

EE224

Developing a delay model

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To develop a delay model you need spice decks for the transistors you will use in your design.


Names are the same, the files for n and p are different.

```
.MODEL CMOSN NMOS (
+VERSION = 3.1          TNOM    = 27          LEVEL  = 49
+XJ          = 1E-7      NCH     = 2.3549E17    TOX    = 4.1E-9
+K1          = 0.5911956 K2     = 3.921742E-3    VTH0   = 0.3721873
+K3B        = 2.3408239 WO     = 1E-7          K3     = 1.000151E-3
+DVT0W      = 0         DVT1W  = 0          NLX    = 1.651214E-7
+DVT0       = 1.6194969 DVT1   = 0.4434883    DVT2W  = 0
                                     DVT2   = 0.0377411
```

```
.MODEL CMOSP PMOS (
+VERSION = 3.1          TNOM    = 27          LEVEL  = 49
+XJ          = 1E-7      NCH     = 4.1589E17    TOX    = 4.1E-9
+K1          = 0.5733099 K2     = 0.0278862    VTH0   = -0.3872686
+K3B        = 12.2321319 WO     = 1.003165E-6    K3     = 0.0995787
+DVT0W      = 0         DVT1W  = 0          NLX    = 9.90278E-8
+DVT0       = 0.4215552 DVT1   = 0.271132    DVT2W  = 0
+U0         = 114.9805241 UA     = 1.520989E-9    DVT2   = 0.1
+UC         = -1E-10    VSAT   = 1.885817E5   UB     = 1E-21
+AGS        = 0.4141676 BO     = 3.739781E-7    AO     = 1.8494892
                                     B1     = 2.127694E-6
```

<http://www.mosis.org>

The values for A and R are not easy to get from a spice deck



What me worry?

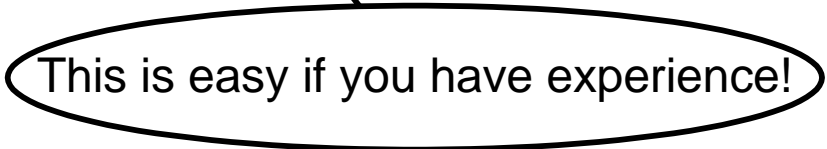
Since we need to back fit A and R anyway, it does not matter.



I do not like this.

Unfortunately, A and R can vary with width and propagation delay.

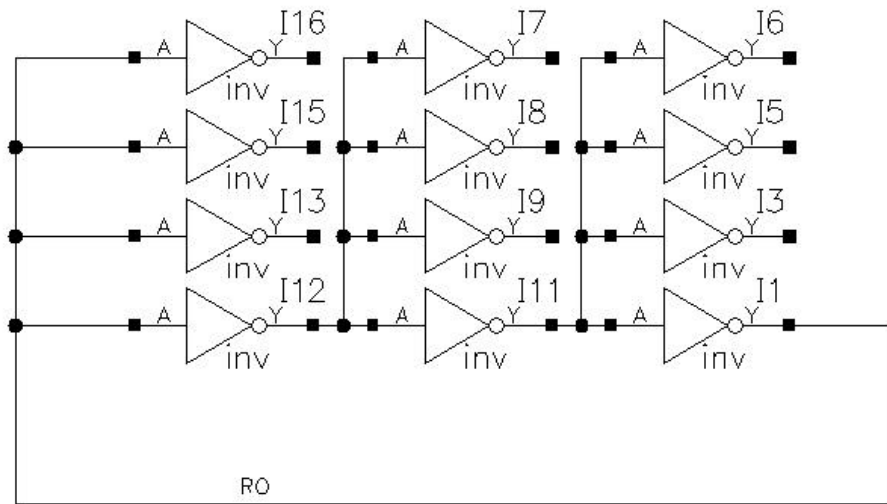
We need to decide which range of widths and propagation delays we are going to extract our model for.



This is easy if you have experience!

Do not worry if you have no experience!

We can find a range of propagation delays and widths by using a special kind of ring oscillator.



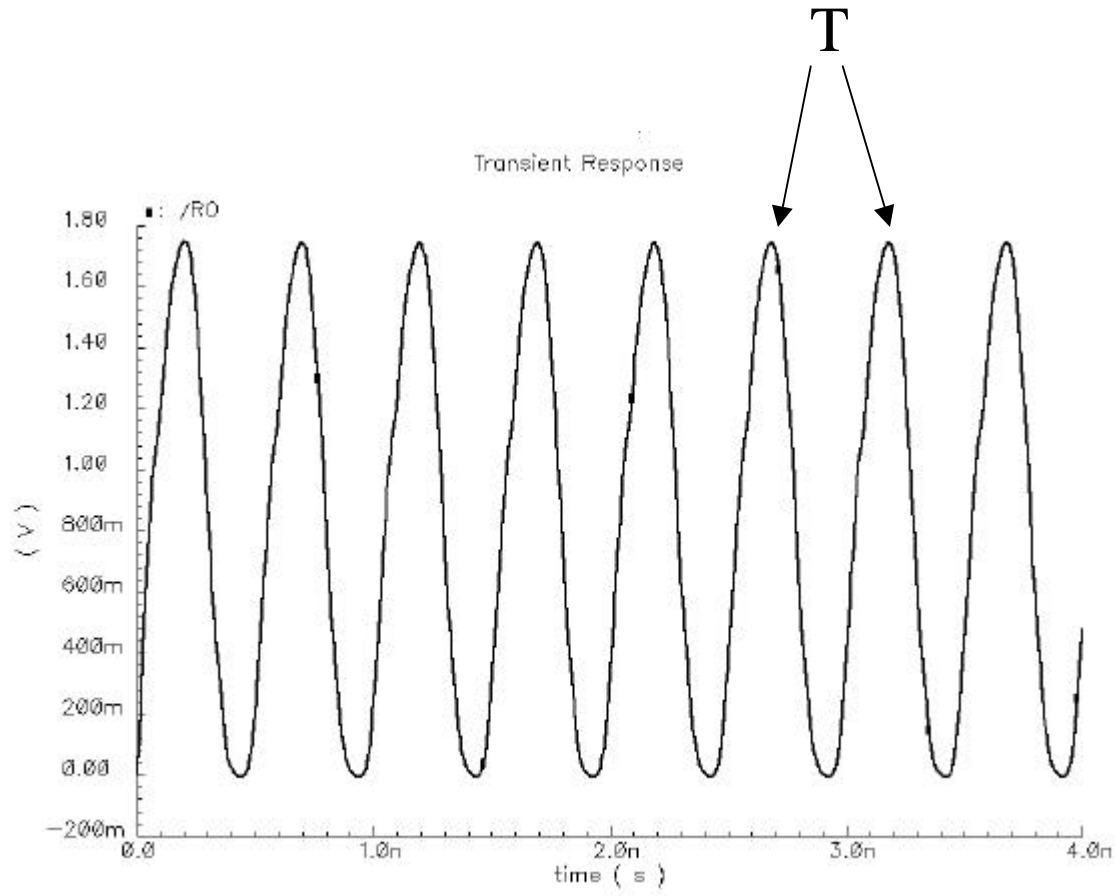
We sweep a range of $WP=2WN$ values and measure the frequency (and thus delay).

The extra inverters give a “reasonable load”

Average Propagation delay = $1/(2 \times \text{frequency of RO} \times \text{Number of stages})$

Using a ring oscillator!

vdd=1.8v, n=3.

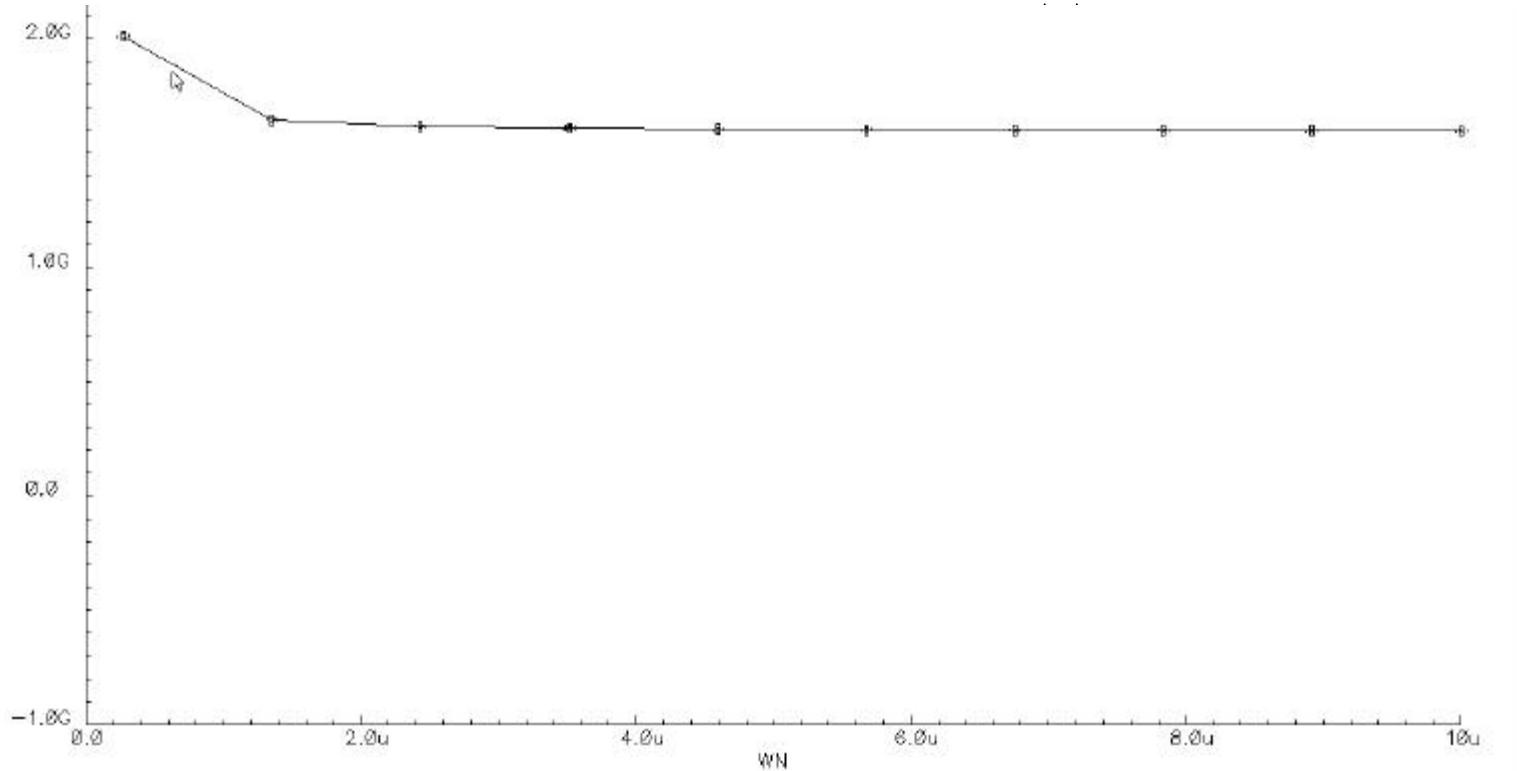


Average Propagation delay = $1/(2 \times \text{frequency of RO} \times \text{Number of stages})$

The propagation delay of interest is about 80ps over a wide range of widths for a large load.

vdd=1.8v, n=3.

T

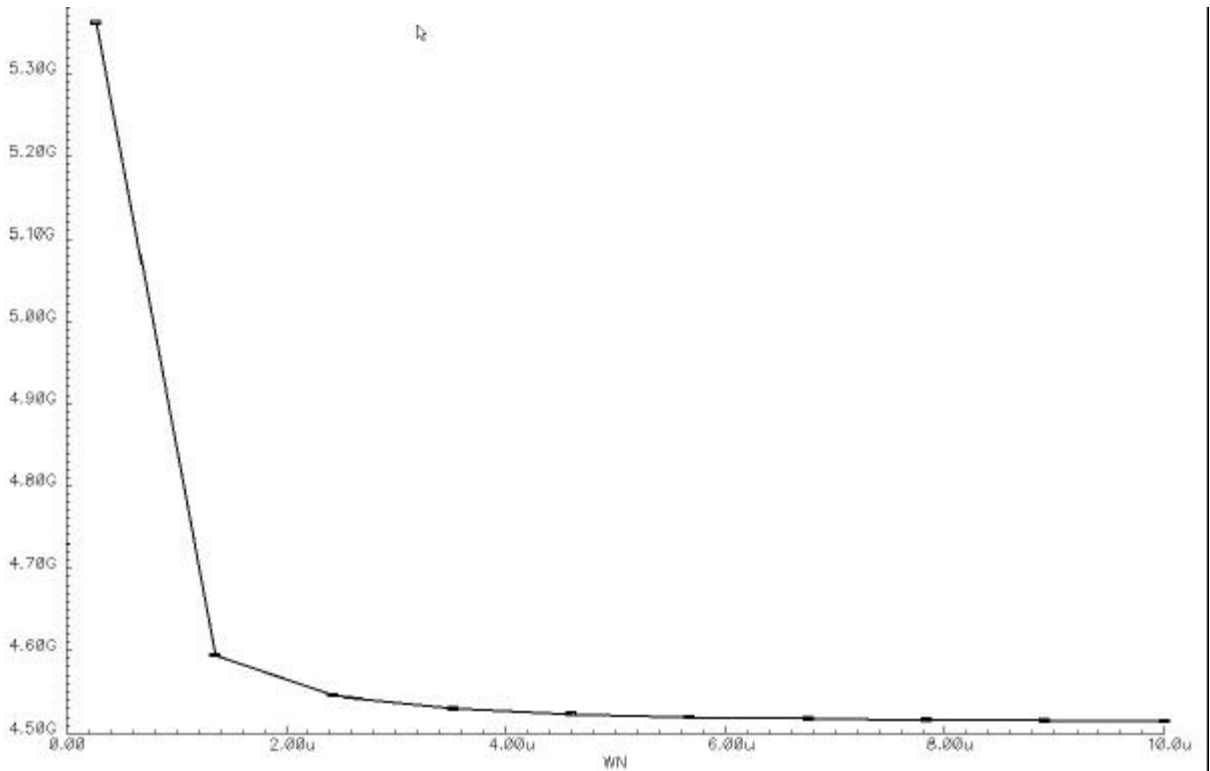


Average Propagation delay = $1 / (2 \times \text{frequency of RO} \times \text{Number of stages})$

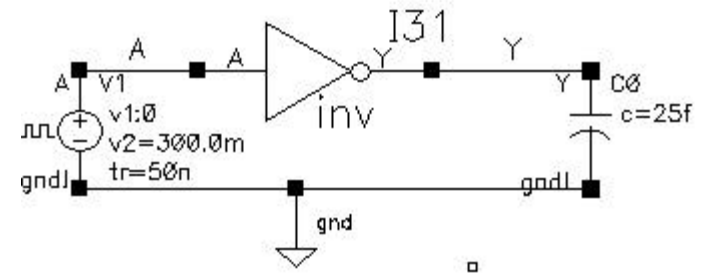
The propagation delay of interest is about 40ps over a wide range of widths for hardly any load.

vdd=1.8v, n=3.

Frequency



To extract A and R we will create an inverter test bench with vdd=1.8V, external load=25fF, and propagation delay specified to be 50ps



Guess

$$A := 10000\Omega \quad C_{J\text{SWN}} := 2.47 \cdot 10^{-12} \frac{\text{F}}{\text{cm}} \quad C_{\text{JN}} := 9.53 \cdot 10^{-8} \frac{\text{F}}{\text{cm}^2} \quad C_{\text{GDON}} := 8.35 \cdot 10^{-12} \frac{\text{F}}{\text{cm}}$$

$$L_{\text{N}} := .18 \cdot 10^{-4} \text{cm} \quad K_{\text{EQ}} := \frac{-2\sqrt{.84}}{-1.8} \cdot (\sqrt{.84 + 1.8} - \sqrt{.84}) \quad K_{\text{EQ}} = 0.721 \quad D_{\text{D}} := .36 \cdot 10^{-4} \text{cm}$$

$$C_{\text{g}} := 25 \cdot 10^{-15} \text{F} \quad N := 1 \quad N_{\text{SN}} := 1$$

$$\tau_{\text{PHL}} := .05 \cdot 10^{-9} \text{s} \quad M := 1 \quad N_{\text{SP}} := 1 \quad S := 1 \quad R := 2 \cdot \frac{N_{\text{SP}} \cdot S}{N_{\text{SN}}}$$

$$W_{\text{N}} := \frac{C_{\text{g}} + C_{\text{JSWN}} \cdot 2 \cdot D_{\text{D}} \cdot K_{\text{EQ}} \cdot (N + M)}{\frac{\tau_{\text{PHL}}}{N_{\text{SN}} \cdot L_{\text{N}} \cdot A} - (N + M \cdot R) \cdot (C_{\text{JSWN}} \cdot 2 \cdot K_{\text{EQ}} + C_{\text{JN}} \cdot D_{\text{D}} \cdot K_{\text{EQ}} + 2 \cdot C_{\text{GDON}})}$$

Guess

$$W_{\text{N}} = 1.205 \times 10^{-4} \text{cm}$$

$$W_{\text{P}} := R \cdot W_{\text{N}} \quad W_{\text{P}} = 2.41 \times 10^{-4} \text{cm}$$

To extract A and R use initial WN and WP Values and refine with successive spice runs

$$\tau_{\text{PHL_M}} := (55.93 - 5) \cdot 10^{-12} \text{ s}$$

$$\tau_{\text{PLH_M}} := (1060 - 1005) \cdot 10^{-12} \text{ s}$$

$$W_{\text{N}} := \frac{\tau_{\text{PHL_M}}}{\tau_{\text{PHL}}} \cdot W_{\text{N}}$$

$$W_{\text{N}} = 1.228 \times 10^{-4} \text{ cm}$$

$$\text{Error} := \frac{\tau_{\text{PHL}} - \tau_{\text{PHL_M}}}{\tau_{\text{PHL}}} \cdot 100$$

$$\text{Error} = -1.86$$

$$W_{\text{P}} := \frac{\tau_{\text{PLH_M}}}{\tau_{\text{PLH}}} \cdot W_{\text{P}}$$

$$W_{\text{P}} = 2.651 \times 10^{-4} \text{ cm}$$

$$\text{Error} := \frac{\tau_{\text{PLH}} - \tau_{\text{PLH_M}}}{\tau_{\text{PLH}}} \cdot 100$$

$$\text{Error} = -10$$

Use these values next run.

Repeat this until you are less than 1% error

$$\tau_{\text{PHL_M}} := (55.28 - 5) \cdot 10^{-14} \text{ s}$$

$$\tau_{\text{PLH_M}} := (1055.2 - 1005) \cdot 10^{-12} \text{ s}$$

$$W_{\text{N}} := \frac{\tau_{\text{PHL_M}}}{\tau_{\text{PHL}}} \cdot W_{\text{N}}$$

$$W_{\text{N}} = 1.277 \times 10^{-4} \text{ cm}$$

$$\text{Error} := \frac{\tau_{\text{PHL}} - \tau_{\text{PHL_M}}}{\tau_{\text{PHL}}} \cdot 100$$

$$\text{Error} = -0.56$$

$$W_{\text{P}} := \frac{\tau_{\text{PLH_M}}}{\tau_{\text{PLH}}} \cdot W_{\text{P}}$$

$$W_{\text{P}} = 2.758 \times 10^{-4} \text{ cm}$$

$$\text{Error} := \frac{\tau_{\text{PLH}} - \tau_{\text{PLH_M}}}{\tau_{\text{PLH}}} \cdot 100$$

$$\text{Error} = -0.4$$

Note: We use this level of accuracy for extraction only!
Parameters can vary by 10% in fabricated designs.

Extract R by taking the WP/WN ratio of the transistors that met specification

$$R := \frac{W_P}{W_N} \quad R = 2.16$$

This is for an nmos that is mostly velocity saturated

Extract A with the prop delay, R, WN and WP values found from simulation

Change this value

$$A := 10300\Omega \quad C_{J\text{SWN}} := 2.47 \cdot 10^{-12} \frac{\text{F}}{\text{cm}} \quad C_{\text{JN}} := 9.53 \cdot 10^{-8} \frac{\text{F}}{\text{cm}^2} \quad C_{\text{GDON}} := 8.35 \cdot 10^{-12} \frac{\text{F}}{\text{cm}}$$

$$L_{\text{N}} := .18 \cdot 10^{-4} \text{cm} \quad K_{\text{EQ}} := \frac{-2\sqrt{.84}}{-1.8} \cdot (\sqrt{.84 + 1.8} - \sqrt{.84}) \quad K_{\text{EQ}} = 0.721 \quad D_{\text{D}} := .36 \cdot 10^{-4} \text{cm}$$

$$C_{\text{g}} := 25 \cdot 10^{-15} \text{F} \quad N := 1 \quad N_{\text{SN}} := 1$$

$$\tau_{\text{PHL}} := .05 \cdot 10^{-9} \text{s} \quad M := 1 \quad N_{\text{SP}} := 1 \quad S := 1 \quad R := 2.16$$

$$W_{\text{N}} := \frac{C_{\text{g}} + C_{\text{JSWN}} \cdot 2 \cdot D_{\text{D}} \cdot K_{\text{EQ}} \cdot (N + M)}{\frac{\tau_{\text{PHL}}}{N_{\text{SN}} \cdot L_{\text{N}} \cdot A} - (N + M \cdot R) \cdot (C_{\text{JSWN}} \cdot 2K_{\text{EQ}} + C_{\text{JN}} \cdot D_{\text{D}} \cdot K_{\text{EQ}} + 2 \cdot C_{\text{GDON}})}$$

Are we done?

$$W_{\text{N}} = 1.277 \times 10^{-4} \text{cm} \quad \leftarrow \text{Until these match simulation}$$

$$W_{\text{P}} := R \cdot W_{\text{N}} \quad W_{\text{P}} = 2.758 \times 10^{-4} \text{cm} \quad \leftarrow$$

Attempt to break the model by changing the load

$$A := 10300\Omega \quad C_{J\text{SWN}} := 2.47 \cdot 10^{-12} \frac{\text{F}}{\text{cm}} \quad C_{\text{JN}} := 9.53 \cdot 10^{-8} \frac{\text{F}}{\text{cm}^2} \quad C_{\text{GDON}} := 8.35 \cdot 10^{-12} \frac{\text{F}}{\text{cm}}$$

$$L_{\text{N}} := .18 \cdot 10^{-4} \text{cm} \quad K_{\text{EQ}} := \frac{-2\sqrt{.84}}{-1.8} \cdot (\sqrt{.84 + 1.8} - \sqrt{.84}) \quad K_{\text{EQ}} = 0.721 \quad D_{\text{D}} := .36 \cdot 10^{-4} \text{cm}$$

$$C_{\text{g}} := 50 \cdot 10^{-15} \text{F} \quad N := 1 \quad N_{\text{SN}} := 1$$

$$\tau_{\text{PHL}} := .05 \cdot 10^{-9} \text{s} \quad M := 1 \quad N_{\text{SP}} := 1 \quad S := 1 \quad R := 2.16$$

$$W_{\text{N}} := \frac{C_{\text{g}} + C_{\text{JSWN}} \cdot 2 \cdot D_{\text{D}} \cdot K_{\text{EQ}} \cdot (N + M)}{\frac{\tau_{\text{PHL}}}{N_{\text{SN}} \cdot L_{\text{N}} \cdot A} - (N + M \cdot R) \cdot (C_{\text{JSWN}} \cdot 2 \cdot K_{\text{EQ}} + C_{\text{JN}} \cdot D_{\text{D}} \cdot K_{\text{EQ}} + 2 \cdot C_{\text{GDON}})}$$

$$W_{\text{N}} = 2.54 \times 10^{-4} \text{cm}$$

$$W_{\text{P}} := R \cdot W_{\text{N}} \quad W_{\text{P}} = 5.487 \times 10^{-4} \text{cm}$$

Produced and error of less than 3%! for a doubling of C_{g} !

Attempt to break the model by changing the delay

$$A := 10300\Omega \quad C_{J\text{SWN}} := 2.47 \cdot 10^{-12} \frac{\text{F}}{\text{cm}} \quad C_{\text{JN}} := 9.53 \cdot 10^{-8} \frac{\text{F}}{\text{cm}^2} \quad C_{\text{GDON}} := 8.35 \cdot 10^{-12} \frac{\text{F}}{\text{cm}}$$

$$L_{\text{N}} := .18 \cdot 10^{-4} \text{cm} \quad K_{\text{EQ}} := \frac{-2\sqrt{.84}}{-1.8} \cdot (\sqrt{.84 + 1.8} - \sqrt{.84}) \quad K_{\text{EQ}} = 0.721 \quad D_{\text{D}} := .36 \cdot 10^{-4} \text{cm}$$

$$C_{\text{g}} := 25 \cdot 10^{-15} \text{F} \quad N := 1 \quad N_{\text{SN}} := 1$$

$$\tau_{\text{PHL}} := .03 \cdot 10^{-9} \text{s} \quad M := 1 \quad N_{\text{SP}} := 1 \quad S := 1 \quad R := 2.16$$

$$W_{\text{N}} := \frac{C_{\text{g}} + C_{\text{JSWN}} \cdot 2 \cdot D_{\text{D}} \cdot K_{\text{EQ}} \cdot (N + M)}{\frac{\tau_{\text{PHL}}}{N_{\text{SN}} \cdot L_{\text{N}} \cdot A} - (N + M \cdot R) \cdot (C_{\text{JSWN}} \cdot 2K_{\text{EQ}} + C_{\text{JN}} \cdot D_{\text{D}} \cdot K_{\text{EQ}} + 2 \cdot C_{\text{GDON}})}$$

$$W_{\text{N}} = 2.808 \times 10^{-4} \text{cm}$$

$$W_{\text{P}} := R \cdot W_{\text{N}} \quad W_{\text{P}} = 6.064 \times 10^{-4} \text{cm}$$

Produced and error of less than 12%! Note: It was faster than expected.

Attempt to break the model by changing the delay and load

$$C_g := 50 \cdot 10^{-15} \text{ F} \quad N := 1 \quad N_{SN} := 1$$

$$\tau_{PHL} := .03 \cdot 10^{-9} \text{ s} \quad M := 1 \quad N_{SP} := 1 \quad S := 1 \quad R := 2.16$$

$$W_N := \frac{C_g + C_{JSWN} \cdot 2 \cdot D_D \cdot K_{EQ} \cdot (N + M)}{\frac{\tau_{PHL}}{N_{SN} \cdot L_N \cdot A} - (N + M \cdot R) \cdot (C_{JSWN} \cdot 2 \cdot K_{EQ} + C_{JN} \cdot D_D \cdot K_{EQ} + 2 \cdot C_{GDON})}$$

$$W_N = 5.586 \times 10^{-4} \text{ cm}$$

$$W_P := R \cdot W_N \quad W_P = 1.207 \times 10^{-3} \text{ cm}$$

Produced and error of less than 13%! Note: It was faster than expected.

Summary

- We developed a model that will help us select values for W_N and W_P for a CMOS inverter using the TSMC .18 process
 - Reasonably good fit for delays from 30-50ps and loads from 25 to 50fF
- Some companies have a tool that does this automatically
 - You need to know how it work, so when it break, you can fix it!

Summary

- The nmos was velocity saturated, so the R value and the A value will be different for nand and nor gates.