ECE 124a/256c
Transmission Lines as Interconnect

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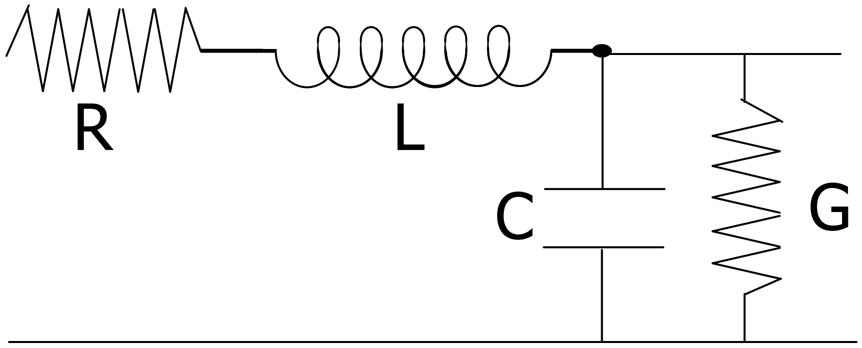
Displays from Bakoglu, Addison-Wesley

Interconnection

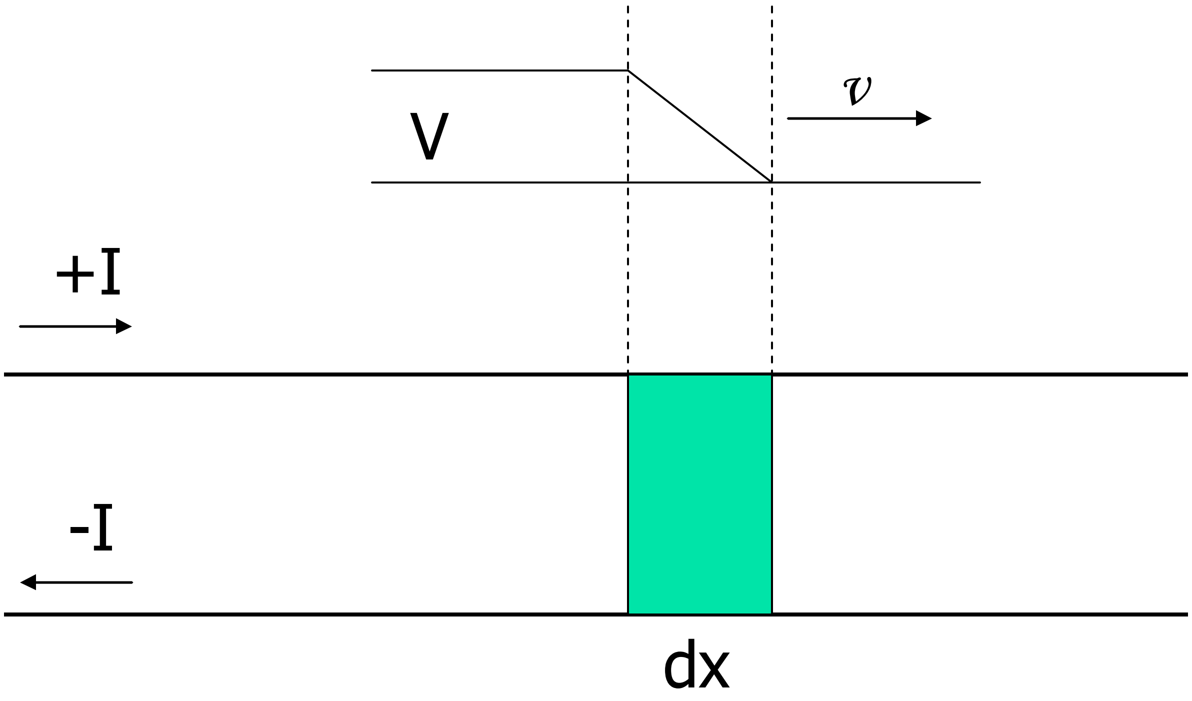
- Circuit rise/fall times approach or exceed speed of light delay through interconnect
- Can no longer model wires as C or RC circuits
- Wire Inductance plays a substantial part
- Speed of light: 1ft/nS = 300um/pS

Fundamentals

- L dI/dt = V is significant to other effects
- Inductance: limit on the rate of change of the current
- E.g. Larger driver will not cause larger current to flow initially



Lossless Tranmission R=G=0



- Step of V volts propagating with velocity *v*
- Initially no current flows – after step passes, current of +I
- After Step Voltage V exists between the wires

Lossless Tranmission R=G=0

- Maxwell's equation: $\Phi = \iint_S B \bullet dS$
- B is field, dS is the normal vector to the surface
- Φ is the flux
- For closed surface Flux and current are proportional

$$L = \frac{\Phi}{I}$$

Lossless Tranmission R=G=0

- For Transmission Line I and Φ are defined per unit length
- At front of wave: $d\Phi = d(IL) = ILdx$
- Faraday's Law: V = dΦ/dt = IL dx/dt = IL*v*
- Voltage in line is across a capacitance Q=CV
- I must be: $I = \frac{dQ}{dt} = \frac{d(CV)}{dt} = CV\frac{dx}{dt} = CVv$
- Combining, we get: $v = \frac{1}{\sqrt{LC}}$
- Also: $Z = \frac{V}{I} = \sqrt{\frac{L}{C}}$

Units

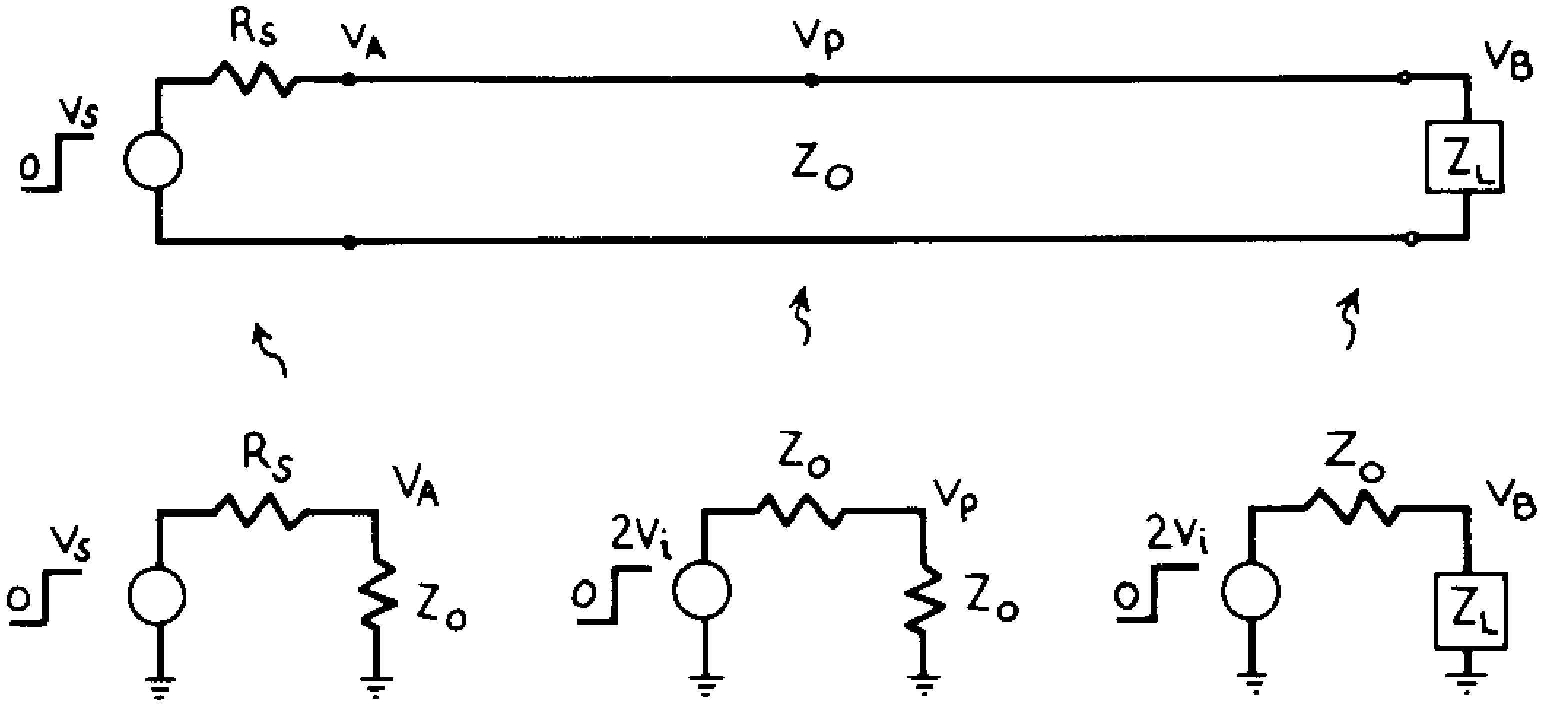
- The previous derivation assumed $\varepsilon = \mu = 1$
- In MKS units: $v = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{c}{\sqrt{\varepsilon_r \mu_r}}$
- c is the speed of light = 29.972cm/nS
- For typical IC materials $\mu_r = 1$
- So: $Z_0 = \frac{\sqrt{\varepsilon_r}}{cC}$ $L = \frac{\varepsilon_r}{c^2 C}$

Typical Lines

- We can characterize a lossless line by its Capacitance per unit length and its dielectric constant.

Material	Dielectric Constant	Propagation Velocity
Polymide	2.5-3.5	16-19 cm/nS
SiO_2	3.9	15
Epoxy PC	5.0	13
Alumina	9.5	10

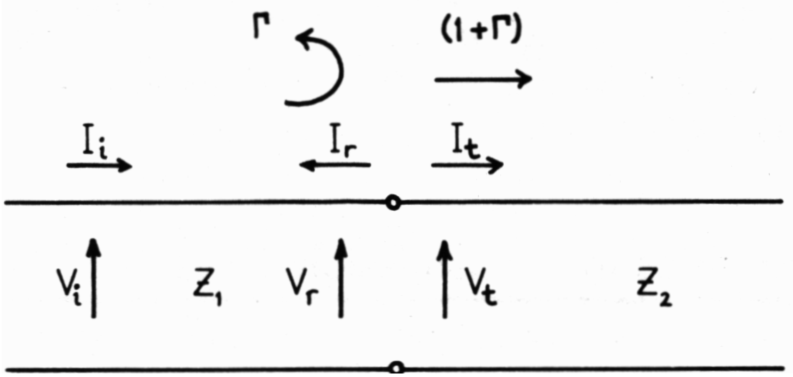
Circuit Models



Circuit Models II

- Driver End
  - TM modeled by resistor of value Z
  - Input voltage is function of driver and line impedance: $V_{line} = \frac{Z}{R_S + Z} V_S$
- Inside Line
  - Drive modeled by Step of $2V_i$ with source resistance Z
  - Remaining TM as above (resistor)
- Load End
  - Drive modeled by Step of $2V_i$ with source resistance Z
  - Voltage on load of impedance Z_L: $V_L = \frac{Z_L}{Z + Z_L} 2V_i$

Discontinuity in the line (Impedance)

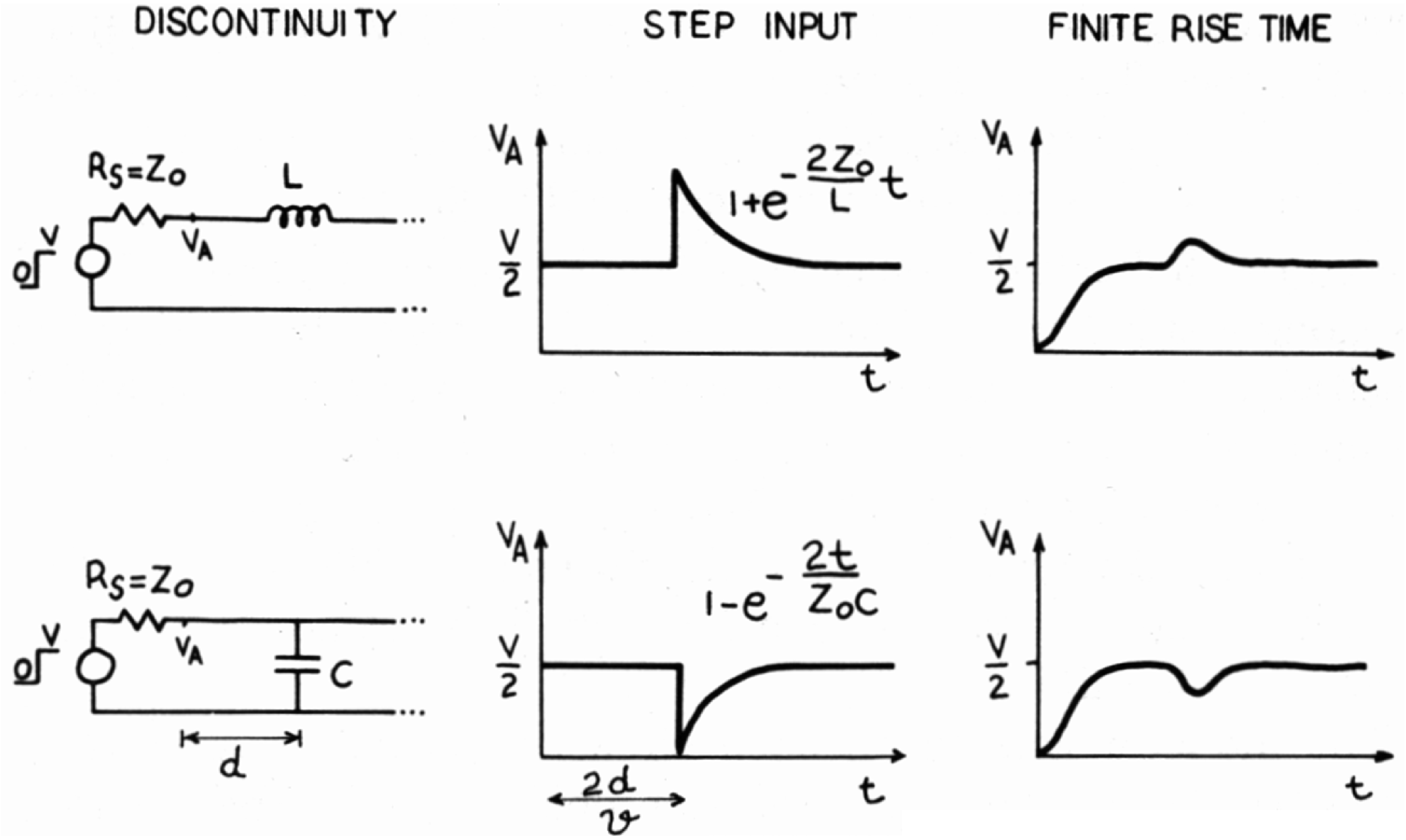


- Abrupt interface of 2 TM-lines
  - Incident wave: $V_i = I_i Z_1$ Reflected Wave: $V_r = I_r Z_1$
  - Transmitted Wave: $V_t = I_t Z_2$
  - Conservation of charge: $I_i = I_r + I_t$
  - Voltages across interface: $V_i + V_r = V_t$
  - We have: $\frac{V_i}{Z_1} = \frac{V_r}{Z_1} + \frac{V_t}{Z_2}$ $V_r = V_i \frac{Z_2 - Z_1}{Z_2 + Z_1}$ $V_t = V_i \frac{2Z_2}{Z_2 + Z_1}$

Reflection/Transmission Coefficients

- The Coefficient of Reflection Γ = V_r/V_i $= \dfrac{Z_2 - Z_1}{Z_2 + Z_1}$
- V_i incident from Z_1 into Z_2 has a reflection amplitude Γv_i
- Similarly, the Transmitted Amplitude = $1+\Gamma$ $= \dfrac{2Z_2}{Z_1 + Z_2}$

Inductive and Capacitive Discontinuities



Typical Package Pins

Package	Capacitance (pF)	Inductance (nH)
40 pin DIP (plastic)	3.5	28
40 pin DIP (Ceramic)	7	20
68 pin PLCC	2	7
68 pin PGA	2	7
256 pin PGA (with gnd plane)	5	15
Wire bond (per mm)	1	1
Solder Bump	0.5	0.5

Discontinuity Amplitude

- The Amplitude of discontinuity
  - Strength of discontinuity
  - Rise/Fall time of Impinging Wave
- To first order Magnitude is:
- Inductive: $V_{peak} = \frac{L_D V_i}{2Zt_r}$ Capacitive: $V_{peak} = -\frac{C_D Z V_i}{2t_r}$

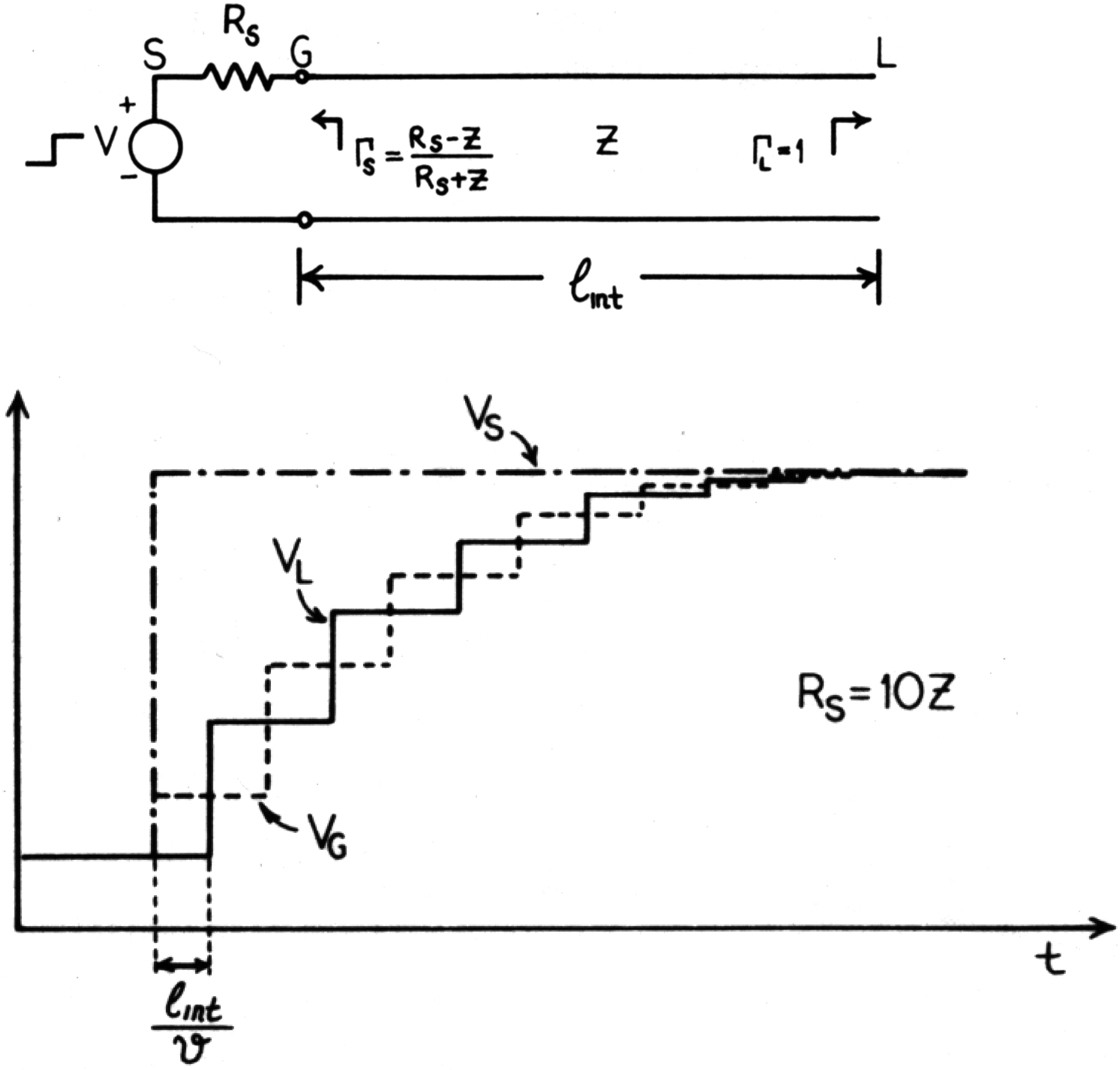
Critical Length (TM-analysis?)

- TM-line effects significant if: $t_r < 2.5\ t_f$
- Flight time tf = d/v $= \frac{d\sqrt{\varepsilon_r}}{c}$

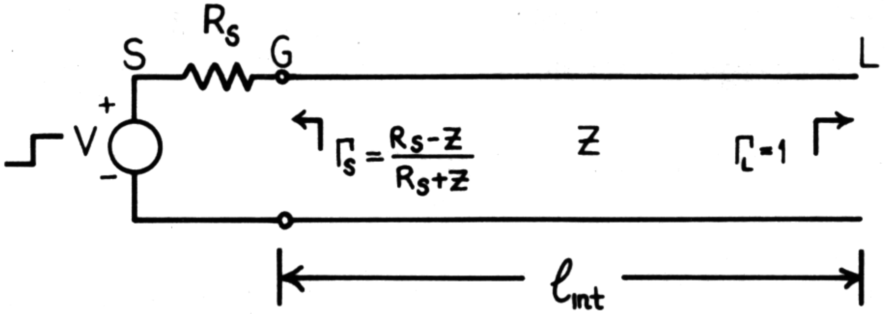
Rise Time (pS)	**Critical Length (15 cm/nS)**
25	150μm
75	0.45
200	1.3
500	3.0
1000	6.0
2000	12.0

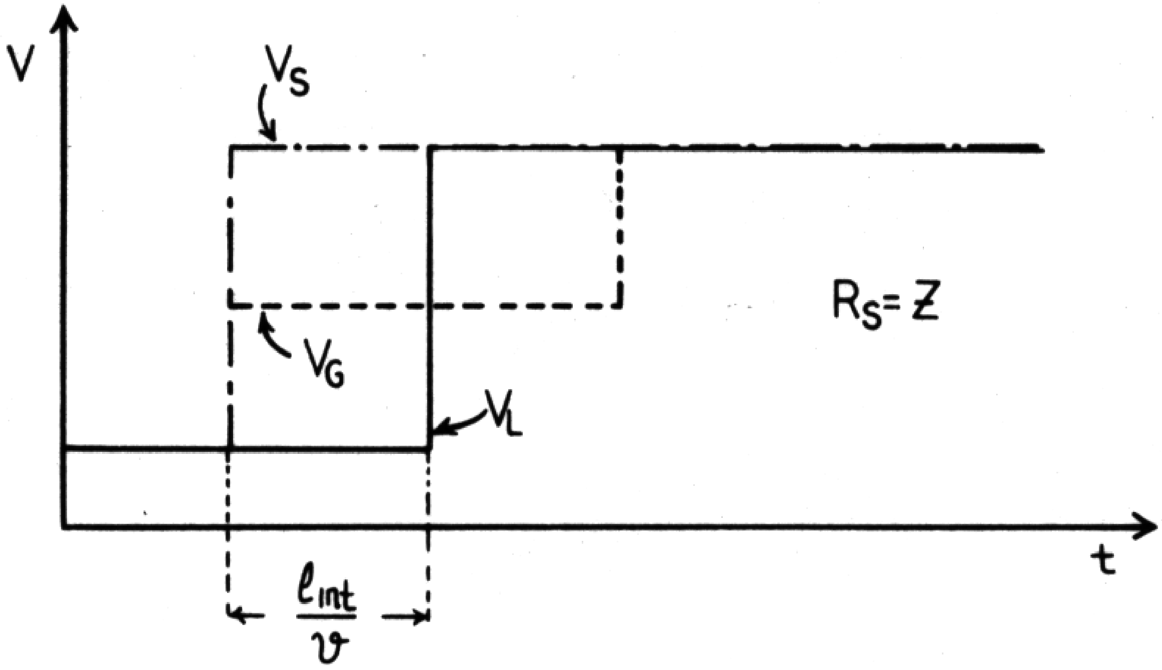
Technology	**On-Chip Rise time**	**Off-Chip Rise time**
CMOS (0.1)	18-70pS	200-2000pS
GaAs/ SiGe/ (ECL)	2-50pS	8-300pS

Un-terminated Line R_s = 10Z

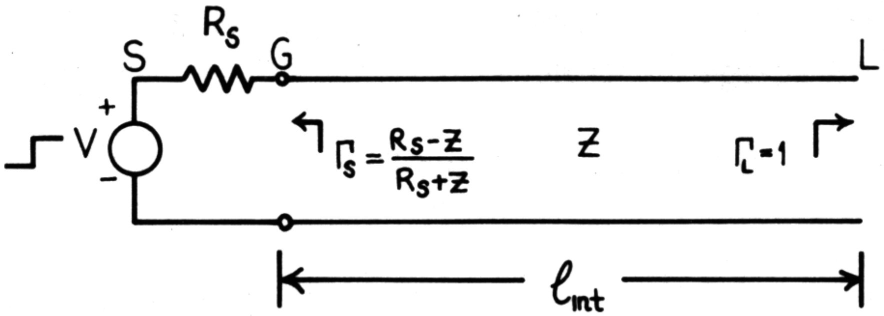


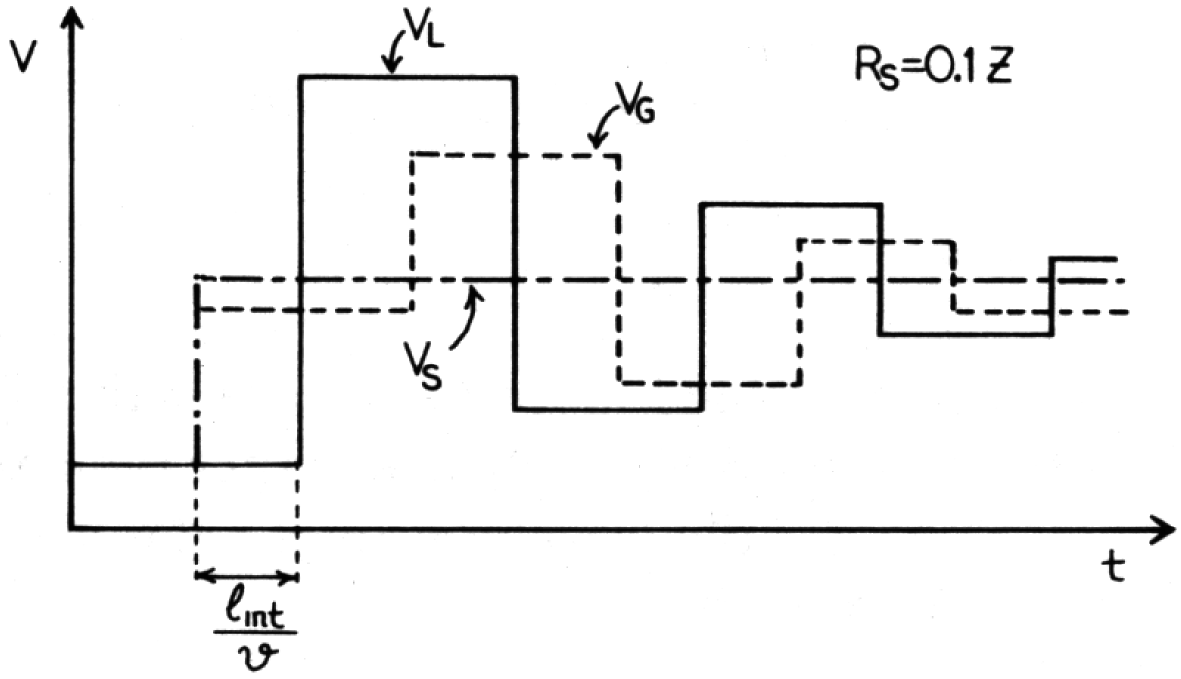
Un-terminated Line $R_s = Z$





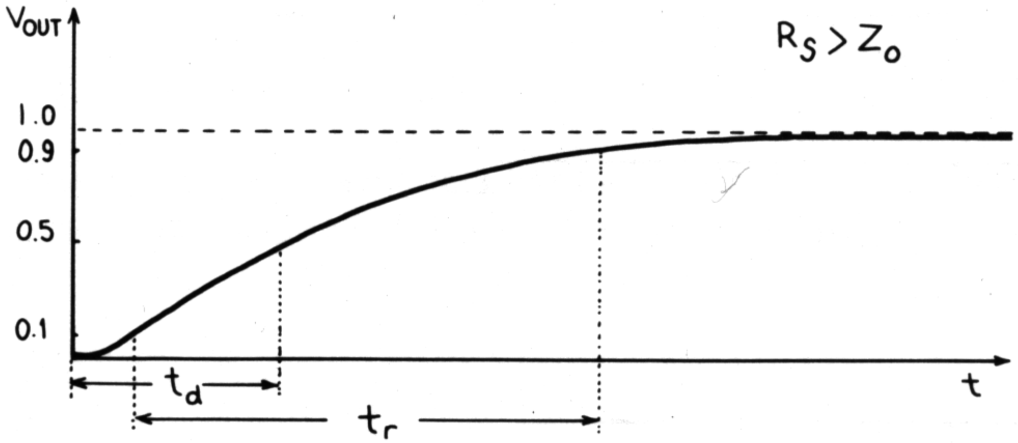
Un-terminated Line $R_s = 0.1Z$

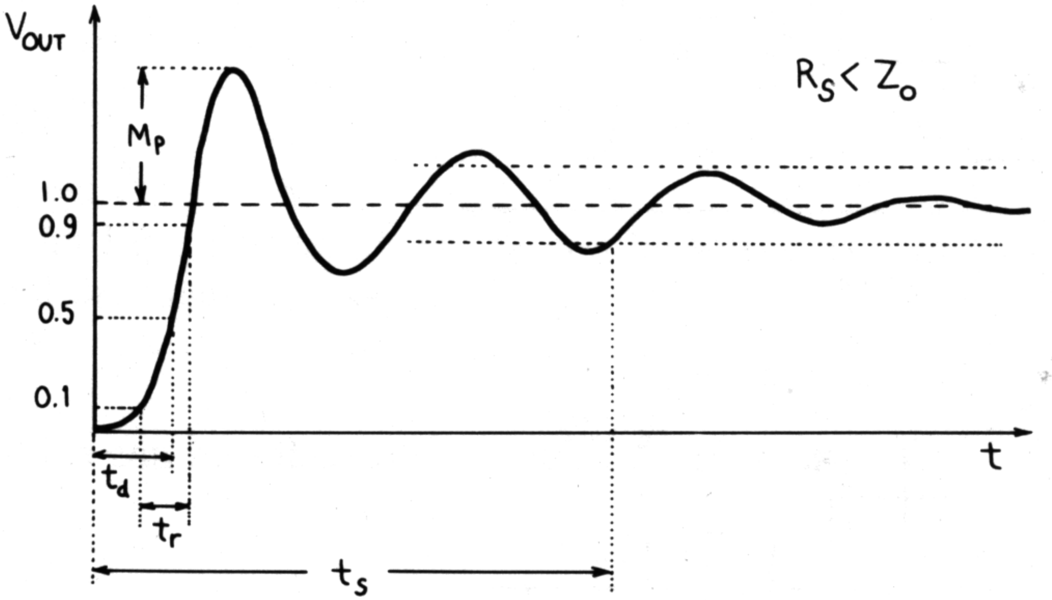




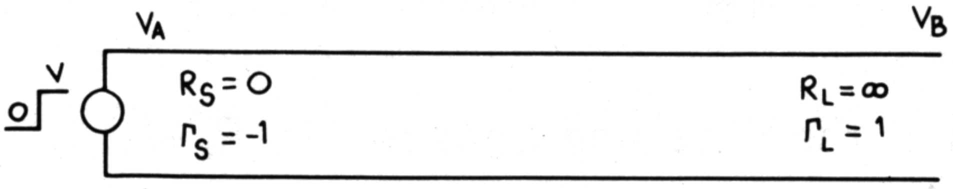
Unterminated Line (finite rise time)

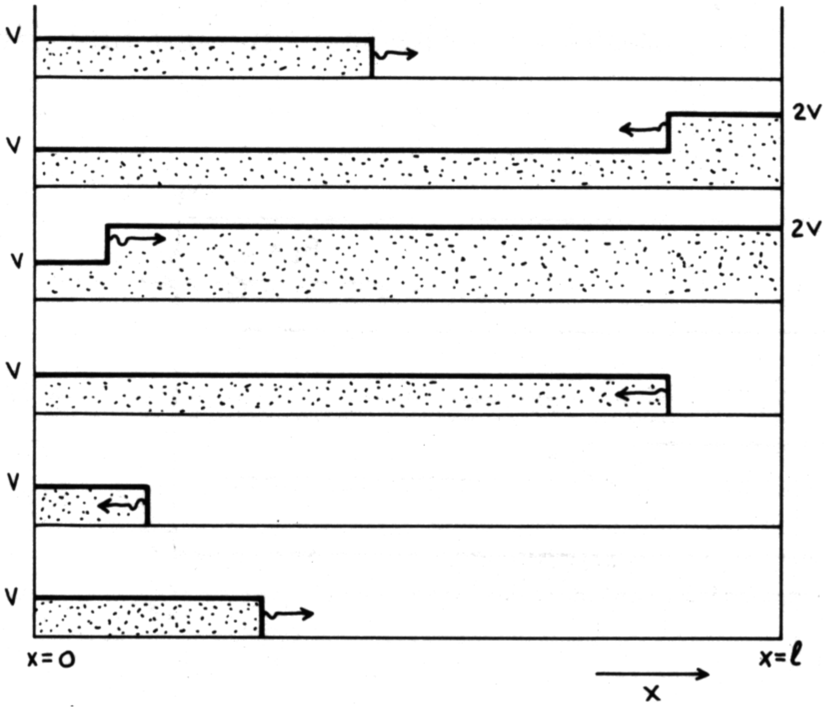
- Rise Time **Never** Zero
- For
- $R_s > Z_o$, $t_r > t_f$
  - Exponential Rise
- Rs<Z0, $t_r \approx t_f = l / v$
  - "Ringing"
  - Settling time can be much longer than t_f.

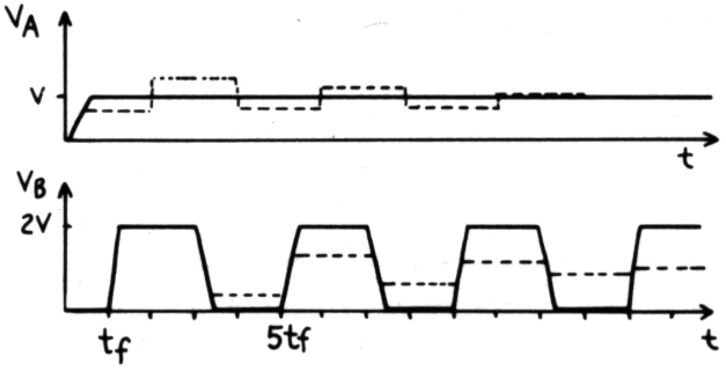




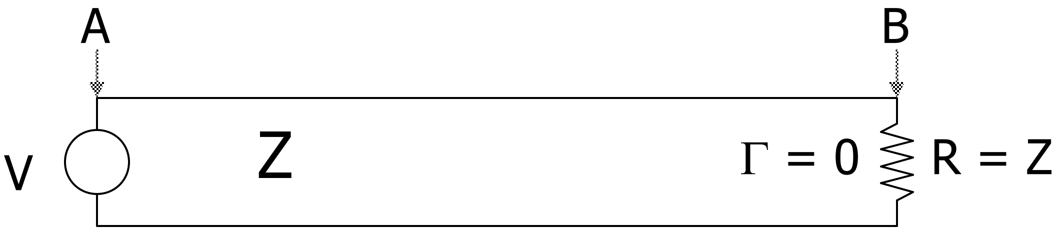
Line Termination (None)

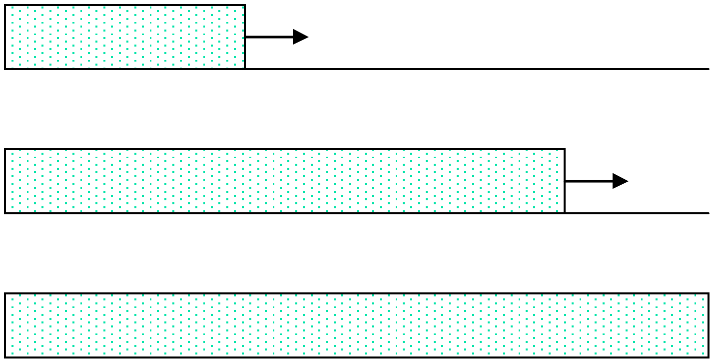


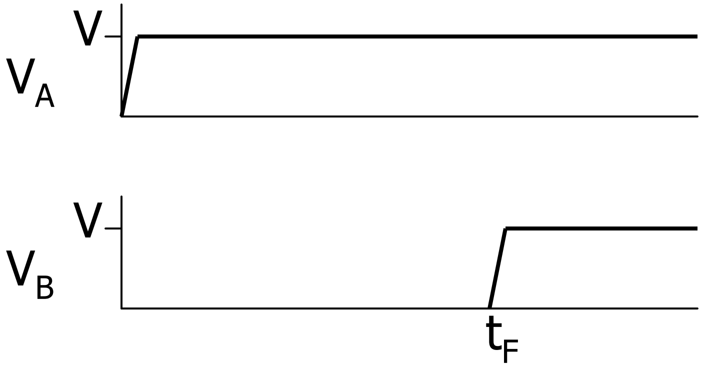




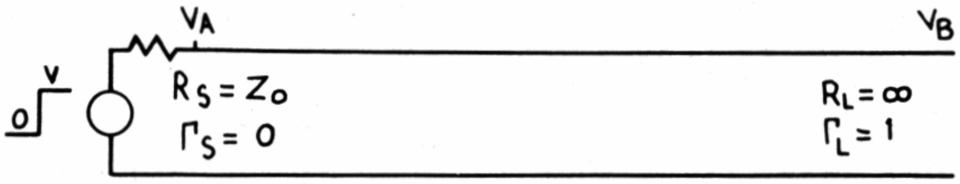
Line Termination (End)

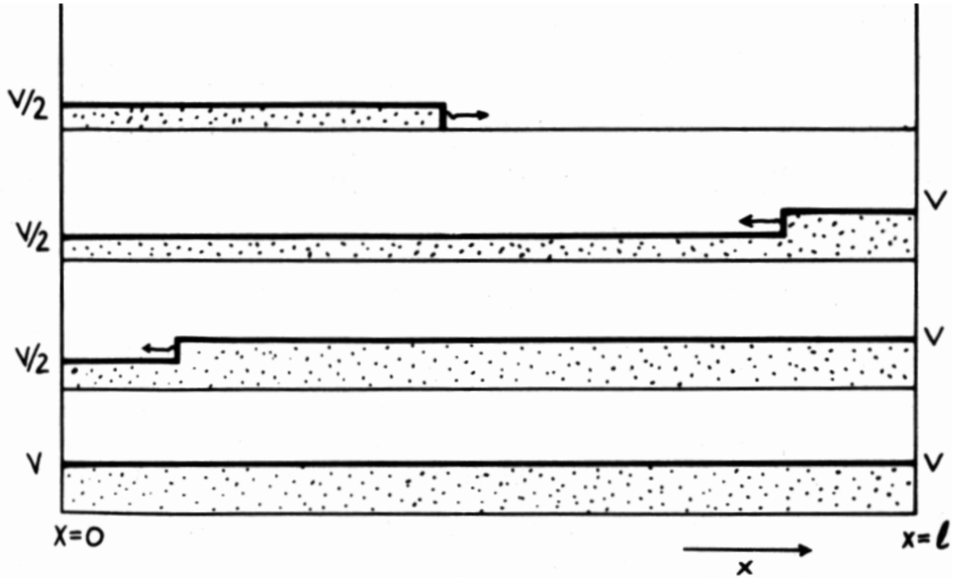


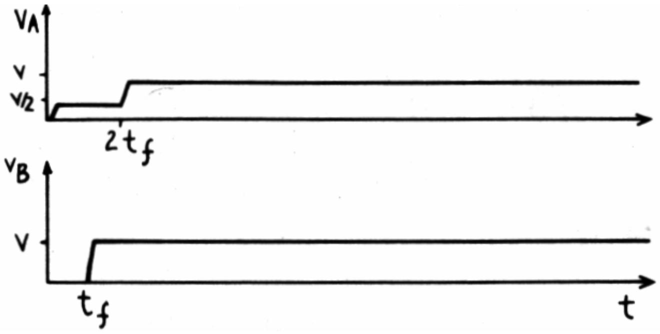




Line Termination: (Source)





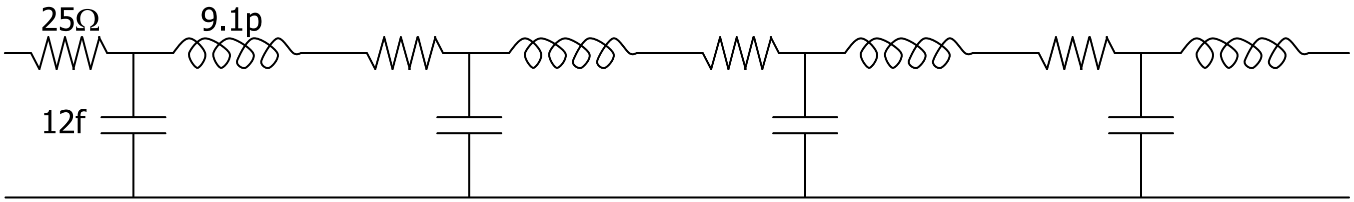


Piece-Wise Modeling

- Create a circuit model for short section of line
  - Length < rise-time/3 at local propagation velocity
  - E.G. 50μm for 25pS on chip, 150nm wide, 350nm tall
- Assume sea of dielectric and perfect ground plane (this time)
  - C = 2.4pF/cm = 240fF/mm = 12fF/50μm
  - L = $3.9/c^2C$ = 1.81nH/cm = 0.181nH/mm = 9.1pH/50μm
  - R = ρ L/(W H) =

0.005cm*2.67μΩcm/(0.000015cm*0.000035cm) = 25Ω/50μm

200μm:



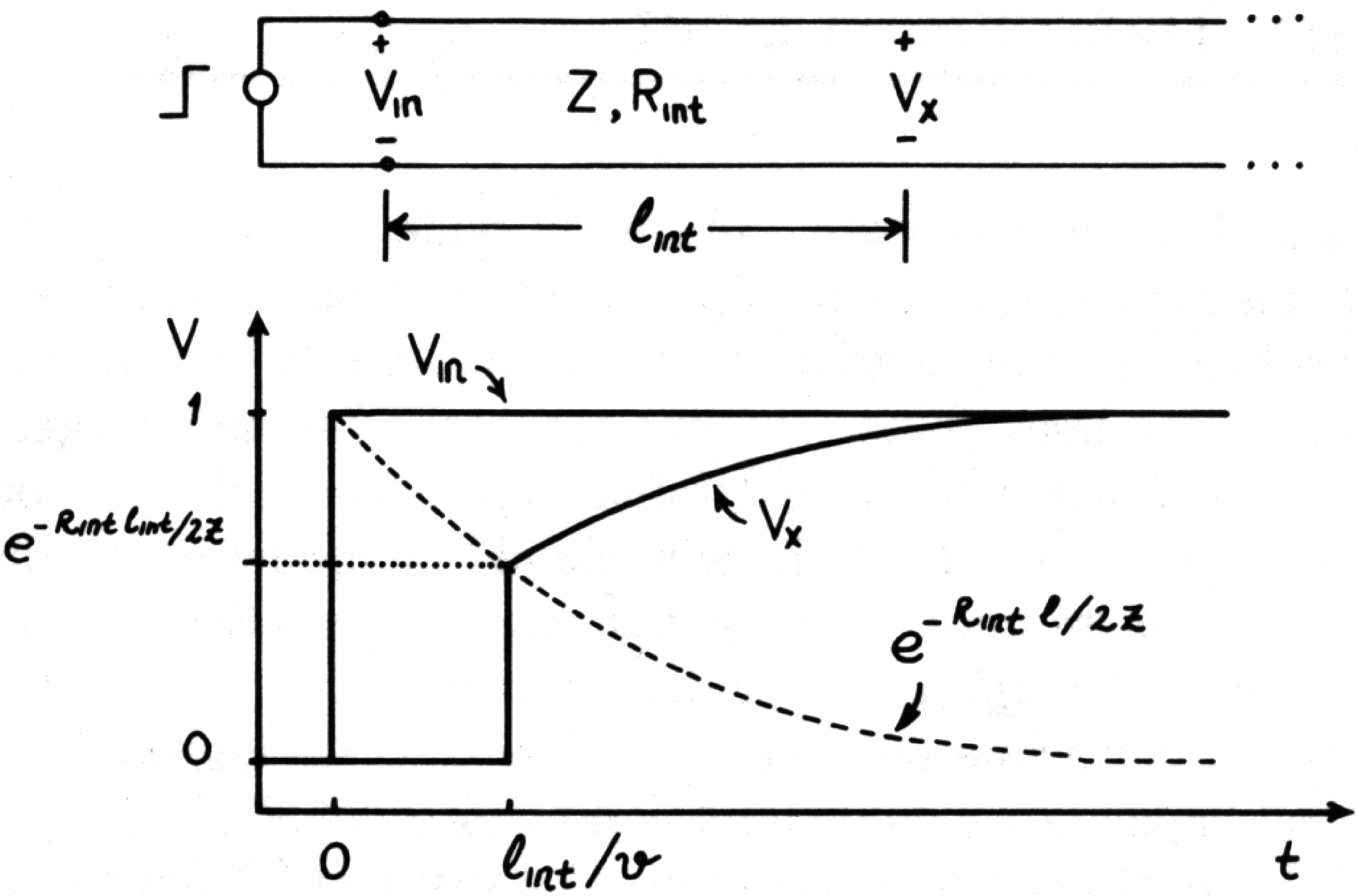
Lossy Transmission

- Attenuation of Signal
  - Resistive Loss, Skin-Effect Loss, Dielectric Loss
- For uniform line with constant R, L, C, G per length:

$$\frac{V(x=l)}{V(x=0)}=e^{-\alpha l}$$

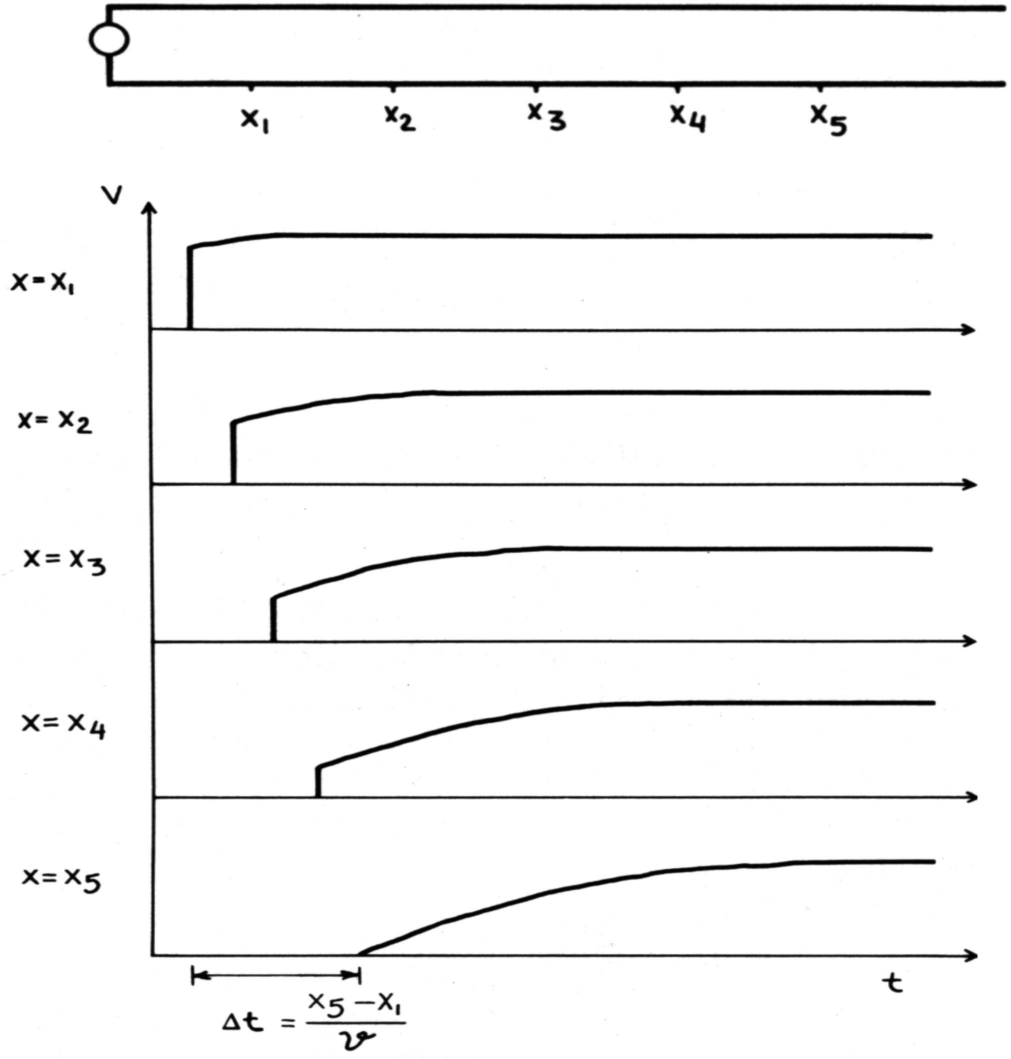
$$\alpha=\alpha_R+\alpha_G=\frac{R}{2}\sqrt{\frac{C}{L}}+\frac{G}{2}\sqrt{\frac{L}{C}}=\frac{R}{2Z_0}+\frac{GZ_0}{2}$$

Conductor Loss (Resistance)



Conductor Loss (step input)

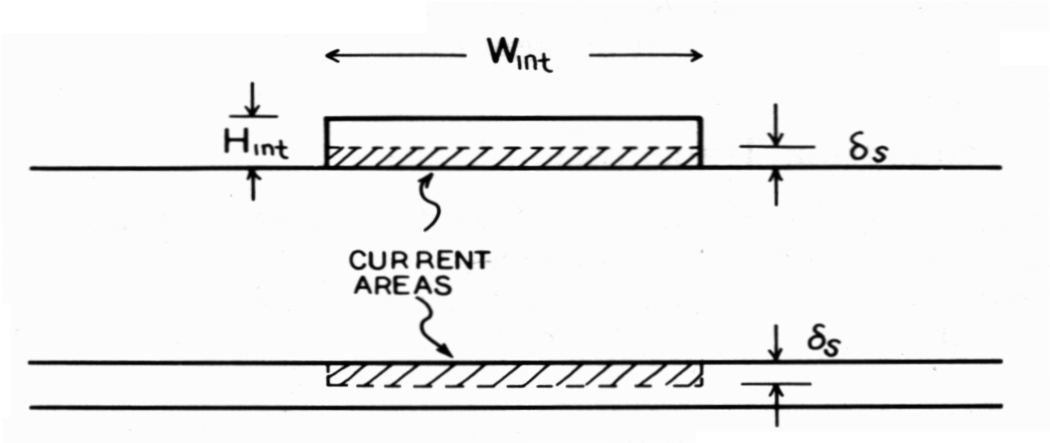
- Initial step declines exponentially as $R\ell/2Z$
- Closely approximates RC dominated line when $R\ell >> 2Z$
- Beyond this point, line is diffusive
- For large resistance, we cannot ignore the backward distrbitued reflection



Conductor Loss (Skin Effect)

- An ideal conductor would exclude any electric or magnetic field change – most have finite resistance
- The depth of the field penetration is mediated by the frequency of the wave – at higher frequencies, less of the conductor is available for conducting the current
- For resistivity ρ (Ωcm), frequency f (Hz) the depth is: $\delta = \sqrt{\frac{\rho}{\pi\mu f}}$
- A conductor thickness t > 2δ will not have significantly lower loss
- For Al at 1GHz skin depth is 2.8μm

Skin Effect in stripline (circuit board)



- Resistive attenuation: $\alpha = R/2Z = \dfrac{\rho}{2WHZ}$
- At high frequencies: $\alpha = \dfrac{2R_{skin}}{2Z} = \dfrac{\rho}{W\delta Z} = \dfrac{\sqrt{\pi\mu f\rho}}{WZ}$

Dielectric Loss

- Material Loss tangent: $\tan\delta_D = \dfrac{G}{\omega C} = \dfrac{\sigma_D}{\omega\varepsilon_r}$
- Attenuation: $\alpha_D = \dfrac{GZ}{2}$

$$= \pi f C \tan\delta_D \sqrt{L/C}$$

$$= \pi f \tan\delta_D \sqrt{LC}$$

$$= \pi / c\sqrt{\varepsilon_r} \tan\delta_D$$