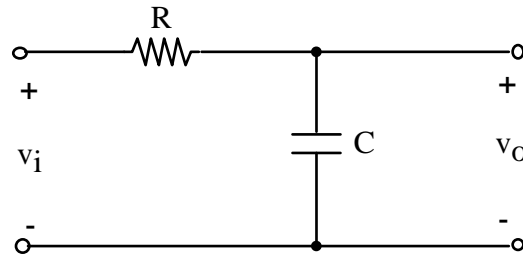


# Frequency Dependence of Interconnections

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# RC Network



A is the steady-state gain of the network;

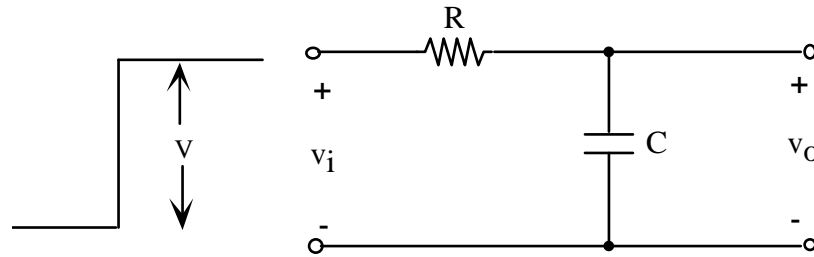
$$|A| = \frac{1}{\sqrt{1 + (f / f_2)^2}}$$

$$f_2 = \frac{1}{2\pi RC}$$

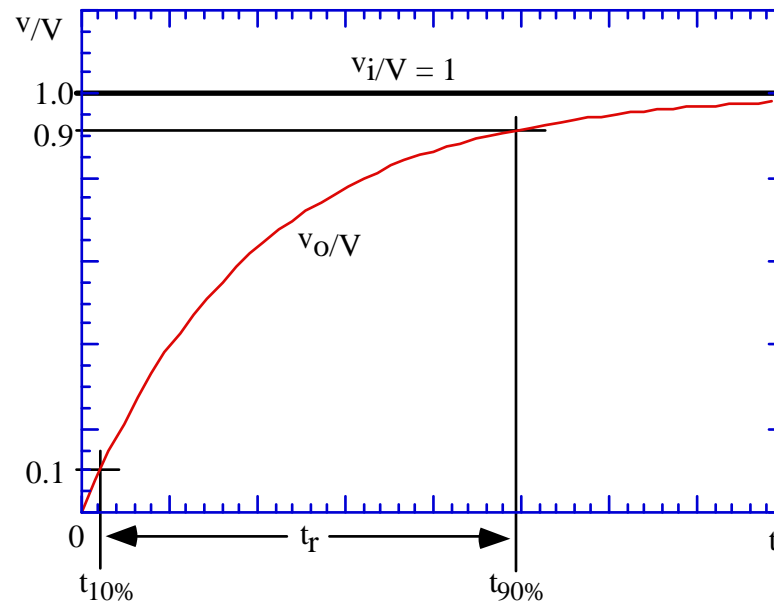
$$A = \frac{v_o(f)}{v_i(f)}$$

The gain falls to **0.707** of its low-frequency value at the frequency  $f_2$ .  $f_2$  is the *upper 3-dB frequency* or the **3-dB bandwidth** of the RC network.

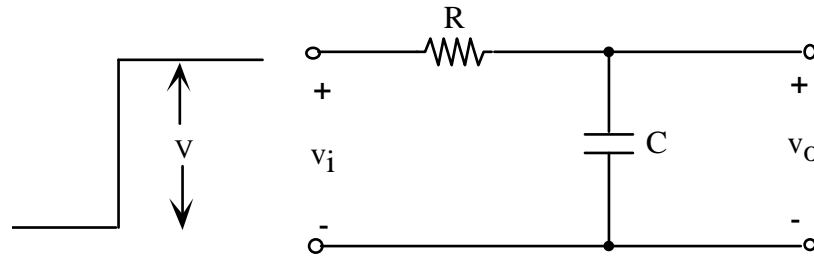
# RC Network



$$v_o = V(1 - e^{-t/RC})$$



# RC Network



Rise time :  $t_r = t_{90\%} - t_{10\%}$

$$t_r = 2.2RC = \frac{2.2}{2\pi f_2} = \frac{0.35}{f_2}$$

**Rule of thumb: A 1-ns pulse requires a circuit with a 3-dB bandwidth of the order of 2 GHz.**

# Frequency Dependence of Lumped Circuit Models

- At higher frequencies, a lumped circuit model is no longer accurate for interconnects and one must use a distributed model
- Transition frequency depends on the dimensions and relative magnitude of the interconnect parameters.

$$f \approx \frac{0.3 \times 10^9}{10d\sqrt{\epsilon_r}}$$

$$t_r \approx \frac{0.35}{f}$$

# Lumped Circuit or Transmission Line?

- **Determine frequency or bandwidth of signal**
  - RF/Microwave:  $f =$  operating frequency
  - Digital:  $f = 0.35/t_r$
- **Determine the propagation velocity and wavelength**
  - Material medium  $v = c/(\epsilon_r)^{1/2}$
  - Obtain wavelength  $\lambda = v/f$
- **Compare wavelength with feature size**
  - If  $\lambda \gg d$ , use lumped circuit:  $L_{tot} = L * \text{length}$ ,  $C_{tot} = C * \text{length}$
  - If  $\lambda \approx 10d$  or  $\lambda < 10d$ , use transmission-line model

# Frequency Dependence of Lumped Circuit Models

<u>Level</u>	<u>Dimension</u>	<u>Frequency</u>	<u>Edge rate</u>
PCB line	10 in	> 55 MHz	< 7ns
Package	1 in	> 400 MHz	< 0.9 ns
VLSI int*	100 um	> 8 GHz	< 50 ps

\* Using RC criterion for distributed effect

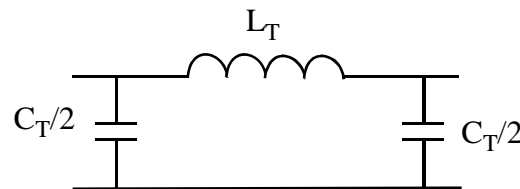
# Modeling Interconnections

Low Frequency

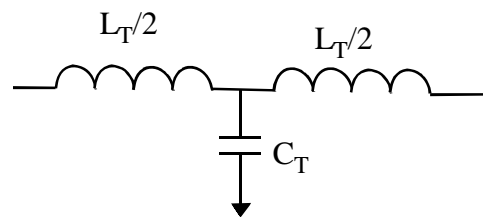


Short

Mid-range  
Frequency

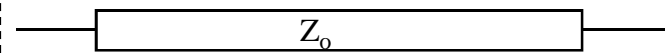


or



Lumped  
Reactive CKT

High Frequency



Transmission  
Line