Interconnect

Course Material for Interconnect

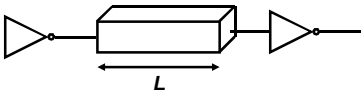
Chapter 4, 2nd ed.

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

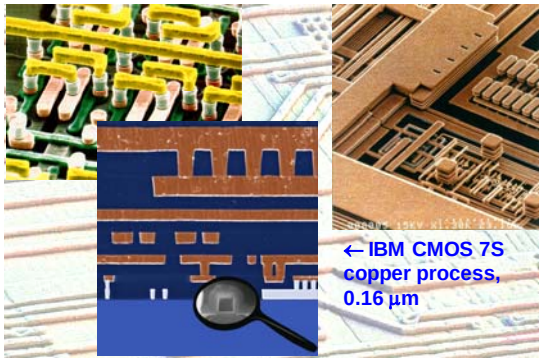
Replacement voor Distributed RC line: Elmore Delay

Interconnect



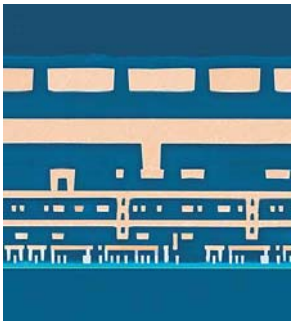
- Wires are **not ideal** interconnections
- They may have non-negligible **capacitance, resistance, inductance**
- These are called **wire parasitics**
- Can **dominate** performance of chip
- Must be accounted for during **design**
- Using **approximate models**
- Detailed **post-layout verification**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

Wires

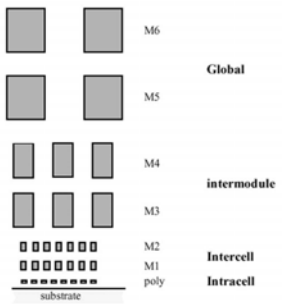


← IBM CMOS 7S copper process, 0.16 µm

Interconnect Hierarchy

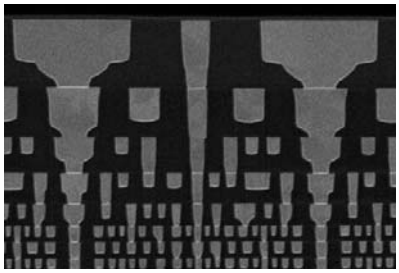


Cross-section of IBM 0.13 µ process



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

45 nm Interconnect Technology



8 interconnect layers in 45 nm technology

[Ingerly – iitc – 2008]

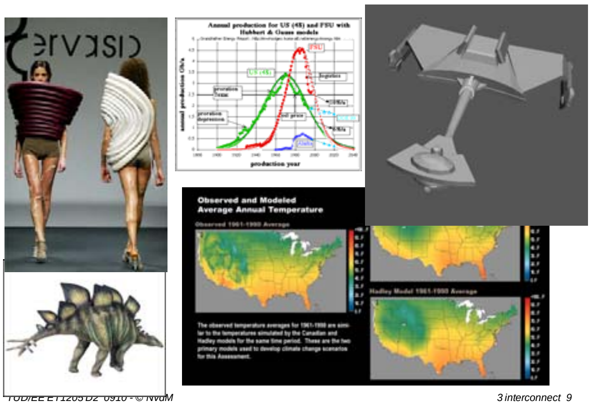
Outline

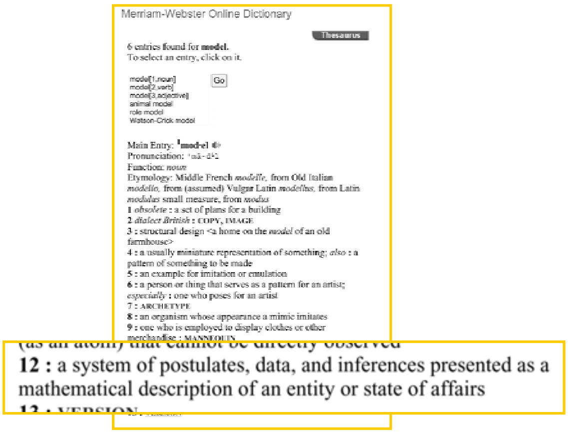
- Capacitance
  - Area/perimeter model, coupling
- Resistance
  - Sheet resistance
- Interconnect delay
  - Delay metrics, rc delay, Elmore delay

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: **mod·el**
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

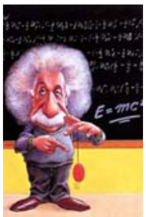
12 : a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs

Modeling

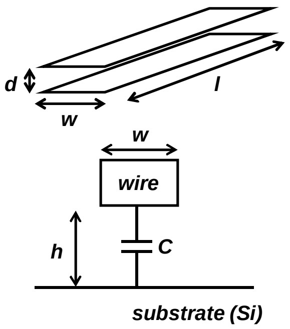
- An **abstraction** of (the properties) of something to help **understanding** and **predicting** its behavior
- **Domain Specific**: weather, climate, economy, stock market, ...
- Different models for something to **answer different questions**
- **Black-Box** modeling vs. **Physically Based**

After Einstein:

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



Wire Capacitance – Parallel Plate



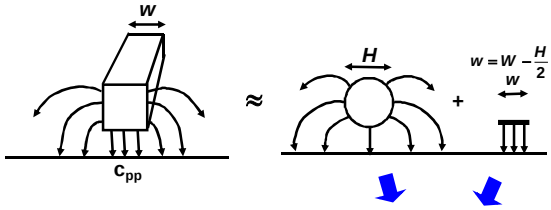
$$C = \frac{\varepsilon_0 \varepsilon_r w l}{d}$$

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

ε_0 = 8.85 pF/m

ε_r = 3.9 (SiO_2)

Wire Capacitance – Fringing Fields



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

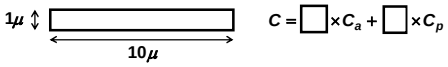
- Works reasonably well in practice
- Not directly applicable for interconnects with varying widths

Wire Capacitance – Area/Perimeter Model

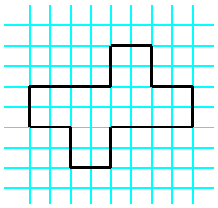
- C_a was calculated with modified wire width
- Formula inapplicable for irregular interconnects (non-constant width)

- 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	$aF/\mu m$



Area / Perimeter Capacitance Model

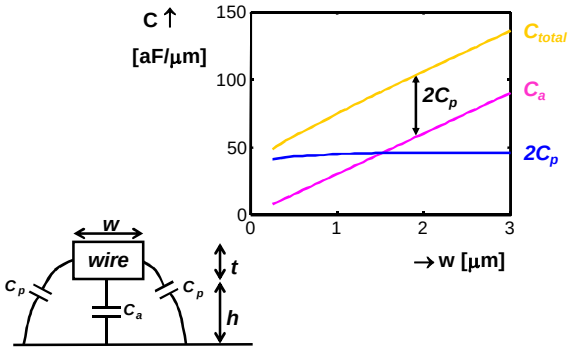


$C = \square \times C_a + \square \times C_p$

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

  How accurate is this model?

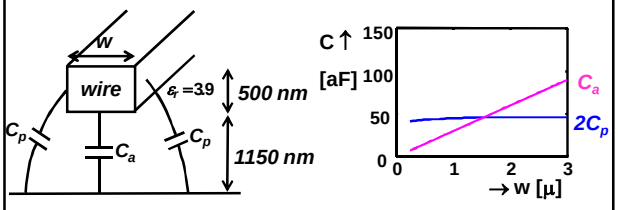
Derivation of C_a, C_p



Derivation of C_a, C_p

- 2D (cross-section) numerical computation (or measurement)
- C_l : total wire capacitance per unit length
- $C_a = \varepsilon_0 \varepsilon_r / h$
- $C_p = \frac{1}{2}(C_l - C_a \times w)$
- 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

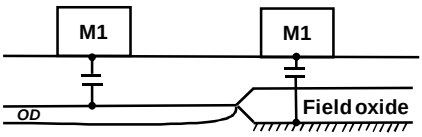
Area / Perimeter Capacitance



- 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
$C_a = 41$	$C_a = 30$	$aF/\mu m^2$
$C_p = 47$	$C_p = 40$	$aF/\mu m$

Capacitance Date (Table 4.2)

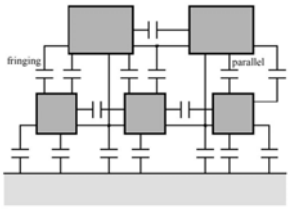
INTERCONNECT MODELS

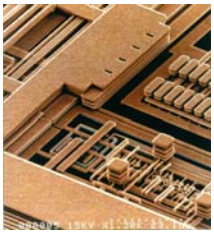
Wire area and fringe capacitances (for 0.25 µm CMOS process)

Rows represent the top plate of the capacitor, and columns represent the bottom plate. The area capacitances are expressed in aF/µm², while the fringe capacitances (given in the shaded rows) are in aF/µm.

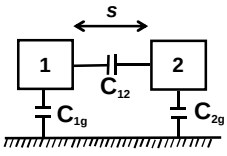
	Field	Active	Poly	Al1	Al2	Al3	Al4
Poly	88	←bottom					
	54	←fringe					
Al1	30	41	57	←bottom			
	40	47	54	←fringe			
Al2	13	15	17	36			
	25	27	29	45			

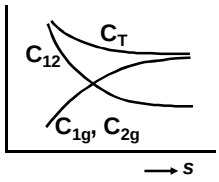
Coupling Capacitances





Coupling Capacitances (2).



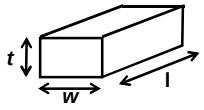


- $C_T = C_{1g} + C_{12} = C_{2g} + C_{12}$ fairly constant
- Use that as first order model
- Interconnect capacitance design data (e.g. Table 4.3)
- In practice: many pages of very many numbers
- Or: field solvers

Resistance

- Sheet resistance

Wire Resistance



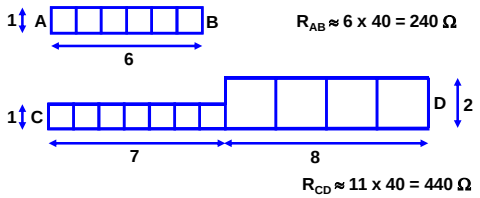
- Proportional to l
- Inversely proportional to w and t (cross-sectional area)
- Proportional to ρ: specific resistance, material property [Ωm]
- $R = \rho l/wt$
- Aluminum: $\rho = 2.7 \times 10^{-8}$ Ωm
  Copper: $\rho = 1.7 \times 10^{-8}$ Ωm

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.

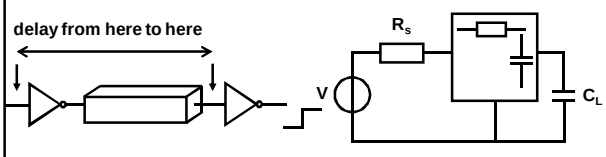
An interconnect line is made from a material that has a resistivity of ρ = 4 μΩ-cm. The interconnect is 1200 Å thick, where 1 Angstrom (Å) is 10^{-10} m. The line has a width of 0.6 μm.

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

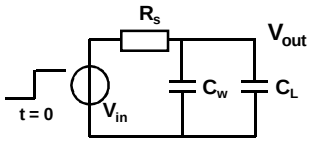
- Delay metrics, rc delay, Elmore delay

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



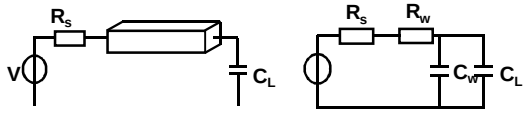
Assume wire behaves purely capacitive

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

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

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

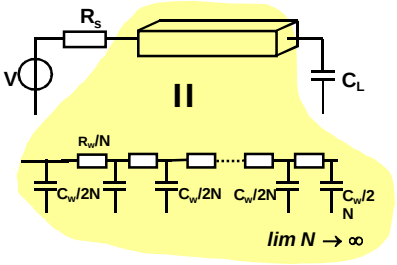
Wire Resistance

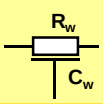


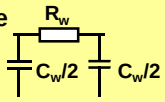
Now, assume wire capacitance *and resistance*

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

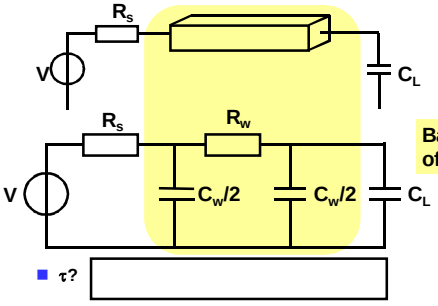
Uniform RC Line



Symbol 

[Always] use first order model 

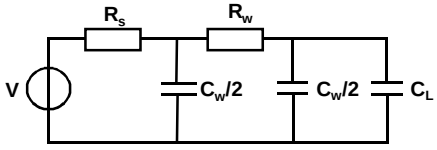
RC Delay (Uniform RC Line)



Basic π-model of wire

- τ?

Equivalent Time Constant



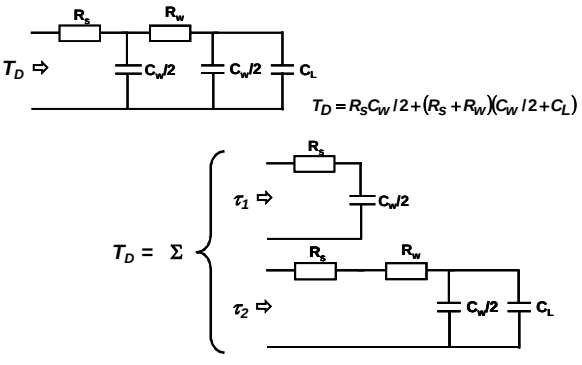
- Multiple time-constants
- Need for one "equivalent" number
- Offered by *Elmore Delay* T_D

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

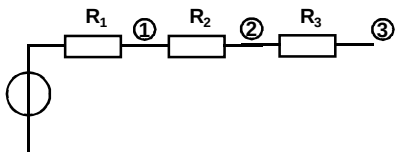
- Effective "one number" model for delay

How to compute Elmore Delay?

Equivalent Time Constant

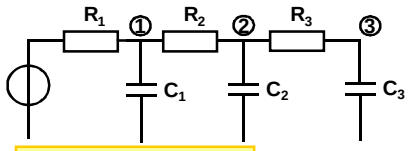


Shared Path Resistance



- 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
- $R_{12} = R_1 \quad R_{13} = R_1 \quad R_{23} =$ ☐

Elmore Delay for RC ladders



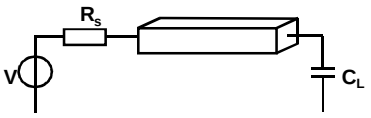
- **Define:** $T_{Di} = \sum_{k=1}^{N} R_{ik} C_k$

Elmore Delay

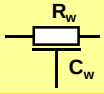
We will use $0.69 \times T_{di}$ as approximation of wire delay ($t_{50\%}$)

- $T_{D1} = R_{11}C_1 + R_{12}C_2 + R_{13}C_3 =$
  $= R_1C_1 + R_1C_2 + R_1C_3$
  $T_{D_3} = R_{31}C_1 + R_{32}C_2 + R_{33}C_3 =$
  $= R_1C_1 + (R_1 + R_2)C_2 + (R_1 + R_2 + R_3)C_3$
- $T_{D_2} =$

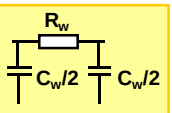
Elmore Delay for Distributed RC Lines



Symbol

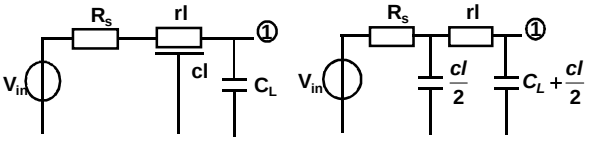


Symmetric π-model



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

Canonical Driver-Line-Load



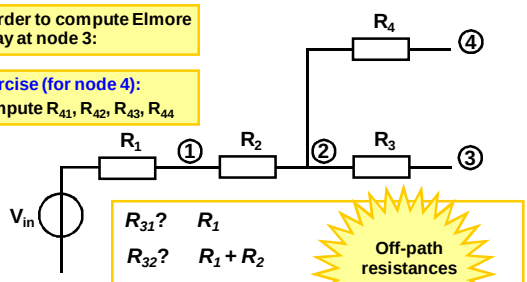
- $T_{D_1} = R_s \frac{cl}{2} + (R_s + rl)\left(C_L + \frac{cl}{2}\right)$
  $= R_s(cl + C_L) + rlC_L + \frac{1}{2}rcl^2$

- **Delay quadratic in line length**

Shared Path Resistance for Tree Structures

In order to compute Elmore Delay at node 3:

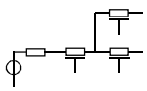
Exercise (for node 4):
Compute R_{41}, R_{42}, R_{43}, R_{44}



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

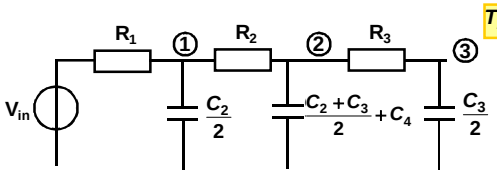
Elmore Delay for Tree Structures.



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