CHAPTER 9

Differential and Multistage Amplifiers

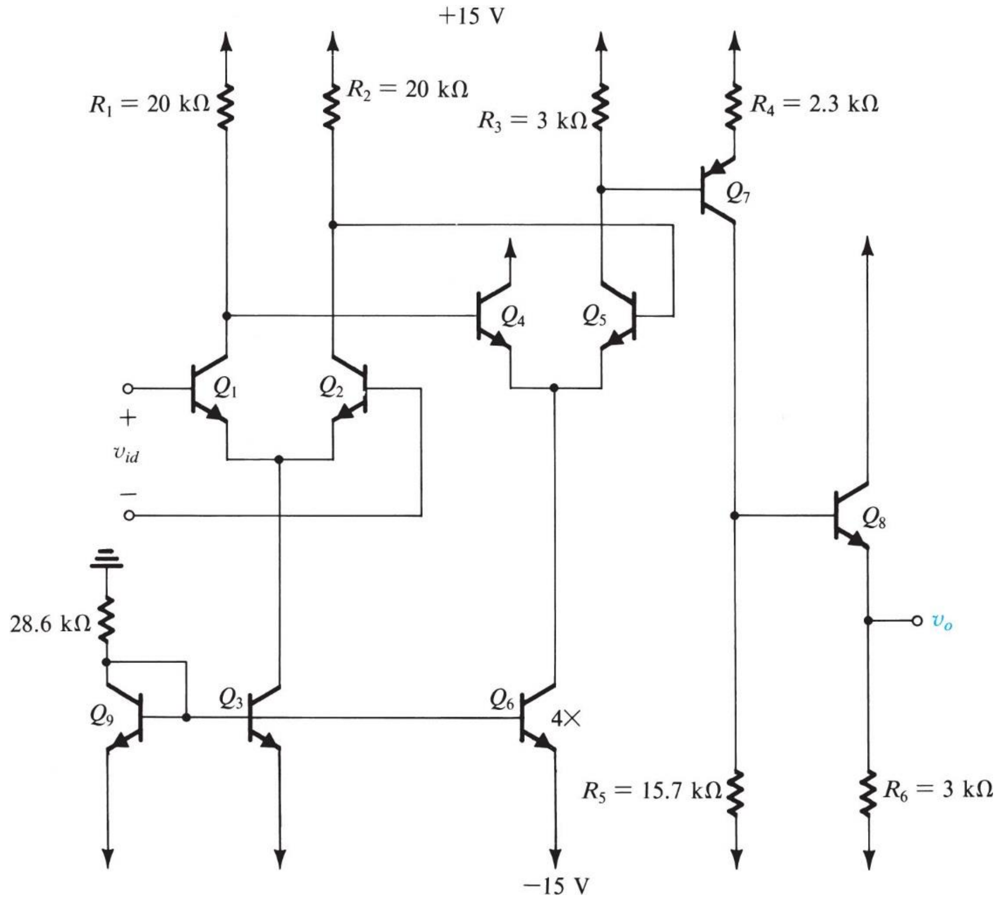


Figure 9.41 A four-stage bipolar op amp.

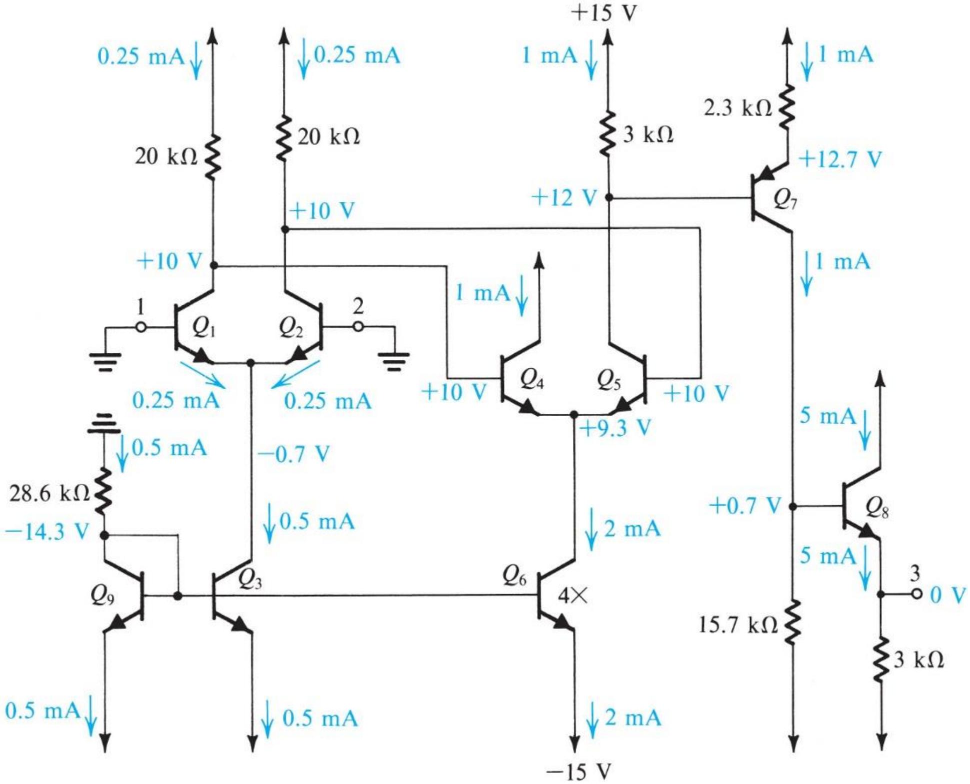


Figure 9.42 Circuit for Example 9.7.

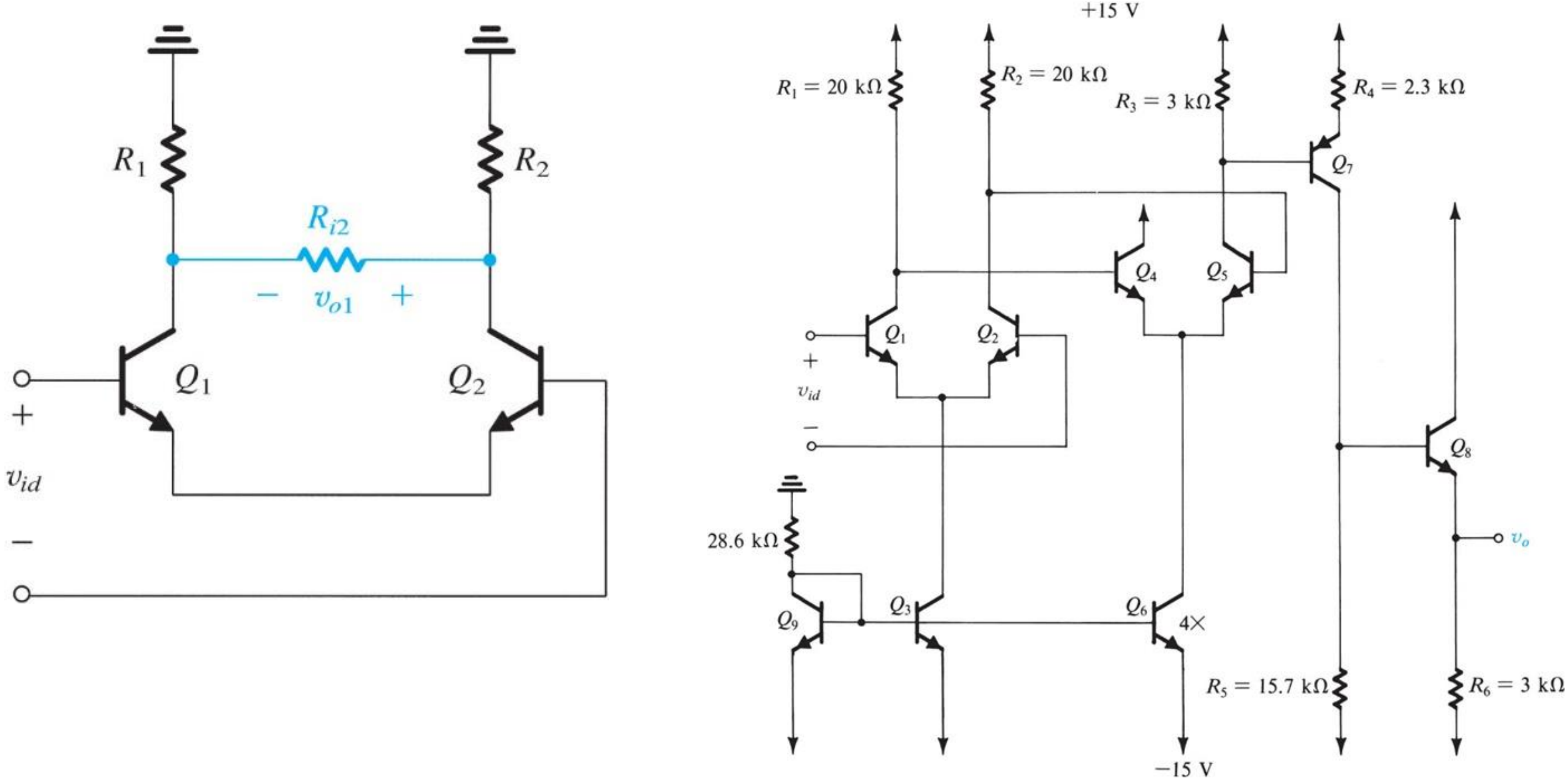


Figure 9.43 Equivalent circuit for calculating the gain of the input stage of the amplifier in Fig. 9.41.

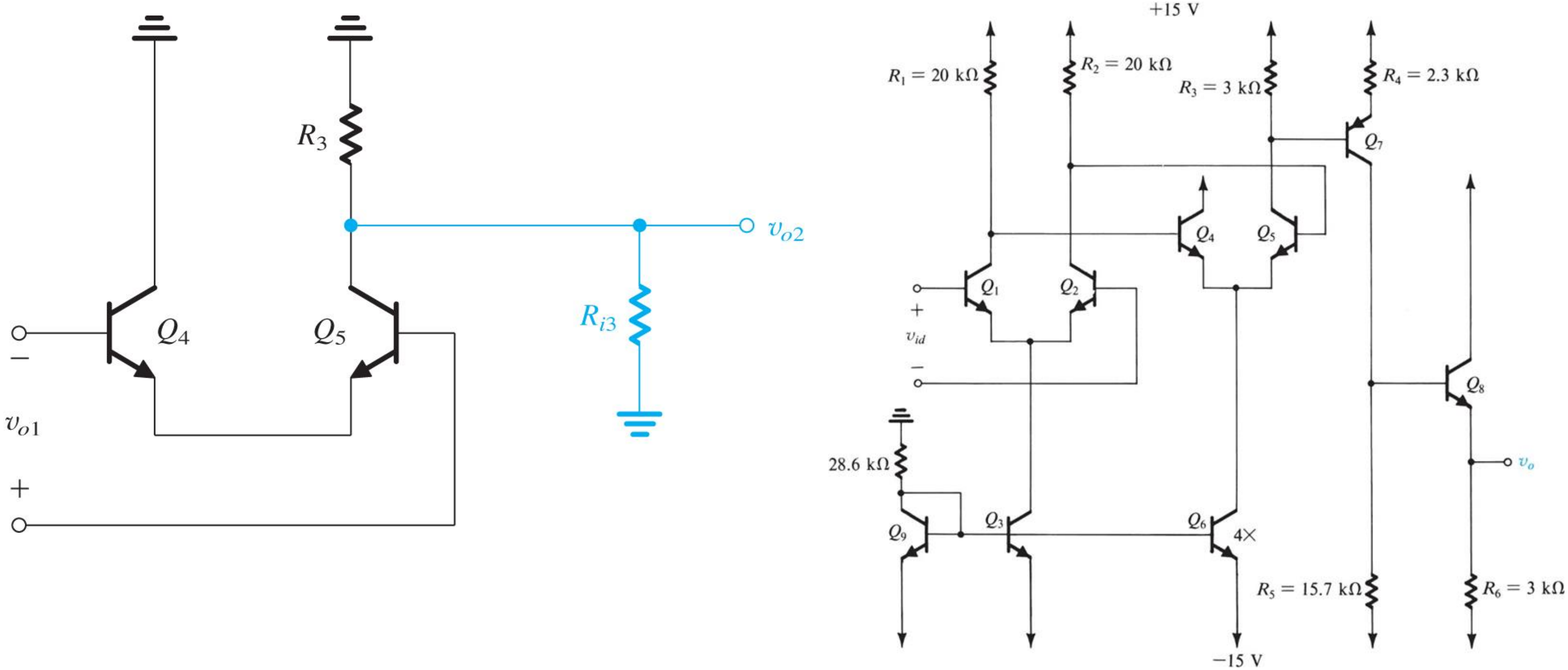
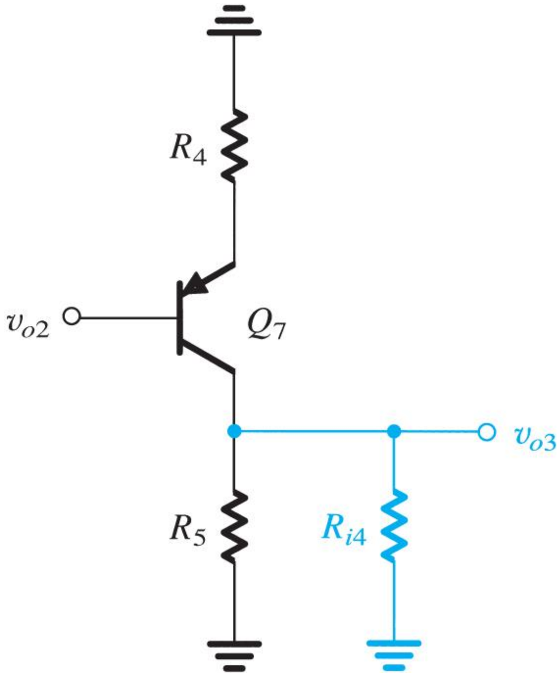


Figure 9.44 Equivalent circuit for calculating the gain of the second stage of the amplifier in Fig. 9.41.



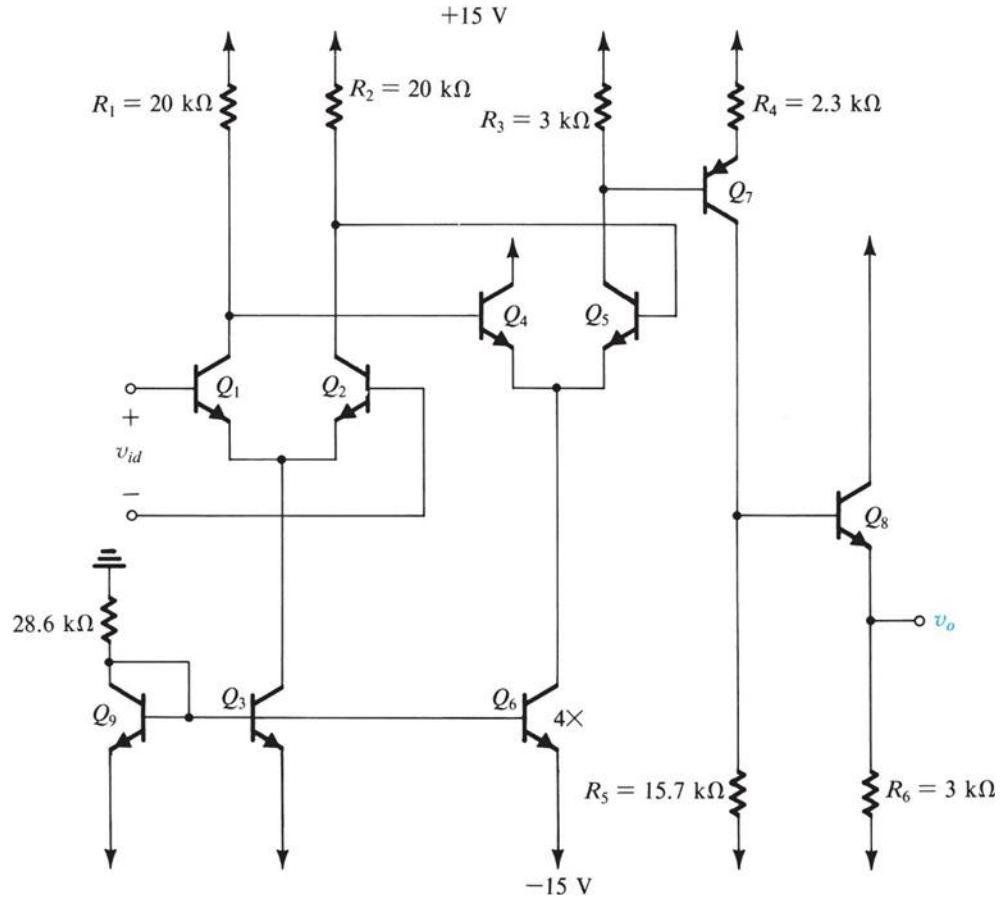
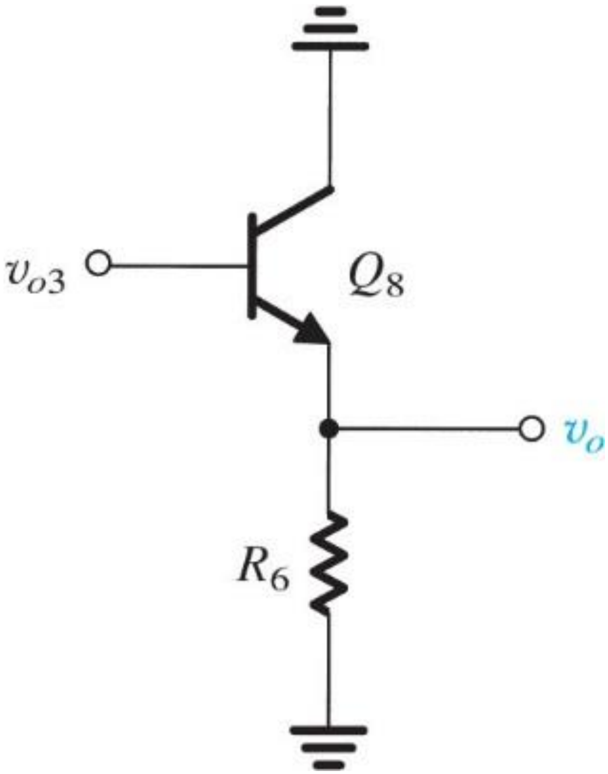


Figure 9.45 Equivalent circuit for evaluating the gain of the third stage in the amplifier circuit of Fig. 9.41.



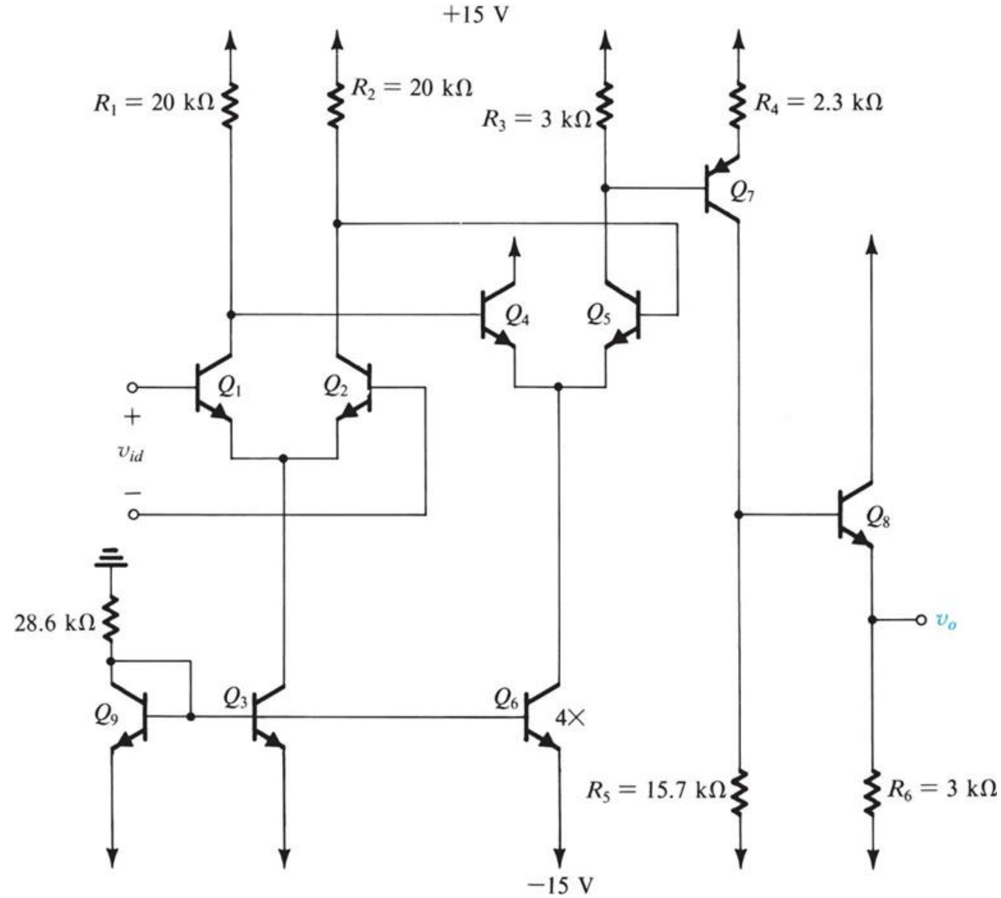


Figure 9.46 Equivalent circuit of the output stage of the amplifier circuit of Fig. 9.41.

Solution

The input differential resistance R_{id} is given by

$$R_{id} = r_{\pi 1} + r_{\pi 2}$$

Since each of Q_1 and Q_2 is operating at an emitter current of 0.25 mA, it follows that

$$r_{e1} = r_{e2} = \frac{25}{0.25} = 100\ \Omega$$

Assume $\beta = 100$; then

$$r_{\pi 1} = r_{\pi 2} = 101 \times 100 = 10.1\ \text{k}\Omega$$

Thus,

$$R_{id} = 20.2\ \text{k}\Omega$$

To evaluate the gain of the first stage, we first find the input resistance of the second stage, R_{i2},

$$R_{i2} = r_{\pi 4} + r_{\pi 5}$$

Q_4 and Q_5 are each operating at an emitter current of 1 mA; thus

$$r_{e4} = r_{e5} = 25\ \Omega$$

$$r_{\pi 4} = r_{\pi 5} = 101 \times 25 = 2.525\ \text{k}\Omega$$

Thus $R_{i2} = 5.05\ \text{k}\Omega$. This resistance appears between the collectors of Q_1 and Q_2, as shown in Fig. 9.43. Thus the gain of the first stage will be

$$A_1 \equiv \frac{v_{o1}}{v_{id}} \simeq \frac{\text{Total resistance in collector circuit}}{\text{Total resistance in emitter circuit}}$$

$$= \frac{R_{i2} \parallel (R_1 + R_2)}{r_{e1} + r_{e2}}$$

$$= \frac{5.05\ \text{k}\Omega \parallel 40\ \text{k}\Omega}{200\ \Omega} = 22.4\ \text{V/V}$$

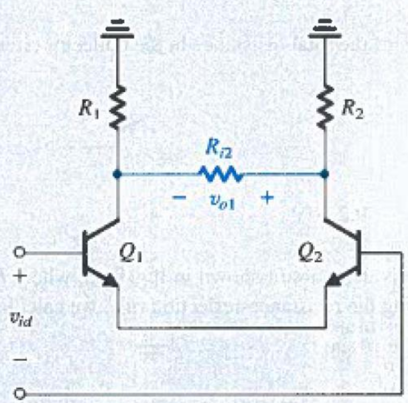


Figure 9.43 Equivalent circuit for calculating the gain of the input stage of the amplifier in Fig. 9.41.

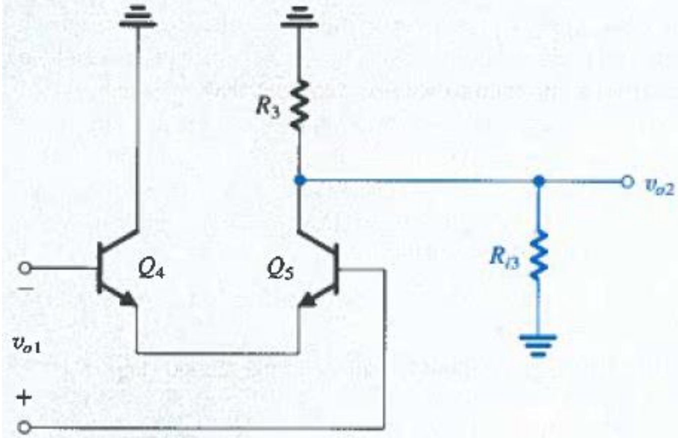


Figure 9.44 Equivalent circuit for calculating the gain of the second stage of the amplifier in Fig. 9.41.

Figure 9.44 shows an equivalent circuit for calculating the gain of the second stage. As indicated, the input voltage to the second stage is the output voltage of the first stage, v_{o1}. Also shown is the resistance R_{i3}, which is the input resistance of the third stage formed by Q_7. The value of R_{i3} can be found by multiplying the total resistance in the emitter of Q_7 by $(\beta + 1)$:

$$R_{i3} = (\beta + 1)(R_4 + r_{e7})$$

Since Q_7 is operating at an emitter current of 1 mA,

$$r_{e7} = \frac{25}{1} = 25\ \Omega$$

$$R_{i3} = 101 \times 2.325 = 234.8\ \text{k}\Omega$$

We can now find the gain A_2 of the second stage as the ratio of the total resistance in the collector circuit to the total resistance in the emitter circuit:

$$A_2 \equiv \frac{v_{o2}}{v_{o1}} \simeq -\frac{R_3 \| R_{i3}}{r_{e4} + r_{e5}}$$

$$= -\frac{3\ \text{k}\Omega \| 234.8\ \text{k}\Omega}{50\ \Omega} = -59.2\ \text{V/V}$$

To obtain the gain of the third stage we refer to the equivalent circuit shown in Fig. 9.45, where R_{i4} is the input resistance of the output stage formed by Q_8. Using the resistance-reflection rule, we calculate the value of R_{i4} as

$$R_{i4} = (\beta + 1)(r_{e8} + R_6)$$

where

$$r_{e8} = \frac{25}{5} = 5\ \Omega$$

$$R_{i4} = 101(5+3000) = 303.5\ \text{k}\Omega$$

The gain of the third stage is given by

$$A_3 \equiv \frac{v_{o3}}{v_{o2}} \simeq -\frac{R_5 \| R_{i4}}{r_{e7} + R_4}$$

$$= -\frac{15.7\ \text{k}\Omega \| 303.5\ \text{k}\Omega}{2.325\ \text{k}\Omega} = -6.42\ \text{V/V}$$

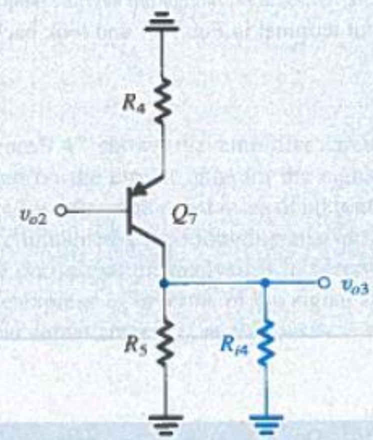


Figure 9.45 Equivalent circuit for evaluating the gain of the third stage in the amplifier circuit of Fig. 9.41.

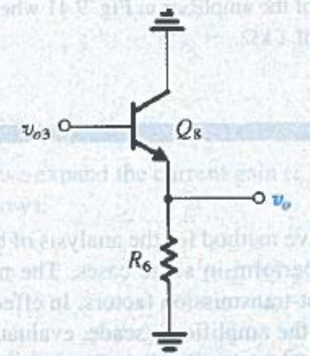


Figure 9.46 Equivalent circuit of the output stage of the amplifier circuit of Fig. 9.41.

Example 9.8 *continued*

Finally, to obtain the gain A_4 of the output stage we refer to the equivalent circuit in Fig. 9.46 and write

$$A_4 \equiv \frac{v_o}{v_{o3}} = \frac{R_6}{R_6 + r_{e8}}$$

$$= \frac{3000}{3000 + 5} = 0.998 \simeq 1$$

The overall voltage gain of the amplifier can then be obtained as follows:

$$\frac{v_o}{v_{id}} = A_1 A_2 A_3 A_4 = 8513 \text{ V/V}$$

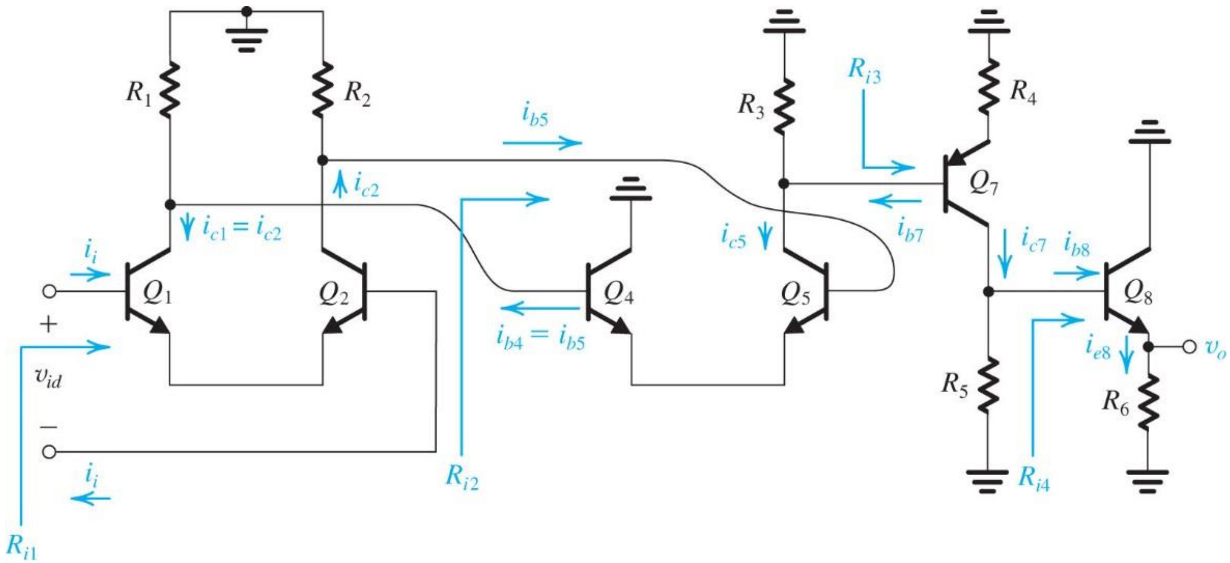
or 78.6 dB.

To obtain the output resistance R_o we "grab hold" of the output terminal in Fig. 9.41 and look back into the circuit. By inspection we find

$$R_o = R_6 \| [r_{e8} + R_5/(\beta + 1)]$$

which gives

$$R_o = 152\ \Omega$$



$$\frac{i_{e8}}{i_{b8}} = \beta_8 + 1$$

$$\frac{i_{b8}}{i_{c7}} = \frac{R_5}{R_5 + R_{i4}}$$

$$\frac{i_{c7}}{i_{b7}} = \beta_7$$

$$\frac{i_{b7}}{i_{c5}} = \frac{R_3}{R_3 + R_{i3}}$$

$$\frac{i_{c5}}{i_{b5}} = \beta_5$$

$$\frac{i_{b5}}{i_{c2}} = \frac{(R_1 + R_2)}{(R_1 + R_2) + R_{i2}}$$

$$\frac{i_{c2}}{i_i} = \beta_2$$

$$v_o = R_6 i_{e8}$$

$$v_{id} = R_{i1} i_i$$

$$\frac{v_o}{v_{id}} = \frac{R_6}{R_{i1}} \frac{i_{e8}}{i_i}$$

$$\frac{i_{e8}}{i_i} = \frac{i_{e8}}{i_{b8}} \times \frac{i_{b8}}{i_{c7}} \times \frac{i_{c7}}{i_{b7}} \times \frac{i_{b7}}{i_{c5}} \times \frac{i_{c5}}{i_{b5}} \times \frac{i_{b5}}{i_{c2}} \times \frac{i_{c2}}{i_i}$$

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