EE4341/EE6341 Advanced Analog Circuits

Tutorial 6

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Q1. Fig. 1 shows a class-A power amplifier with a capacitor coupled load $R_L = 100\ \Omega$. The BJT has a current gain $\beta = 50$. The power supply $V_{CC} = +12$ V and the BJT is to be biased at $V_{CEQ} = 6$ V. Assume $V_{BE} = 0.7$ V and $V_{CE,sat} \approx 0$ V for your calculation. Ignore the output resistance of the BJT and the reactance of coupling capacitors.

(a) Determine the value of R_C for maximum possible conversion efficiency.

(b) Calculate the DC biasing collector current I_{CQ} and the value of R_B to provide the biasing.

(c) Calculate the peak load voltage and current, and the conversion efficiency.

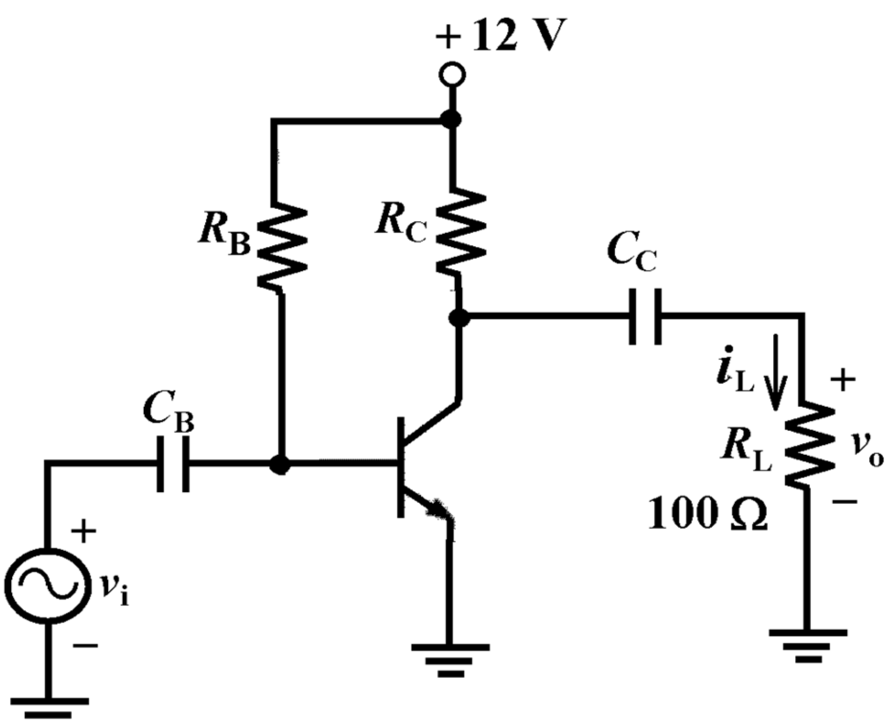
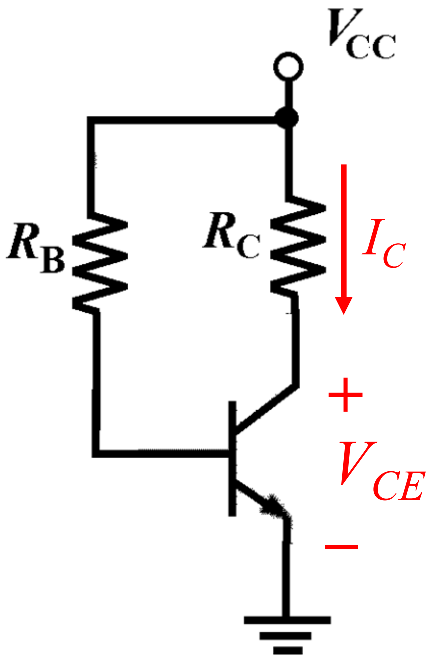


Figure 1

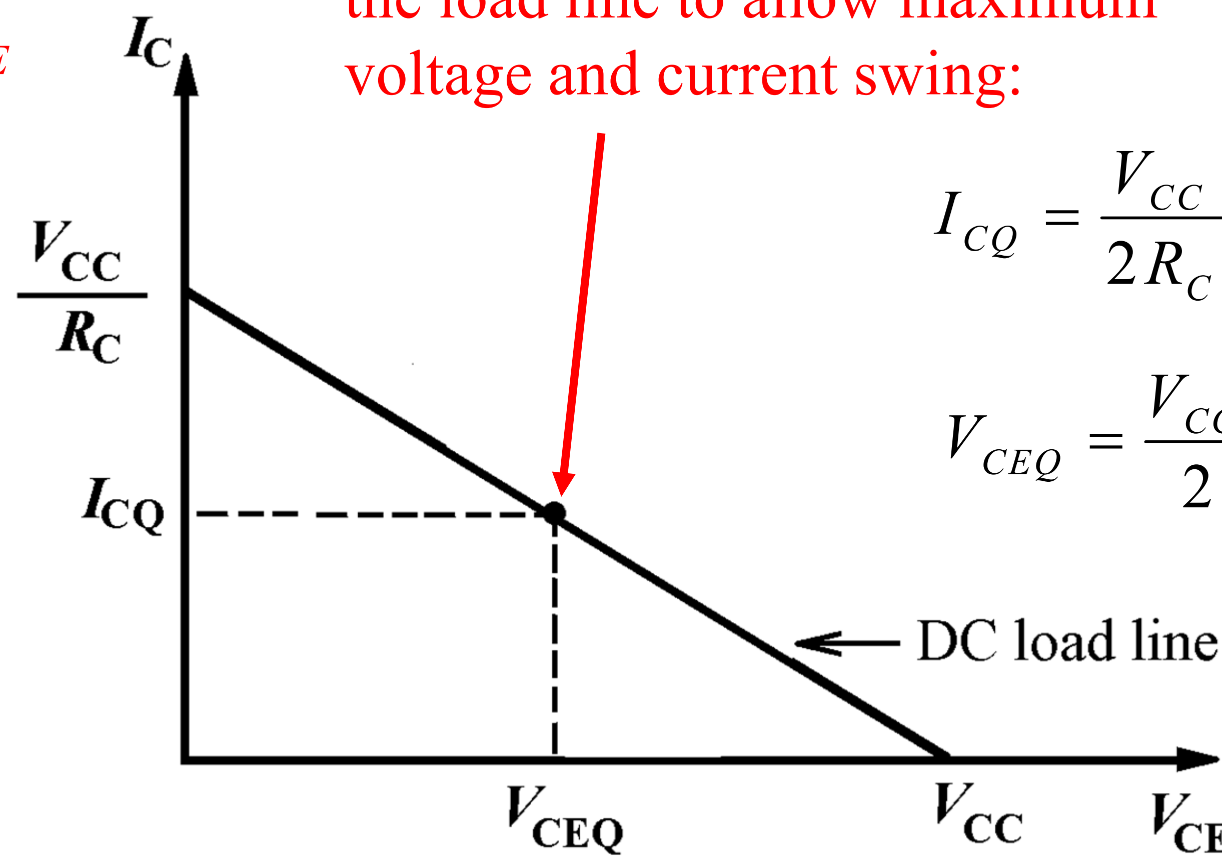
(a) DC load line: $V_{CC} = I_C R_C + V_{CE}$



When $I_C = 0$: $V_{CE} = V_{CC}$

When $V_{CE} = 0$: $I_C = \dfrac{V_{CC}}{R_C}$

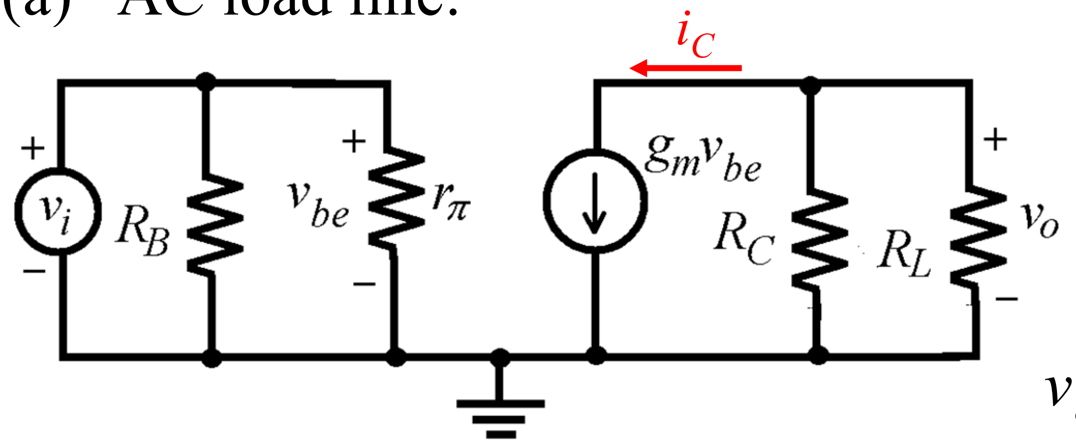
Q-point is selected at mid-point of the load line to allow maximum voltage and current swing:



$$I_{CQ} = \frac{V_{CC}}{2R_C}$$

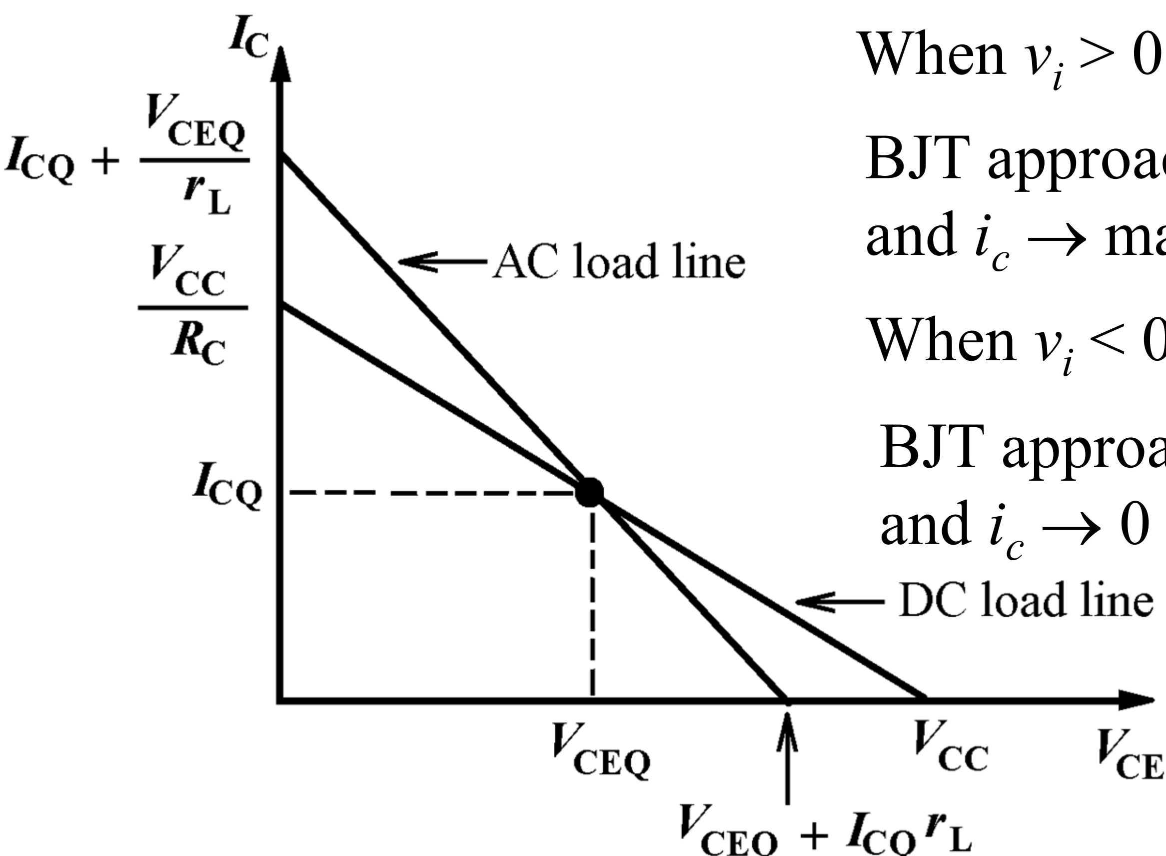
$$V_{CEQ} = \frac{V_{CC}}{2}$$

(a) AC load line:



$$r_L = R_C // R_L$$

$$v_o = -g_m v_{be} r_L = -g_m v_i r_L$$

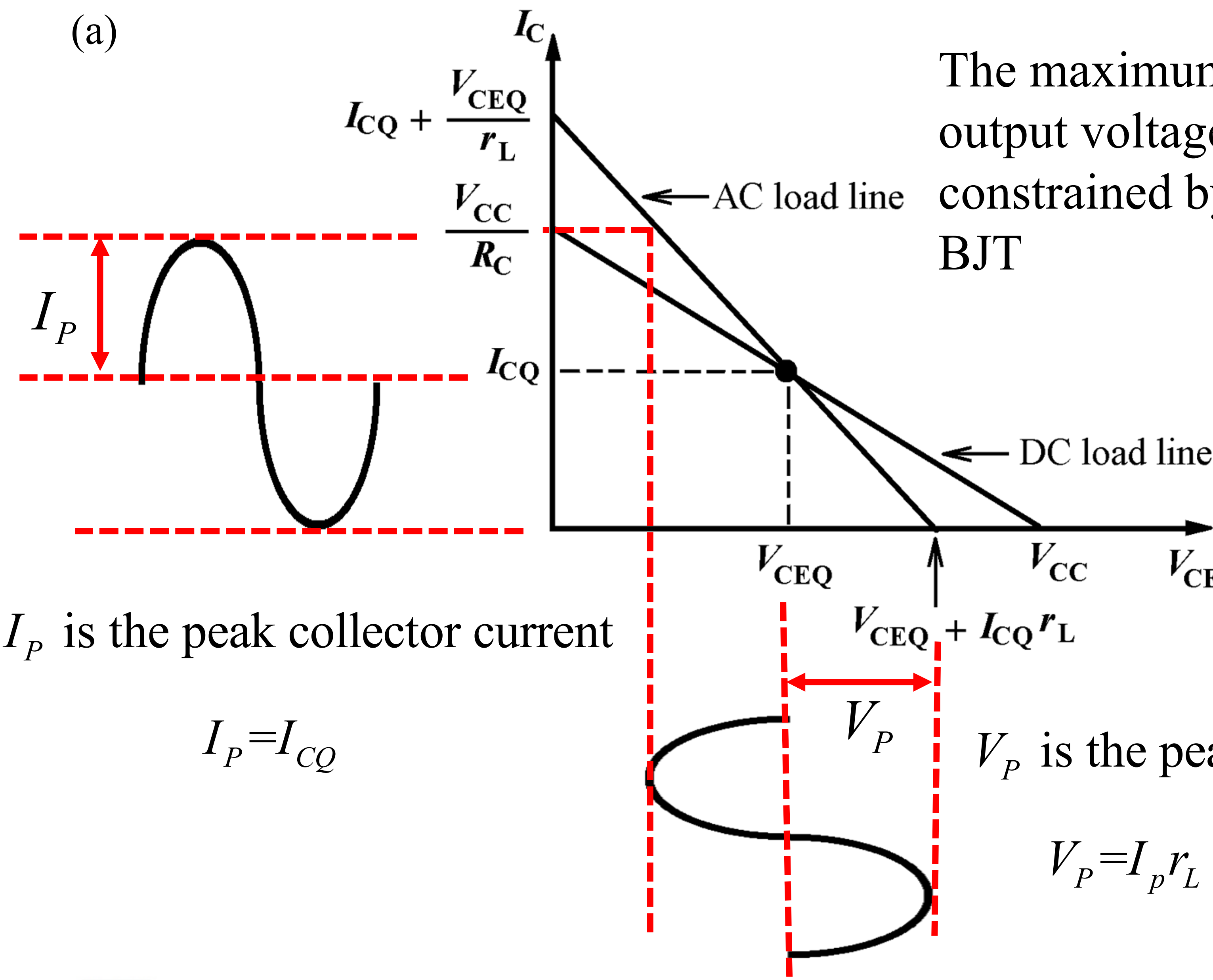


When $v_i > 0$: $v_{CE} = V_{CEQ} - g_m v_i r_L$

BJT approaches saturation $v_{CE} \rightarrow 0$ and $i_c \rightarrow \max$

When $v_i < 0$: $v_{CE} = V_{CEQ} + g_m v_i r_L$

BJT approaches cut-off $v_{CE} \rightarrow \max$ and $i_c \rightarrow 0$



The maximum undistorted output voltage swing is constrained by cutoff of BJT

I_P is the peak collector current

$$I_P = I_{CQ}$$

V_P is the peak load voltage

$$V_P = I_p r_L = I_{CQ} r_L$$

Average power to the load:

$$\bar{P}_L = \frac{V_P I_P}{2} = \frac{V_P{}^2}{2R_L} = \frac{\left(I_{CQ} r_L\right)^2}{2R_L} \qquad\qquad I_{CQ} = \frac{V_{CC}}{2R_C}$$

$$\therefore \bar{P}_L = \frac{\left(I_{CQ} r_L\right)^2}{2R_L} = \frac{V_{CC}{}^2 r_L{}^2}{8R_C{}^2 R_L}$$

Average power from the power supply (ignore the current in R_B first):

$$\bar{P}_S = V_{CC} I_{CQ} = \frac{V_{CC}{}^2}{2R_C}$$

$$\eta = \frac{\bar{P}_L}{\bar{P}_S} = \frac{V_{CC}{}^2 r_L{}^2}{8R_C{}^2 R_L} \times \frac{2R_C}{V_{CC}{}^2} = \frac{r_L{}^2}{4R_C R_L}$$

$$\eta = \frac{r_L^{\ 2}}{4R_C R_L} \qquad r_L = R_C // R_L = \frac{R_C R_L}{R_C + R_L}$$

$$\therefore \eta = \frac{R_C^{\ 2} R_L^{\ 2}}{\left(R_C + R_L\right)^2} \times \frac{1}{4R_C R_L} = \frac{R_C R_L}{4\left(R_C + R_L\right)^2}$$

To find R_C for maximum conversion efficiency:

$$\frac{\partial \eta}{\partial R_C} = \frac{4\left(R_C + R_L\right)^2 R_L - R_C R_L \times 8\left(R_C + R_L\right)}{16\left(R_C + R_L\right)^4}$$

$$= \frac{R_L}{4\left(R_C + R_L\right)^2} - \frac{R_C R_L}{2\left(R_C + R_L\right)^3} = 0$$

$$\frac{1}{4} = \frac{R_C}{2\left(R_C + R_L\right)} \Rightarrow 2R_C + 2R_L = 4R_C \Rightarrow R_L = R_C$$

$R_C = R_L = 100\ \Omega$

$$\eta = \frac{r_L^{\ 2}}{4R_C R_L} = \frac{50^2}{4 \times 100 \times 100} = 0.0625\ (6.25\%)$$

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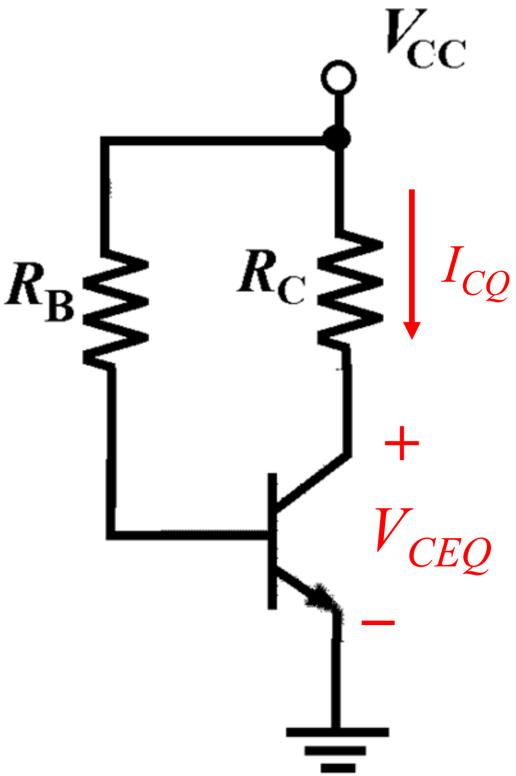
(b) DC biasing:



$$V_{CC} = I_{CQ} R_C + V_{CEQ}$$

$$I_{CQ} = \frac{V_{CC} - V_{CEQ}}{R_C} = \frac{12 - 6}{100} = 60 \text{ mA}$$

$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{60 \text{ mA}}{50} = 1.2 \text{ mA}$$

$$R_B = \frac{V_{CC} - V_{BE}}{I_{BQ}} = \frac{12 - 0.7}{1.2 \text{ mA}} = 9.42 \text{ k}\Omega$$

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(c) The peak load voltage:

$$V_P = I_{CQ} r_L = 60\text{ mA} \times 50\ \Omega = 3\text{ V} \qquad I_P = \frac{V_P}{R_L} = \frac{3}{100} = 30\text{ mA}$$

$$\overline{P}_L = \frac{V_P I_P}{2} = \frac{3\text{ V} \times 30\text{ mA}}{2} = 45\text{ mW}$$

$$\overline{P}_S = V_{CC}\left(I_{CQ} + I_{BQ}\right) = 12\text{ V } \times 61.2\text{ mA} = 734.4\text{ mW}$$

$$\eta = \frac{\overline{P}_L}{\overline{P}_S} = \frac{45}{734.4} \times 100 = 6.13\%$$

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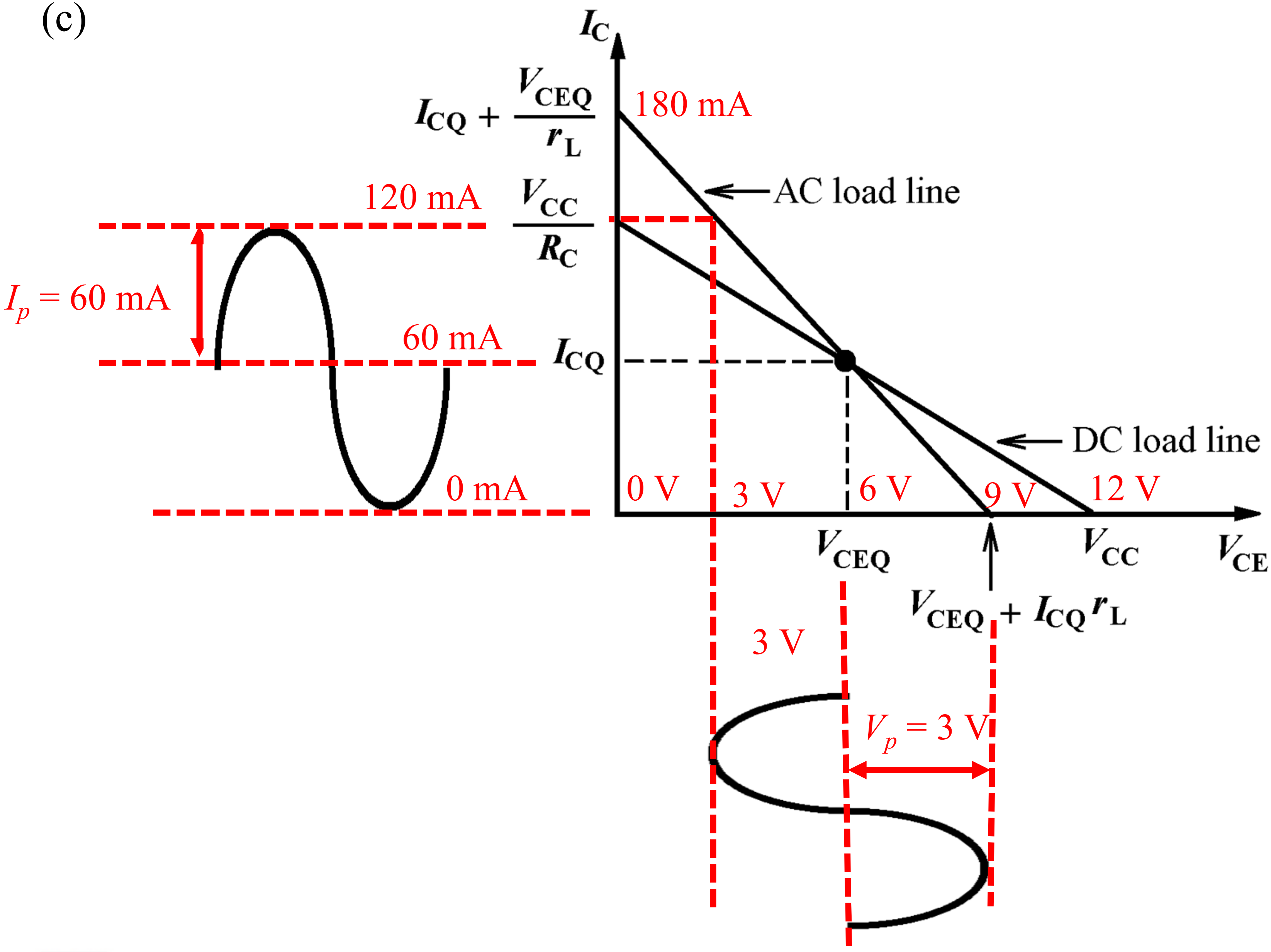
(c)



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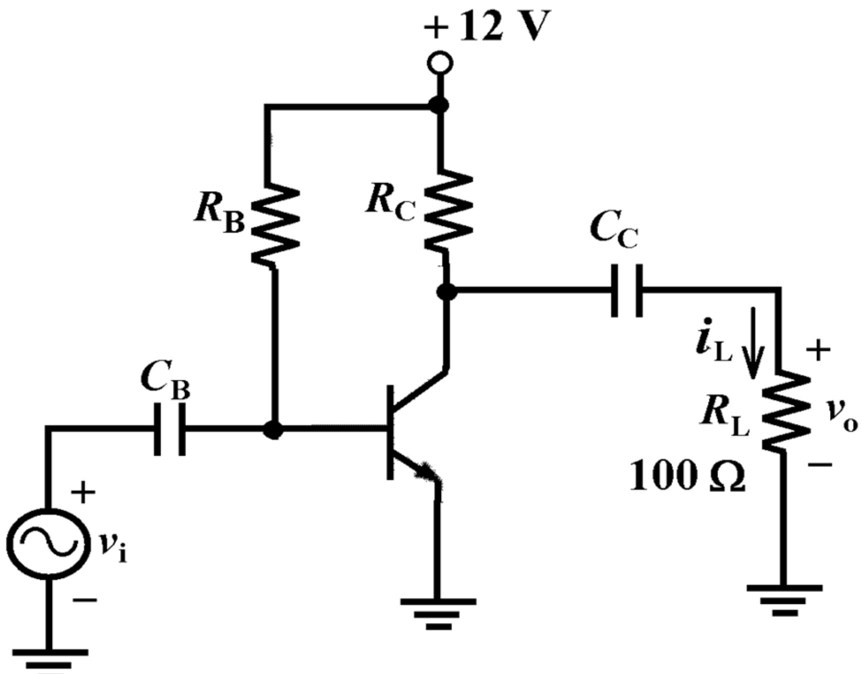


The classical class A amplifier has very poor efficiency and not suitable to be used as a power amplifier .

A power amplifier requires two stages:

- First stage provides the maximum voltage swing with negligible current
- Second stage (also known as output stage) delivers sufficient current to the load while maintaining full voltage swing.

2. An emitter follower power amplifier with a load $R_L = 1\ \text{k}\Omega$ is shown in Fig. 2. The transistor parameters are: $\beta = 200$, $V_{BE} = 0.7$ V and $V_{CE(sat)} = 0.2$ V.

(a) Determine the value of R that will produce maximum possible output signal swing.

(b) What are the value of I_Q and the maximum and minimum values of i_{E1} and i_L?

(c) Calculate the conversion efficiency.

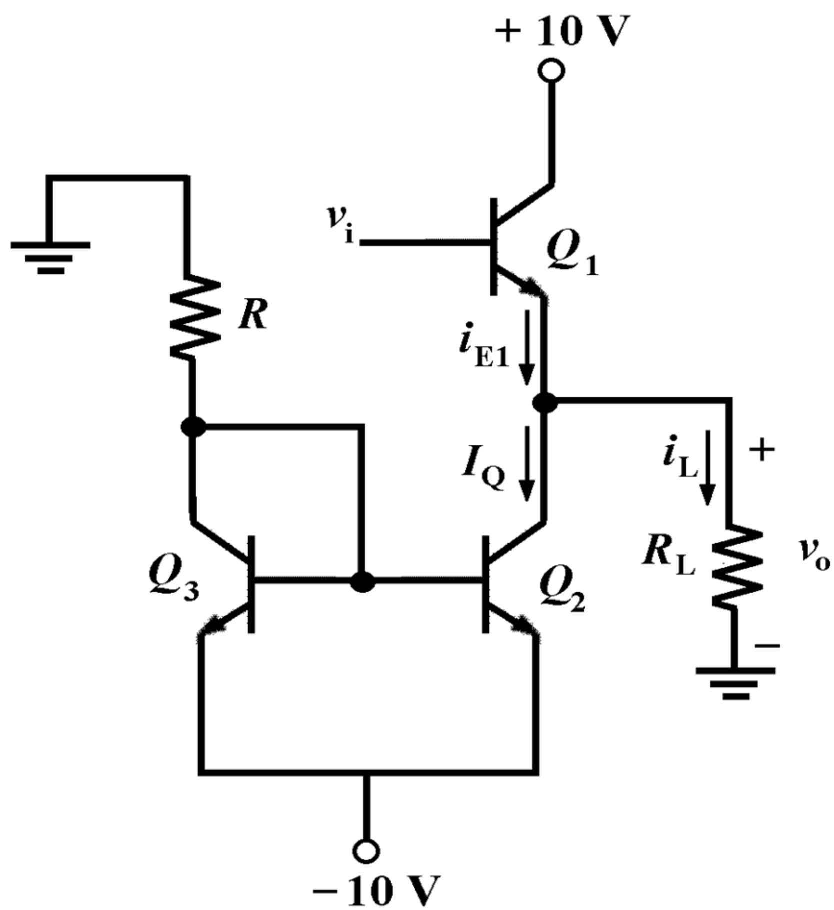


Figure 2

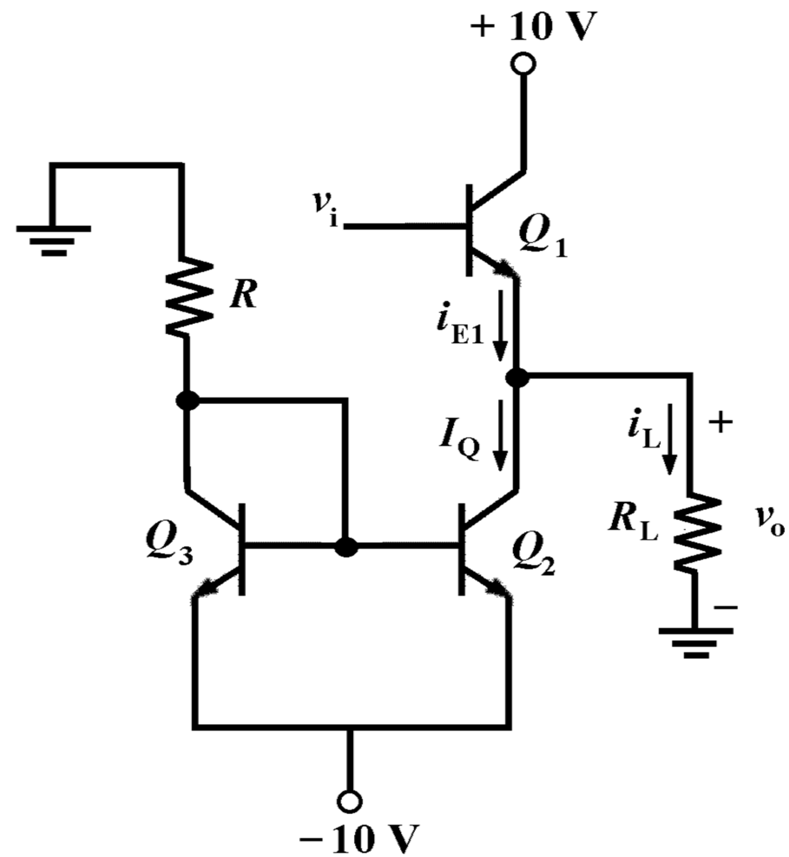
(a)

$$v_o = v_i - V_{BE1}$$

$$v_{BE1} = \frac{kT}{q} ln\left(\frac{i_{C1}}{I_S}\right)$$

$$i_{C1} \approx i_{E1} = I_Q + i_L = I_Q + \frac{v_o}{R_L}$$

$$v_o = v_i - \frac{kT}{q} ln\left(\frac{I_Q + \frac{v_o}{R_L}}{I_S}\right)$$



When $v_i > 0$, the maximum voltage swing is when Q_1 is saturated:

$$v_o = V_{CC} - V_{CEsat1}$$

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When v_i <0, the output voltage swing is when Q_1 reaches cut-off, i.e. $i_{c1} = 0$:

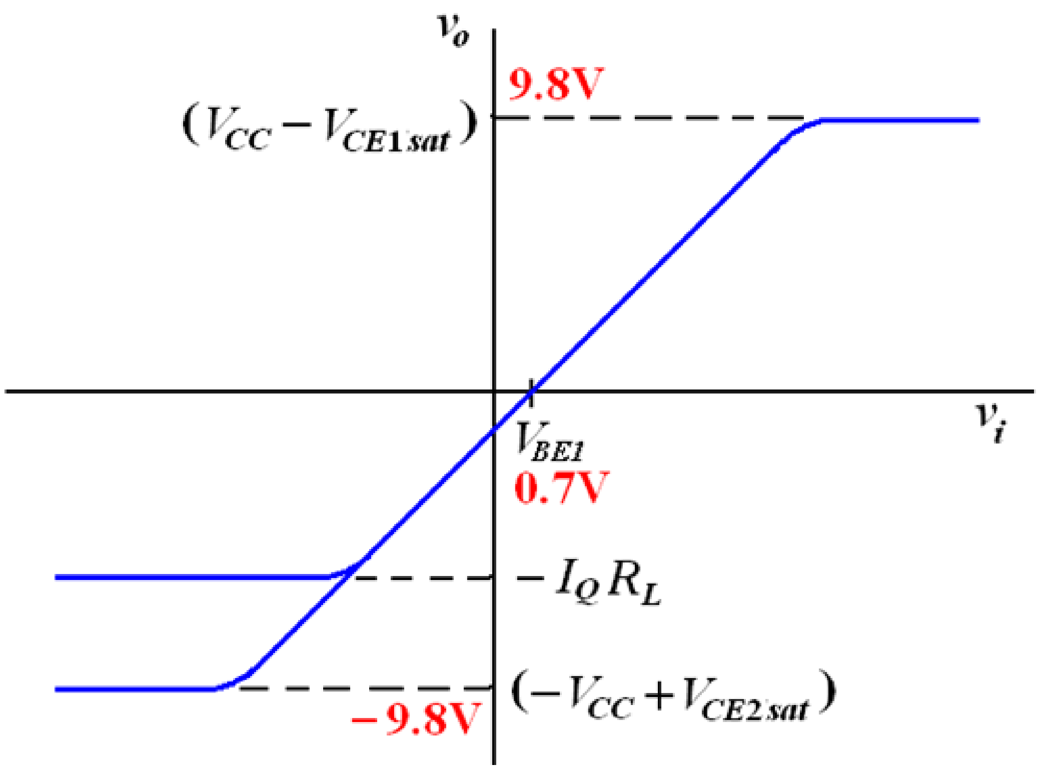
$$i_{c1} \approx i_{E1} = I_Q + i_L = 0$$

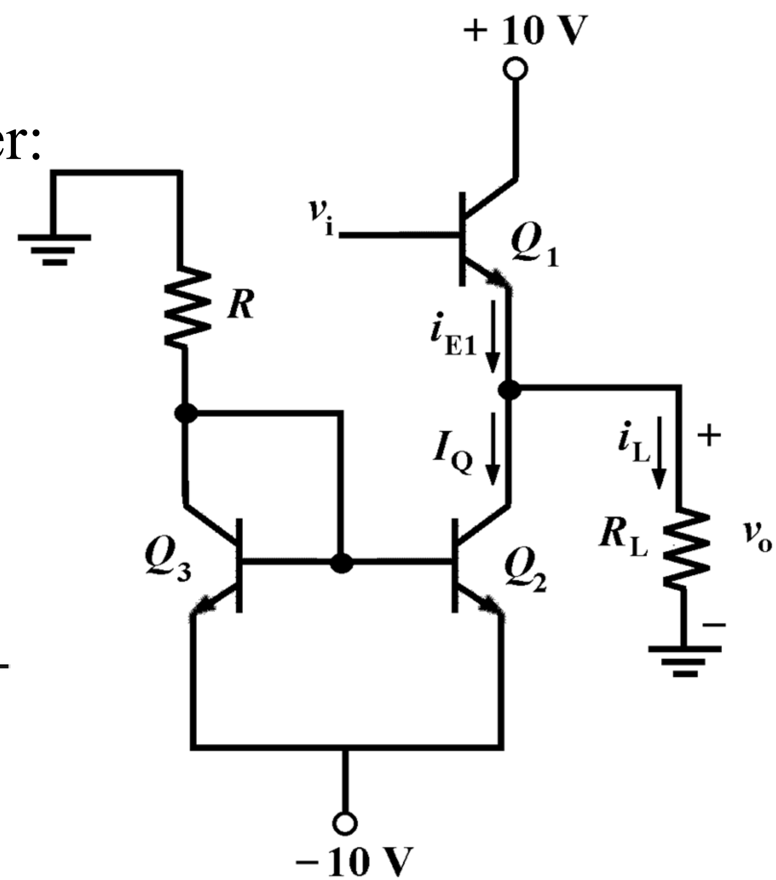
Note: i_L is –ve, as v_i <0

$$I_Q + \frac{v_o}{R_L} = 0 \quad \therefore v_o = -I_Q R_L$$

Hence, depending on I_Q, the output is either:

$$v_o = -I_Q R_L \text{ or } -V_{CC} + V_{CEsat2}$$



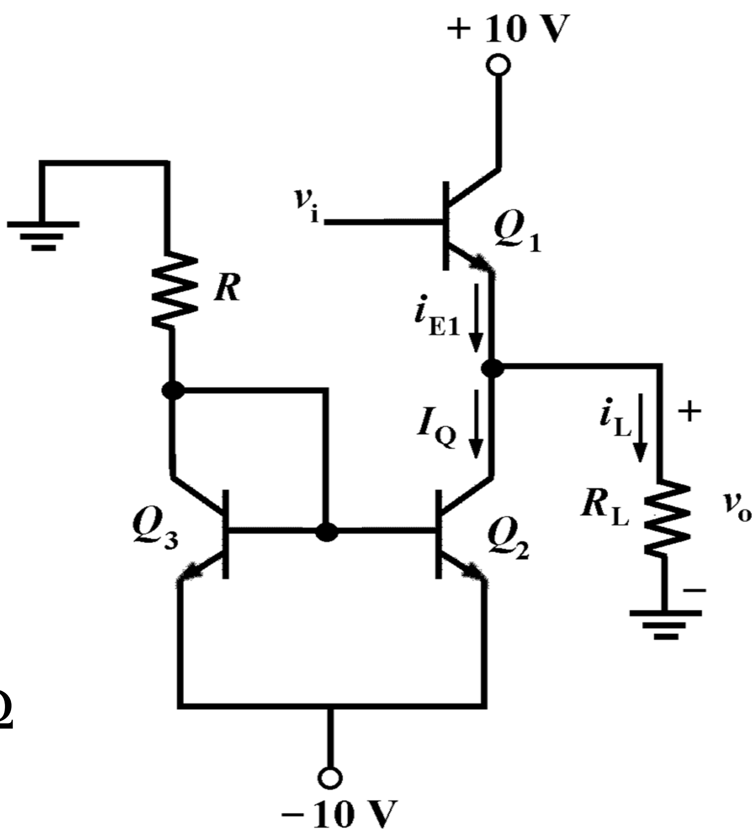


To achieve maximum negative output voltage of $-V_{CC} + V_{CEsat2}$

The required minimum biasing:

$$I_Q \geq \frac{\left|-V_{CC} + V_{CEsat2}\right|}{R_L}$$

I_Q must fulfill the following condition:



$$I_Q = \frac{\left|-V_{CC} + V_{CEsat2}\right|}{R_L} = \frac{10 - 0.2}{1\text{k}} = 9.8\ \text{mA}$$

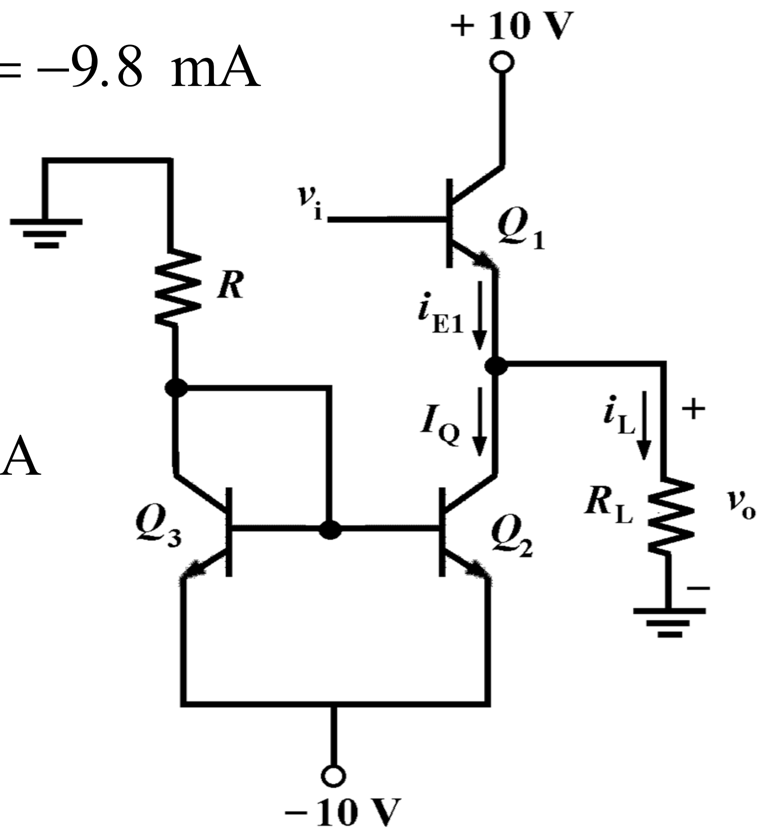
$$\therefore R = \frac{0 - V_{BE3} - \left(-V_{CC}\right)}{I_Q} = \frac{0 - 0.7 + 10}{9.8\text{m}} = 950\,\Omega$$

(b)

With $R = 950\ \Omega$, $I_Q = 9.8\ \text{mA}$

$$i_{L,max} = \frac{v_{o,max}}{R_L} = \frac{V_{CC} - V_{CE1sat}}{R_L} = \frac{10-0.2}{1\text{k}} = 9.8\ \text{mA}$$

$$i_{L,min} = \frac{v_{o,min}}{R_L} = \frac{-V_{CC} + V_{CE2sat}}{R_L} = \frac{-10+0.2}{1\text{k}} = -9.8\ \text{mA}$$



$$i_{E1,max} = I_Q + i_{L,max} = 9.8\text{mA} + 9.8\text{mA} = 19.6\ \text{mA}$$

$$i_{E1,min} = I_Q + i_{L,min} = 9.8\text{mA} - 9.8\text{mA} = 0$$

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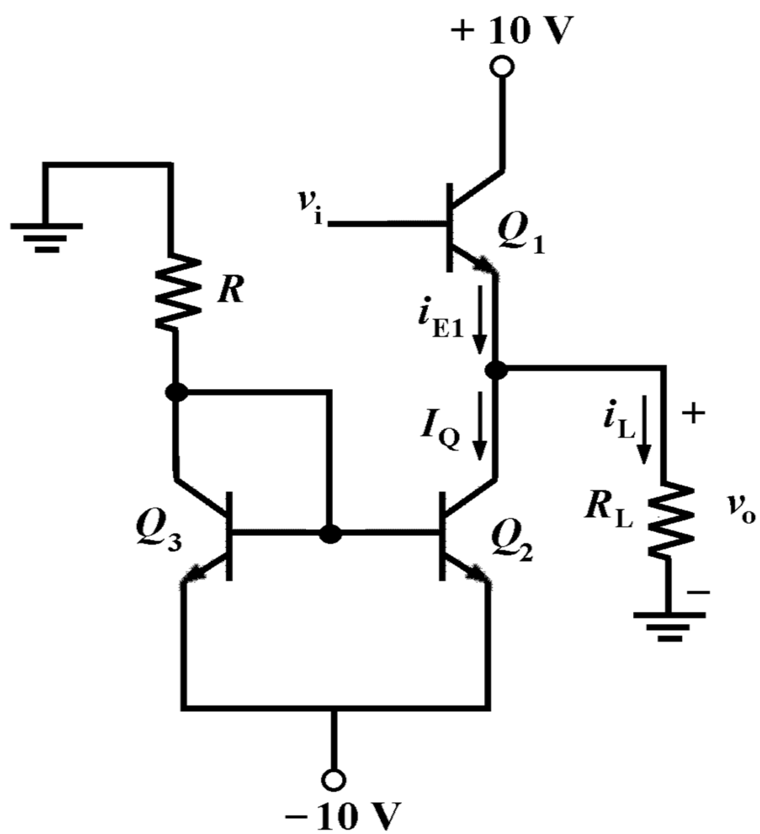
(c)

Average power to the load:

$$\overline{P_L} = \frac{V_p I_p}{2} = \left(\frac{v_{o,max}{}^2}{2R_L}\right) = \frac{1}{2} \times \frac{9.8^2}{1\text{k}} = 48\,\text{mW}$$

The biasing currents for Q_1, Q_2 and Q_3 are I_Q:



Average power from the power supply:

$$\overline{P_S} = I_Q V_{CC} + I_Q\left[V_{CC} - \left(-V_{CC}\right)\right]$$
$$= 3I_Q V_{CC} = 3 \times 9.8m \times 10 = 294\ \text{mW}$$

$$\eta = \frac{\overline{P_L}}{\overline{P_S}} \times 100 = \frac{48}{294} \times 100 = 16.32\,\%$$

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3. Consider a BiCMOS follower amplifier circuit shown in Fig. 3. The BJT parameters are: $V_{BE} = 0.7$ V and $V_{CE(sat)} = 0.2$ V. The MOSFET parameters are: $V_{TN} = -1.8$ V and $K_n = \frac{1}{2}k'_n\left(\frac{W}{L}\right) = 12$ mA/V^2.

(a) Determine the maximum and minimum values of output voltage and the corresponding values of input voltage for the amplifier to operate in the linear region when: (i) R_L is removed (open-circuit) (ii) $R_L = 500\ \Omega$

(b) Determine the smallest possible value of R_L if a 2 V peak sine wave is produced at output. What is the corresponding conversion efficiency?

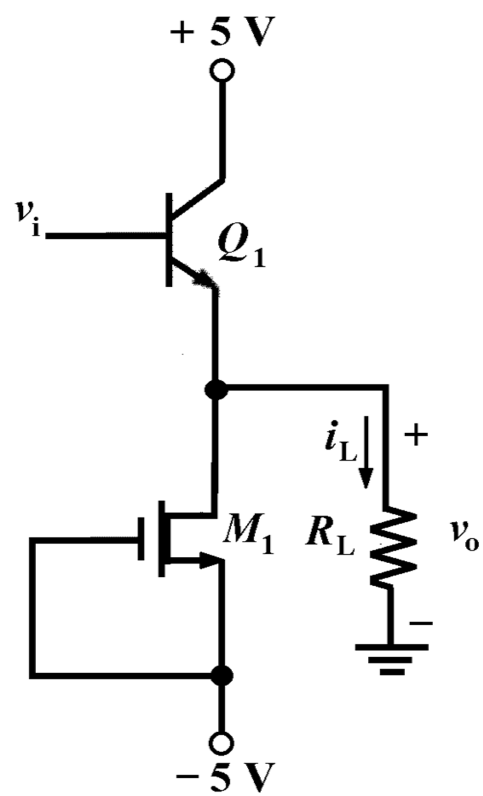

Figure 3

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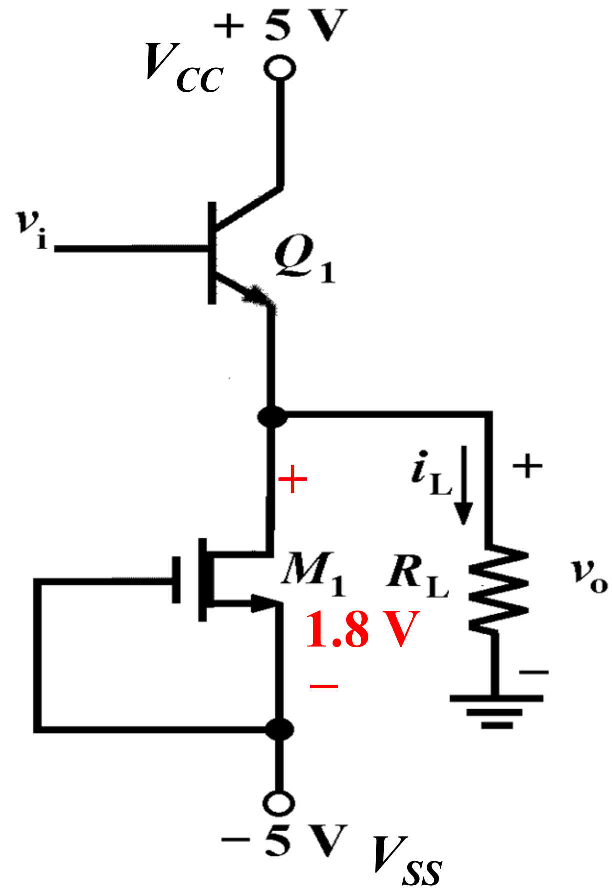
Note: The MOSFET is a depletion NMOS as V_{TN} is –ve.

$$I_{DQ} = K_n \left(v_{GS} - V_{TN}\right)^2 = 12m\left[0-(-1.8)\right]^2 = 38.9 \text{ mA}$$

The MOSFET must be kept in saturation mode so that it maintains as a constant current source:

$$V_{DS} \geq V_{GS} - V_{TN}$$
$$V_{DS} \geq 0-(-1.8)$$
$$V_{DS} \geq 1.8 \text{ V}$$



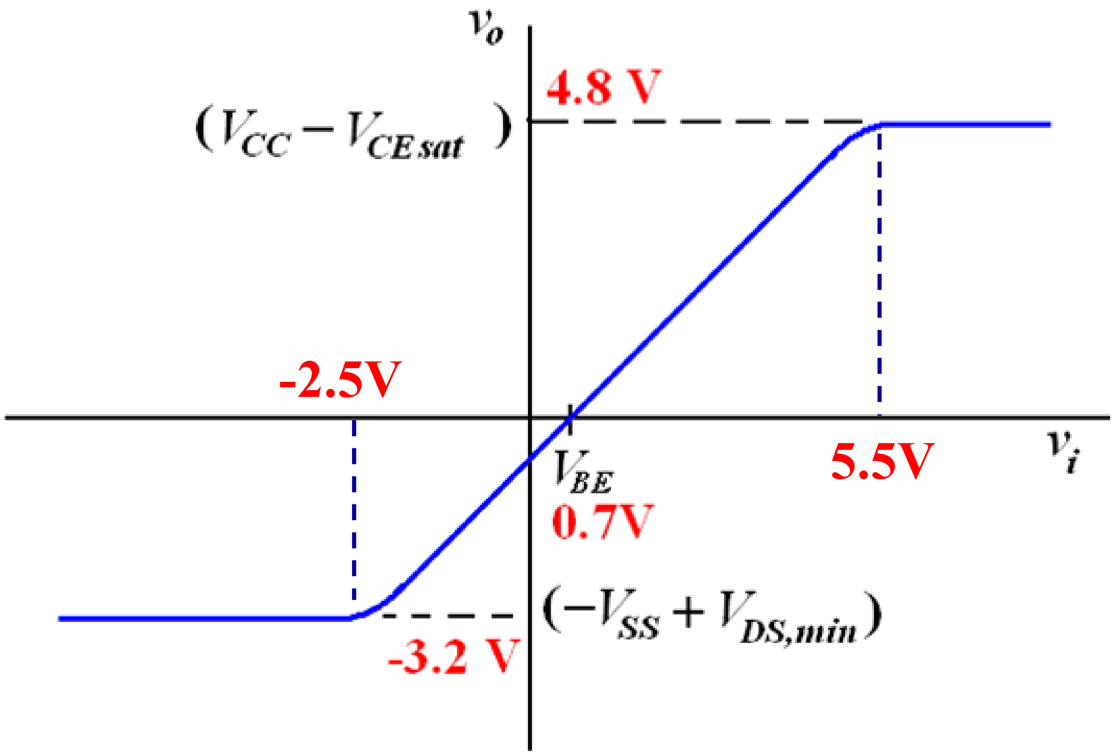
(a) $R_L = \infty$ (open-circuit)

$$v_{o,\max} = V_{CC} - v_{CEsat} = 5 - 0.2 = 4.8 \text{ V}$$

$$v_{o,\min} = V_{SS} + v_{DS,\min} = -5 + 1.8 = -3.2 \text{ V}$$

$$v_{i,\max} = v_{o,\max} + V_{BE} = 4.8 + 0.7 = 5.5 \text{ V}$$

$$v_{i,\min} = v_{o,\min} + V_{BE} = -3.2 + 0.7 = -2.5 \text{ V}$$



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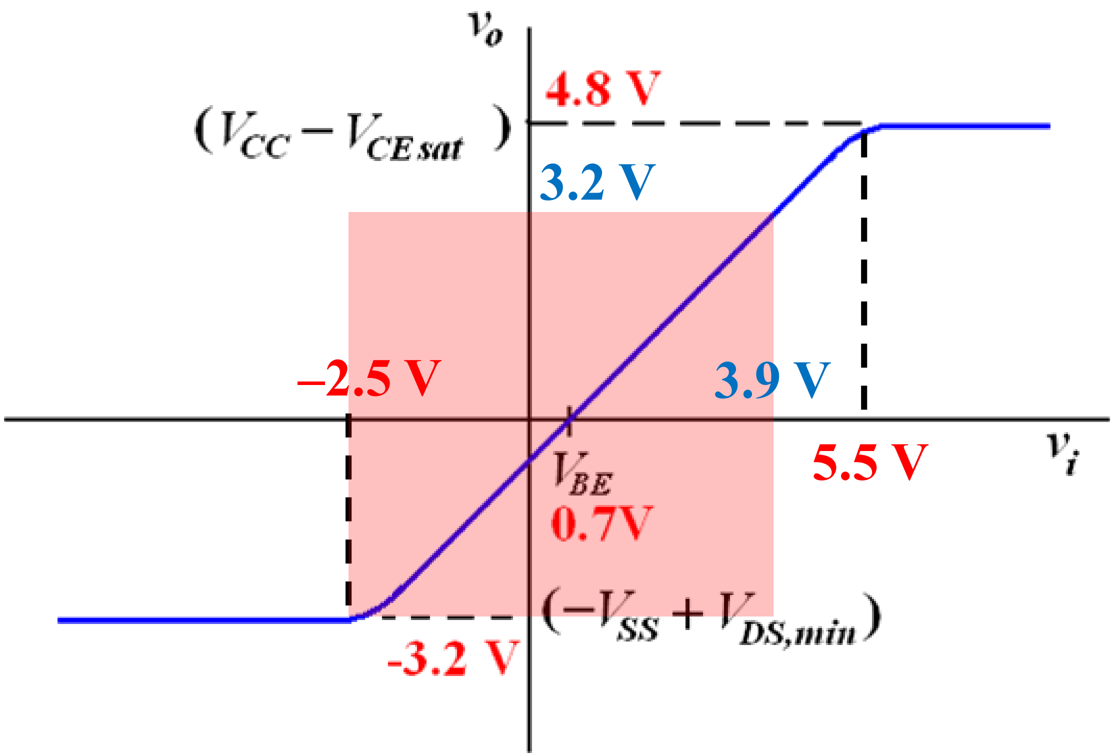

To obtain maximum output voltage swing without clipping:

$$-3.2 \text{ V} \leq v_o \leq 3.2 \text{ V}$$

The corresponding input voltage swing:

$$-2.5 \text{ V} \leq v_i \leq 3.9 \text{ V}$$

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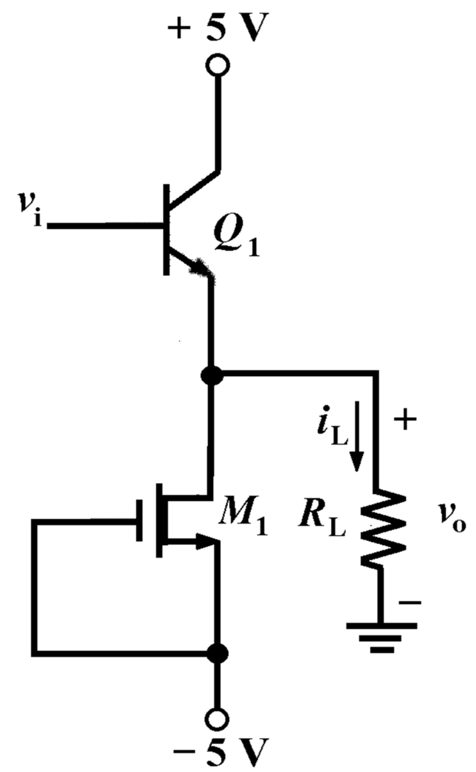
(b) R_L =500 Ω

$$v_{o,\min} = -I_{DQ}R_L = -38.9\text{m}\times 500 = -19.45\ \text{V} \ \text{ or } \ -3.2\ \text{V}$$

$$\therefore v_{o,\min} = \ -3.2\ \text{V}$$



Similarly, to obtain maximum output voltage swing without clipping:

$$-3.2\ \text{V} \le v_o \le 3.2\ \ \text{V}$$

The corresponding input voltage swing:

$$-2.5\ \text{V} \le v_i \le 3.9\ \ \text{V}$$

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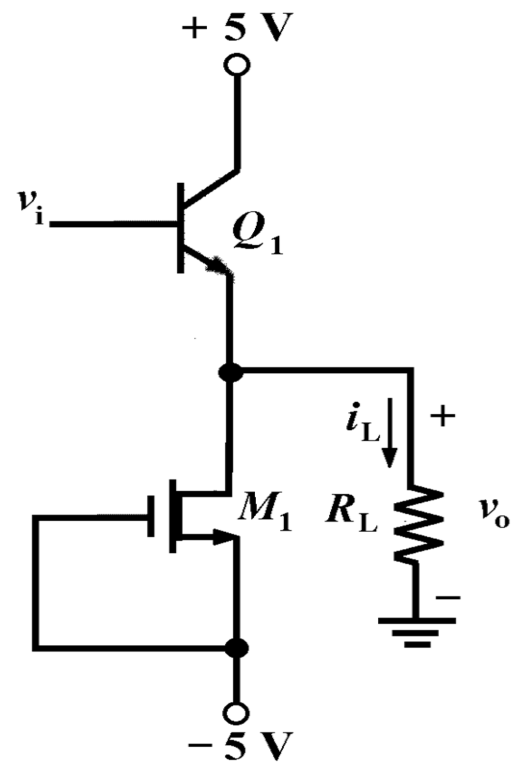
$$-2 \text{ V} \le v_o \le 2 \text{ V}$$

The negative swing sets the limit, $v_o = -2\text{V}$.



$$v_{o,\min} = -I_{DQ} R_L = -2 \text{ V}$$

$$\therefore R_L = \frac{v_{o,\min}}{I_{DQ}} = \frac{2}{38.9m} = 51.4 \ \Omega$$

$$\therefore v_{i,min} = -2 + 0.7 = -1.3 \text{ V}$$

$$\overline{P_L} = \frac{1}{2}\left(\frac{V_p^{\ 2}}{R_L}\right) = \frac{1}{2} \times \frac{2^2}{51.4} = 38.9\text{mW}$$

$$\overline{P_S} = I_{DQ}\left[V_{CC} - \left(-V_{SS}\right)\right] = 38.9m \times 10 = 389 \ \text{ mW}$$

$$\eta = \frac{\overline{P_L}}{\overline{P_S}} \times 100 = \frac{38.9}{389} \times 100 = 10 \ \%$$

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