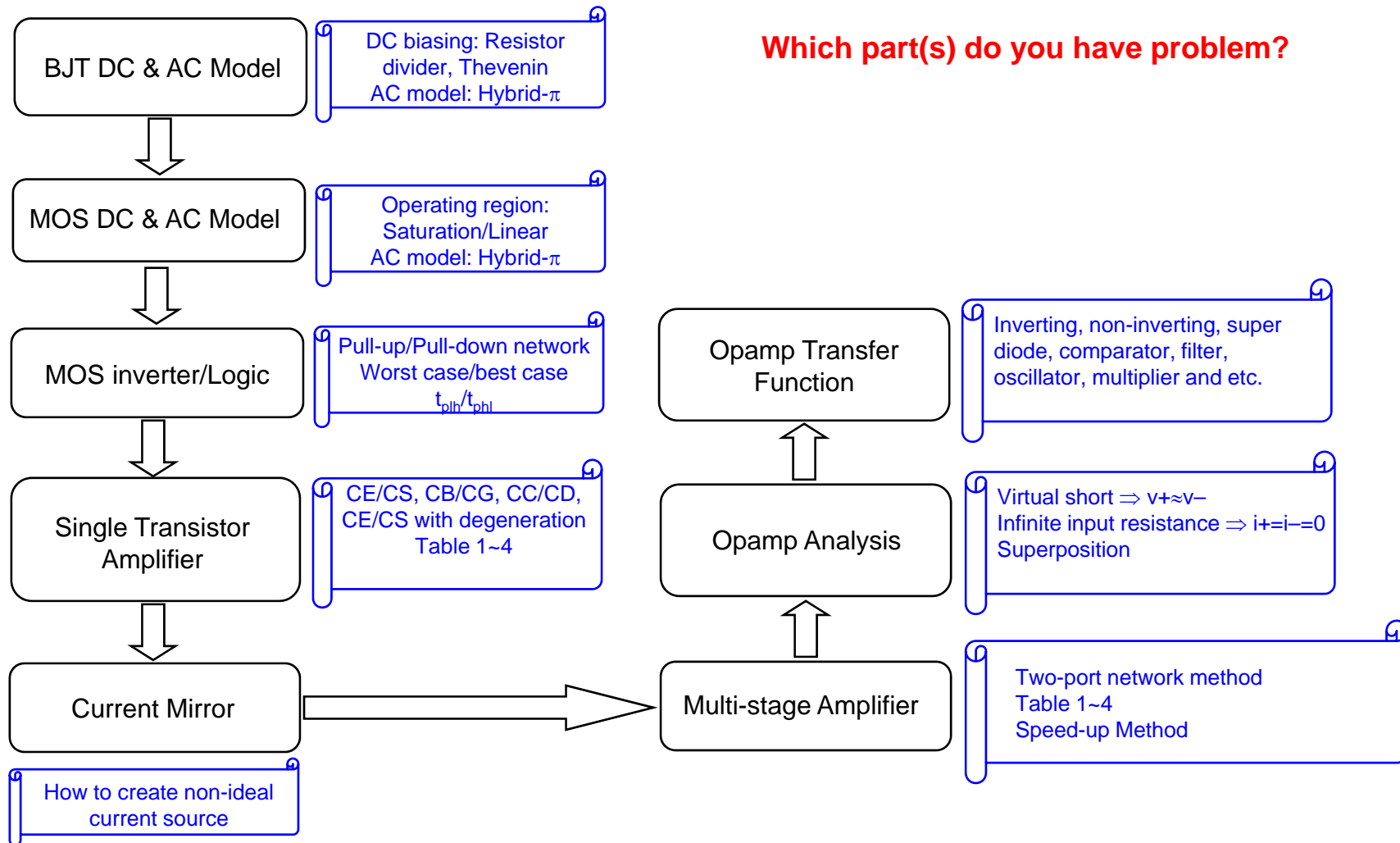


EE2021

Devices and Circuits

Revision

Summary on Materials Covered



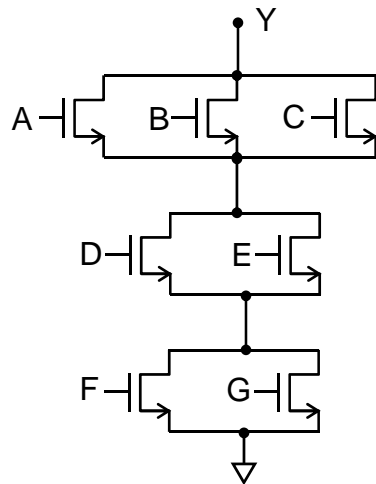
Logic Synthesis

$$Y = \overline{(A+B+C)} \cdot \overline{(D+E)} \cdot \overline{(F+G)}$$

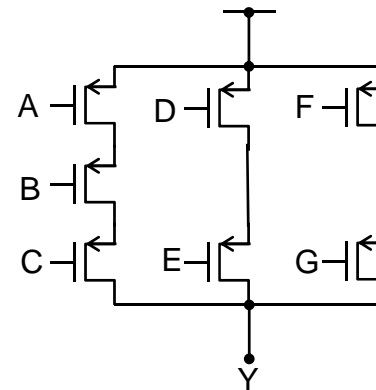
$$= \overline{(A+B+C)} + \overline{(D+E)} + \overline{(F+G)} \quad \text{Hint: Demorgan Theorem}$$

$$= (\overline{A} \cdot \overline{B} \cdot \overline{C}) + (\overline{D} \cdot \overline{E}) + (\overline{F} \cdot \overline{G})$$

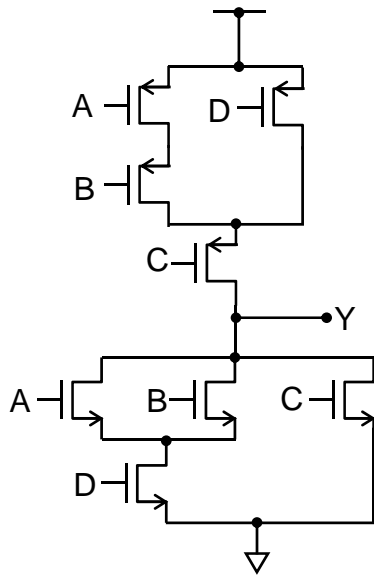
Pull Down Network



Pull Up Network (Duality)



Logic Function



$$\begin{aligned} Y &= \overline{(A+B) \cdot D + C} \\ &= \overline{(A+B) \cdot D} \cdot \overline{C} \\ &= \overline{((A+B) + D)} \cdot \overline{C} \\ &= (\overline{A} \cdot \overline{B} + \overline{D}) \cdot \overline{C} \end{aligned}$$

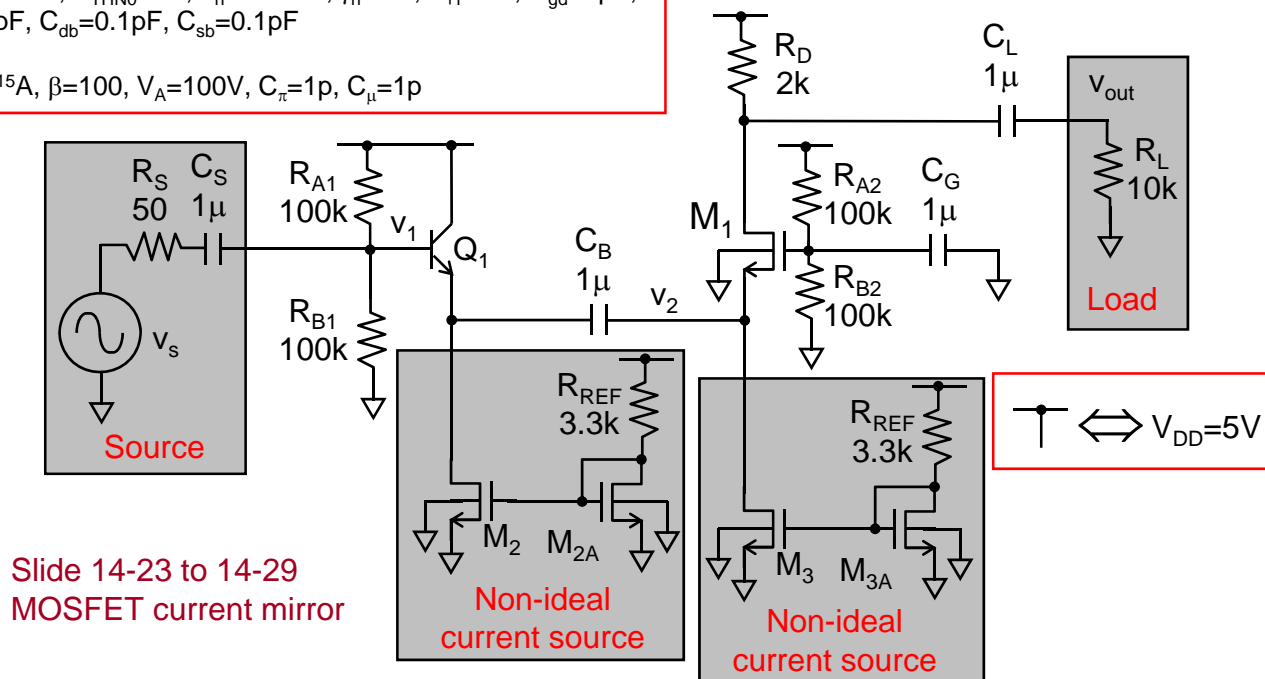
DC Analysis : Identifying

NMOS :

$K_n=2\text{mA/V}^2$, $V_{THN0}=1\text{V}$, $\lambda_n=0.01\text{V}^{-1}$, $\gamma_n=0.5$, $2\phi_f=0.6$, $C_{gd}=1\text{pF}$,
 $C_{gs}=1\text{pF}$, $C_{db}=0.1\text{pF}$, $C_{sb}=0.1\text{pF}$

BJT :

$I_S=10^{-15}\text{A}$, $\beta=100$, $V_A=100\text{V}$, $C_\pi=1\text{p}$, $C_\mu=1\text{p}$



- Identify AC source, load and non-ideal current source

DC Analysis : DC Biasing

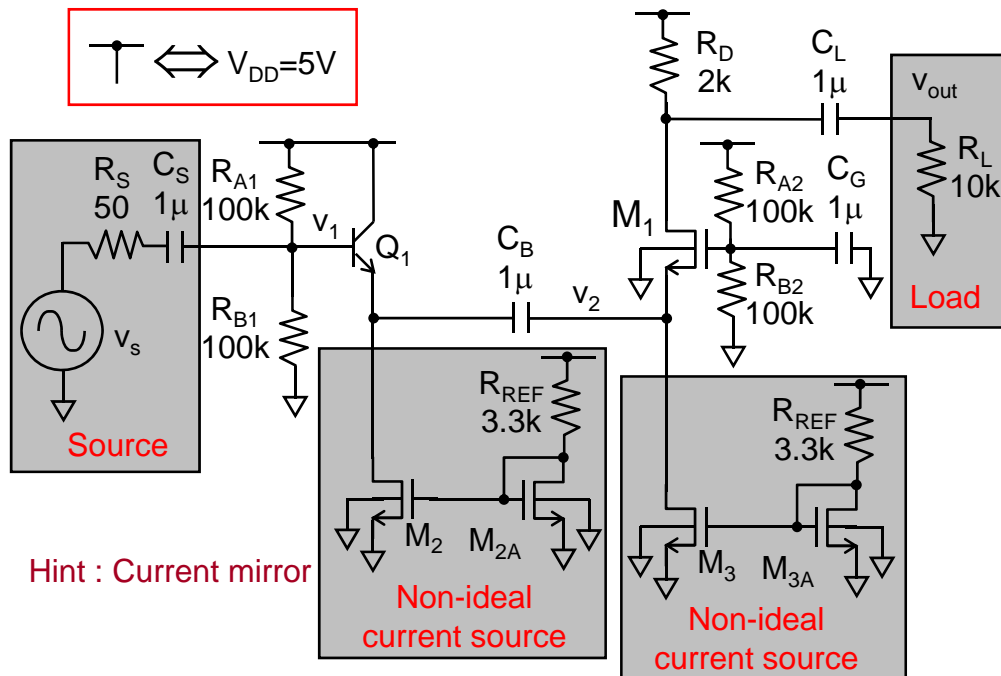
NMOS :

$K_n=2\text{mA/V}^2$, $V_{THN0}=1\text{V}$, $\lambda_n=0.01\text{V}^{-1}$, $\gamma_n=0.5$, $2\phi_f=0.6$, $C_{gd}=1\text{pF}$,
 $C_{gs}=1\text{pF}$, $C_{db}=0.1\text{pF}$, $C_{sb}=0.1\text{pF}$

BJT :

$I_S=10^{-15}\text{A}$, $\beta=100$, $V_A=100\text{V}$, $C_\pi=1\text{p}$, $C_\mu=1\text{p}$

$$\text{---} \Leftrightarrow V_{DD}=5\text{V}$$



Hint : Current mirror

- Find the DC biasing current for Q_1 and M_1

Determine DC Biasing

$$I_{D,M2A} = K_n (V_{GS,M2A} - V_{THN0})^2 \dots\dots (1)$$

$$I_{D,M2A} = \frac{V_{DD} - V_{GS,M2A}}{R_{REF}} \dots\dots (2)$$

$$\Rightarrow 6.6V_{GS,M2A}^2 - 13.2V_{GS,M2A} + 6.6 = 5 - V_{GS,M2A}$$

$$\Rightarrow 6.6V_{GS,M2A}^2 - 12.2V_{GS,M2A} + 1.6 = 0$$

$$\Rightarrow V_{GS,M2A} = \frac{-(-12.2) \pm \sqrt{(12.2)^2 - 4(6.6)(1.6)}}{2(6.6)}$$

$$= 1.71 \text{ or } 0.142 (< V_{THN0} \Rightarrow \text{invalid})$$

$$\Rightarrow I_{C,Q1} \approx I_{D,M2A} = I_{D,M2} = 1\text{mA}$$

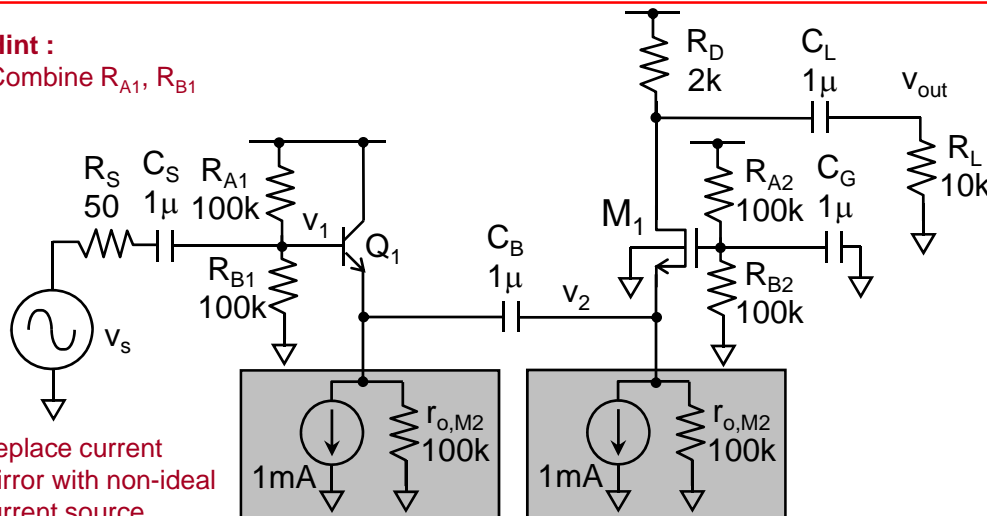
Similarly

$$\Rightarrow I_{D,M1} = I_{D,M3} = I_{D,M3A} = 1\text{mA}$$

AC Analysis : Simplify the Circuit and Find Out AC Small Signal Parameter

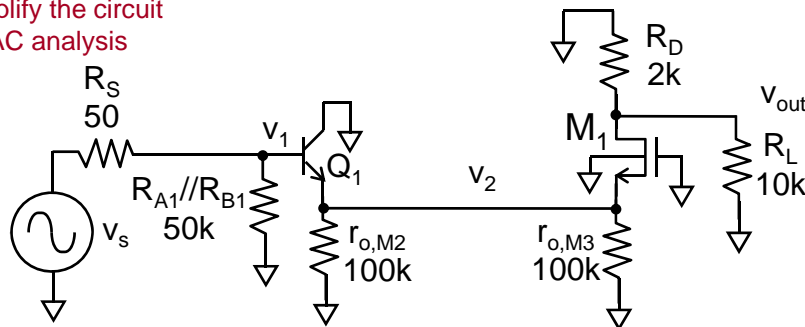
Hint :

Combine R_{A1} , R_{B1}



Replace current mirror with non-ideal current source

Simplify the circuit for AC analysis



Determine AC small signal parameter

$$g_{m,M1} = \sqrt{4K_n I_{D,M1}} = 2.83 \text{ mA/V}$$

$$g_{mb,M1} = -\frac{g_{m,M1}}{4} = -0.71 \text{ mA/V}$$

$$r_{o,M1} = r_{o,M3} = r_{o,M2} = \frac{1}{\lambda_n I_{D,M1}} = 100 \text{ k}$$

$$g_{m,Q1} = \frac{I_C}{V_T} = 40 \text{ mA/V}$$

$$r_{\pi,Q1} = \frac{\beta}{g_{m,Q1}} = 2.5 \text{ k}$$

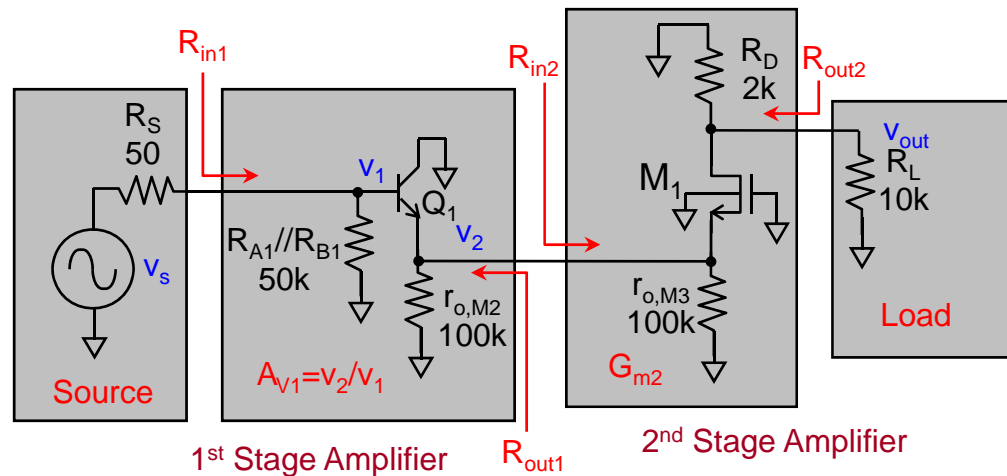
$$r_{o,Q1} = \frac{V_A}{I_{C,Q1}} = 100 \text{ k}$$

Hint :

- 1) DC voltage source → AC ground
- 2) DC current source → Open circuit
- 3) DC block/bypass capacitor → AC short circuit

- Simplify the circuit for AC analysis by replacing current mirror with non-ideal current source
- Find out the AC small signal parameters (g_m , r_{π} , r_o) for transistors Q_1 , M_1 , M_2 , M_3

AC Analysis : Identify Amplifier



1st stage amplifier configuration :
Common Collector (CC)

2nd stage amplifier configuration :
Common Gate (CG)

1st stage amplifier G_{m1} :
Not applicable

Table 3 Configuration C

2nd stage amplifier G_{m2} :
 $-(g_{m,M1} - g_{mb,M1}) = -3.54mA/V$

Table 4 Configuration B

- Identify the 1st and 2nd stage amplifiers by drawing rectangular box surrounding them
- Write down the corresponding two ports-network parameters

AC Analysis : Identify Two-ports Network Parameters (R_{in2} , R_{out1})

Combine R_D and R_L in parallel

Table 2 Configuration D

$$R_{x2} = \frac{1}{g_{m,M1} - g_{mb,M1}} \frac{r_{o,M1} + (R_D // R_L)}{r_{o,M1}}$$

$$\approx \frac{1}{g_{m,M1} - g_{mb,M1}} = 283$$

$$R_{in2} = R_{x2} // r_{o,M3} \approx R_{x2} = \frac{1}{g_{m,M1} - g_{mb,M1}} = 283$$

Combine R_S and $R_{A1} // R_{B1}$ in parallel

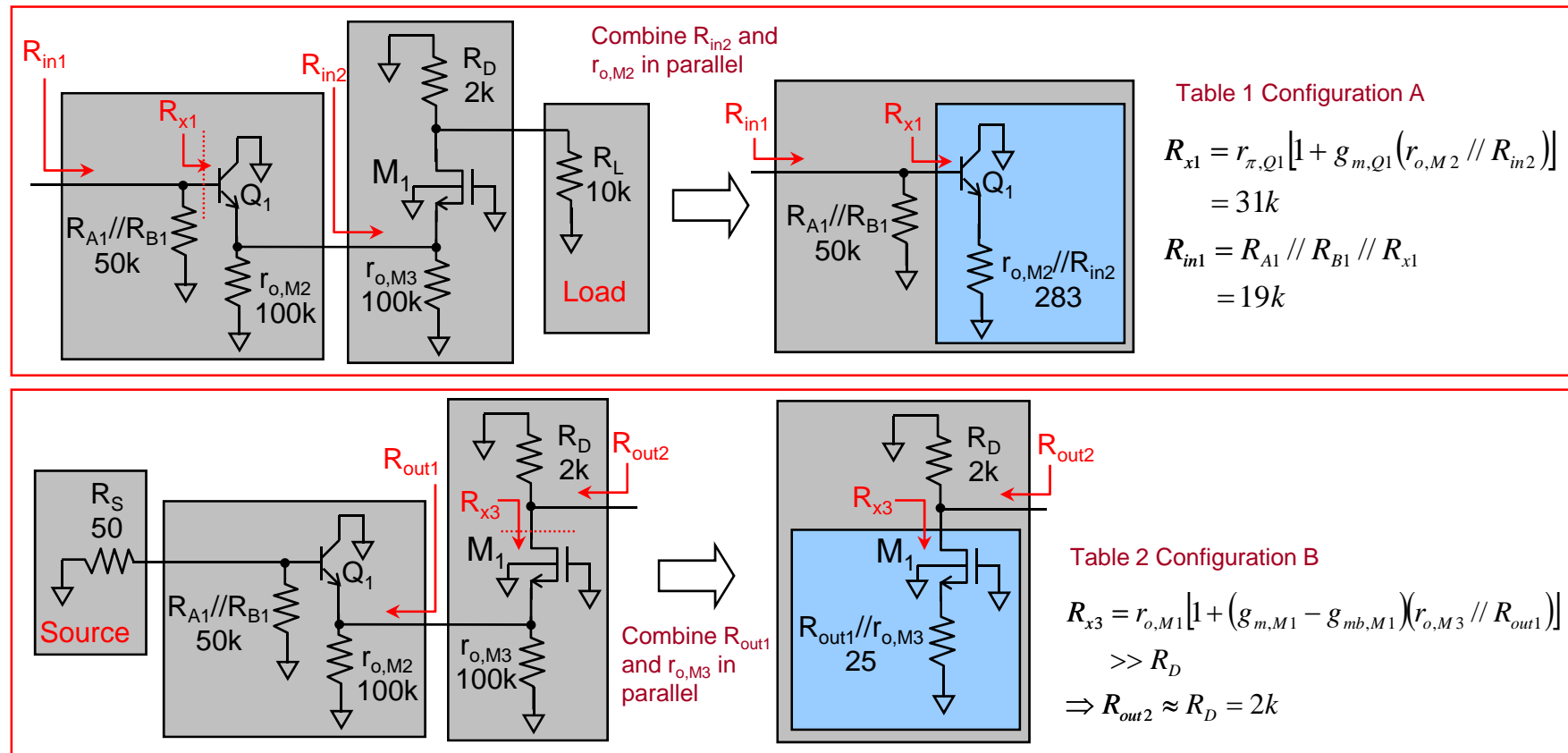
Table 1 Configuration C

$$R_{x4} = \frac{R_S // R_{A1} // R_{B1}}{\beta + 1} + \frac{1}{g_{m,Q1}} \approx \frac{1}{g_{m,Q1}} = 25$$

$$R_{out1} = R_{x4} // r_{o,M2} \approx \frac{1}{g_{m,Q1}} = 25$$

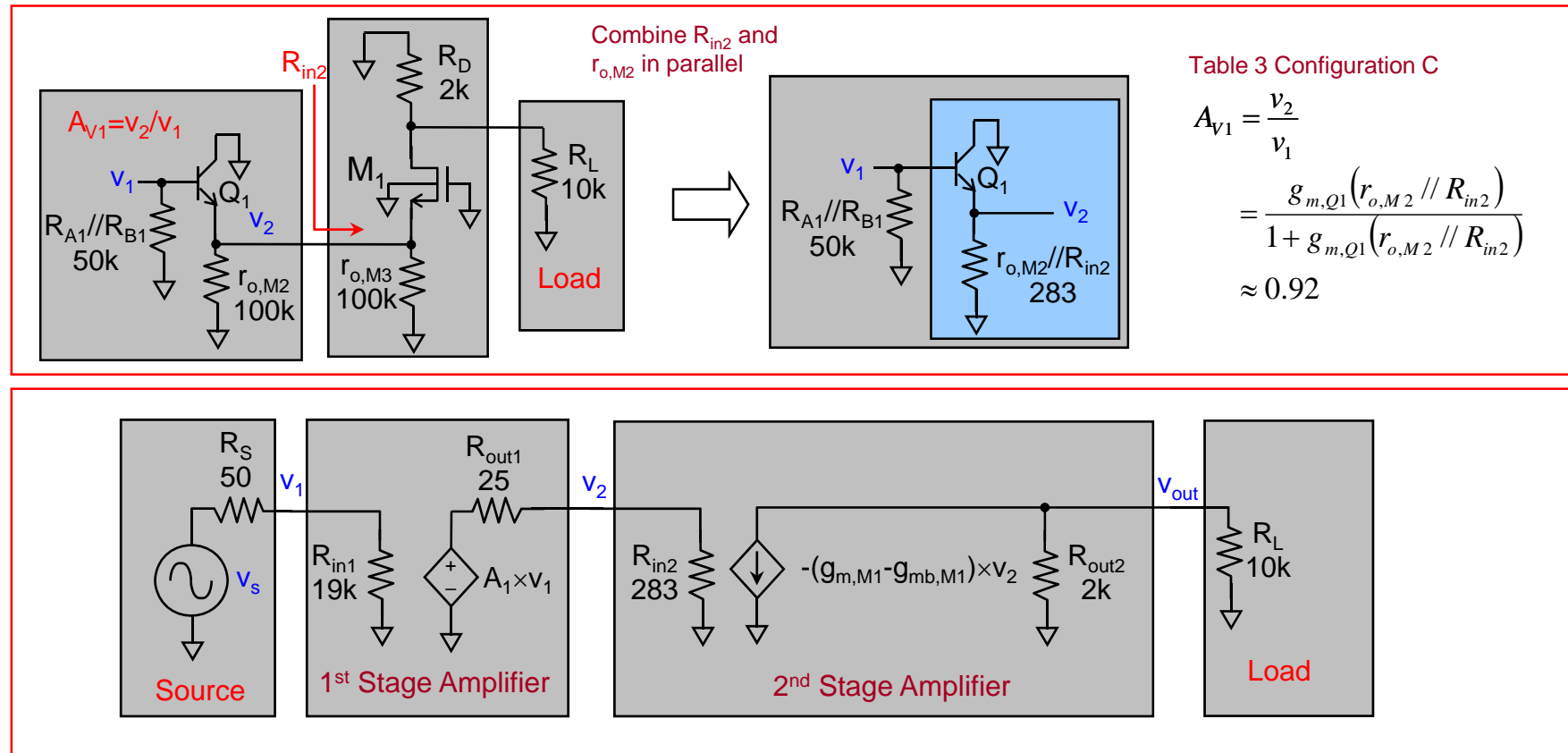
- Estimate R_{in2} and R_{out1} (Throw away half the circuit)

AC Analysis : Identify Two-ports Network Parameters (R_{in1} , R_{out2})



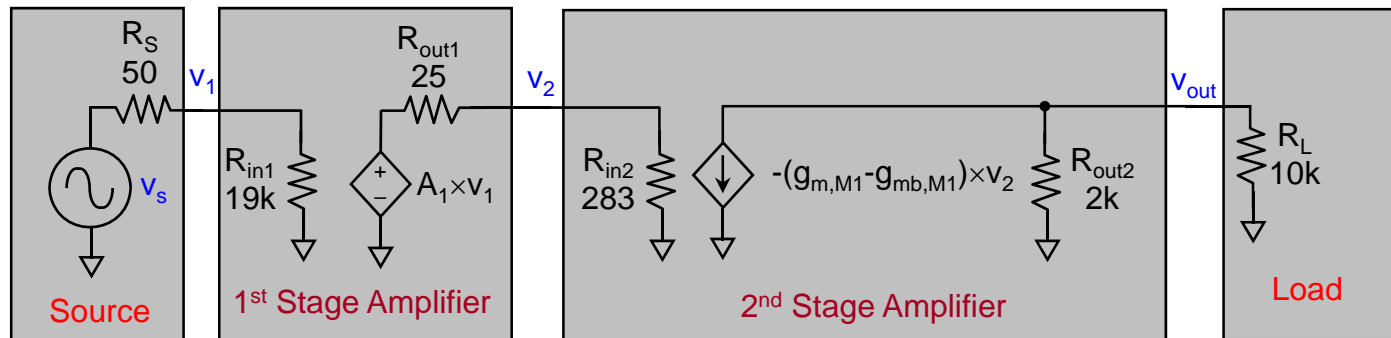
- Estimate R_{in1} and R_{out2}

AC Analysis : Identify $A_{V1}=v_2/v_1$



- Estimate $A_{V1}=v_2/v_1$
- Draw out two-ports network equivalent

AC Analysis : Overall Gain $A_V = v_{out}/v_s$



$$v_1 = \frac{R_{in1}}{R_{in1} + R_S} \times v_s \approx v_s$$

$$v_2 = \frac{g_{m,Q1}(r_{o,M2} // R_{in2})}{1 + g_{m,Q1}(r_{o,M2} // R_{in2})} \times v_1 \approx 0.92 \times v_1 \approx 0.92 \times v_s$$

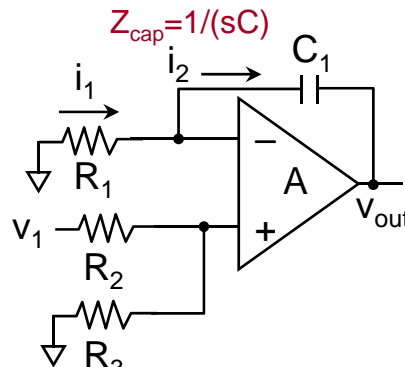
$$v_{out} = (g_{m,M1} - g_{mb,M1})(v_2) \times (R_{out2} // R_L) \approx 5.91 \times v_2 \approx 5.43 \times v_s$$

$$A_V = \frac{v_{out}}{v_s} = \underbrace{\frac{R_{in1}}{R_{in1} + R_S}}_{\text{Resistor Divider}} \times \underbrace{A_{V1}}_{CC} \times \underbrace{G_{m2}(R_{out2} // R_L)}_{CG}$$

$$= \underbrace{\frac{R_{in1}}{R_{in1} + R_S}}_{\text{Resistor Divider}} \times \underbrace{\frac{g_{m,Q1}(r_{o,M2} // R_{in2})}{1 + g_{m,Q1}(r_{o,M2} // R_{in2})}}_{CC} \times \underbrace{(g_{m,M1} - g_{mb,M1})(R_{out2} // R_L)}_{CG} = 5.43$$

- Estimate overall gain $A_V = v_{out}/v_s$

Opamp Circuit Analysis



$Z_{cap} = 1/(sC_1)$

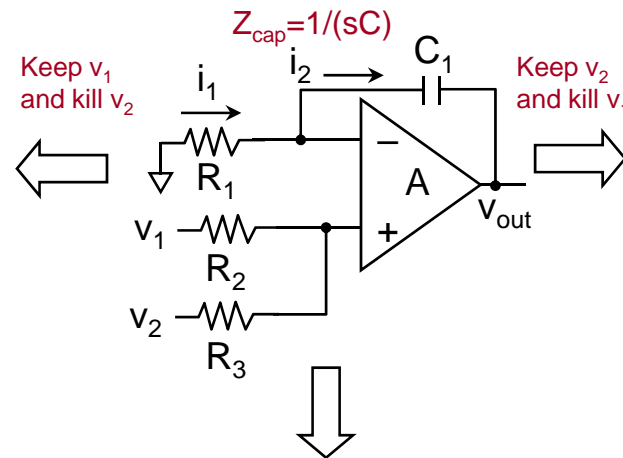
$v_+ = v_1 \times \frac{R_3}{R_2 + R_3} \approx v_- [:: \text{Virtual short}]$

$i_1 = i_2 [:: i_- = i_+ = 0]$

$\Rightarrow \frac{0 - v_-}{R_1} = \frac{v_- - v_{out}}{\frac{1}{sC_1}}$

$\Rightarrow v_{out} = v_- \times \left(1 + \frac{1}{sC_1 R_1}\right)$

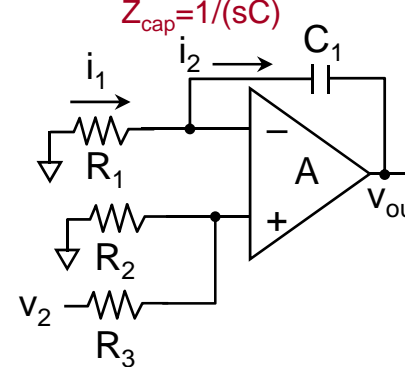
$= v_1 \times \frac{R_3}{R_2 + R_3} \times \left(1 + \frac{1}{sC_1 R_1}\right)$



Superposition :

$$v_{out} = \left(\frac{v_1 \times R_3 + v_2 \times R_2}{R_2 + R_3} \right) \left(1 + \frac{1}{sC_1 R_1} \right)$$

- Virtual short ($v_+ \approx v_-$)
- Infinite input resistance ($i_+ = i_- = 0$)
- Superposition



$Z_{cap} = 1/(sC_1)$

$v_+ = v_2 \times \frac{R_2}{R_3 + R_2} \approx v_- [:: \text{Virtual short}]$

$i_1 = i_2 [:: i_- = i_+ = 0]$

$\Rightarrow \frac{0 - v_-}{R_1} = \frac{v_- - v_{out}}{\frac{1}{sC_1}}$

$\Rightarrow v_{out} = v_- \times \left(1 + \frac{1}{sC_1 R_1}\right)$

$= v_2 \times \frac{R_2}{R_3 + R_2} \times \left(1 + \frac{1}{sC_1 R_1}\right)$

BJT Equivalent Resistance Summary (Table 1)

Blue: look into collector terminal

Red: look into base terminal

Green: look into emitter terminal

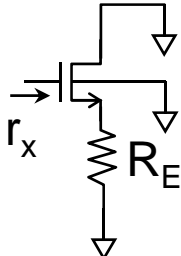
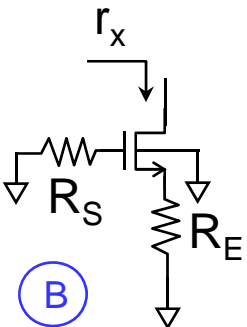
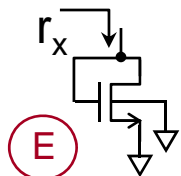
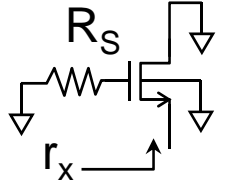
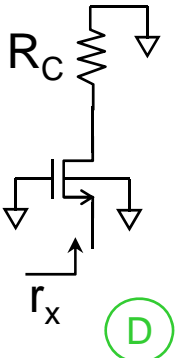
Conf	r_x	Conf	r_x	Conf	r_x
	$r_\pi + (1 + \beta)R_E$ $\approx r_\pi (1 + g_m R_E)$		$r_o \left\{ 1 + g_m \left[(r_\pi + R_S) \parallel R_E \right] \left(\frac{r_\pi}{r_\pi + R_S} \right) \right\}$ <p>If $R_S = 0$ and $r_\pi \ll R_E$ $\Rightarrow r_{x,\max} = r_o (\beta + 1)$</p>		$\frac{1}{g_m}$
	$\frac{R_S + r_\pi}{1 + \beta} \parallel r_o$ $\approx \frac{R_S}{1 + \beta} + \frac{1}{g_m}$		$\frac{1}{g_m} \times \frac{r_o + R_C}{r_o + \frac{R_C}{\beta}}$		

MOS Equivalent Resistance Summary (Table 2)

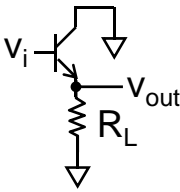
Blue: look into drain terminal

Red: look into gate terminal

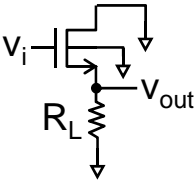
Green: look into source terminal

Conf	r_x	Conf	r_x	Conf	r_x
 (A)	∞	 (B)	$r_o [1 + (g_m - g_{mb}) R_E]$	 (E)	$\frac{1}{g_m}$
 (C)	$\frac{1}{g_m - g_{mb}}$	 (D)	$\frac{1}{g_m - g_{mb}} \times \frac{r_o + R_C}{r_o}$		

BJT Summary (Table 3)

BJT	G_m	A_v
CE (A)	g_m	Derive Based on 2-ports Network
CB (B)	$-g_m$	Derive Based on 2-ports Network
CC (C) 	Not Applicable	$\frac{g_m R_L}{1 + g_m R_L}$
CE with Emitter Degeneration (D)	$\frac{g_m}{1 + g_m R_E}$	Derive Based on 2-ports Network

MOS Summary (Table 4)

MOS	G_m	A_v
CS (A)	g_m	Derive Based on 2-ports Network
CG (B)	$-(g_m - g_{mb})$ <i>Drop g_{mb} if no body effect</i>	Derive Based on 2-ports Network
CD (C) 	Not Applicable	$\frac{g_m R_L}{1 + (g_m - g_{mb}) R_L} \approx \frac{g_m}{g_m - g_{mb}}$ <i>Drop g_{mb} if no body effect</i>
CS with R_E (D)	$\frac{g_m}{1 + (g_m - g_{mb}) R_E}$ <i>Drop g_{mb} if no body effect</i>	Derive Based on 2-ports Network