ECEN689: Special Topics in High-Speed Links Circuits and Systems
Spring 2010

Lecture 4: Transmission Line Examples

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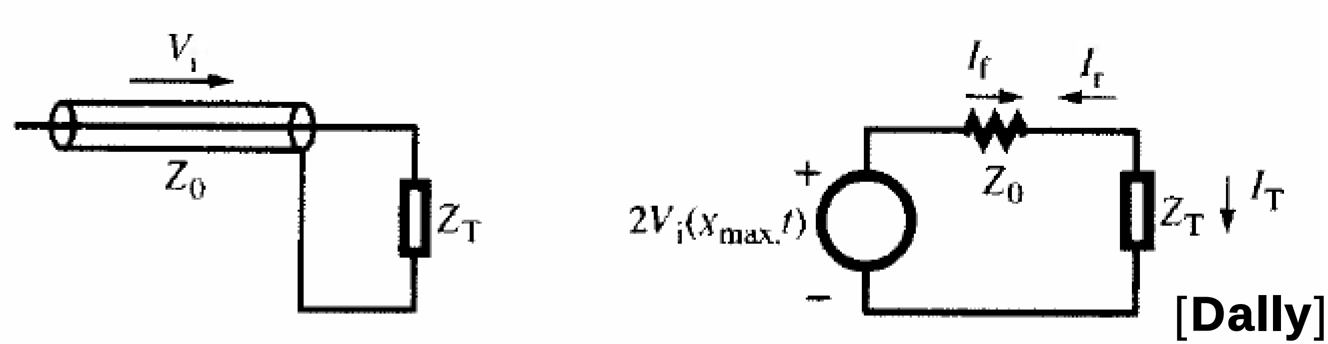
Announcements

- HW1 due 1/29
  - One page summary of recent link design paper
- Current Reading
  - Chapter 3.3 – 3.4
- For next time
  - Chapter 3.6 – 3.7

Agenda

- Transmission Lines
  - Termination examples
  - Differential transmission lines
- Majority of today's material from Dally Chapter 3.3-3.4

Reflections & Telegrapher's Eq.



[**Dally**]

- With a Thevenin-equivalent model of the line:

Termination Current: $$I_T = \frac{2V_i}{Z_0 + Z_T}$$

- KCL at Termination:

$$I_r = I_f - I_T$$

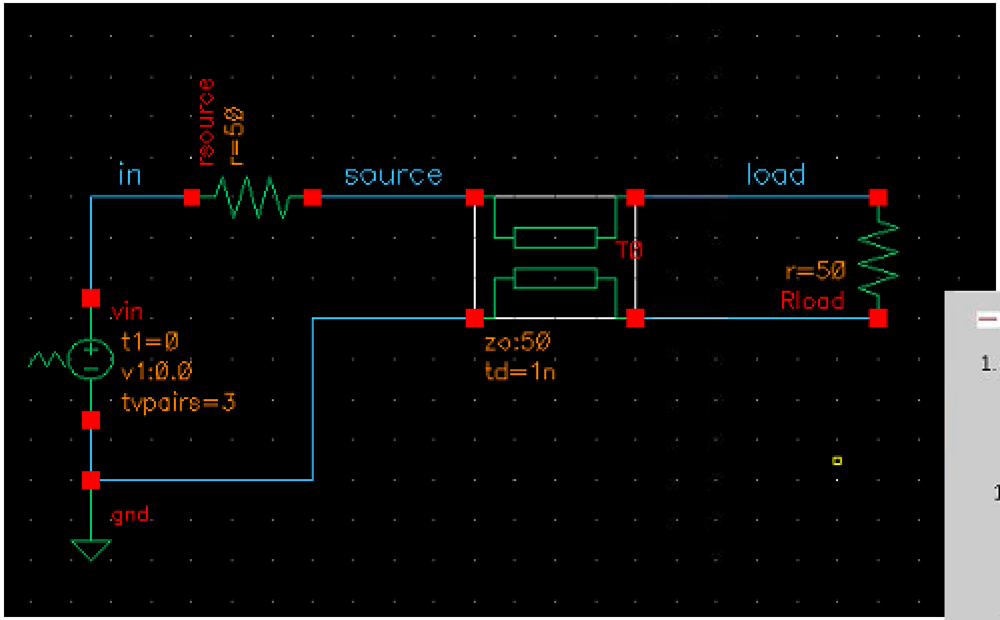
$$I_r = \frac{V_i}{Z_0} - \frac{2V_i}{Z_T + Z_0}$$

$$I_r = \frac{V_i}{Z_0}\left(\frac{Z_T - Z_0}{Z_T + Z_0}\right)$$

Telegrapher's Equation or
Reflection Coefficient

$$\boxed{k_r = \frac{I_r}{I_i} = \frac{V_r}{V_i} = \frac{Z_T - Z_0}{Z_T + Z_0}}$$

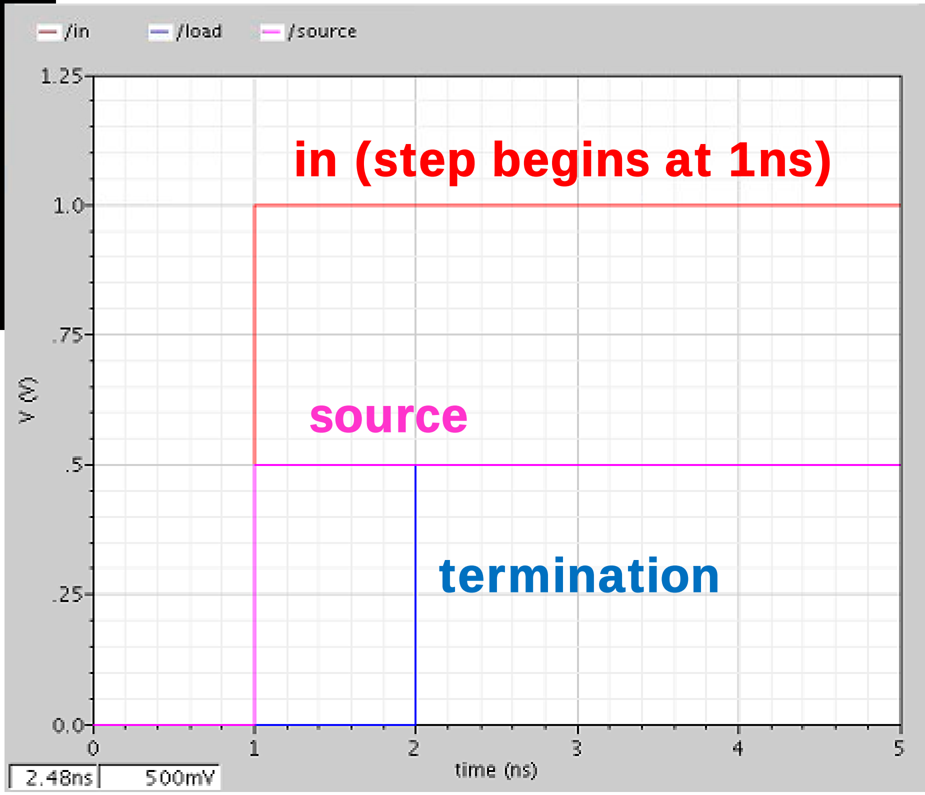
Termination Examples - Ideal



R_S = 50Ω

Z_0 = 50Ω, t_d = 1ns

R_T = 50Ω

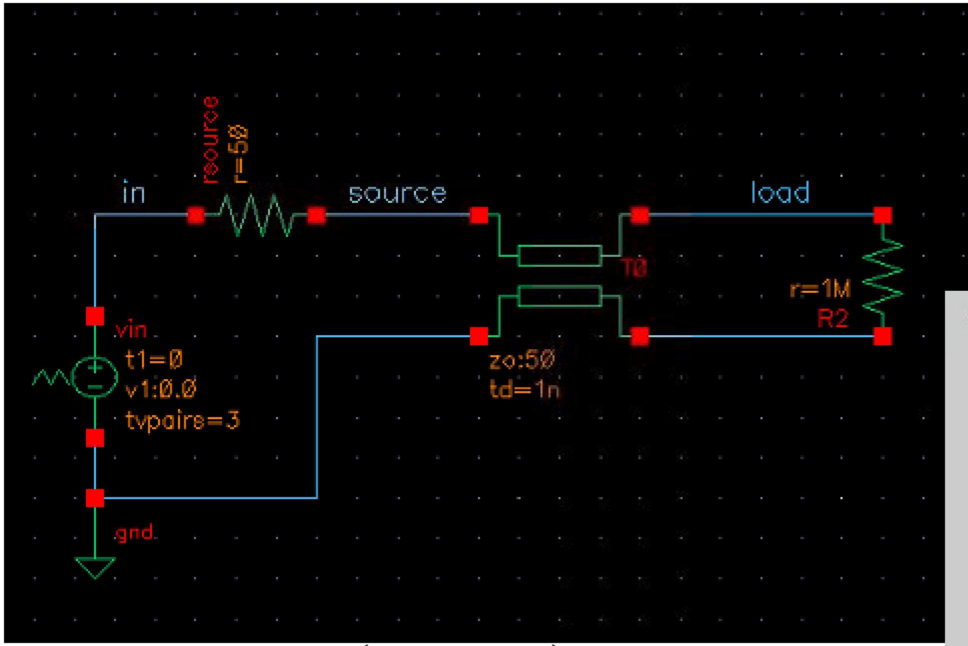


$$V_i = 1V\left(\frac{50}{50+50}\right) = 0.5V$$

$$k_{rT} = \frac{50-50}{50+50} = 0$$

$$k_{rS} = \frac{50-50}{50+50} = 0$$

Termination Examples - Open



R_S = 50Ω

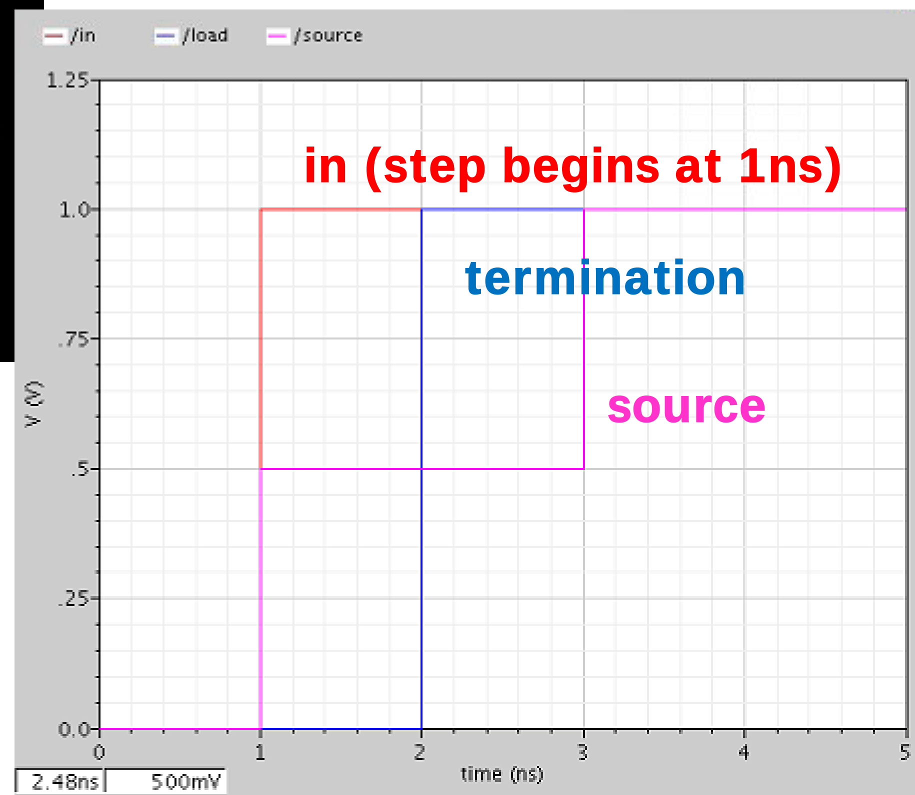
Z_0 = 50Ω, t_d = 1ns

R_T ~ ∞ (1MΩ)

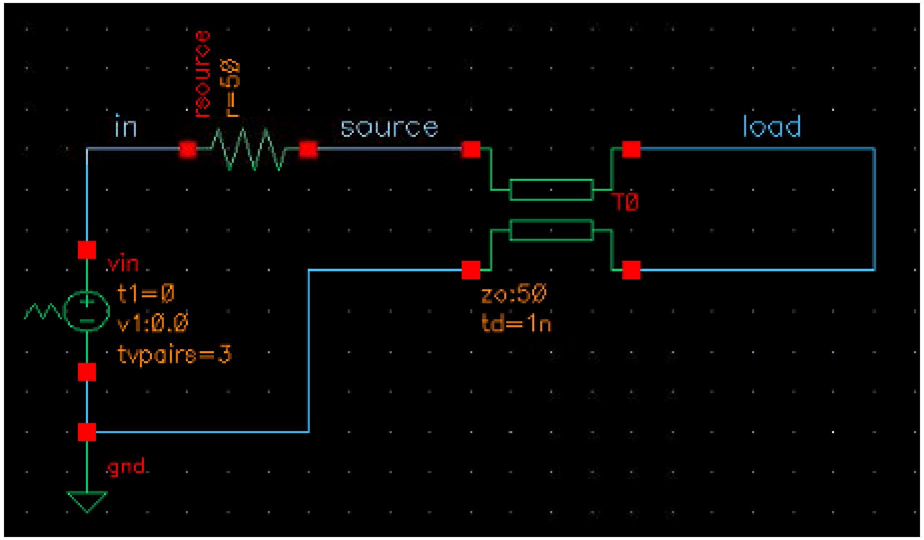
$$V_i = 1V\left(\frac{50}{50+50}\right) = 0.5V$$

$$k_{rT} = \frac{\infty - 50}{\infty + 50} = +1$$

$$k_{rS} = \frac{50-50}{50+50} = 0$$



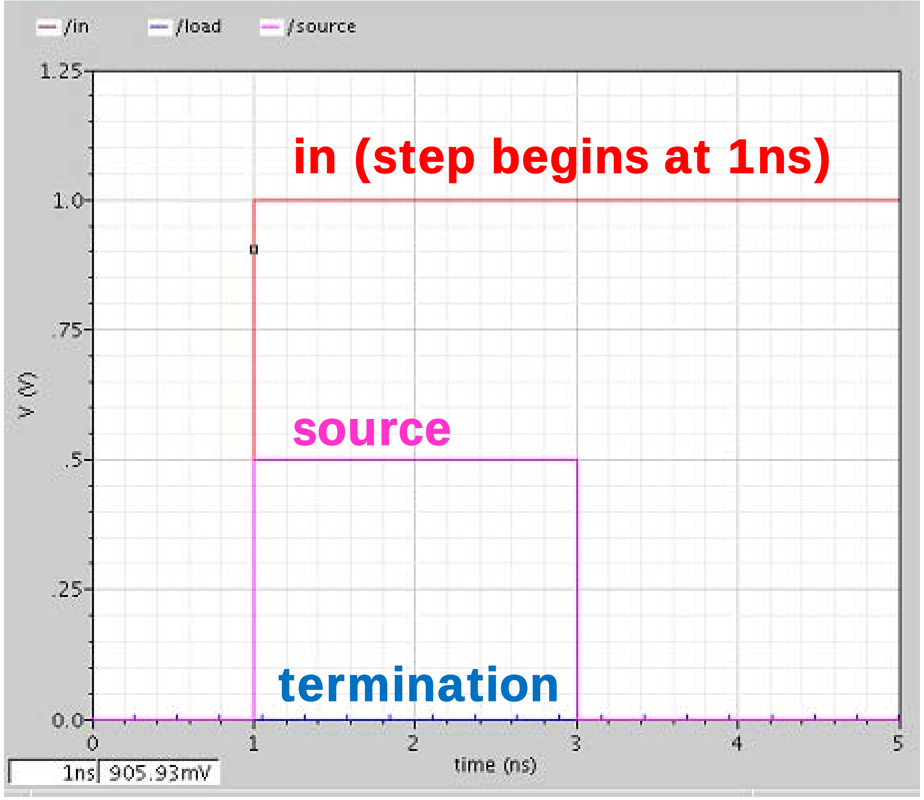
Termination Examples - Short



R_S = 50Ω

Z_0 = 50Ω, t_d = 1ns

R_T = 0Ω

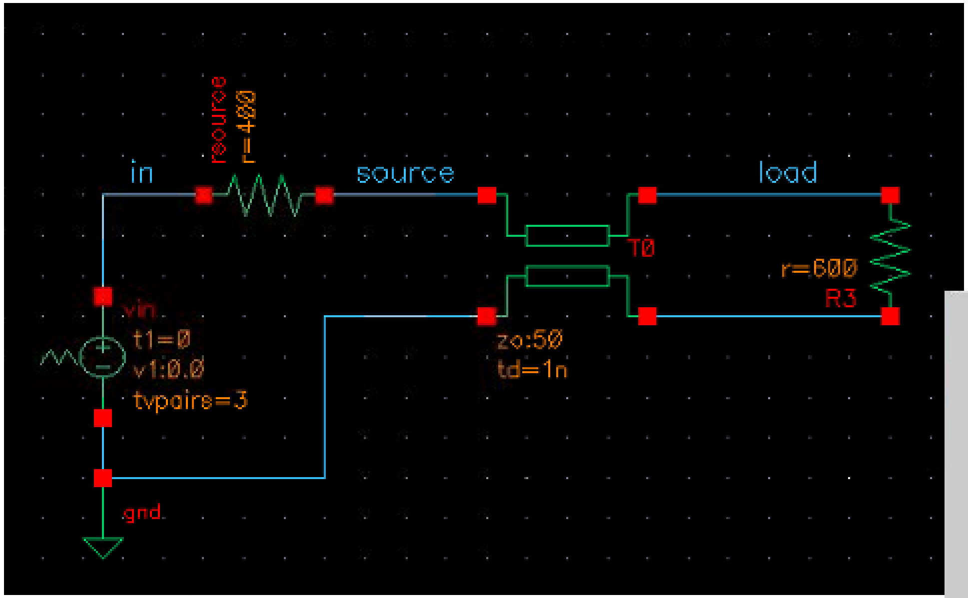


$$V_i = 1V\left(\frac{50}{50+50}\right) = 0.5V$$

$$k_{rT} = \frac{0-50}{0+50} = -1$$

$$k_{rS} = \frac{50-50}{50+50} = 0$$

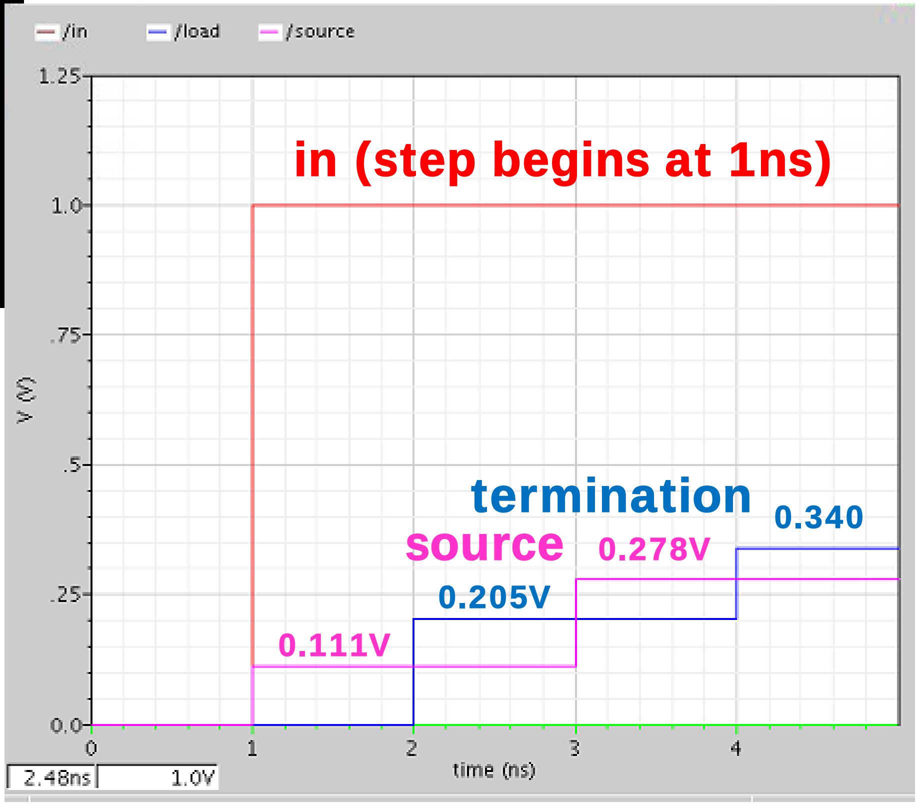
Arbitrary Termination Example



R_S = 400Ω

Z_0 = 50Ω, t_d = 1ns

R_T = 600Ω



$$V_i = 1V\left(\frac{50}{400+50}\right) = 0.111V$$

$$k_{rT} = \frac{600-50}{600+50} = 0.846$$

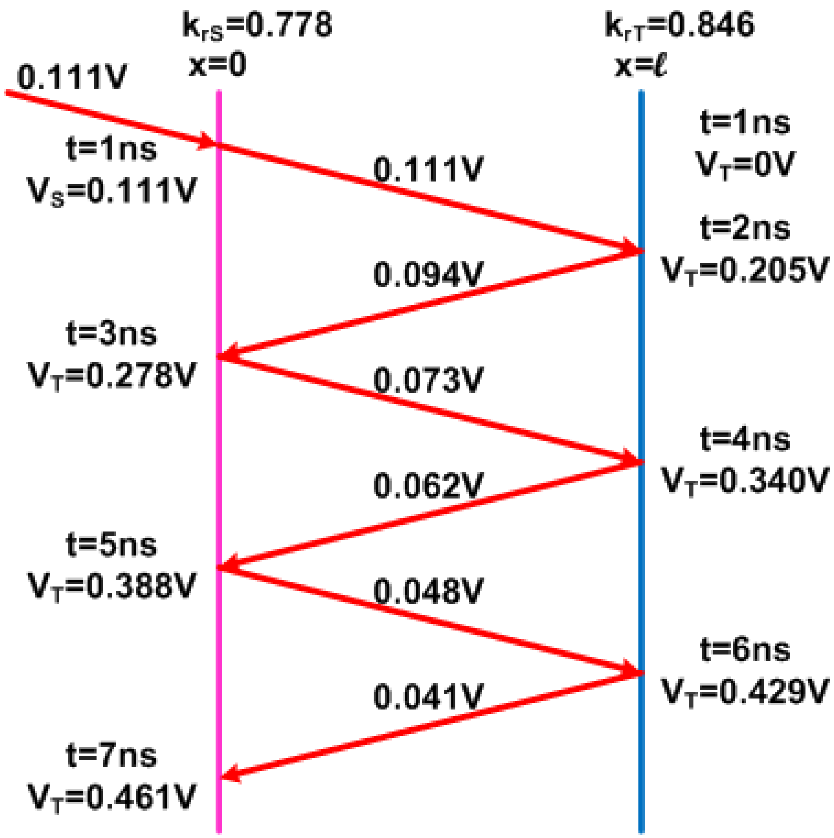
$$k_{rS} = \frac{400-50}{400+50} = 0.778$$

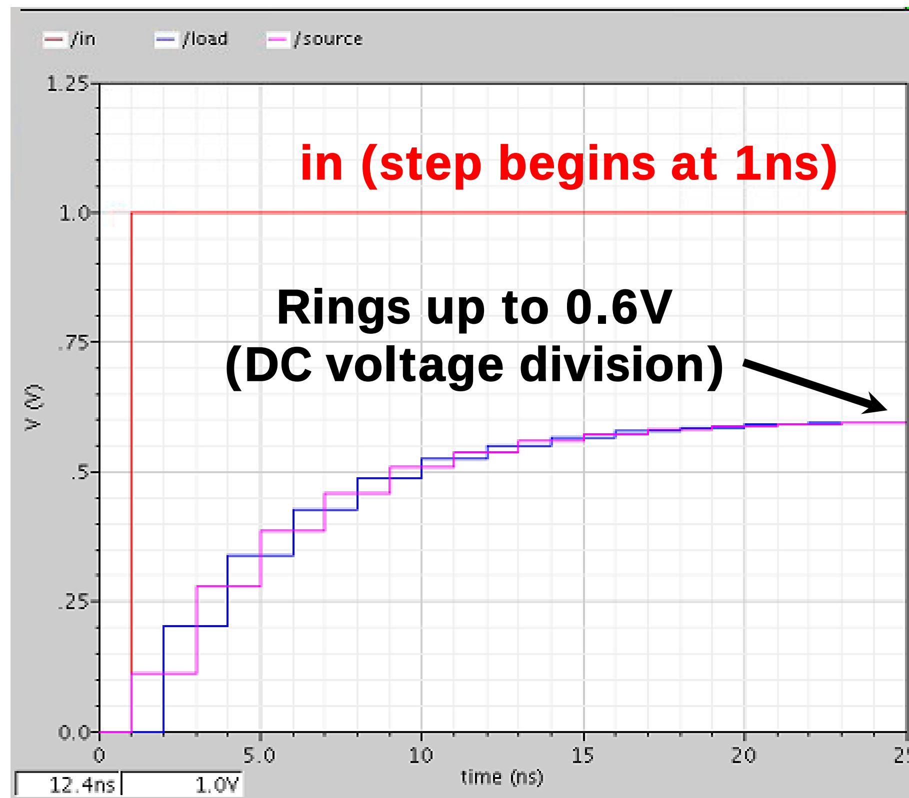
Lattice Diagram

$R_S = 400\Omega$

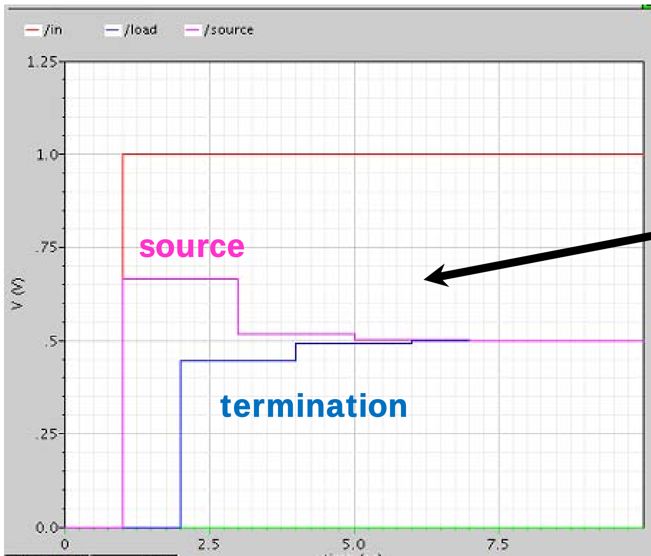
$Z_0 = 50\Omega$, $t_d = 1ns$

$R_T = 600\Omega$





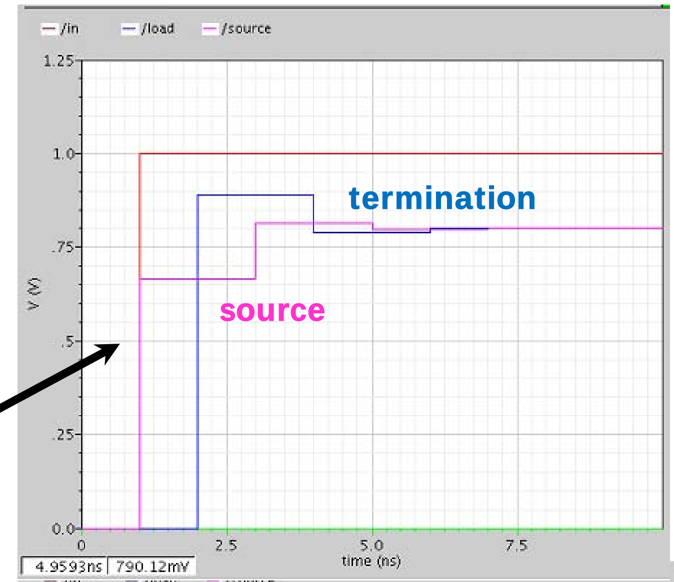
Termination Reflection Patterns



R_S = 25Ω, RT = 25Ω

kr_S & kr_T < 0

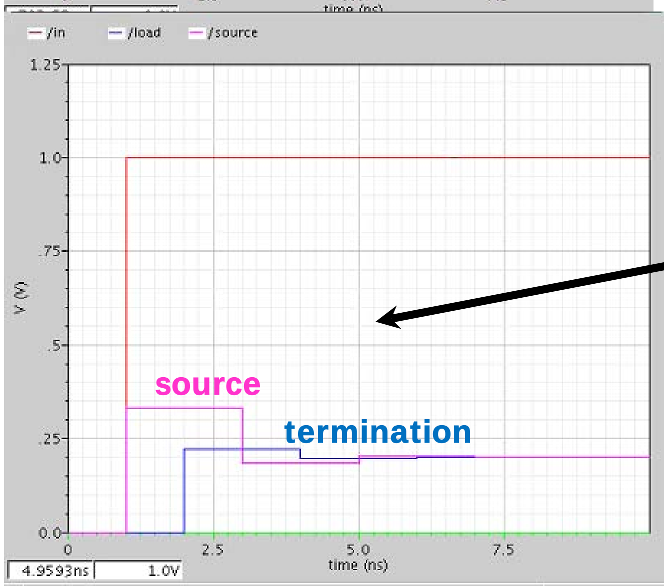
Voltages Converge



R_S = 25Ω, RT = 100Ω

kr_S < 0 & kr_T > 0

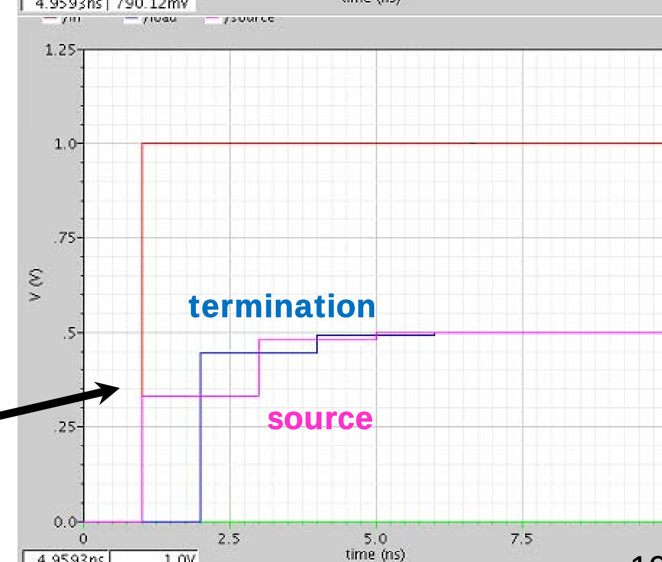
Voltages Oscillate



R_S = 100Ω, RT = 25Ω

kr_S > 0 & kr_T < 0

Voltages Oscillate



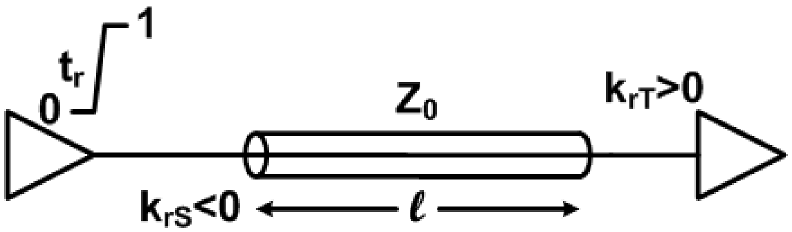
R_S = 100Ω, RT = 100Ω

kr_S > 0 & kr_T < 0

Voltages Ring Up

Termination Schemes

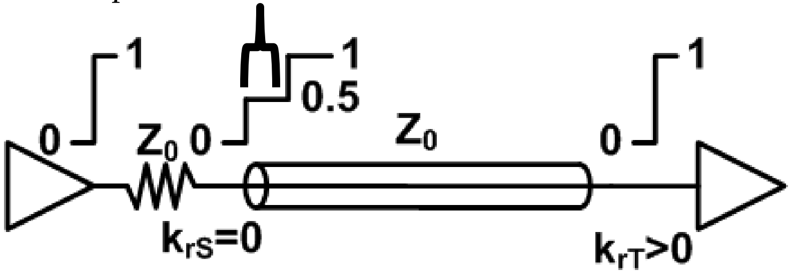
- No Termination
  - Little to absorb line energy
  - Can generate oscillating waveform
  - Line must be **very short** relative to signal transition time
    - n = 4 - 6
  - Limited off-chip use



$$t_r > nT_{round-trip} = 2nl\sqrt{LC}$$

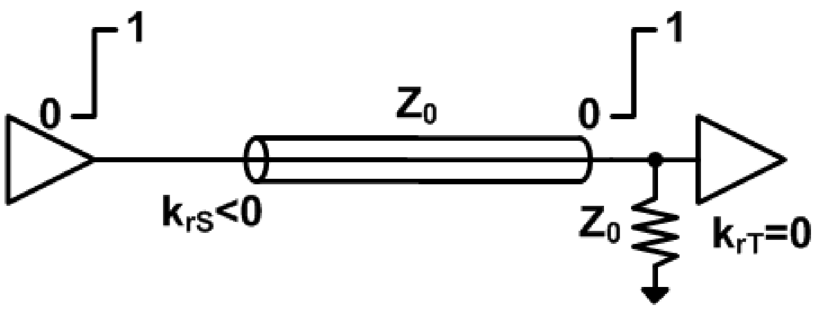
- Source Termination
  - Source output takes 2 steps up
  - Used in moderate speed point-to-point connections

$$t_{porch} \cong 2l\sqrt{LC}$$

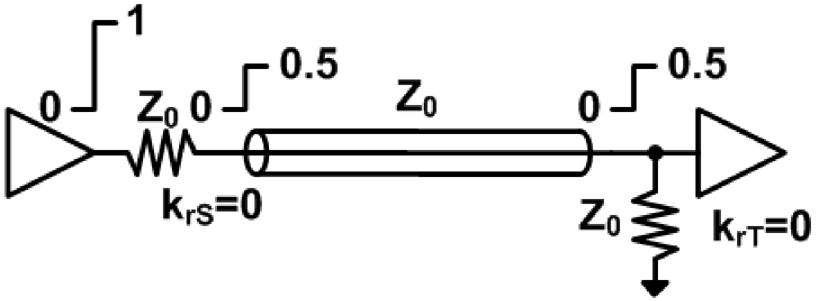


Termination Schemes

- Receiver Termination
  - No reflection from receiver
  - Watch out for intermediate impedance discontinuities
    - Little to absorb reflections at driver



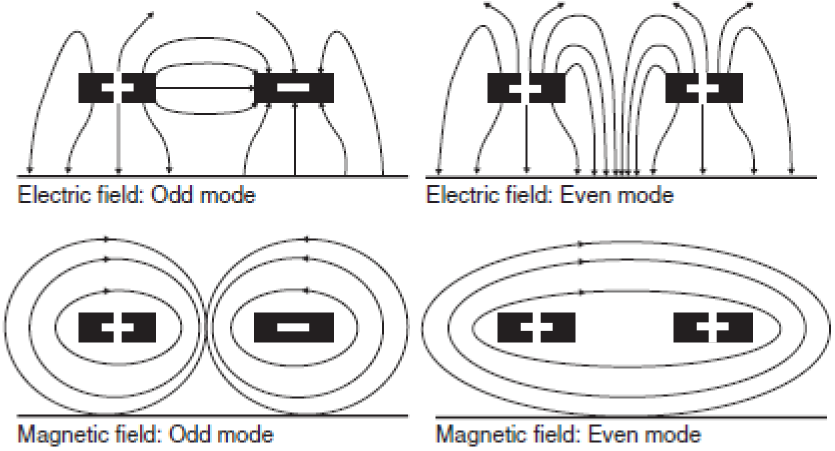
- Double Termination
  - Best configuration for min reflections
    - Reflections absorbed at both driver and receiver
  - Get half the swing relative to single termination
  - Most common termination scheme for high performance serial links



Differential Transmission Lines

- Differential signaling advantages
  - Self-referenced
  - Common-mode noise rejection
  - Increased signal swing
  - Reduced self-induced power-supply noise

- Requires 2x the number of signaling pins relative to single-ended signaling
  - But, smaller ratio of supply/signal (return) pins
  - Total pin overhead is typically 1.3-1.8x (vs 2x)



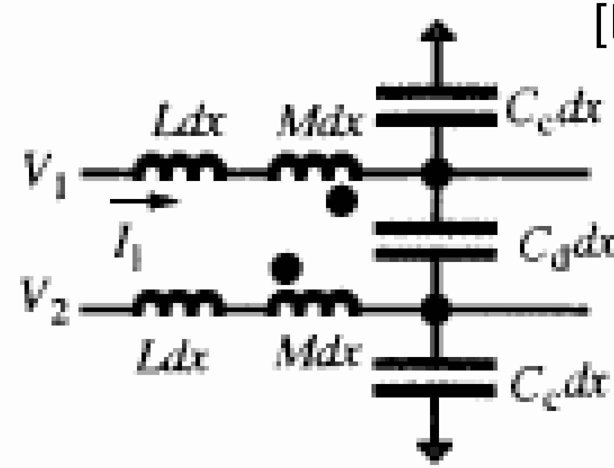
[**Hall**]

Balanced Transmission Lines

- Even (common) mode excitation
  - Effective C = C_C
  - Effective L = L + M
- Odd (differential) mode excitation
  - Effective C = $C_C + 2C_d$
  - Effective L = L – M

$$Z_{DIFF} = 2Z_{even}, \quad Z_{CM} = \frac{Z_{odd}}{2}$$

[Dally]

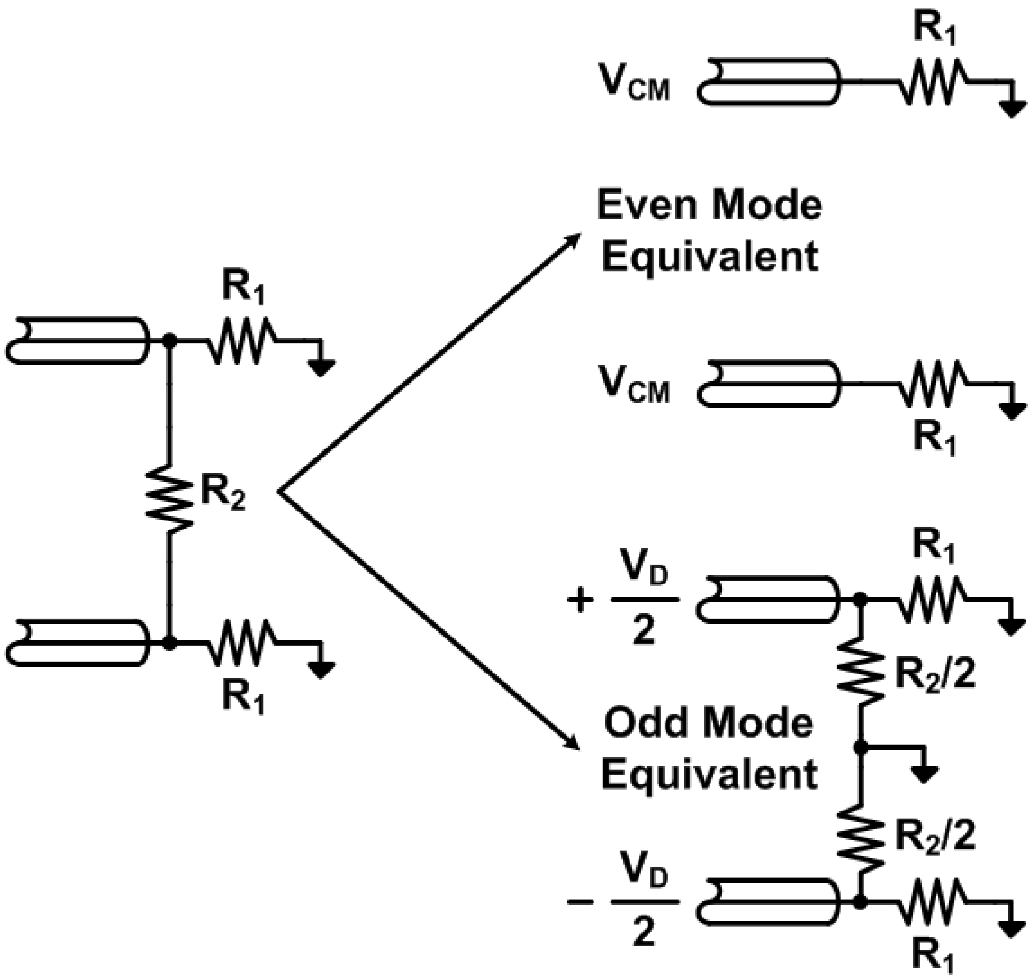


(a) Model of a Balanced Line

$$Z_{even} = \left(\frac{L+M}{C_c}\right)^{1/2}$$

$$Z_{odd} = \left(\frac{L-M}{C_c + 2C_d}\right)^{1/2}$$

PI-Termination

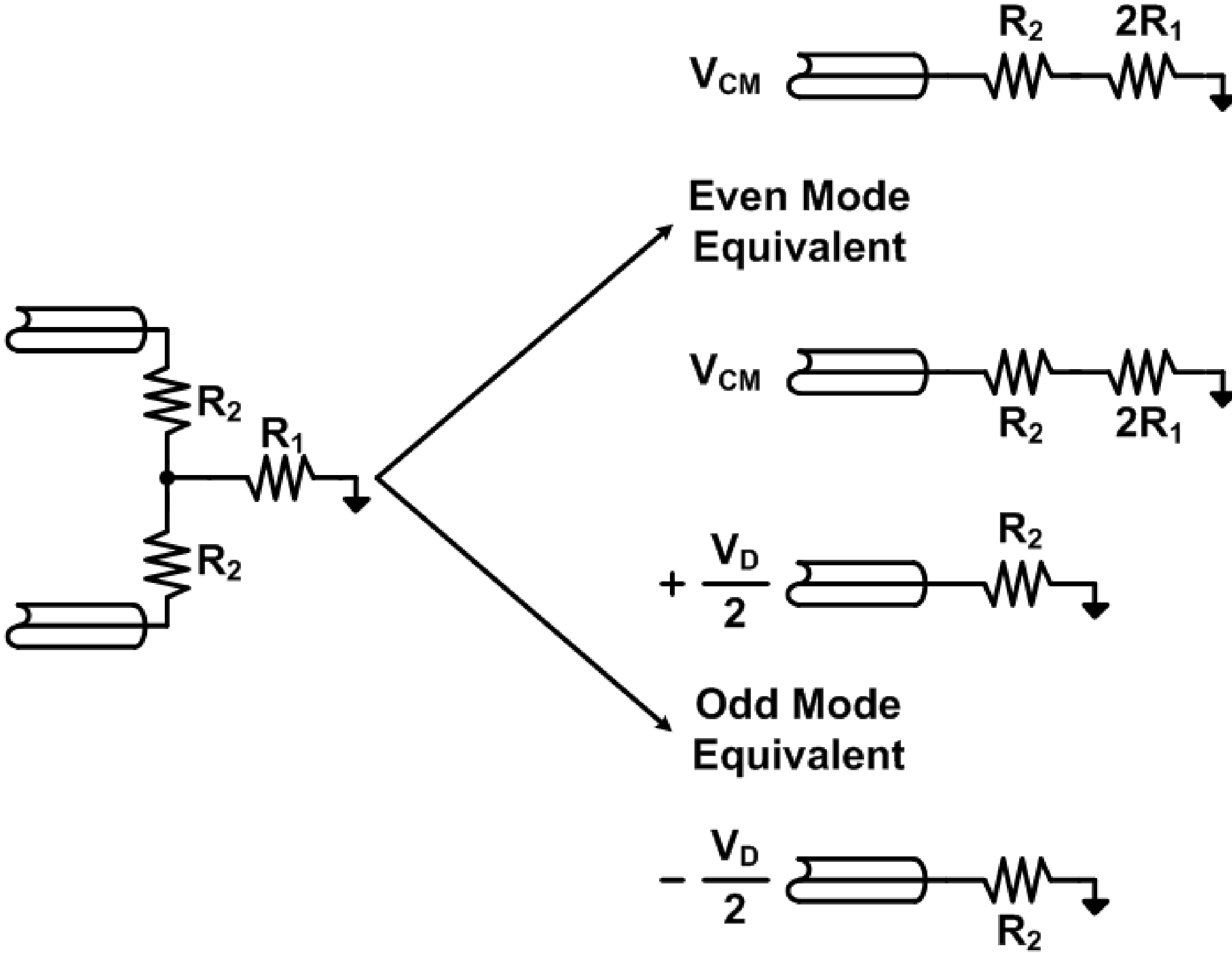


$$Z_{even} = R_1$$

$$Z_{odd} = R_1 \parallel R_2/2 = Z_{even} \parallel R_2/2$$

$$R_2 = 2\left(\frac{Z_{odd} Z_{even}}{Z_{even} - Z_{odd}}\right)$$

T-Termination



$$Z_{odd} = R_2 + 2R_1$$

$$Z_{odd} = R_2$$

$$R_1 = \frac{1}{2}\left(Z_{even} - Z_{odd}\right)$$

Next Time

- Channel modeling
  - Time domain reflectometer (TDR)
  - Network analysis