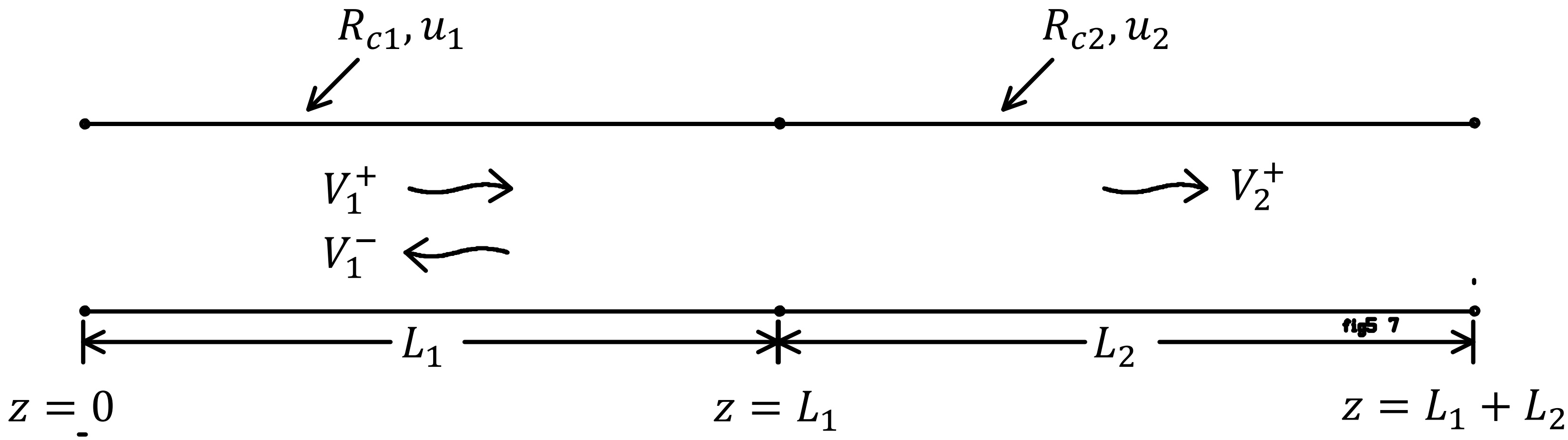
$$I_1(z,t) = \frac{V_1^+(z,t)}{R_{c1}} - \frac{V_1^-(z,t)}{R_{c1}} \qquad I_2(z,t) = \frac{V_2^+(z,t)}{R_{c2}}$$

Enforce KVL: $V_1(L_1,t) = V_2(L_1,t)$

At the junction, z= L_1 $\quad V_1(L_1,t) = V_1^+(L_1,t) + V_1^-(L_1,t) \qquad V_2(L_1,t) = V_2^+(L_1,t)$

$$V_1^+(L_1,t) + V_1^-(L_1,t) = V_2^+(L_1,t)$$

For incidence from the left:



$$V_1(z,t) = V_1^+(z,t) + V_1^-(z,t) \qquad V_2(z,t) = V_2^+(z,t)$$

$$I_1(z,t) = \frac{V_1^+(z,t)}{R_{c1}} - \frac{V_1^-(z,t)}{R_{c1}} \qquad I_2(z,t) = \frac{V_2^+(z,t)}{R_{c2}}$$

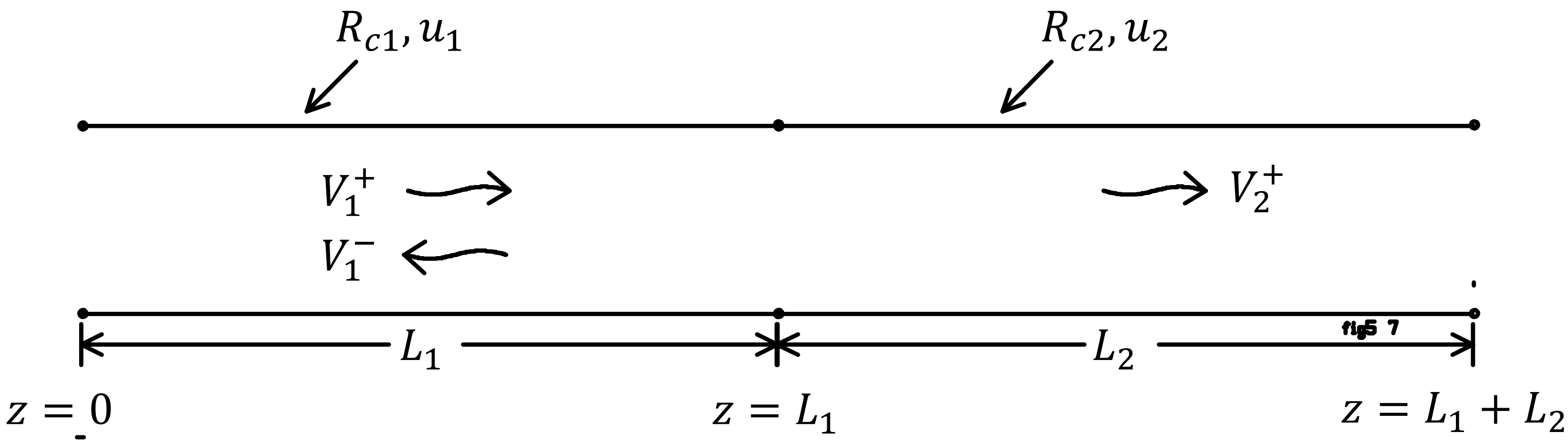
Enforce KCL:

$$I_1(L_1,t) = I_2(L_1,t)$$

At the junction:

$$I_1(L_1,t) = \frac{V_1^+(L_1,t)}{R_{c1}} - \frac{V_1^-(L_1,t)}{R_{c1}} \qquad I_2(L_1,t) = \frac{V_2^+(L_1,t)}{R_{c2}}$$

$$\frac{V_1^+(L_1,t)}{R_{c1}} - \frac{V_1^-(L_1,t)}{R_{c1}} = \frac{V_2^+(L_1,t)}{R_{c2}}$$



KVL: $$V_1^+(L_1,t) + V_1^-(L_1,t) = V_2^+(L_1,t)$$

KCL: $$\frac{V_1^+(L_1,t)}{R_{c1}} - \frac{V_1^-(L_1,t)}{R_{c1}} = \frac{V_2^+(L_1,t)}{R_{c2}}$$

Solve the equations:

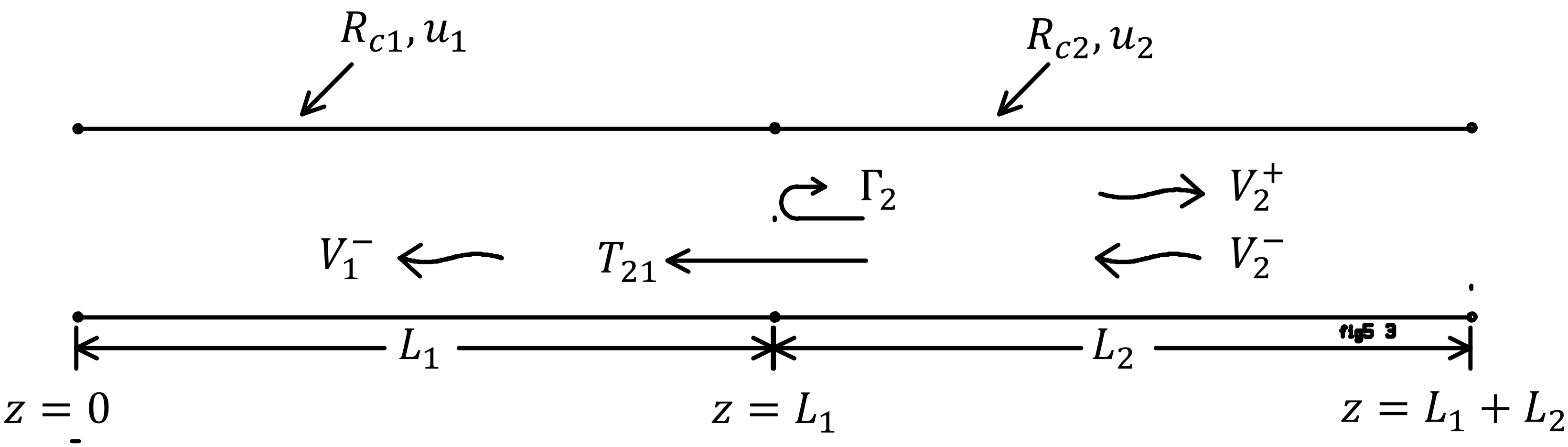
$$V_1^- = \frac{R_{c2} - R_{c1}}{R_{c2} + R_{c1}} V_1^+$$

$$V_2^+ = \frac{2R_{c2}}{R_{c1} + R_{c2}} V_1^+$$

Reflection Coefficient: $$\Gamma_1 = \frac{V_1^-}{V_1^+} \qquad \Gamma_1 = \frac{R_{c2} - R_{c1}}{R_{c2} + R_{c1}} \qquad V_1^- = \Gamma_1 V_1^+$$

Transmission Coefficient: $$T_{12} = \frac{V_2^+}{V_1^+} \qquad T_{12} = \frac{2R_{c2}}{R_{c1} + R_{c2}} \qquad V_2^+ = T_{12} V_1^+$$

For incidence from the right:



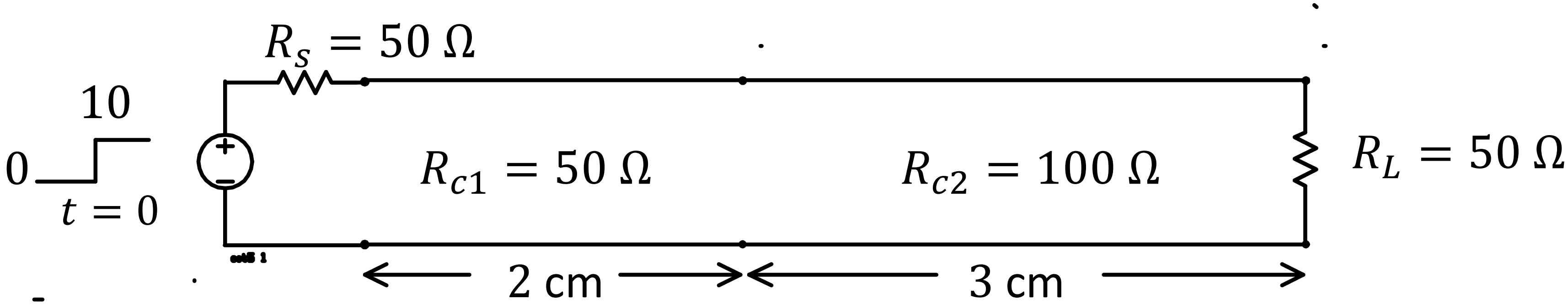
Incidence from the right, given V_2^- with $V_1^+ = 0$

Homework: Enforce KVL and KCL and show that

$$\Gamma_2 = \frac{R_{c1} - R_{c2}}{R_{c1} + R_{c2}} \qquad V_2^+ = \Gamma_2 V_2^-$$

$$T_{21} = \frac{2R_{c1}}{R_{c1} + R_{c2}} \qquad V_1^- = T_{21} V_2^-$$

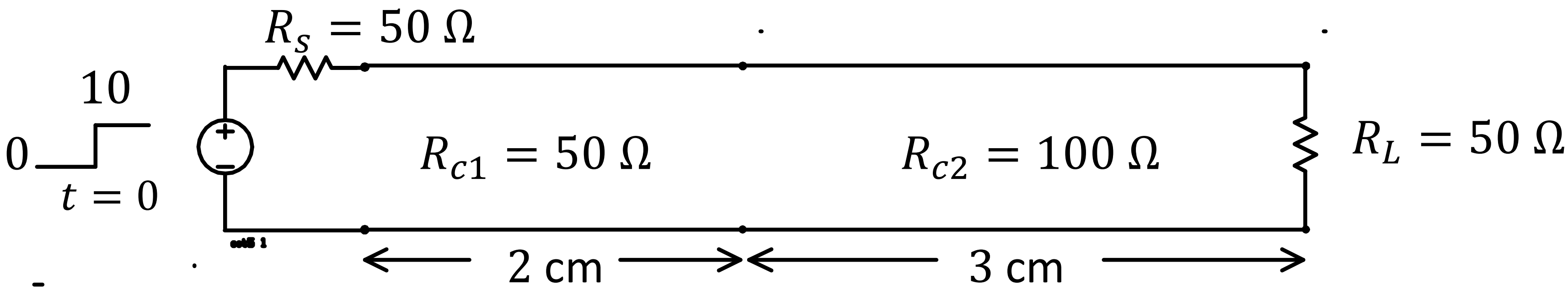
Example



A voltage source has internal resistance $R_s = 50$ ohms and generates a 10 volt step function that starts at $t = 0$. It is connected to a 2 cm transmission line with $R_{c1} = 50$ ohms, which is in turn connected to a 3 cm line with $R_{c2} = 100$ ohms. Both lines have speed of propagation $u = 20$ cm/ns. The load at the end of line #2 is $R_L = 50$ ohms.

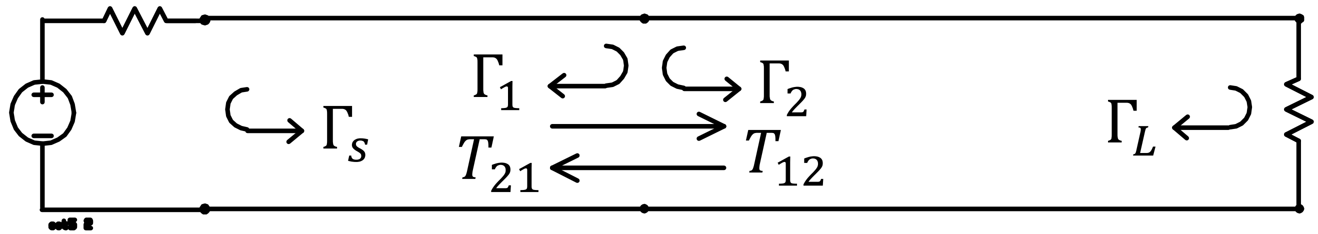
1.Graph the voltage across the load and across the generator as a funcation of tine.

2.Find the final value of the load voltage as as $t \to \infty$.



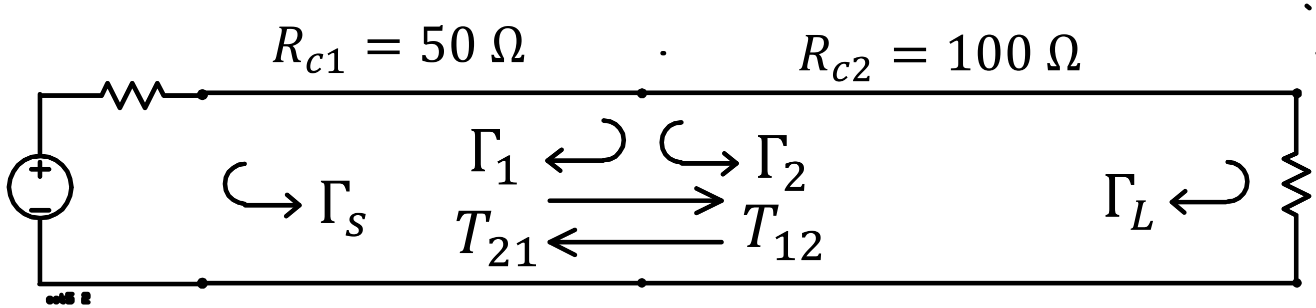
Delay times: $T_1 = \frac{L_1}{u} = \frac{2}{20} = 0.10\ \text{ns}$ $\quad T_2 = \frac{L_2}{u} = \frac{3}{20} = 0.15\ \text{ns}$

Find V_1^+: $V_1(z=0) = \frac{R_{c1}}{R_s + R_{c1}} V_s = \frac{50}{50+50} x10 = 5\ \text{volts.}$ So $V_1^+ = 5$ volts



$$\Gamma_s = \frac{R_s - R_{c1}}{R_s + R_{c1}} = \frac{50-50}{50+50} = 0$$

$$\Gamma_L = \frac{R_L - R_{c2}}{R_L + R_{c2}} = \frac{50-100}{50+100} = \frac{-50}{150} = -0.3333$$



Junction from left to right:

$$\Gamma_1 = \frac{R_{c2} - R_{c1}}{R_{c2} + R_{c1}} = \frac{100 - 50}{100 + 50} = \frac{50}{150} = 0.3333$$

$$T_{12} = \frac{2R_{c2}}{R_{c2} + R_{c1}} = \frac{2x100}{100 + 50} = \frac{200}{150} = 1.3333$$

Junction from right to left:

$$\Gamma_2 = \frac{R_{c1} - R_{c2}}{R_{c1} + R_{c2}} = \frac{50 - 100}{50 + 100} = \frac{-50}{150} = -0.3333$$

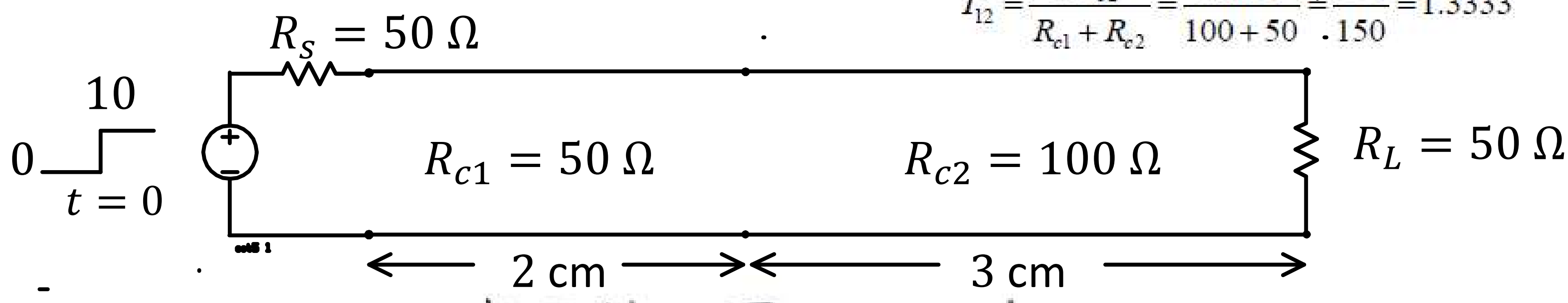
$$T_{21} = \frac{2R_{c1}}{R_{c1} + R_{c2}} = \frac{2x50}{100 + 50} = \frac{100}{150} = 0.6667$$

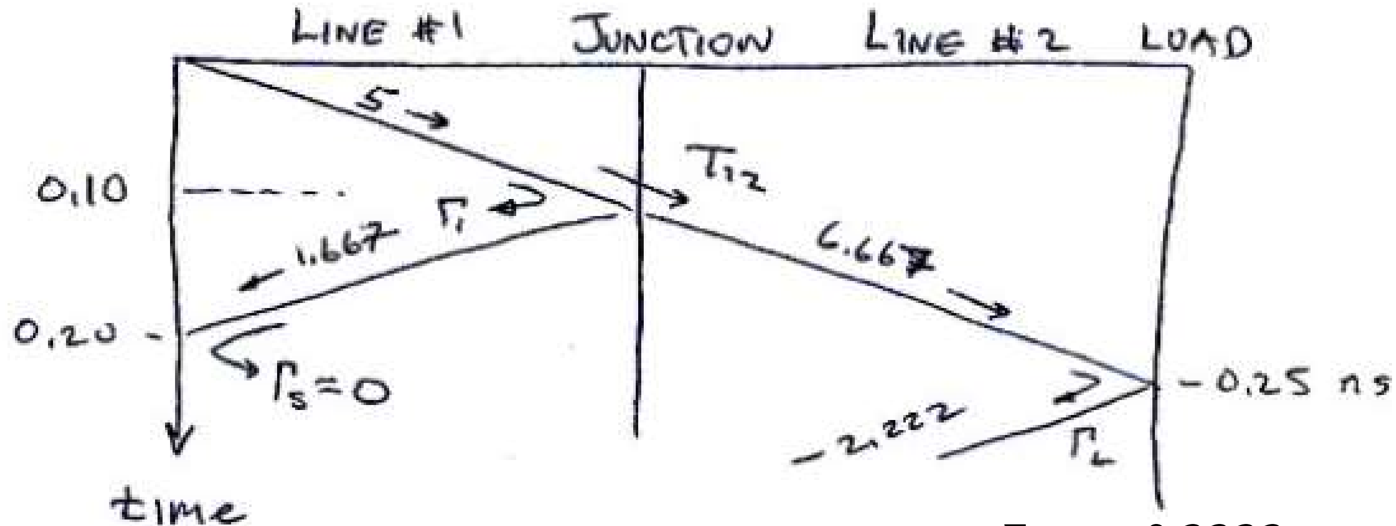
Draw a bounce diagram:

Junction from left to right:

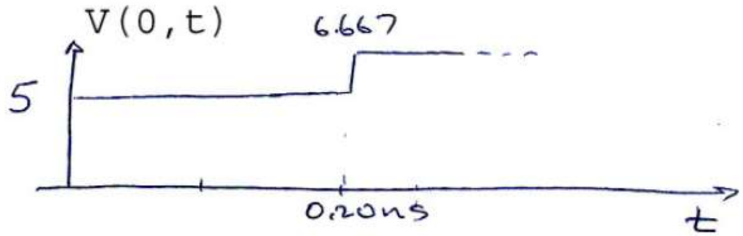
$$\Gamma_1 = \frac{R_{c2} - R_{c1}}{R_{c2} + R_{c1}} = \frac{100 - 50}{100 + 50} = \frac{50}{150} = 0.3333$$

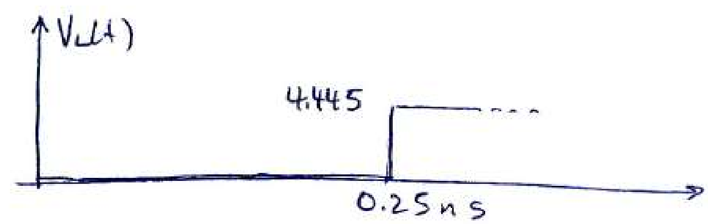
$$T_{12} = \frac{2R_{c2}}{R_{c1} + R_{c2}} = \frac{2x100}{100 + 50} \doteq \frac{200}{150} = 1.3333$$





$\Gamma_L = -0.3333$



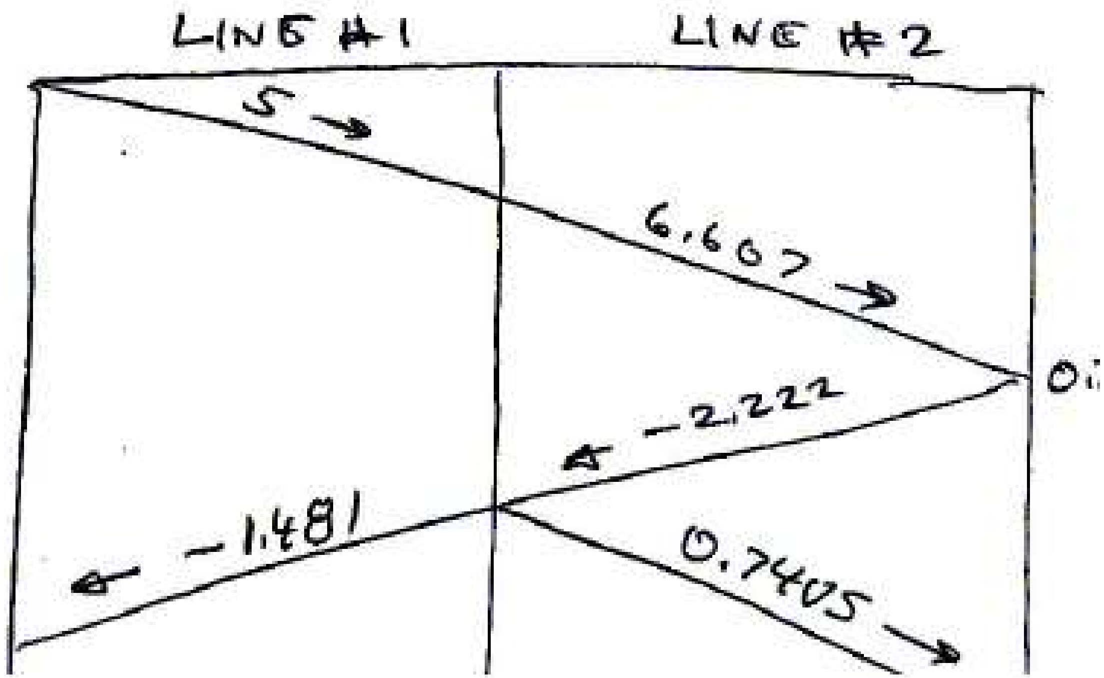


At the junction:

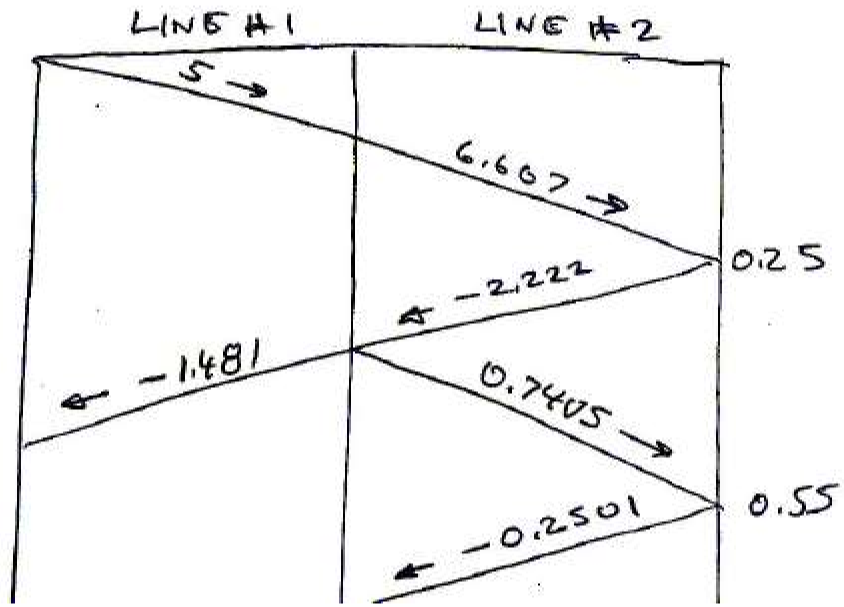
Junction from right to left:

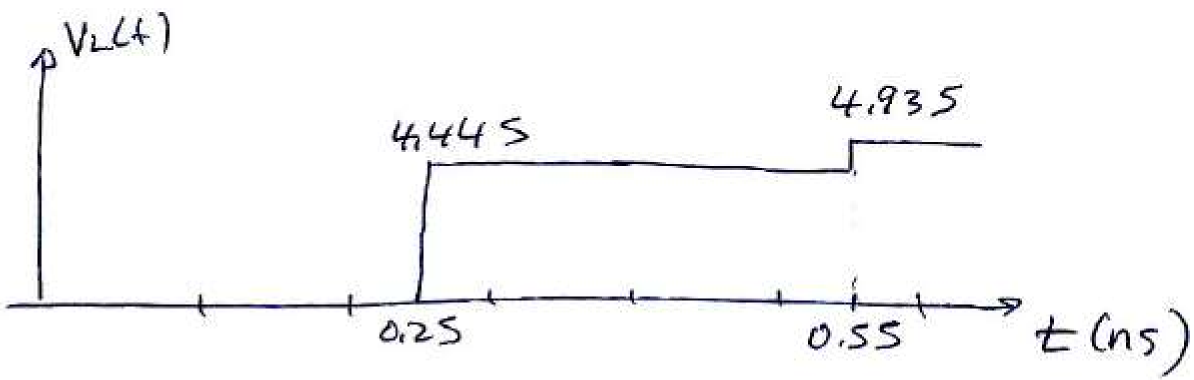
$$\Gamma_2 = \frac{R_{c1} - R_{c2}}{R_{c1} + R_{c2}} = \frac{50-100}{100+50} = \frac{-50}{150} = -0.3333$$

$$T_{21} = \frac{2R_{c1}}{R_{c1} + R_{c2}} = \frac{2x50}{100+50} = \frac{100}{150} = 0.6667$$

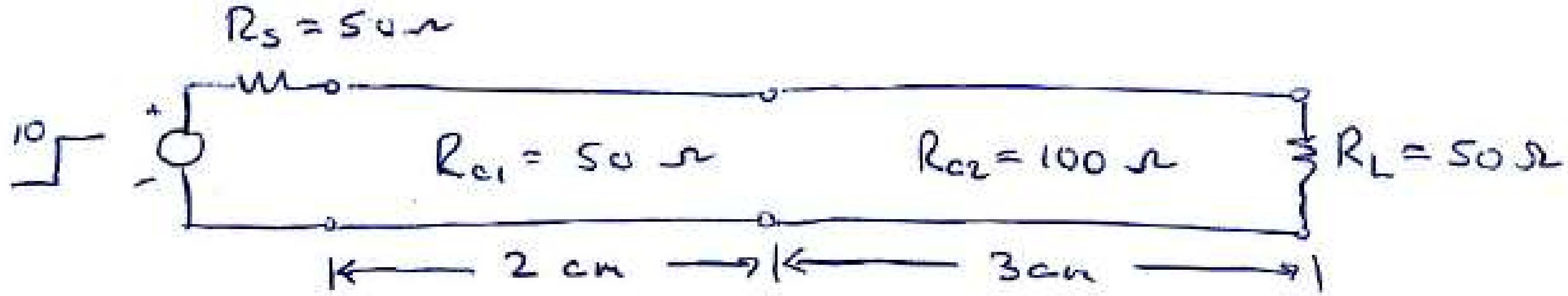


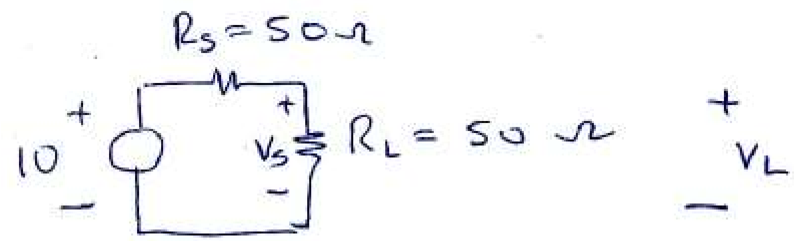
Voltage at the load:





Final values:

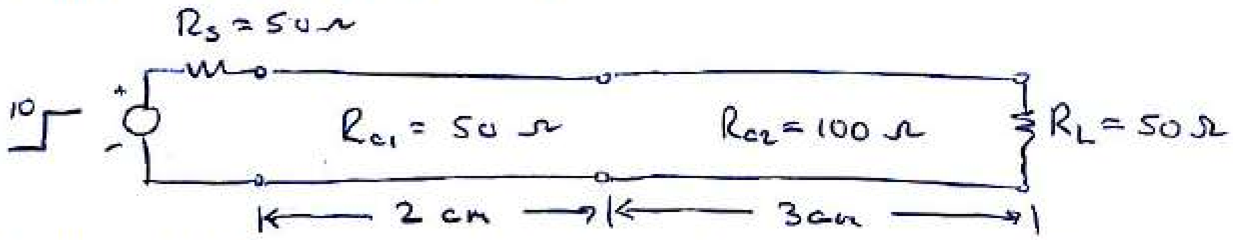




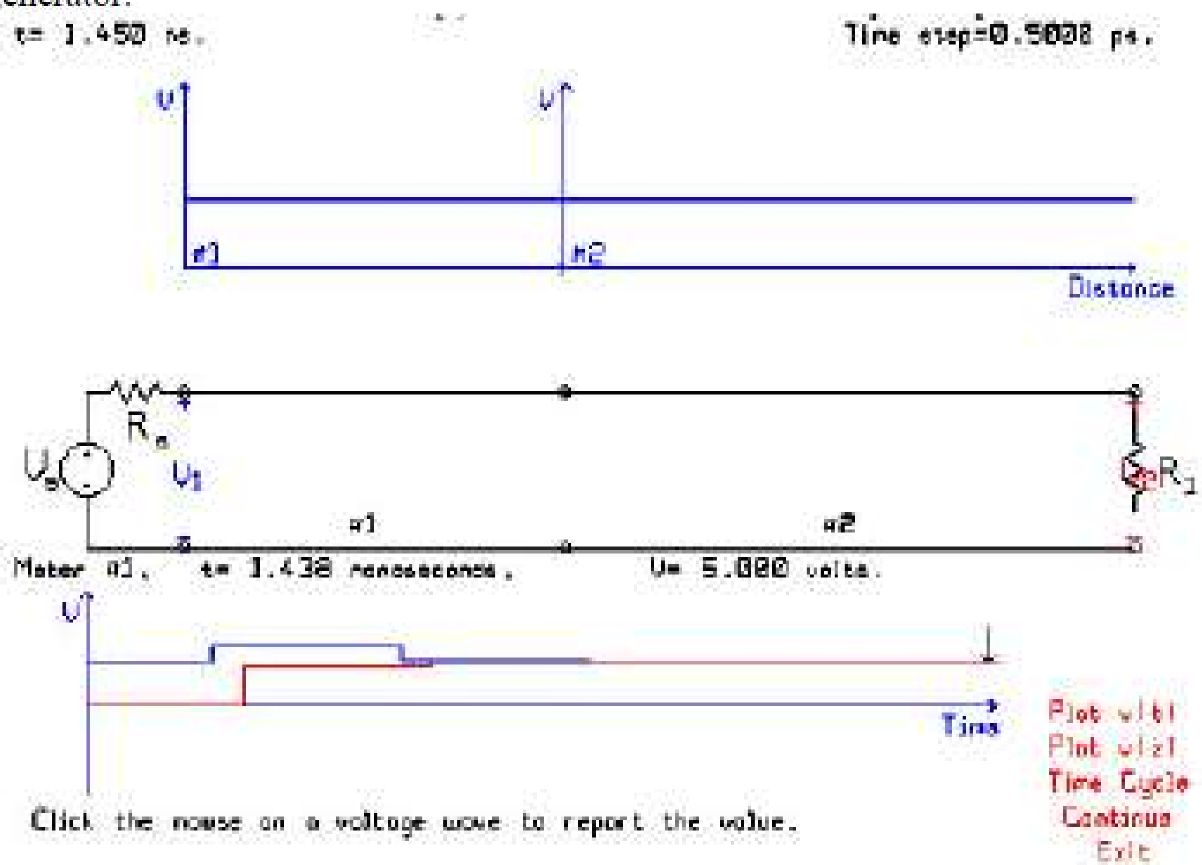
$V_s = 5$ volts

$V_L = 5$ volts

Simulate this problem with BOUNCE:



A voltage source has internal resistance 50 ohms and generates a 10-volt step function at t=0. It is connected to a 2-cm line with $R_{c1} = 50$ ohms, which is in turn connected to a 3-cm line with $R_{c2} = 100$ ohms. Both lines have speed of propagation $u = 20$ cm/ns. Graph the voltage across the load, and the voltage across the generator.



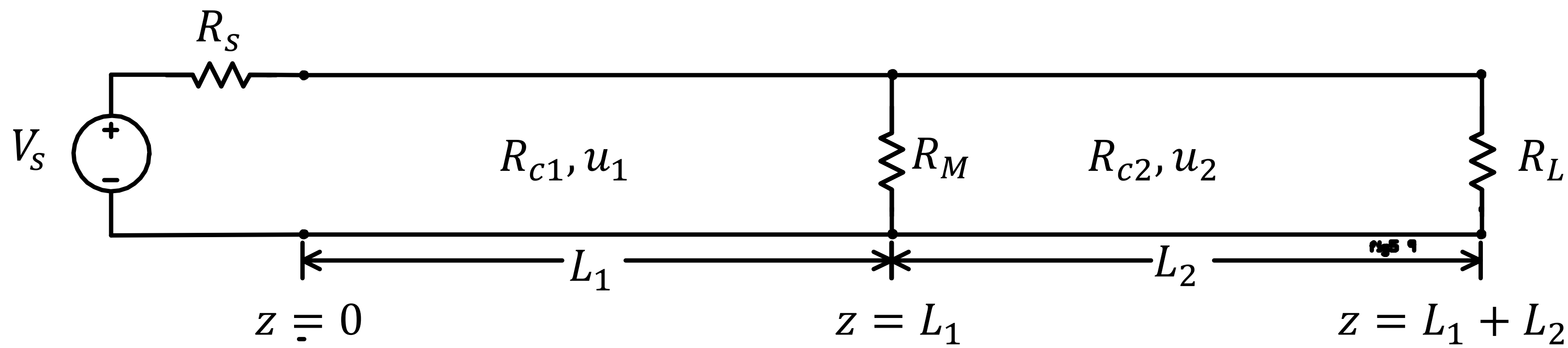
Transmission Line Topics:

1. Junctions Between Transmission Lines Done!
2. Transmission Line with Shunt Load
3. Branching Transmission Lines
4. Inductive and Capacitive Terminations
5. Time Domain Reflectometry

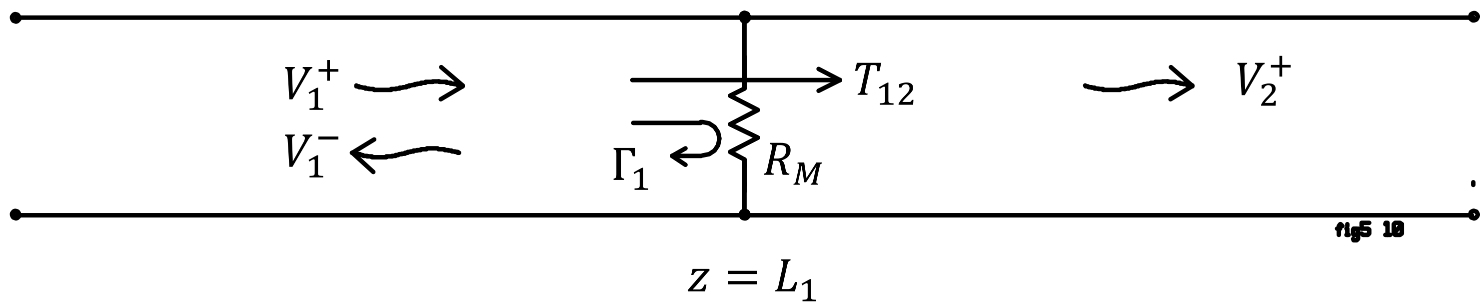
(Class Test)

6. The Sinusoidal Steady State

Transmission Line with Shunt Load



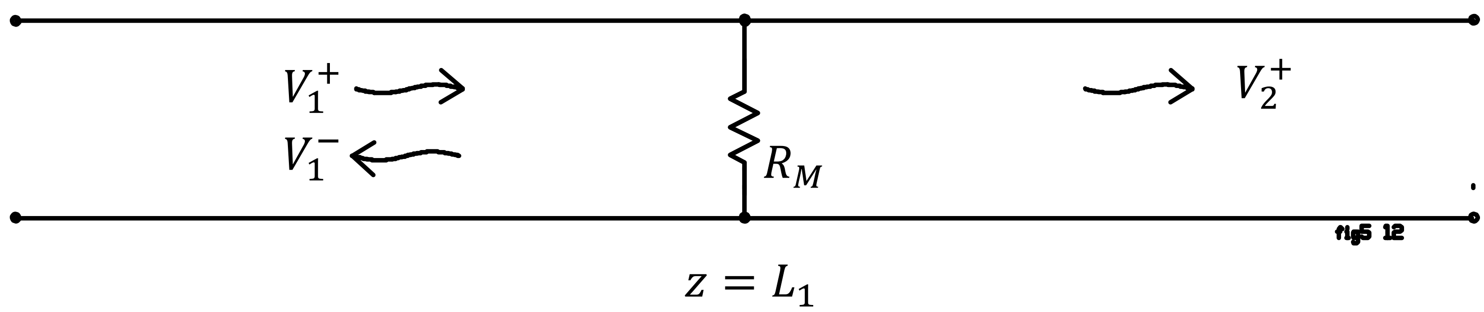
Incidence from the left:



$$V_1^- = \Gamma_1 V_1^+$$

$$V_2^+ = T_{12} V_1^+$$

Use KCL and KVL to find the reflection coefficient and the transmission coefficient:



$$V_1(z,t) = V_1^+(z,t) + V_1^-(z,t)$$

$$I_1(z,t) = \frac{V_1^+(z,t)}{R_{c1}} - \frac{V_1^-(z,t)}{R_{c1}}$$

$$V_2(z,t) = V_2^+(z,t)$$

$$I_2(z,t) = \frac{V_2^+(z,t)}{R_{c2}}$$

At the junction at $z = L_1$:

$$V_1(L_1,t) = V_1^+(L_1,t) + V_1^-(L_1,t)$$

$$I_1(L_1,t) = \frac{V_1^+(L_1,t)}{R_{c1}} - \frac{V_1^-(L_1,t)}{R_{c1}}$$

$$V_2(L_1,t) = V_2^+(L_1,t)$$

$$I_2(L_1,t) = \frac{V_2^+(L_1,t_2)}{R_{c2}}$$

KVL: $$V_1^+(L_1,t) + V_1^-(L_1,t) = V_2^+(L_1,t)$$ $$V_1^+ + V_1^- = V_2^+$$

KCL: $$\frac{V_1^+(L_1,t)}{R_{c1}} - \frac{V_1^-(L_1,t)}{R_{c1}} = \frac{V_2^+(L_1,t)}{R_{c2}} + \frac{V_2^+(L_1,t)}{R_M}$$ $$\frac{V_1^+}{R_{c1}} - \frac{V_1^-}{R_{c1}} = \frac{V_2^+}{R_{c2}} + \frac{V_2^+}{R_M}$$

Solve the equations:

KVL: $$V_1^+ + V_1^- = V_2^+$$

KCL: $$\frac{V_1^+}{R_{c1}} - \frac{V_1^-}{R_{c1}} = \frac{V_2^+}{R_{c2}} + \frac{V_2^+}{R_M}$$

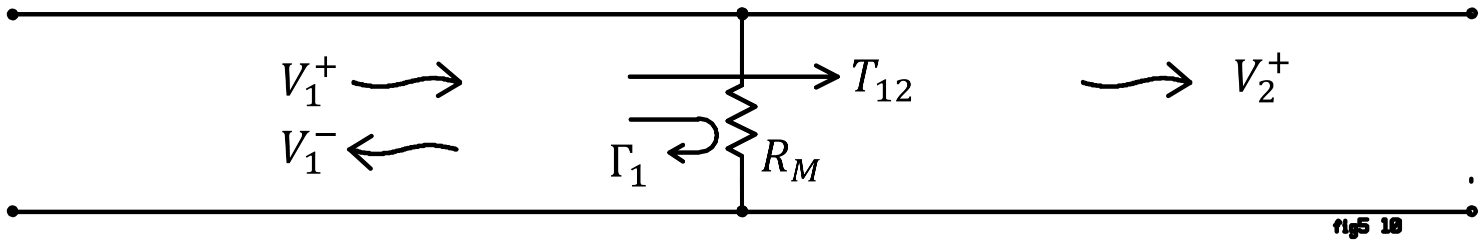
Homework: solve the equations to show that

$$R_p = \frac{R_M R_{c2}}{R_M + R_{c2}}$$

$$V_1^- = \frac{R_p - R_{c1}}{R_p + R_{c1}} V_1^+$$

$$V_2^+ = \frac{2R_p}{R_{c1} + R_p} V_1^+$$

Reflection and transmission coefficients:



$z = L_1$

$$R_p = \frac{R_M R_{c2}}{R_M + R_{c2}}$$

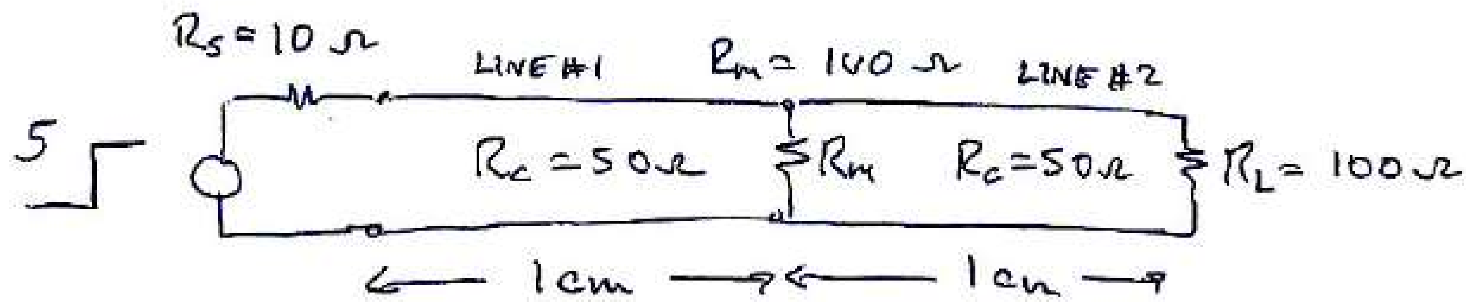
- Define the "reflection coefficient" for the junction as

$$\Gamma_1 = \frac{R_p - R_{c1}}{R_p + R_{c1}} \qquad \text{so} \qquad V_1^- = \Gamma_1 V_1^+$$

- Define the "transmission coefficient" for the junction as

$$T_{12} = \frac{2R_p}{R_{c1} + R_p} \qquad \text{so} \qquad V_2^+ = T_{12} V_1^+$$

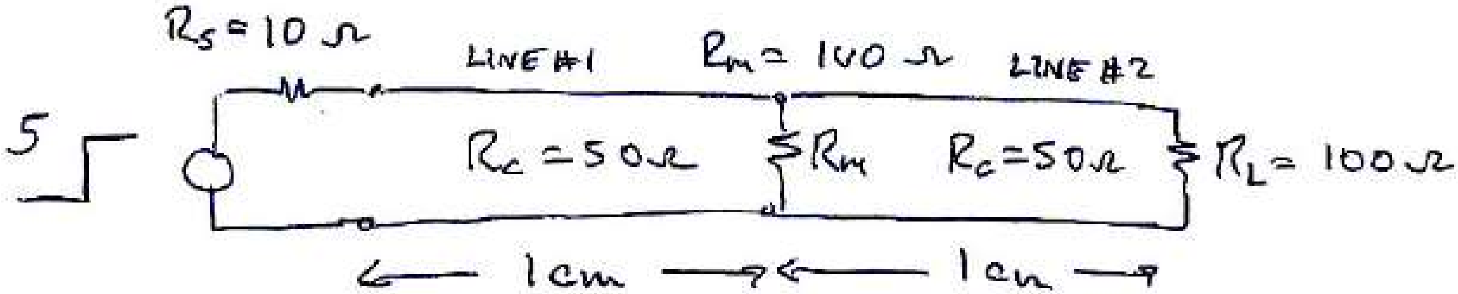
Example



A logic chip with a 10 ohm output resistance produces a step function voltage. It drives two other logic chips over a short interconnect on a circuit board, as shown in the figure. The circuit board paths behave as transmission lines with characteristic resistance 50 ohms and speed-of-propagation 20 cm/ns. At a distance of 1 cm from the logic chip there is a memory chip with input resistance 100 ohms, and at a further 1 cm distance there is another memory chip of input resistance 100 ohms.

Find the voltage across the load 2 cm from the driver chip.
Find the final value as $t \to \infty$.

Solution



$$T_d = \frac{L}{u} = \frac{1}{20} = 0.05 \text{ ns} \qquad T_d = \frac{L}{u} = \frac{1}{20} = 0.05 \text{ ns}$$

$$V_1(z=0) = \frac{R_c}{R_s + R_c} V_s = \frac{50}{50+10} x5 = 4.167 \text{ volts}$$

$$\Gamma_s = \frac{R_s - R_{c1}}{R_s + R_{c1}} = \frac{10-50}{10+50} = -0.6667$$

$$\Gamma_L = \frac{R_L - R_{c2}}{R_L + R_{c2}} = \frac{100-50}{100+50} = \frac{50}{150} = 0.3333$$

Junction from left to right:

$$R_p = \frac{50x100}{50+100} = 33.33 \text{ ohms.}$$

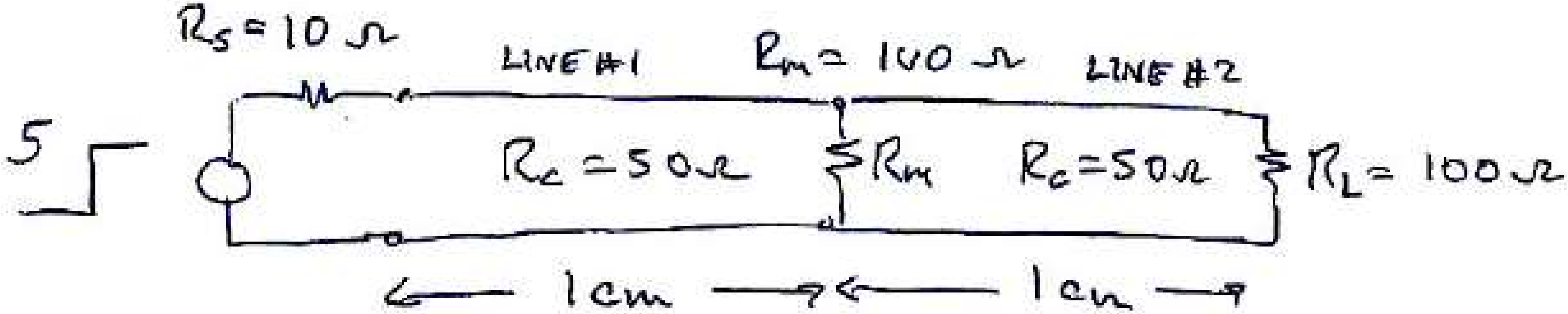
$$\Gamma_1 = \frac{R_p - R_c}{R_p + R_c} = \frac{33.33-50}{33.33+50} = -0.2000$$

$$T_{12} = \frac{2R_p}{R_p + R_c} = \frac{2x33.33}{33.33+50} = 0.8000$$

Junction from right to left:

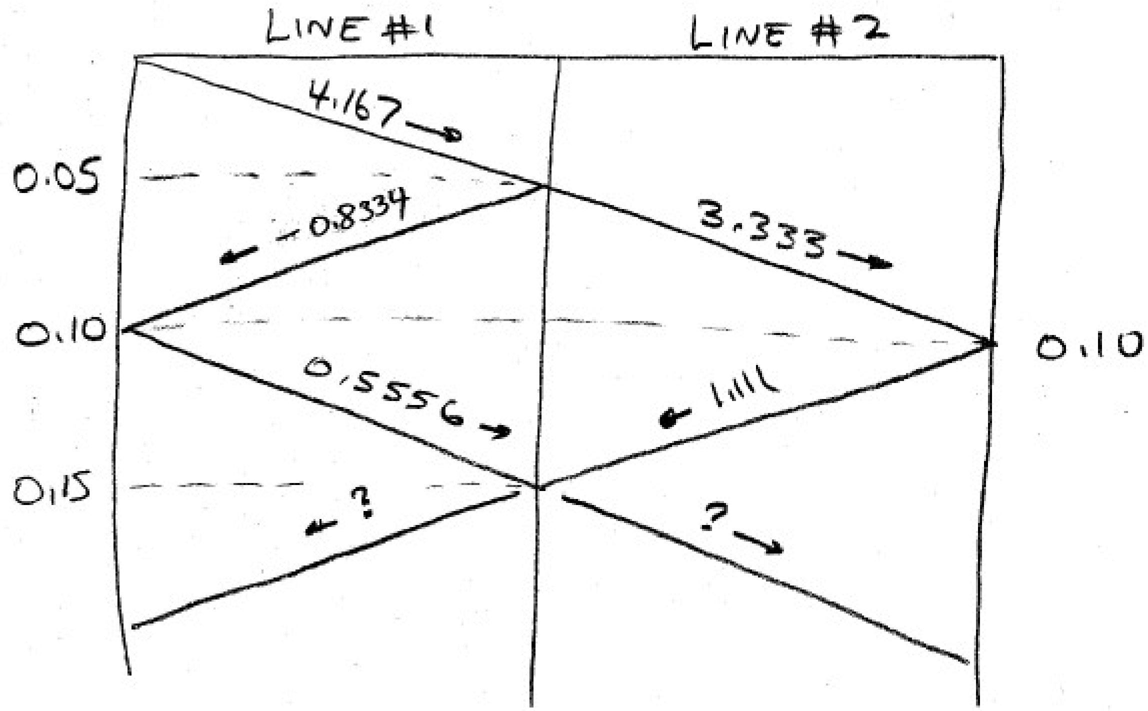
$$\Gamma_2 = -0.2000$$

$$T_{21} = 0.8000$$



$\Gamma_1 = -0.2000$
$T_{12} = 0.8000$

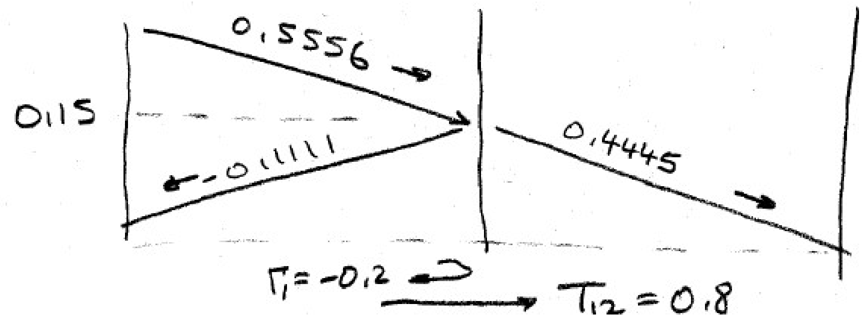
$\Gamma_s = -0.6667$



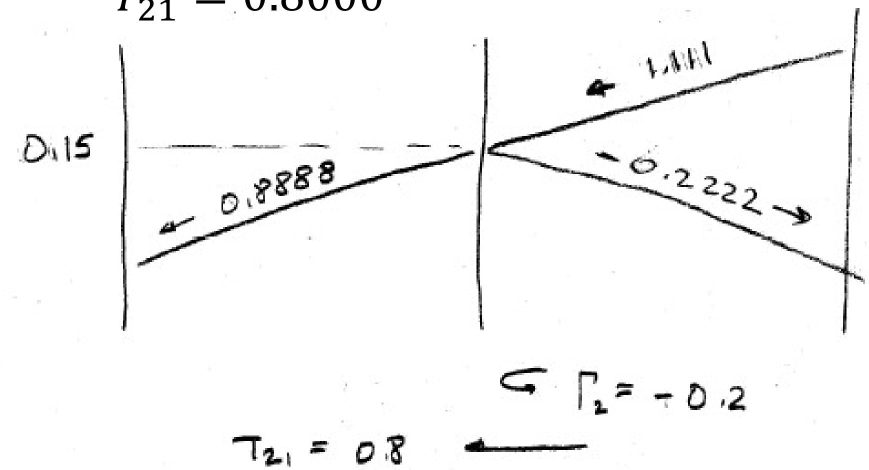
$\Gamma_L = 0.3333$

Decompose into two simpler problems:

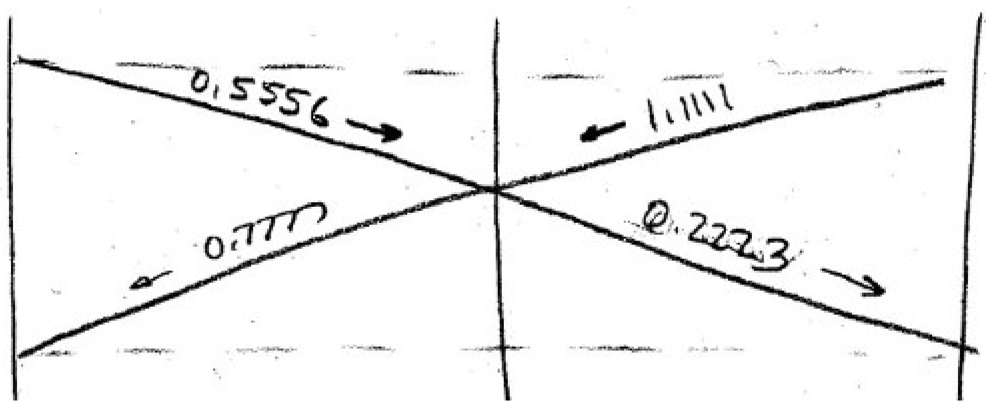
$\Gamma_1 = -0.2000$
$T_{12} = 0.8000$



$\Gamma_2 = -0.2000$
$T_{21} = 0.8000$

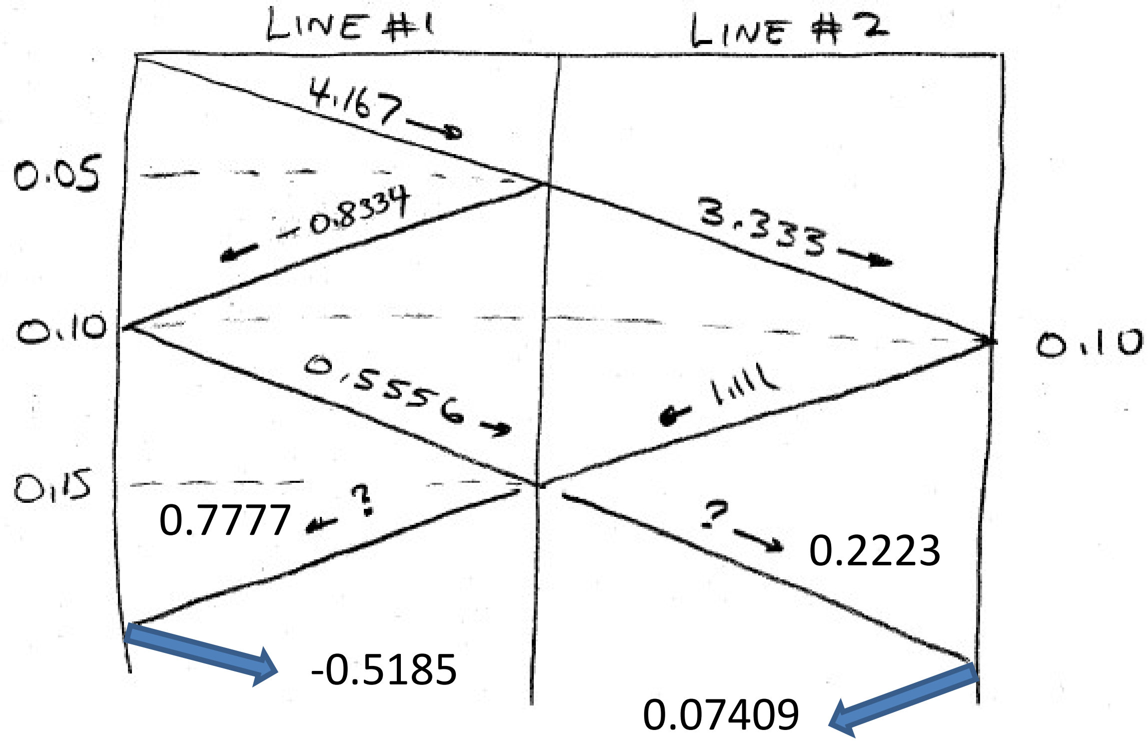


Add up the two parts of the solution:



- line #1: -0.1111+0.8888=0.7777 volts
- line #2: 0.4445-0.2222=0.2223 volts

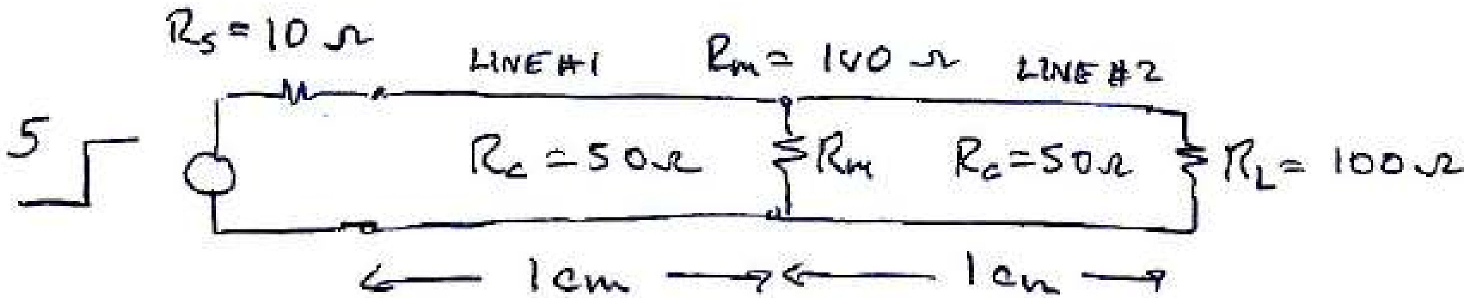
Carry on for one more reflection:



$\Gamma_S = -0.6667$

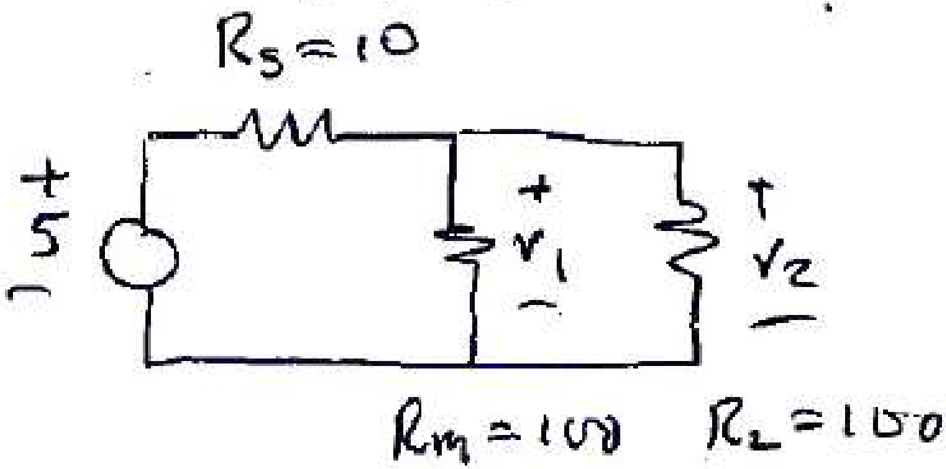
$\Gamma_L = 0.3333$

Find the load voltage:



Final Values

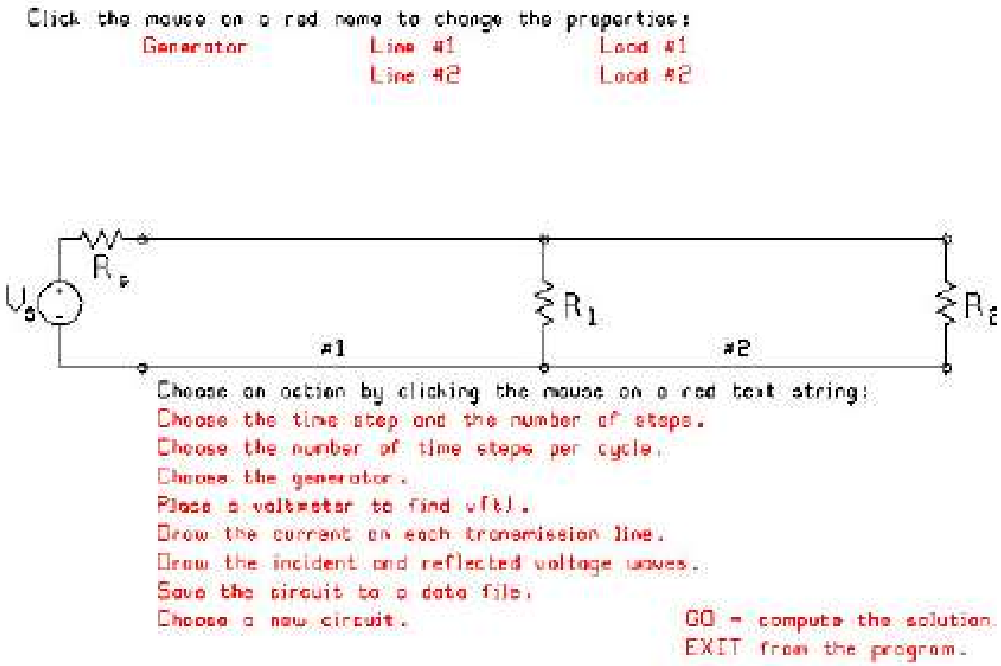
- We can compute the "final values" of the voltages in the transmission line circuit by replacing the transmission lines with short circuits:

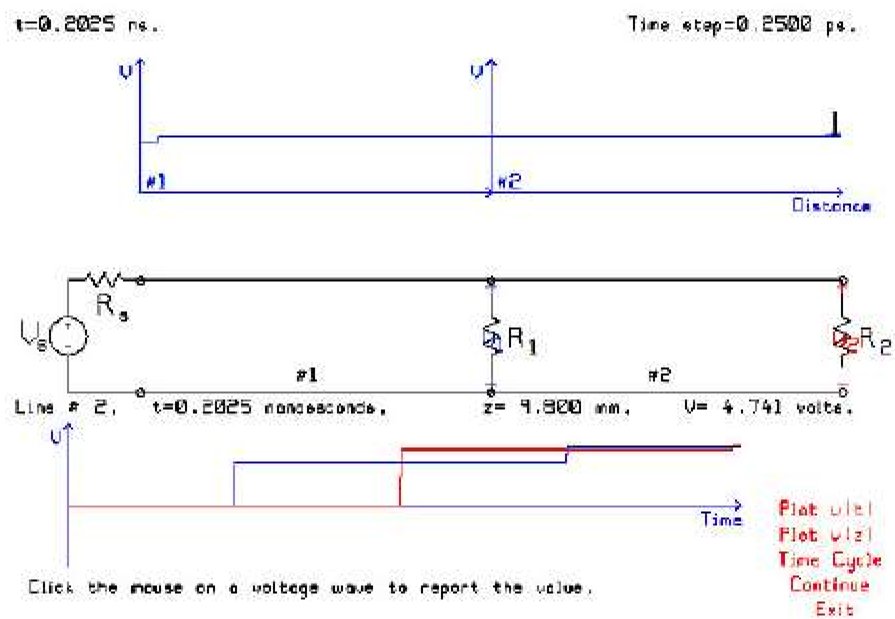


- The circuit is easily solved.
- 100 ohms in parallel with 100 ohms is 50 ohms.
- The voltages are

$$V_1 = V_2 = \frac{50}{10+50} x5 = 4.167 \text{ volts}$$

Verify the solution with BOUNCE:





ELEC353 Lecture Notes Set 5

The homework assignments are posted on the course web site.
http://users.encs.concordia.ca/~trueman/web_page_353.htm

Homework #3: Do homework #3 by February 2, 2018.
Homework #4: Do homework #4 by February 9, 2018.
Homework #5: Do homework #4 by February 15, 2018.

Mid-term test: Thursday February 15, 2018

- The mid-term test will include a question on the “life long learning” topic of A.C. circuit analysis.
- See the course web site for sample mid-term tests, including question 3 on A.C. circuit analysis.
- Study tip:
  - Download the question paper for a mid-term from a previous year.
  - Spend one hour 15 minutes solving the test with your calculator and the formula sheet, but no textbook or notes.
  - Grade your answer against the solution to the test!

Tentative final exam date: Wednesday April 25, 2018, 9:00 to 12:00.

Transmission Line Topics:

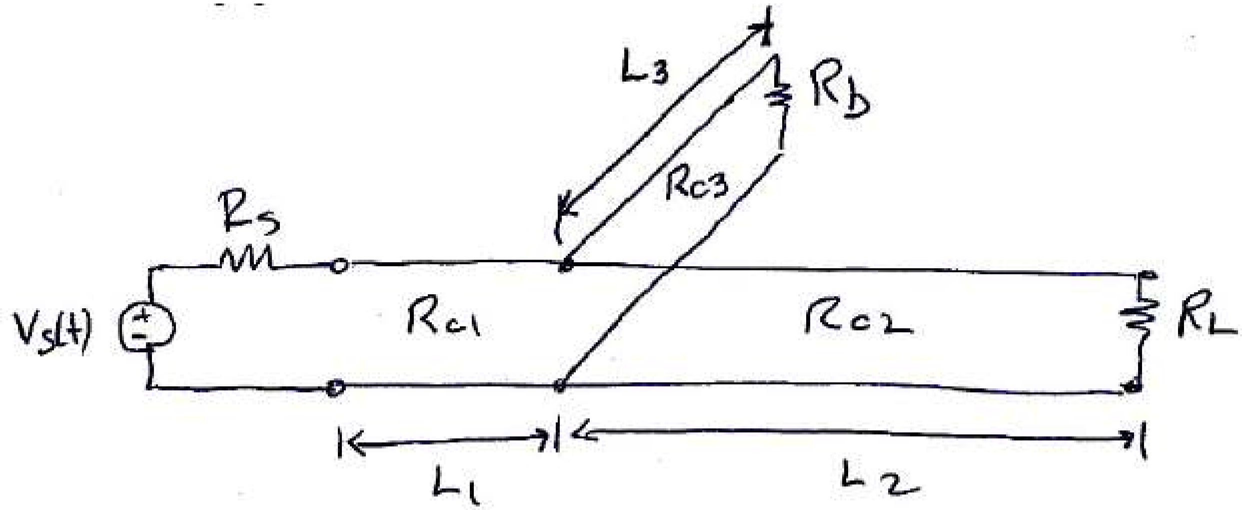
1. Junctions Between Transmission Lines Done!
2. Transmission Line with Shunt Load Done!
3. Branching Transmission Lines
4. Inductive and Capacitive Terminations
5. Time Domain Reflectometry

(Class Test)

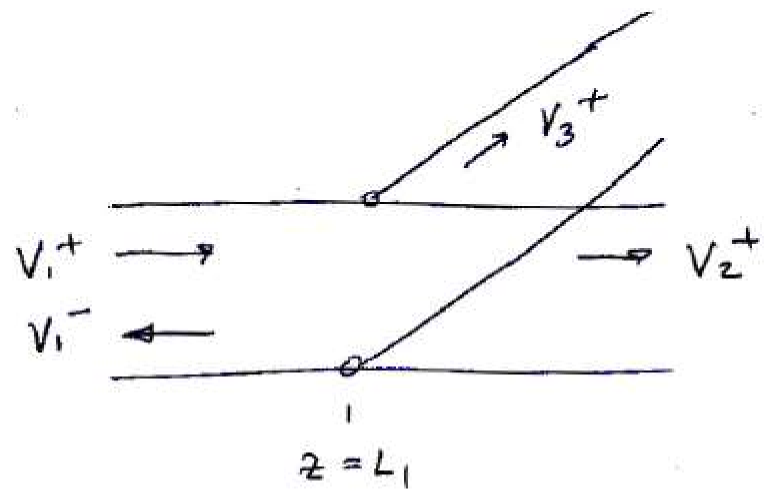
6. The Sinusoidal Steady State

Branching Transmission Lines

Inan and Inan page 57



Reflection and transmission coefficients:



$$V_1^- = \Gamma_1 V_1^+$$

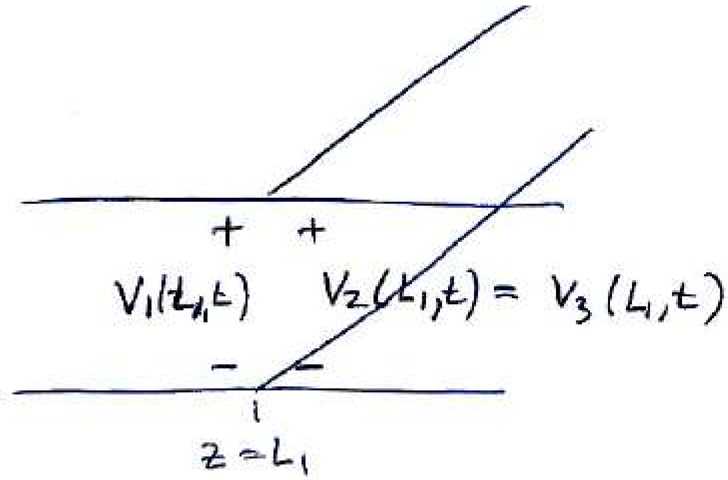
$$V_2^+ = T_{12} V_1^+$$

$$V_3^+ = T_{13} V_1^+$$

Enforce KVL

At $z = L_1$,

$$V_1(L_1,t) = V_1^+(L_1,t) + V_1^-(L_1,t)$$
$$V_2(L_1,t) = V_2^+(L_1,t)$$
$$V_3(L_1,t) = V_3^+(L_1,t)$$



$$V_1(L_1,t) = V_2(L_1,t) = V_3(L_1,t)$$

$$V_1^+(L_1,t) + V_1^-(L_1,t) = V_2^+(L_1,t) = V_3^+(L_1,t)$$

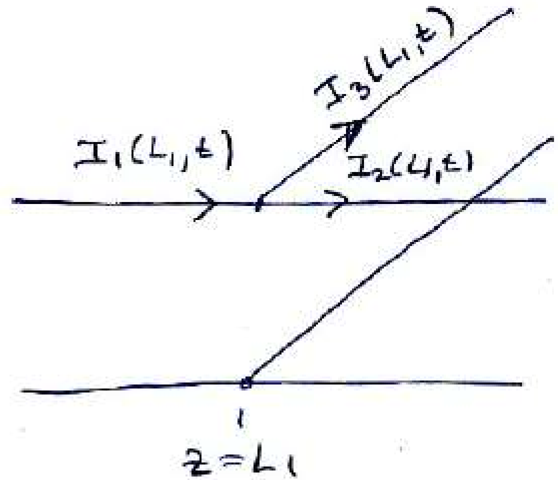
$$V_1^+ + V_1^- = V_2^+ = V_3^+$$

Enforce KCL

$$I_1(L_1,t)=\frac{V_1^+(L_1,t)}{R_{c1}}-\frac{V_1^-(L_1,t)}{R_{c1}}$$

$$I_2(L_1,t)=\frac{V_2^+(L_1,t)}{R_{c2}}$$

$$I_3(L_1,t)=\frac{V_3^+(L_1,t)}{R_{c3}}$$



$$I_1(L_1,t)=I_2(L_1,t)+I_3(L_1,t)$$

$$\frac{V_1^+(L_1,t)}{R_{c1}}-\frac{V_1^-(L_1,t)}{R_{c1}}=\frac{V_2^+(L_1,t)}{R_{c2}}+\frac{V_3^+(L_1,t)}{R_{c3}}$$

$$\frac{V_1^+}{R_{c1}}-\frac{V_1^-}{R_{c1}}=\frac{V_2^+}{R_{c2}}+\frac{V_3^+}{R_{c3}}$$

Solving the equations:

$$V_1^+ + V_1^- = V_2^+ = V_3^+$$

$$\frac{V_1^+}{R_{c1}} - \frac{V_1^-}{R_{c1}} = \frac{V_2^+}{R_{c2}} + \frac{V_3^+}{R_{c3}}$$

$$R_p = \frac{R_{c2}R_{c3}}{R_{c2} + R_{c3}}$$

$$V_1^- = \frac{R_p - R_{c1}}{R_p + R_{c1}} V_1^+$$

$$\Gamma_1 = \frac{R_p - R_{c1}}{R_p + R_{c1}}$$

$$V_1^- = \Gamma_1 V_1^+$$

$$V_2^+ = \frac{2R_p}{R_{c1} + R_p} V_1^+$$

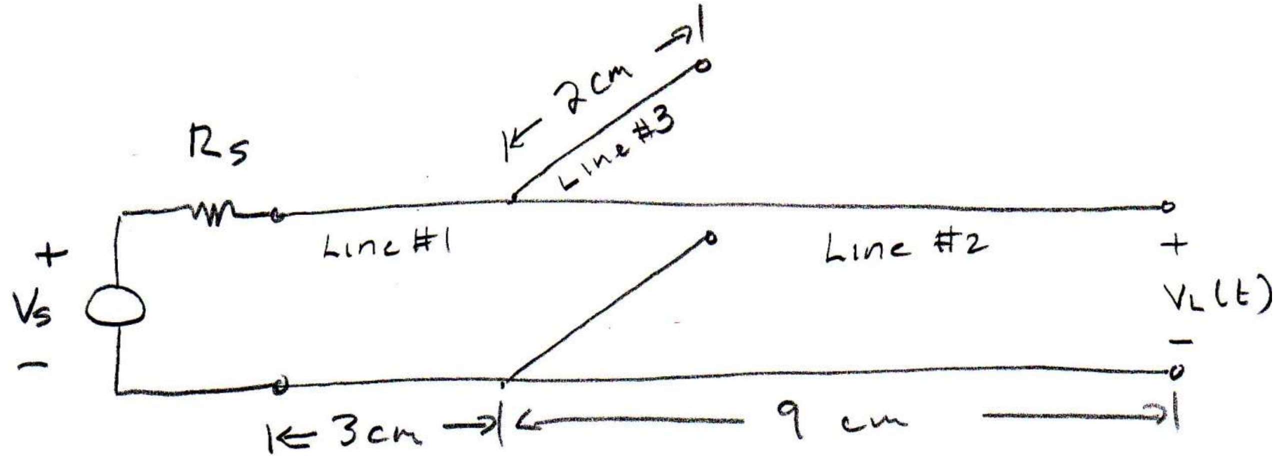
$$V_3^+ = \frac{2R_p}{R_{c1} + R_p} V_1^+$$

$$T_{12} = T_{13} = \frac{2R_p}{R_{c1} + R_p}$$

$$V_2^+ = T_{12} V_1^+$$

$$V_3^+ = T_{13} V_1^+$$

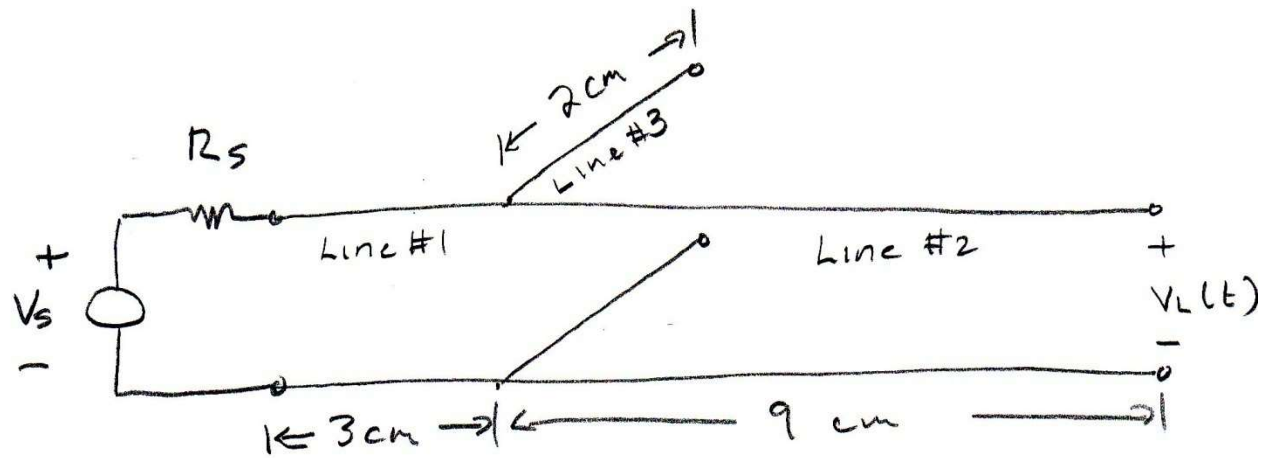
Example



- Consider a fast CMOS logic family, with a rise time of 0.1 ns.
- The input resistance of a logic gate in this family is very high, but the input of each gate has an input capacitance of 1 pF.
- A logic gate output with a 100-ohm internal resistance and a 5 volt open-circuit voltage must be connected to a gate input 12 cm away.
- Also, at 3 cm distance form the gate output, there is a 2 cm branch to another gate with a high input resistance.
- The circuit is shown above:
  - Line #1 is 3 cm long.
  - Line #2 is 9 cm long.
  - Line #3 is the branch and is 2 cm long.
  - All three lines have characteristic resistance $R_c = 50$ ohms and speed of propagation $u = 14$ cm/ns.
- Later we will use BOUNCE to find the time required for the voltage at the load to rise to 4.5 volts and remain above that level.

Initial Model for Hand Calculation

- *Approximate* the generator as a 5-volt step function with *zero* rise time.
- *Neglect* the CMOS gate input capacitance.
- The circuit is then simple enough to solve by hand calculation.
- Find the *first three interactions* at the load using a bounce diagram.



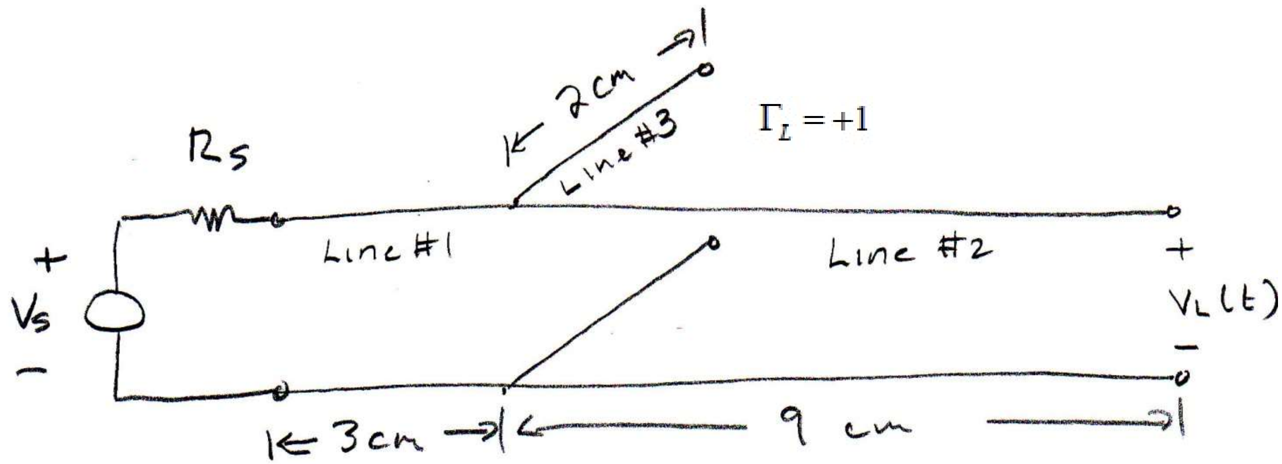
$V_s = 5$ volts $\quad R_s = 100\Omega \quad R_c = 50\Omega \quad u = 14$ cm/ns

$$V(0) = \frac{R_c}{R_s + R_c} V_s = \frac{50}{50+100} x5 = 1.667 \text{ volts}$$

Line #1, length 3 cm: $T_{d1} = \frac{L_1}{u} = \frac{3}{14} = 0.214$ ns

Line #2, length 9 cm: $T_{d2} = \frac{L_2}{u} = \frac{9}{14} = 0.643$ ns

Line #3, length 2 cm: $T_{d3} = \frac{L_3}{u} = \frac{2}{14} = 0.143$ ns



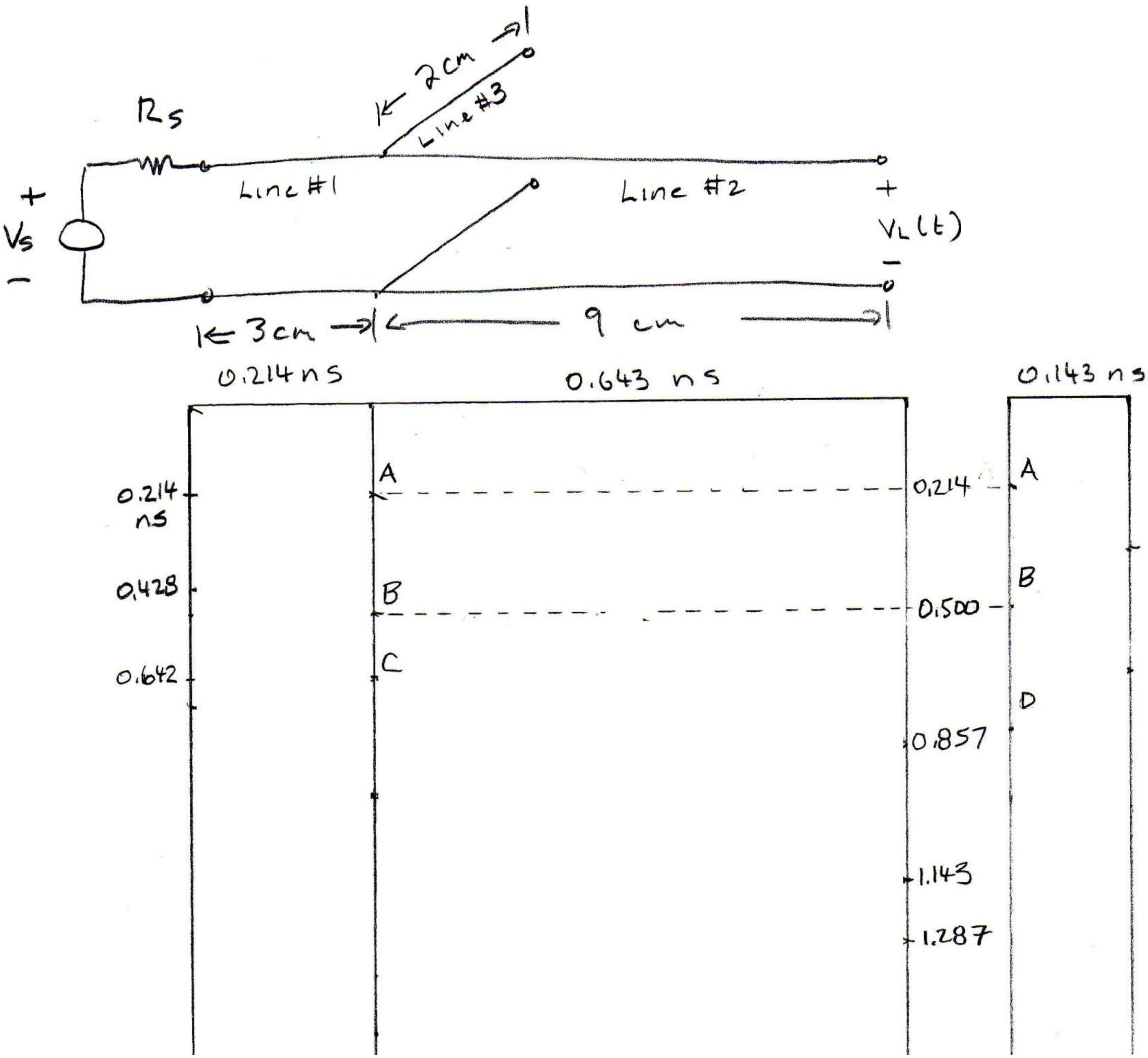
$$\Gamma_s = \frac{R_s - R_c}{R_s + R_c} = \frac{100-50}{100+50} = 0.3333$$

$$\Gamma_L = +1$$

At the junction: $R_p = \dfrac{R_c R_c}{R_c + R_c} = \dfrac{R_c}{2} = 25 \text{ ohms}$

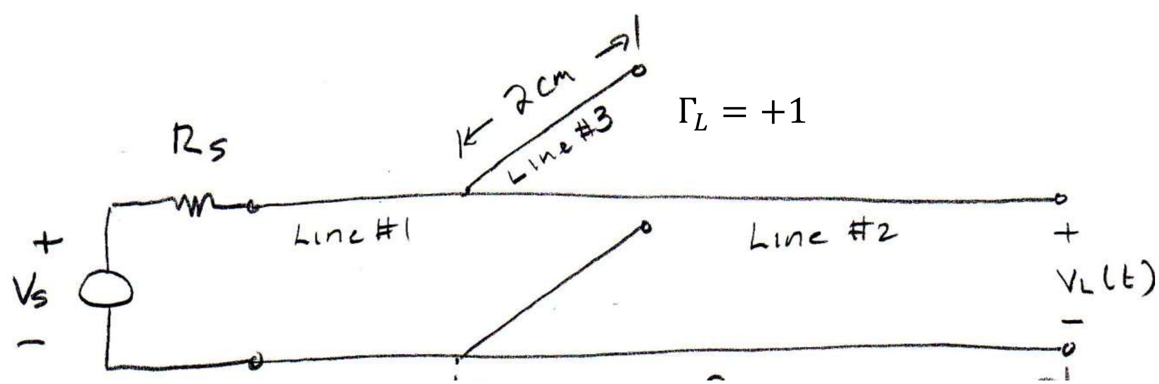
$$\Gamma_J = \frac{R_p - R_c}{R_p + R_c} = \frac{25-50}{25+50} = -0.3333$$

$$T_J = \frac{2R_p}{R_p + R_c} = \frac{2x25}{25+50} = 0.6667$$



Rs
2 cm
Line #3
Line #1
Line #2
+
Vs
−
+
VL(t)
−
3 cm
9 cm
0.214 ns
0.643 ns
0.143 ns
0.214 ns
0.428
0.642
A
B
C
0.214
0.500
0.857
1.143
1.287
A
B
D

Draw a bounce diagram for each of the three transmission lines:



$\Gamma_L = +1$

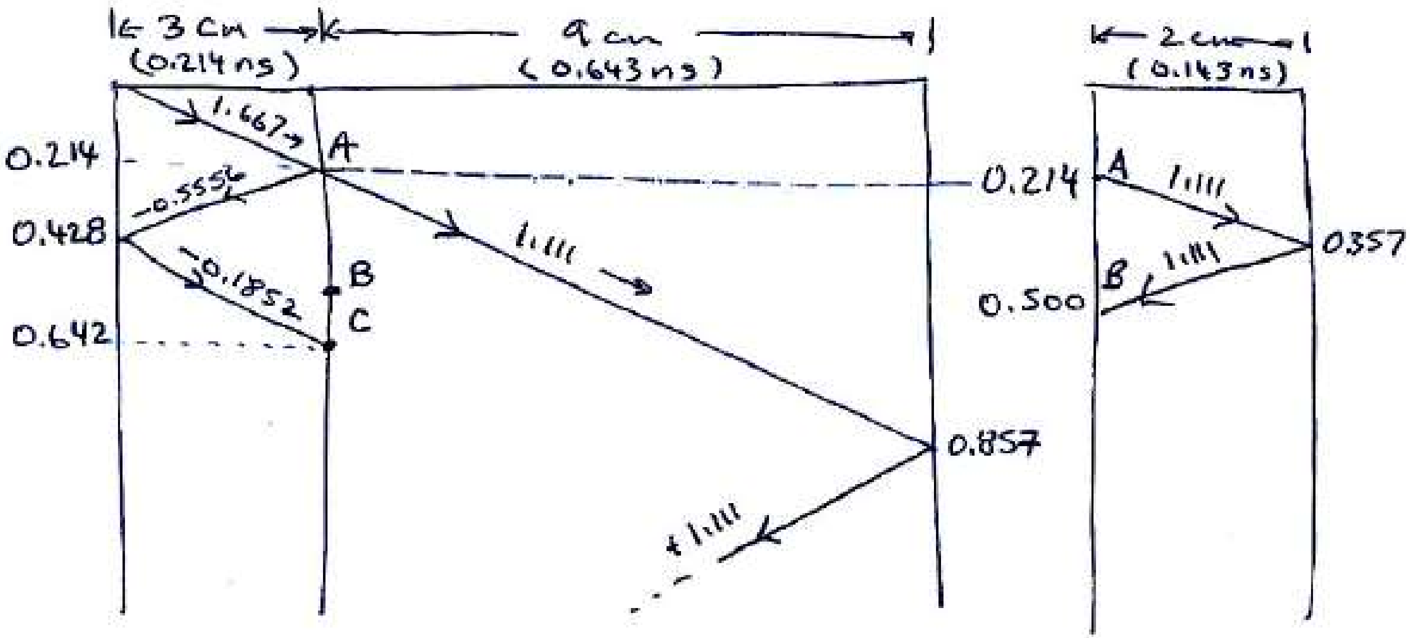
$\Gamma_s = +0.3333$

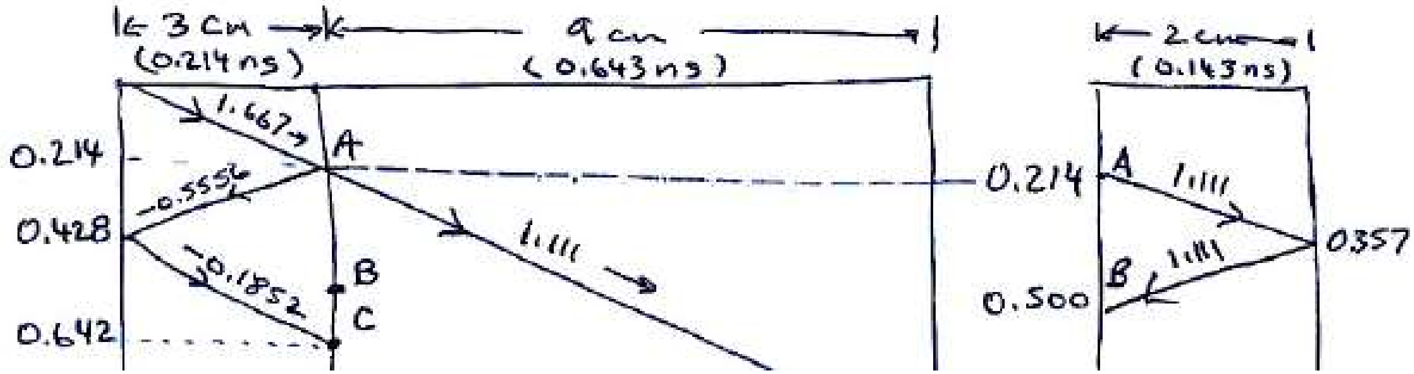
$\Gamma_L = +1$

$$\Gamma_J = \frac{R_p - R_c}{R_p + R_c} = \frac{25-50}{25+50} = -0.3333$$

$$T_J = \frac{2R_p}{R_p + R_c} = \frac{2x25}{25+50} = 0.6667$$

$$\Gamma_s = \frac{R_s - R_c}{R_s + R_c} = \frac{100-50}{100+50} = 0.3333$$

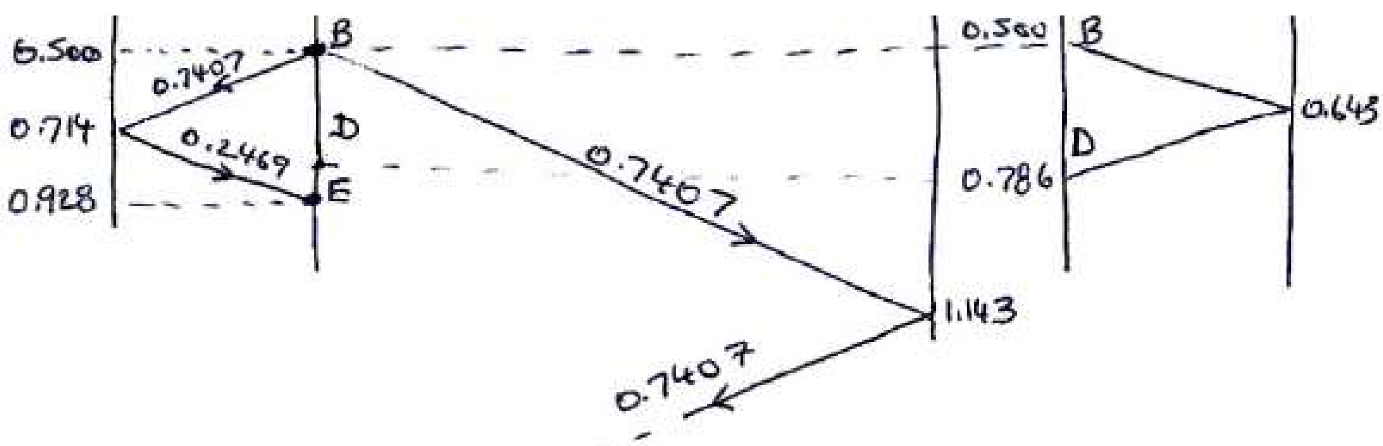


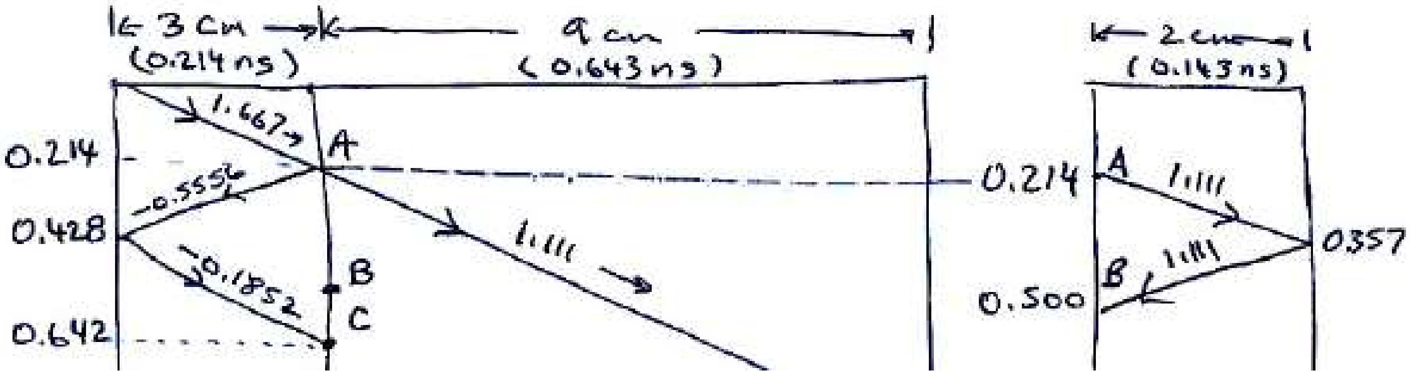


$$\Gamma_J = \frac{R_p - R_c}{R_p + R_c} = \frac{25-50}{25+50} = -0.3333$$

$$T_J = \frac{2R_p}{R_p + R_c} = \frac{2x25}{25+50} = 0.6667$$

From Point B to the Load:

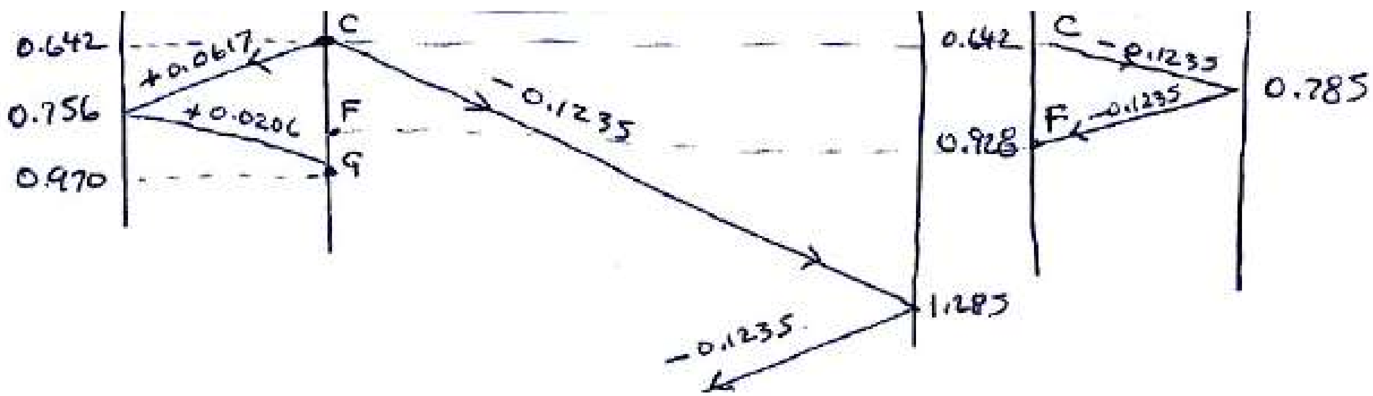




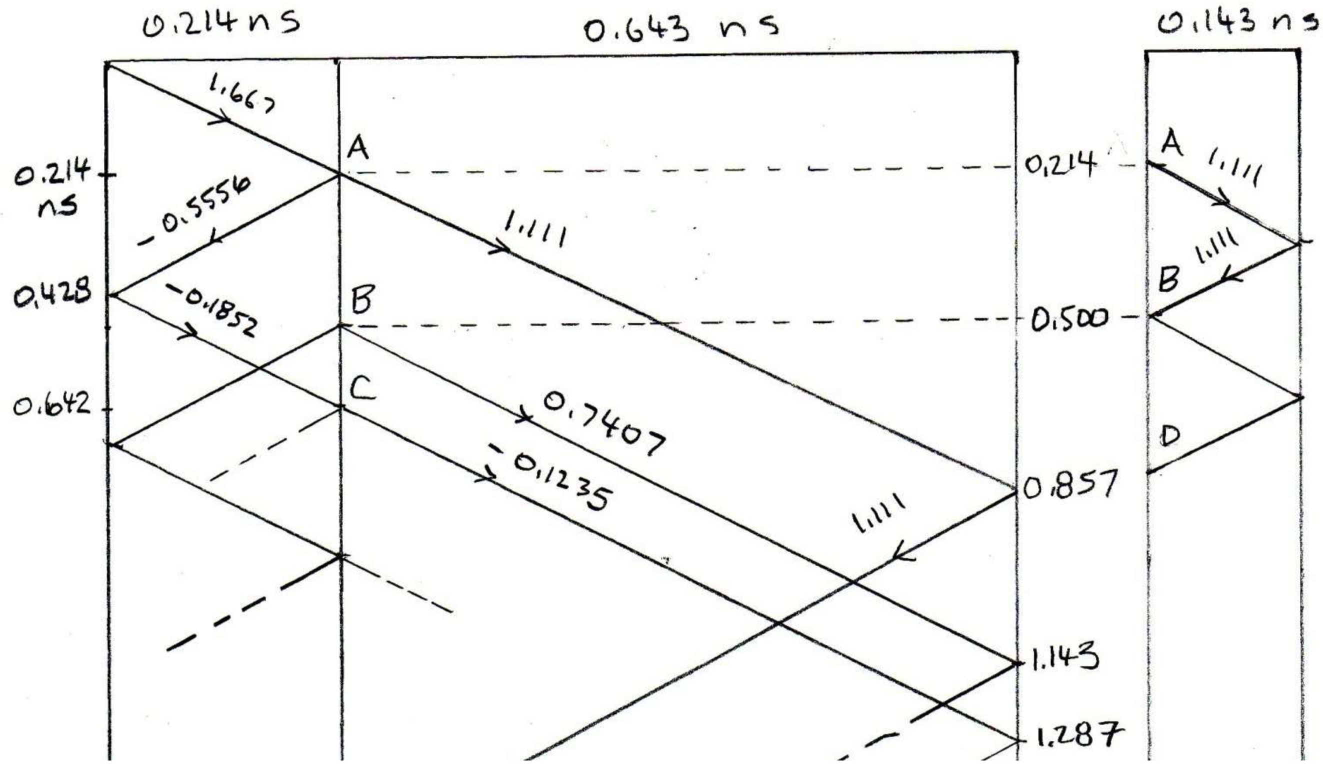
$$\Gamma_J = \frac{R_p - R_c}{R_p + R_c} = \frac{25-50}{25+50} = -0.3333$$

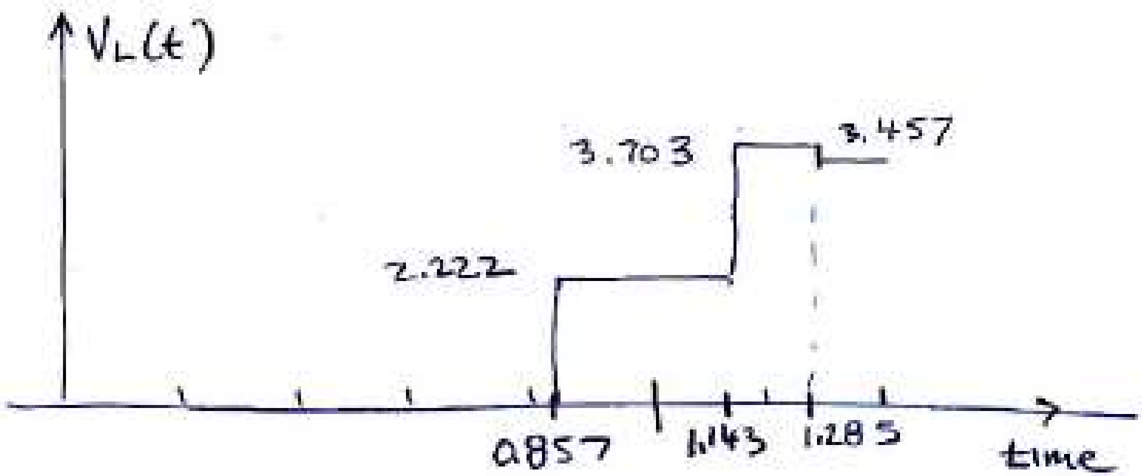
$$T_J = \frac{2R_p}{R_p + R_c} = \frac{2x25}{25+50} = 0.6667$$

From Point C to the Load:

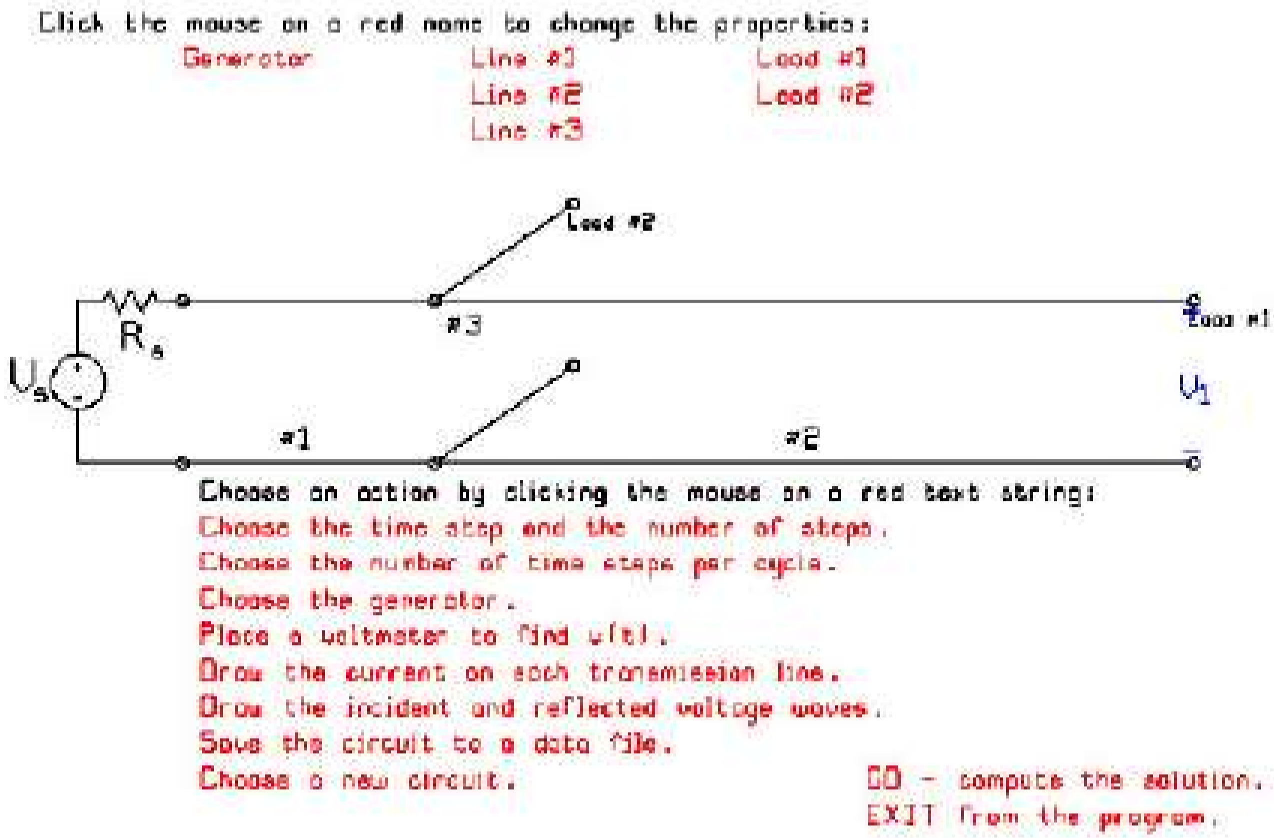


Put all the information onto one bounce diagram:



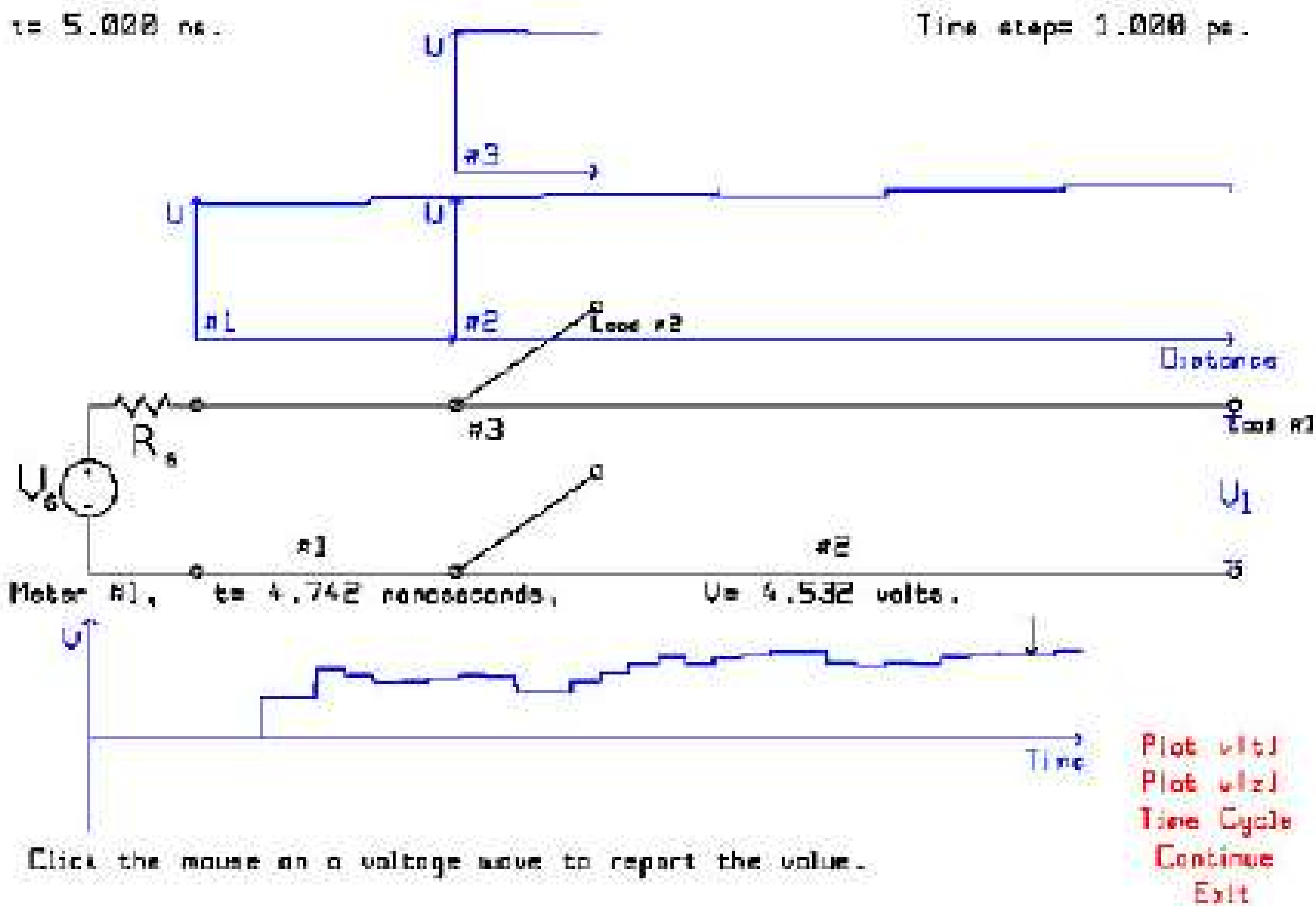


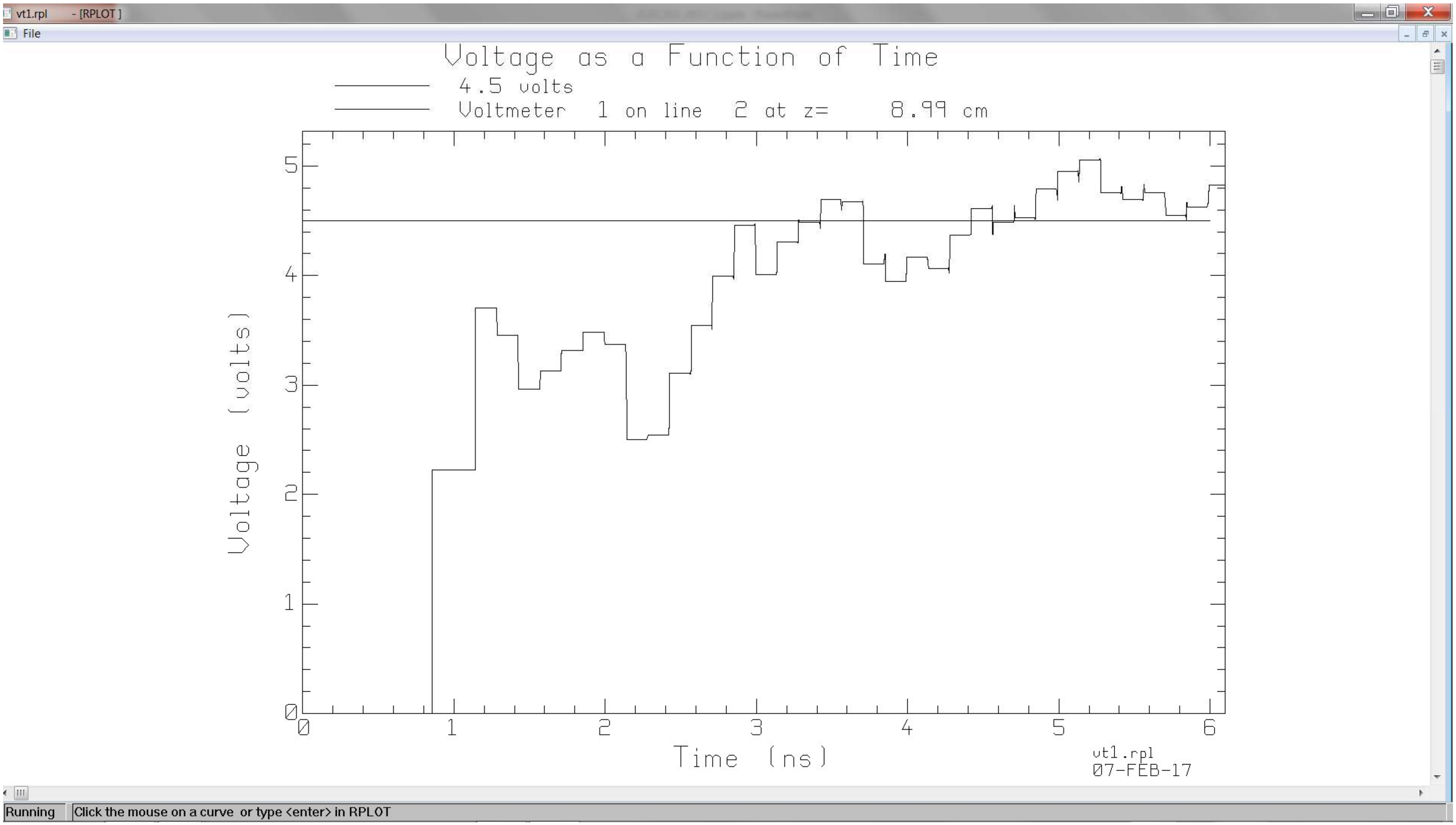
Solution by Computation with BOUNCE



Find the time for the load voltage to reach 4.5 volts and remain above 4.5 volts.

Time required to rise above 4.5 volts and remain above 4.5 volts:

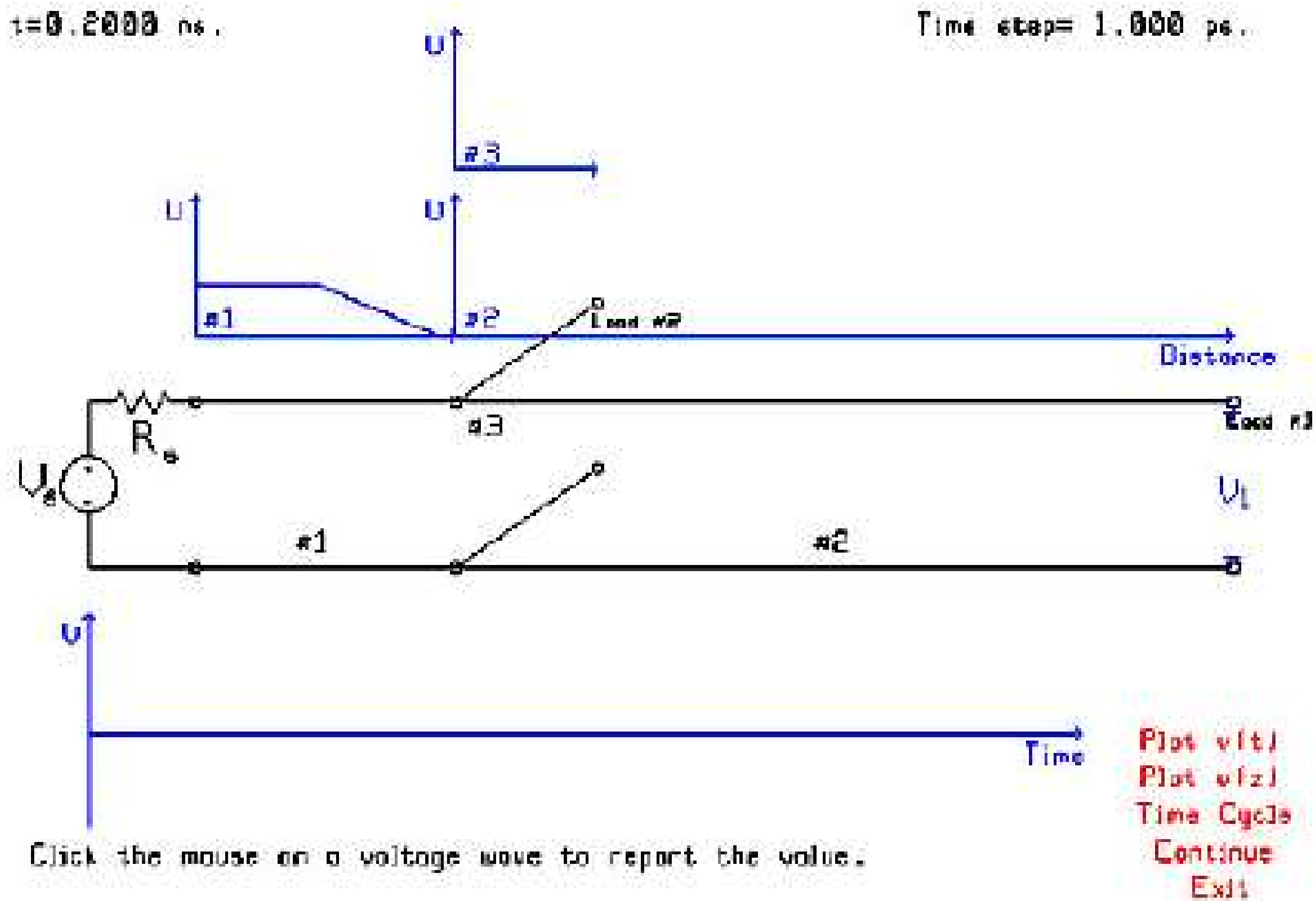


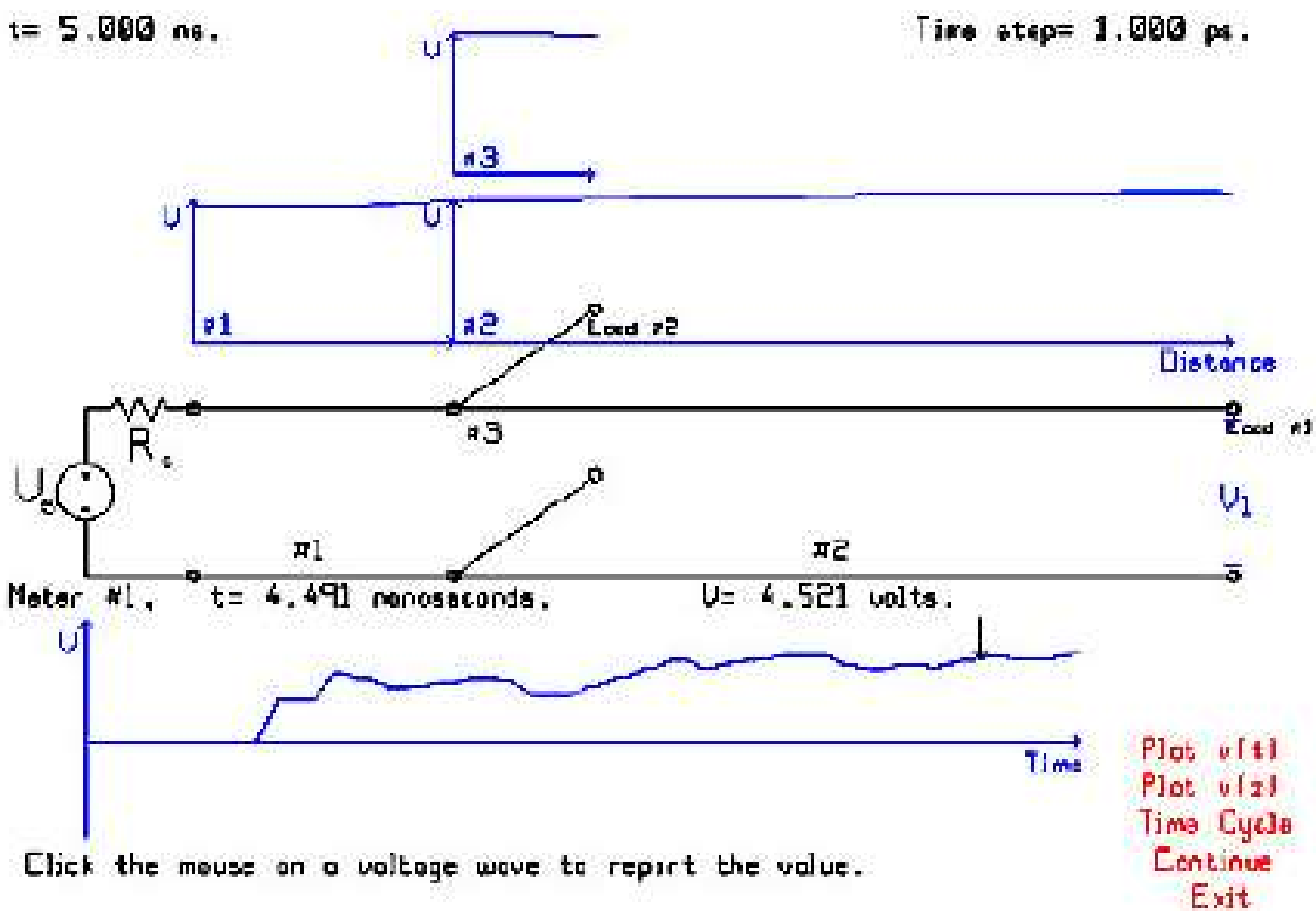


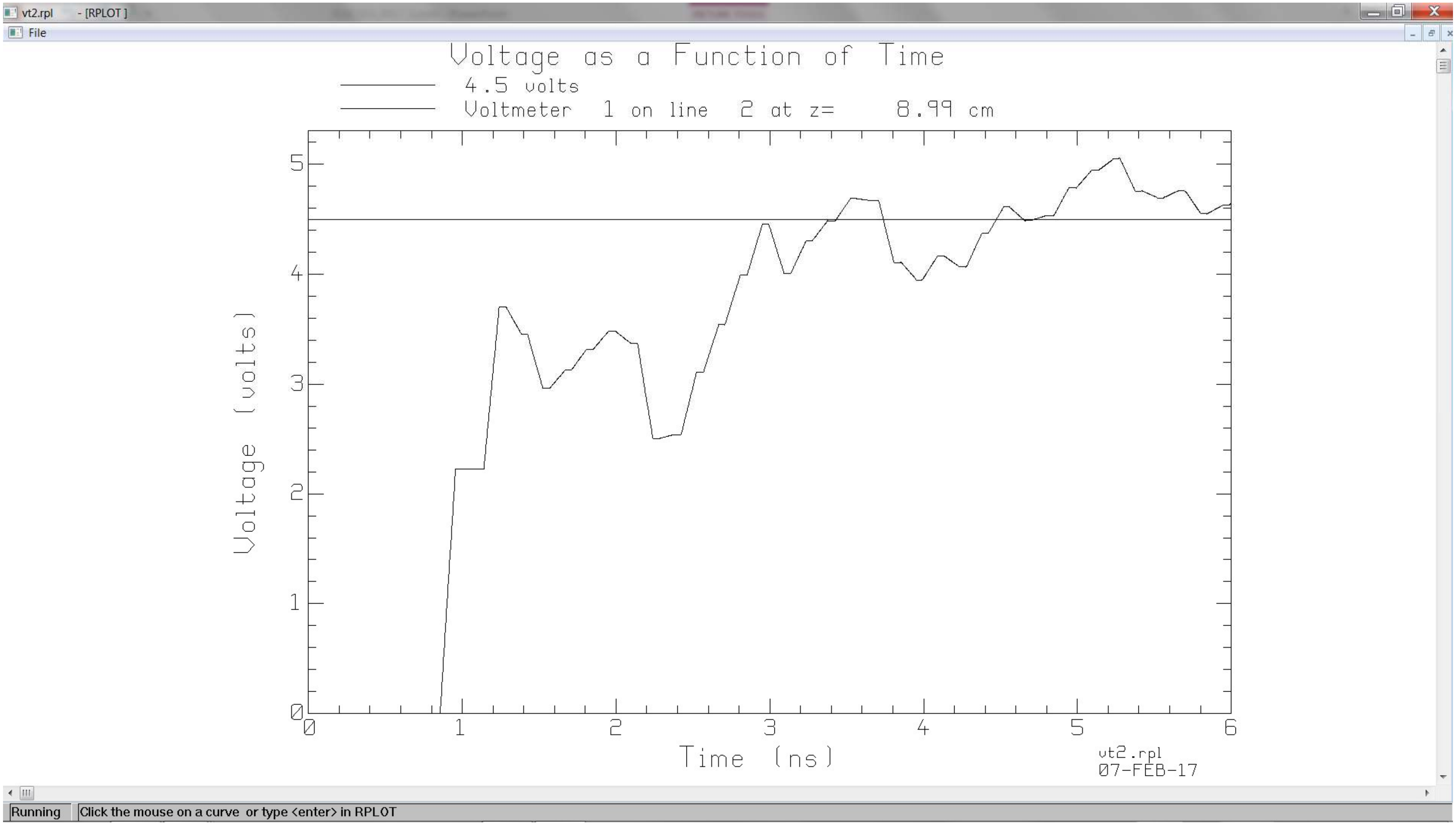
The load voltage remains above 4.5 volts for t>4.706 ns

Accounting for Rise Time

Let the rise time of the source voltage be 0.1 ns



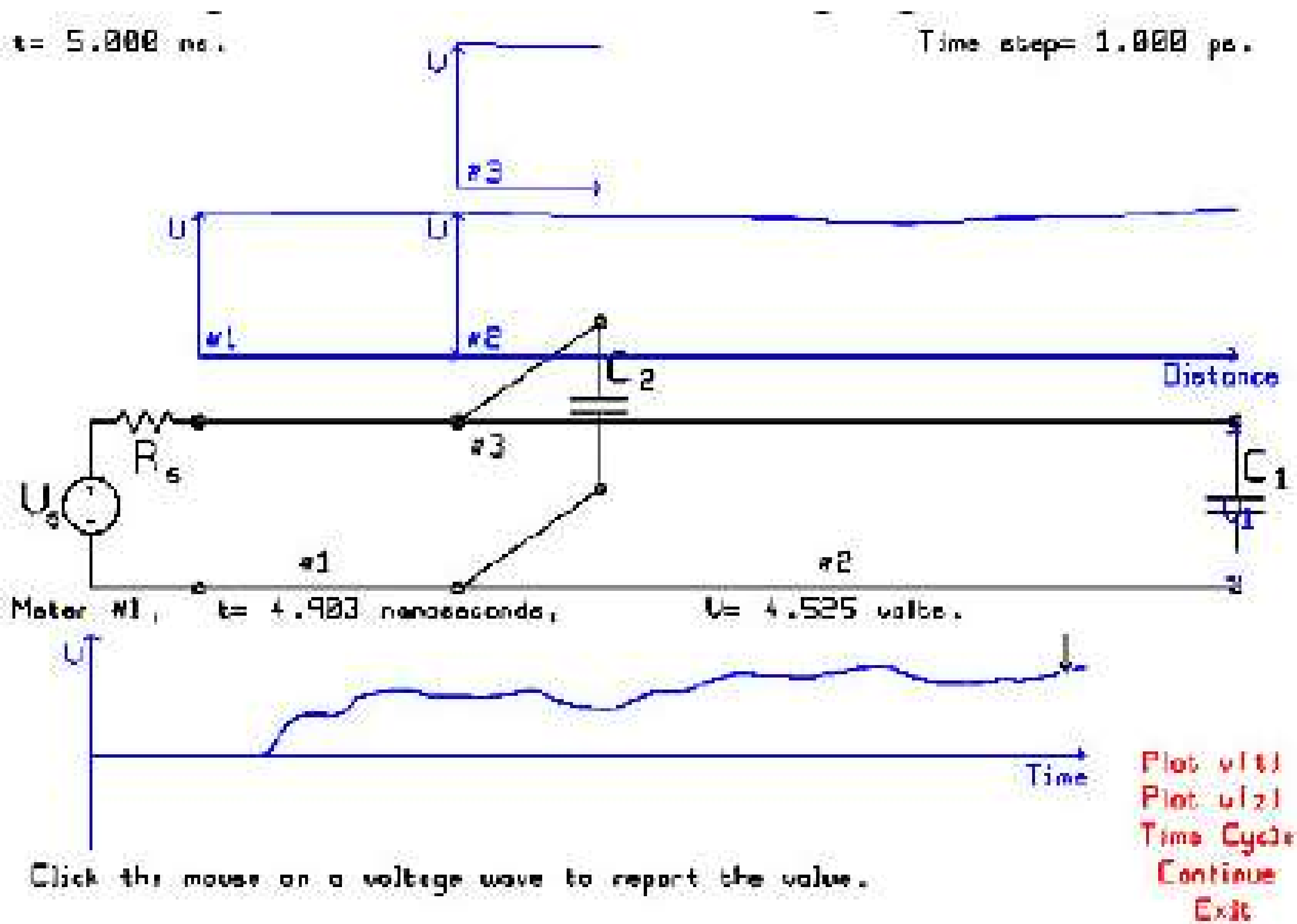

t= 5.000 ns.
Time step= 1.000 ps.
V
#3
V
V
#1
#2
Load #2
Distance
#3
Load #1
R_s
V_s
V_1
#1
#2
Meter #1, t= 4.491 nanoseconds. V= 4.521 volts.
V
Time
Plot v(t)
Plot v(z)
Time Cycle
Continue
Exit
Click the mouse on a voltage wave to report the value.

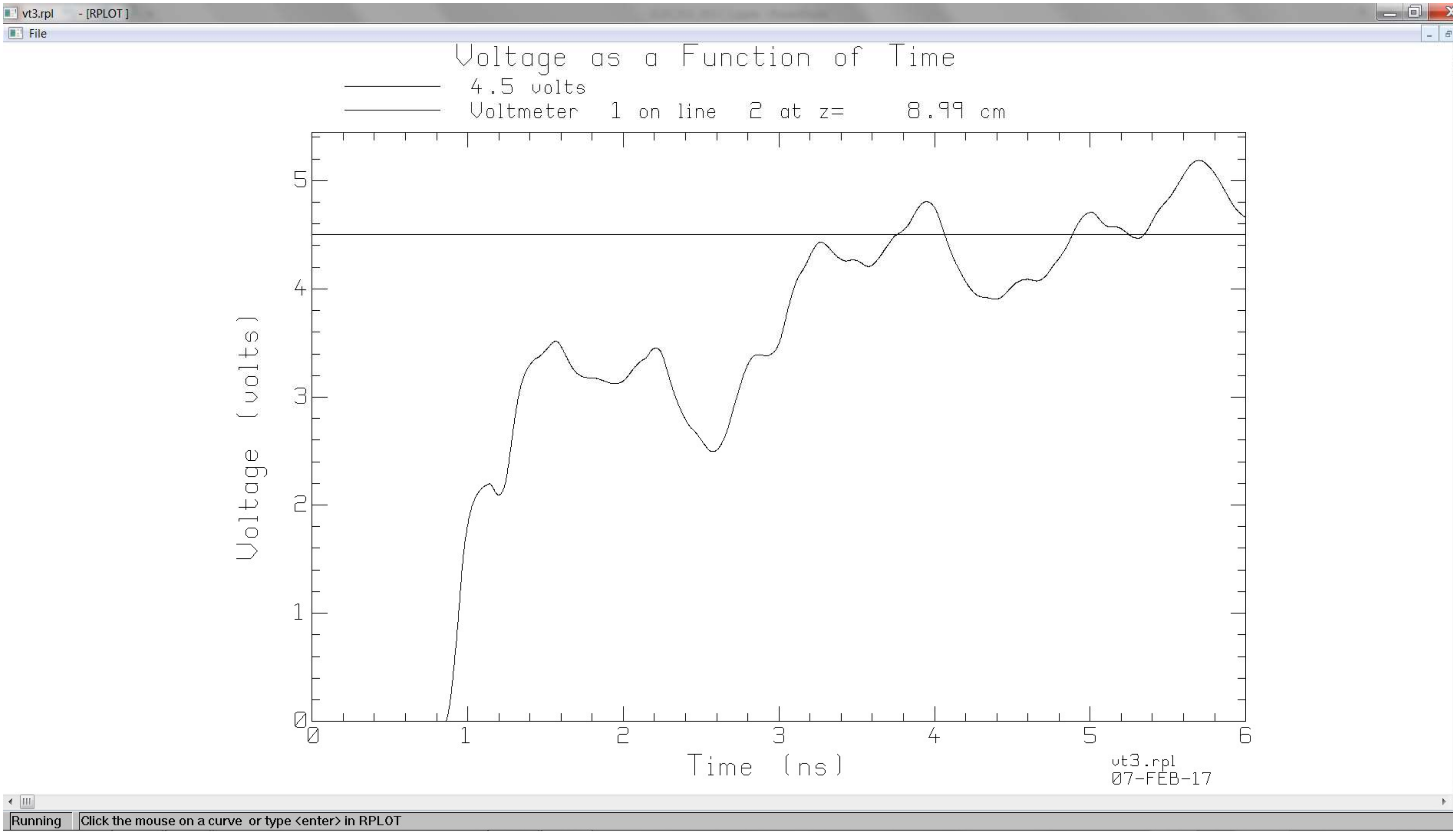


The load voltage remains above 4.5 volts for t>4.724 ns

Including the Gate Input Capacitance

Model the input of the CMOS chip as a 1 pF capacitor.

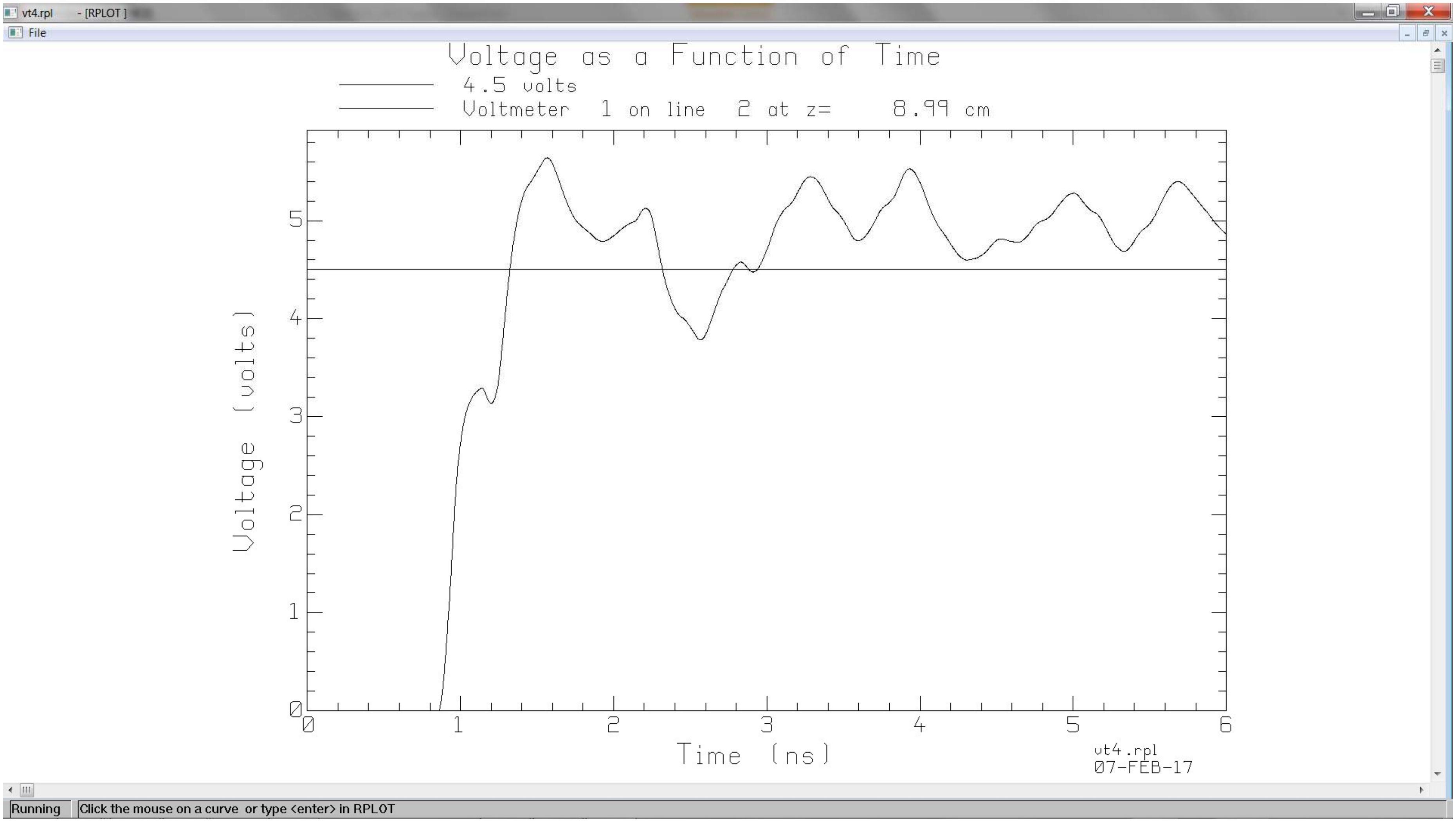




The load voltage remains above 4.5 volts for t>5.348 ns

Improving the Performance

1. Match the source to the transmission line to eliminate reflections from the source.



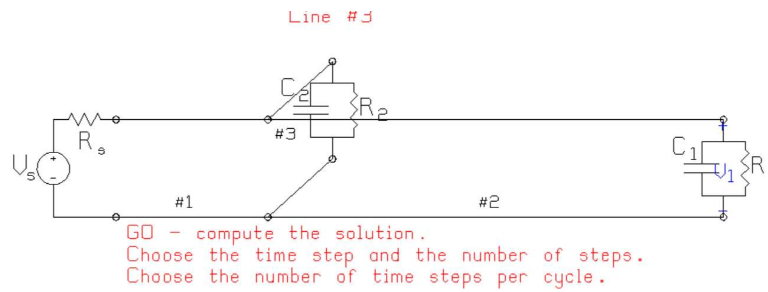
The load voltage is 4.5 volts or higher for t>2.938 ns.

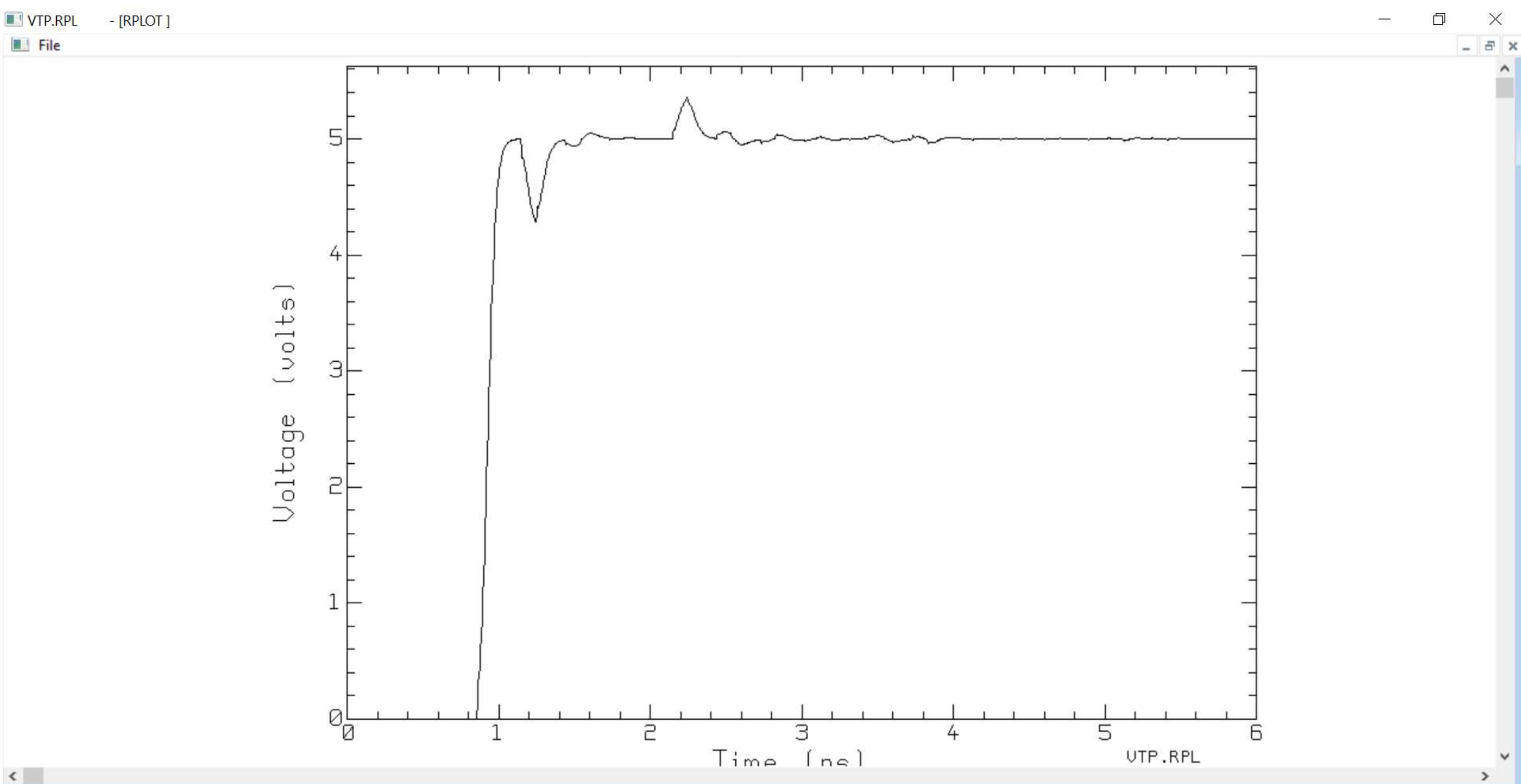
Improving the Performance

1.Match the source

2. And match the loads by putting a 50-ohm parallel resistor.

3.Increase the source to 15 v so that the final value is 5





The load voltage is 4.5 volts or higher for t>1.28 ns.