Introduction to CMOS VLSI Design

Lecture 4: DC & Transient Response

Outline

- DC Response
- Logic Levels and Noise Margins
- Transient Response
- Delay Estimation

Activity

1) If the width of a transistor increases, the current will

increase decrease not change

2) If the length of a transistor increases, the current will

increase decrease not change

3) If the supply voltage of a chip increases, the maximum transistor current will

increase decrease not change

4) If the width of a transistor increases, its gate capacitance will

increase decrease not change

5) If the length of a transistor increases, its gate capacitance will

increase decrease not change

6) If the supply voltage of a chip increases, the gate capacitance of each transistor will

increase decrease not change

Activity

1) If the width of a transistor increases, the current will

increase decrease not change

2) If the length of a transistor increases, the current will

increase **decrease** not change

3) If the supply voltage of a chip increases, the maximum transistor current will

increase decrease not change

4) If the width of a transistor increases, its gate capacitance will

increase decrease not change

5) If the length of a transistor increases, its gate capacitance will

increase decrease not change

6) If the supply voltage of a chip increases, the gate capacitance of each transistor will

increase decrease **not change**

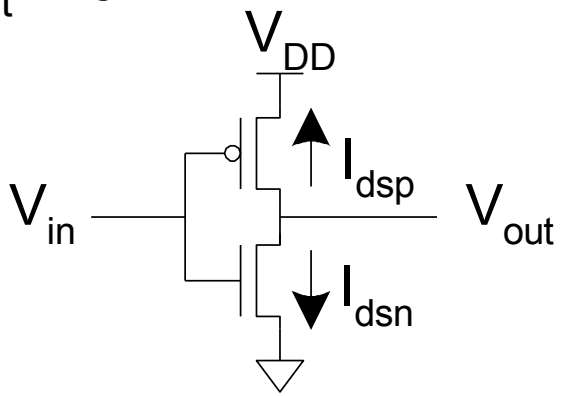
2長度越長 電阻越大 電流越小
3供給電壓
4電晶體越長 越寬 電容也就越長 越大

輸出

DC Response

- DC Response: V_{out} vs. V_{in} for a gate
- Ex: Inverter
  - When $V_{in} = 0$ -> $V_{out} = V_{DD}$
  - When $V_{in} = V_{DD}$ -> $V_{out} = 0$
  - In between, V_{out} depends on transistor size and current
  - By KCL, must settle such that $I_{dsn} = |I_{dsp}|$
  - We could solve equations
  - But graphical solution gives more insight

輸出 取決於
電晶體的大小 和 電流

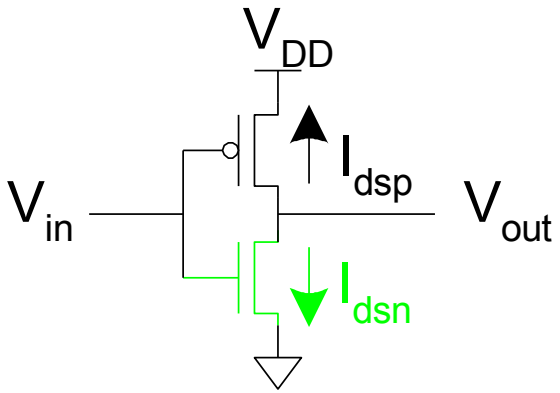


Transistor Operation

- Current depends on region of transistor behavior
- For what V_{in} and V_{out} are nMOS and pMOS in
  - Cutoff?
  - Linear?
  - Saturation?

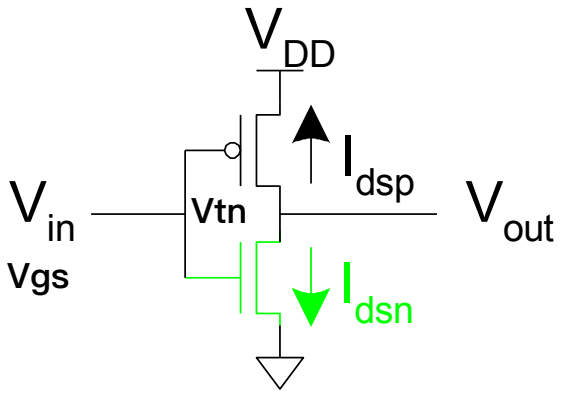
nMOS Operation

Cutoff	Linear	Saturated
V_{gsn} <	V_{gsn} >	V_{gsn} >
	V_{dsn} <	V_{dsn} >



nMOS Operation

Cutoff	Linear	Saturated
$V_{gsn} < V_{tn}$ 這裡是要走下面的狀況 1導通	$V_{gsn} > V_{tn}$ $V_{dsn} < V_{gsn} - V_{tn}$	$V_{gsn} > V_{tn}$ $V_{dsn} > V_{gsn} - V_{tn}$

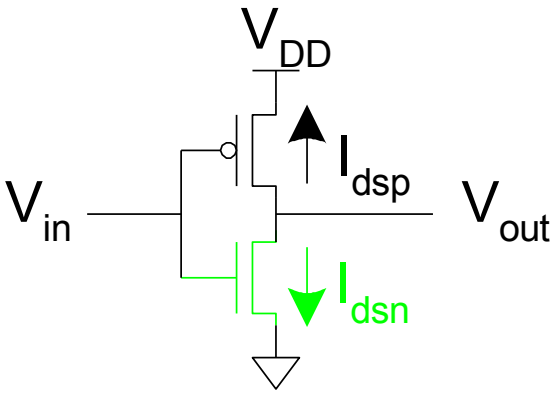


nMOS Operation

Cutoff	Linear	Saturated
$V_{gsn} < V_{tn}$	$V_{gsn} > V_{tn}$ $V_{dsn} < V_{gsn} - V_{tn}$	$V_{gsn} > V_{tn}$ $V_{dsn} > V_{gsn} - V_{tn}$

$V_{gsn} = V_{in}$

$V_{dsn} = V_{out}$

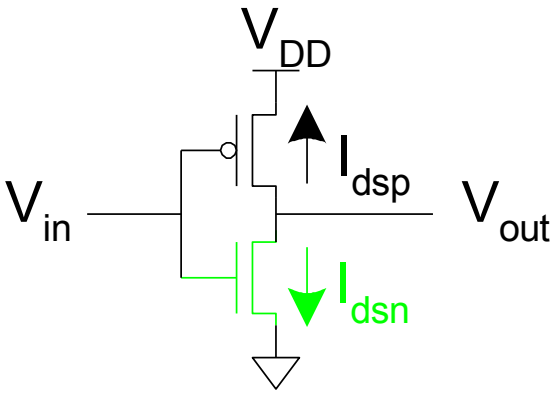


nMOS Operation

Cutoff	Linear	Saturated
$V_{gsn} < V_{tn}$ $V_{in} < V_{tn}$	$V_{gsn} > V_{tn}$ $V_{in} > V_{tn}$ $V_{dsn} < V_{gsn} - V_{tn}$ $V_{out} < V_{in} - V_{tn}$	$V_{gsn} > V_{tn}$ $V_{in} > V_{tn}$ $V_{dsn} > V_{gsn} - V_{tn}$ $V_{out} > V_{in} - V_{tn}$

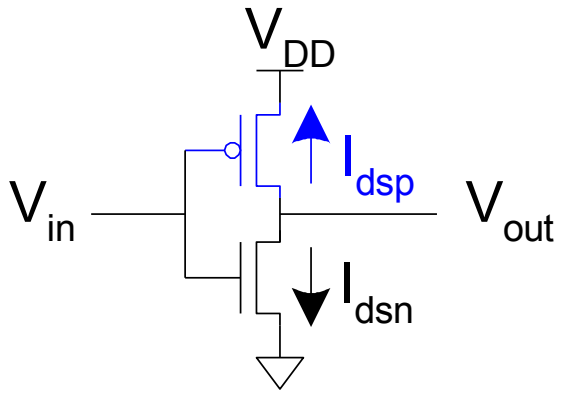
$V_{gsn} = V_{in}$

$V_{dsn} = V_{out}$



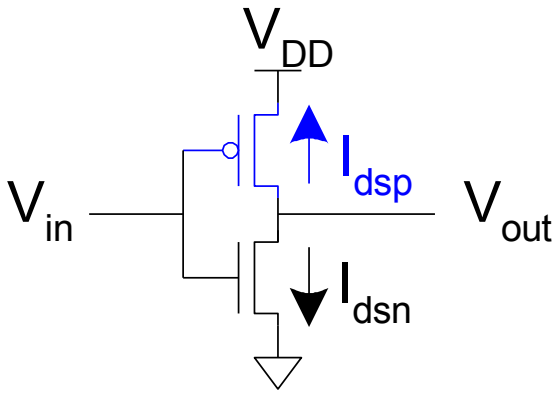
pMOS Operation

Cutoff	Linear	Saturated
$V_{gsp} >$	$V_{gsp} <$ $V_{dsp} >$	$V_{gsp} <$ $V_{dsp} <$



pMOS Operation

Cutoff	Linear	Saturated
$V_{gsp} > V_{tp}$	$V_{gsp} < V_{tp}$ $V_{dsp} > V_{gsp} - V_{tp}$	$V_{gsp} < V_{tp}$ $V_{dsp} < V_{gsp} - V_{tp}$



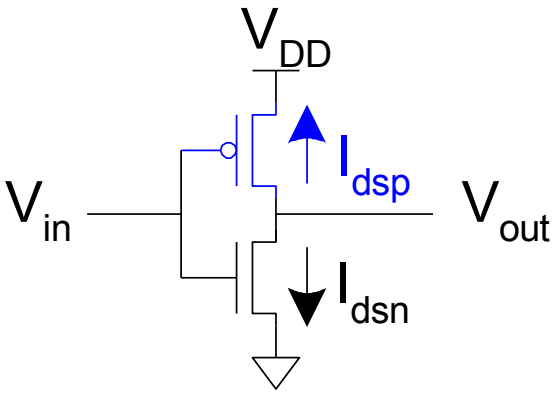
pMOS Operation

Cutoff	Linear	Saturated
$V_{gsp} > V_{tp}$	$V_{gsp} < V_{tp}$ $V_{dsp} > V_{gsp} - V_{tp}$	$V_{gsp} < V_{tp}$ $V_{dsp} < V_{gsp} - V_{tp}$

$V_{gsp} = V_{in} - V_{DD}$

$V_{dsp} = V_{out} - V_{DD}$

$V_{tp} < 0$



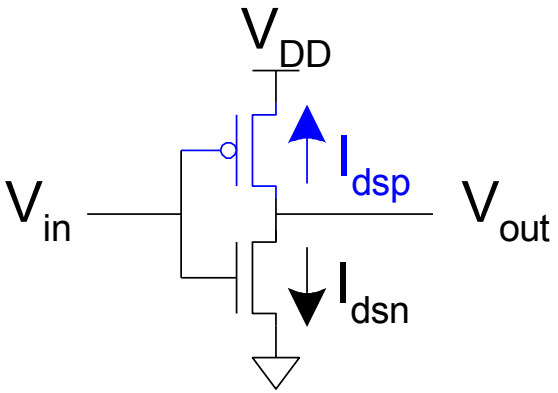
pMOS Operation

Cutoff	Linear	Saturated
$V_{gsp} > V_{tp}$ $V_{in} > V_{DD} + V_{tp}$ 這裡是要走上面的狀況 Pmos 0導通	$V_{gsp} < V_{tp}$ $V_{in} < V_{DD} + V_{tp}$ $V_{dsp} > V_{gsp} - V_{tp}$ $V_{out} > V_{in} - V_{tp}$	$V_{gsp} < V_{tp}$ $V_{in} < V_{DD} + V_{tp}$ $V_{dsp} < V_{gsp} - V_{tp}$ $V_{out} < V_{in} - V_{tp}$

$V_{gsp} = V_{in} - V_{DD}$

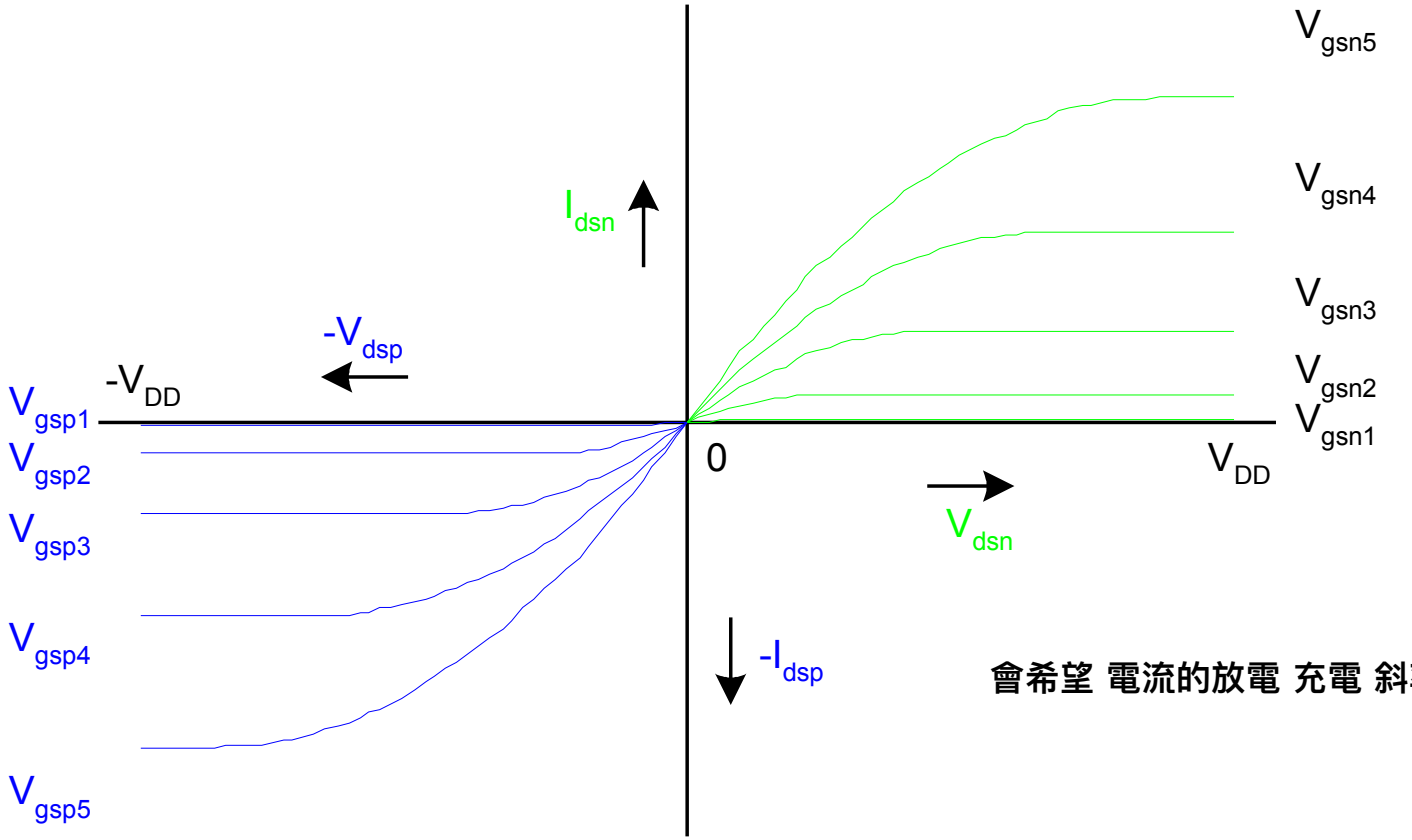
$V_{dsp} = V_{out} - V_{DD}$

$V_{tp} < 0$

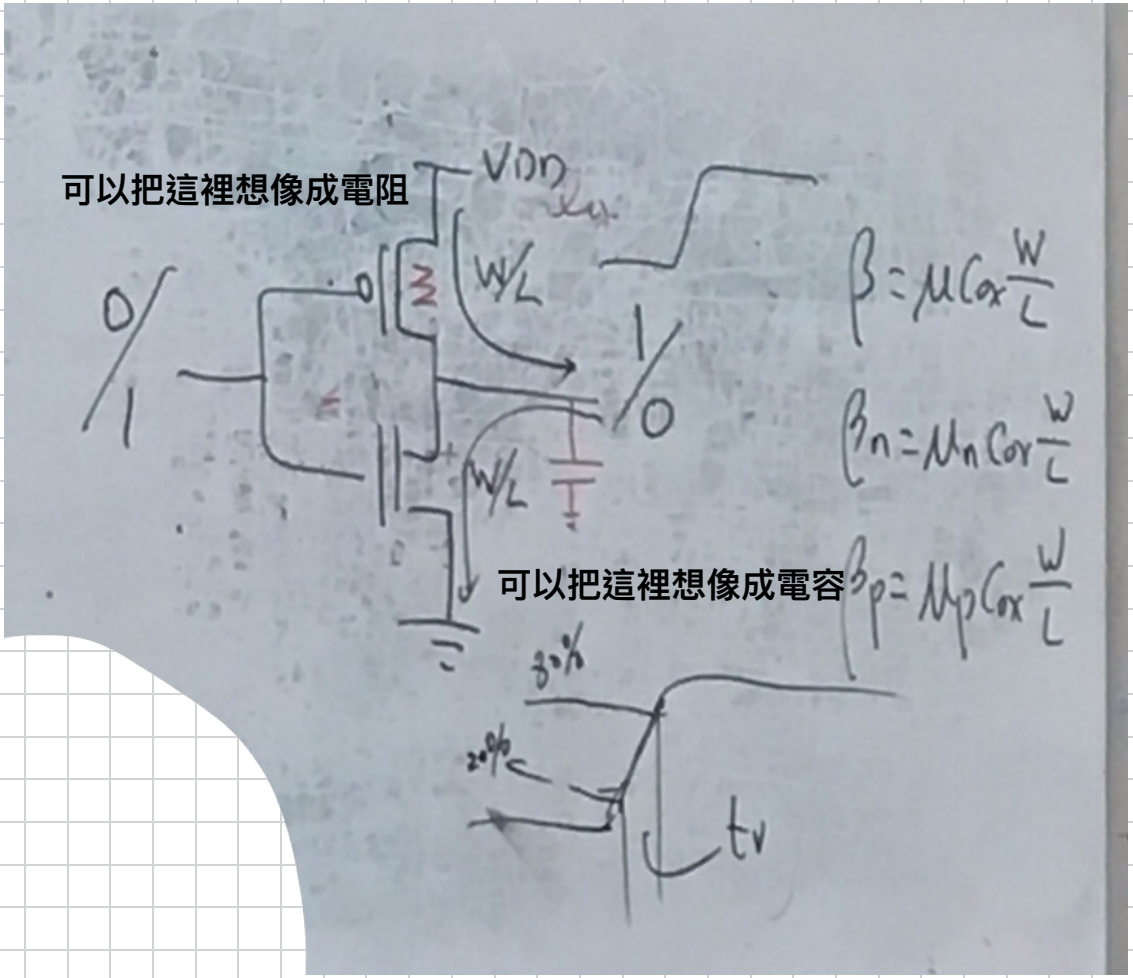


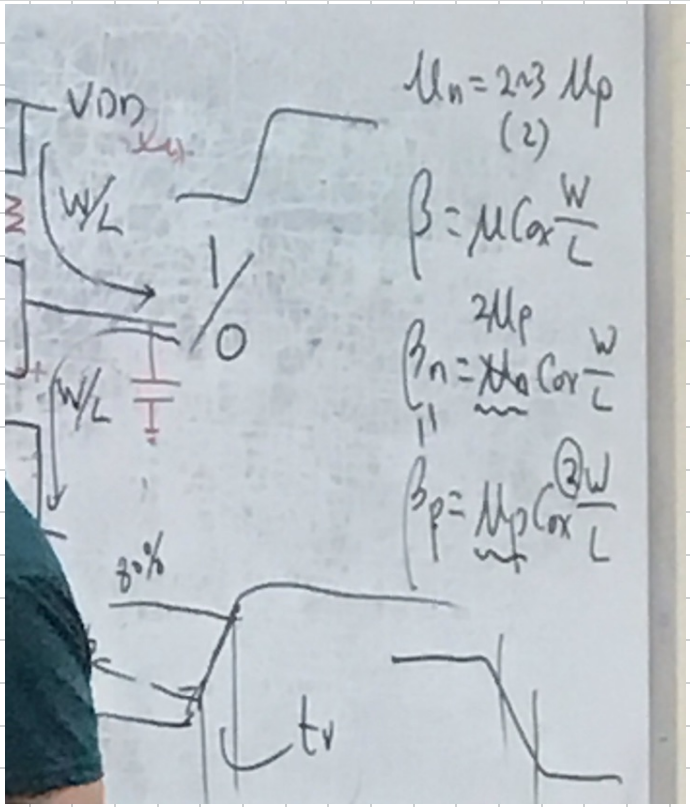
I-V Characteristics

- Make pMOS is wider than nMOS such that $\beta_n = \beta_p$

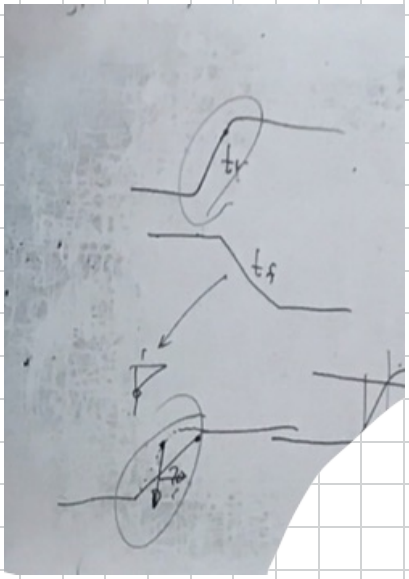


會希望 電流的放電 充電 斜率是一樣的



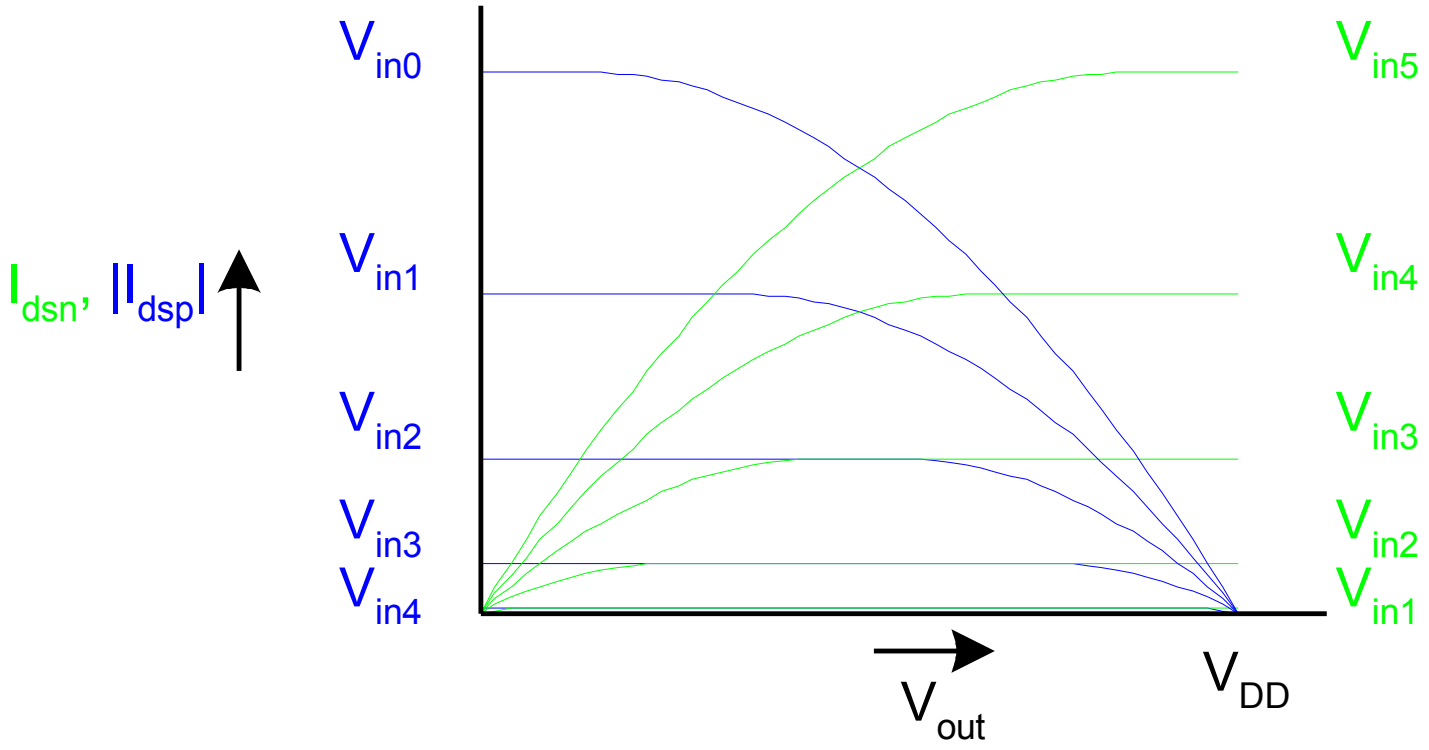


Beta 當作 導電係數



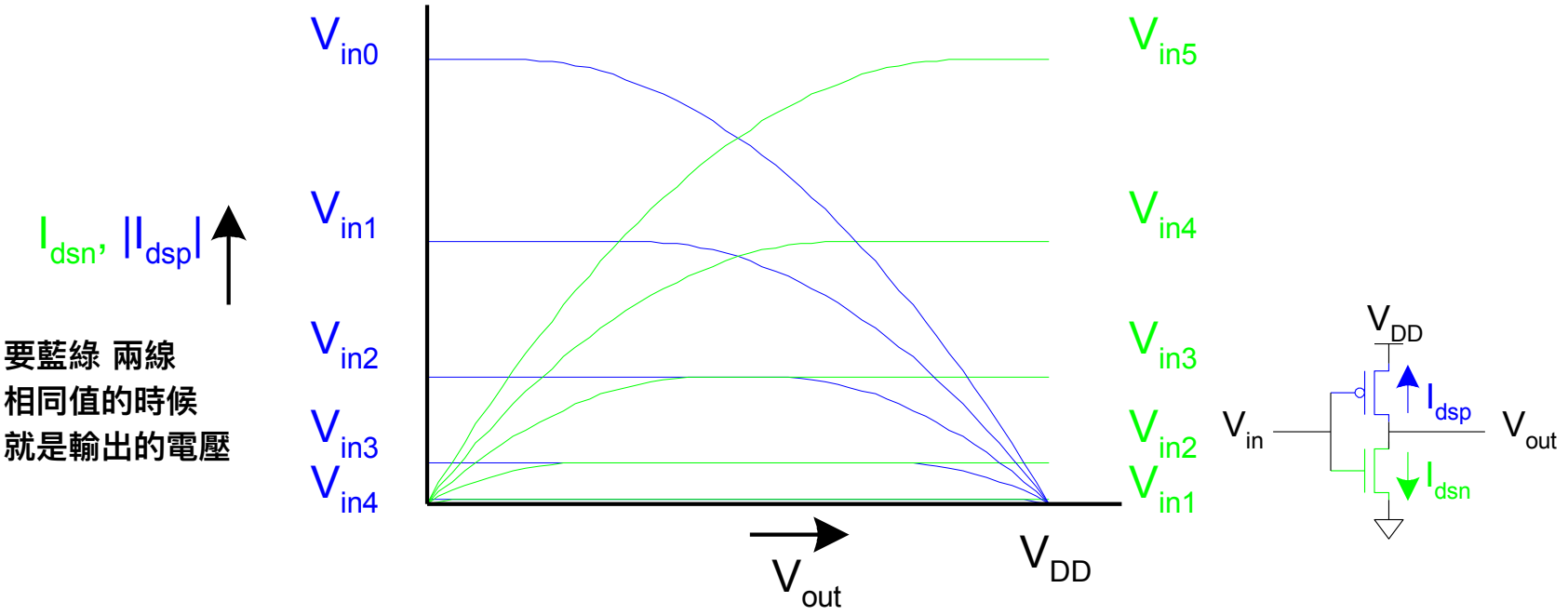
如果斜率不一樣 就會有延遲 會不好決定收取時間

Current vs. V_{out}, V_{in}



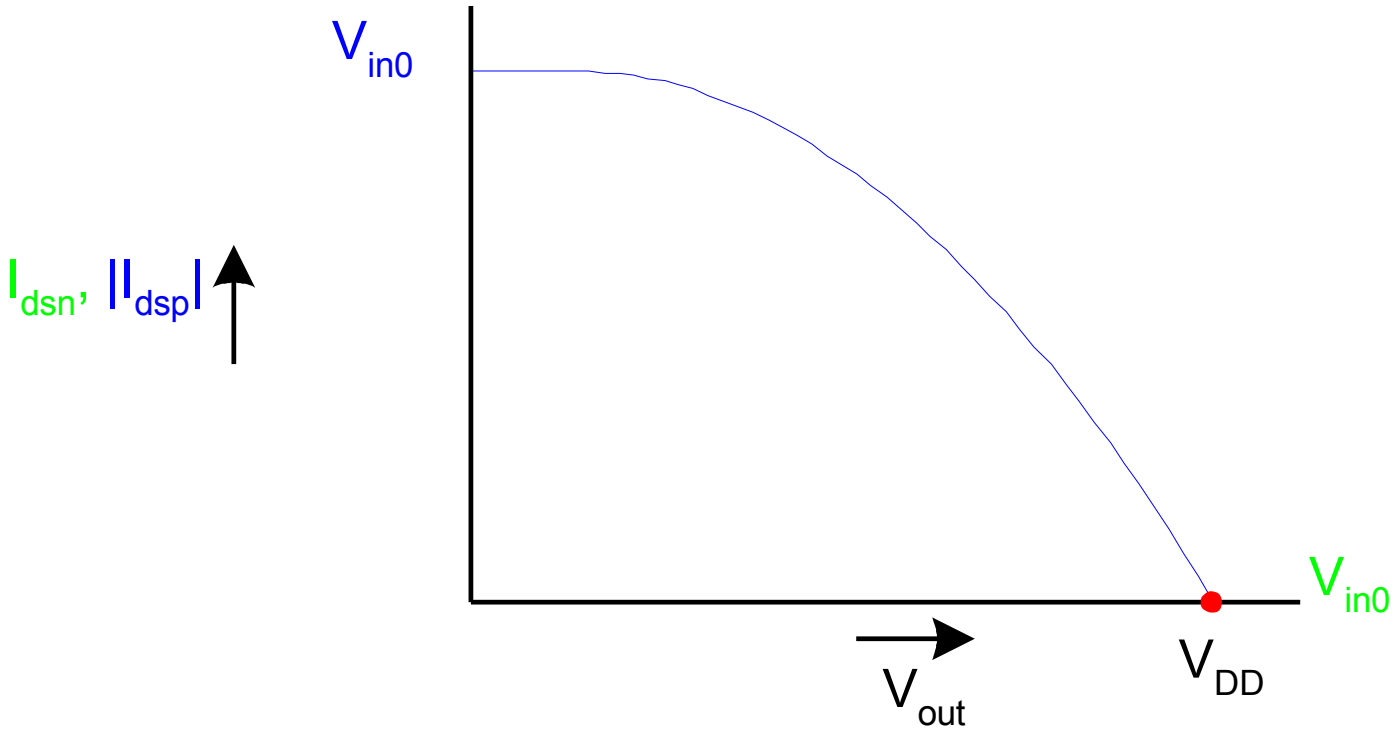
Load Line Analysis

- For a given V_{in}:
  - Plot I_{dsn}, I_{dsp} vs. V_{out}
  - V_{out} must be where |currents| are equal in



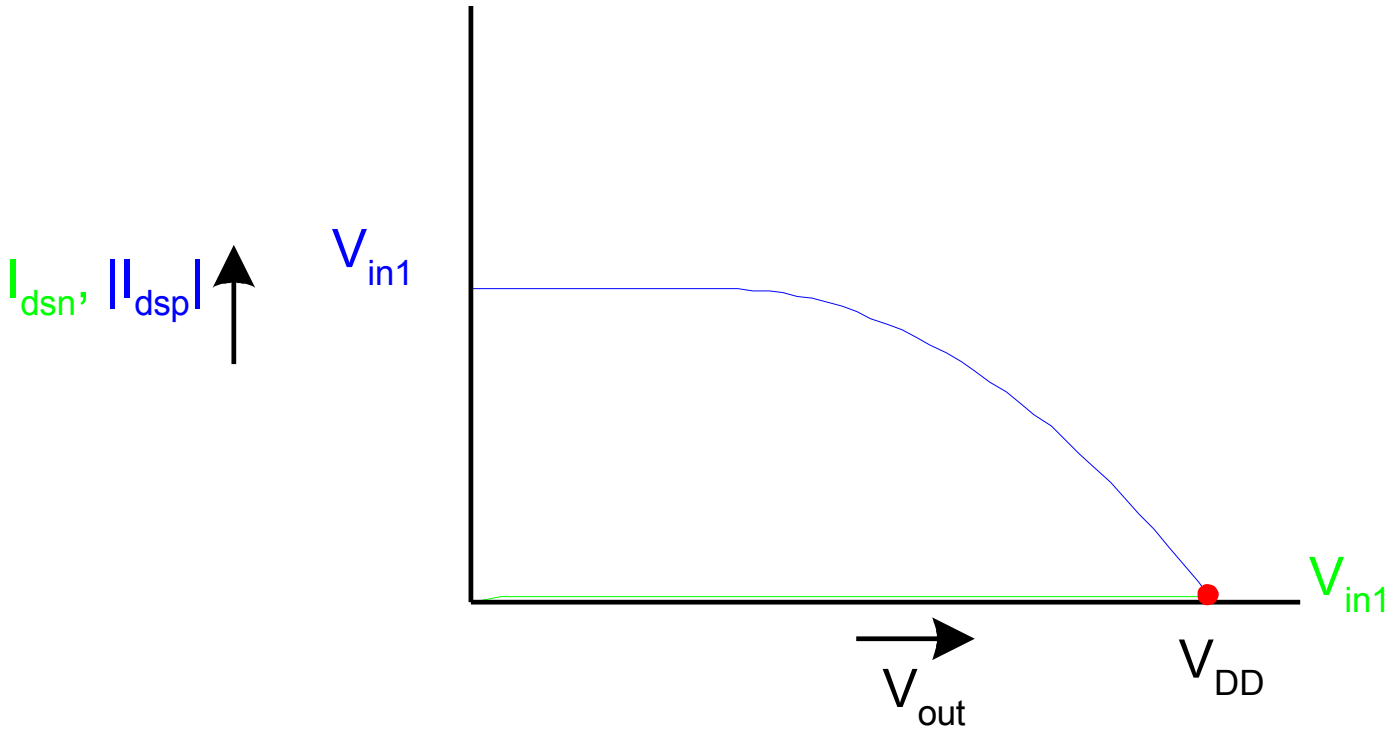
Load Line Analysis

- $V_{in} = 0$



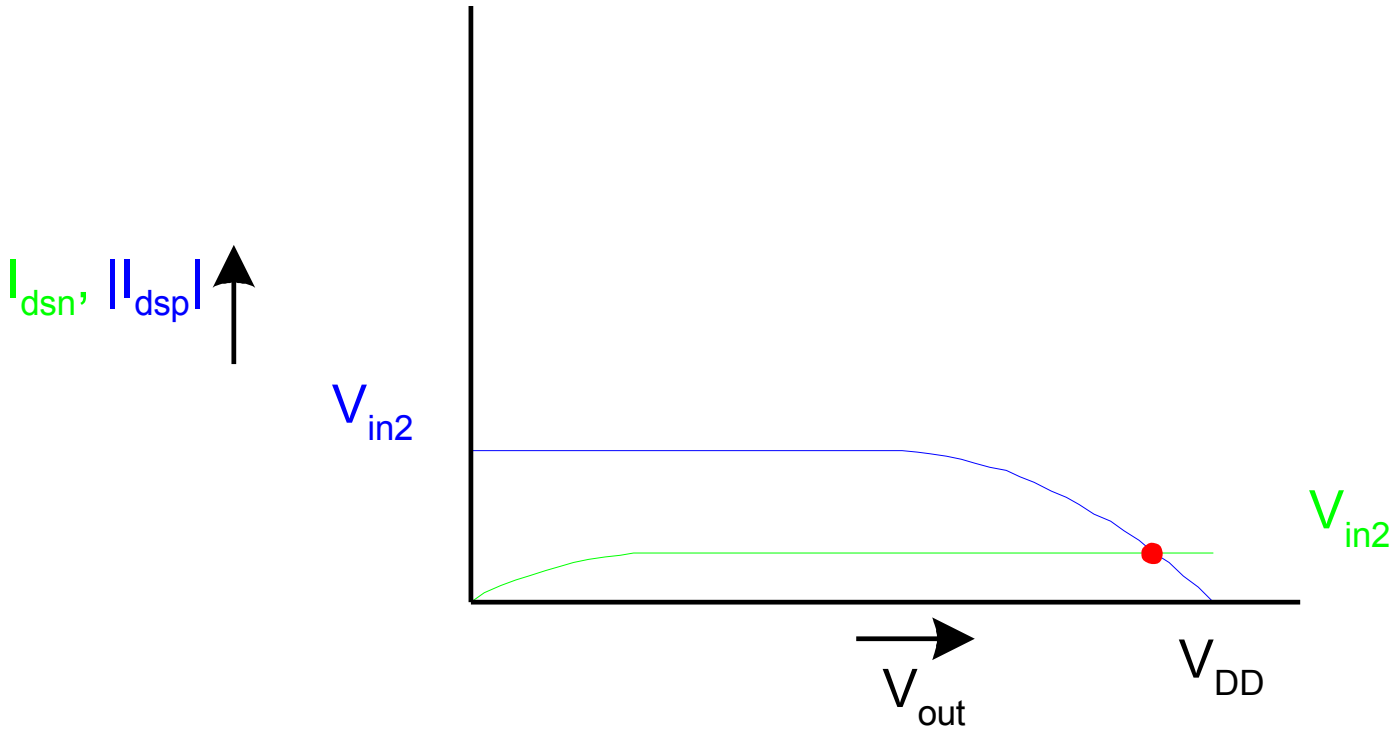
Load Line Analysis

- $V_{in} = 0.2V_{DD}$



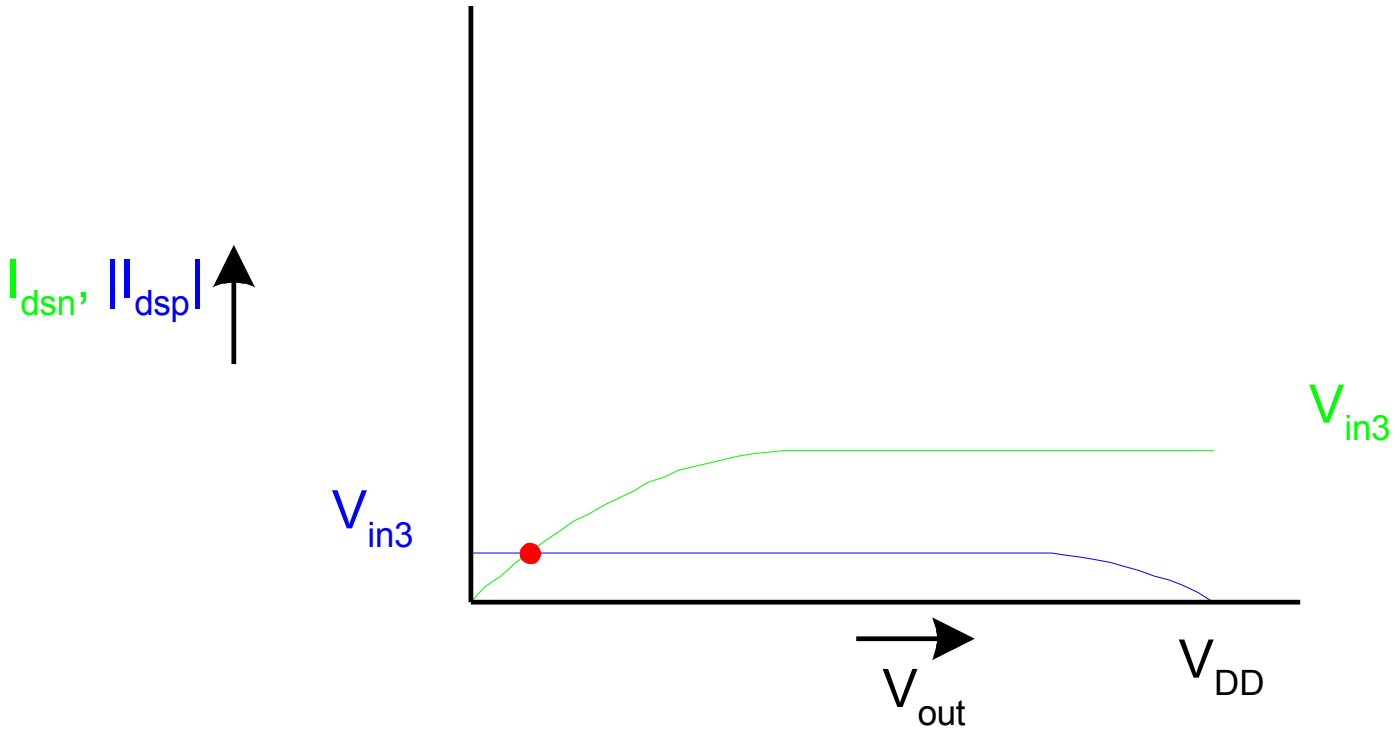
Load Line Analysis

- $V_{in} = 0.4V_{DD}$



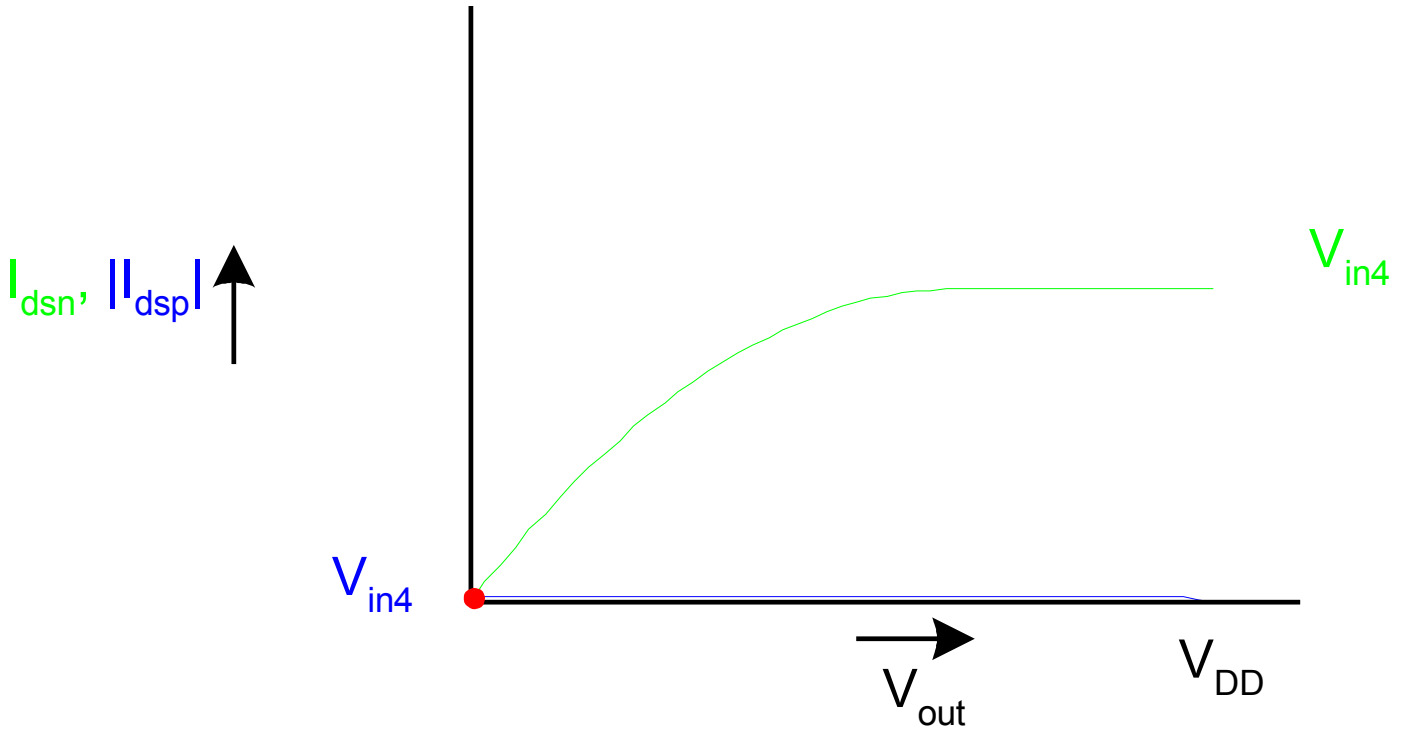
Load Line Analysis

- $V_{in} = 0.6V_{DD}$



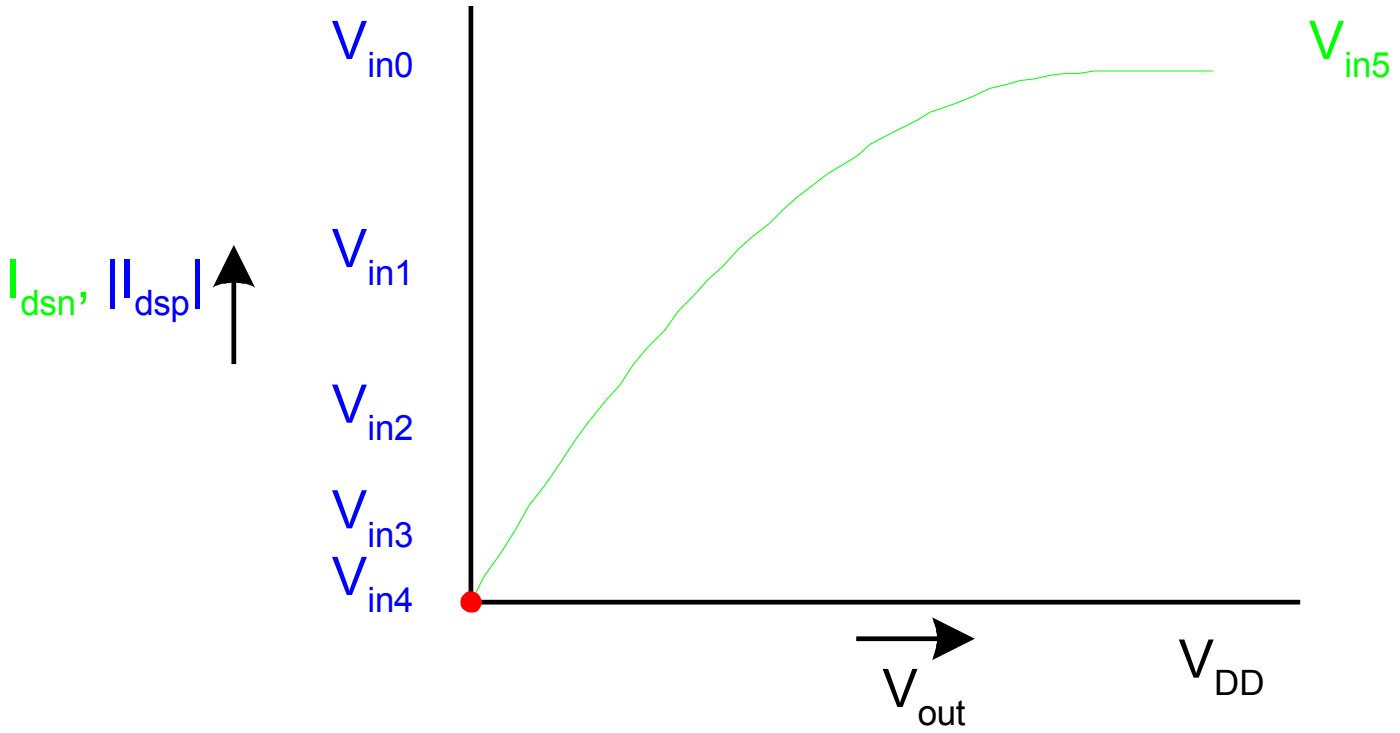
Load Line Analysis

- $V_{in} = 0.8V_{DD}$

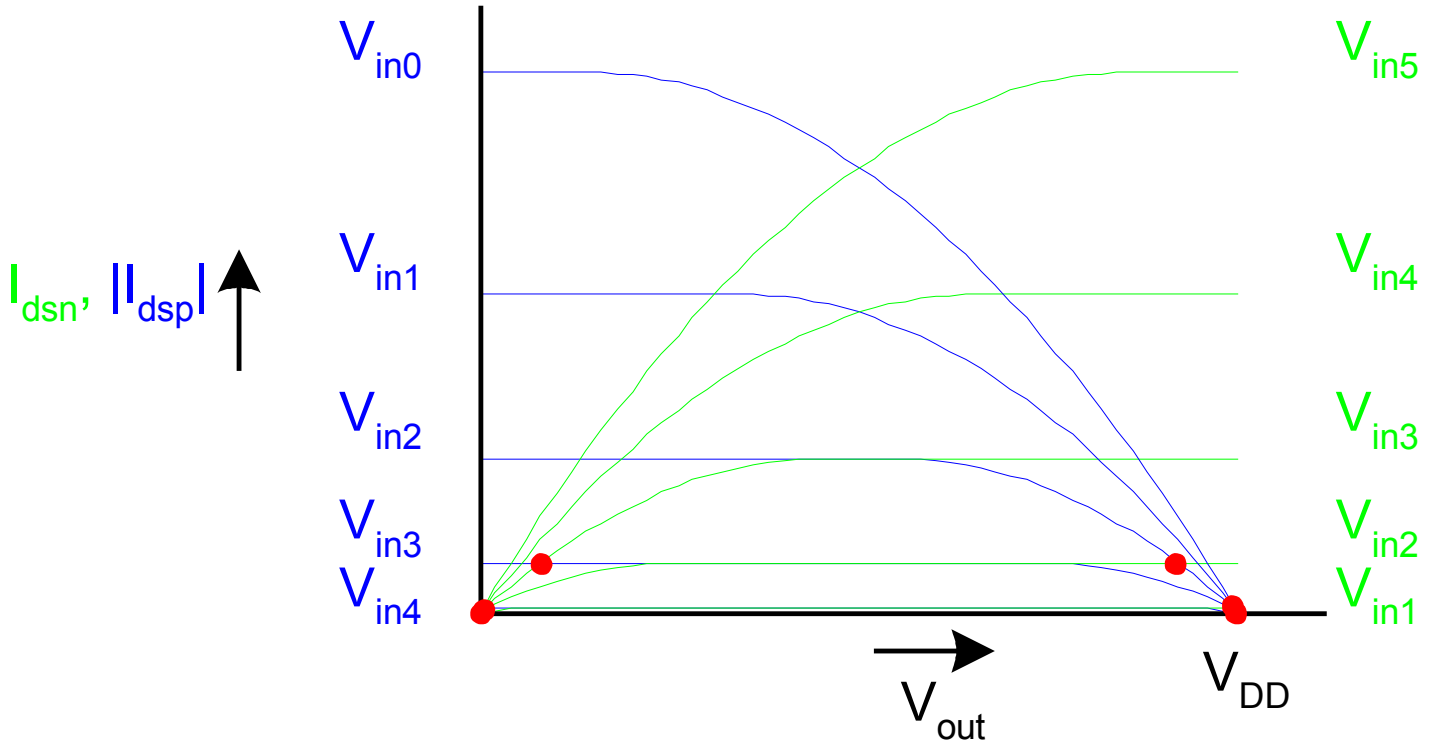


Load Line Analysis

- $V_{in} = V_{DD}$

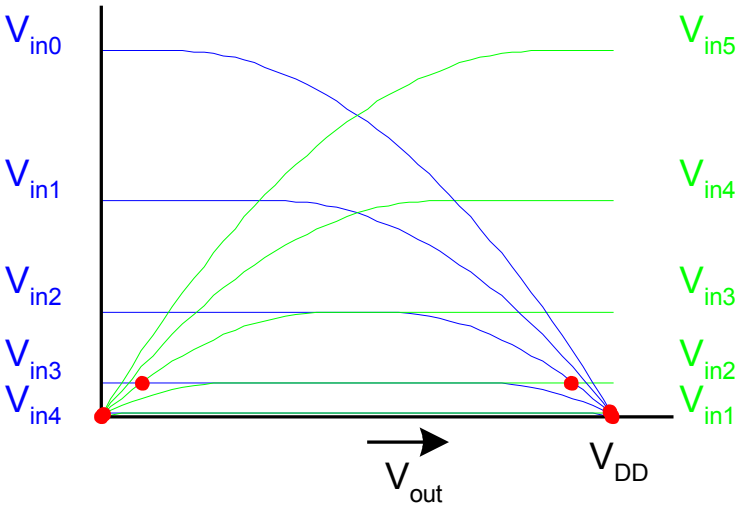


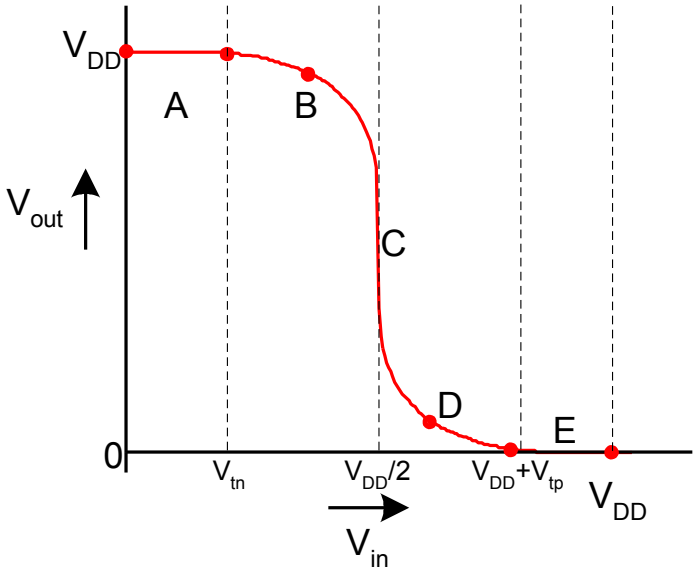
Load Line Summary



DC Transfer Curve

- Transcribe points onto V_{in} vs. V_{out} plot



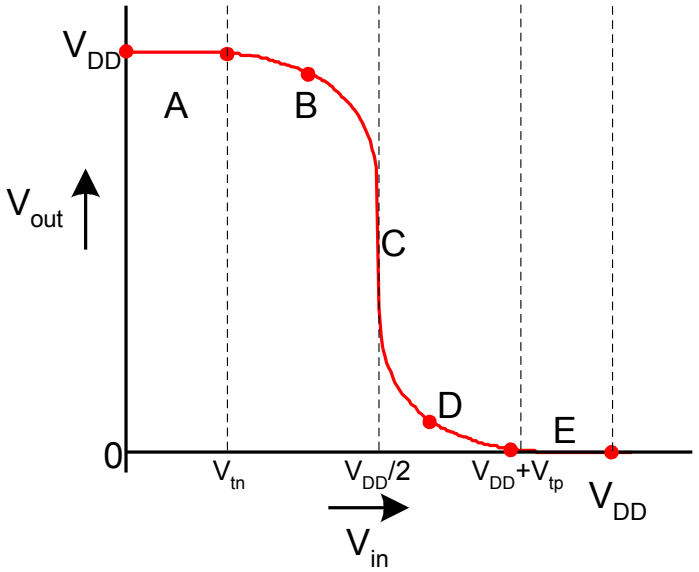


因為這是一個not 所以輸出越高 就會越接近0

Operating Regions

- Revisit transistor operating regions

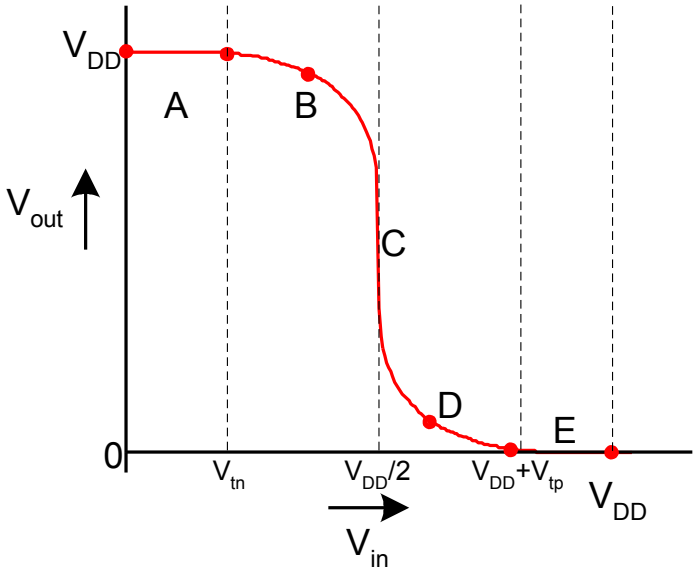
Region	nMOS	pMOS
A		
B		
C		
D		
E		



Operating Regions

- Revisit transistor operating regions

Region	nMOS	pMOS
A	Cutoff	Linear
B	Saturation	Linear
C	Saturation	Saturation
D	Linear	Saturation
E	Linear	Cutoff

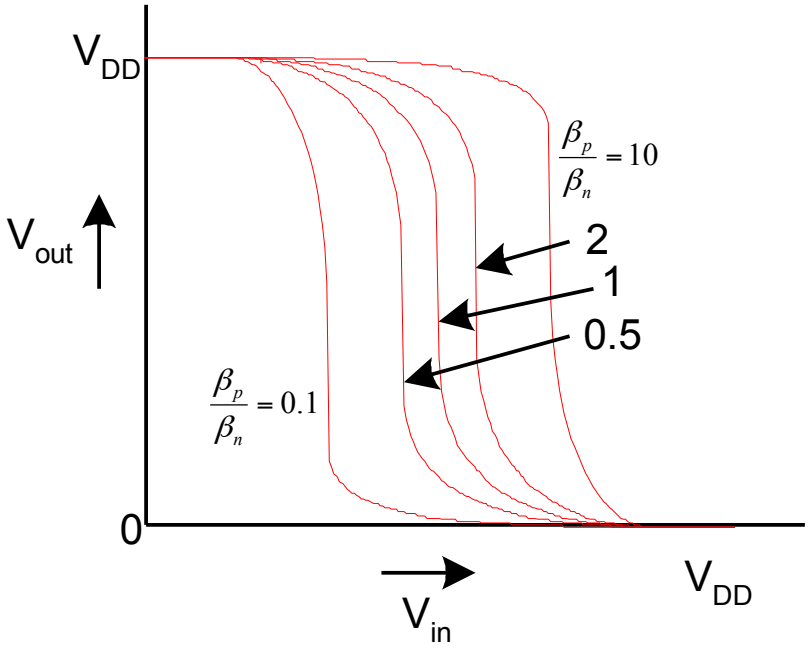


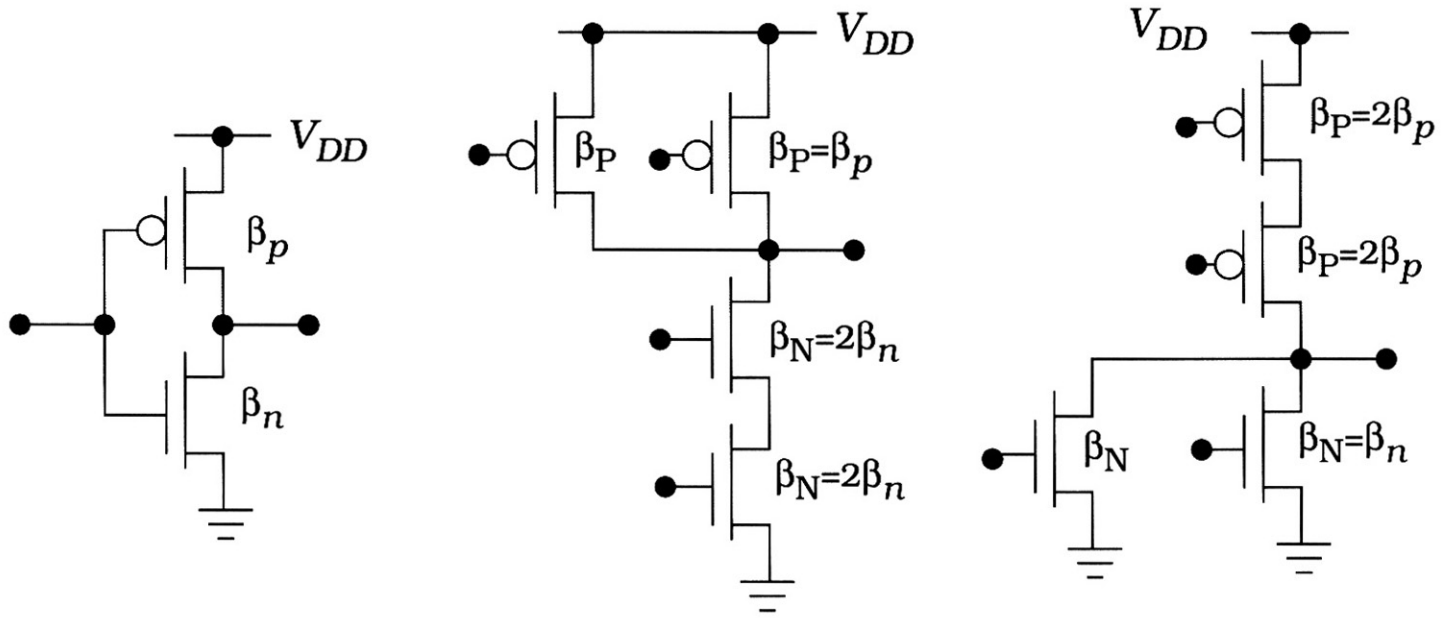
重點 波形 需要都是一樣的

對稱設計 充電時 降電時 都要波形一樣

Beta Ratio

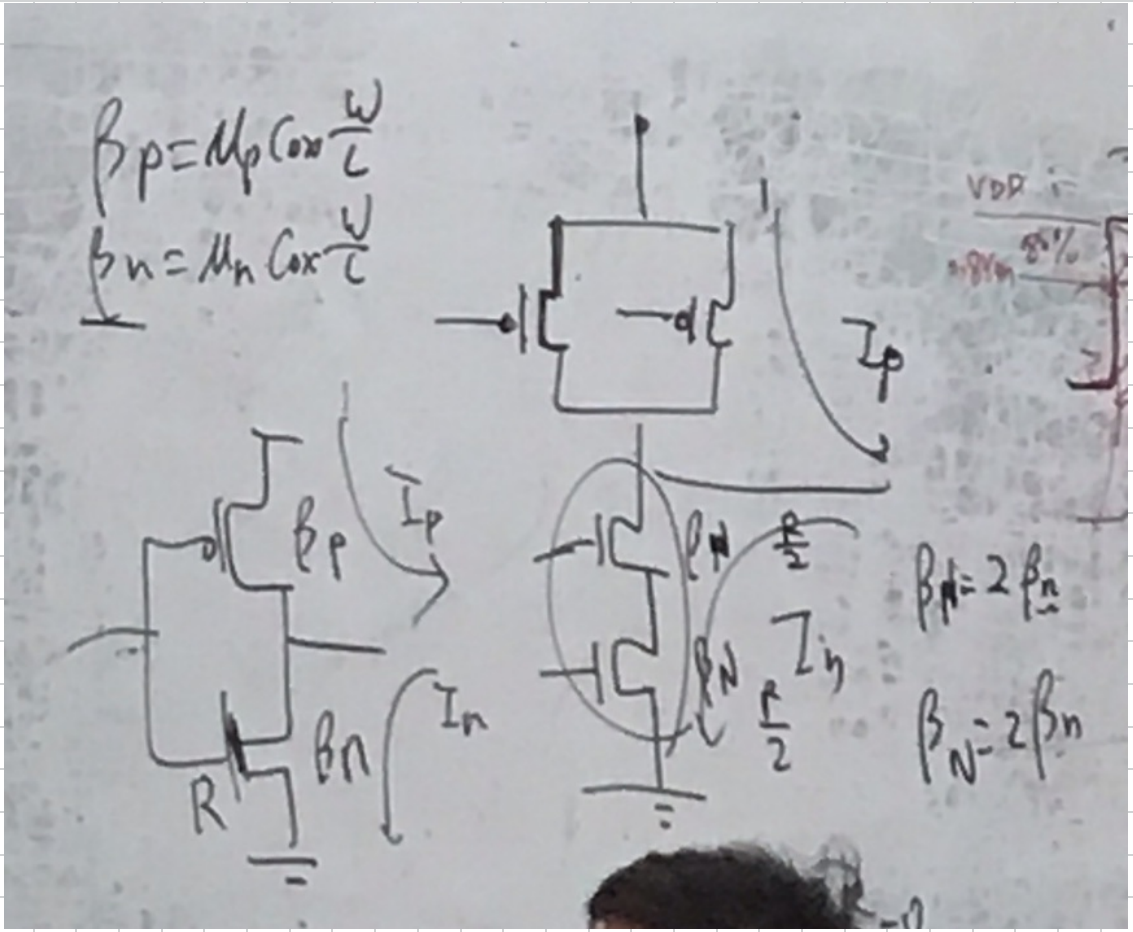
- If $\beta_p / \beta_n \neq 1$, switching point will move from $V_{DD}/2$
- Called *skewed* gate
- Other gates: collapse into equivalent inverter





(a) Inverter (b) NAND2 (c) NOR2

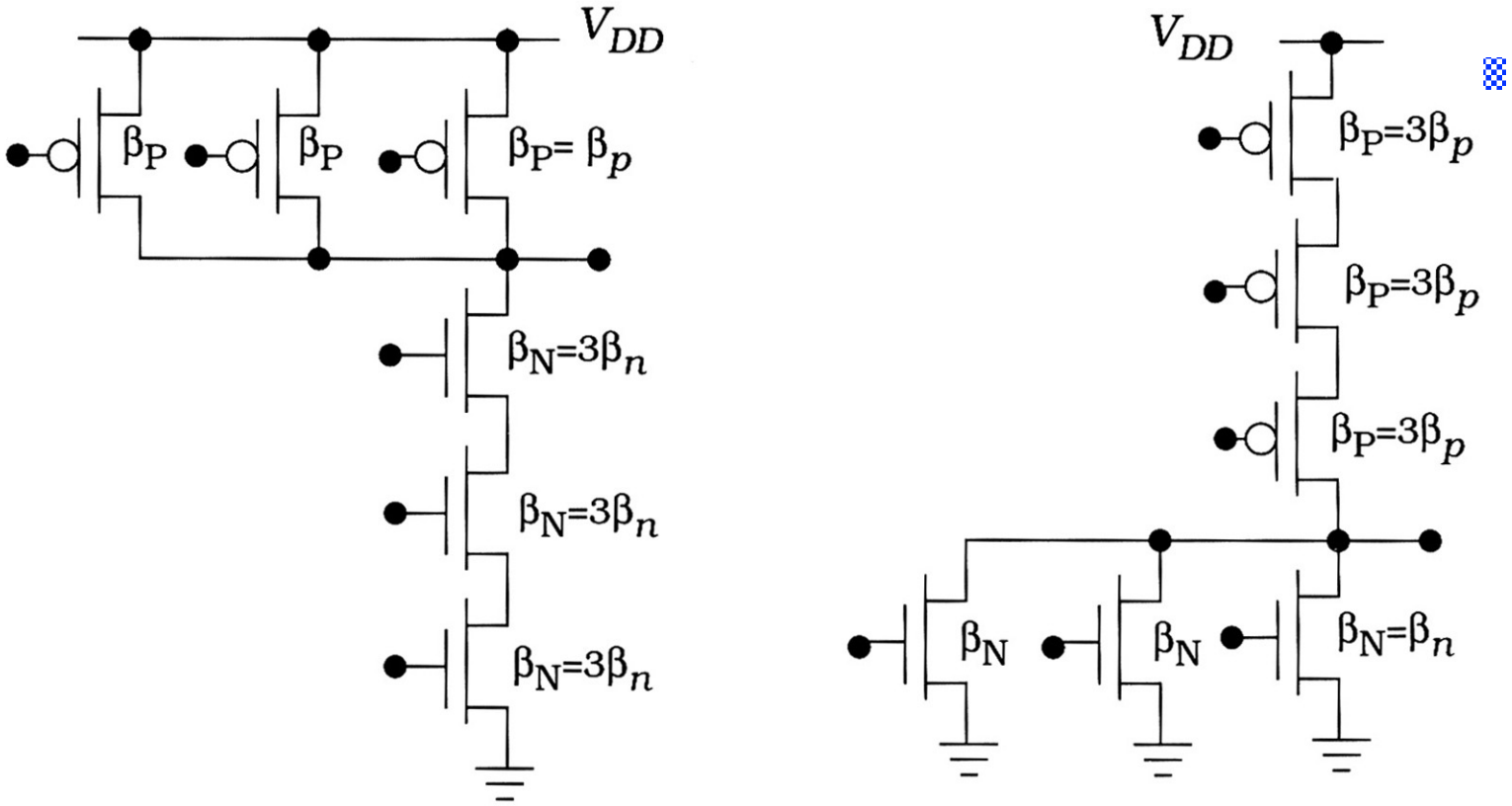
Figure 7.34 Relative FET sizing



這裡是調整w 寬度 來 控制電阻

因為電阻 都要和原本的 not 的 電阻 一樣

因為 串連 電阻會加起來
所以串連的電阻 都要變成 R/2



(a) NAND3 (b) NOR3

Figure 7.35 Sizing for 3-input gates

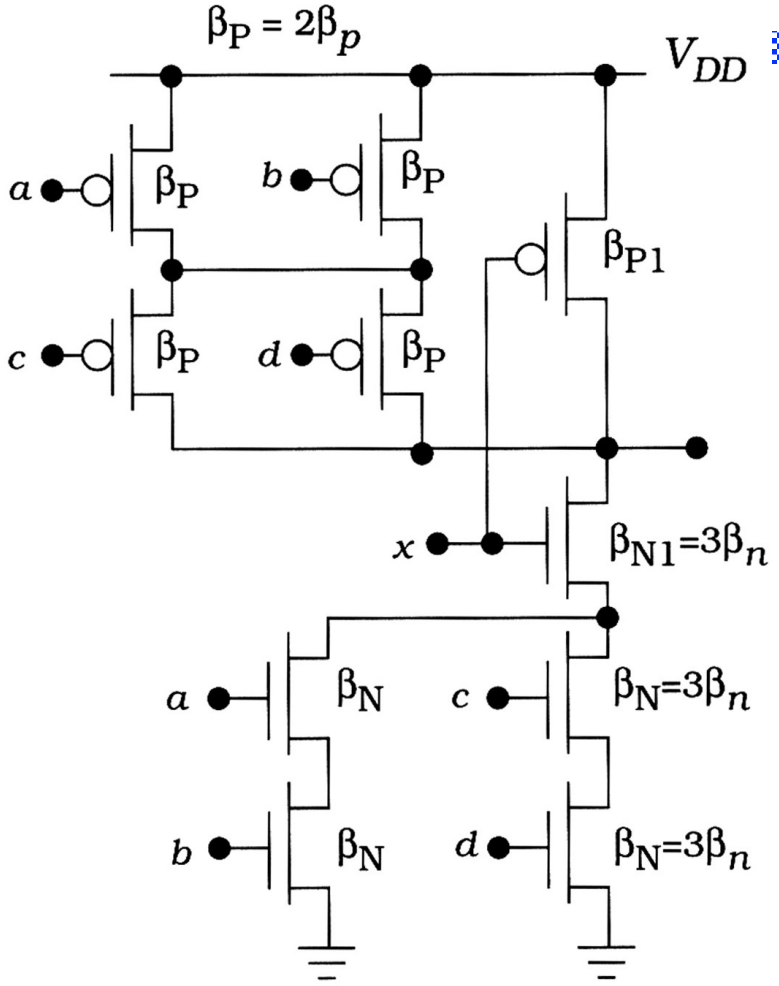
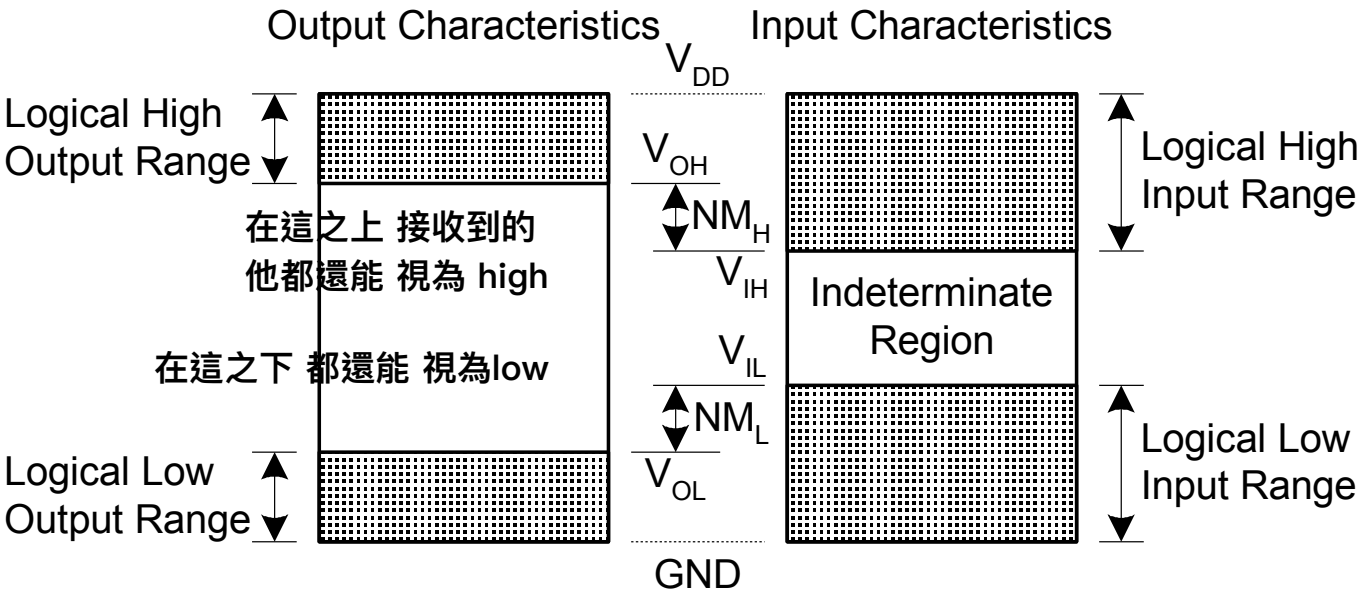


Figure 7.36 Sizing of a complex logic gate

Noise Margin 越大越好
代表能容錯的範圍 越大

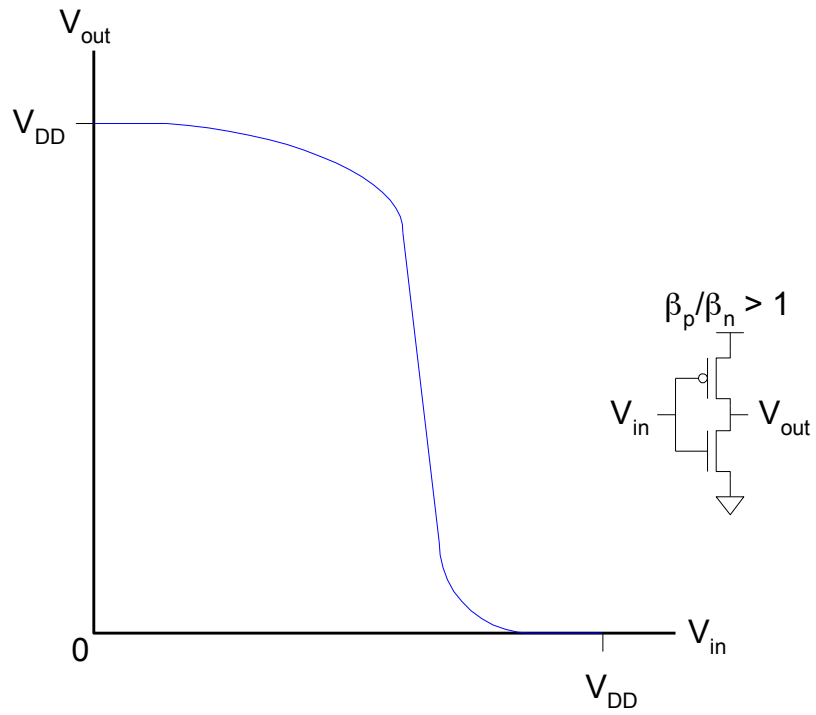
Noise Margins

- How much noise can a gate input see before it does not recognize the input?



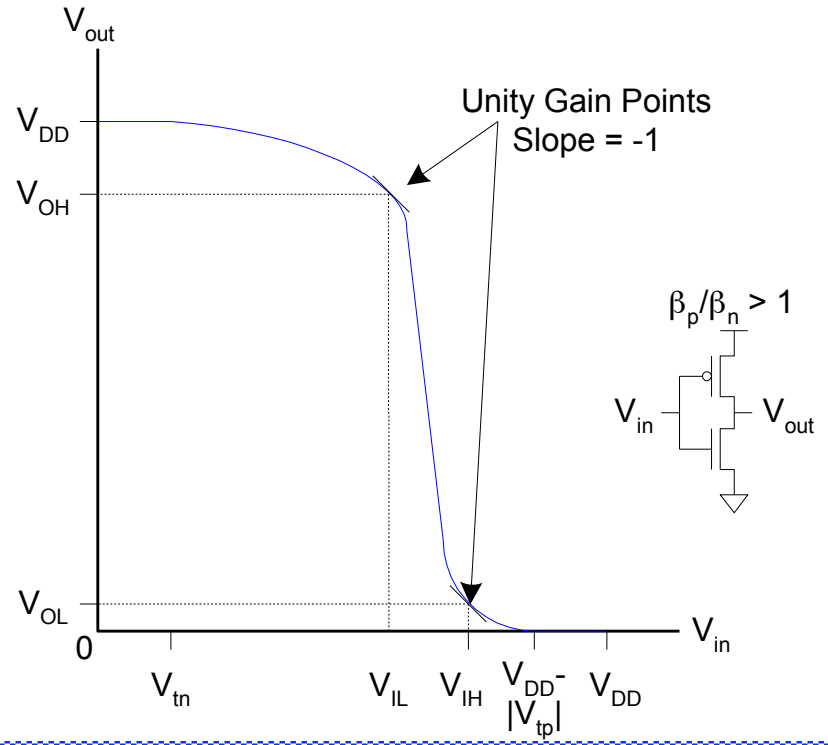
Logic Levels

- To maximize noise margins, select logic levels at



Logic Levels

- To maximize noise margins, select logic levels at
  - unity gain point of DC transfer characteristic



Transient Response

- *DC analysis* tells us V_{out} if V_{in} is constant
- *Transient analysis* tells us $V_{out}(t)$ if $V_{in}(t)$ changes
  - Requires solving differential equations
- Input is usually considered to be a step or ramp
  - From 0 to V_{DD} or vice versa

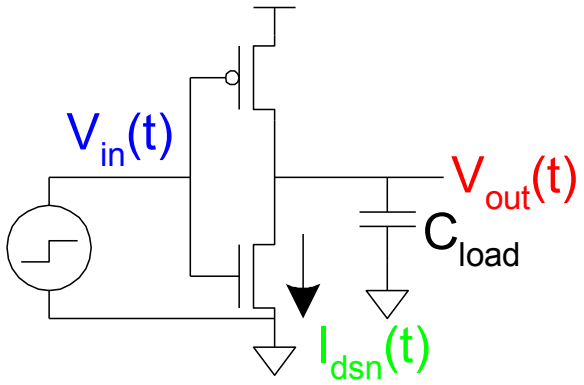
Inverter Step Response

- Ex: find step response of inverter driving load cap

$$V_{in}(t) =$$

$$V_{out}(t < t_0) =$$

$$\frac{dV_{out}(t)}{dt} =$$



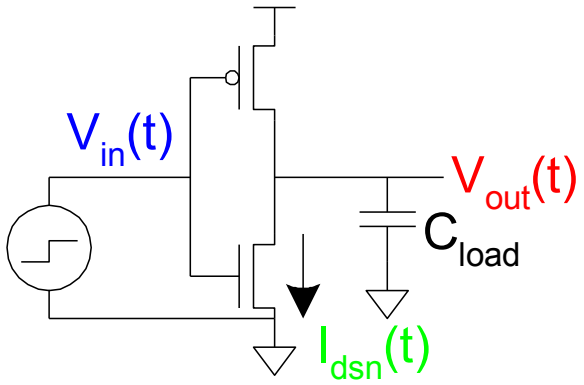
Inverter Step Response

- Ex: find step response of inverter driving load cap

$$V_{in}(t) = u(t - t_0)V_{DD}$$

$$V_{out}(t < t_0) =$$

$$\frac{dV_{out}(t)}{dt} =$$



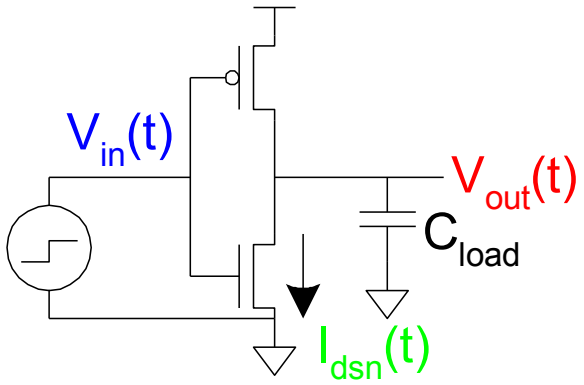
Inverter Step Response

- Ex: find step response of inverter driving load cap

$$V_{in}(t) = u(t - t_0)V_{DD}$$

$$V_{out}(t < t_0) = V_{DD}$$

$$\frac{dV_{out}(t)}{dt} =$$



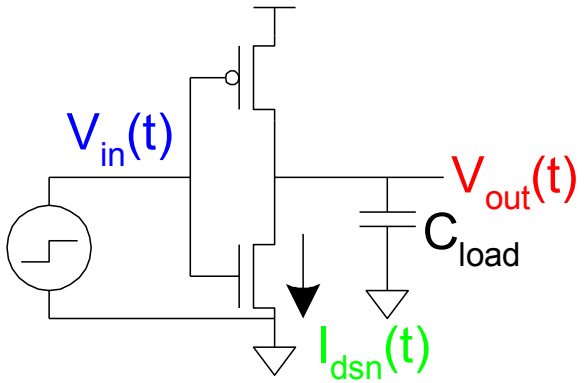
Inverter Step Response

- Ex: find step response of inverter driving load cap

$$V_{in}(t) = u(t - t_0)V_{DD}$$

$$V_{out}(t < t_0) = V_{DD}$$

$$\frac{dV_{out}(t)}{dt} = -\frac{I_{dsn}(t)}{C_{load}}$$



$$I_{dsn}(t) = \begin{cases} t \le t_0 \\ V_{out} > V_{DD} - V_t \\ V_{out} < V_{DD} - V_t \end{cases}$$

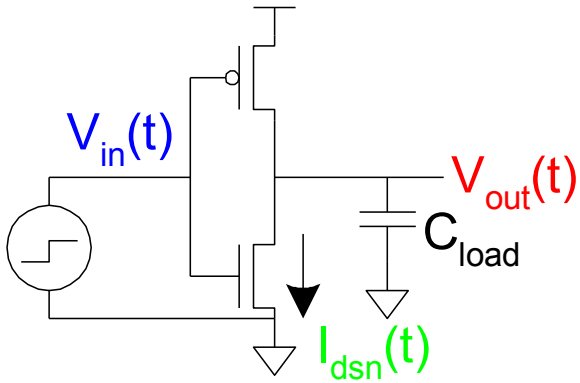
Inverter Step Response

- Ex: find step response of inverter driving load cap

$$V_{in}(t) = u(t - t_0)V_{DD}$$

$$V_{out}(t < t_0) = V_{DD}$$

$$\frac{dV_{out}(t)}{dt} = -\frac{I_{dsn}(t)}{C_{load}}$$



$$I_{dsn}(t) = \begin{cases} 0 & t \le t_0 \\ \frac{\beta}{2}(V_{DD} - V)^2 & V_{out} > V_{DD} - V_t \\ \beta\left(V_{DD} - V_t - V_{out}(t)/2\right)V_{out}(t) & V_{out} < V_{DD} - V_t \end{cases}$$

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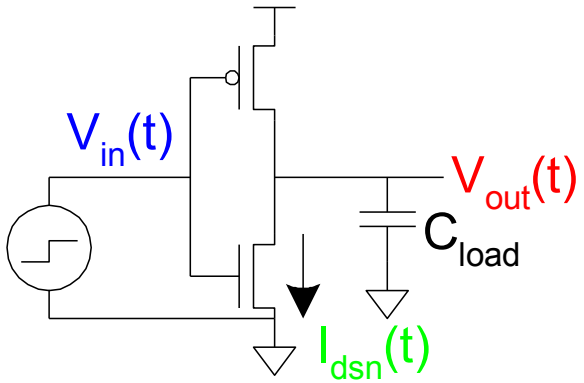

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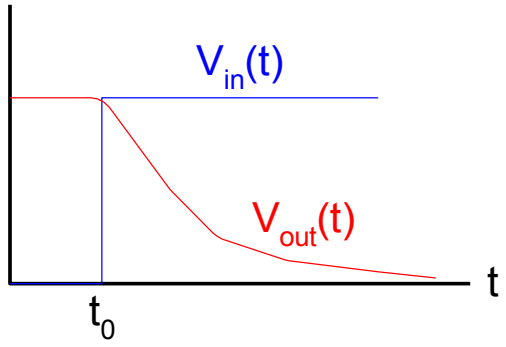


Delay Definitions

- t_{pdr}:
- t_{pdf}:
- t_{pd}:
- t_r:
- t_f: *fall time*

Delay Definitions

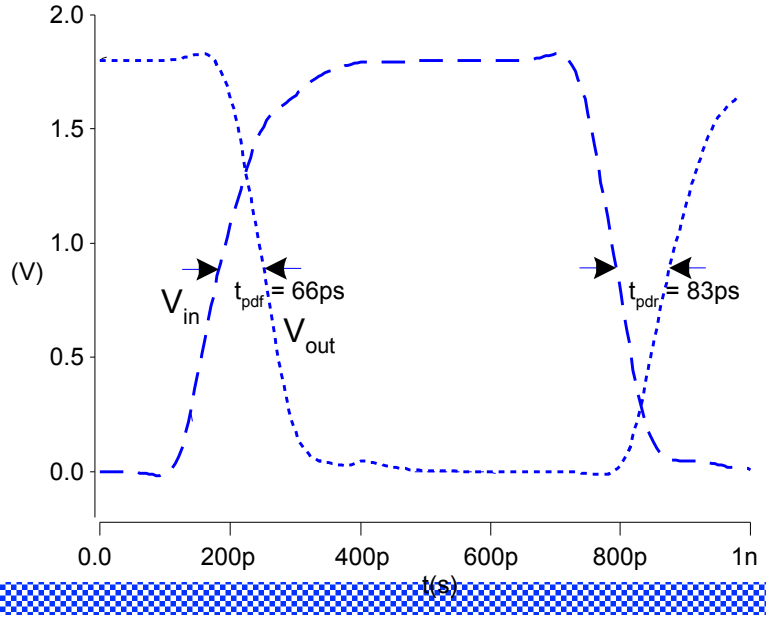
- t_{pdr}: *rising propagation delay* 傳遞延遲
  - From input to rising output crossing $V_{DD}/2$
- t_{pdf}: *falling propagation delay*
  - From input to falling output crossing $V_{DD}/2$
- t_{pd}: *average propagation delay*
  - $t_{pd} = (t_{pdr} + t_{pdf})/2$
- t_r: *rise time*
  - From output crossing $0.2\ V_{DD}$ to $0.8\ V_{DD}$
- t_f: *fall time*
  - From output crossing $0.8\ V_{DD}$ to $0.2\ V_{DD}$

Delay Definitions

- **t_{cdr}**: *rising contamination delay*
  - From input to rising output crossing $V_{DD}/2$
- **t_{cdf}**: *falling contamination delay*
  - From input to falling output crossing $V_{DD}/2$
- **t_{cd}**: *average contamination delay*
  - $t_{pd} = (t_{cdr} + t_{cdf})/2$

Simulated Inverter Delay

- Solving differential equations by hand is too hard
- SPICE simulator solves the equations numerically
  - Uses more accurate I-V models too!
- But simulations take time to write

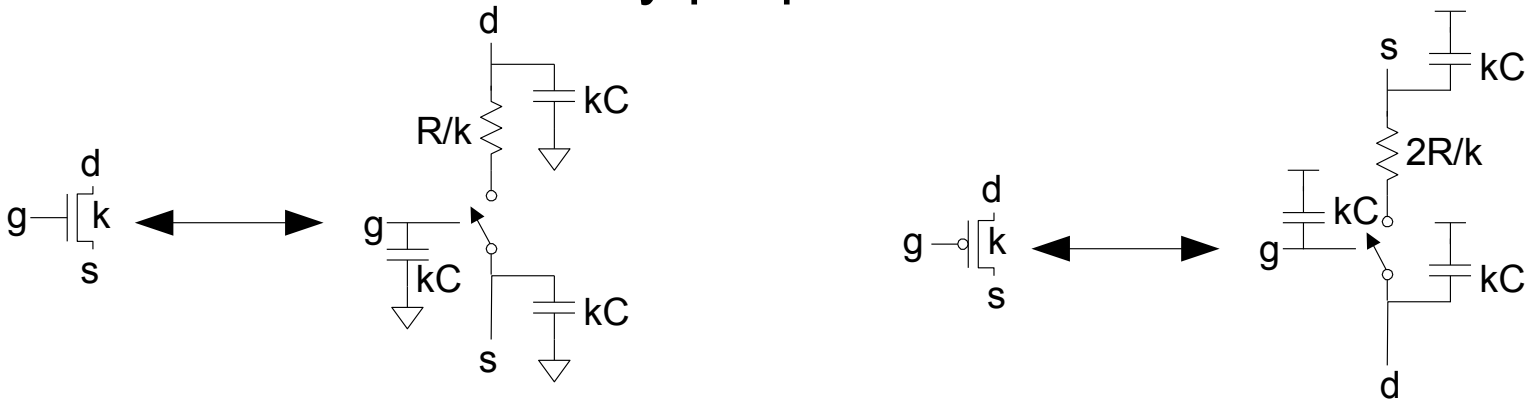


Delay Estimation

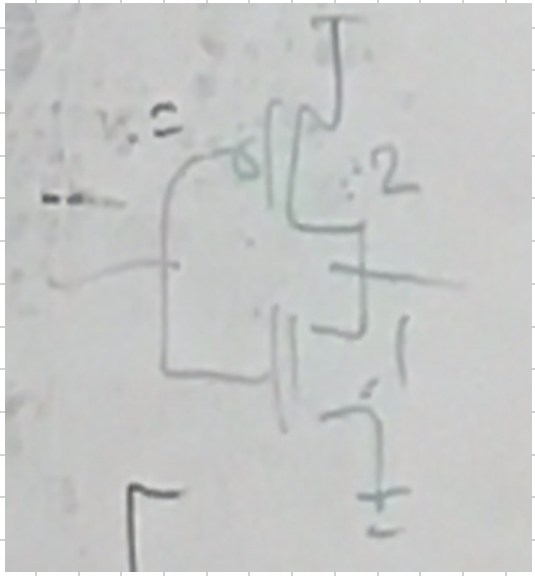
- We would like to be able to easily estimate delay
  - Not as accurate as simulation
  - But easier to ask "What if?"
- The step response usually looks like a 1st order RC response with a decaying exponential.
- Use RC delay models to estimate delay
  - C = total capacitance on output node
  - Use *effective resistance* R
  - So that t_{pd} = RC
- Characterize transistors by finding their effective R
  - Depends on average current as gate switches

RC Delay Models

- Use equivalent circuits for MOS transistors
  - Ideal switch + capacitance and ON resistance
  - Unit nMOS has resistance R, capacitance C
  - Unit pMOS has resistance 2R, capacitance C
- Capacitance proportional to width
- Resistance inversely proportional to width



這裡是在算基本的擴散電容



Example: 3-input NAND

- Sketch a 3-input NAND with transistor widths chosen to achieve effective rise and fall resistances equal to a unit inverter (R).

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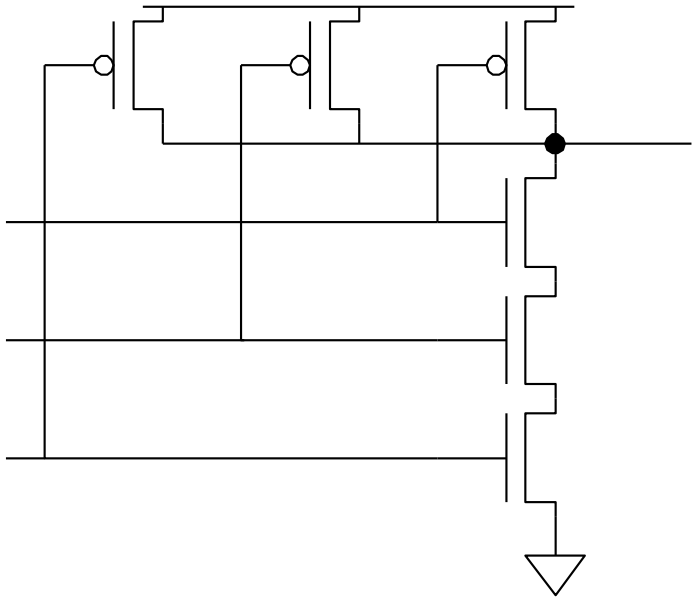

Example: 3-input NAND

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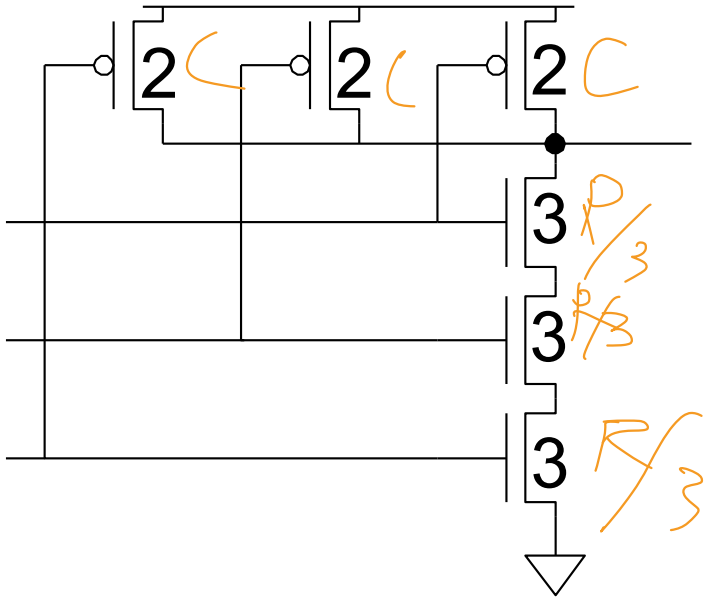
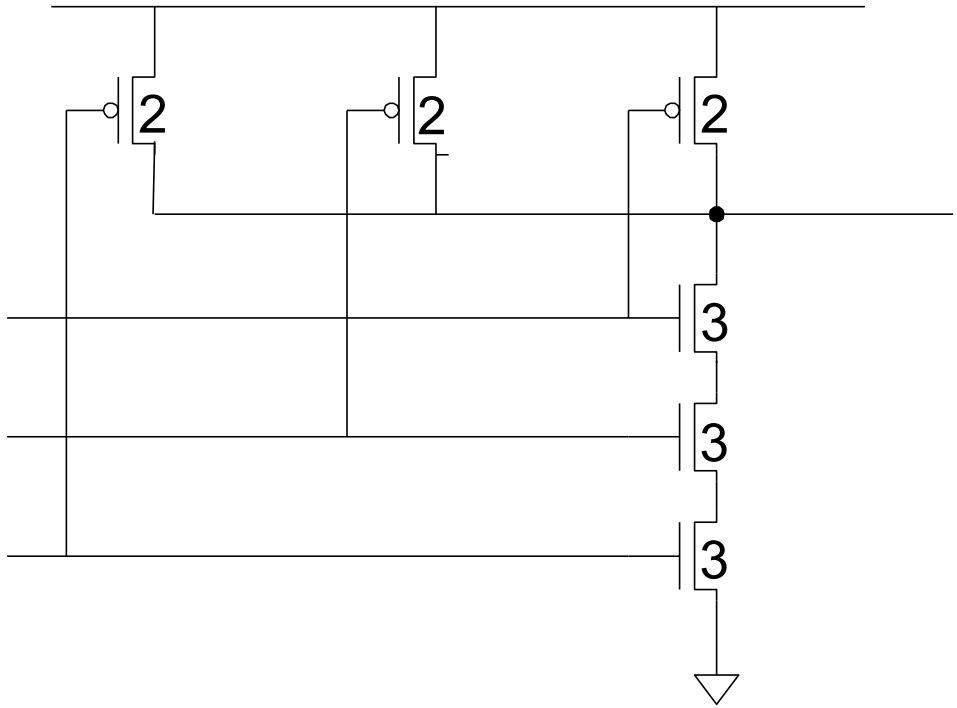
他為了把電阻變小



因為串連 電阻變三倍
把

3-input NAND Caps

- Annotate the 3-input NAND gate with gate and diffusion capacitance.



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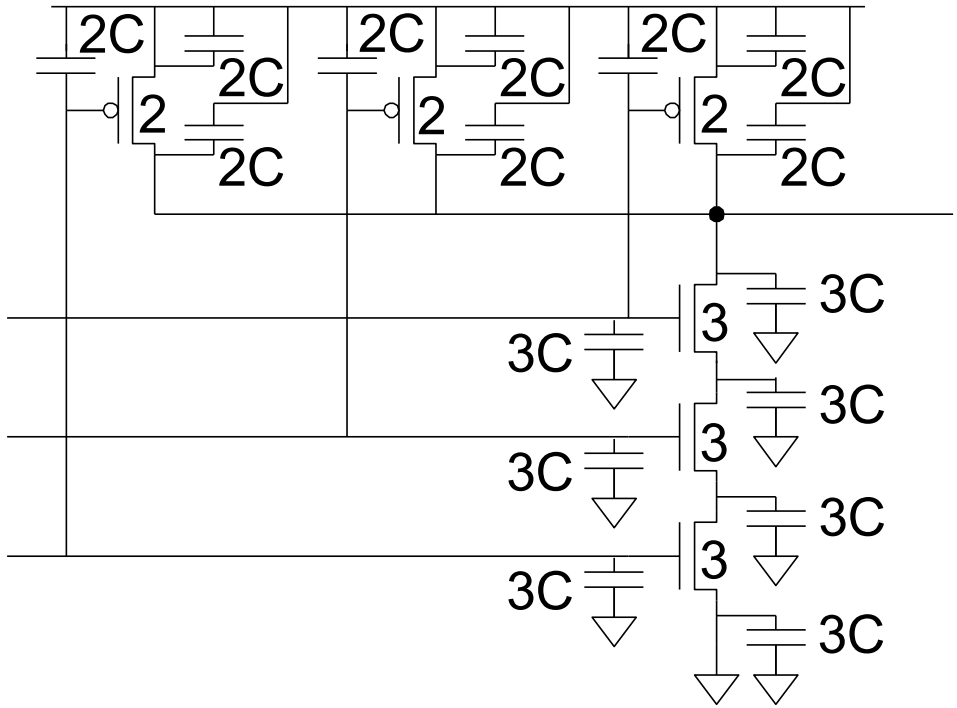

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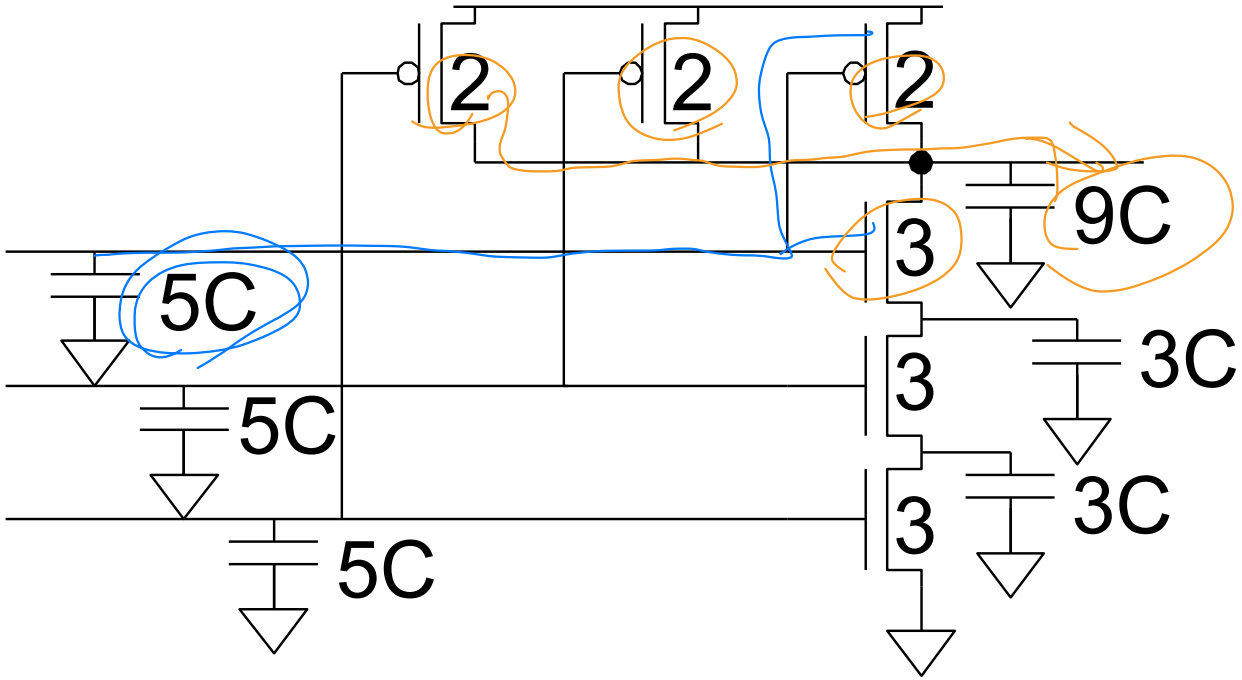
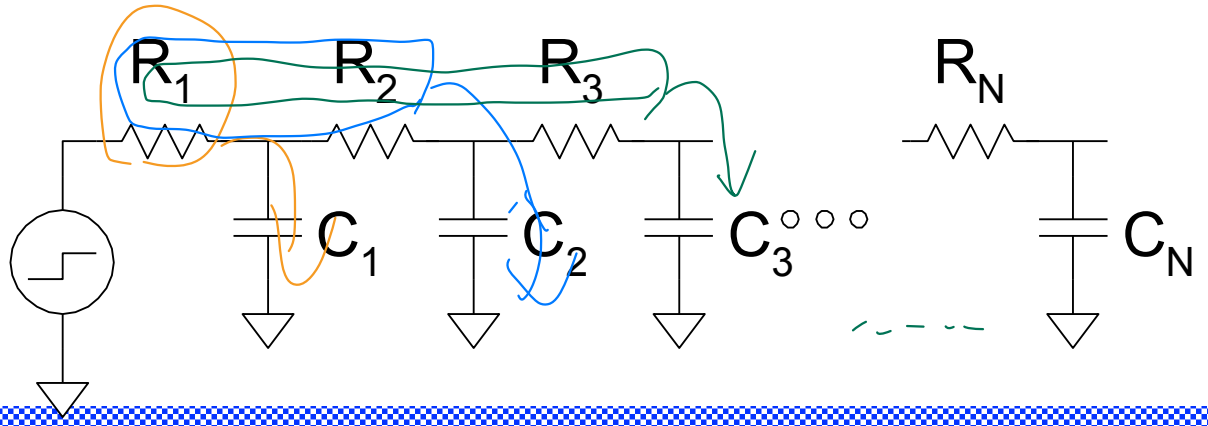


Elmore Delay

- ON transistors look like resistors
- Pullup or pulldown network modeled as *RC ladder*
- Elmore delay of RC ladder

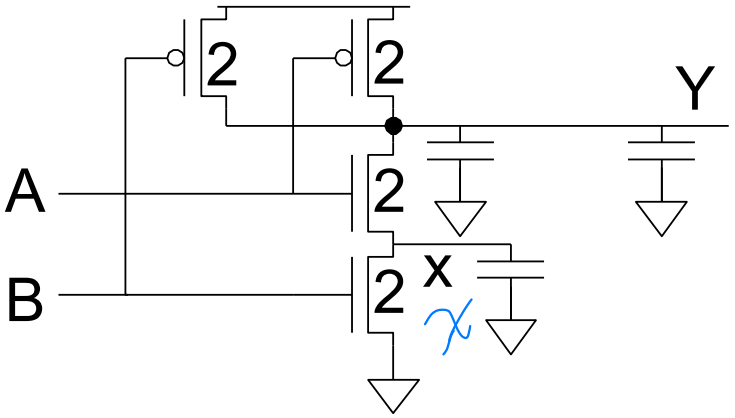
$$t_{pd} \approx \sum_{\text{nodes } i} R_{i-to-source} C_i$$

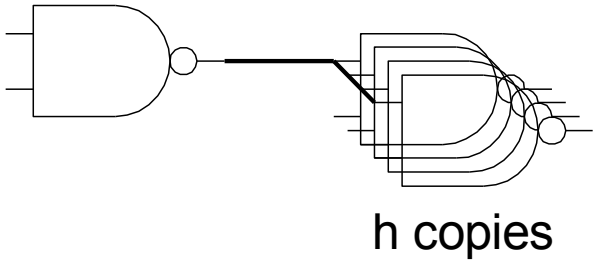
$$= R_1 C_1 + (R_1 + R_2) C_2 + \ldots + (R_1 + R_2 + \ldots + R_N) C_N$$



Example: 2-input NAND

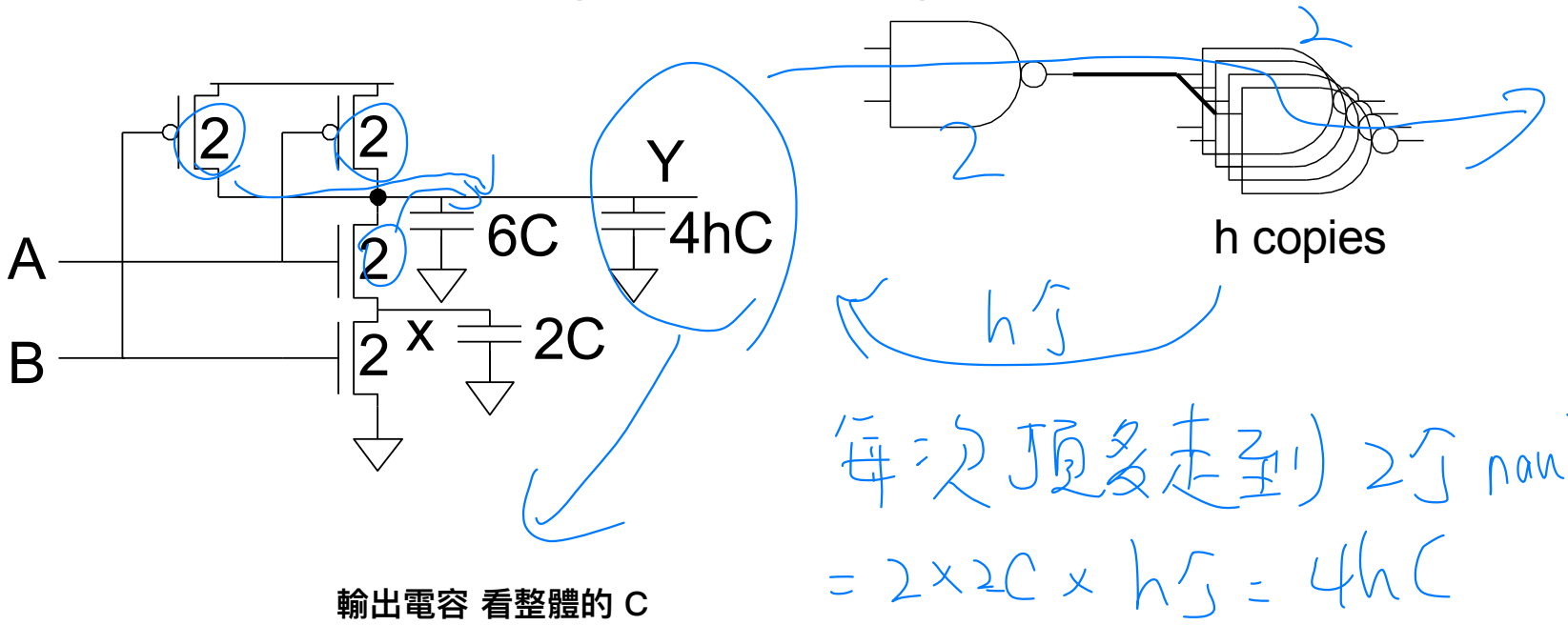
- Estimate worst-case rising and falling delay of 2-input NAND driving *h* identical gates.





Example: 2-input NAND

- Estimate rising and falling propagation delays of a 2-input NAND driving *h* identical gates.



輸出電容 看整體的 C

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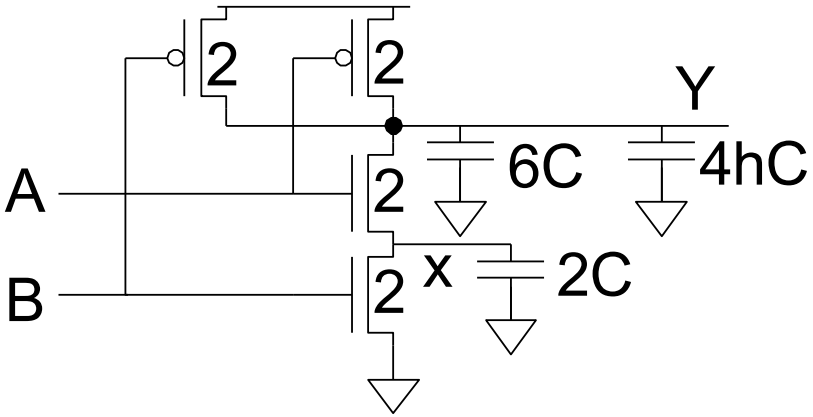

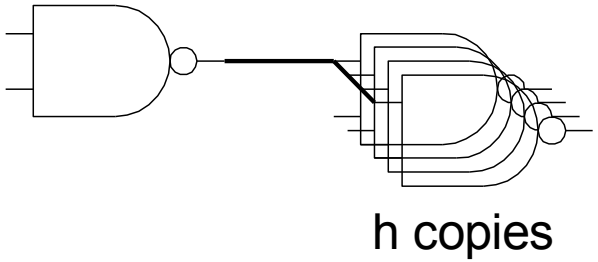

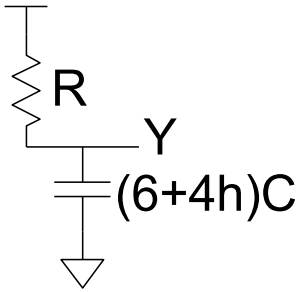

$$t_{pdr} =$$

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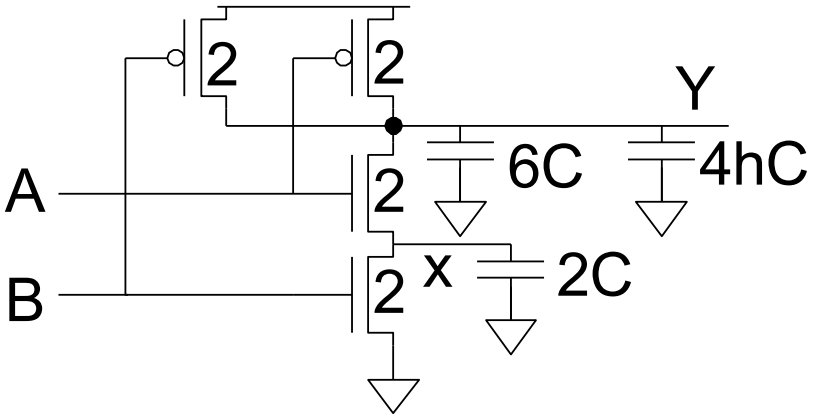

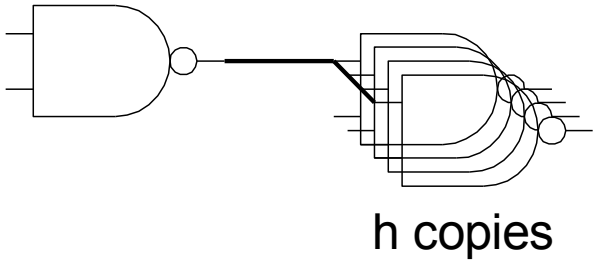

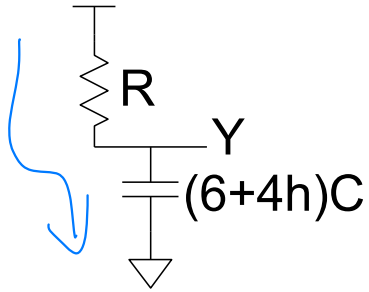

$$t_{pdr} = (6 + 4h)RC$$

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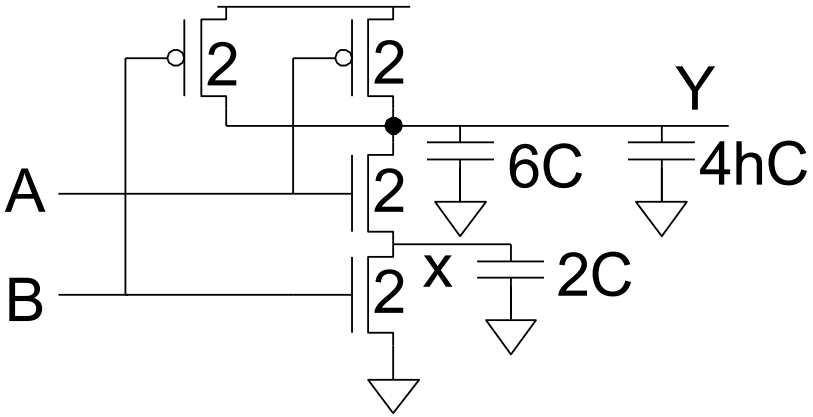

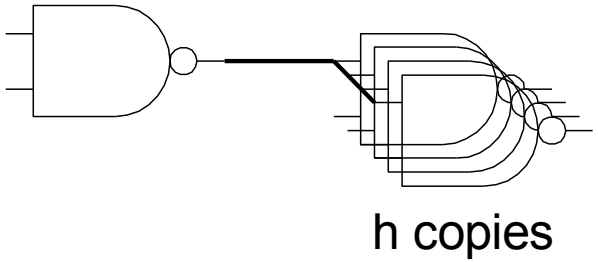

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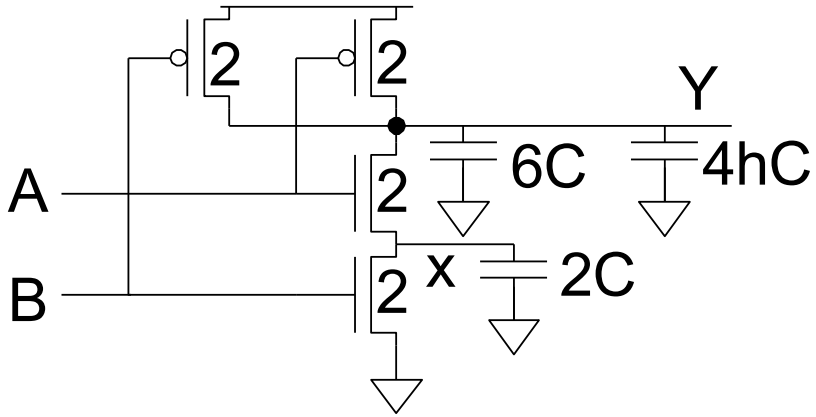

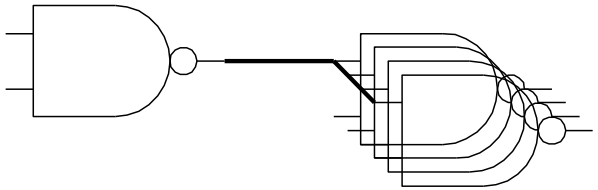

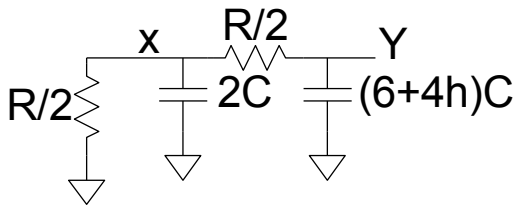

$$t_{pdf} =$$

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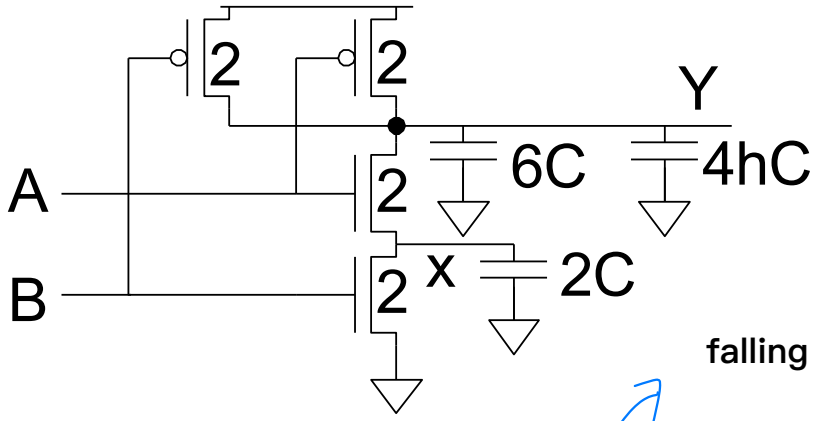
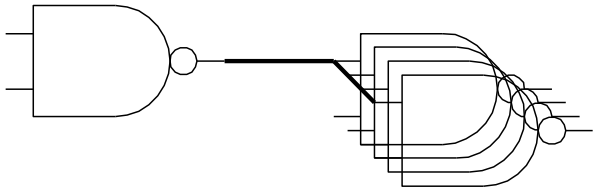
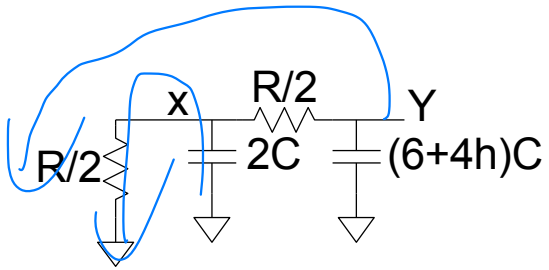




falling propagation delay



$$t_{pdf} = (2C)\left(\frac{R}{2}\right) + \left[(6+4h)C\right]\left(\frac{R}{2}+\frac{R}{2}\right)$$

$$= (7+4h)RC$$

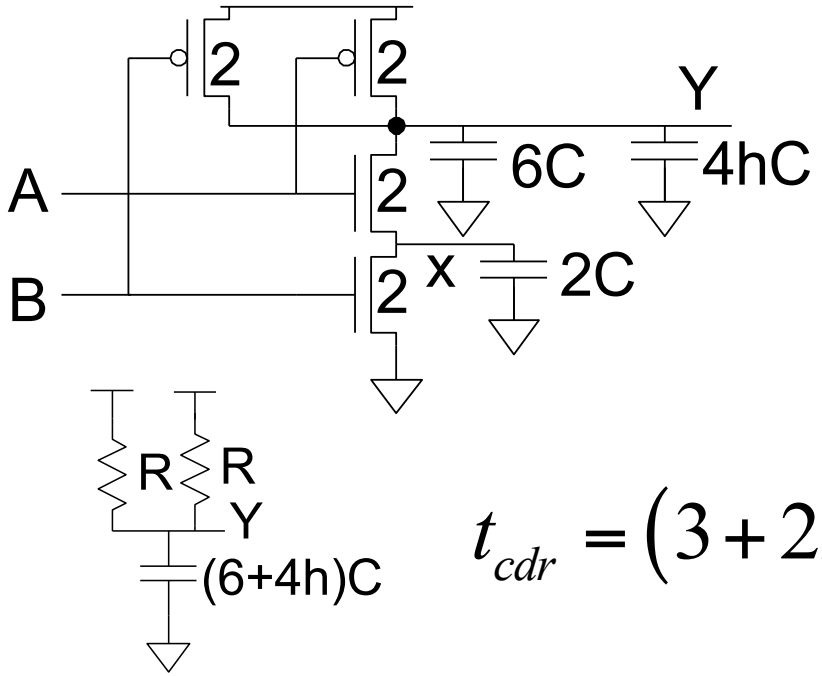
這樣放電

Delay Components

- Delay has two parts
  - *Parasitic delay* 寄生 延遲？
    - 6 or 7 RC
    - Independent of load
  - *Effort delay*
    - 4h RC
    - Proportional to load capacitance

Contamination Delay

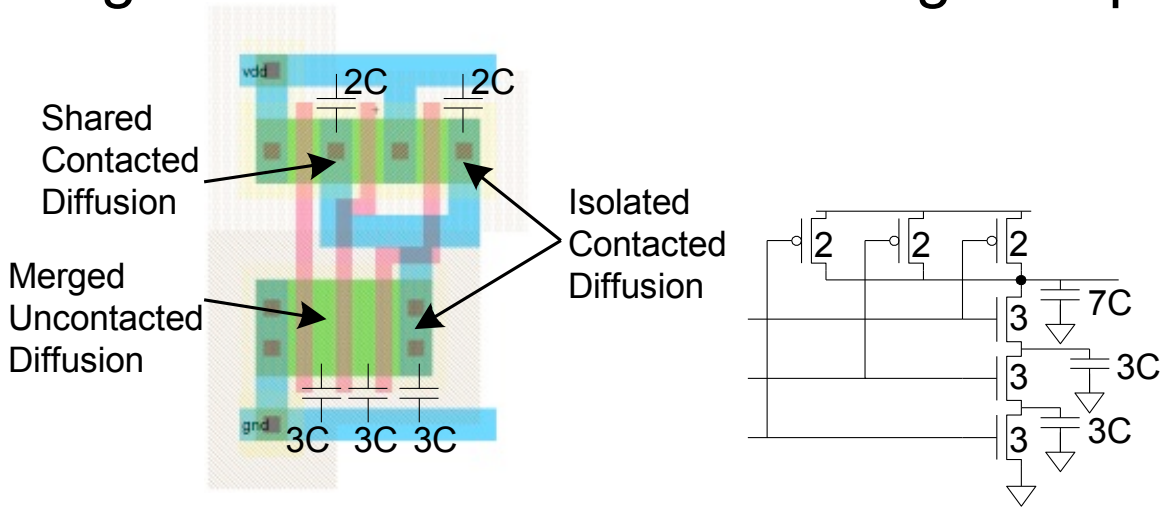
- Best-case (contamination) delay can be substantially less than propagation delay.
- Ex: If both inputs fall simultaneously



$$t_{cdr} = (3 + 2h)RC$$

Diffusion Capacitance

- we assumed contacted diffusion on every s / d.
- Good layout minimizes diffusion area
- Ex: NAND3 layout shares one diffusion contact
  - Reduces output capacitance by 2C
  - Merged uncontacted diffusion might help too



左邊比較好

Layout Comparison

- Which layout is better?