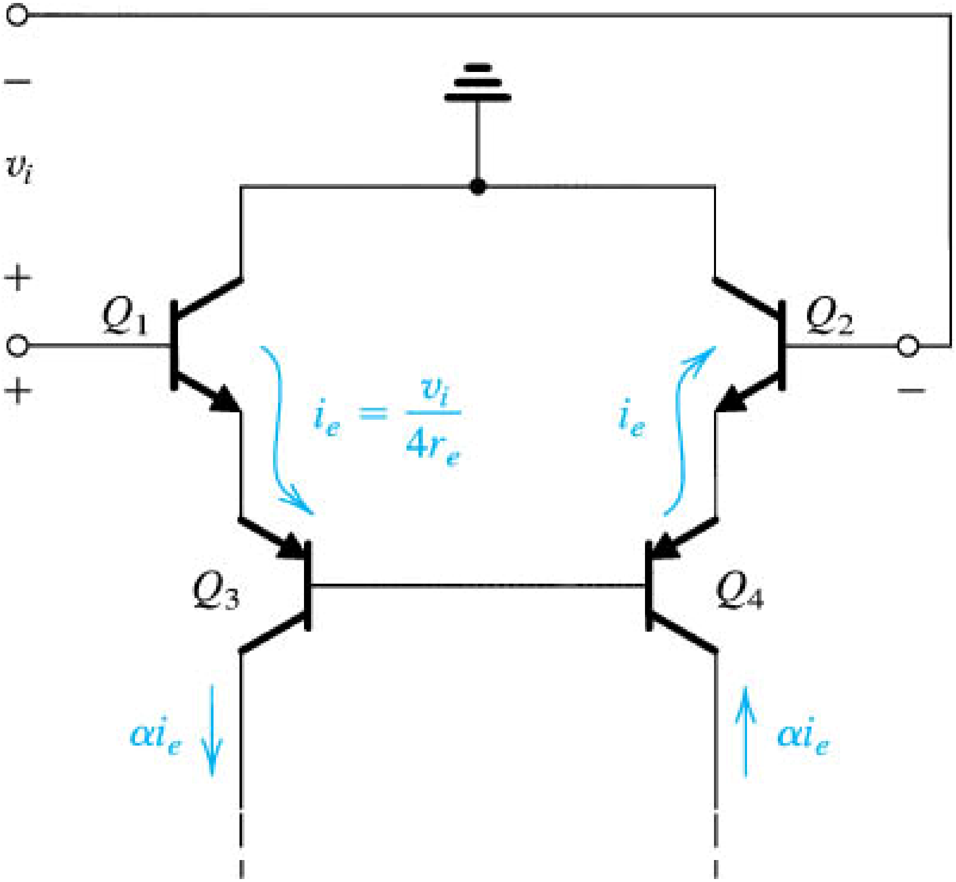
Small-Signal Analysis of the 741

We can analyze the small-signal voltage gain of the 741 op-amp by dividing it into its basic circuits and using results previously obtained in the DC analysis.

The Input Stage



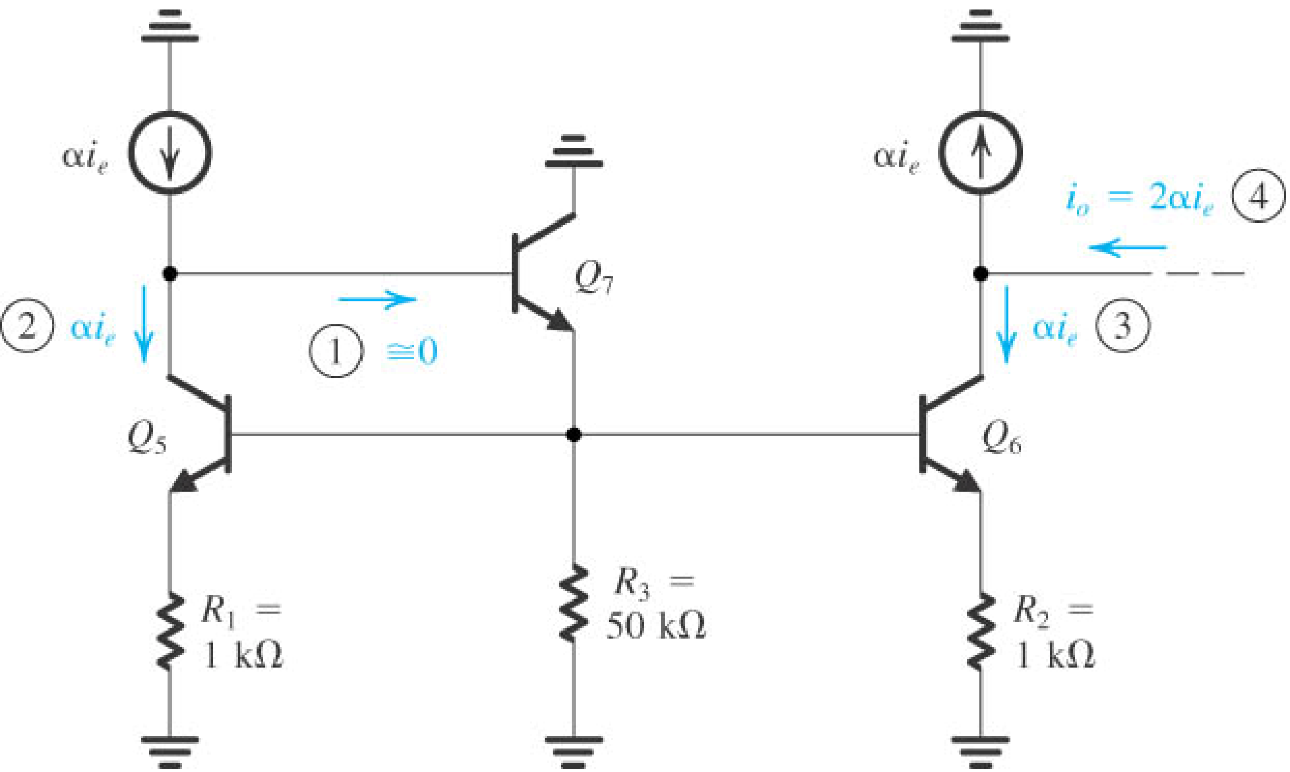
$$i_e = \frac{v_i}{4r_e}$$

$$r_e = \frac{V_T}{I} = \frac{25\,\text{mV}}{9.5\,\mu\text{A}} = 2.63\,\text{k}\Omega$$

$$R_{id} = 4(\beta_N + 1)r_e$$

For $\beta_\text{N} = 200,\ R_{id} = 2.1\,\text{M}\Omega$

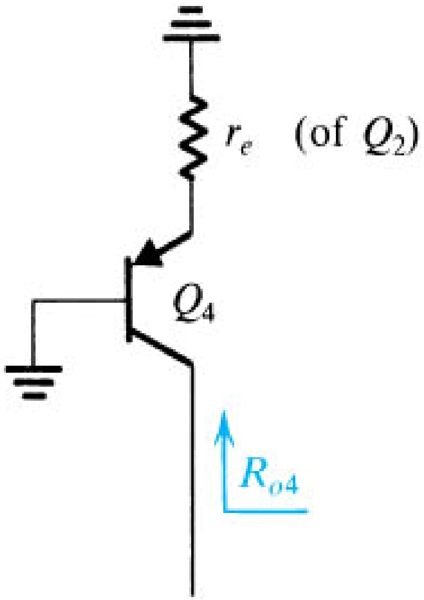
The load circuit of the input stage



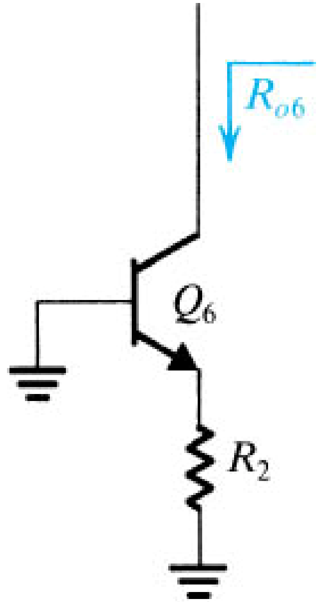
$$i_o = 2\alpha i_e$$

$$G_{m1} = \frac{i_o}{v_i} = \frac{\alpha}{2r_e}$$

Finding R_{o5} and R_{o6}



(a)



(b)

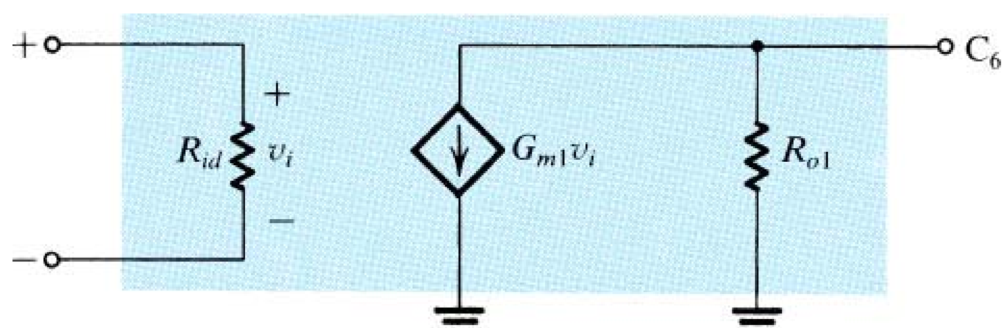
$$R_o = r_o[1 + g_m(R_E // r_\pi)$$

$$R_E = r_e = 2.63\ \text{k}\Omega$$

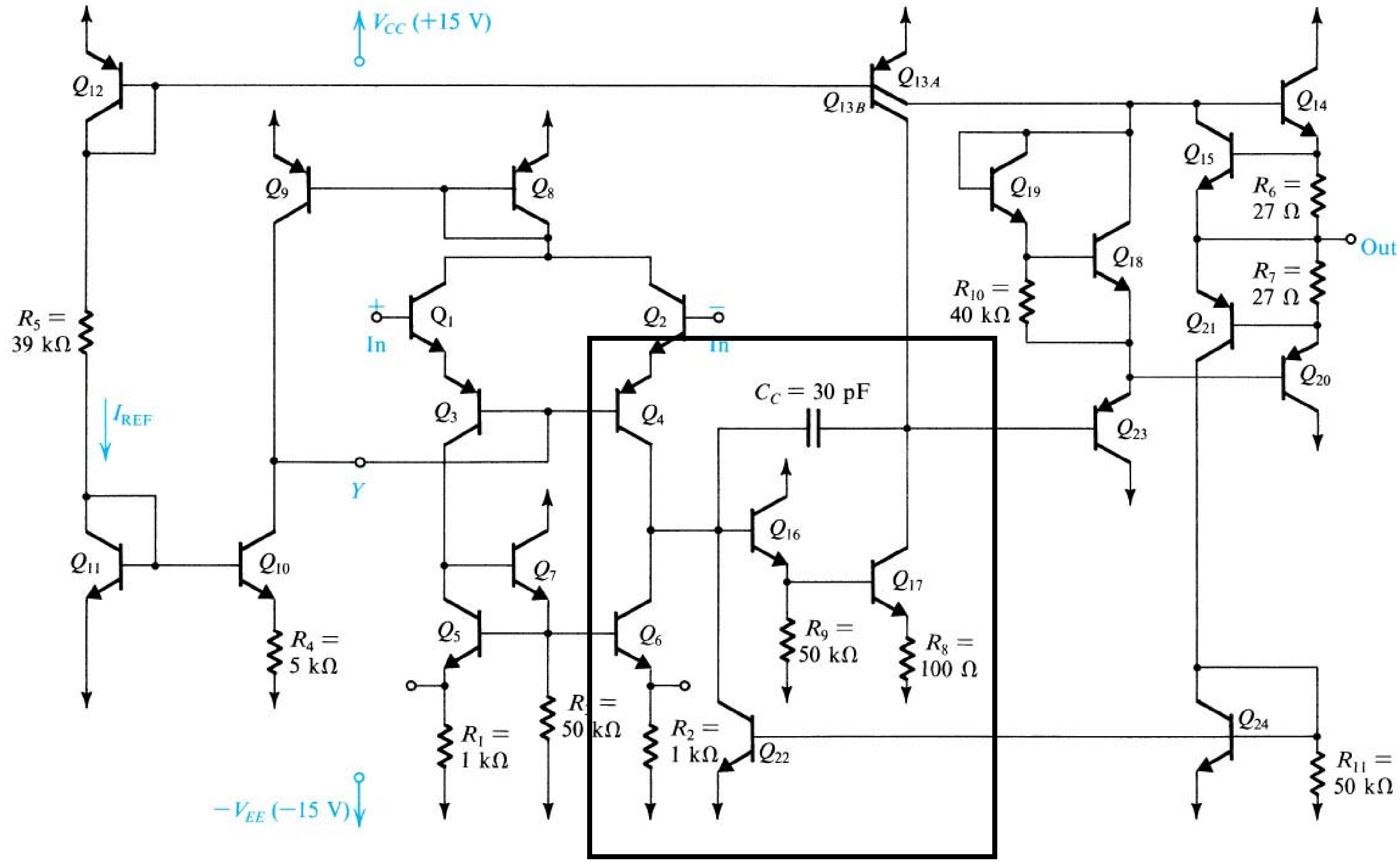
$$r_o = V_A / I;\ V_A = 50\ \text{V};\ I = 9.5\ \mu\text{A}$$

$$R_{o4} = 10.5\ \text{M}\Omega;\ \ R_{06} = 18.2\ \text{M}\Omega$$

$$R_{o4} // R_{o6} = R_{o1} = 6.7\ \text{M}\Omega$$



Example: Determine the small-signal differential voltage gain of the 741 op-amp input stage. Assume transistor gain of β = 200 and Early voltages of V_A = 50 V.



$$A_d = -g_m(r_{o4} \,//\, R_{ac1} \,//\, R_{i2}) = \frac{I_{CQ}}{V_T}(r_{o4} \,//\, R_{ac1} \,//\, R_{i2})$$

$$R_{act1} = r_{o6}[1 + g_{m6}(R_2 \,//\, r_{\pi 6}]$$

$$R_{i2} = r_{\pi 16} + (\beta + 1)R_E$$

$$R_E = R_9 \,//[r_{\pi 17} + (\beta + 1)R_8]$$

$$r_{\pi 17} = \frac{\beta V_T}{I_{C17}} = \frac{200 \times 0.026}{0.54} = 9.63\ \mathrm{k\Omega}$$

$$R_E = 50 \,//[9.63 + (201)(0.1)] = 18.6\ \mathrm{k\Omega}$$

$$r_{\pi 16} = \frac{\beta V_T}{I_{C16}} = \frac{200 \times 0.026}{0.0158} = 329\ \mathrm{k\Omega}$$

$$R_{i2} = 329 + (201)(18.6) = 4.07\ \mathrm{M\Omega}$$

$$r_{\pi 6} = \frac{\beta V_T}{I_{C6}} = \frac{200 \times 0.026}{0.0095} = 547\ \mathrm{k\Omega}$$

$$g_{m6} = \frac{I_{C6}}{V_T} = \frac{0.0095}{0.026} = 0.365\ \mathrm{mA/V}$$

$$r_{o6} = \frac{V_A}{I_{C6}} = \frac{50}{0.0095} = 5.26\ \mathrm{M\Omega}$$

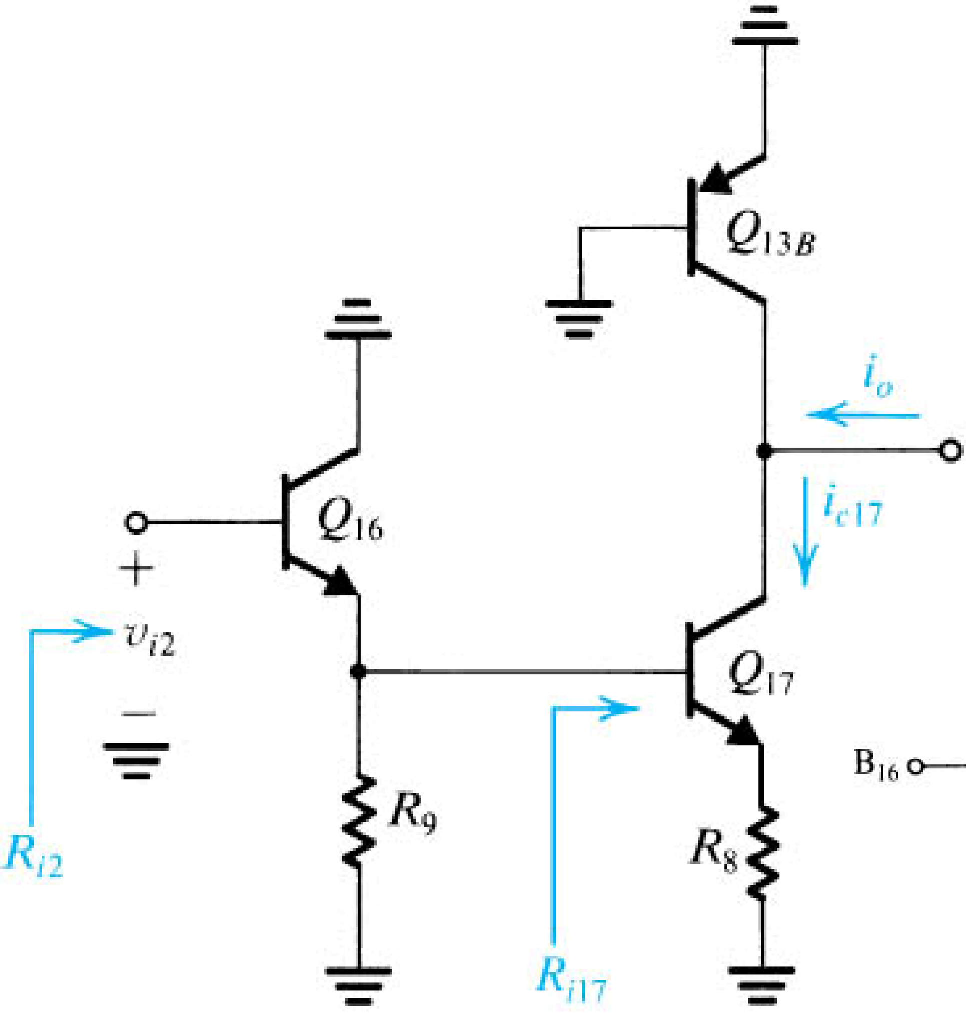
$$R_{act1} = 5.26[1 + 0.365(1//547)] = 7.18\ \mathrm{M\Omega}$$

$$r_{o4} = \frac{V_A}{I_{C4}} = \frac{50}{0.0095} = 5.26\ \mathrm{M\Omega}$$

$$A_d = -(\frac{9.5}{0.026})(5.26 // 7.18 // 4.07) = -636$$

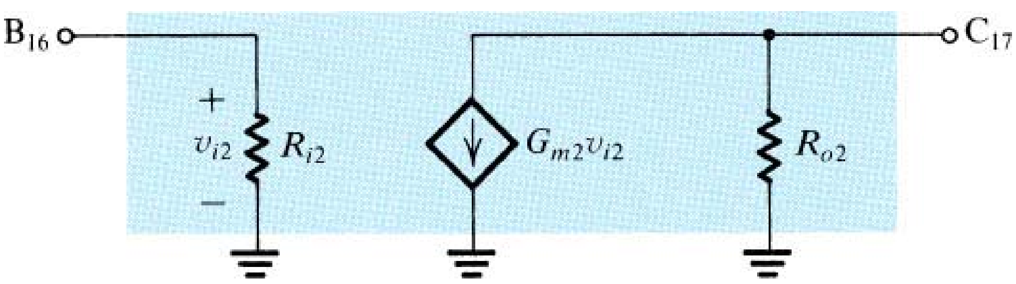
The Gain (Second) Stage

$$R_{i2} = (\beta_{16} + 1)[r_{e16} + R_9 // (\beta_{17} + 1)(r_{e17} + R_8)]$$



$$R_{o2} = (R_{o13B} // R_{o17}) = 81\,\text{k}\Omega$$

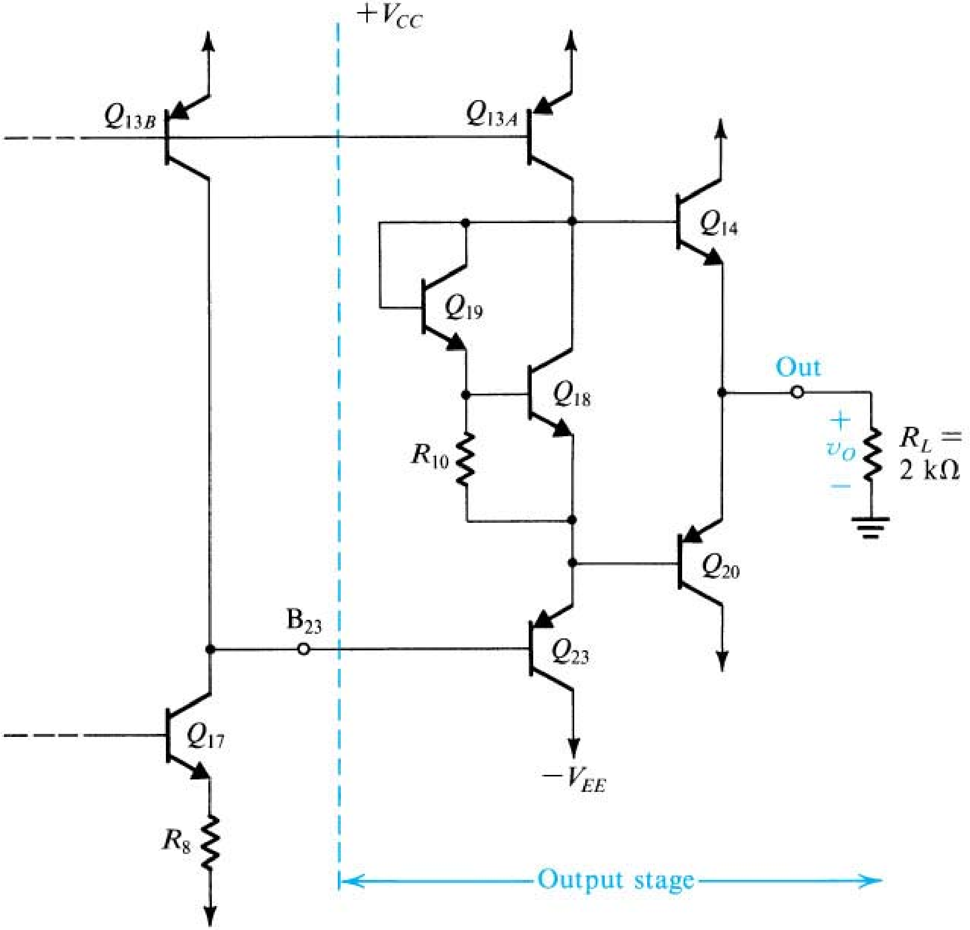
$$R_{o13B} = r_{o13B}$$

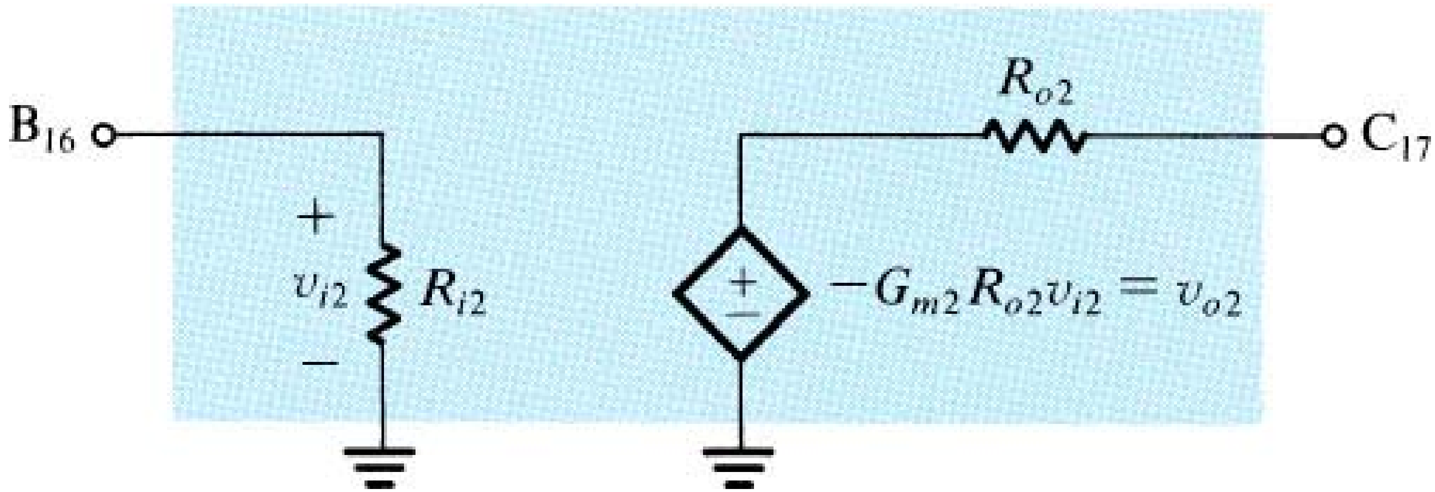


The Output Stage

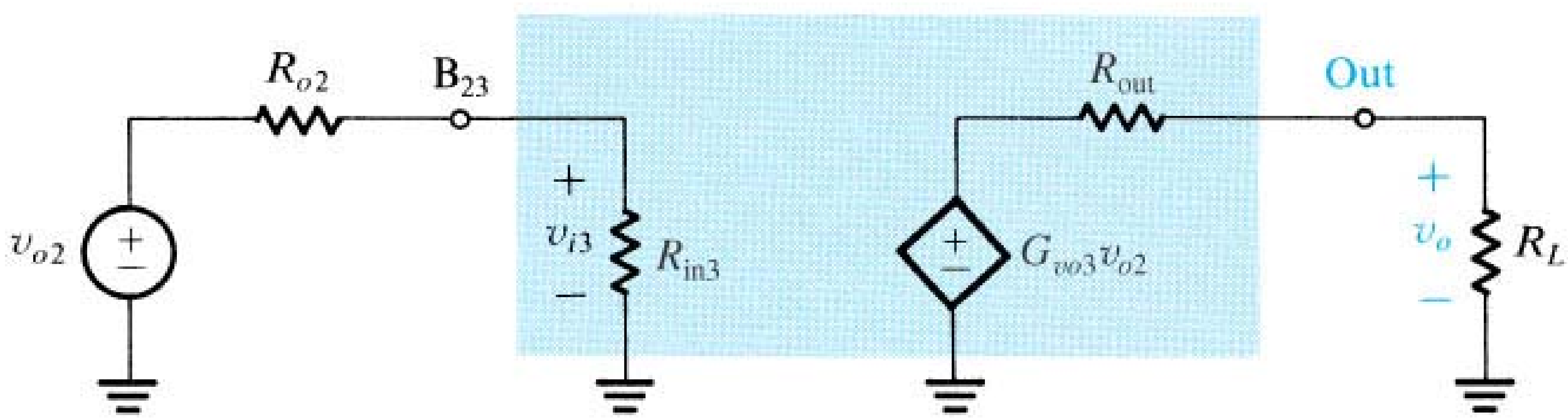
$$v_{o\,\max} = V_C C - V_{CE\mathrm{sat}} - V_{BE14}$$

$$v_{o\,\min} = -V_{EE} + V_{CE\mathrm{sat}} + V_{EB23} + V_{EB20}$$



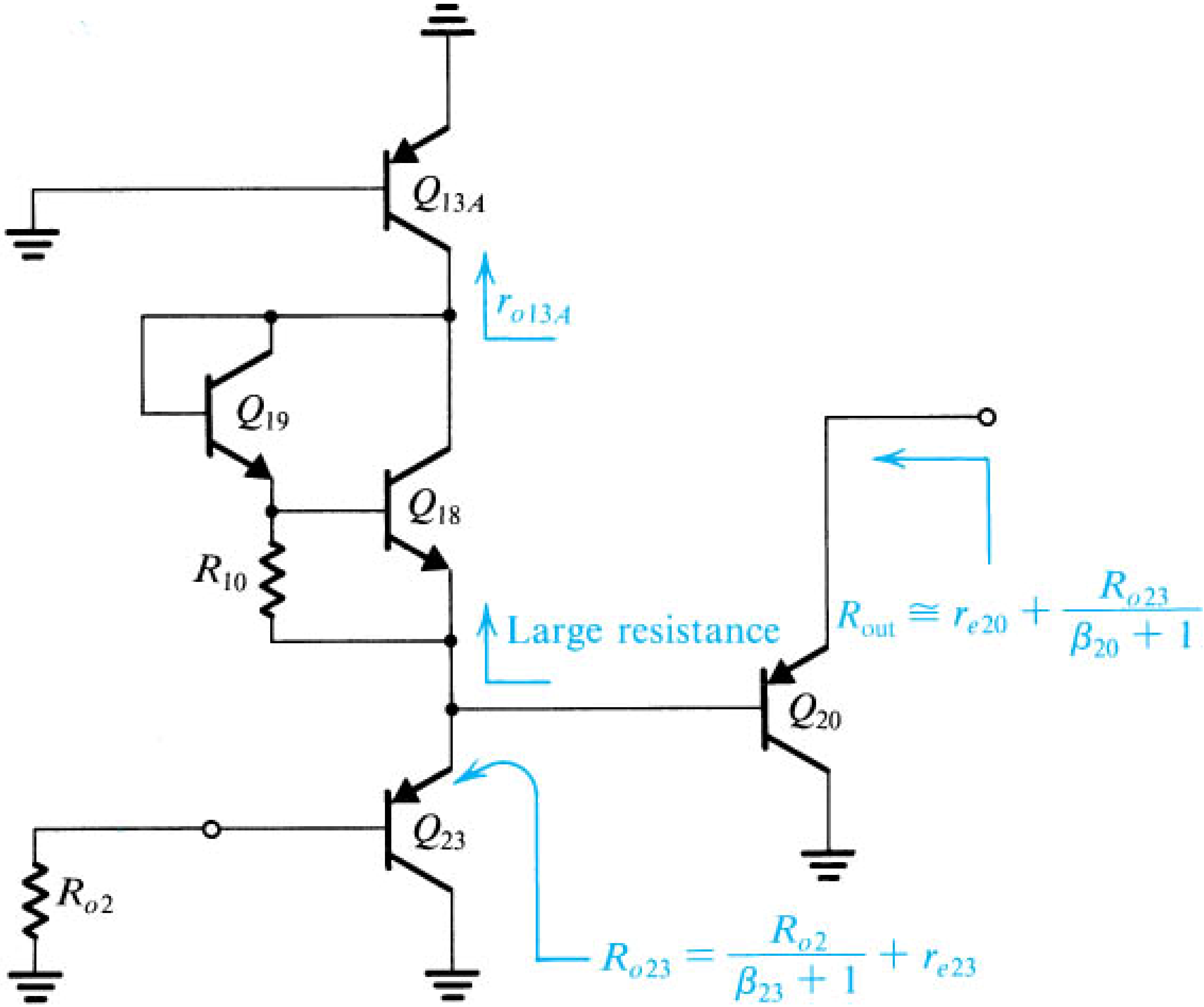


B_{16}
R_{o2}
C_{17}
+
v_{i2}
−
R_{i2}
$-G_{m2}R_{o2}v_{i2} = v_{o2}$

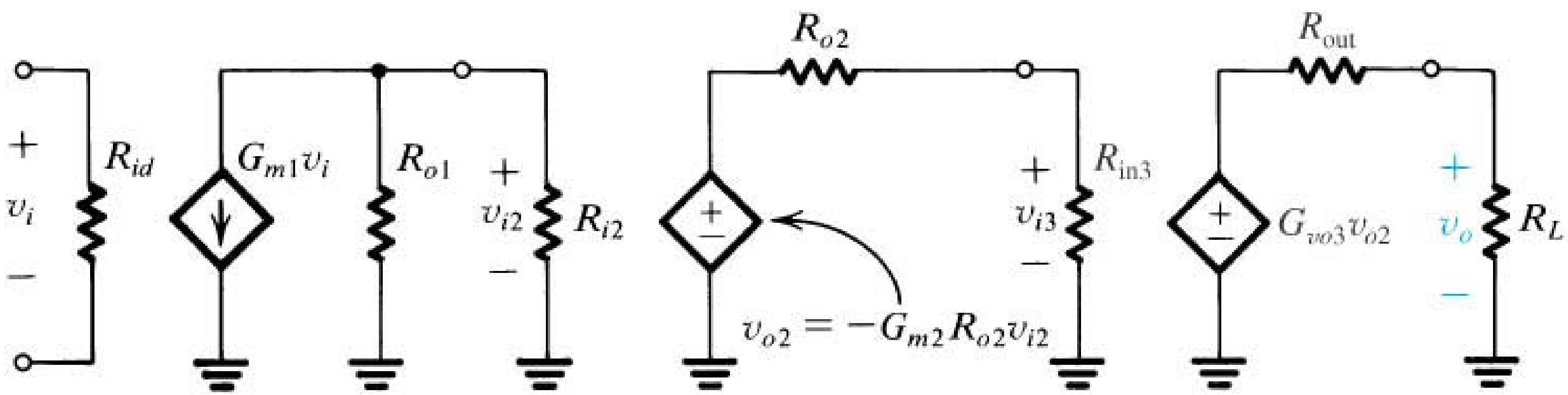


R_{o2}
B_{23}
R_{out}
Out
v_{o2}
+
v_{i3}
−
R_{in3}
$G_{vo3}v_{o2}$
+
v_o
−
R_L

Circuit for Finding the Output Resistance R_{out}



Gain, Frequency Response, and Slew Rate of the 741



$$\frac{v_o}{v_i} = \frac{v_{i2}}{v_i}\frac{v_{o2}}{v_{i2}}\frac{v_o}{v_{o2}}$$

$$-G_{m1}(R_{o1} // R_{12})(-G_{m2}R_{o2})G_{vo3}\frac{R_L}{R_L + R_{out}}$$

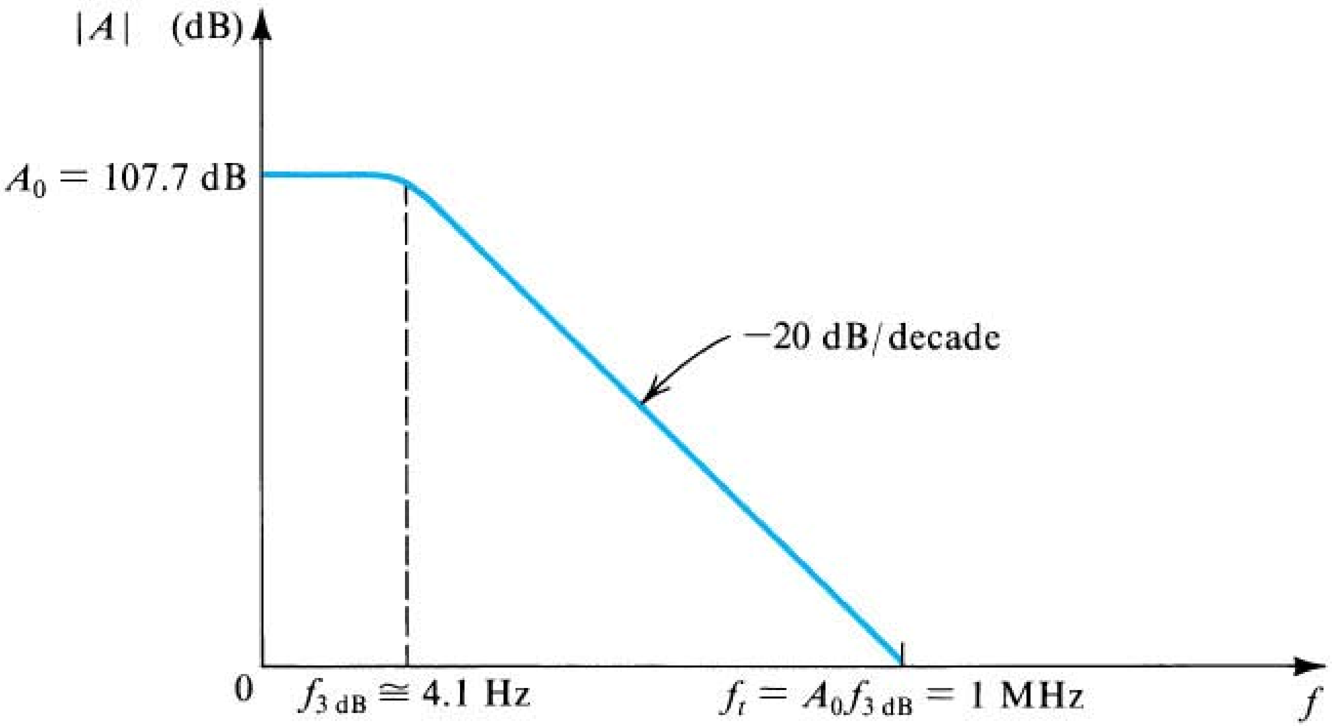
$$A_o = 243147 \text{ V/V}$$

Frequency Response

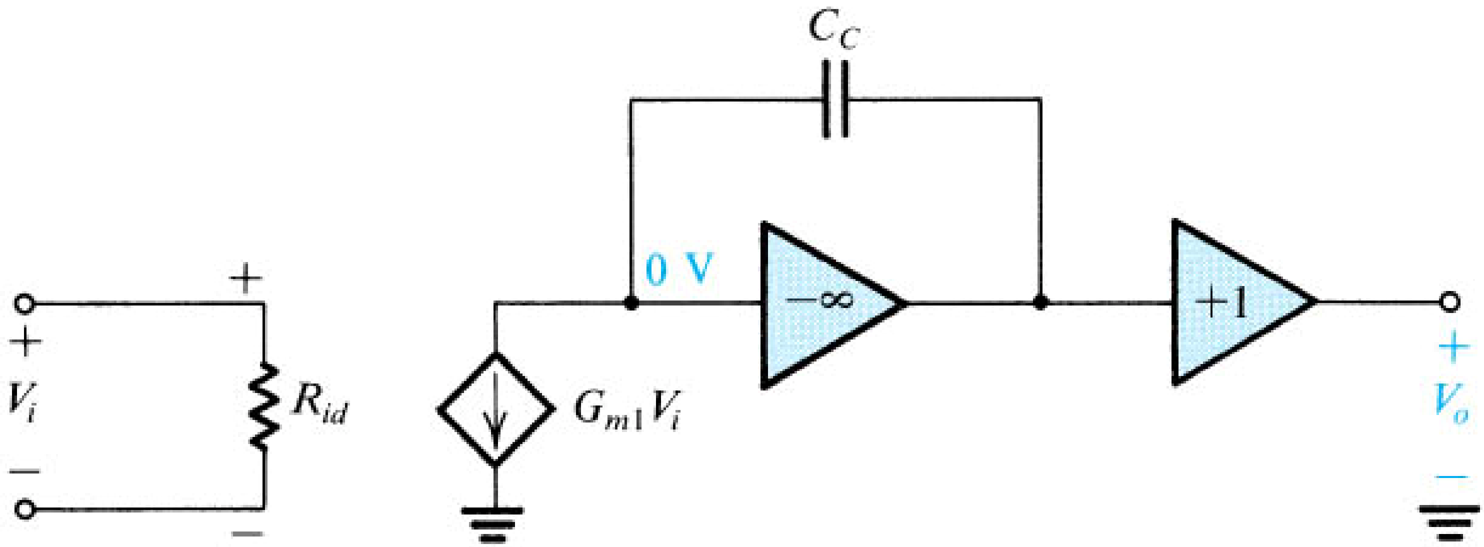
$$C_{in} = C_C(1+|A_2|)$$

$$R_t = (R_{o1} // R_{i2}) = (6.7\ \mathrm{M\Omega} // 4\ \mathrm{M\Omega}) = 2.5\ \mathrm{M\Omega}$$

$$f_p = \frac{1}{2\pi C_{in} R_t} = 4.1\ \mathrm{Hz}$$



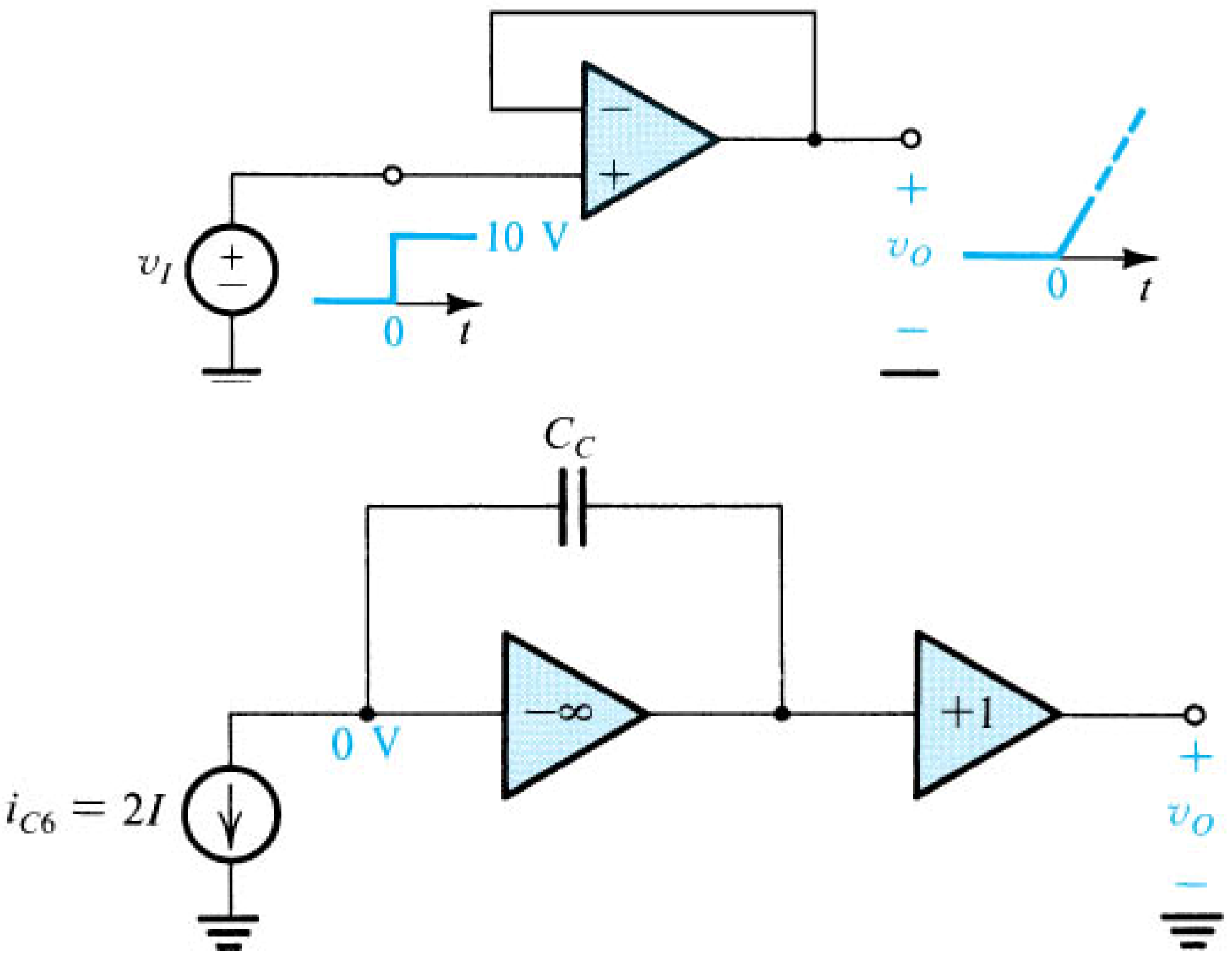
A Simple Model of the 741



$$A(s) = \frac{V_o(s)}{V_i(s)} = \frac{G_{m1}}{sC_C}$$

$$A(j\omega) = \frac{G_{m1}}{j\omega C_C}; \omega t = \frac{G_{m1}}{C_C}$$

Slew Rate



$$v_O(t) = \frac{2I}{C_C} t$$

$$SR = \frac{2I}{C_C}$$