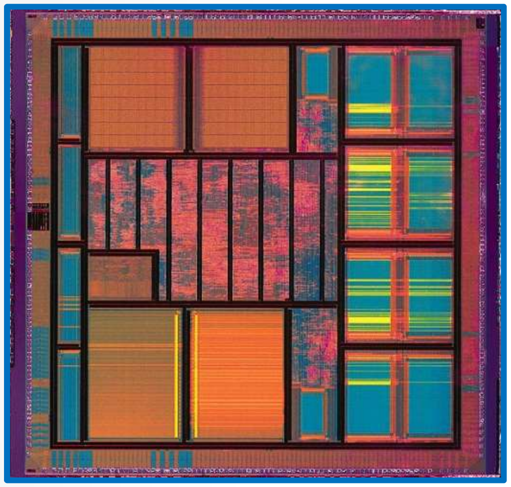
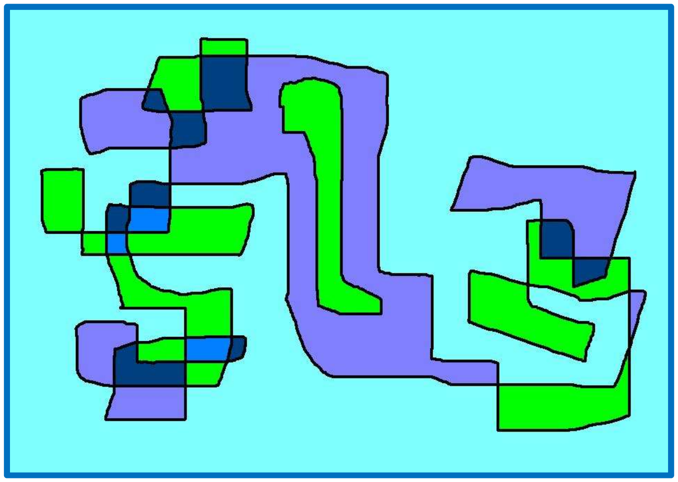
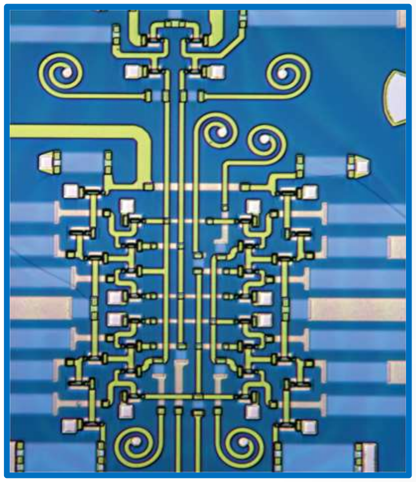




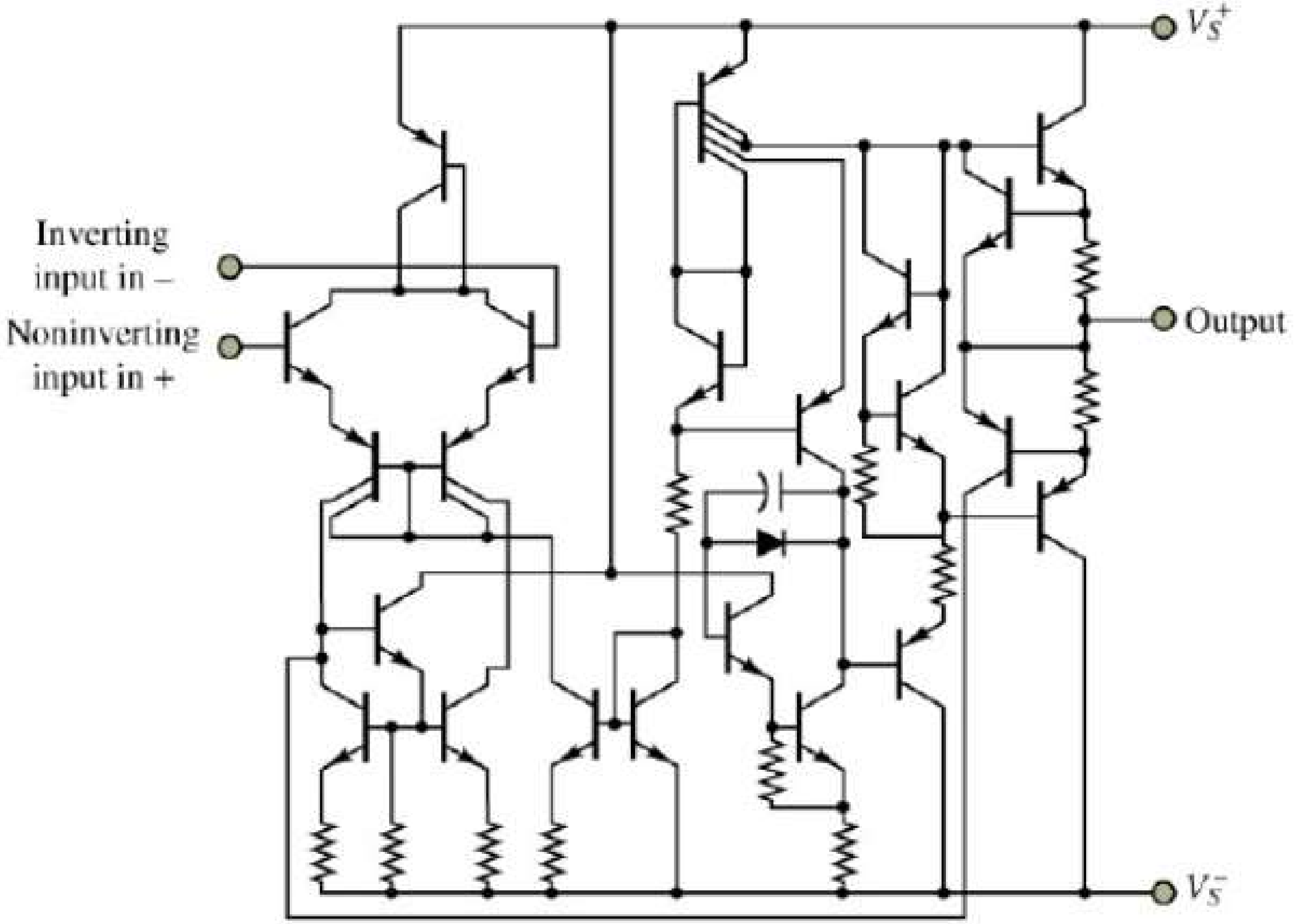


ENE/EIE 211 : Electronic Devices and Circuit Design II

Lecture 5: Differential Amps

The BJT Differential Pair

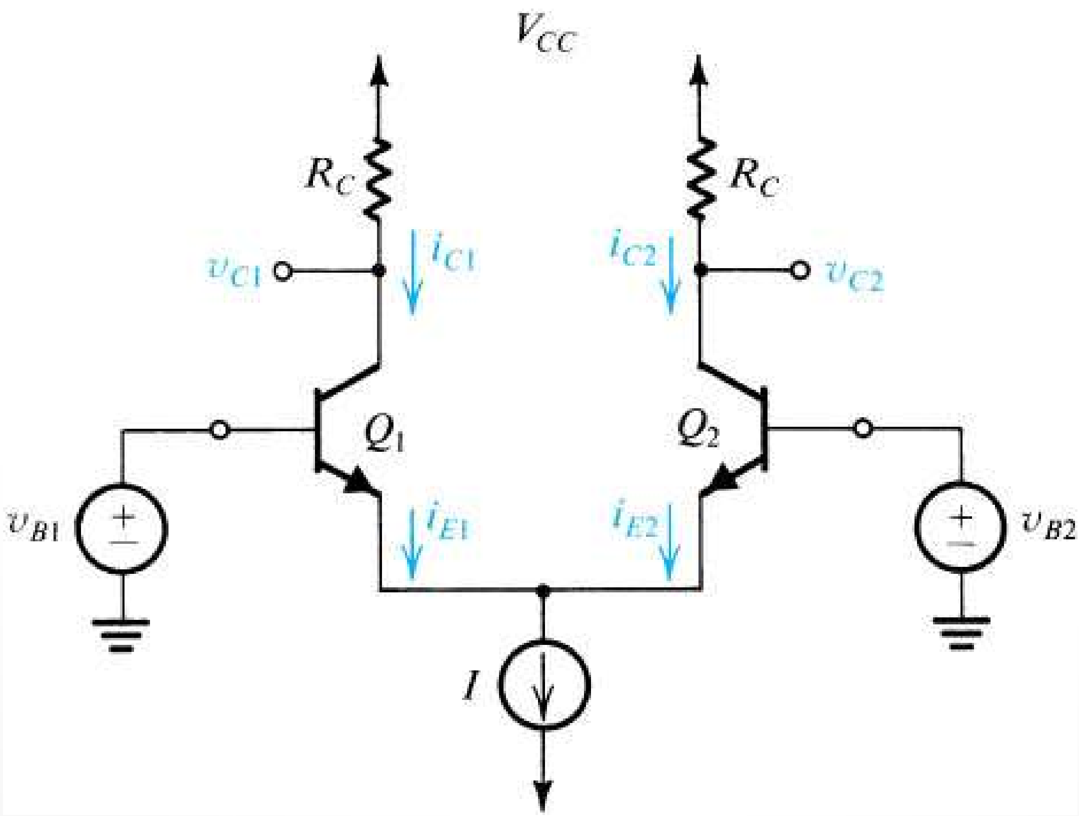
The differential pair or differential amplifier configuration is the most widely used building block in analog integrated ckt design. For instance, the input stage of every op amp is a differential amplifier. Also, the BJT differential amp is the basis of a very-high-speed logic circuit family called emitter-coupled logic (ECL).



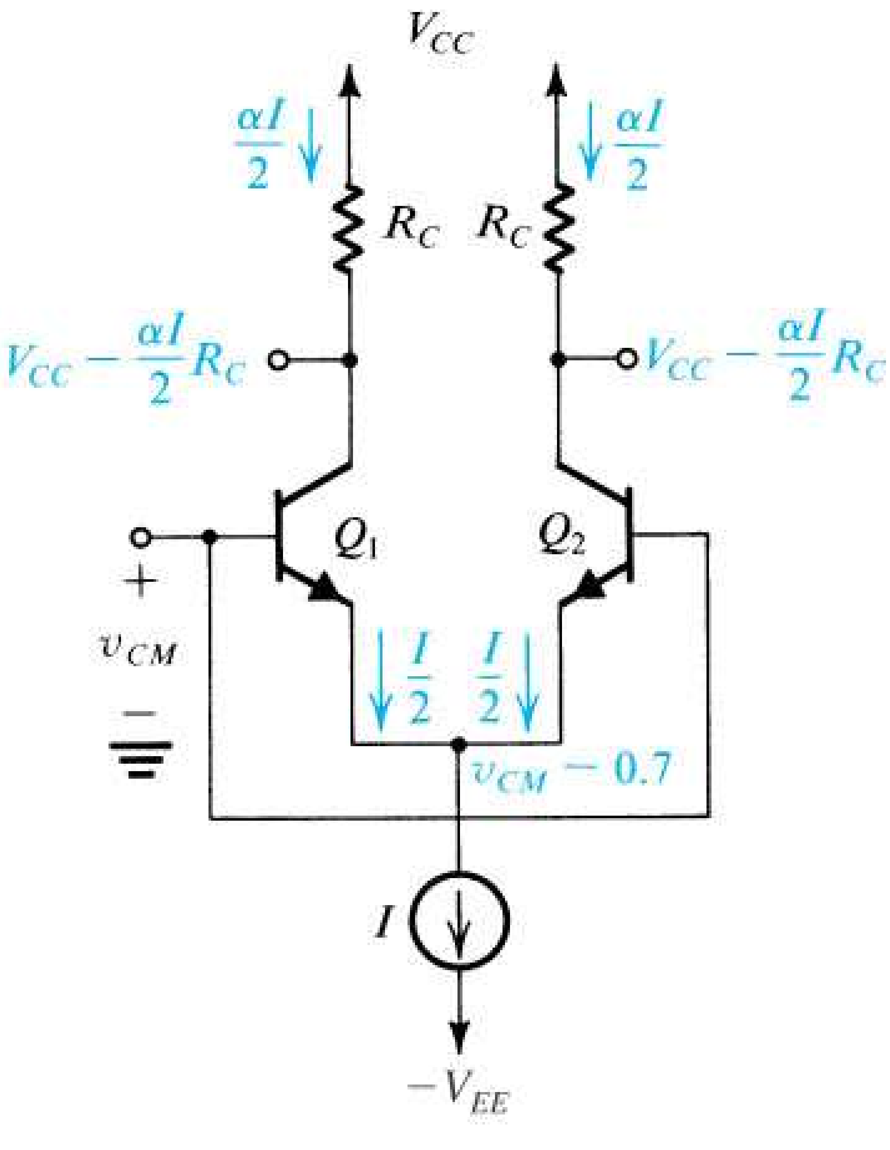
IC op-amp diagram

The Configuration and the Basic Operation

It consists of two matched transistors Q1 and Q2, whose emitter are joined together and biased by a constant-current source I. The latter is usually implemented by a transistor ckt of the type we studied previously. Sometimes the collectors of both transistors may be connected to an active loads (such as transistors) instead of a resistive load. It is essential that the collectors of both transistors never enter saturation.



A common-mode operation



(a)

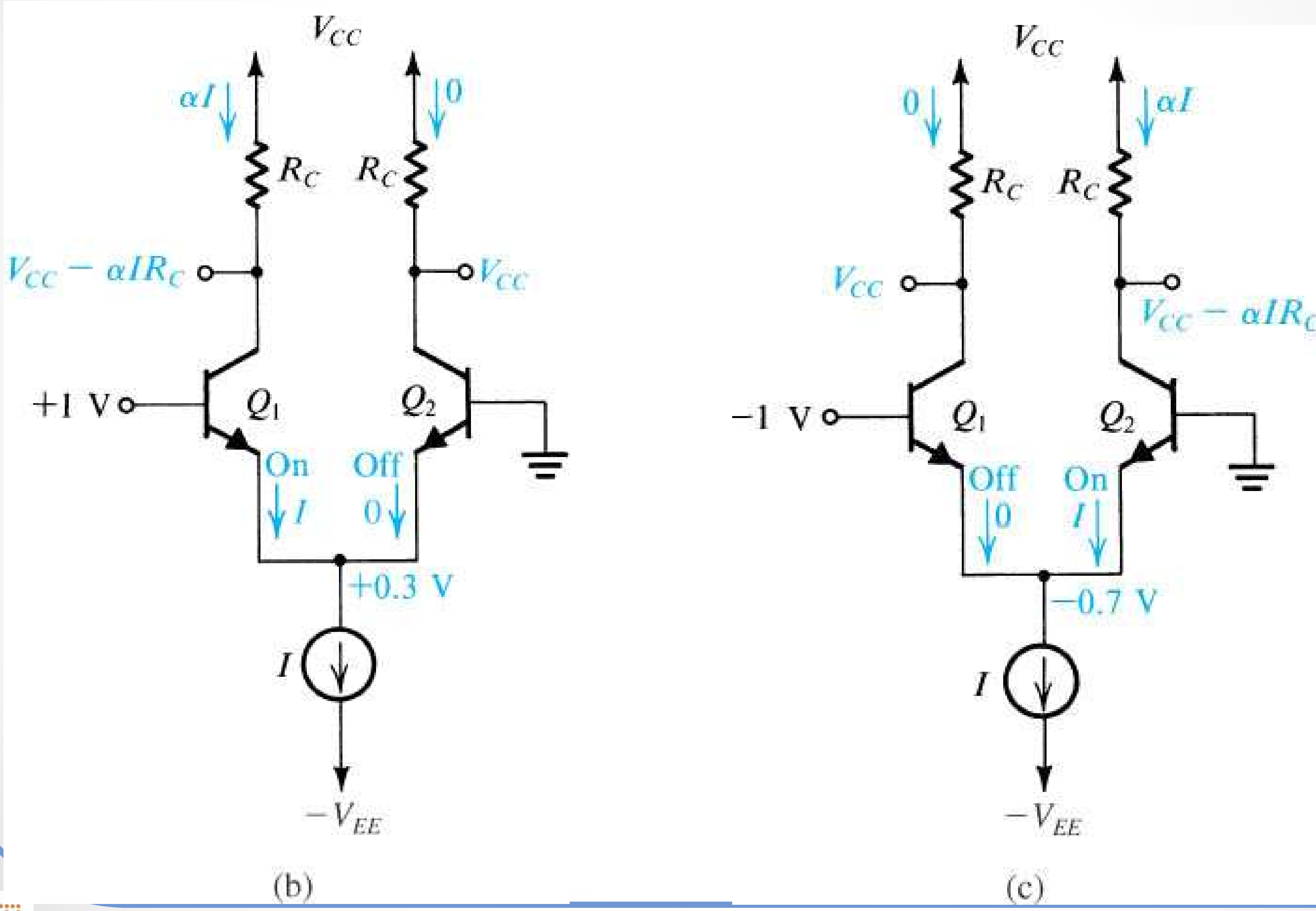
$$\boxed{I_{C1} - I_{C2} = 0}$$

$$\boxed{V_{C1} - V_{C2} = 0}$$

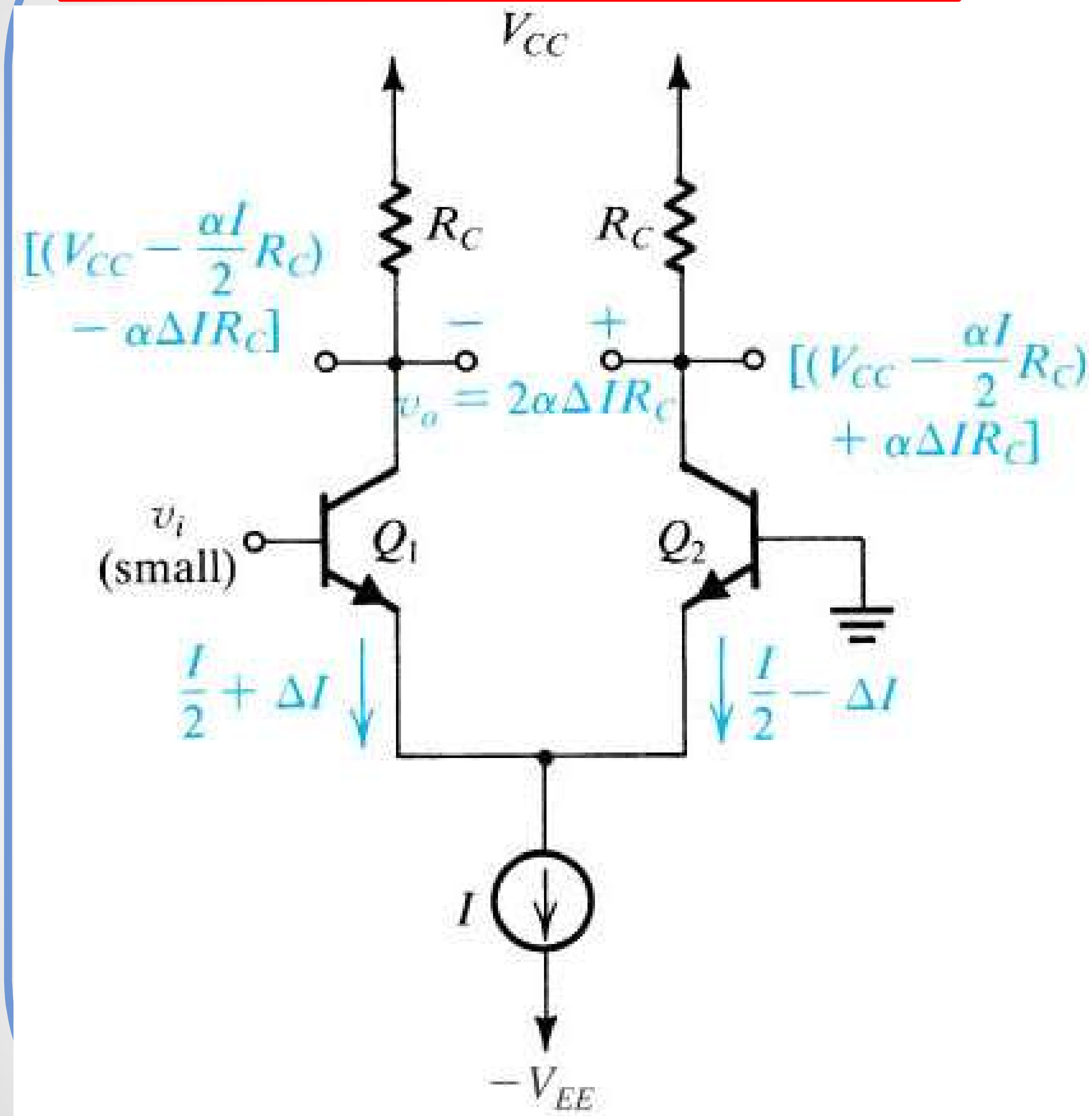
As long as Q1 and Q2 remain in the active region the current I will still divide equally between Q1 and Q2 and the voltages at the collectors will not change.

Thus, the differential pair does not respond (i.e. it rejects) common-mode input signals.

A differential-mode operation: shows the current-steering ability



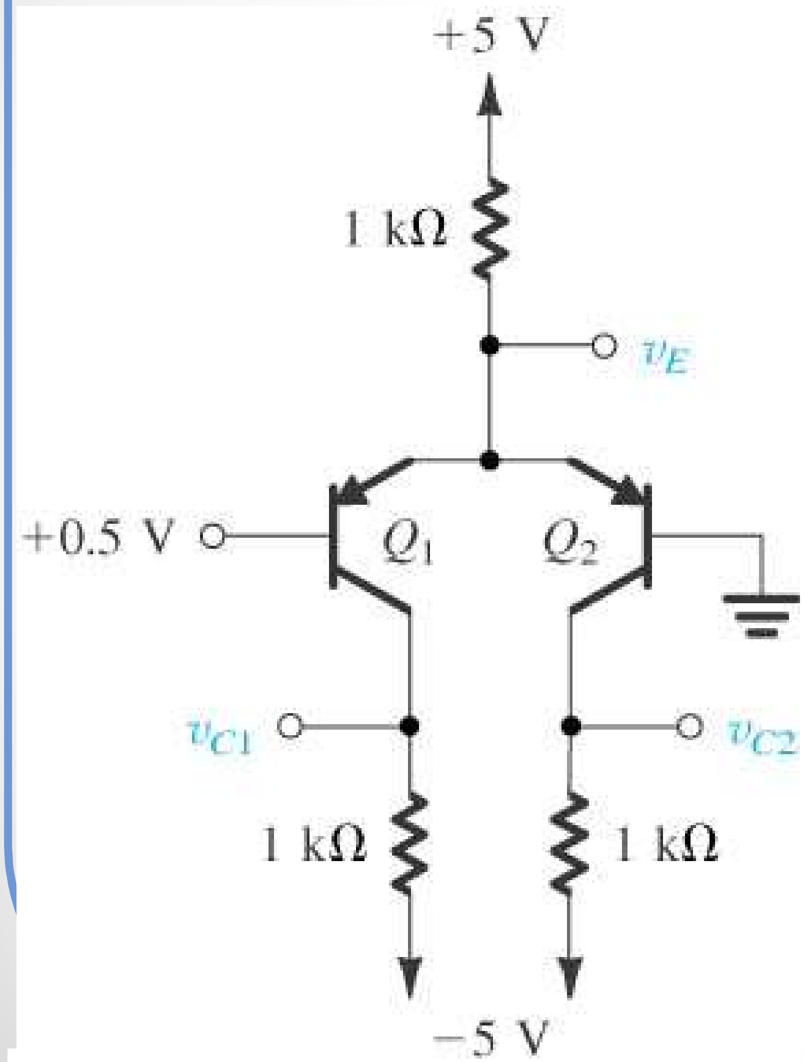
A differential-mode operation: a general case



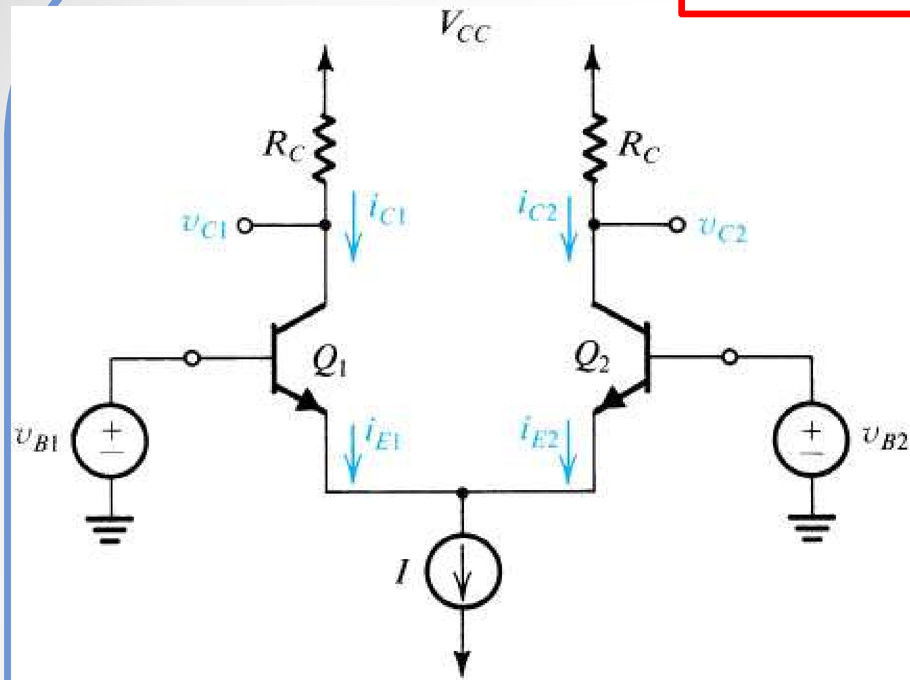
(d)

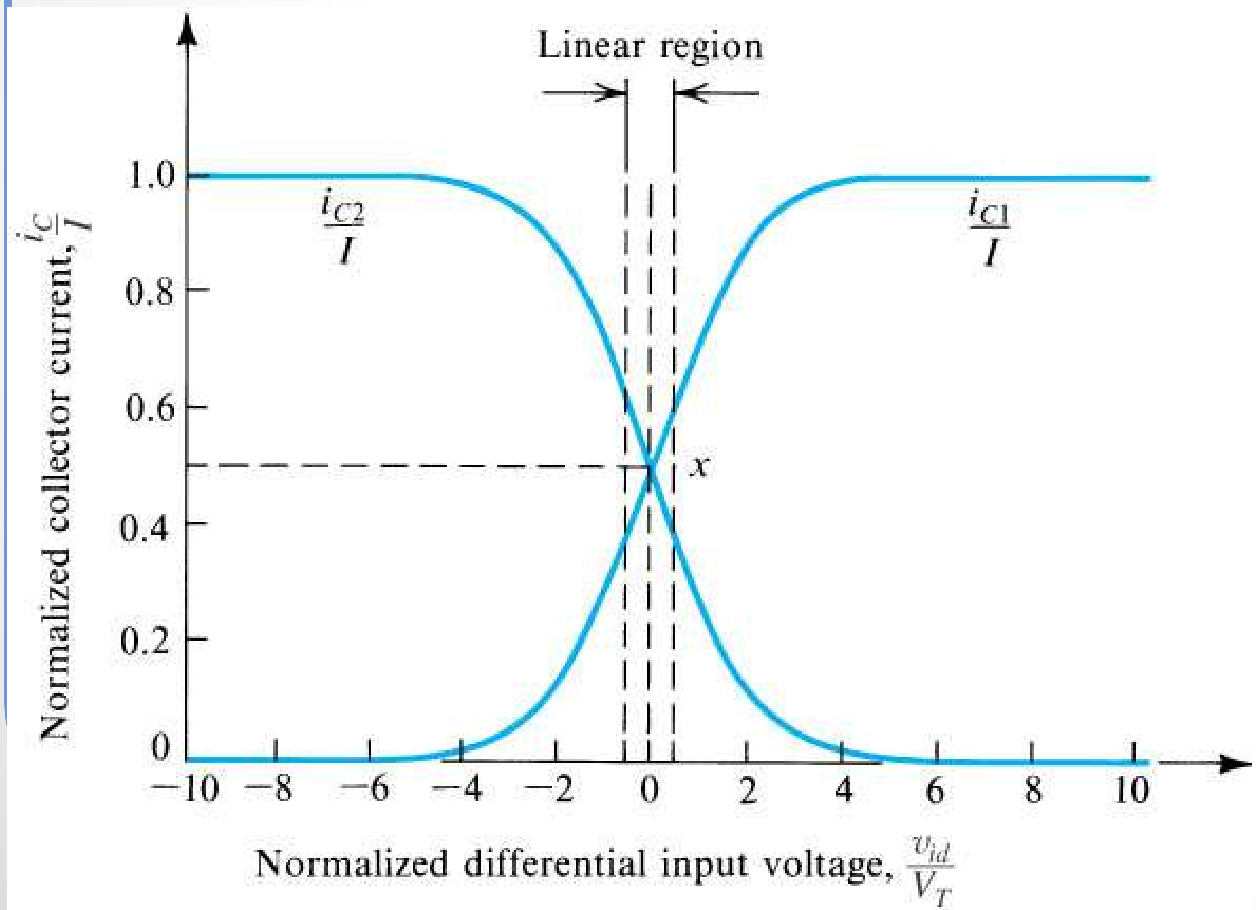
The differential pair responds to large differential mode signals. In fact, with relatively small difference voltages we are able to steer the entire bias current from one side of the pair to the other.

Example: Find v_E, v_{C1} and v_{C2} in the ckt below. Assume that $|v_{BE}|$ of a conducting transistor is approximately 0.7 V and that $\alpha = 1$.

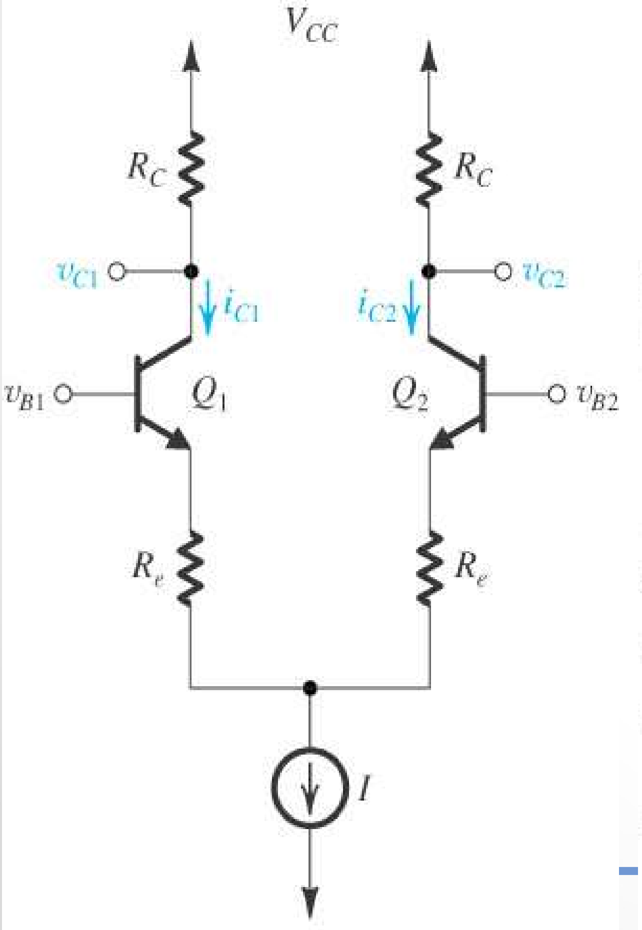


Large signal operation

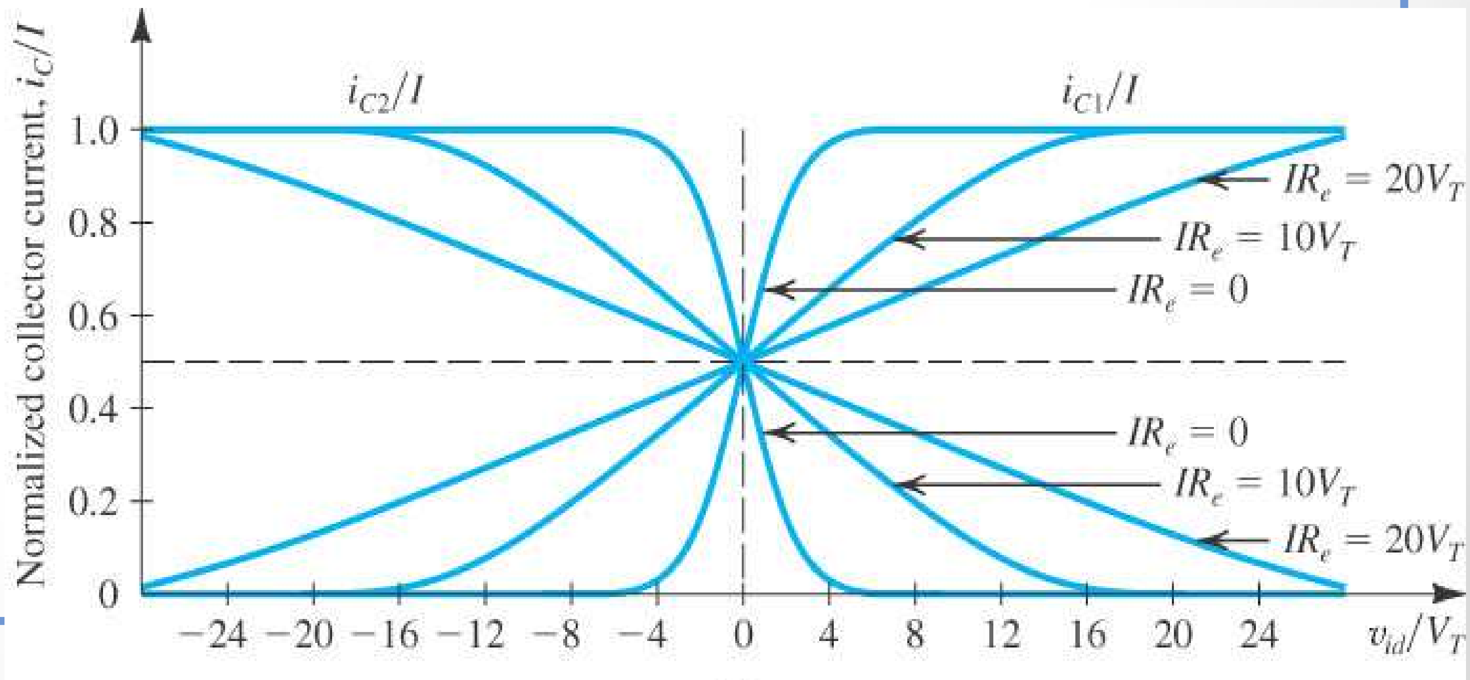



Linear region
1.0
0.8
0.6
0.4
0.2
0
$\frac{i_{C2}}{I}$
$\frac{i_{C1}}{I}$
x
−10 −8 −6 −4 −2 0 2 4 6 8 10
Normalized collector current, $\frac{i_C}{I}$
Normalized differential input voltage, $\frac{v_{id}}{V_T}$

Adding resistors Re can extend the linear range of operation. But the expansion of the linear range is obtained at the expense of reduced g_m (which is the slope of the transfer curve at v_{id} = 0) and hence reduced gain.

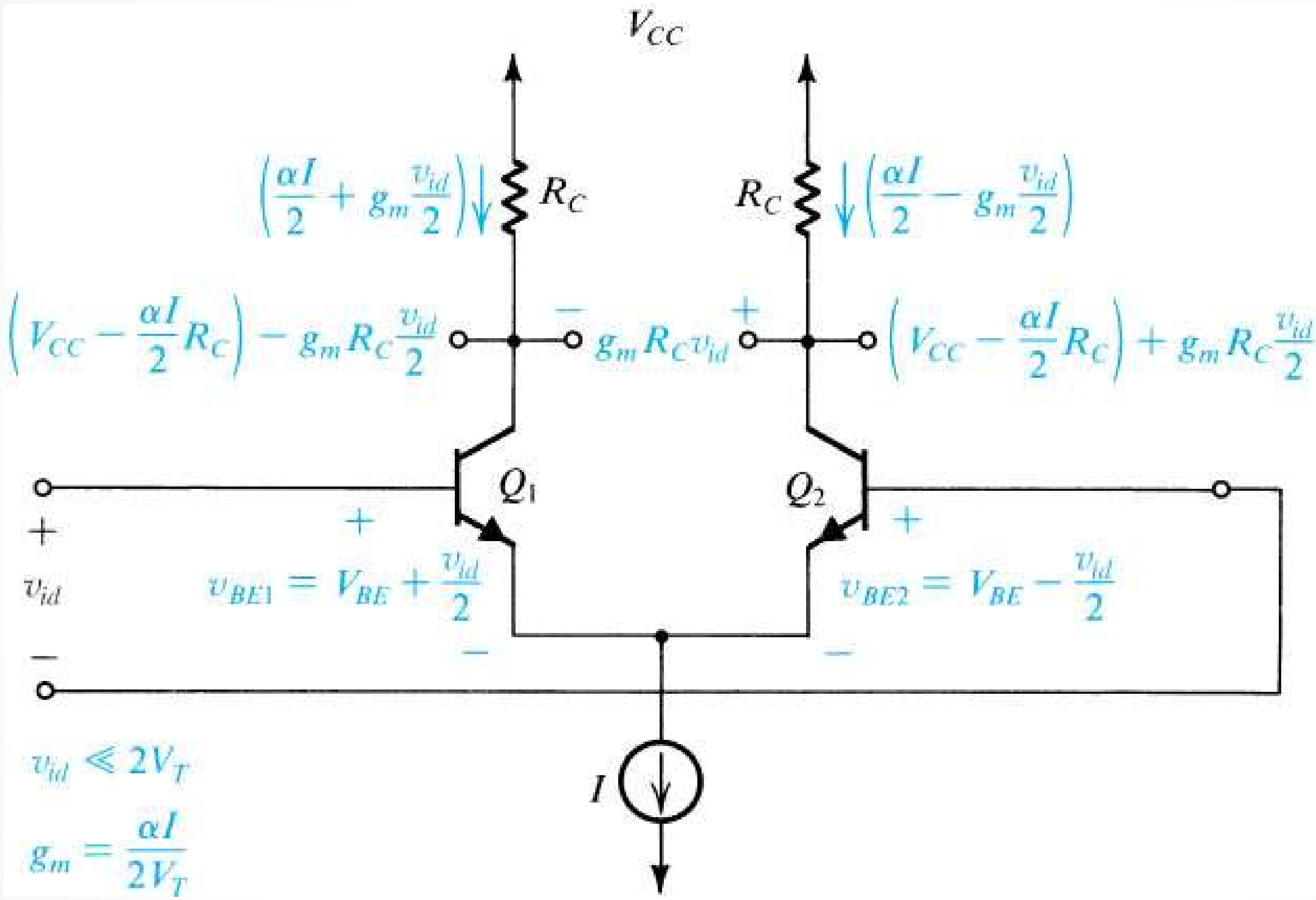


(a)



(b)

Small-signal operation

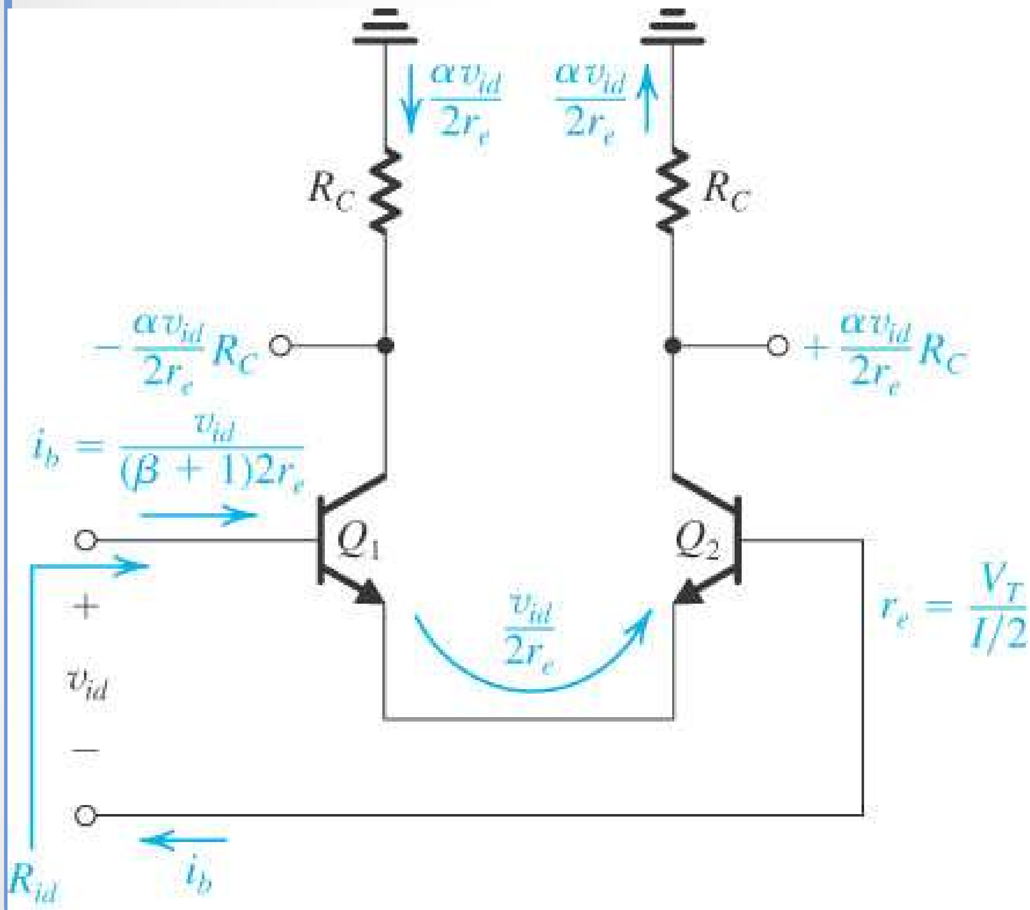


$$i_{C1} = I_{C1} + i_{c1} = \frac{\alpha I}{1 + e^{-v_{id}/V_T}} \approx \frac{\alpha I}{2} + \frac{\alpha I}{2V_T}\frac{v_{id}}{2}$$

$$i_{C2} = I_{C2} + i_{c2} = \frac{\alpha I}{1 + e^{+v_{id}/V_T}} \approx \frac{\alpha I}{2} - \frac{\alpha I}{2V_T}\frac{v_{id}}{2}$$

$$\boxed{g_m = \frac{I_C}{V_T} = \frac{\alpha I/2}{V_T}}$$

Input Resistance

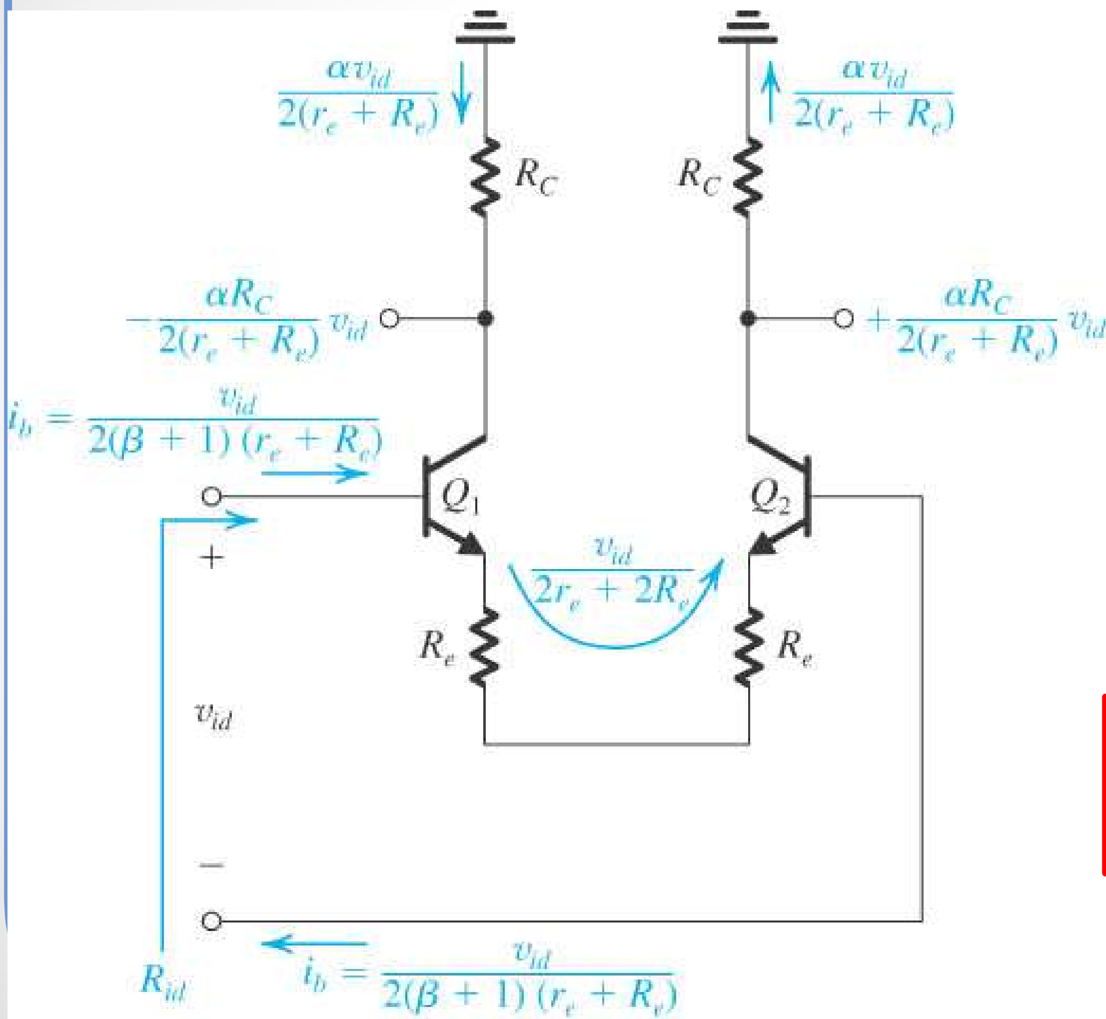


$$i_e = \frac{v_{id}}{2r_e}$$

$$i_b = \frac{i_e}{\beta+1} = \frac{v_{id}/2r_e}{\beta+1}$$

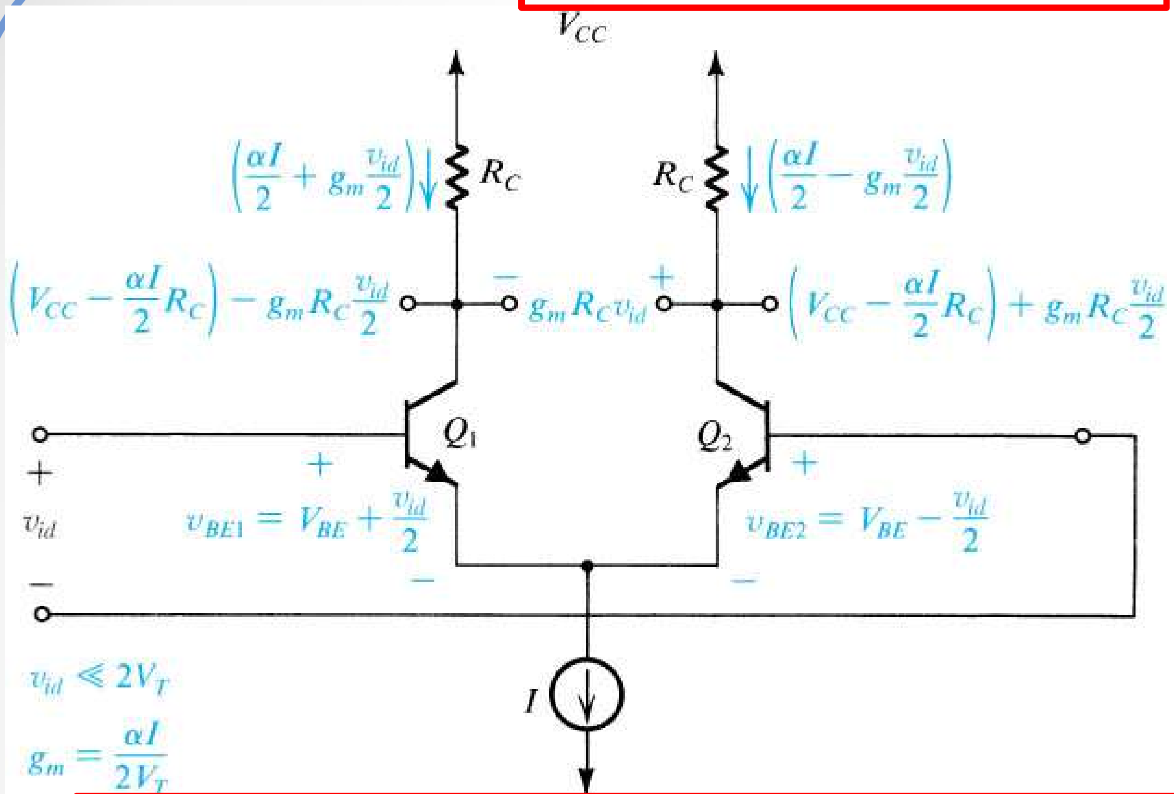
$$\boxed{R_{id} = \frac{v_{id}}{i_b} = (\beta+1)2r_e = 2r_\pi}$$

Input resistance with resistors Re's in the emitters



$$R_{id} = \frac{v_{id}}{i_b} = (\beta + 1)(2r_e + 2R_e)$$

Differential Voltage Gain



If the output is taken differentially, $A_d = \dfrac{v_{c1} - v_{c2}}{v_d} = -g_m R_C$

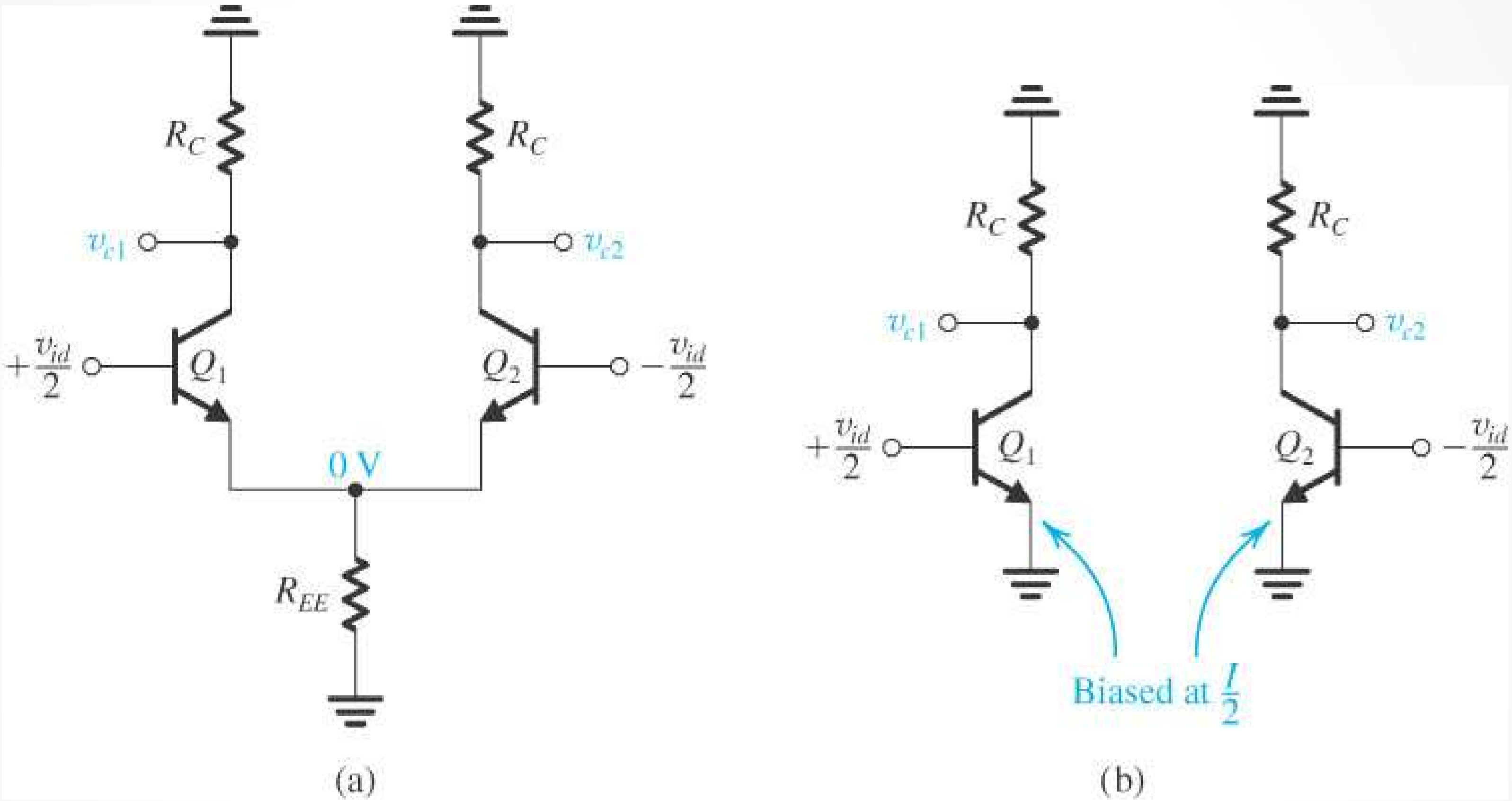
If the output is taken single-endedly, $A_d = \dfrac{v_{c1}}{v_d} = -\dfrac{1}{2} g_m R_C$

For the diff amp with resistances in the emitters, and the output is taken differentially,

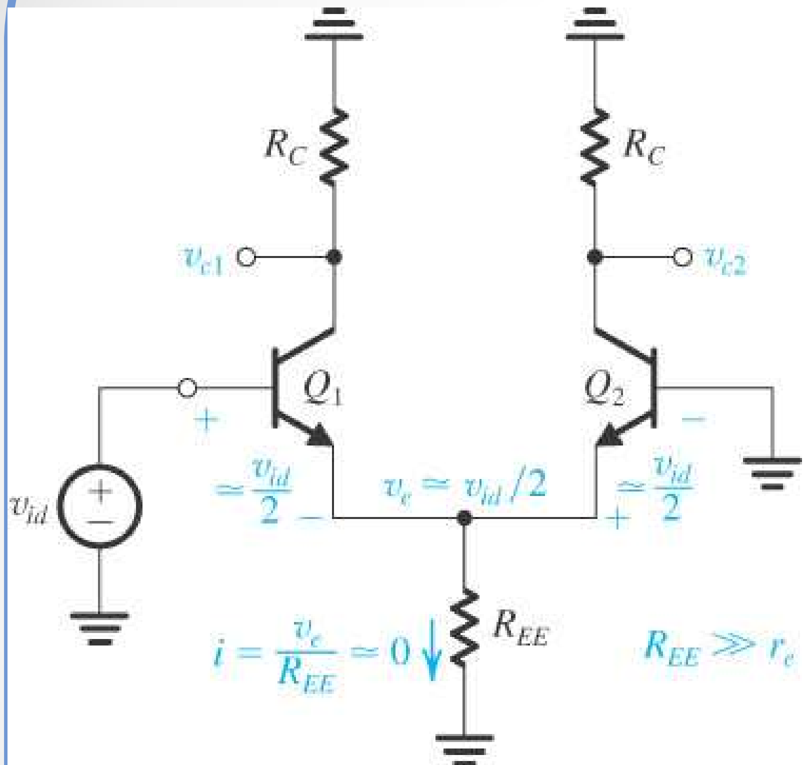
$$A_d = -\frac{\alpha(2R_C)}{2r_e + 2R_e} = -\frac{R_C}{r_e + R_e}$$

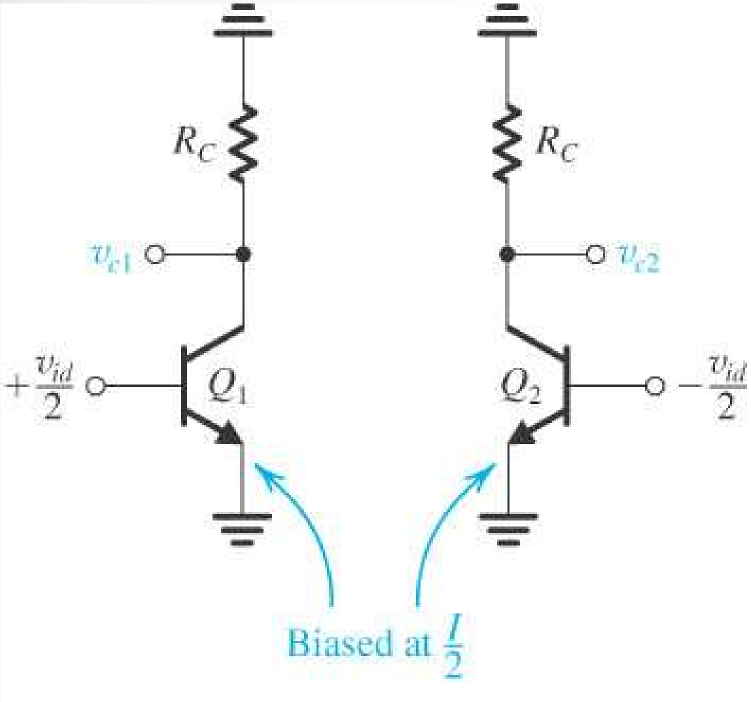
Equivalence of differential amp to a common-emitter amp

1. The differential signal vid is applied in a complementary (or balanced) manner.



2. The differential signal vid is applied in a single-ended manner.





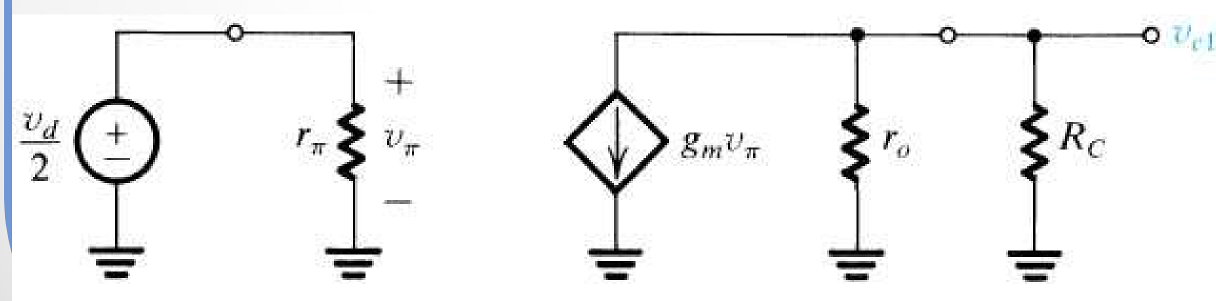
(b)

Since $v_{C2} = -v_{C1}$, the two common-emitter transistors yield similar results about the performance of the diff amp. Thus, only one is needed to analyze the differential small-signal operation of the amp, and it is known as the differential half-circuit.

Its low-freq equivalent model is shown below. Keep in mind, the bias current is at I/2 for each of the halves.

When output is taken differentially, the gain is given by

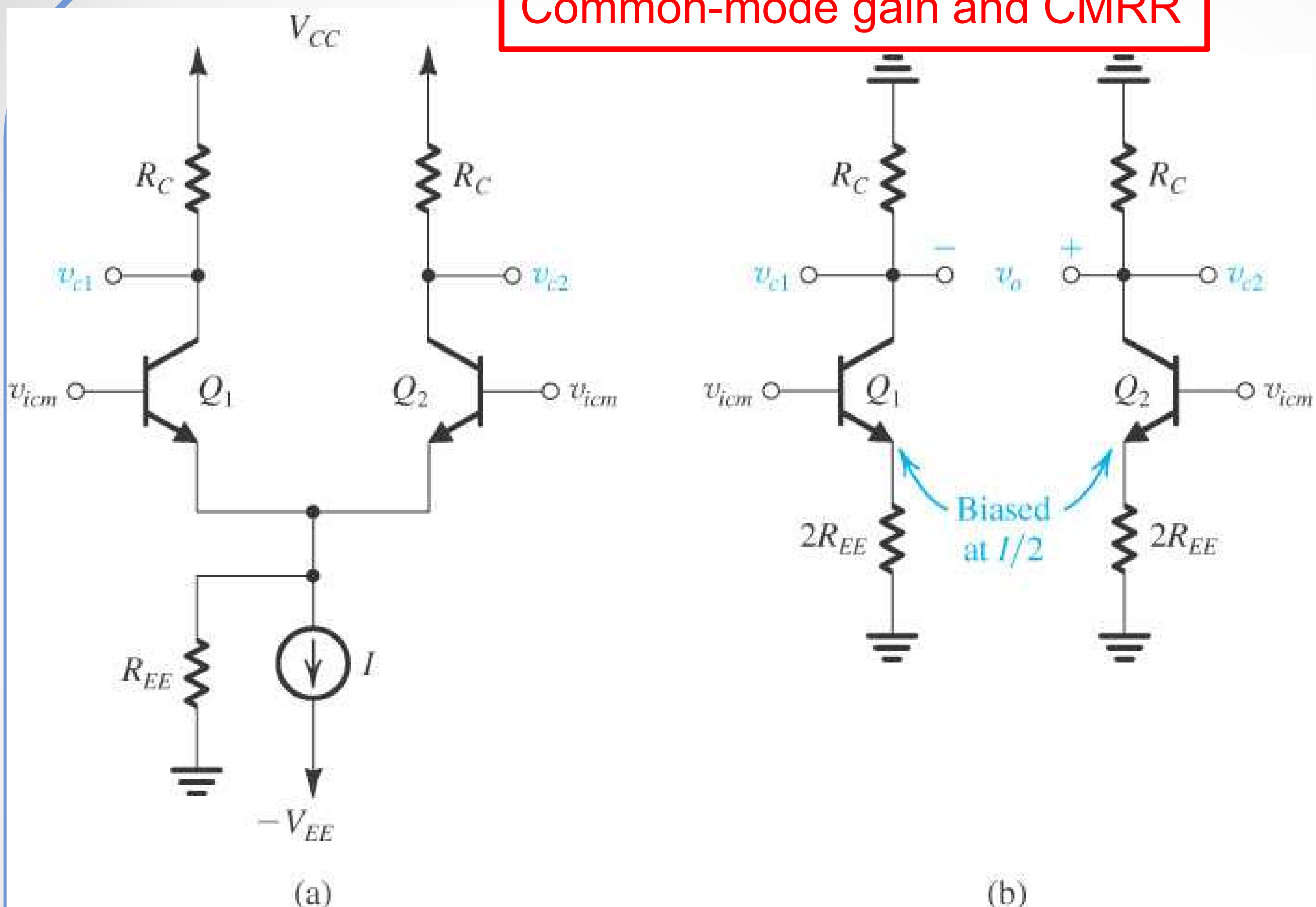
$$\boxed{A_d = -g_m(R_C \,||\, r_o)}$$



(a) (b)

- The voltage gain of the diff amp (when the output is taken differentially) is equal to the voltage gain of the half-circuit. - The input differential resistance is twice of the half-circuit, that is $2r_e$.

Common-mode gain and CMRR



$$v_{c1} = -v_{icm}\frac{\alpha R_C}{2R_{EE}+r_e} \approx -v_{icm}\frac{\alpha R_C}{2R_{EE}}; \quad v_{c2} = -v_{icm}\frac{\alpha R_C}{2R_{EE}+r_e} \approx -v_{icm}\frac{\alpha R_C}{2R_{EE}}$$

$$A_{cm} = v_{c1} - v_{c2} = 0$$ for differential-ended output

$$A_{cm} = v_{c2} = -\frac{\alpha R_C}{2R_{EE}}$$ for single-ended output

$$CMRR = 20\log\left|\frac{A_d}{A_{cm}}\right|$$

$$CMRR = \infty$$ for differential-ended output

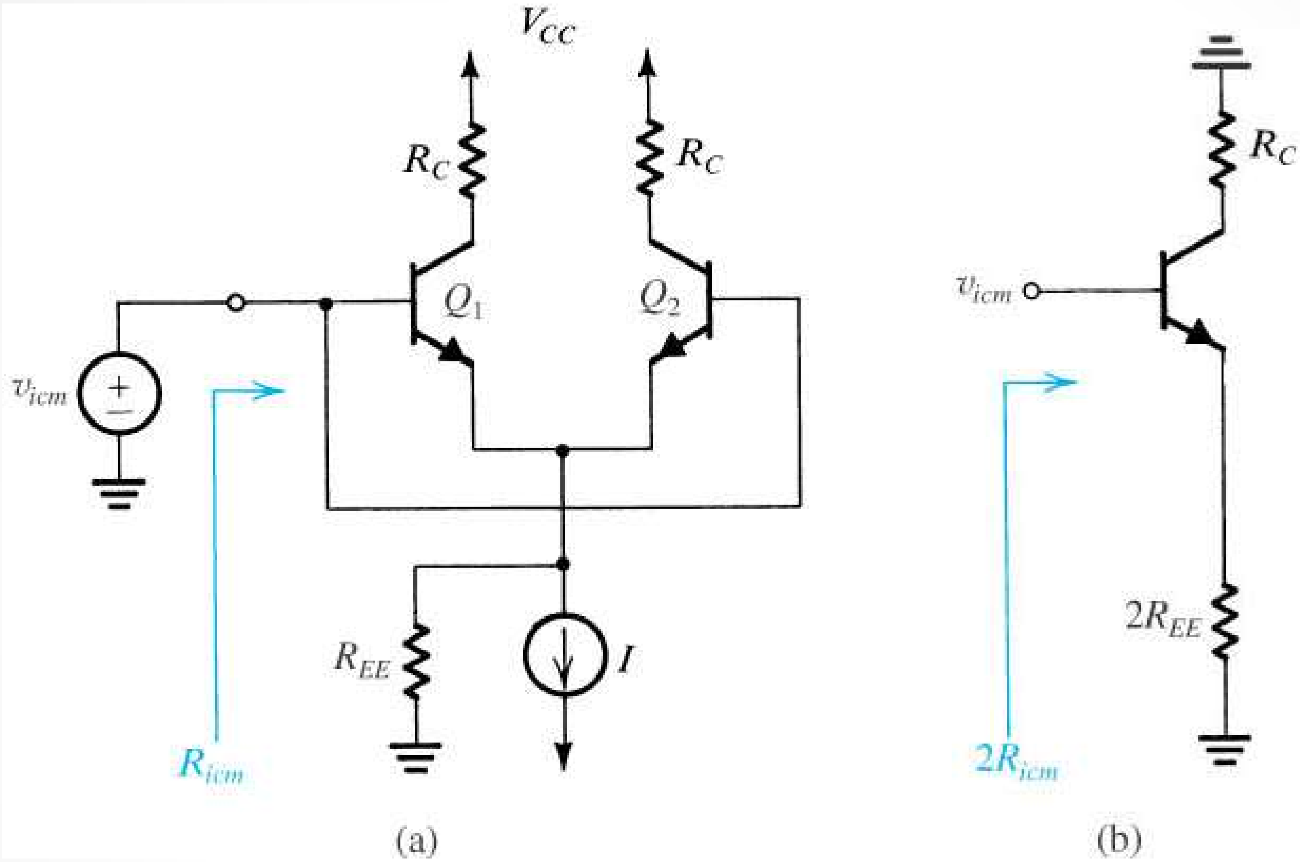
$$CMRR = 20\log\left|g_m R_{EE}\right|$$ for single-ended output because $A_d = -\frac{1}{2} g_m R_C$

$$v_o = A_d(v_1 - v_2) + A_{cm}\left(\frac{v_1 + v_2}{2}\right)$$

If the diff amp is not symmetric due to the mismatched between R_C's, then

$$A_{cm} = \frac{\alpha \Delta R_C}{2R_{EE} + r_e}$$

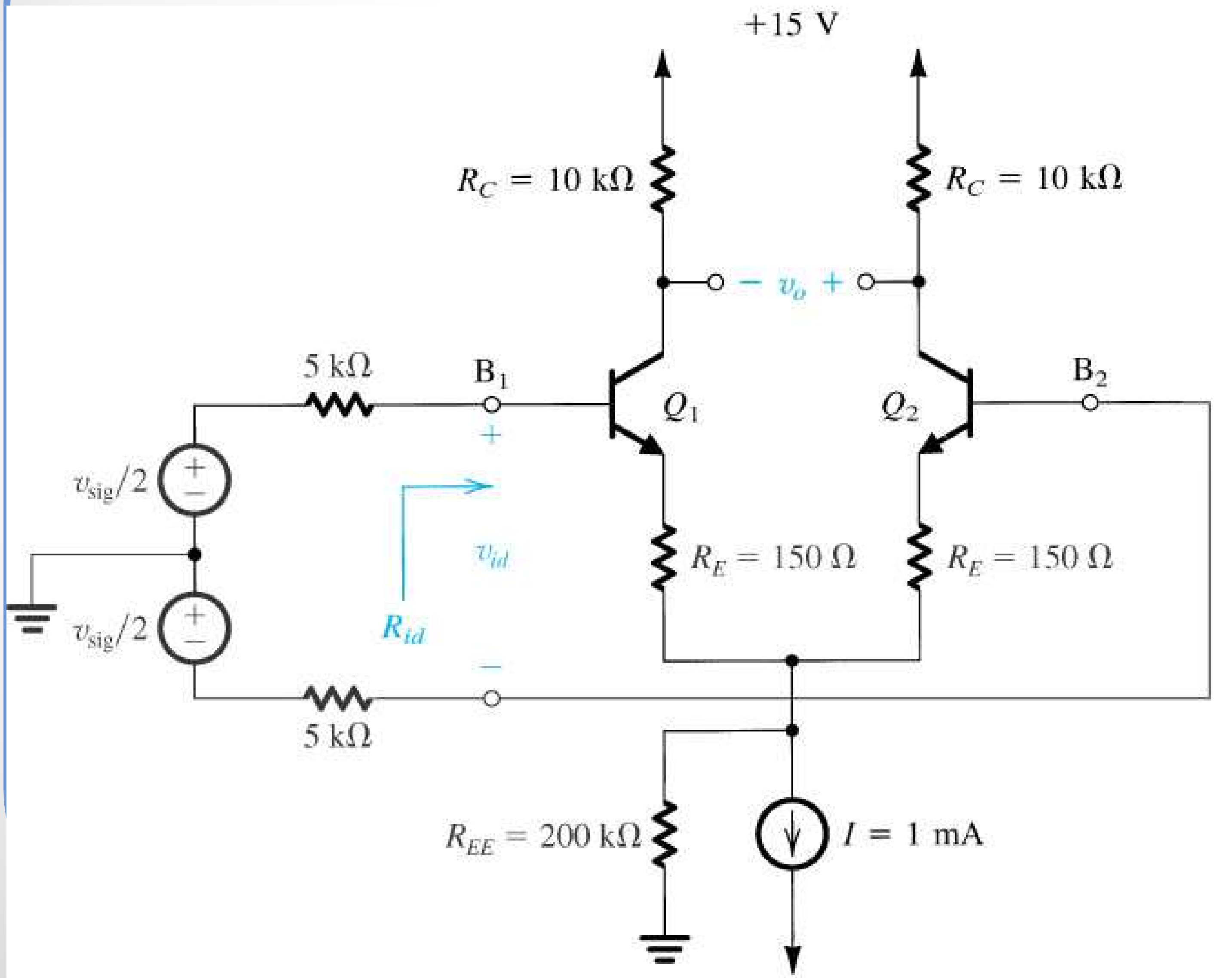
Input common-mode resistance



$$2R_{icm} \approx (\beta+1)((2R_{EE}+2r_e)\,||\,r_o)$$

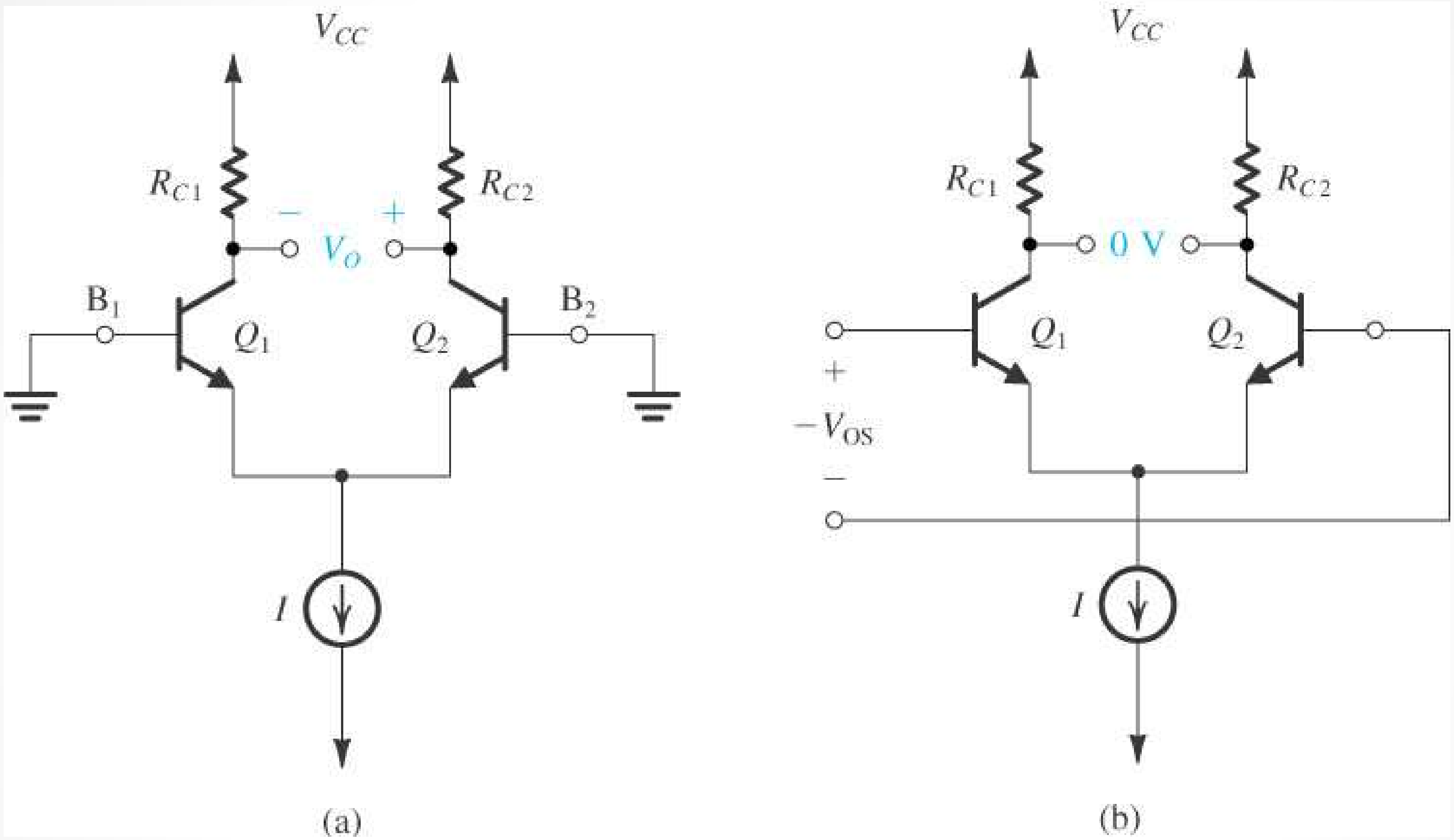
$$\boxed{R_{icm} \approx (\beta+1)((R_{EE}+r_e)\,||\,\frac{r_o}{2})}$$

Example: from the ckt below, determine the following parameters:



a) The input differential resistance Rid
b) The overall differential voltage gain v_o/v_{sig} (neglect the effect of r_o)
c) The worst-case common-mode gain if the two collector resistances are accurate to within +/- 1 %
d) The CMRR in dB
e) The input common-mode resistance (assuming that the Early voltage V_A = 100 V)

Input offset voltage of the bipolar differential pair



(a) The BJT differential pair with both inputs grounded. Device mismatches result in a finite dc output V_O. **(b)** Application of the input offset voltage V_{OS} ; V_O/A_d to the input terminals with opposite polarity reduces V_O to zero.

The input offset voltage due to the mismatches between R_{C1} and R_{C2} is given by

$$\left|V_{OS}\right| = V_T \left(\frac{\Delta R_C}{R_C}\right)$$

The input offset voltage due to the mismatches between the emitter-base junction area is given by

$$\left|V_{OS}\right| = V_T \left(\frac{\Delta I_S}{I_S}\right)$$

Since the two contributions are not correlated, an estimate of the total input offset voltage can be found as

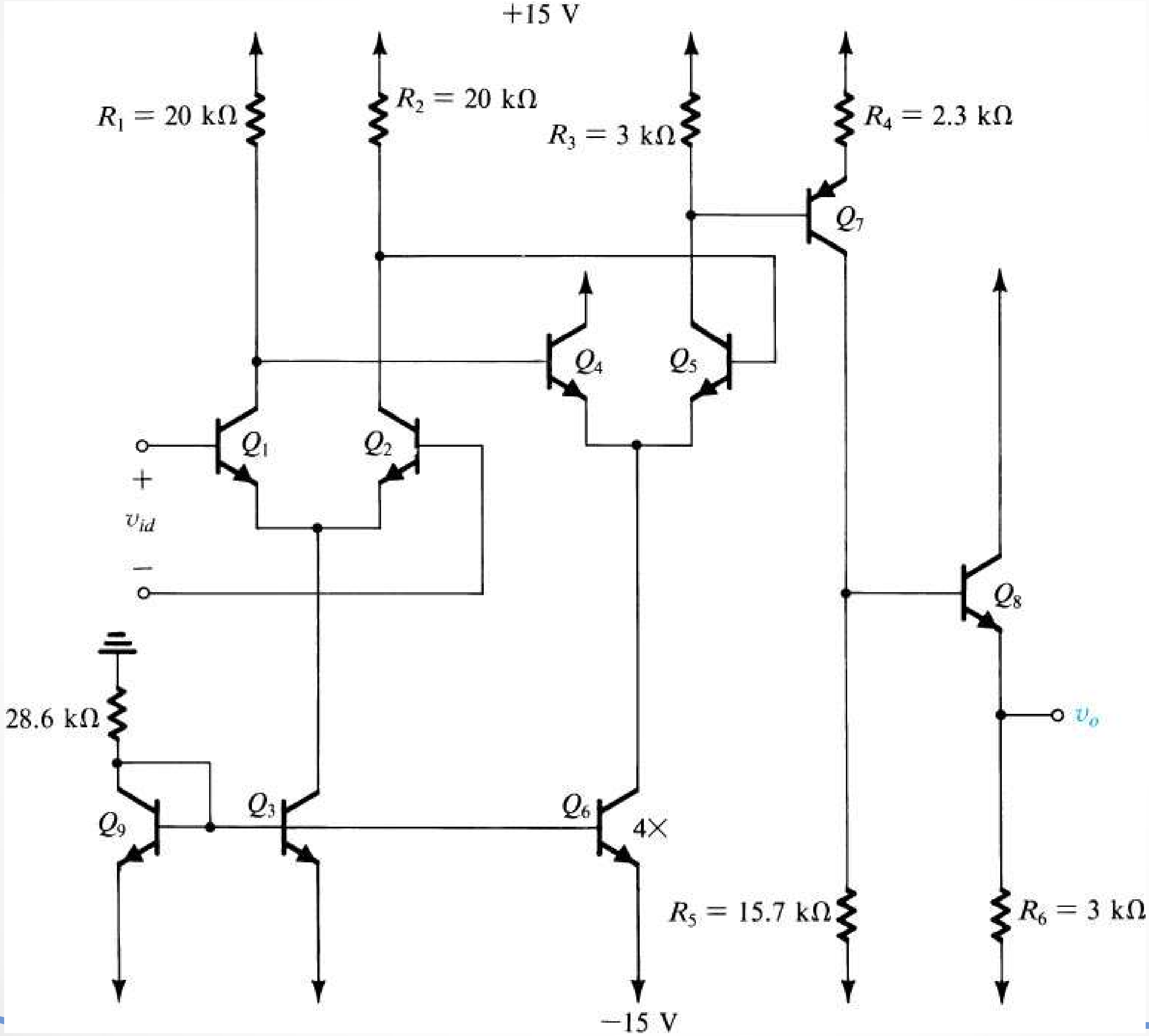
$$\left|V_{OS}\right| = V_T \sqrt{\left(\frac{\Delta R_C}{R_C}\right)^2 + \left(\frac{\Delta I_S}{I_S}\right)^2}$$

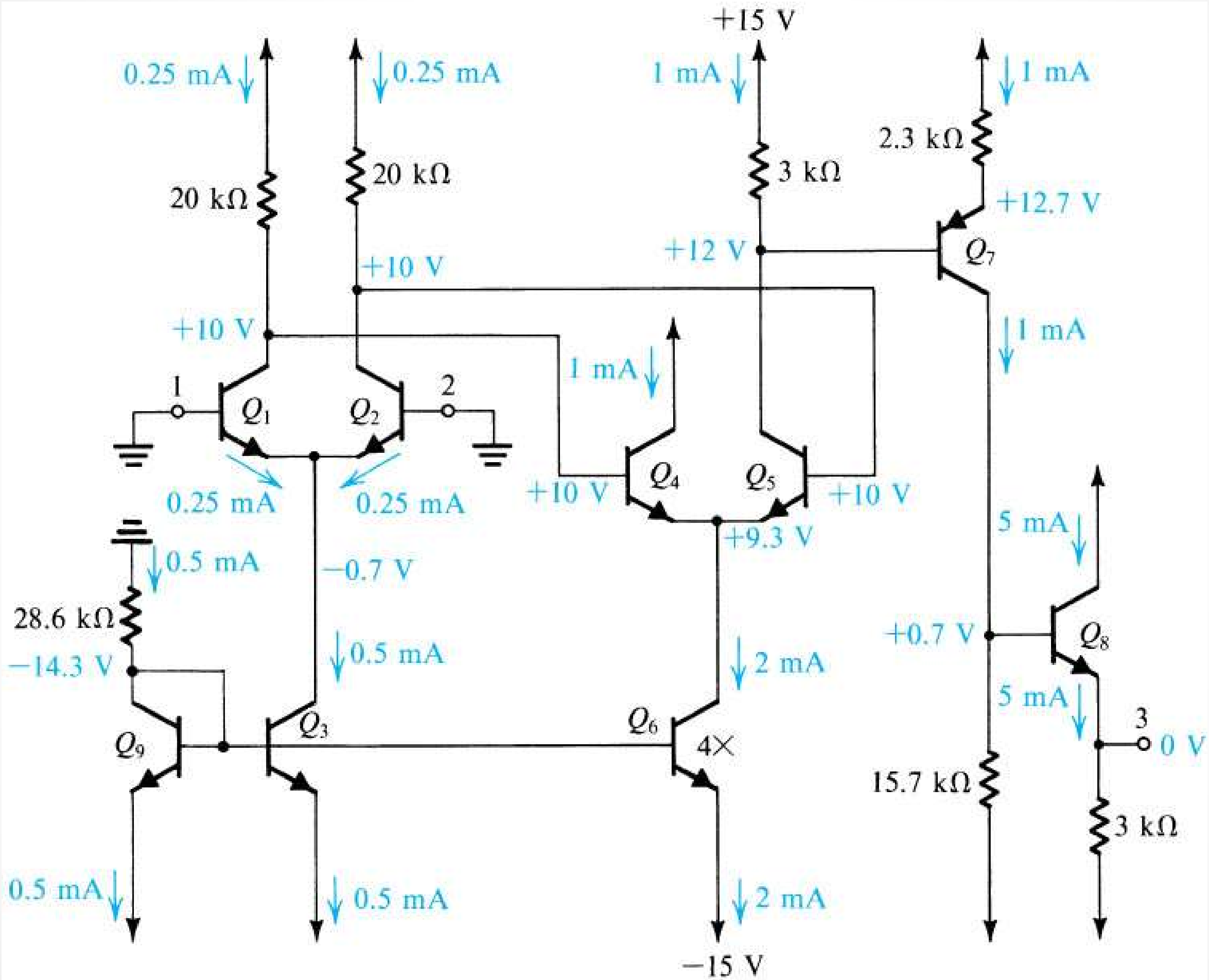
If there is a mismatch in β, there will be an offset current of

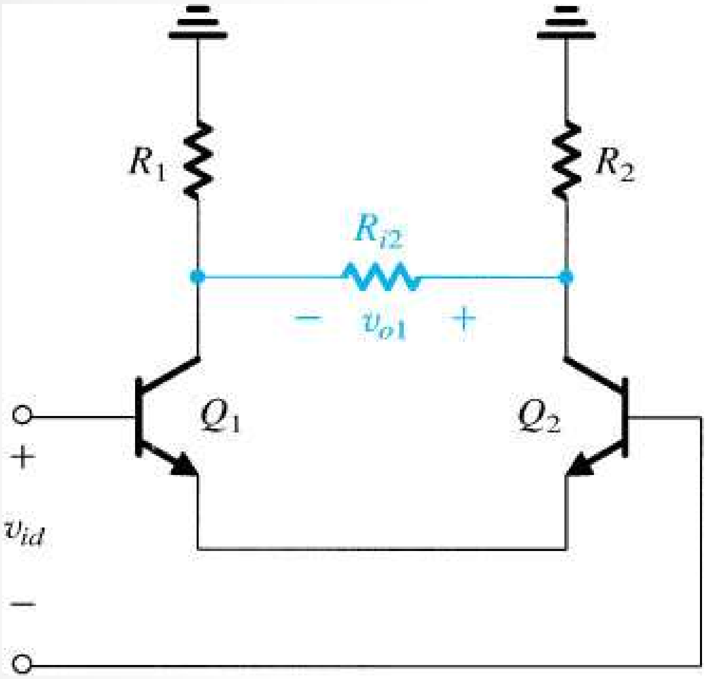
$$I_{OS} = I_B\left(\frac{\Delta\beta}{\beta}\right)$$

where I_B is the input bias current.

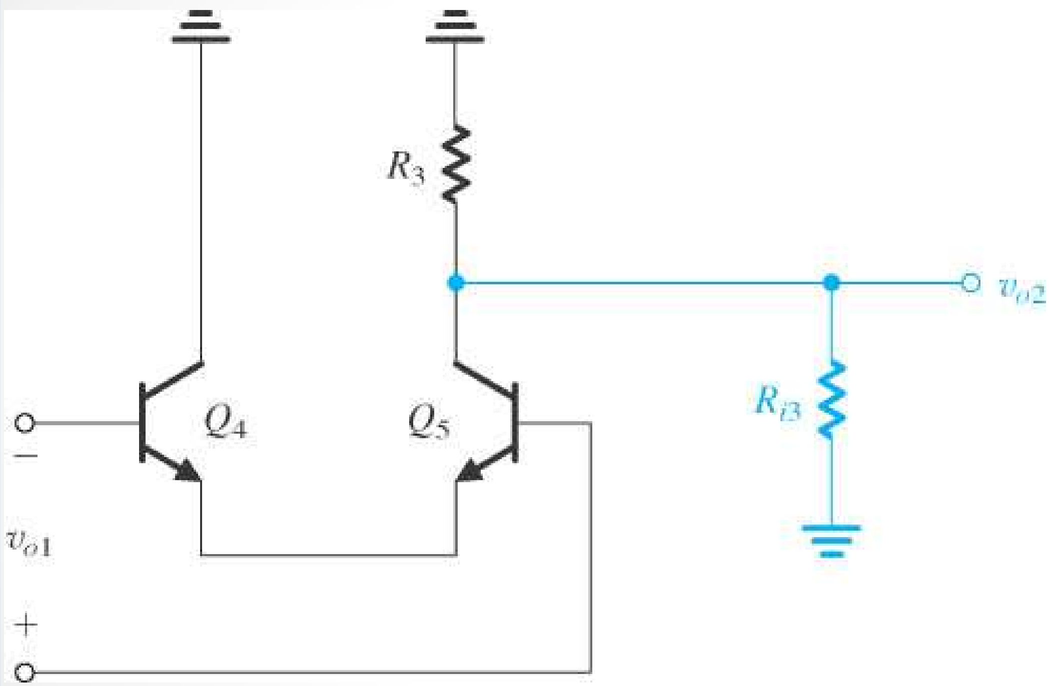
Example: a multistage bipolar op amp

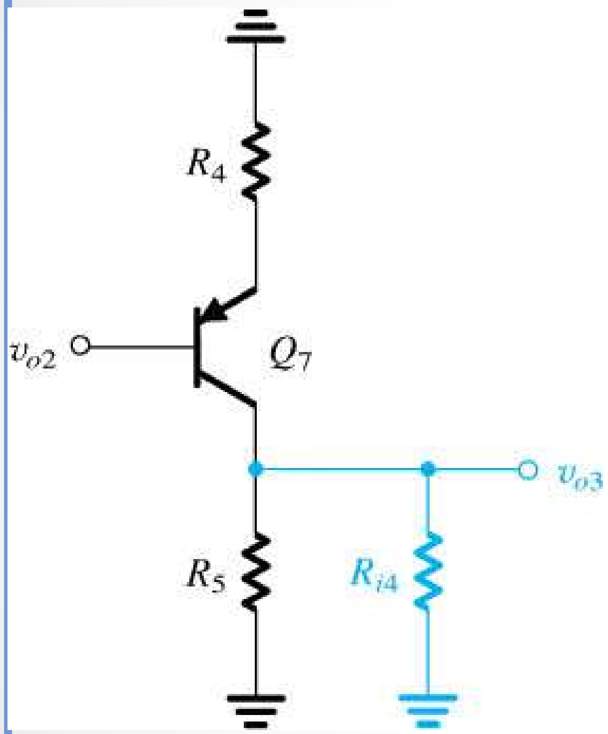



+15 V
0.25 mA
0.25 mA
1 mA
1 mA
20 kΩ
20 kΩ
3 kΩ
2.3 kΩ
+12.7 V
+12 V
Q_7
+10 V
+10 V
1 mA
1 mA
1
2
Q_1
Q_2
Q_4
Q_5
+10 V
+10 V
0.25 mA
0.25 mA
+9.3 V
5 mA
0.5 mA
−0.7 V
28.6 kΩ
−14.3 V
0.5 mA
2 mA
+0.7 V
Q_8
5 mA
3
0 V
Q_9
Q_3
Q_6
4×
15.7 kΩ
3 kΩ
0.5 mA
0.5 mA
2 mA
−15 V

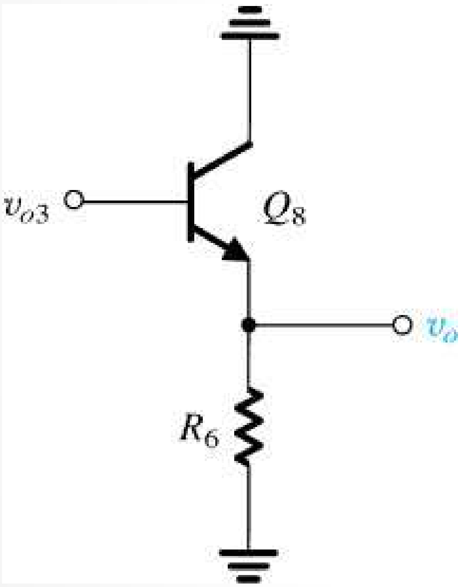


R_1
R_2
R_{i2}
$-$ v_{o1} $+$
Q_1
Q_2
$+$
v_{id}
$-$

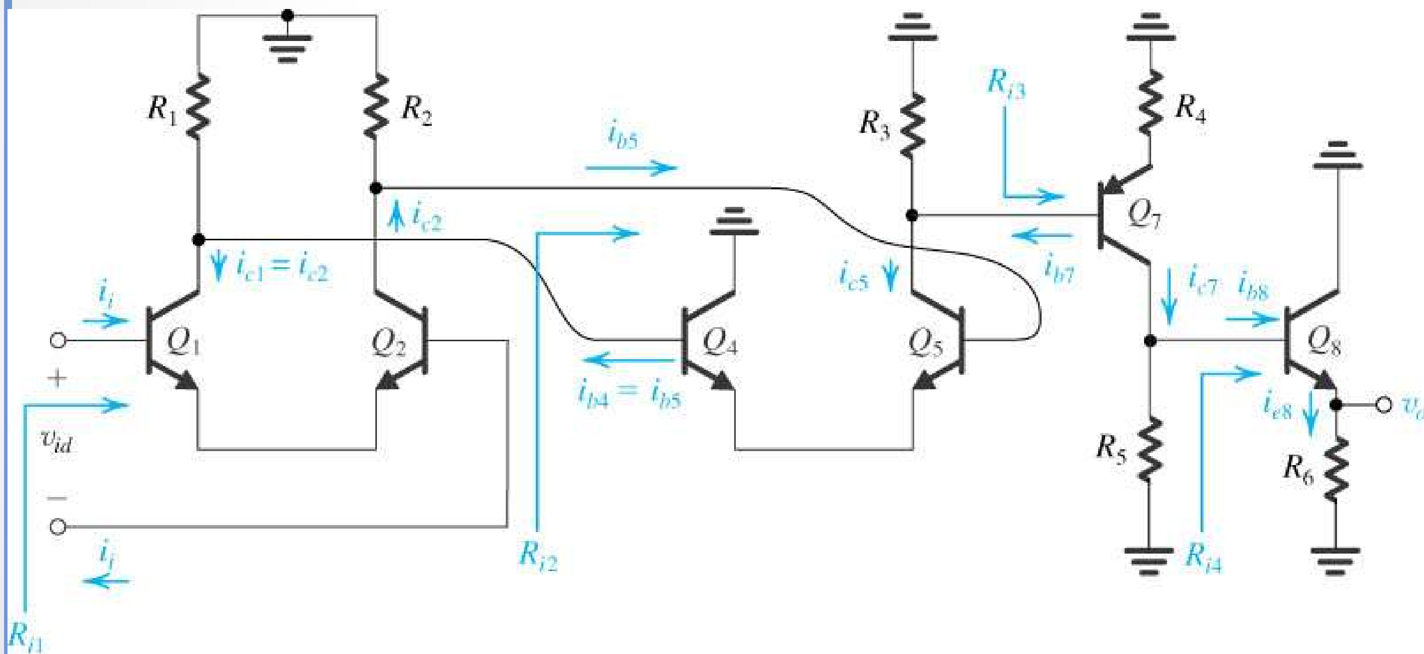

R_3
v_{o2}
R_{i3}
Q_4
Q_5
−
v_{o1}
+

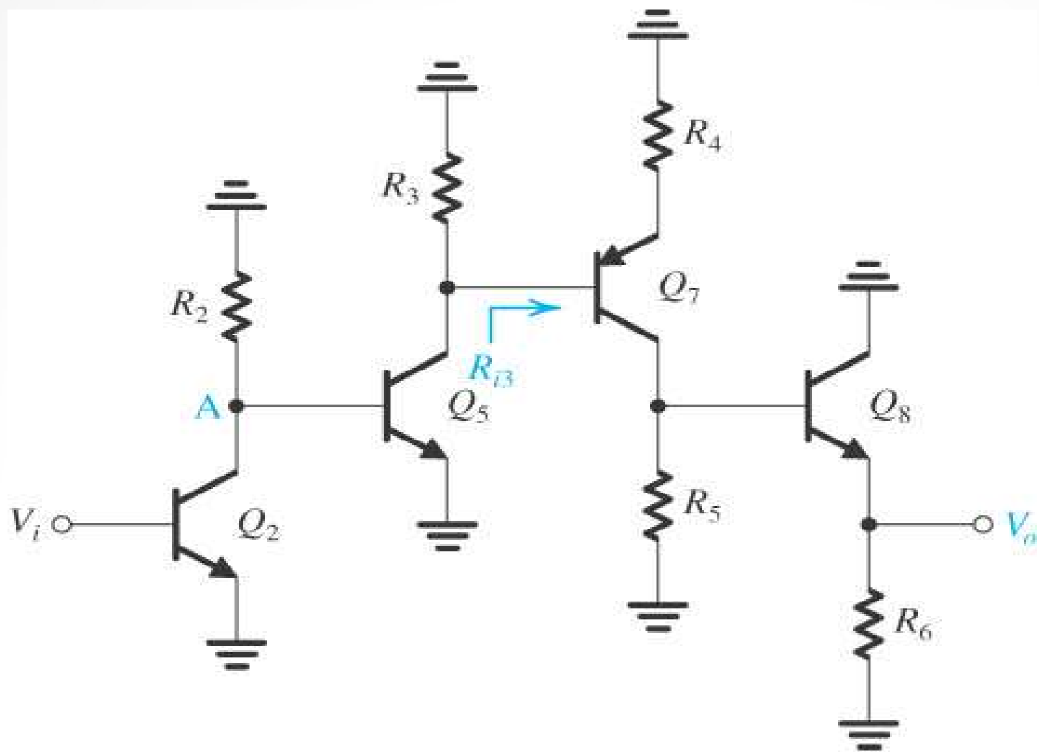


R_4
v_{o2}
Q_7
v_{o3}
R_5
R_{i4}



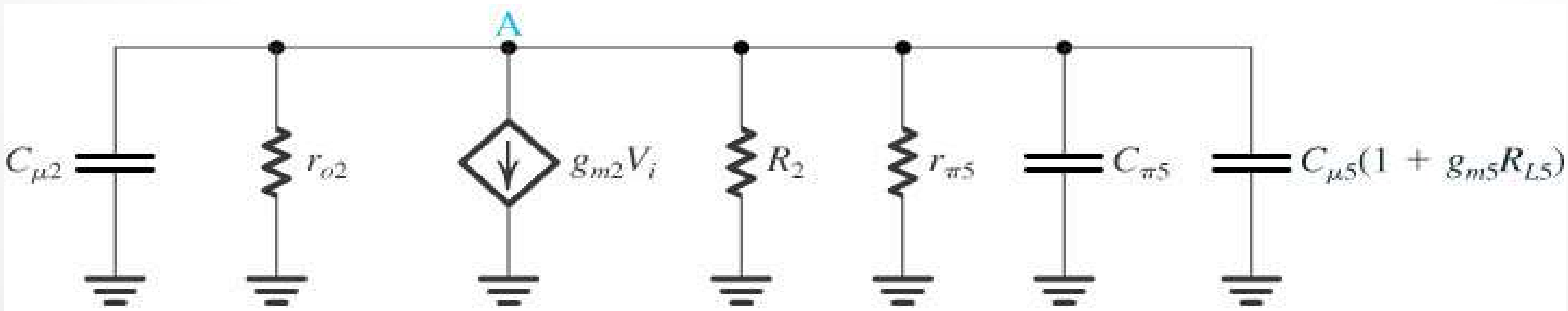
v_{o3}
Q_8
v_o
R_6


R_1
R_2
R_3
R_4
R_5
R_6
Q_1
Q_2
Q_4
Q_5
Q_7
Q_8
i_{b5}
i_{c2}
$i_{c1} = i_{c2}$
i_i
$i_{b4} = i_{b5}$
i_{c5}
i_{b7}
i_{c7}
i_{b8}
i_{e8}
R_{i1}
R_{i2}
R_{i3}
R_{i4}
v_{id}
+
−
v_o



R_4
R_3
Q_7
R_2
R_{i3}
A
Q_5
Q_8
R_5
V_i
Q_2
V_o
R_6

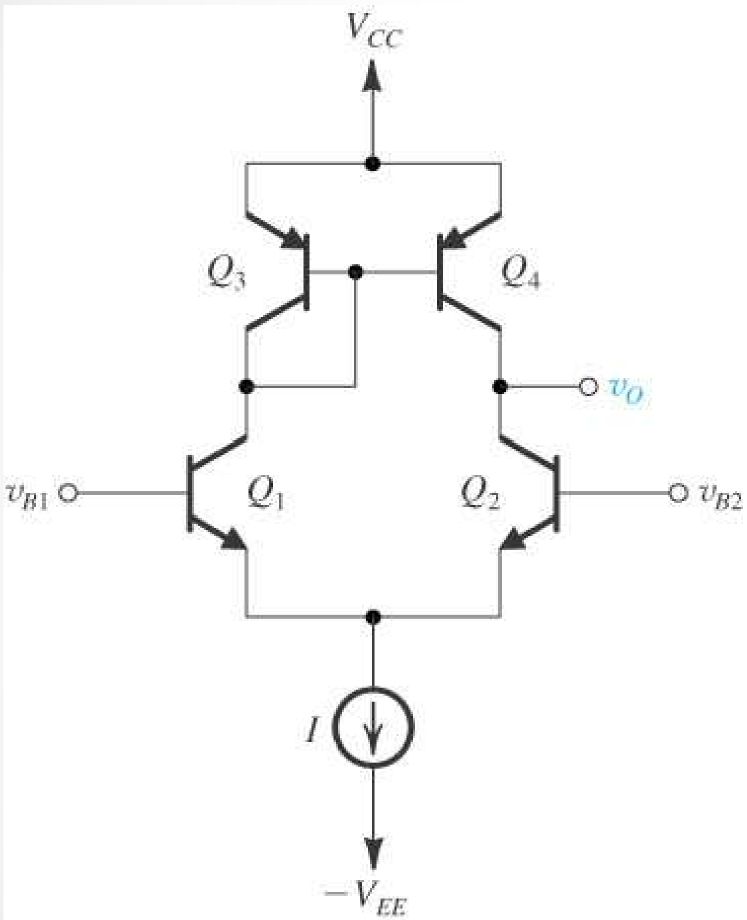
(a)



A
$C_{\mu 2}$
r_{o2}
$g_{m2}V_i$
R_2
$r_{\pi 5}$
$C_{\pi 5}$
$C_{\mu 5}(1 + g_{m5}R_{L5})$

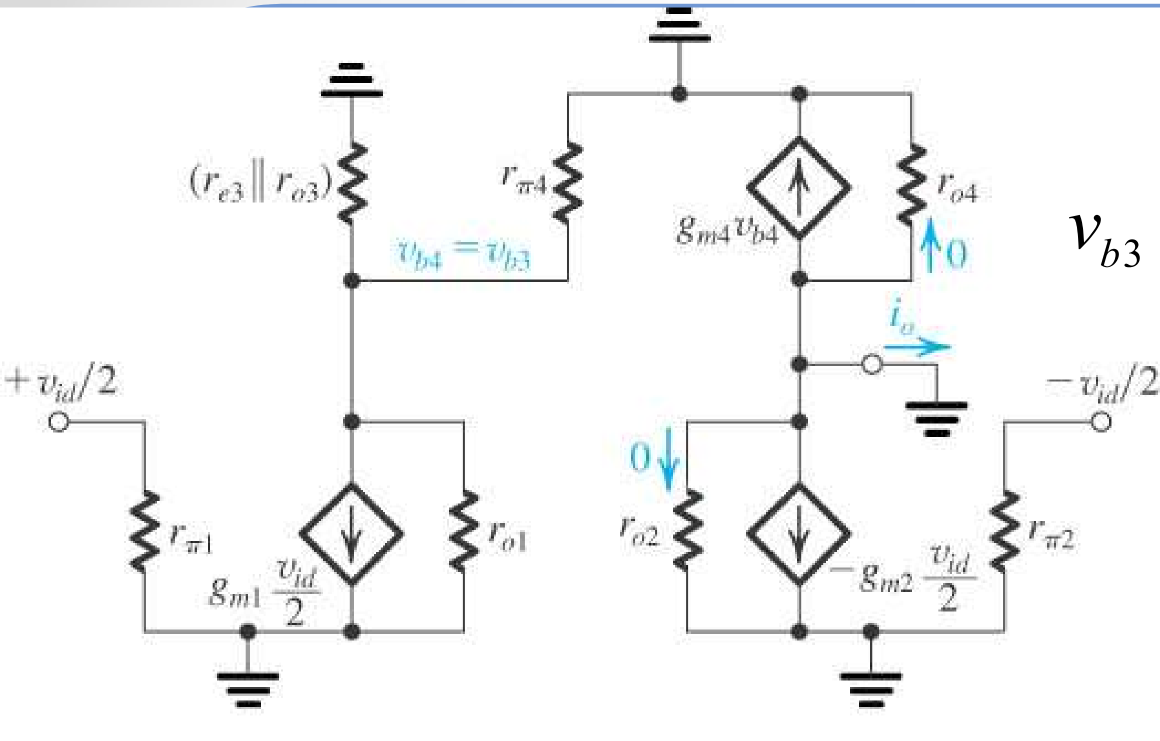
(b)

The bipolar differential pair with active load



(a)

- Q3 and Q4 act as active loads.
- An improved performance over the passive load version.
- An effective way to convert from a differential-ended output to a single-ended output



(b)

$$v_{b3} = -g_{m1}\left(\frac{v_{id}}{2}\right)(r_{e3} \| r_{o3} \| r_{o1} \| r_{\pi 4})$$

$$= -g_{m1} r_{e3}\left(\frac{v_{id}}{2}\right)$$

$$g_{m4} v_{b4} = -g_{m4} g_{m1} r_{e3}\left(\frac{v_{id}}{2}\right)$$

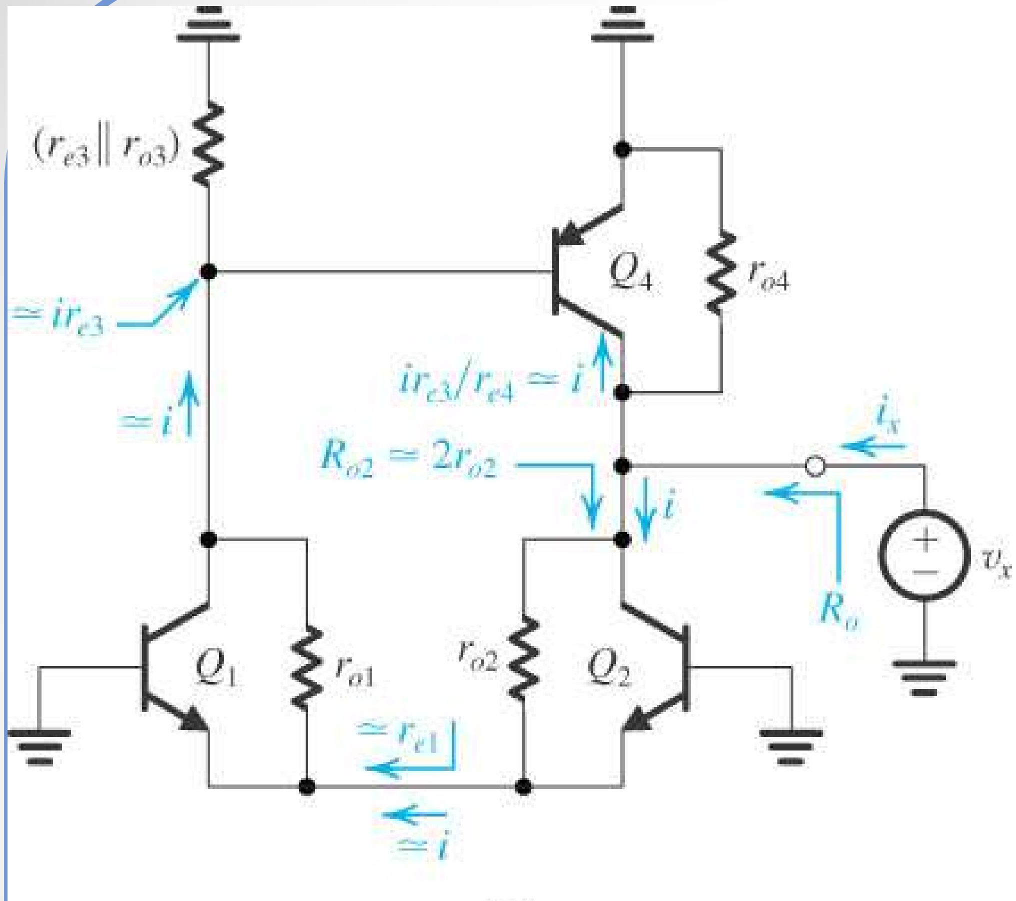
$$i_o = g_{m2}\left(\frac{v_{id}}{2}\right) - g_{m4} v_{b4}$$

$$r_{e3} = \alpha_3 / g_{m3} = \alpha / g_m \approx 1 / g_m$$

$$i_o = g_{m2}\left(\frac{v_{id}}{2}\right) + g_{m4} g_{m1} r_{e3}\left(\frac{v_{id}}{2}\right)$$

$$g_{m1} = g_{m2} = g_{m4} = g_m = \frac{I/2}{V_T}$$

$$\boxed{G_m = g_m}$$



(c)

$$R_{o2} = r_{o2}[1 + g_{m2}(r_{e1} \| r_{\pi 2})]$$
$$= r_{o2}[1 + g_{m2} r_{e1}]$$
$$= 2r_{o2}$$

$$i = \frac{v_x}{R_{o2}} = \frac{v_x}{2r_{o2}}$$

$$i_x = 2i + \frac{v_x}{r_{o4}} = \frac{v_x}{r_{o2}} + \frac{v_x}{r_{o4}}$$

$$\boxed{R_o = \frac{v_x}{i_x} = r_{o2} \| r_{o4}}$$

$$\boxed{A_d = \frac{v_o}{v_{id}} = g_m(r_{o2} \| r_{o4}) = -\frac{1}{2} g_m r_o}$$

$$\boxed{R_{id} = 2r_\pi}$$

Reference

Microelectronic Circuits by Adel S. Sedra & Kenneth C. Smith. Saunders College Publishing


OSMOSIS
Diffusion of molecules from a place of higher concentration to a place of lower concentration until the concentration on both sides is equal
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