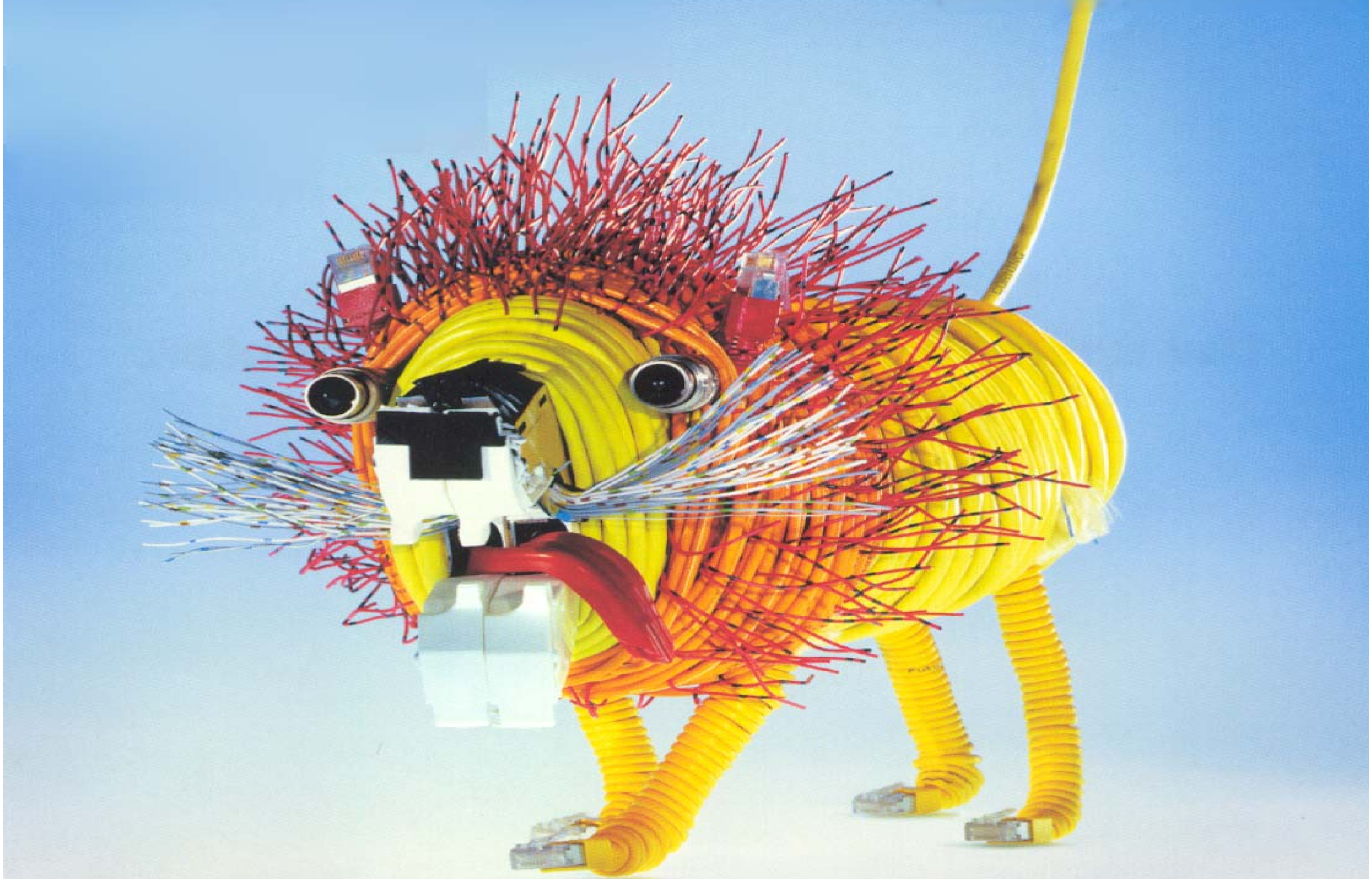
Interconnect



Lion. Michael P. Giordano. October 2000

Course Material for Interconnect

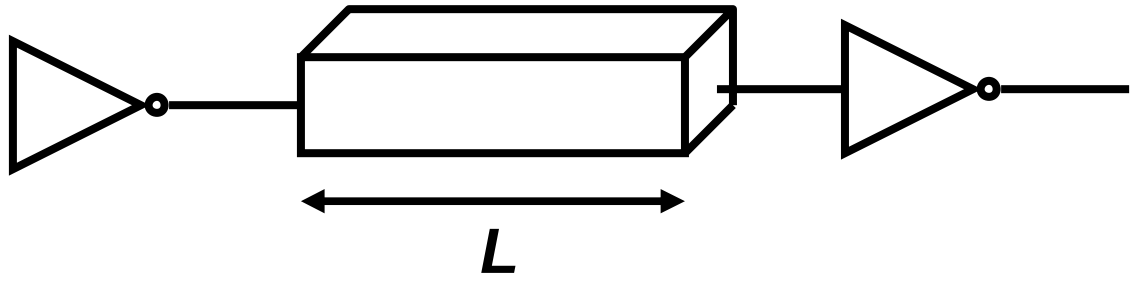
Chapter 4, 2nd ed.

P = primair, I = Illustratie, O = overslaan

P	4.1	Introduction	136
P	4.2	A First Glance	136 –138
P	4.3	Interconnect Parameters	138 – e.v.
O		So far we have …. (onder example 4.2)	147 – 148
O	4.3.3	Inductance	148 – 150
P	4.4	Electrical Wire Models	150 – 156
I	4.4.4	Distributed rc line – *hiervoor is vervangende stof*	156 – 159 (1)
O	4.4.5	The transmission line	159 – e.v.
O	4.5	Spice wire models	170 – 171
I	4.5.3	Perspective: a look into the future	171 – 174

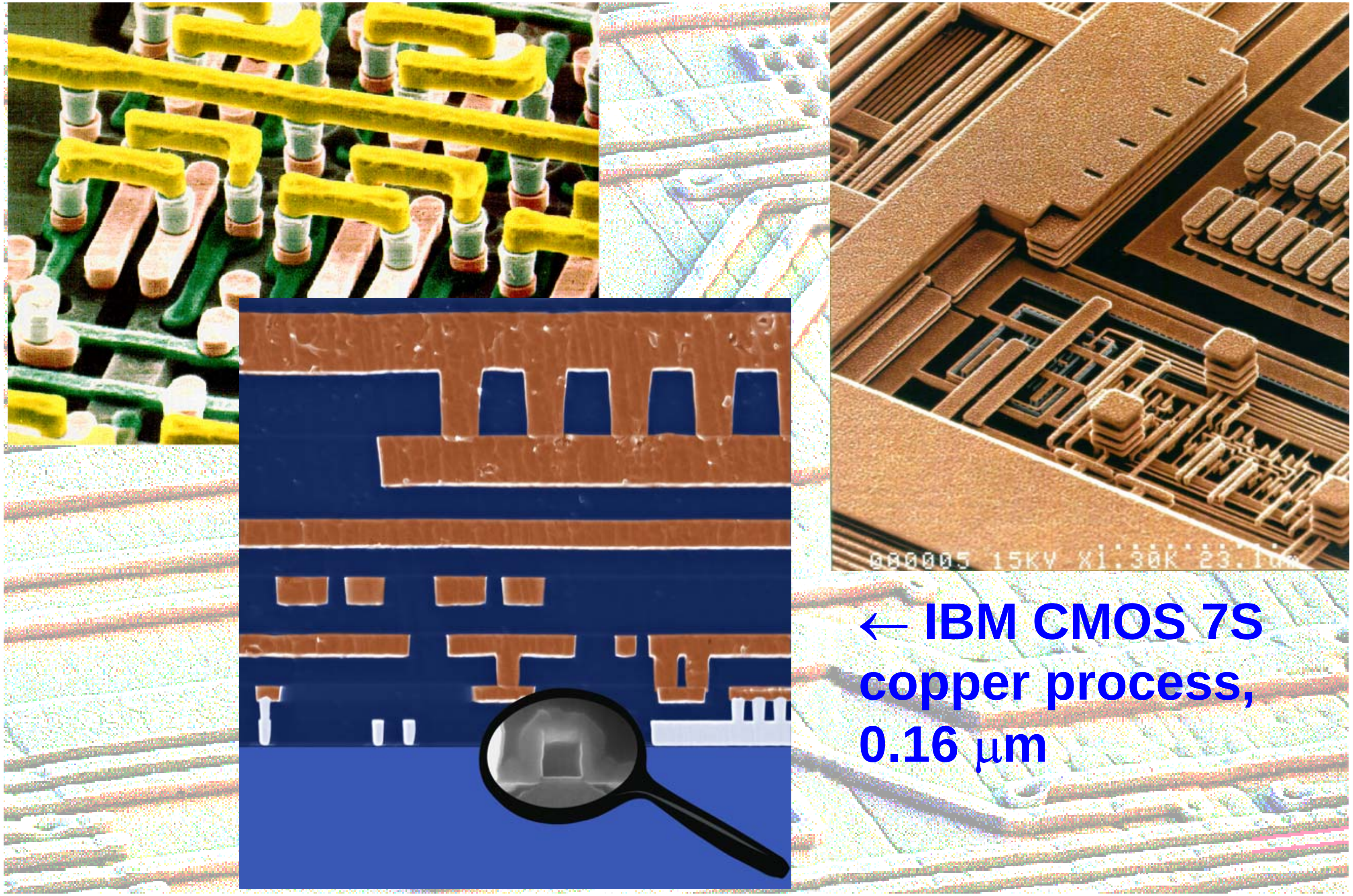
Replacement voor Distributed RC line: Elmore Delay

Interconnect



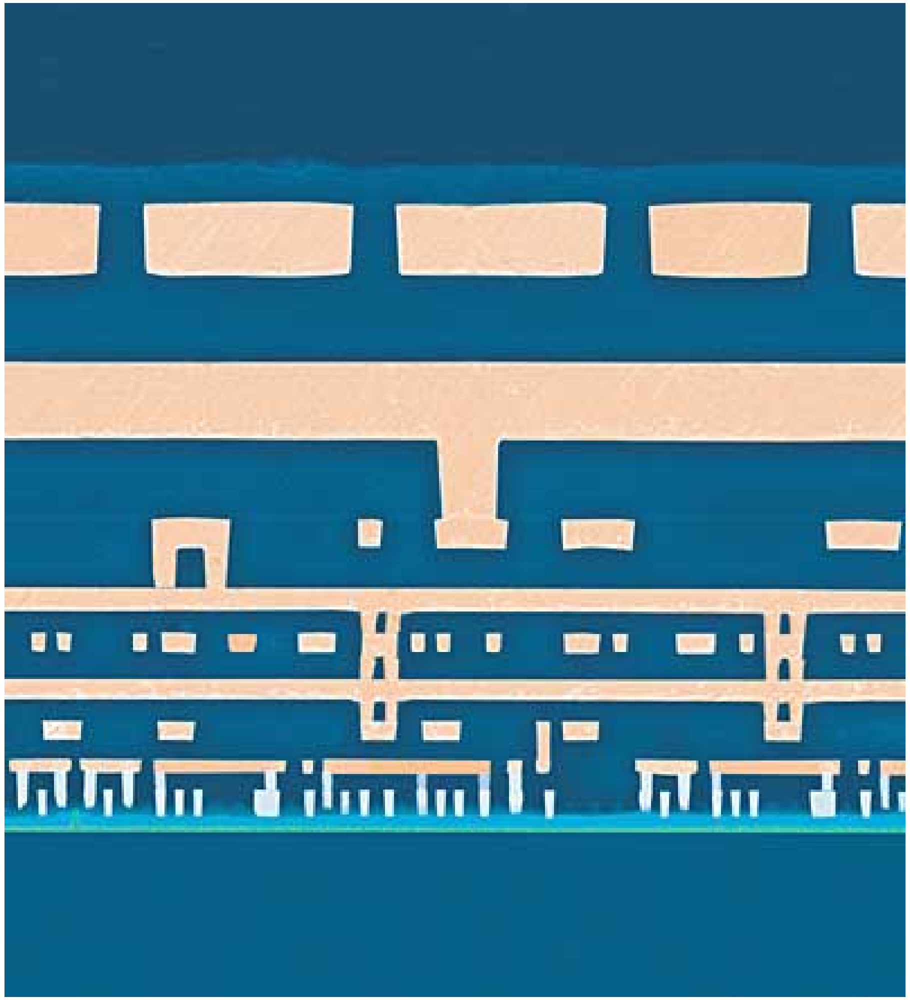
- **Wires are not ideal interconnections**
- **They may have non-negligible capacitance, resistance, inductance**
- **These are called wire parasitics**
- **Can dominate performance of chip**
- **Must be accounted for during design**
- **Using approximate models**
- **Detailed post-layout verification also necessary**

Wires

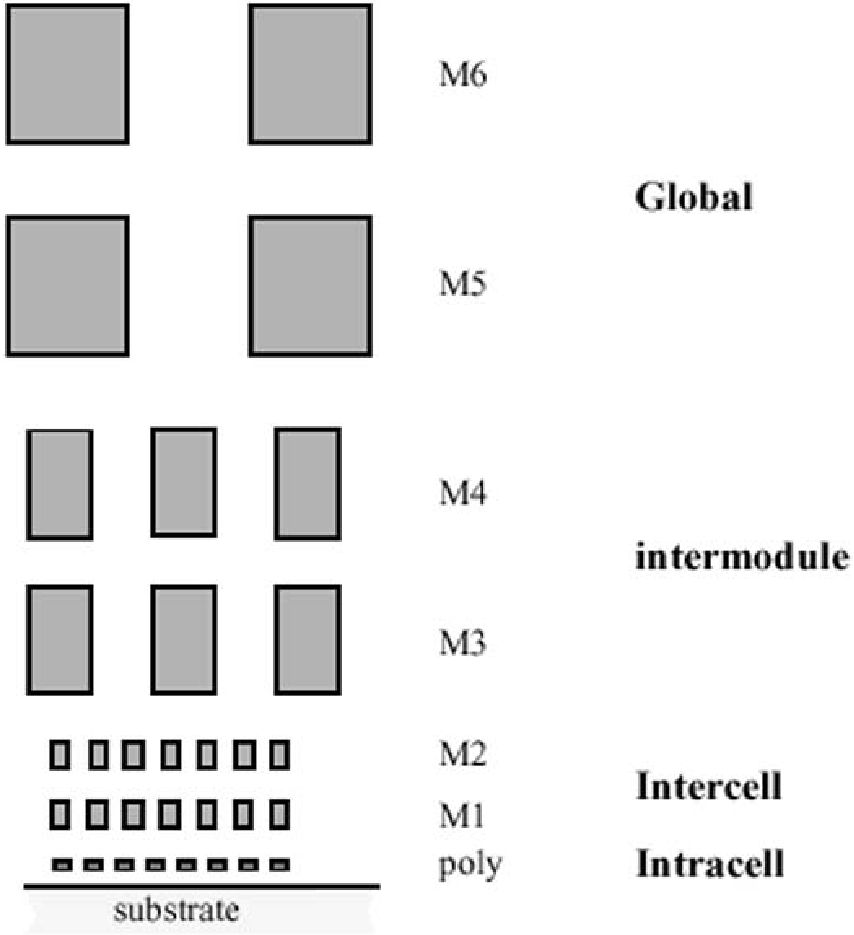


← IBM CMOS 7S copper process, 0.16 μm

Interconnect Hierarchy

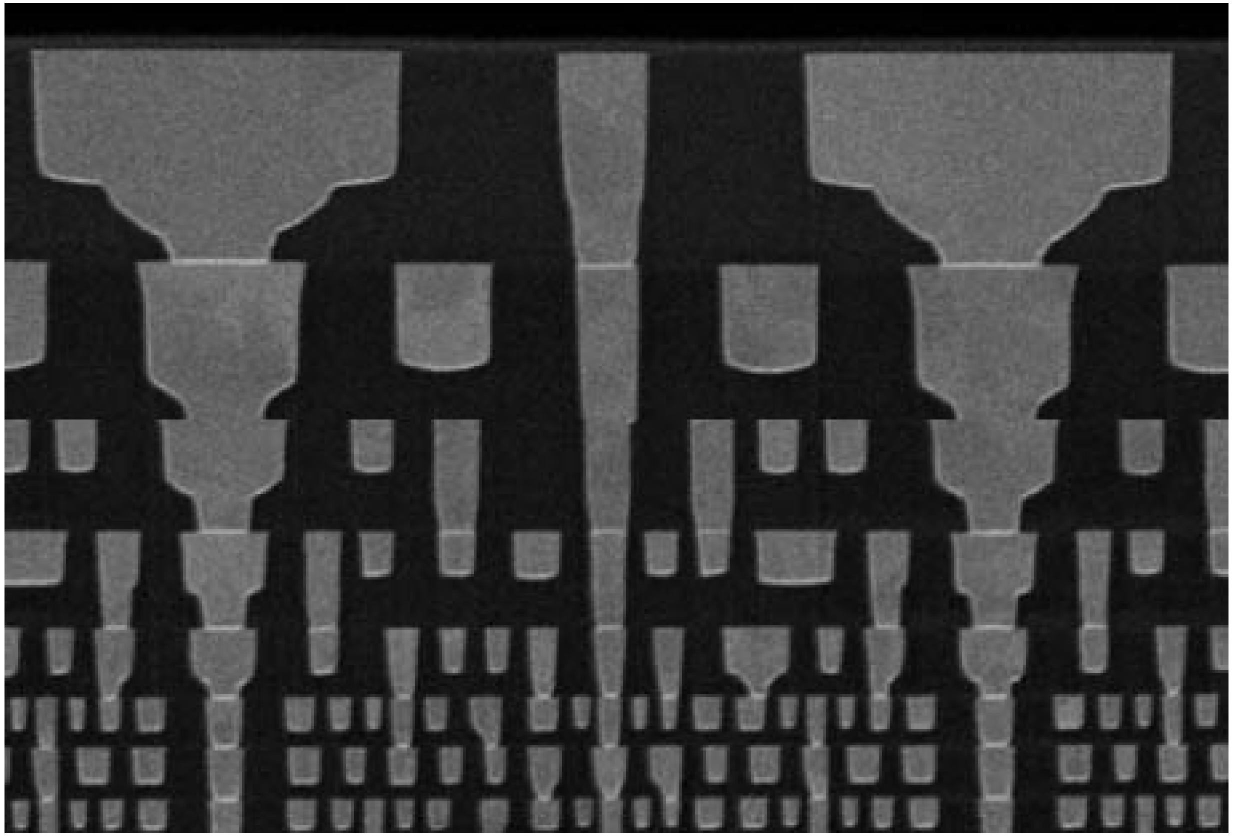


Cross-section of IBM 0.13 μ process



Example Interconnect Hierarchy for typical 0.25μ process (Layer Stack)

45 nm Interconnect Technology



8 interconnect layers in 45 nm technology

[Ingerly – iitc – 2008]

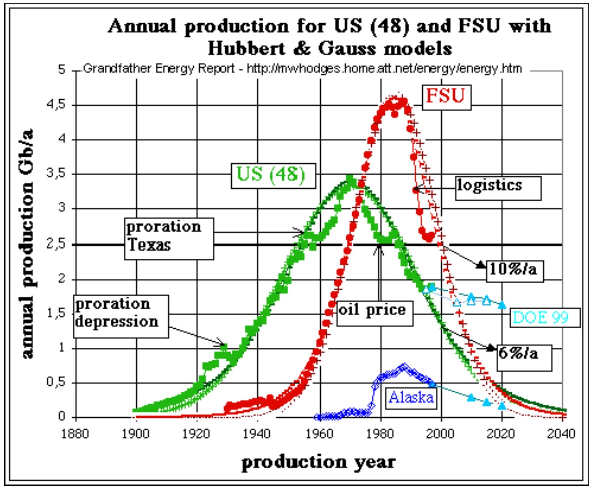
Outline

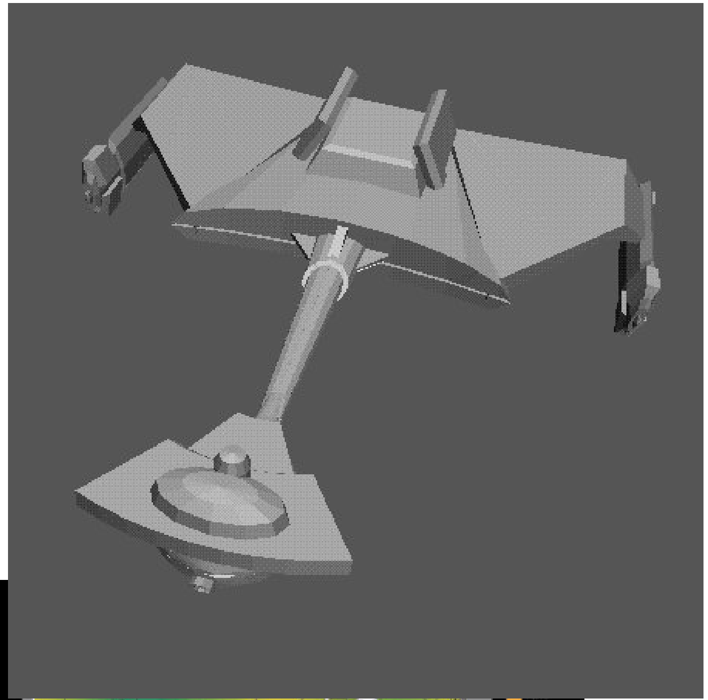
- **Capacitance**
  - **Area/perimeter model, coupling**
- **Resistance**
  - **Sheet resistance**
- **Interconnect delay**
  - **Delay metrics, rc delay, Elmore delay**

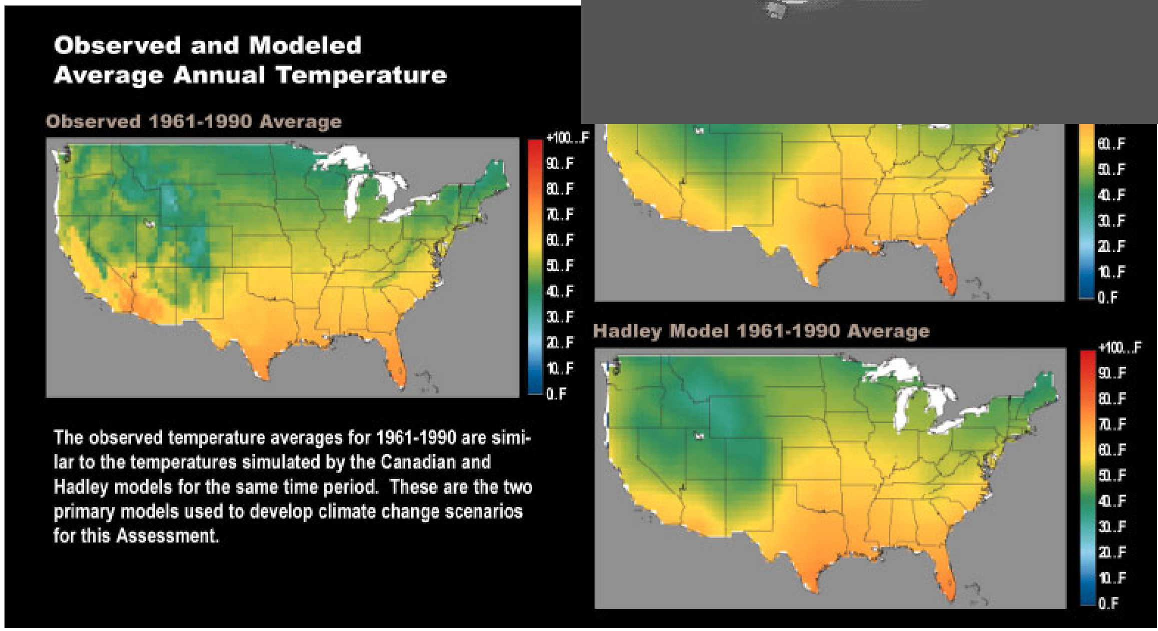
Capacitance

- **Area/perimeter model, coupling**

Wake Up!   Models ahead!







Merriam-Webster Online Dictionary

Thesaurus

6 entries found for **model.**
To select an entry, click on it.

model[1,noun]
model[2,verb]
model[3,adjective]
animal model
role model
Watson-Crick model

Go

Main Entry: [1]**mod·el**
Pronunciation: 'mä-dᵊl
Function: *noun*
Etymology: Middle French *modelle,* from Old Italian *modello,* from (assumed) Vulgar Latin *modellus,* from Latin *modulus* small measure, from *modus*
1 *obsolete* **:** a set of plans for a building
2 *dialect British* **:** COPY, IMAGE
3 : structural design <a home on the *model* of an old farmhouse>
4 : a usually miniature representation of something; *also* **:** a pattern of something to be made
5 : an example for imitation or emulation
6 : a person or thing that serves as a pattern for an artist; *especially* **:** one who poses for an artist
7 : ARCHETYPE
8 : an organism whose appearance a mimic imitates
9 : one who is employed to display clothes or other merchandise **:** MANNEQUIN

(as an atom) that cannot be directly observed
12 : a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs
13 : VERSION

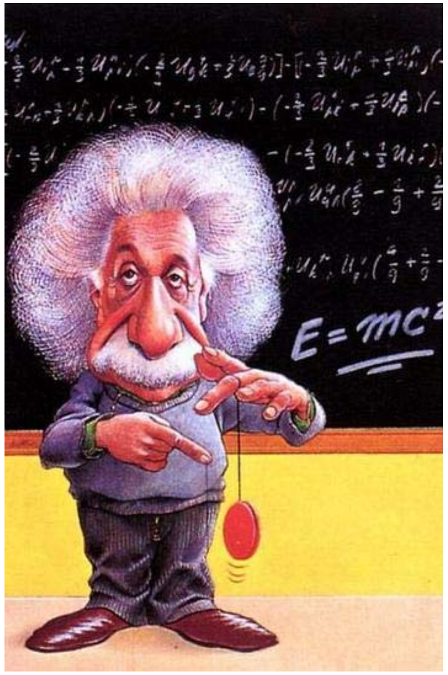
13 : VERSION

Modeling

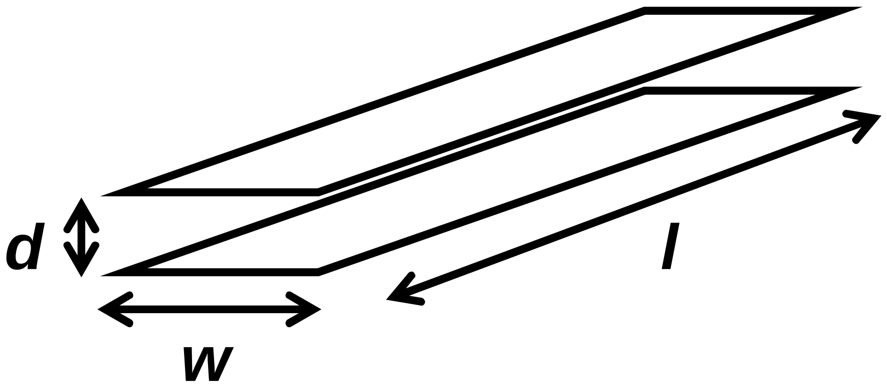
- **An abstraction of (the properties) of something to help understanding and predicting its behavior**
- **Domain Specific: weather, climate, economy, stock market, ...**
- **Different models for something to answer different questions**
- **Black-Box modeling vs. Physically Based**

After Einstein:

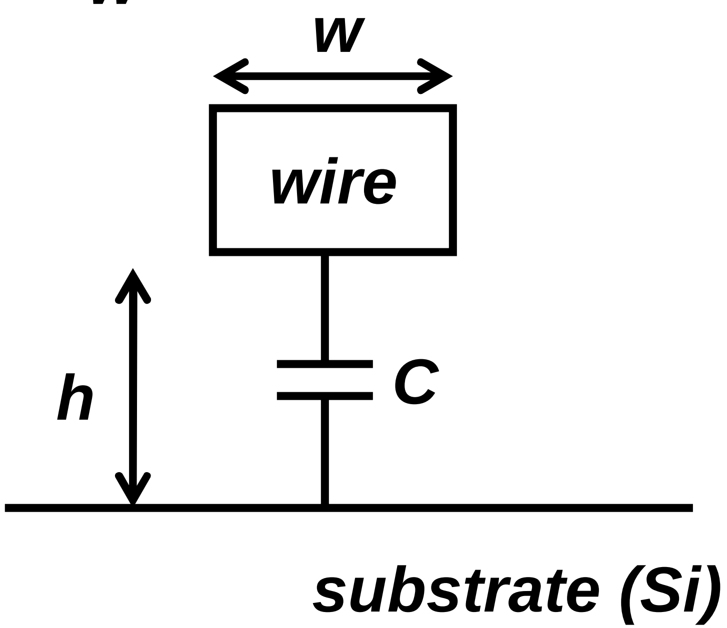
<a model> should be as simple as possible, but not simpler



Wire Capacitance – Parallel Plate



$$C = \frac{\varepsilon_0 \varepsilon_r w l}{d}$$

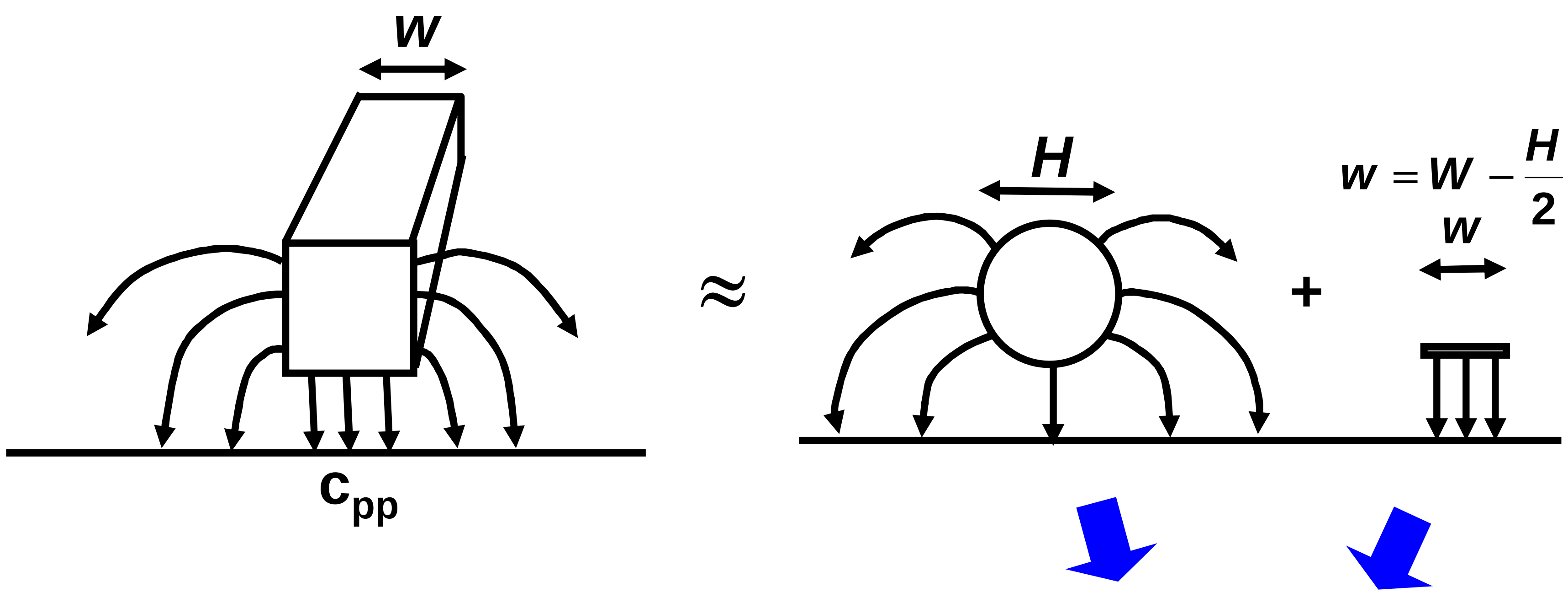


$$\frac{C}{l} = \varepsilon_0 \varepsilon_r \frac{w}{h}$$

ε_0 = 8.85 pF/m

ε_r = 3.9 (SiO_2)

Wire Capacitance – Fringing Fields



$$c_{wire} = c_{fringe} + c_{pp} = \frac{2\pi\varepsilon_{di}}{\log(t_{di}/H)} + \frac{w\varepsilon_{di}}{t_{di}}$$

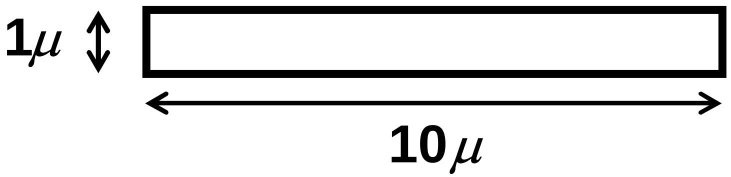
- **Works reasonably well in practice**
- **Not directly applicable for interconnects with varying widths**

Wire Capacitance – Area/Perimeter Model

- C_a was calculated with modified wire width
- Formula inapplicable for irregular interconnects (non-constant width)

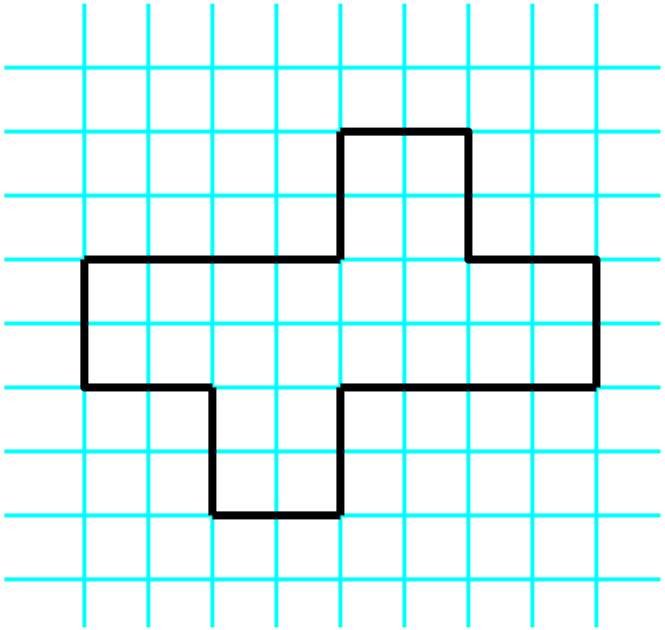
- More practical approximation

$C = A \times C_a + P \times C_p$	units	alternative
A = Area	m^2	μm^2
C_a = Area capacitance	F/m^2	$aF/\mu m^2$
P = Perimeter	m	μm
C_p = Perimeter capacitance	F/m	$aF/\mu m$



$$C = \square \times C_a + \square \times C_p$$

Area / Perimeter Capacitance Model

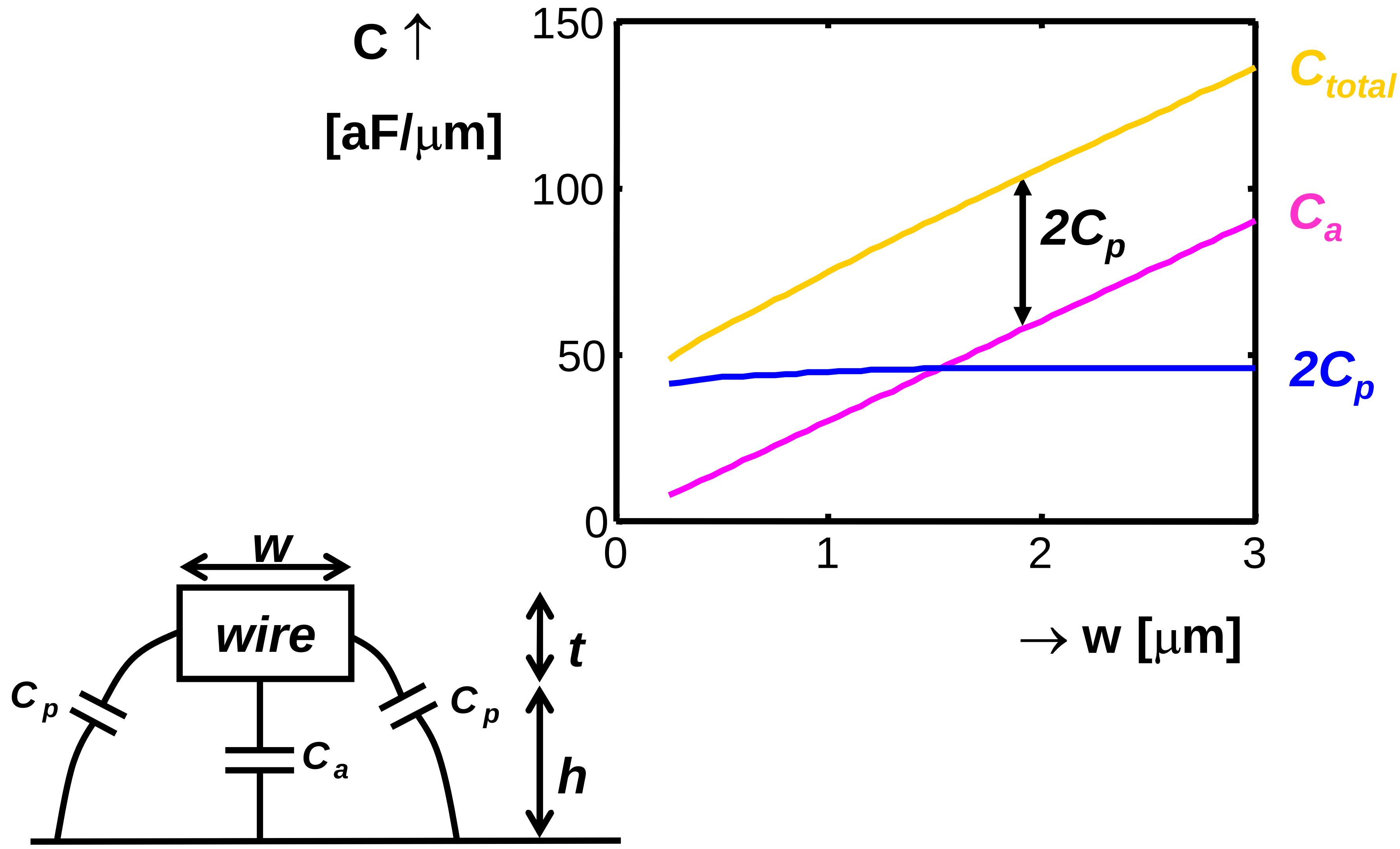


$$C = \square \times C_a + \square \times C_p$$

- **Question: How to derive C_a, C_p ?**

How accurate is this model?

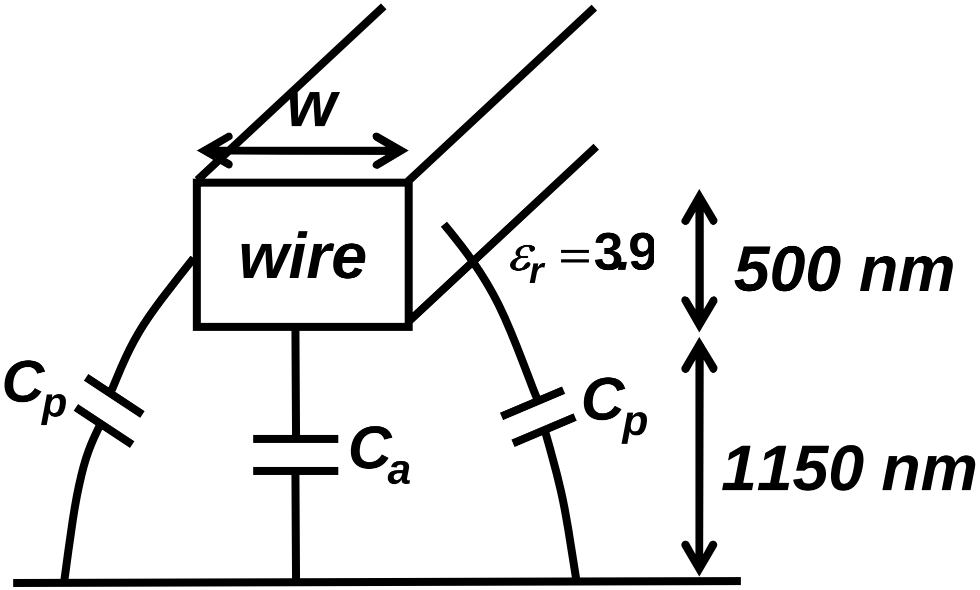
Derivation of c_a, c_p

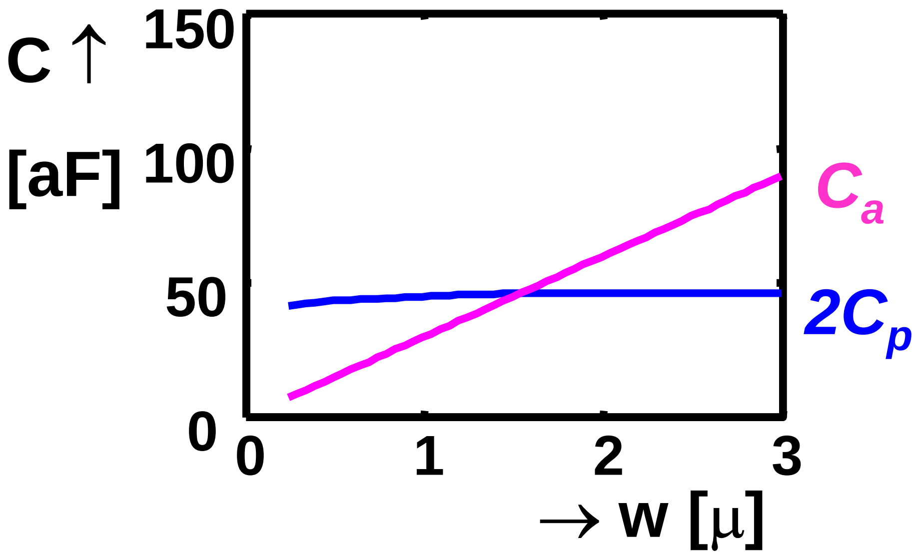


Derivation of c_a, c_p

- **2D (cross-section) numerical computation (or measurement)**
- C_l **: total wire capacitance per unit length**
- $C_a = \varepsilon_0 \varepsilon_r / h$
- $C_p = 1/2 (C_l - C_a \times w)$
- C_p **depends on t, h ➔ determined by technology, layer**
- C_p **would depend slightly on w (see previous graph), this dependence is often ignored in practice**

Area / Perimeter Capacitance

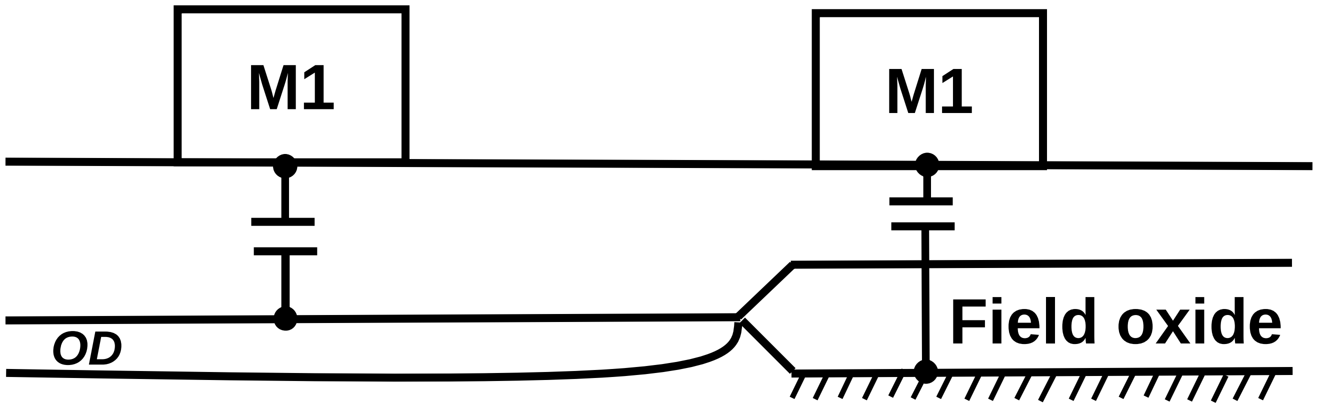




- C_p **dominates for many wires**
- C_p **may not be neglected**
- **A constant value for** C_p **is usually a good approximation**
- C_p **is sometimes called** C_f **(fringe capacitance)**

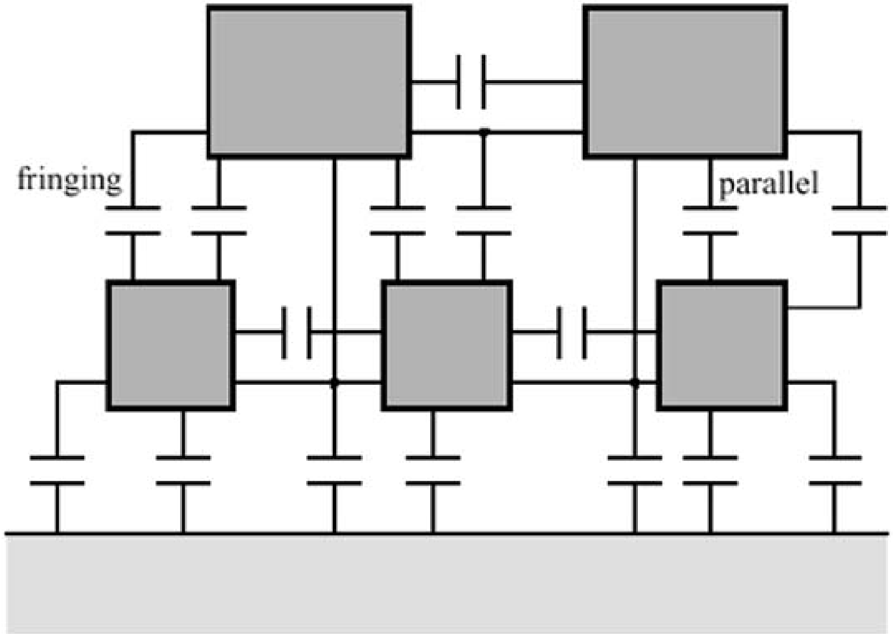
Interconnect Capacitance Design data

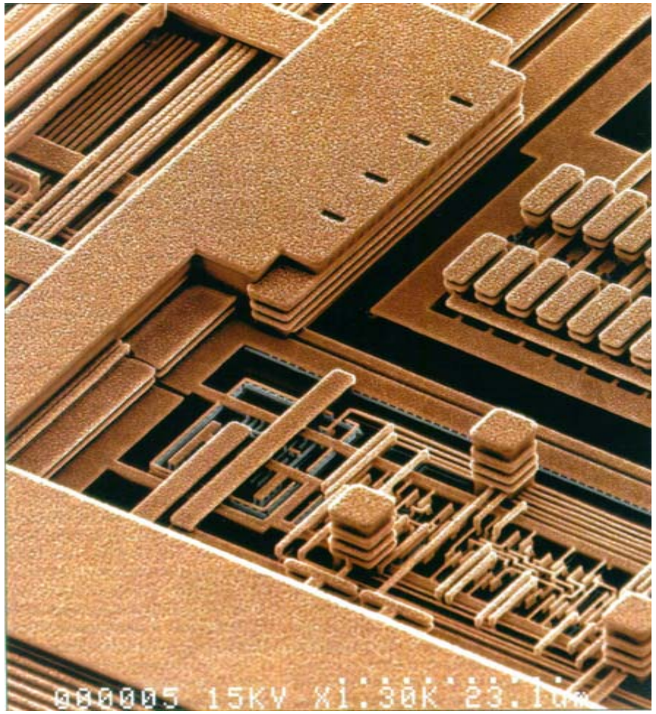
- **See Table 4.2 (or inside backside cover)**
- **Example: M1 over Field vs. M1 over Active (hypothetical)**



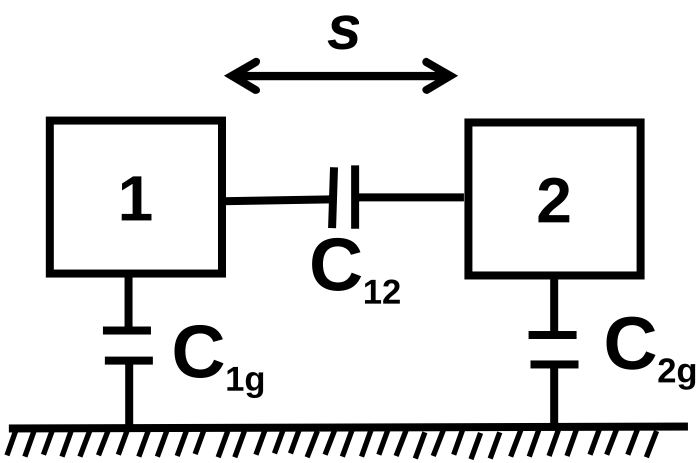
M1 over Active	M1 over Field	Unit
$C_a = 41$	$C_a = 30$	$aF/\mu m^2$
$C_p = 47$	$C_p = 40$	$aF/\mu m$

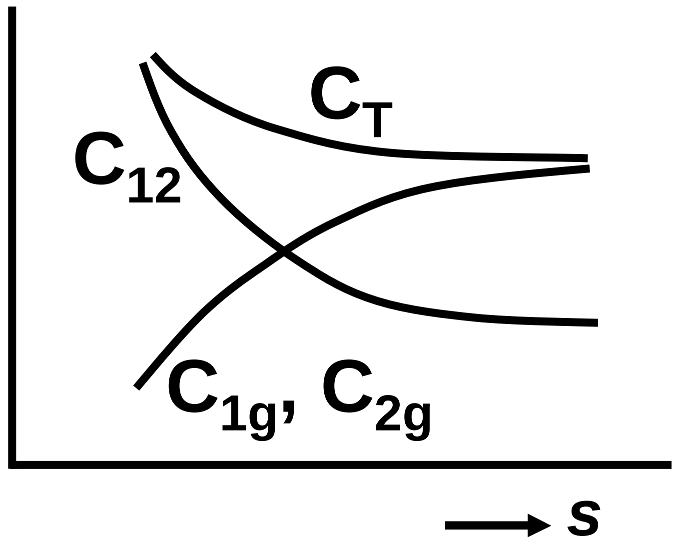
Coupling Capacitances





Coupling Capacitances (2).



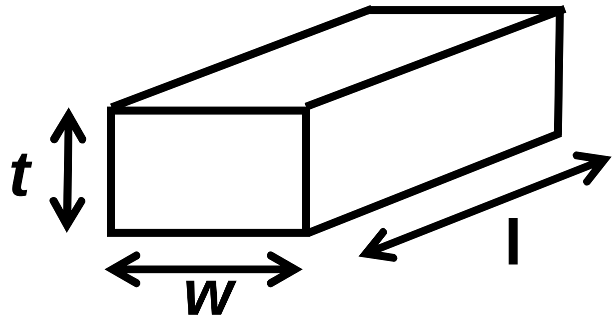


- $C_T = C_{1g} + C_{12} = C_{2g} + C_{12}$ **fairly constant**
- **Use that as first order model**
- **Interconnect capacitance design data (e.g. Table 4.3)**

Resistance

- **Sheet resistance**

Wire Resistance



- **Proportional to l**
- **Inversely proportional to w and t (cross-sectional area)**
- **Proportional to ρ: specific resistance, material property [Ωm]**
- **R = ρl/wt**
- **Aluminum: ρ = 2.7x10^{-8} Ωm**

  Copper: ρ = 1.7x10^{-8} Ωm

Sheet Resistance

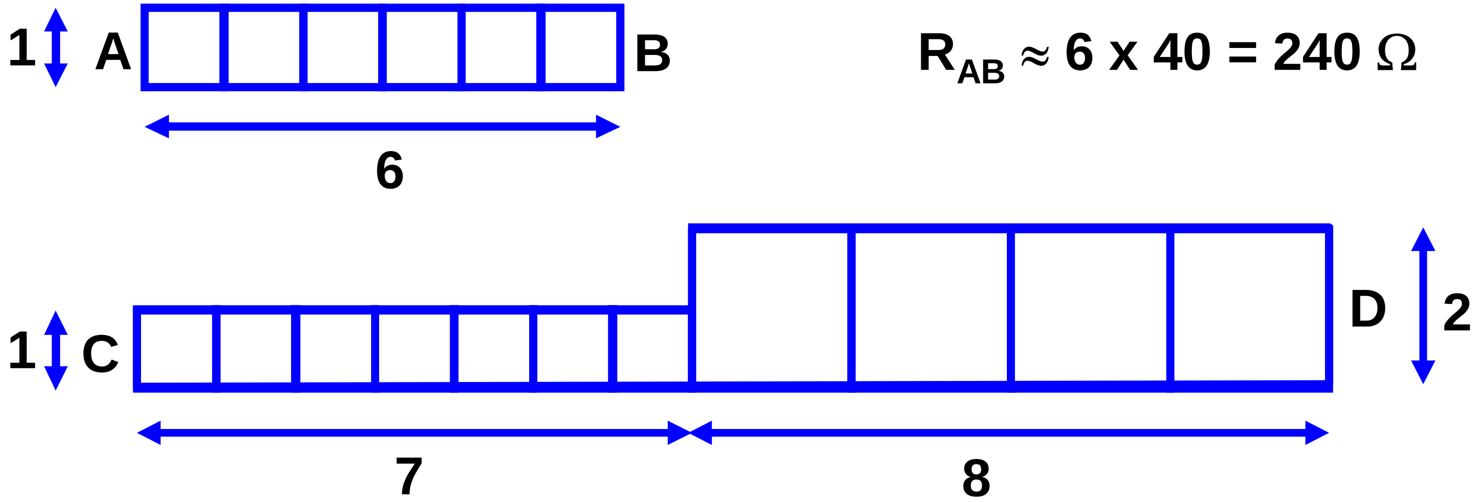
- **R = ρl/wt**
- **t, ρ constant for layer, technology**
- **R = R l/w**
- **R : sheet resistance [Ω/]**

  resistance of a square piece of interconnect

  other symbol: R_s
- **Interconnect resistance design data e.g. Table 4.5 (or inside back-cover)**

Interconnect Resistance

- Assume $R_{\square} = 40\ \Omega$
- Estimate the resistance between A and B in the wire below.



$R_{AB} \approx 6 \times 40 = 240\ \Omega$

$R_{CD} \approx 11 \times 40 = 440\ \Omega$

Engineering is about making controlled approximations to something that is too complicated to compute exactly, while ensuring that the approximate answer still leads to a working (functional, safe, …) system

Exercise.

An interconnect line is made from a material that has a resistivity of $\rho = 4\ \mu\Omega$-cm. The interconnect is 1200 Å thick, where 1 Angstrom (Å) is 10^{-10} m. The line has a width of 0.6 μm.

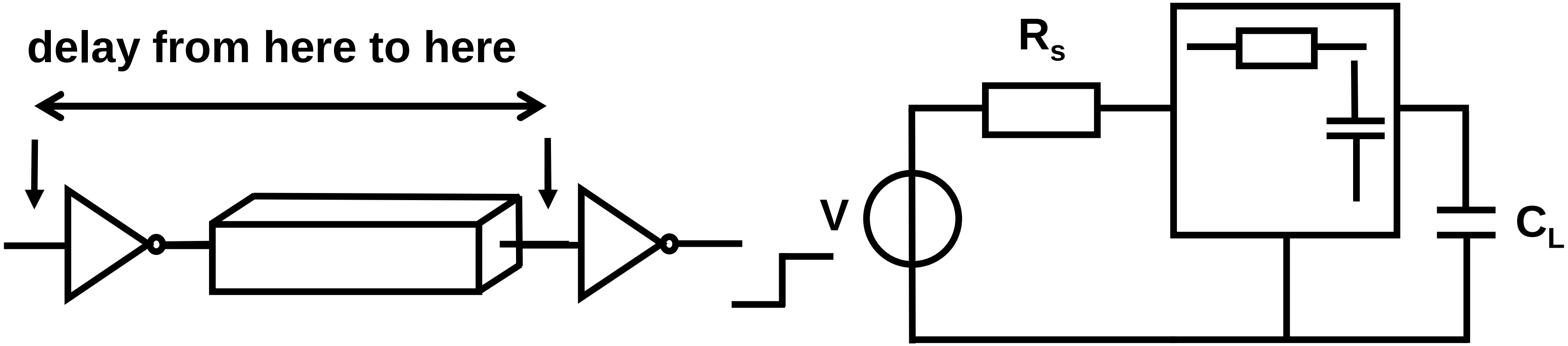
a) Calculate the sheet resistance $R_{\square}$ of the line.

b) Find the line resistance for a line that is 125 μm long.

Interconnect delay

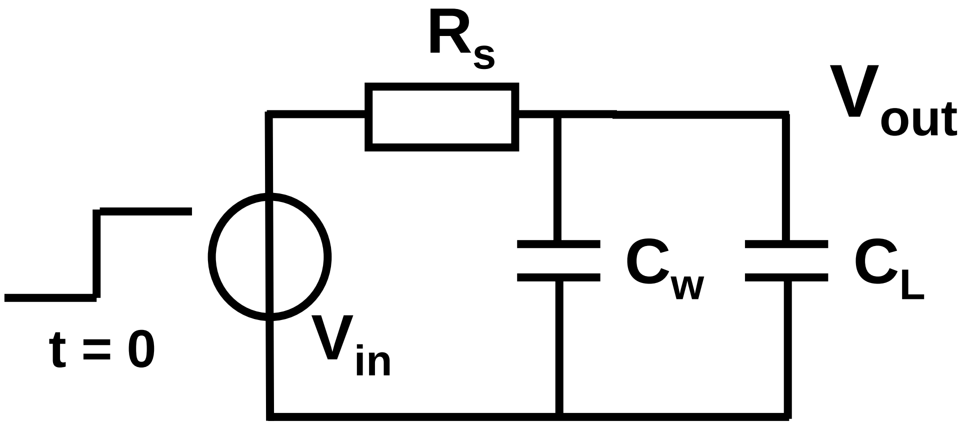
- **Delay metrics, rc delay, Elmore delay**

Delay



- Model driver as linearized Thevenin source V, R_s, assume step input
- Model load as C_L
- Wire is an RC network (two-port)

Wire Capacitance



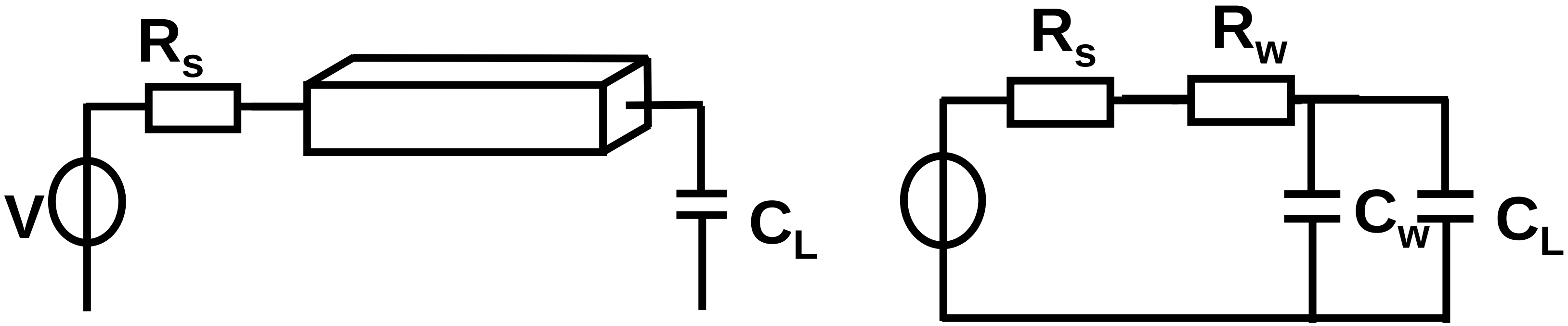
Assume wire behaves purely capacitive

$$(C_w + C_L)\frac{dV_{out}}{dt} + \frac{V_{out} - V_{in}}{R_s} = 0$$

$$V_{out} = V_{in} - \tau \frac{dV_{out}}{dt} \qquad \tau = R_s(C_w + C_L)$$

$$V_{out} = \left(1 - e^{-t/\tau}\right)V_{in}$$

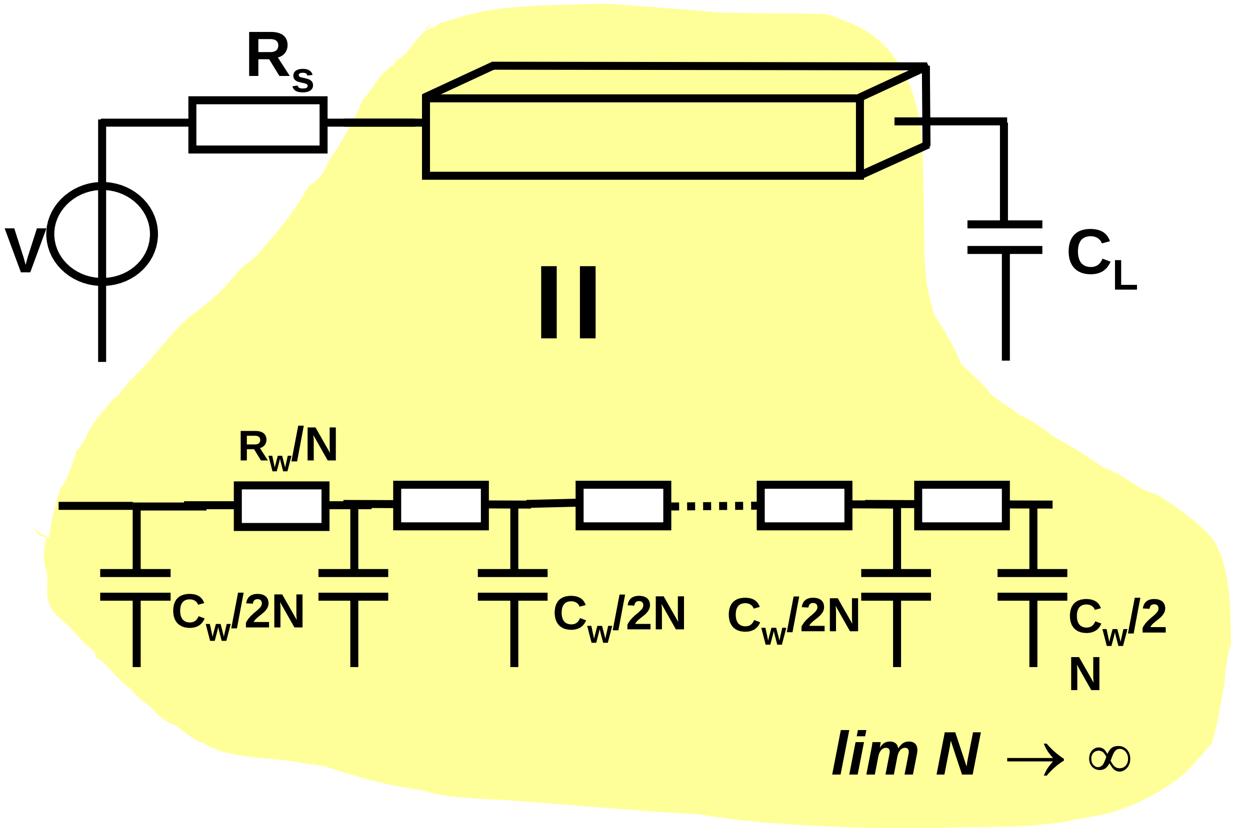
Wire Resistance



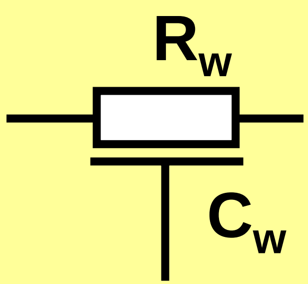
Now, assume wire capacitance *and resistance*

- $\tau = (R_s + R_w)(C_w + C_L)$
- **Is this a good model?**
- **R and C are distributed along the wire**

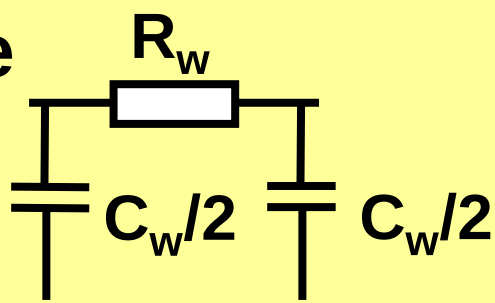
Uniform RC Line



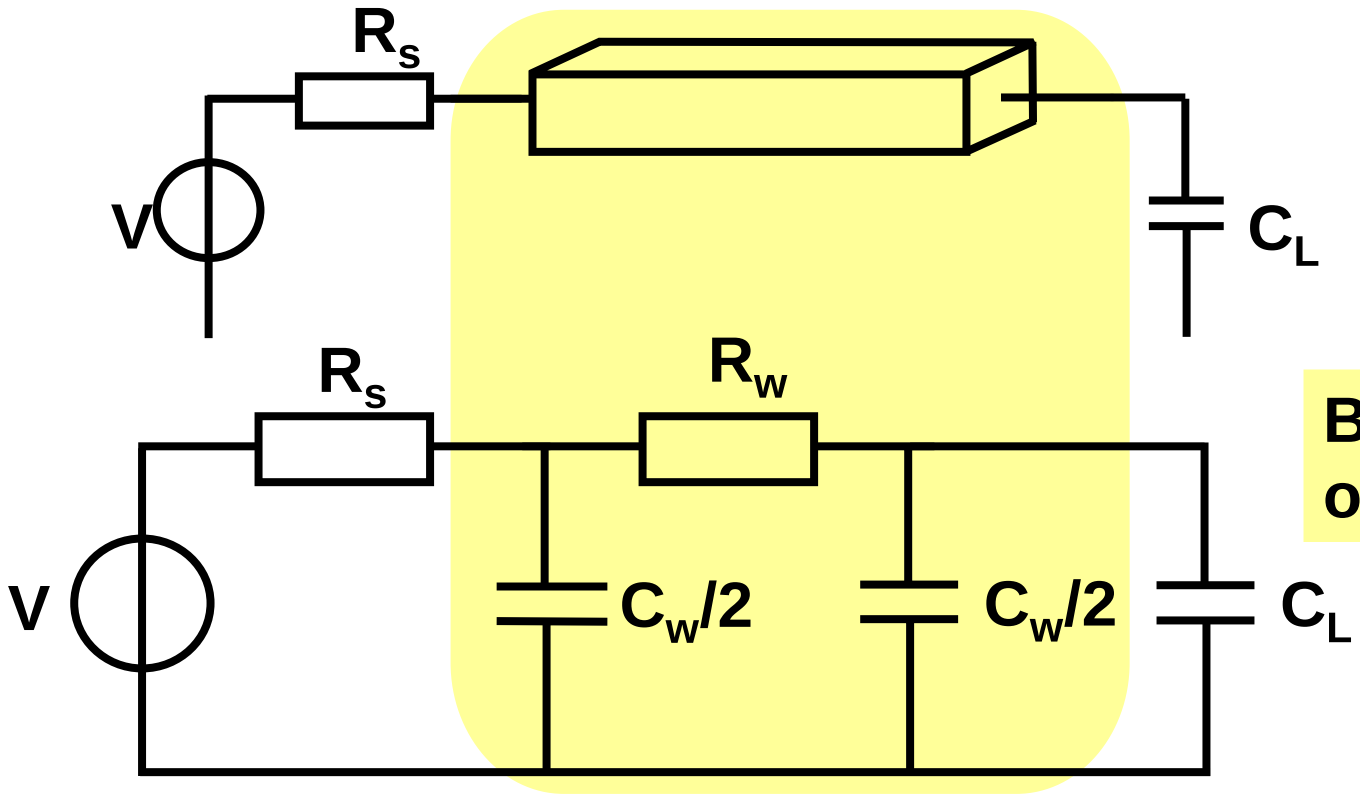
Symbol



[Always] use first order model



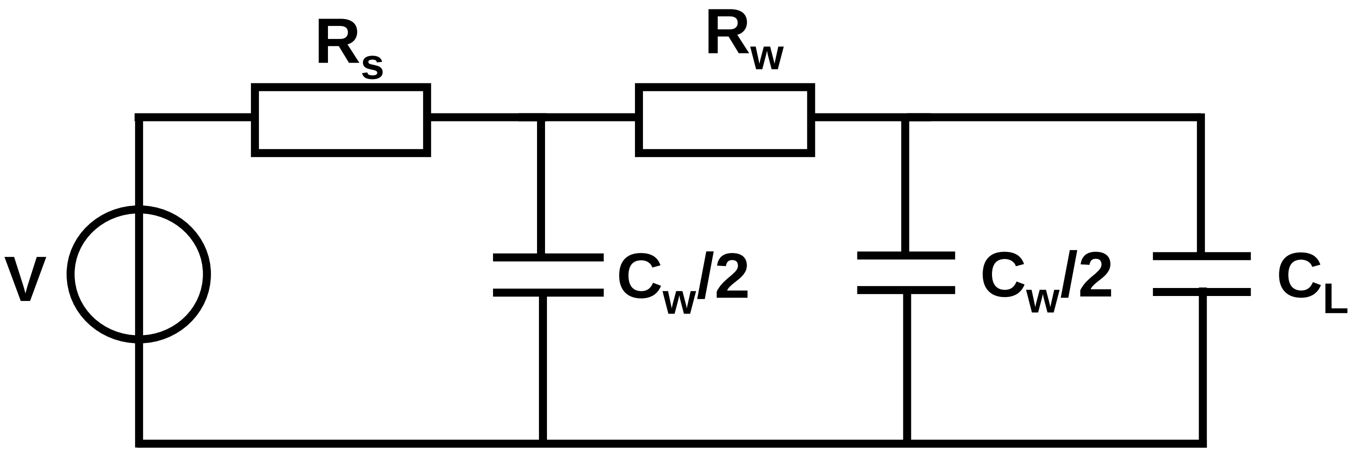
RC Delay (Uniform RC Line)



Basic π-model of wire

- τ?

Equivalent Time Constant



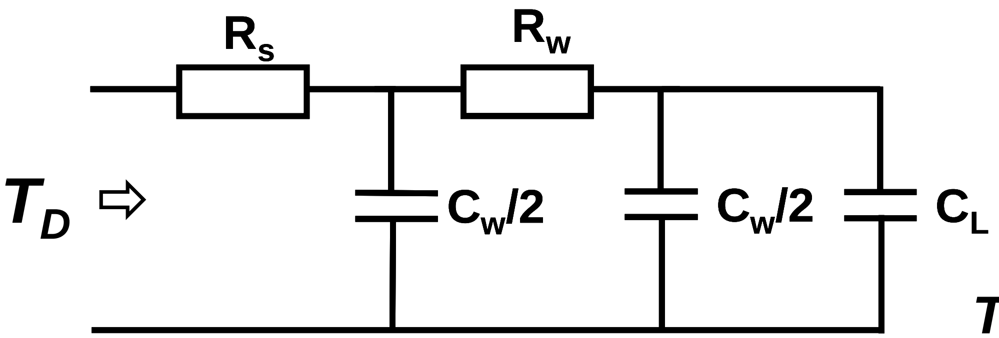
- **Multiple time-constants**
- **Need for one “equivalent” number**
- **Offered by *Elmore Delay T_D***

$$T_D = R_S C_W / 2 + (R_S + R_W)(C_W / 2 + C_L)$$

How to compute Elmore Delay?

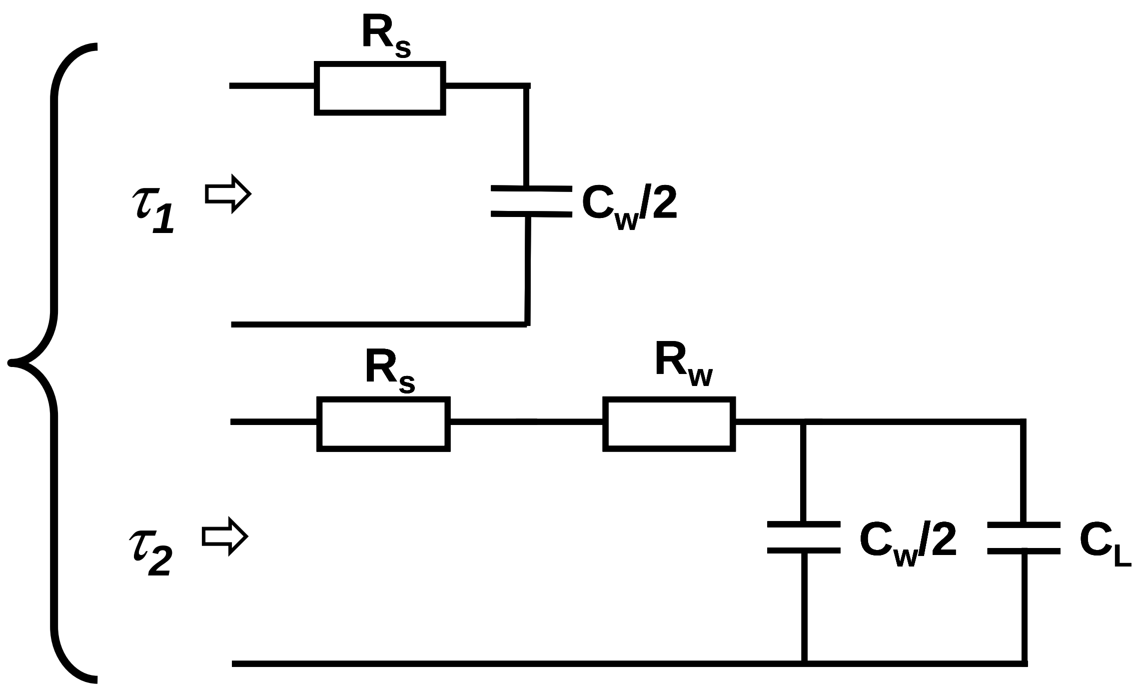
- **Effective “one number” model for delay**

Equivalent Time Constant

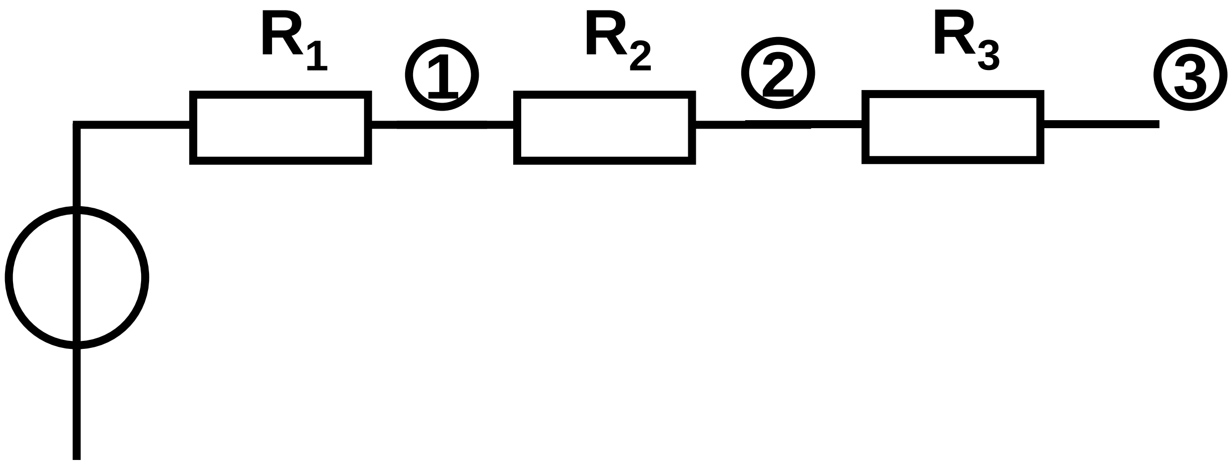


$$T_D = R_S C_W/2 + (R_S + R_W)(C_W/2 + C_L)$$

$T_D = \Sigma$

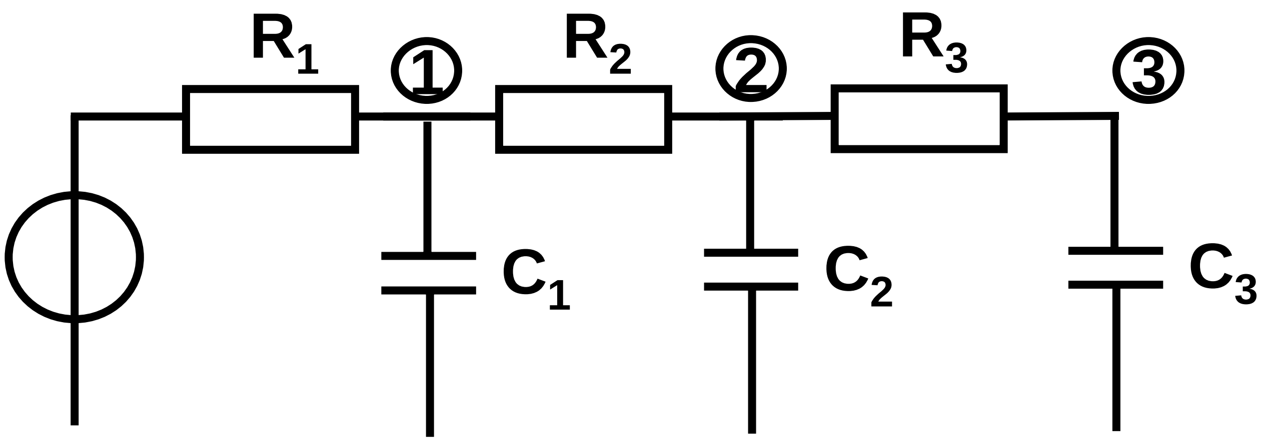


Shared Path Resistance



- **Define: R_{ii} = Resistance from node i to input**
- **Example:** $R_{11} = R_1 \quad R_{22} = R_1 + R_2 \quad R_{33} = R_1 + R_2 + R_3$
- **Define: R_{ik} = Shared path resistance to input for node i and k**
- $R_{12} = R_1 \quad R_{13} = R_1 \quad R_{23} = \boxed{}$

Elmore Delay for RC ladders



- **Define:** $T_{Di} = \sum_{k=1}^{N} R_{ik} C_k$

Elmore Delay

- $T_{D1} = R_{11}C_1 + R_{12}C_2 + R_{13}C_3 =$

  $= R_1C_1 + R_1C_2 + R_1C_3$

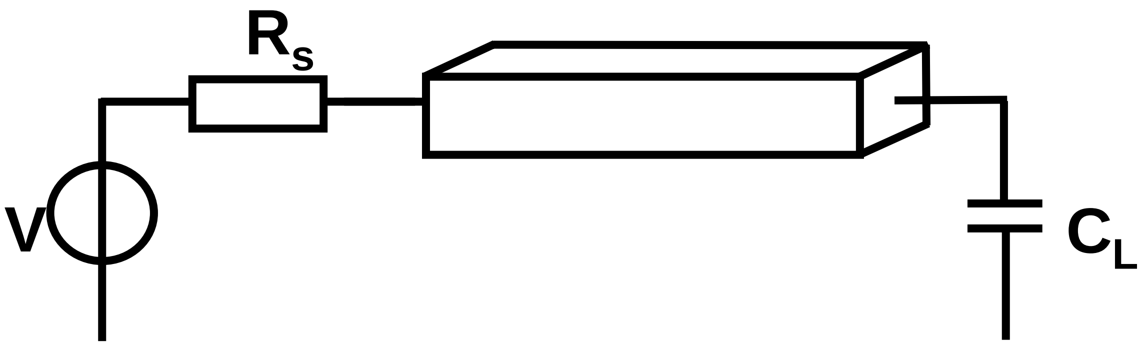
  $T_{D_3} = R_{31}C_1 + R_{32}C_2 + R_{33}C_3 =$

  $= R_1C_1 + (R_1 + R_2)C_2 + (R_1 + R_2 + R_3)C_3$

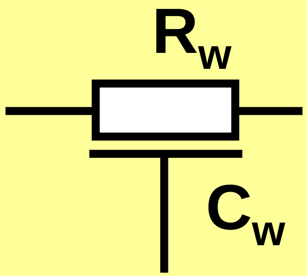
We will use 0.69 x T_{di} as approximation of wire delay ($t_{50\%}$)

- $T_{D_2} =$

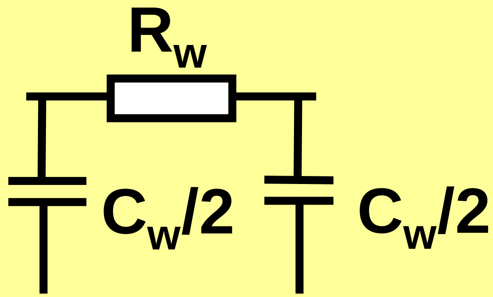
Elmore Delay for Distributed RC Lines



Symbol

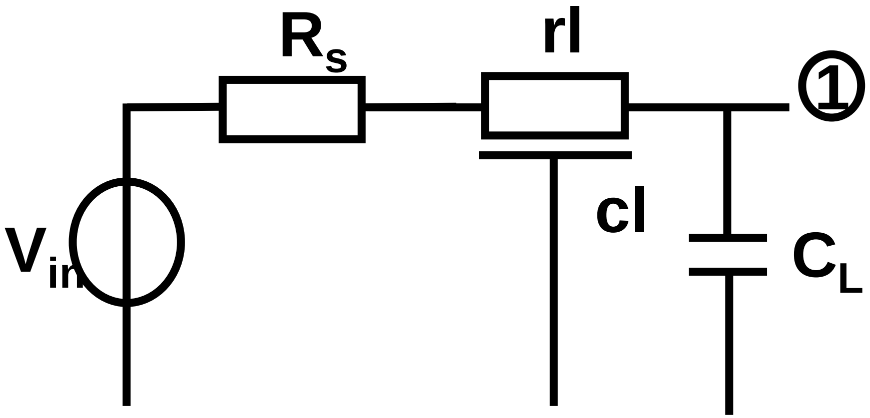


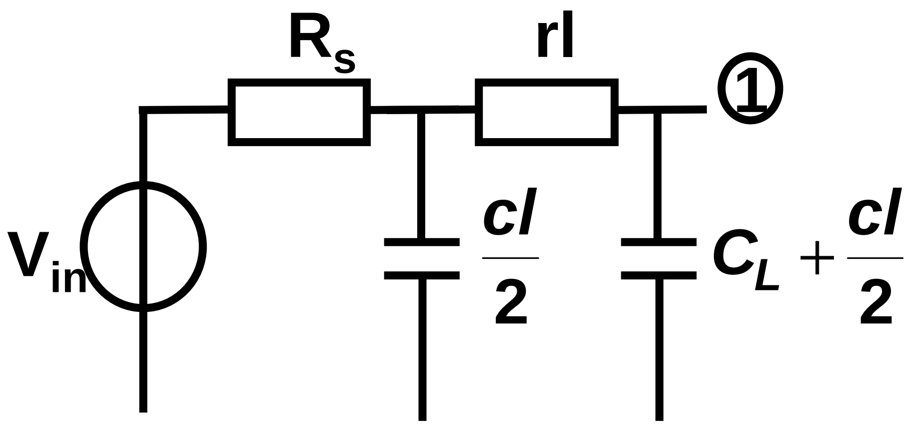
Symmetric π-model



- **Theorem:** **For Elmore Delay calculations, each uniform distributed RC section is equivalent to a symmetric π-model**

Canonical Driver-Line-Load





- $$T_{D_1} = R_s \frac{cl}{2} + (R_s + rl)\left(C_L + \frac{cl}{2}\right)$$
  $$= R_s(cl + C_L) + rlC_L + \frac{1}{2}rcl^2$$

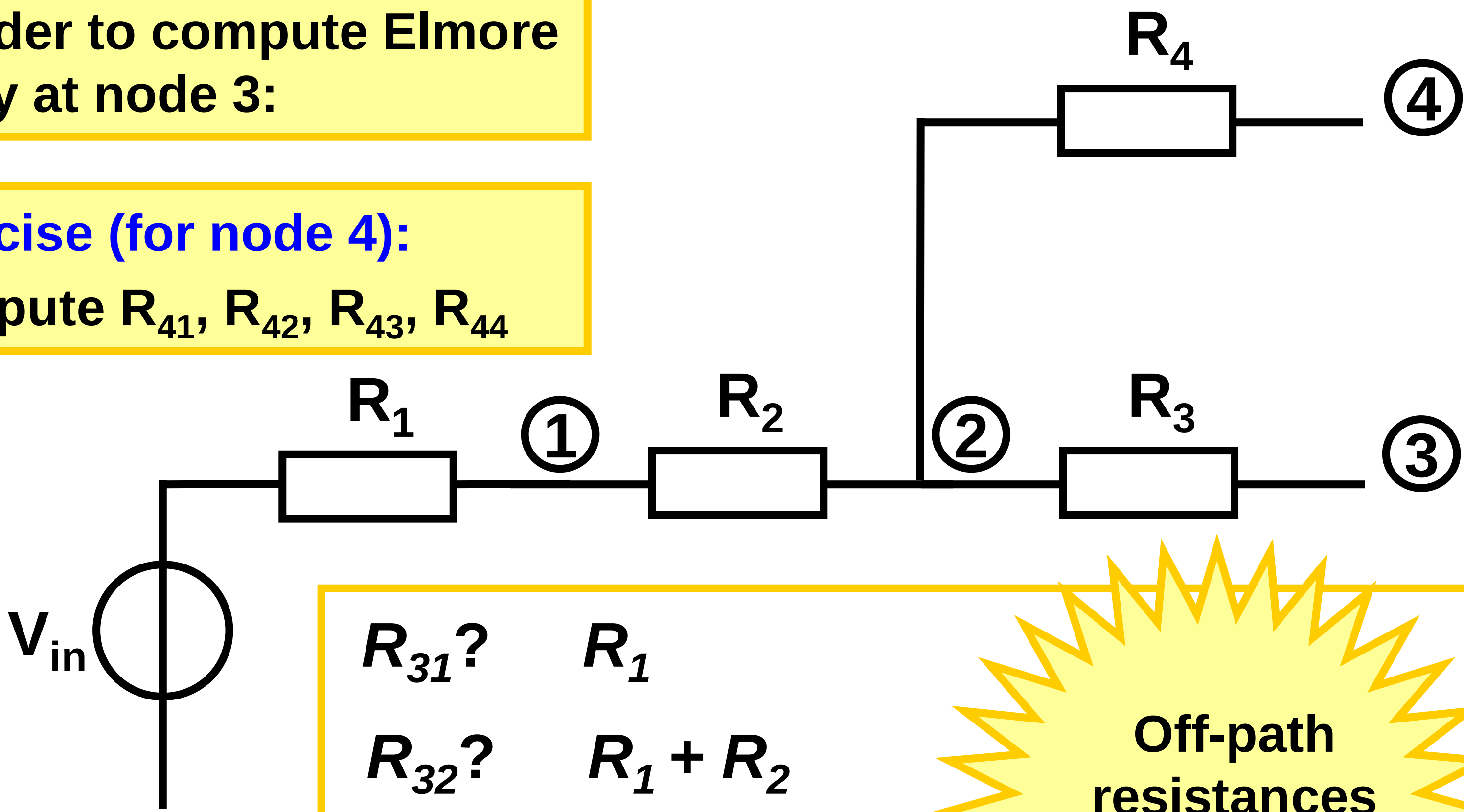
- **Delay quadratic in line length**

Shared Path Resistance for Tree Structures

In order to compute Elmore Delay at node 3:

Exercise (for node 4):

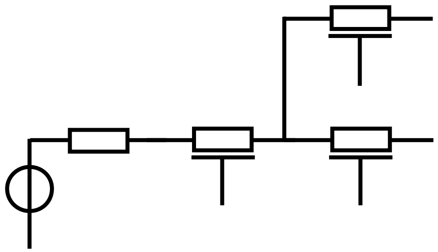
Compute R_{41}, R_{42}, R_{43}, R_{44}



R_{31}?	R_1
R_{32}?	$R_1 + R_2$
R_{33}?	$R_1 + R_2 + R_3$
R_{34}?	$R_1 + R_2$

Off-path resistances don't count

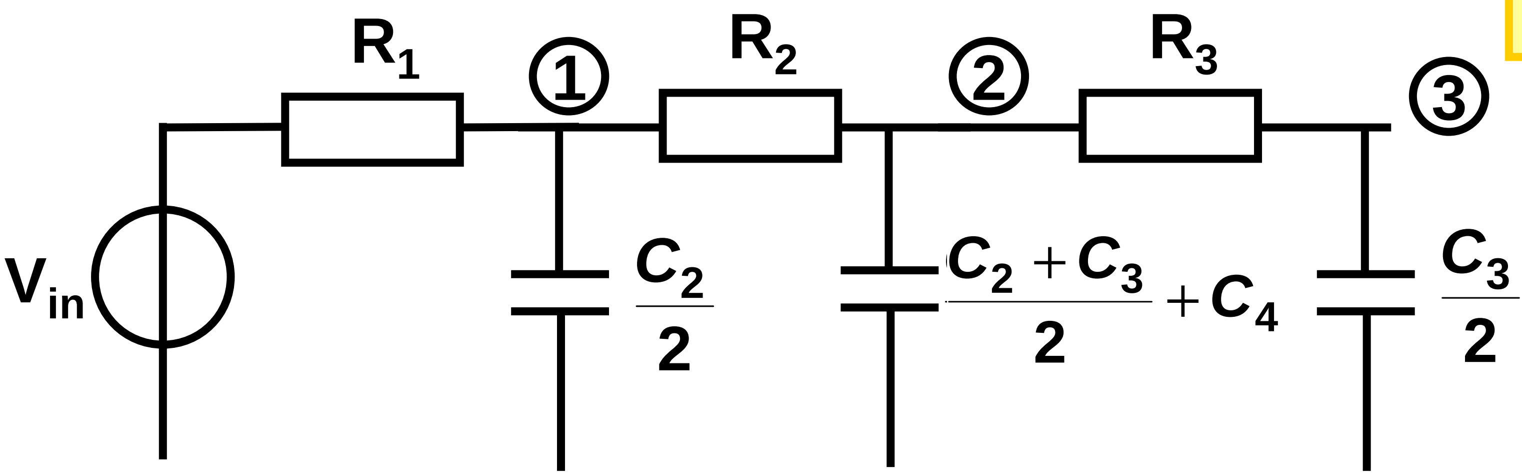
Elmore Delay for Tree Structures.



Exercise: **Compute T_{D1}, T_{D2}, T_{D3}, T_{D4}**

- **Replace RC lines by π-sections**
- **Given observation node i, then only resistances along the path from input to node i can possibly count**
- **Make others zero**
- **Compute as if RC ladder**

T_{D3}?



Summary

- **Capacitance**
  Area/perimeter model, coupling
- **Resistance**
  Sheet resistance
- **Interconnect delay**
  Delay metrics, rc delay, Elmore delay