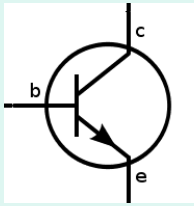
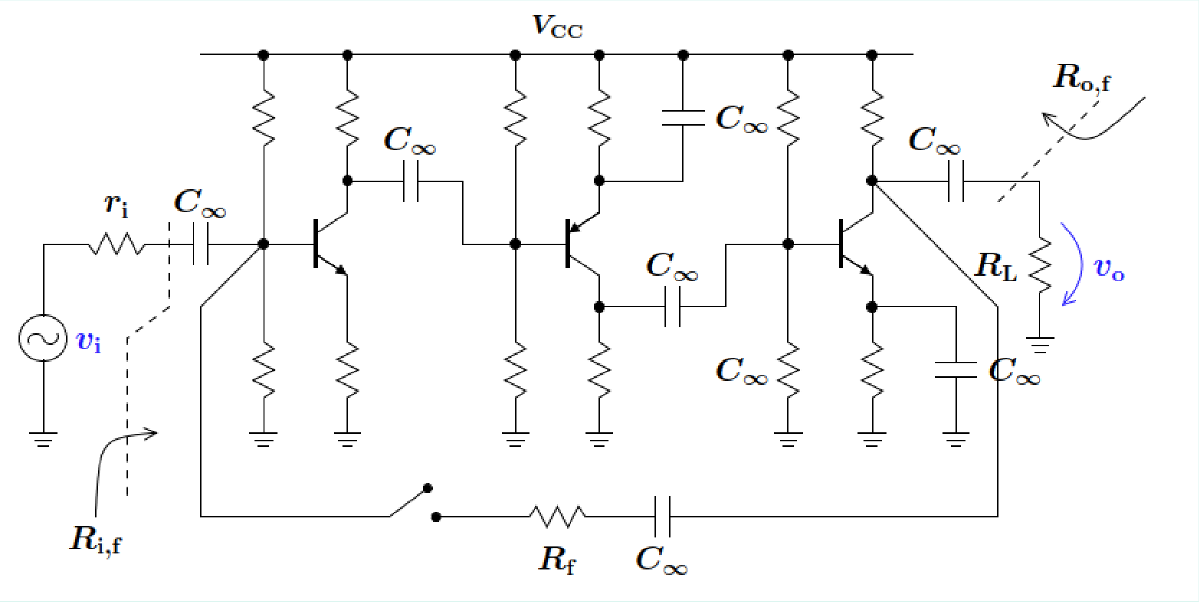
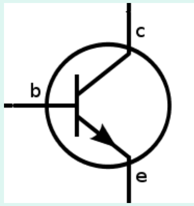


ELEC 301 - Differential amplifier

L19 - Oct 23

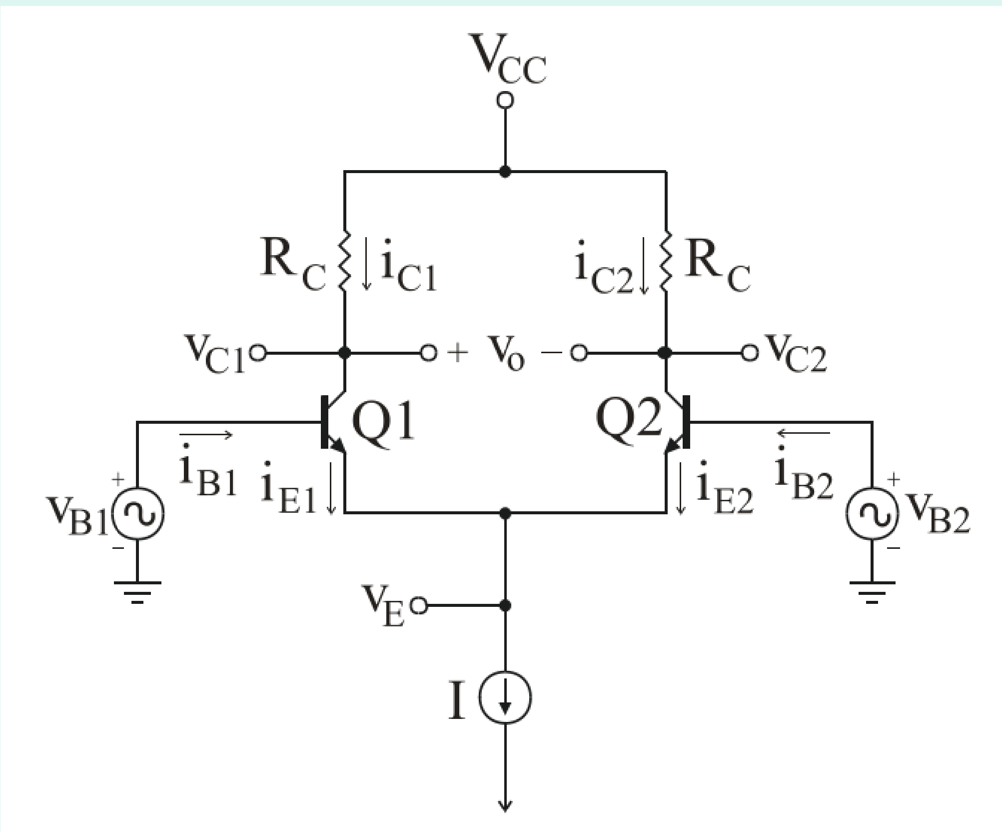
Instructor: Edmond Cretu



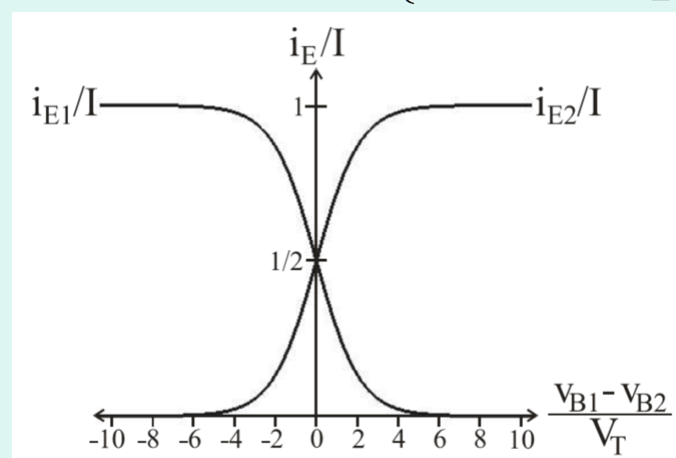


Last time

- Review of single stage BJT amplifiers
- Differential amplifier block
- Signal pairs decompositions - symmetric (CM) and antisymmetric (DM) components



$$\begin{cases} v_{InC} = \dfrac{v_{B1}+v_{B2}}{2} \\ v_{InD} = v_{B1}-v_{B2} \end{cases} v \Leftrightarrow \begin{cases} v_{B1} = v_{InC} + \dfrac{v_{InD}}{2} \\ v_{B2} = v_{InC} - \dfrac{v_{InD}}{2} \end{cases}$$



$$\frac{v_o}{v_d} = -g_m R_C$$

L19 Q01- differential stage DM

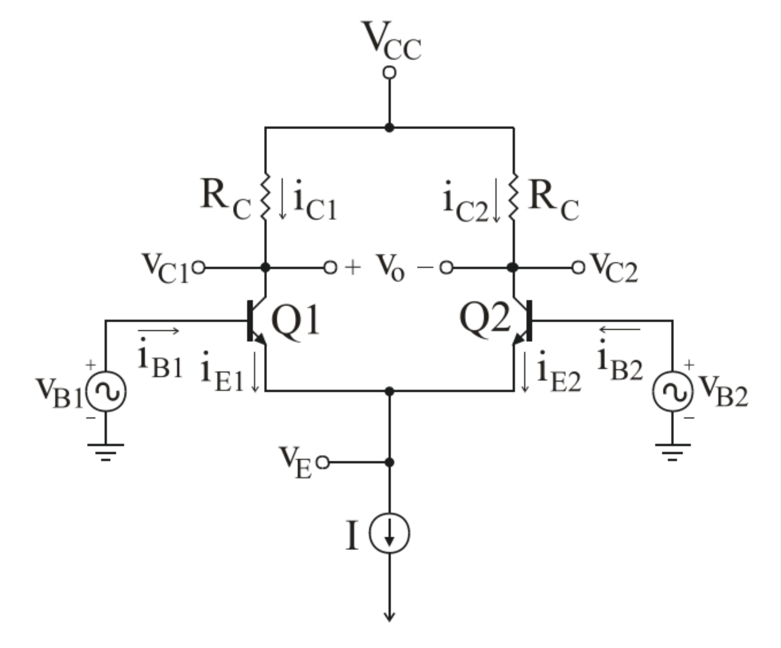
- Assume we apply a pure differential input signal between v_{B1} and v_{B2}, and we have a load resistor R_L between C1 and C2. If we "split" the differential stage into two separate sections, what is the equivalent load resistor each section sees?

A. ∞

B. $2R_L$

C. $R_L/2$

D. 0



L19 Q02 - differential stage CM

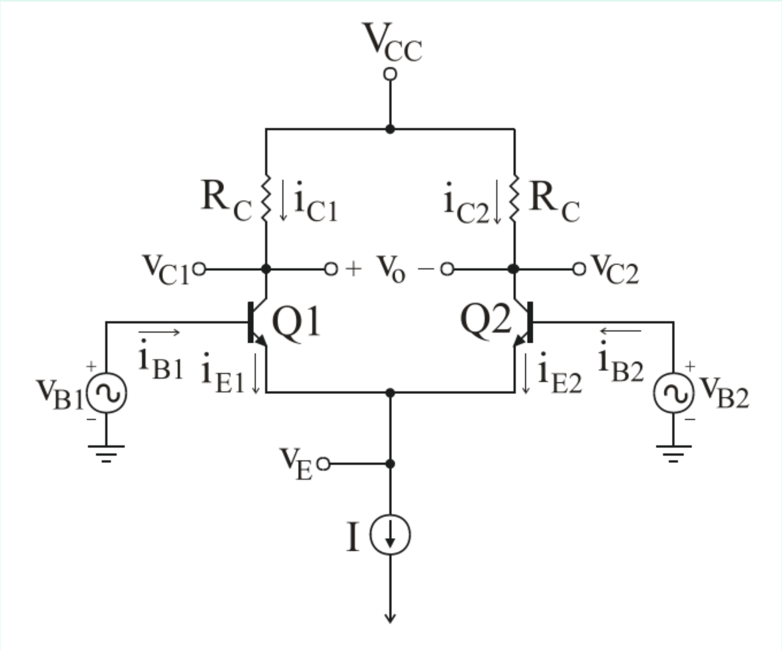
- Assume we apply a pure common input signal between v_{B1} and v_{B2}, and we have a load resistor R_L between C1 and C2. If we "split" the differential stage into two separate sections, what is the equivalent load resistor each section sees?

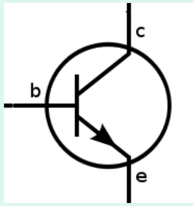
A. ∞

B. $2R_L$

C. $R_L/2$

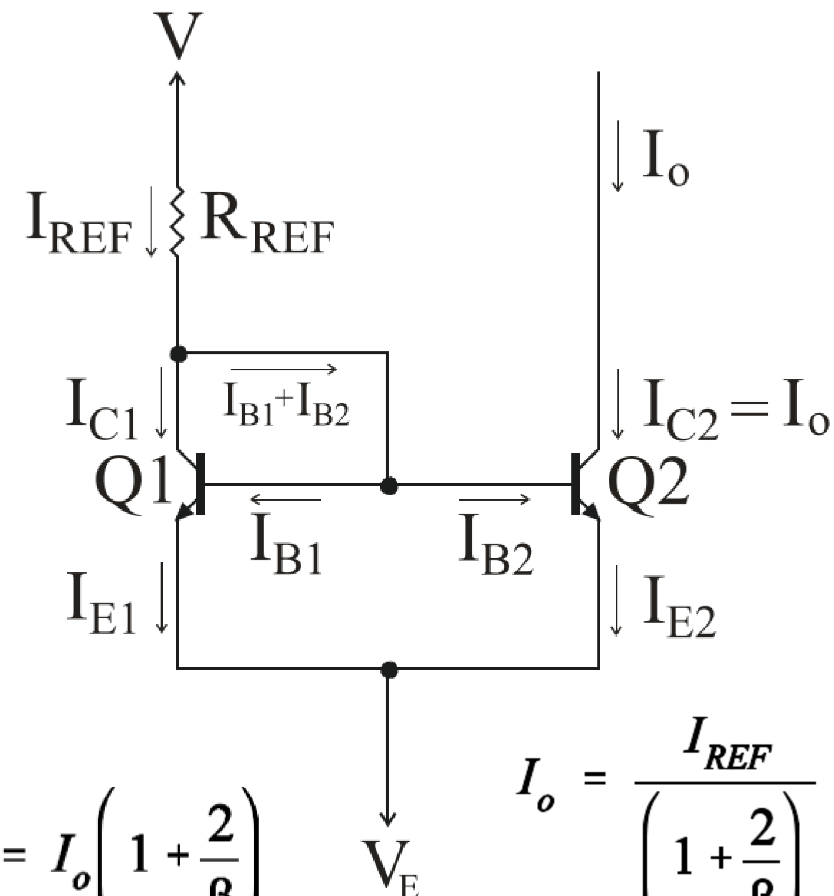
D. 0





The current mirror

- How to implement a current source using transistors?
- Basic idea: “copy” the current from an equivalent transistor having the same v_{BE}



$$I_{REF} = \frac{V-(V_E+V_{BE})}{R_{REF}}$$

$$I_{REF} = I_{E1} + I_{B2}$$

$$I_o = I_{C2} = I_{E2} - I_{B2}$$

Equivalent Q1,Q2 , $v_{BE1}=v_{BE2} \Rightarrow I_{E1}=I_{E2}$

$$I_{REF} - I_o = 2I_{B2}$$

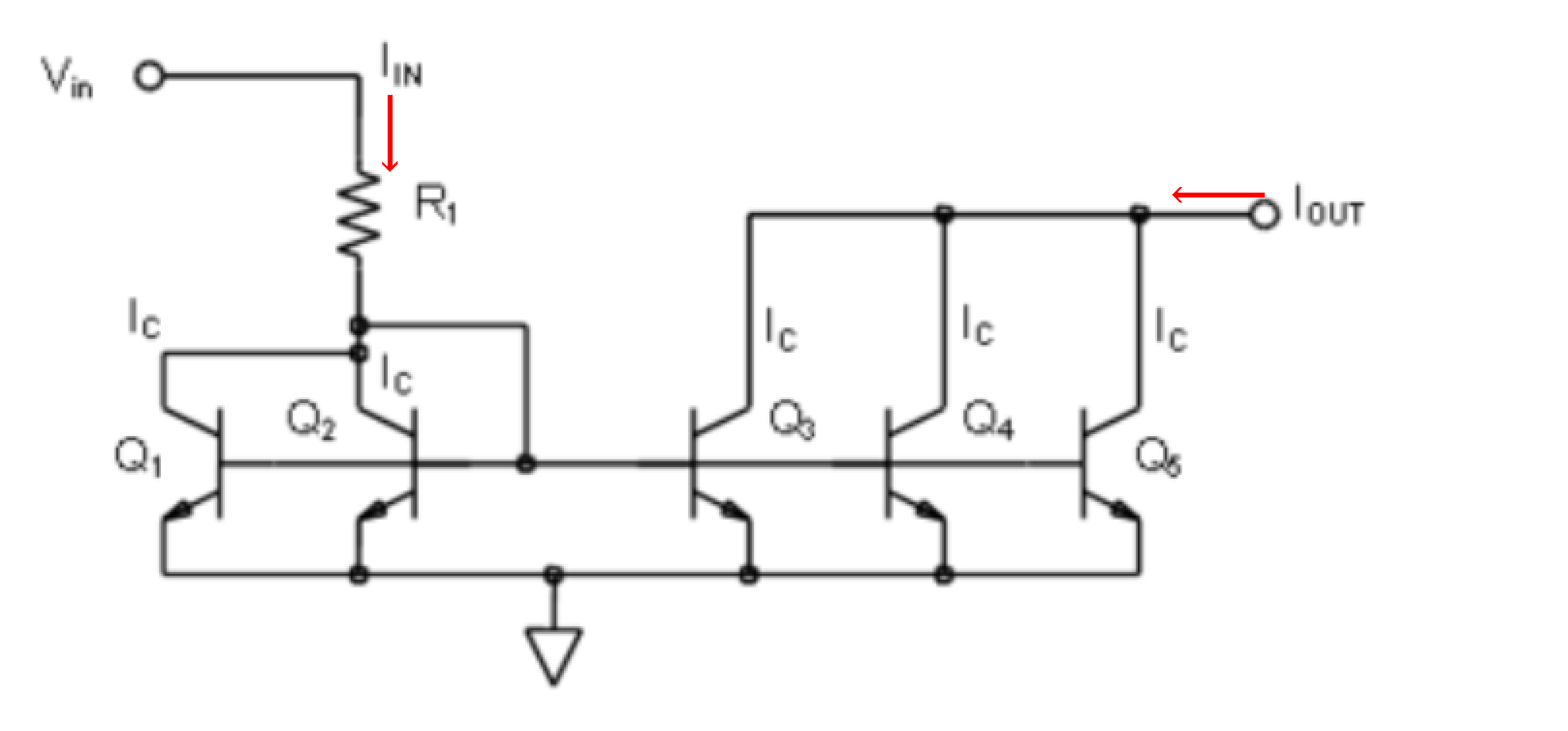
$$I_{REF} = I_o + 2I_{B2} = I_{C2} + 2I_{B2} = I_{C2}\left(1+\frac{2}{\beta}\right) = I_o\left(1+\frac{2}{\beta}\right)$$

$$I_o = \frac{I_{REF}}{\left(1+\frac{2}{\beta}\right)}$$

L19 Q03 - Current mirror

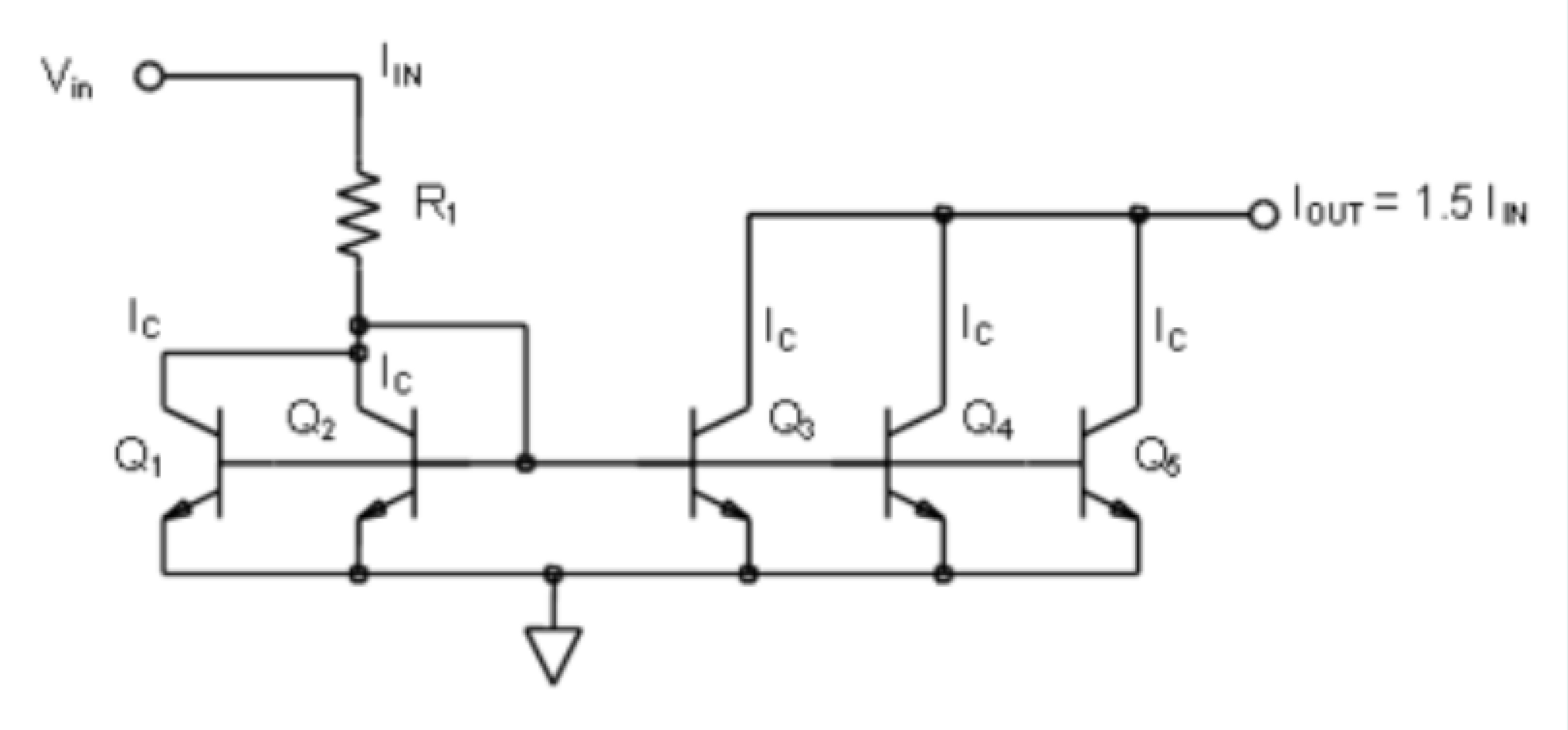
- What is I_{out} in the following circuit? (assume identical transistors)

A. I_{IN}
B. $3I_{IN}$
C. $3/2I_{IN}$
D. $2I_{IN}$



Current mirror with non-unitary gain

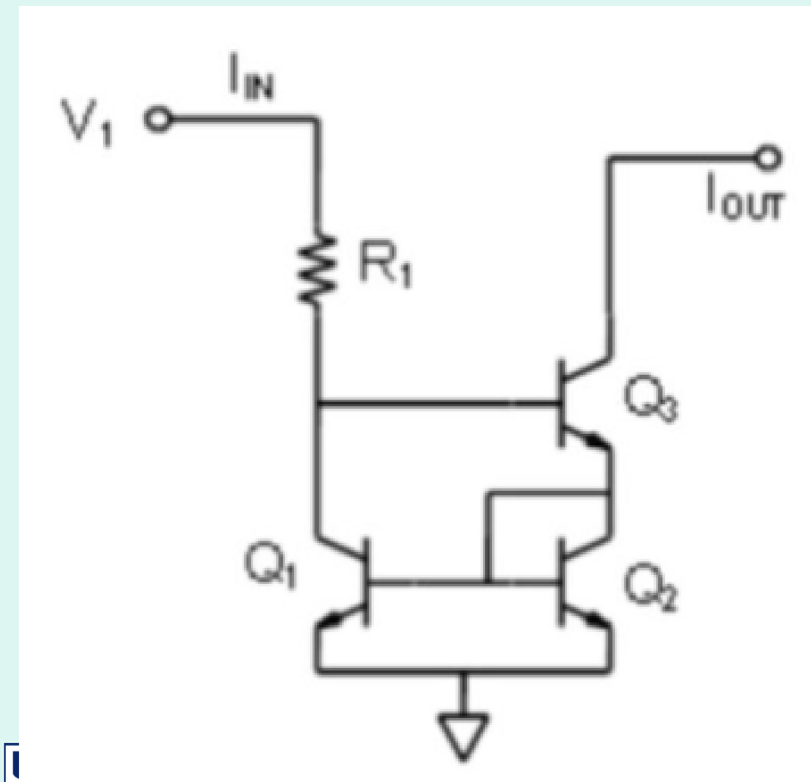
- **Homework 1**: analyze the operation of the following current mirror:



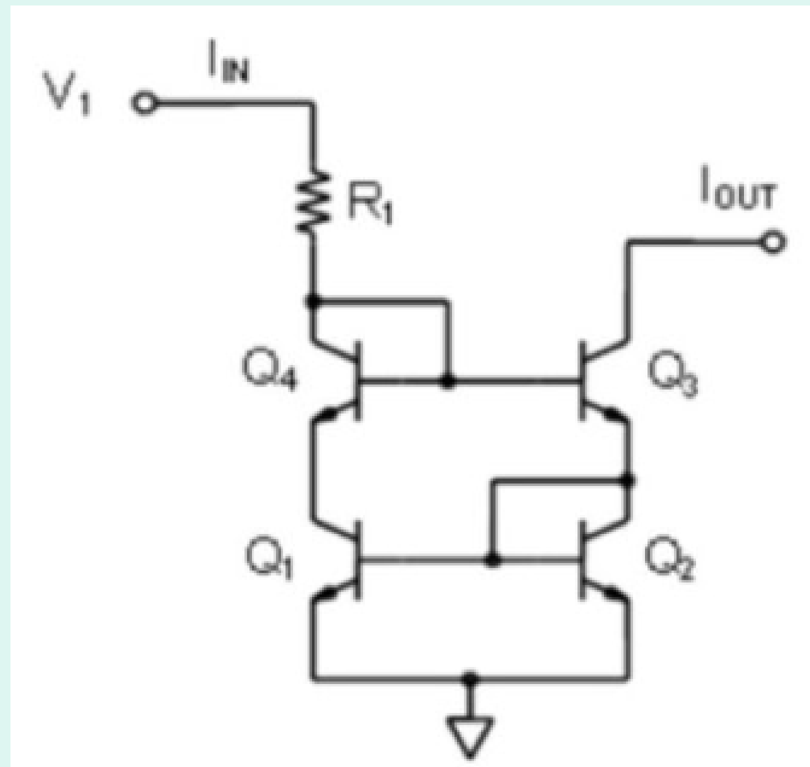
(Source: Analog Devices)

Improved current mirror

- **Homework 2**: analyze the operation of the Wilson current mirror (provides a more constant current source and a more accurate current gain) and improved Wilson current mirror circuits below:



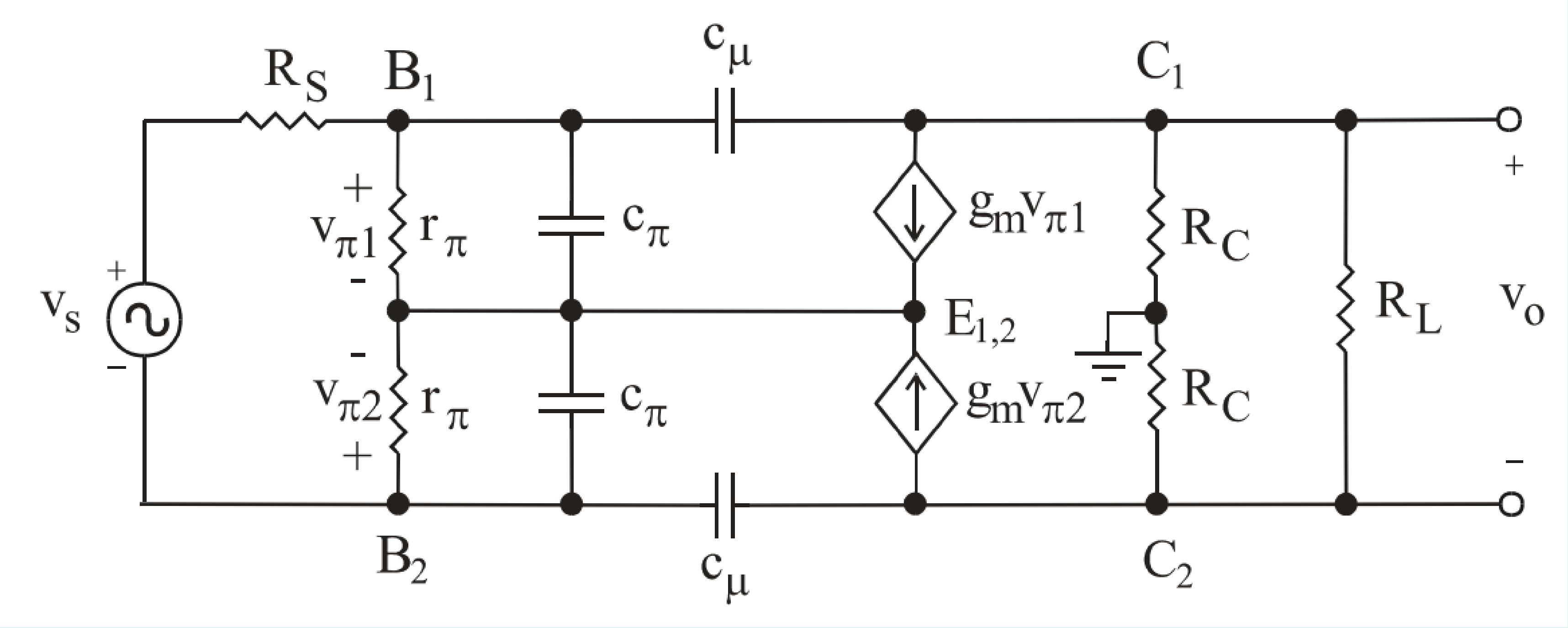
Basic Wilson current mirror



Improved Wilson current mirror

Differential amplifier - frequency response

- We assume equivalent transistors, pure differential excitation (no common-mode input voltage)
- Small signal model:

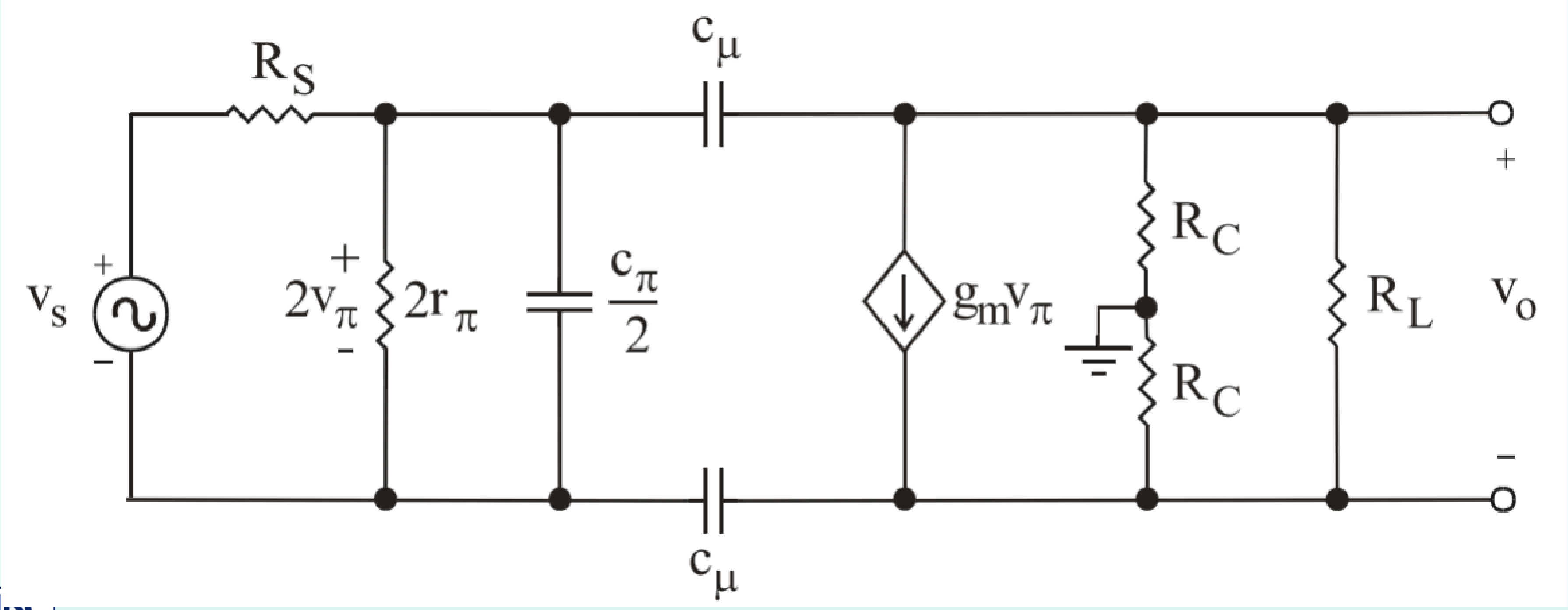


Frequency response (2)

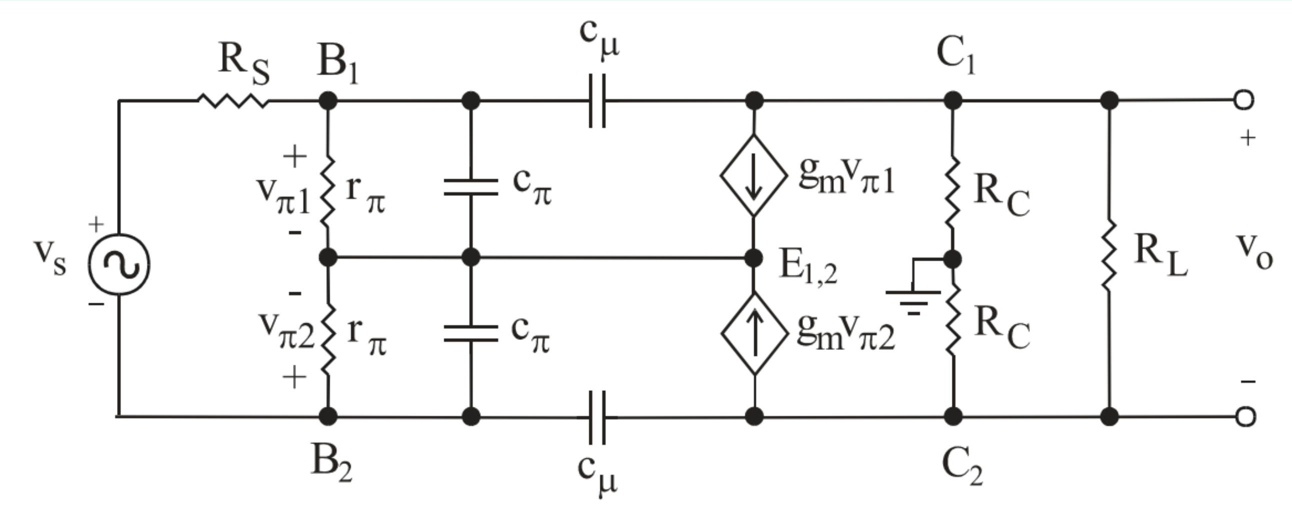
- At the emitters E1, E2 we have:

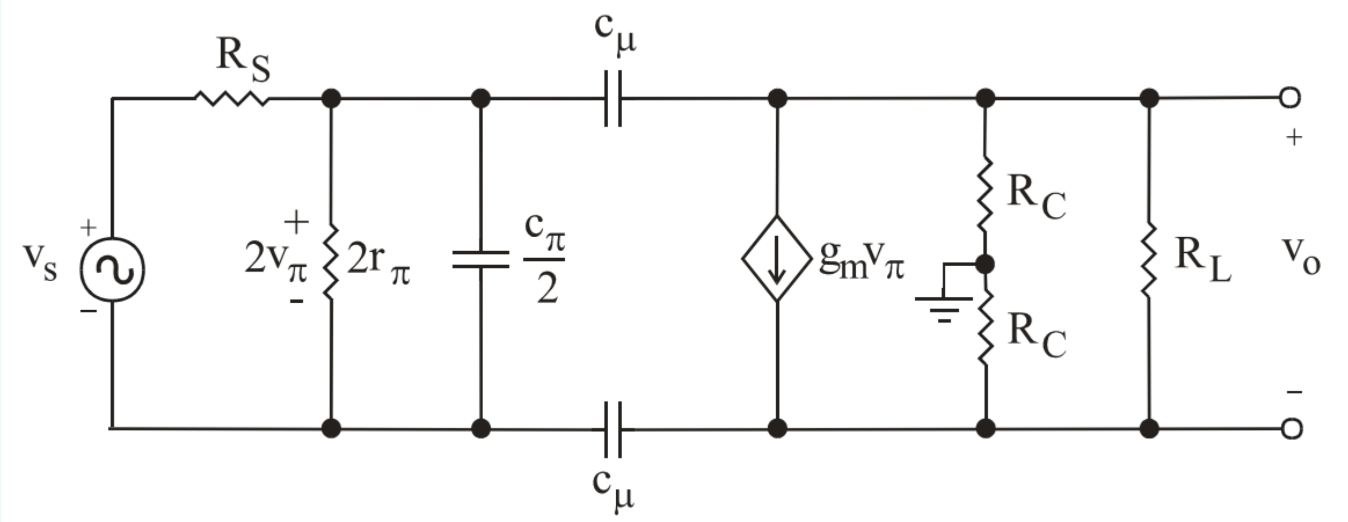
$$v_{\pi 1}(g_\pi + s c_\pi + g_m) + v_{\pi 2}(g_\pi + s c_\pi + g_m) = 0 \qquad v_{\pi 1} = -v_{\pi 2}$$

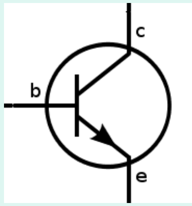
We redraw the equivalent circuit:



Differential gain - symmetry

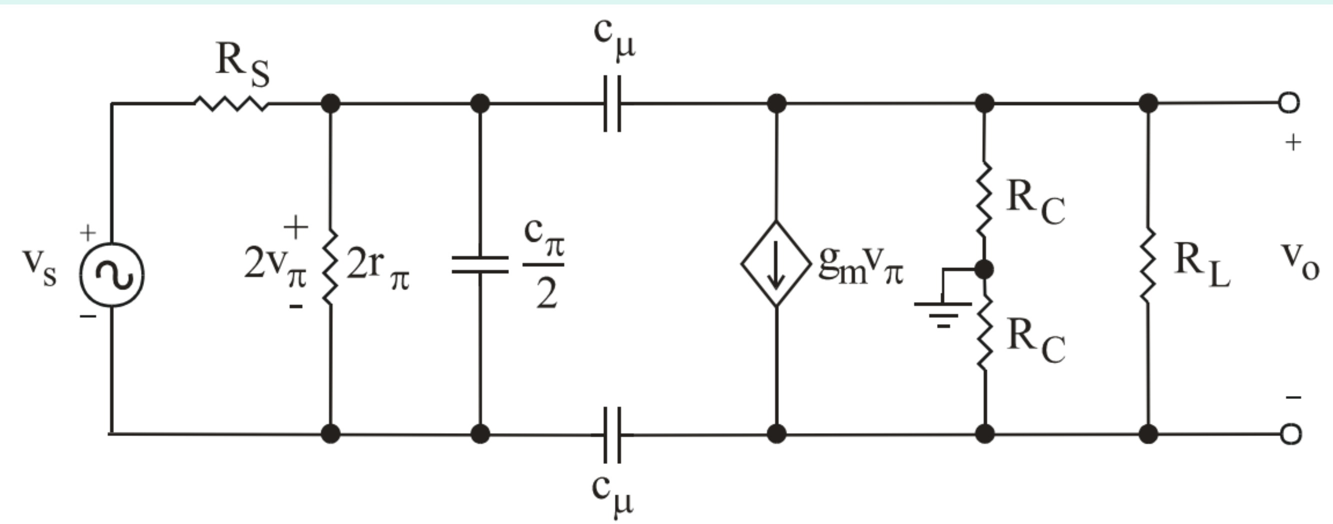


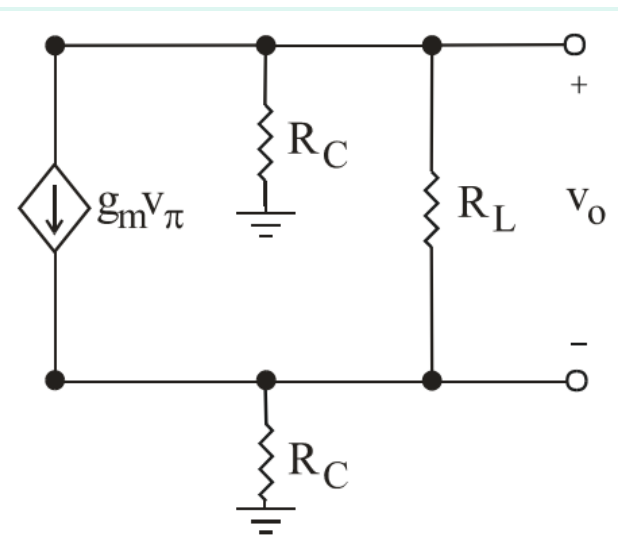


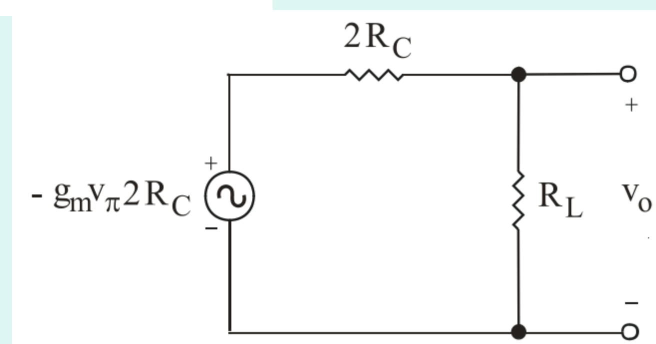


Miller gain

- The Miller gain $k = v_o/(2v_\pi)$



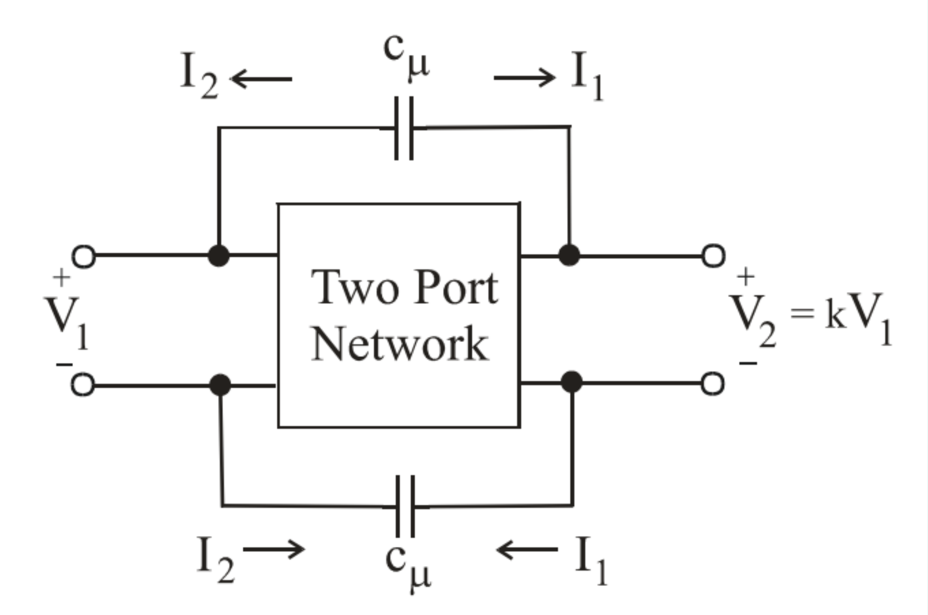




$$k = \frac{v_o}{2v_\pi} = -g_m \frac{2v_\pi}{2v_\pi} R_c \frac{R_L}{R_L + 2R_C}$$

Miller gain (2)

- Use the computed Miller gain



$$V_1 = \frac{I_1}{sc_\mu} + V_2 + \frac{I_1}{sc_\mu}$$

$$V_1 - V_2 = \frac{2}{sc_\mu} I_1$$

$$V_1 - kV_1 = V_1(1-k) = \frac{2}{sc_\mu} I_1$$

$$Z_1 = \frac{V_1}{I_1} = \frac{2}{sc_\mu}\frac{1}{(1-k)} = \frac{1}{\frac{sc_\mu}{2}(1-k)}$$

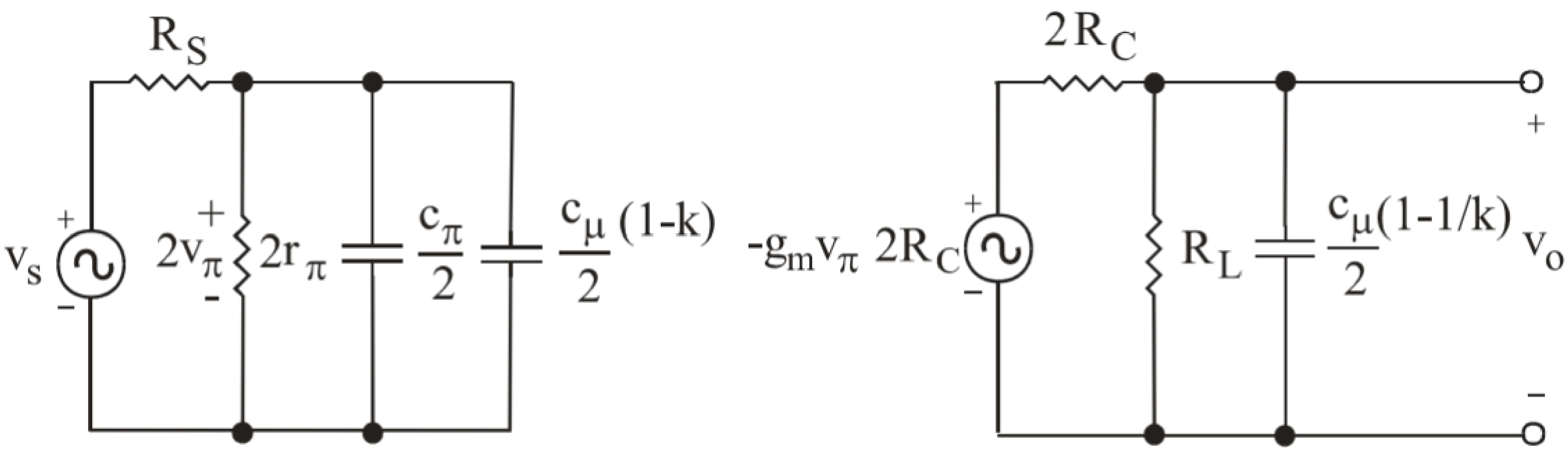
$$V_2 = \frac{I_2}{sc_\mu} + V_1 + \frac{I_2}{sc_\mu}$$

$$V_2 - \frac{V_2}{k} = V_2\left(\frac{k-1}{k}\right) = \frac{2}{sc_\mu} I_2$$

$$Z_2 = \frac{V_2}{I_2} = \frac{2}{sc_\mu}\frac{k}{(k-1)} = \frac{1}{\frac{sc_\mu}{2}\left(1 - \frac{1}{k}\right)}$$

Miller-reduced model - HF behavior

- Complete model



$$k = -g_m R_C \frac{R_L}{R_L + 2R_C}$$

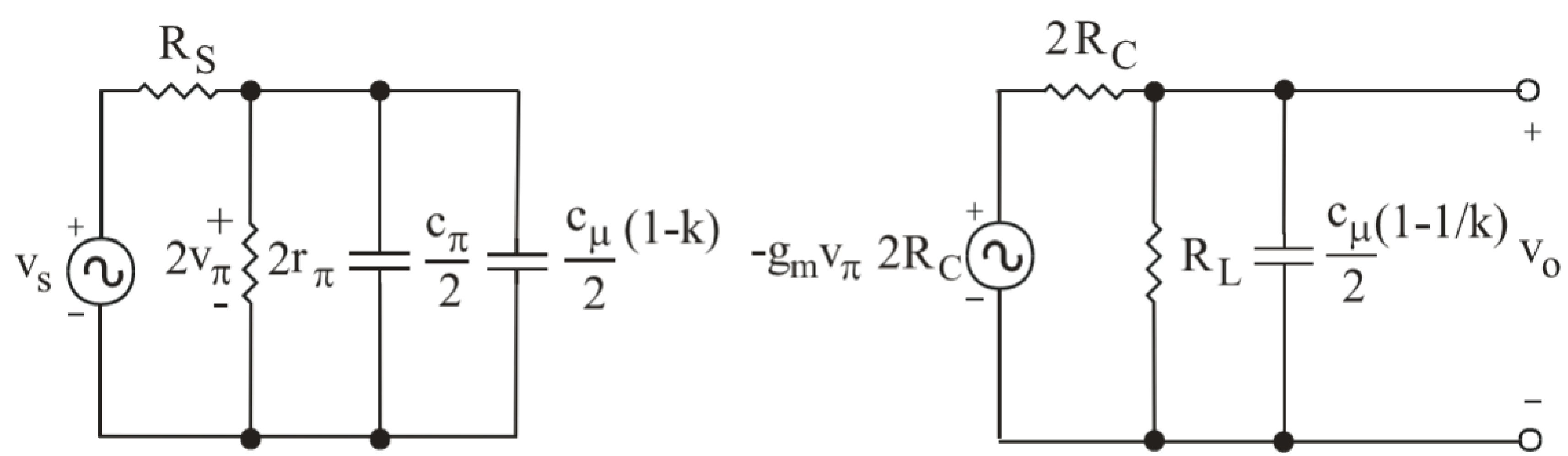
HF poles:

$$\omega_{HP1} = \frac{1}{\left[\frac{c_\pi}{2} + \frac{c_\mu}{2}(1-k)\right] 2r_\pi \| R_S}$$

$$\omega_{HP2} = \frac{1}{\frac{c_\mu}{2}\left(1 - \frac{1}{k}\right) R_L \| 2R_C}$$

Midband gain

- Midband behavior (C_π,C_μ are OC)



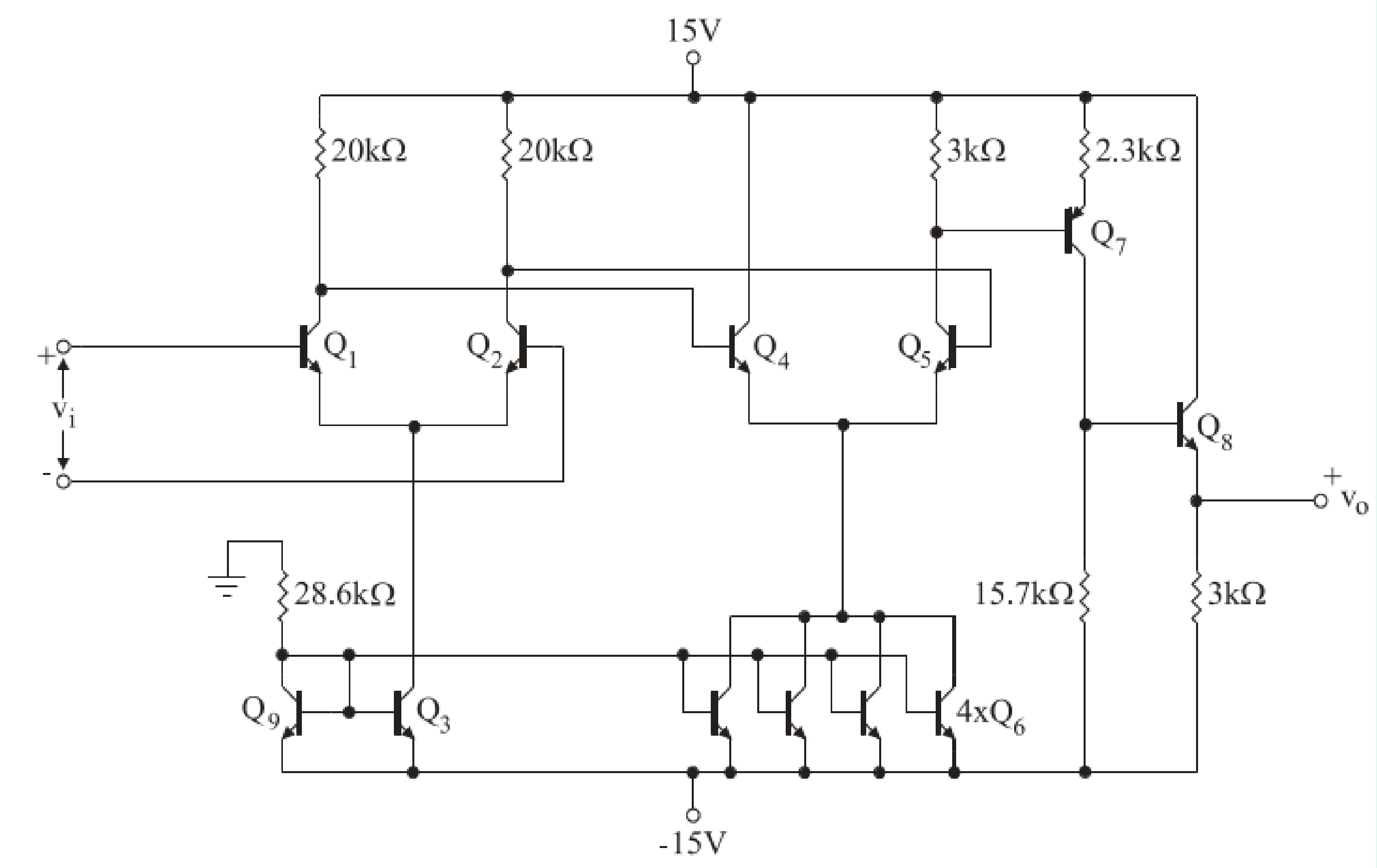
$$k = -g_m R_C \frac{R_L}{R_L + 2R_C}$$

$$v_o = -g_m 2v_\pi R_C \frac{R_L}{R_L + 2R_C} = -g_m v_s \frac{2r_\pi}{2r_\pi + R_S} R_C \frac{R_L}{R_L + 2R_C}$$

$$A_M = \frac{v_o}{v_S} = -g_m R_C \left[\frac{2r_\pi}{2r_\pi + R_S}\right]\left[\frac{R_L}{R_L + 2R_C}\right]$$

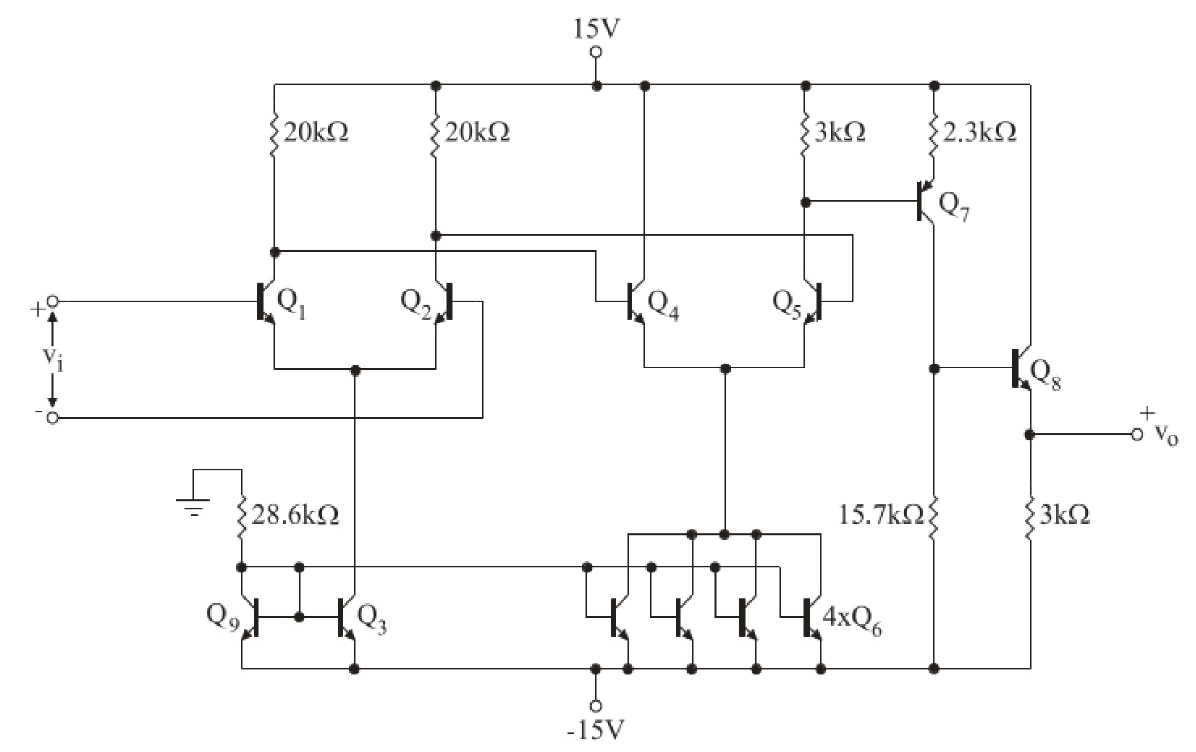
Basic op amp circuit

- A basic opamp architecture - 4 stages:
  - input stage
  - gain stage
  - level shifter
  - output stage



Opamp - quiescent point (DC analysis)

- We assume β=100 for all transistors



$$I_{REF} = \frac{0V - 0.7V - (-15V)}{28.6k\Omega} = 0.5mA$$

$$I_{C3} = I_{REF} = 0.5mA \Rightarrow I_{E1} = I_{E_2} = \frac{I_{REF}}{2}$$

$$I_{C1} = I_{C2} \approx \frac{I_{REF}}{2} = 0.25mA$$

$$g_{m1} = g_{m2} = \frac{0.25mA}{25mV} = 0.01S$$

$$r_{\pi 1} = r_{\pi 2} = \frac{\beta}{g_{m1}} = \frac{100}{0.01}\Omega = 10k\Omega$$

$$I_{C6} = I_{REF} = 0.5mA \Rightarrow I_{C4} = I_{C5} = \frac{4I_{C6}}{2} = 1mA$$

$$g_{m4} = g_{m5} = \frac{1mA}{25mV} = 0.04S$$

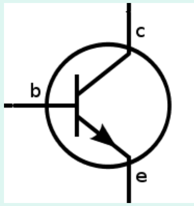
$$r_{\pi 4} = r_{\pi 5} = \frac{\beta}{g_{m4}} = 100 \cdot 25\Omega = 2.5k\Omega$$

$$V_{B7} = V_{C5} = 15V - 3k\Omega I_{C5} = 12V \Rightarrow V_{E7} = 12V + 0.7V = 12.7V$$

$$I_{E7} = \frac{15V - 12.7V}{2.3k\Omega} = 1mA \Rightarrow I_{C7} = \alpha I_{E7} \approx 1mA$$

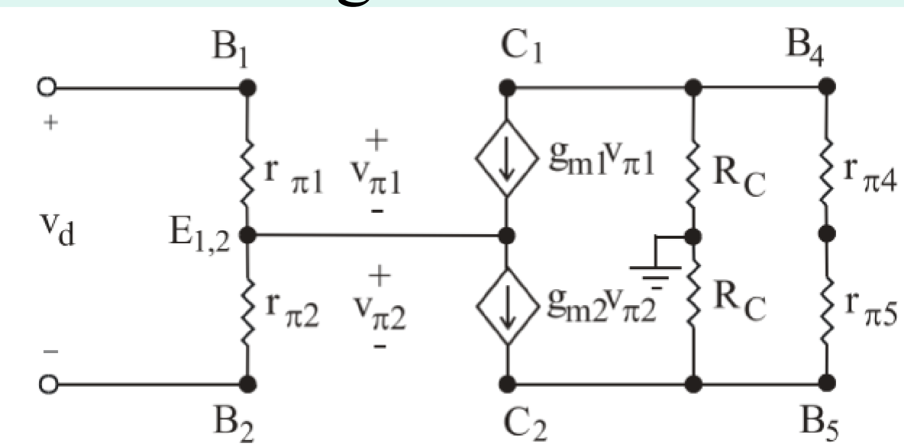
$$g_{m7} = \frac{1mA}{25mV} = 0.04S, \quad r_{\pi 7} = 2.5k\Omega$$

$$R_{i7} = r_{\pi 7} + (\beta + 1) R_{E7} = 2.5K\Omega + 230k\Omega \approx 230k\Omega$$

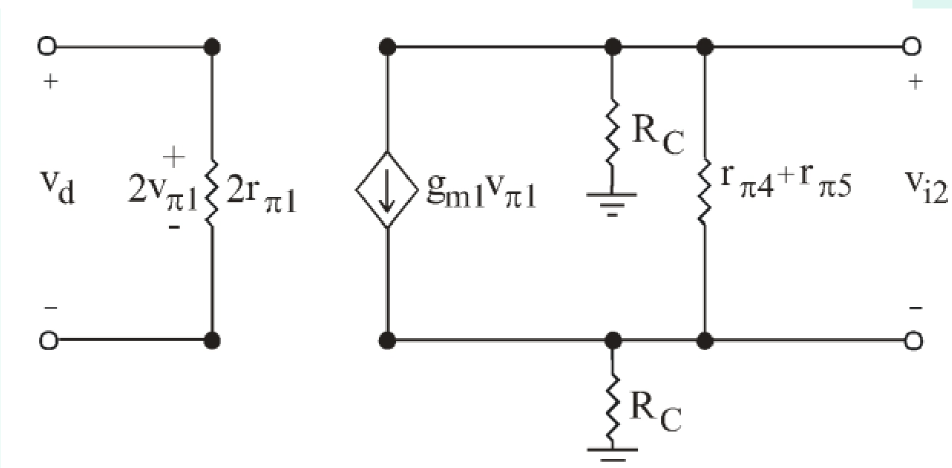


Small signal analysis

- Small signal model: first differential stage



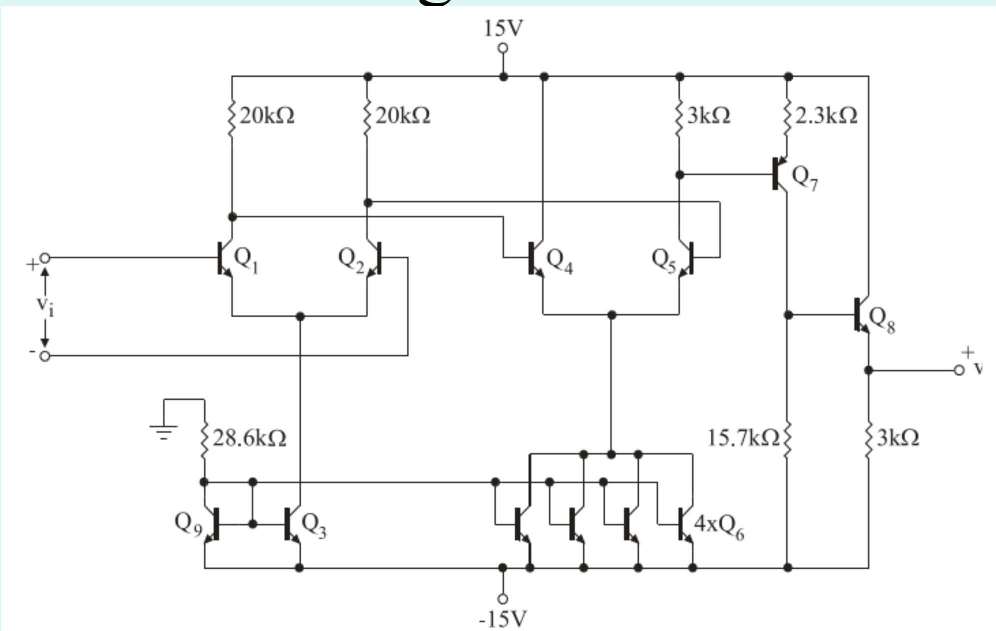
$$A_{M1} = \frac{v_{12}}{v_d} = -0.01S \cdot 20k\Omega \cdot \frac{5k\Omega}{45k\Omega} = -22$$

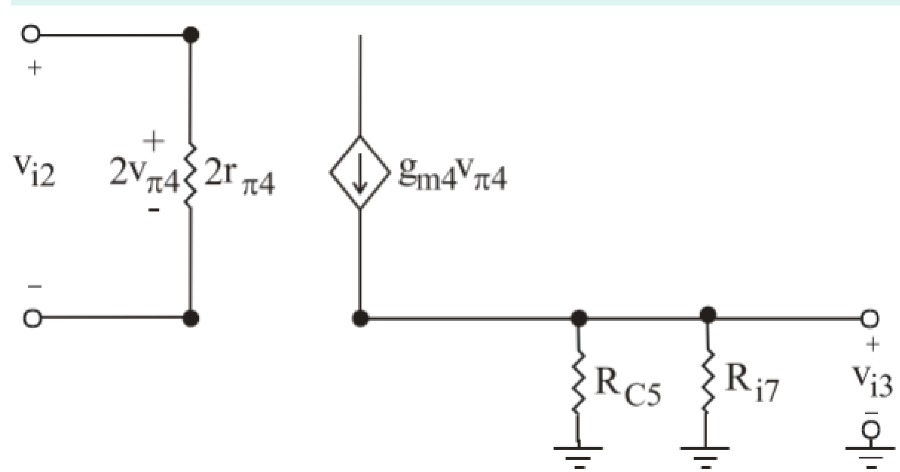


$$v_{o1} = v_{i2} = -g_{m1} v_{\pi 1} \frac{2R_C(r_{\pi 4} + r_{\pi 5})}{r_{\pi 4} + r_{\pi 5} + 2R_C} = -g_{m1} \frac{v_d}{2} 2R_C \frac{(r_{\pi 4} + r_{\pi 5})}{r_{\pi 4} + r_{\pi 5} + 2R_C}$$

Small signal analysis (2)

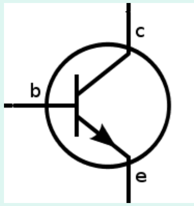
- Next stage - Differential to single-ended





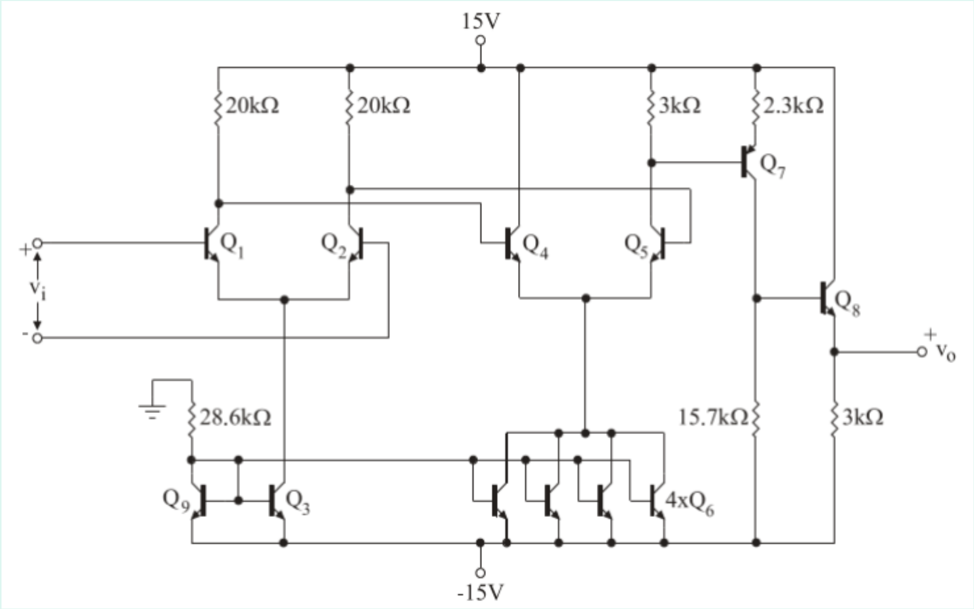
$$v_{o2} = v_{i3} = g_{m4} v_{\pi 4} R_{C5} || R_{i7} = g_{m4} \frac{v_{i2}}{2} R_{C5} || R_{i7}$$

$$A_{M2} = \frac{g_{m4}}{2} R_{C5} \,||\, R_{i7} \approx \frac{g_{m4}}{2} \cdot R_{C5} = 0.02S \cdot 3k\Omega = 60$$



Small signal analysis (3)

- Output stage:

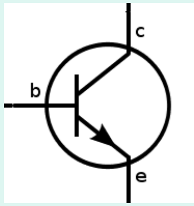


$$R_{i8} = r_{\pi 8} + (\beta + 1) R_{E8} \approx 300k\Omega$$

$$A_{M3} \approx -\frac{R_{C7} \| R_{i8}}{R_{E7}} = -\frac{15.7k\Omega \| 300k\Omega}{2.3k\Omega} = -6.48$$

$$A_{M4} \approx 1$$

$$A_M = A_{M1} A_{M2} A_{M3} A_{M4} = -22 \cdot 60 \cdot (-6.48) \cdot 1 = 8554 \approx 8600$$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