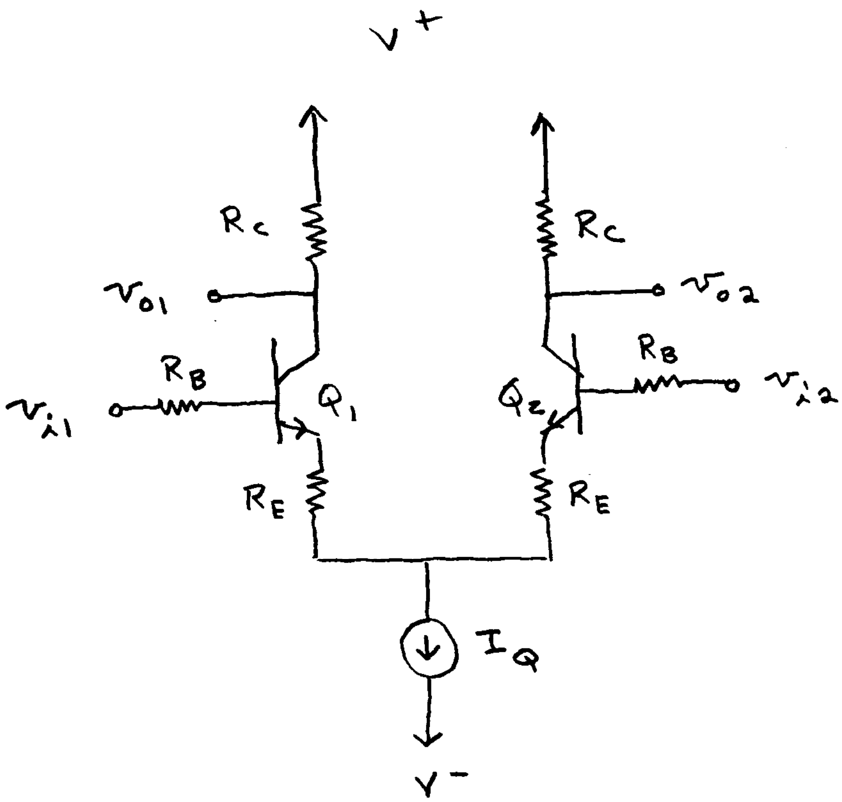
The BJT Differential Amplifier



For the dc bias solution, set $v_{i1} = v_{i2} = 0$. If the BJTs are identical, I_Q splits equally between Q_1 and Q_2.

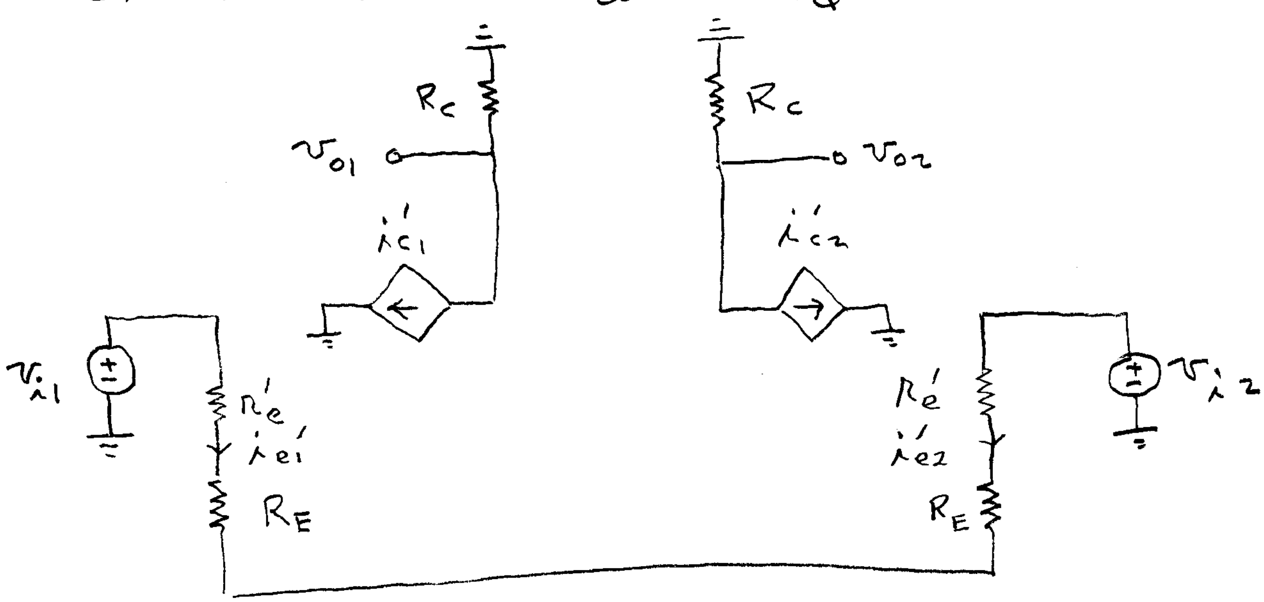
$$\Rightarrow \quad I_{E1} = I_{E2} = \frac{1}{2} I_Q$$

$$I_{C1} = I_{C2} = \frac{\alpha}{2} I_Q$$

For the BJTs to be in the active mode, V_{CB} must be positive. It is given by

$$V_{CB} = V_C - V_B$$
$$= (V^+ - I_C R_C) - (-I_B R_B)$$
$$= V^+ - \frac{\alpha}{2} I_Q R_C + \frac{I_Q}{1+\beta} R_B$$

For the ac small-signal analysis, we use the simplified T model. Because neither end of r_o is at signal ground, we omit it to obtain an approximate analysis. Set $V^+ = V^- = 0$ and $I_Q = 0$.



$$v_{o1} = -i'_{c1} R_c \qquad v_{o2} = -i'_{c2} R_c$$

$$i'_{c1} = \alpha\, i'_{e1} \qquad i'_{c2} = \alpha\, i'_{e2}$$

$$i'_{e1} = \frac{v_{i1} - v_{i2}}{2(r'_e + R_E)} \qquad i'_{e2} = -i'_{e1}$$

$$\Rightarrow \quad v_{o1} = -\frac{\alpha R_C}{2(r'_e + R_E)}(v_{i1} - v_{i2})$$

$$v_{o2} = -v_{o1}$$

$$r'_e = \frac{R_B}{1+\beta} + r_e = \frac{R_B}{1+\beta} + \frac{V_T}{I_E}$$

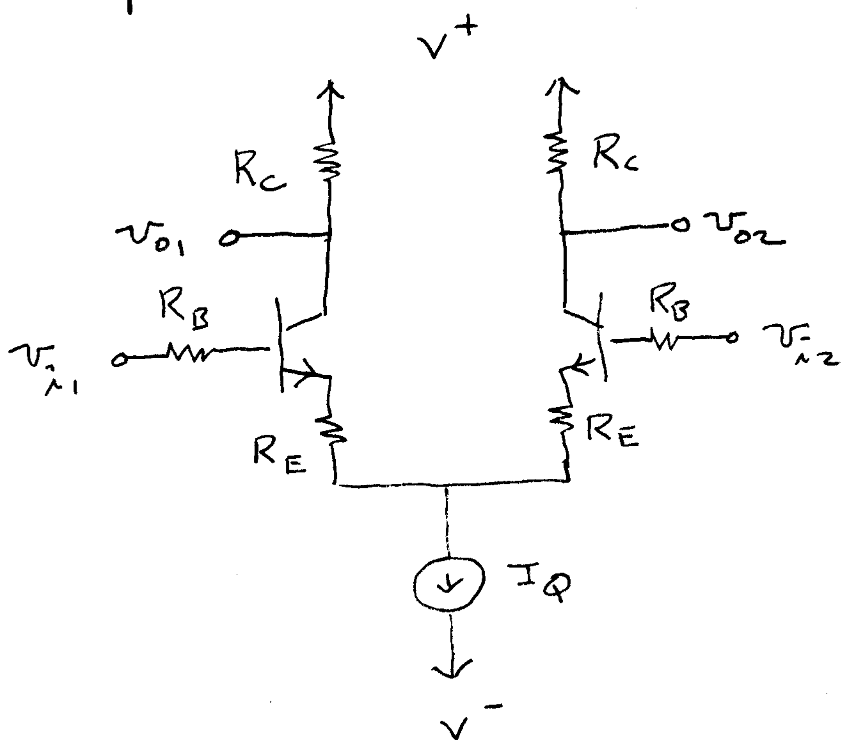
Thus we see that the output voltages are proportional to the difference between the two input voltage.

The differential output voltage is given by

$$v_o = v_{o1} - v_{o2}$$

$$= -\frac{\alpha R_c}{r'_e + R_E}(v_{i1} - v_{i2})$$

Example



$V^+ = +15\,V \quad V^- = -15\,V \quad I_Q = 2\,mA$

$R_C = 7.5\,K\Omega \quad R_B = 100\,\Omega \quad R_E = 50\,\Omega$

$\beta = 99 \quad \alpha = 0.99 \quad V_T = 25\,mV$

$$I_{E1} = I_{E2} = \frac{1}{2} I_Q = 1\,mA$$

$$r_e = \frac{V_T}{I_E} = 25\,\Omega$$

$$r_e' = \frac{R_B}{1+\beta} + r_e = 26\,\Omega$$

$$v_{o1} = -\frac{\alpha R_C}{2(r_e' + R_E)}(v_{i1} - v_{i2})$$

$$= -48.85\,(v_{i1} - v_{i2})$$

$$v_{o2} = -v_{o1} = +48.85\,(v_{i1} - v_{i2})$$

Differential output

$$v_o = v_{o1} - v_{o2} = -97.70\,(v_{i1} - v_{i2})$$

Method of Symmetrical Components

Another method of analyzing the diff amp is to use superposition of differential and common-mode components.

Let $v_{i1} = \frac{1}{2} v_{id} + v_{icm}$

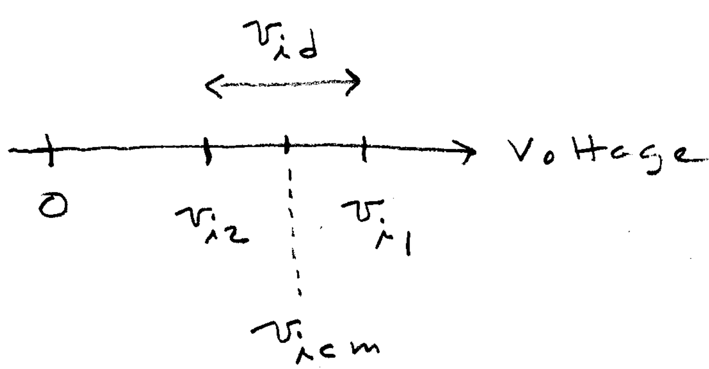
$$v_{i2} = -\frac{1}{2} v_{id} + v_{icm}$$

where v_{id} is the differential input signal and v_{icm} is the common-mode input signal. These are given by

$$v_{id} = v_{i1} - v_{i2}$$

$$v_{icm} = \frac{1}{2}(v_{i1} + v_{i2})$$

Graphical interpretation for $v_{i1} > v_{i2}$

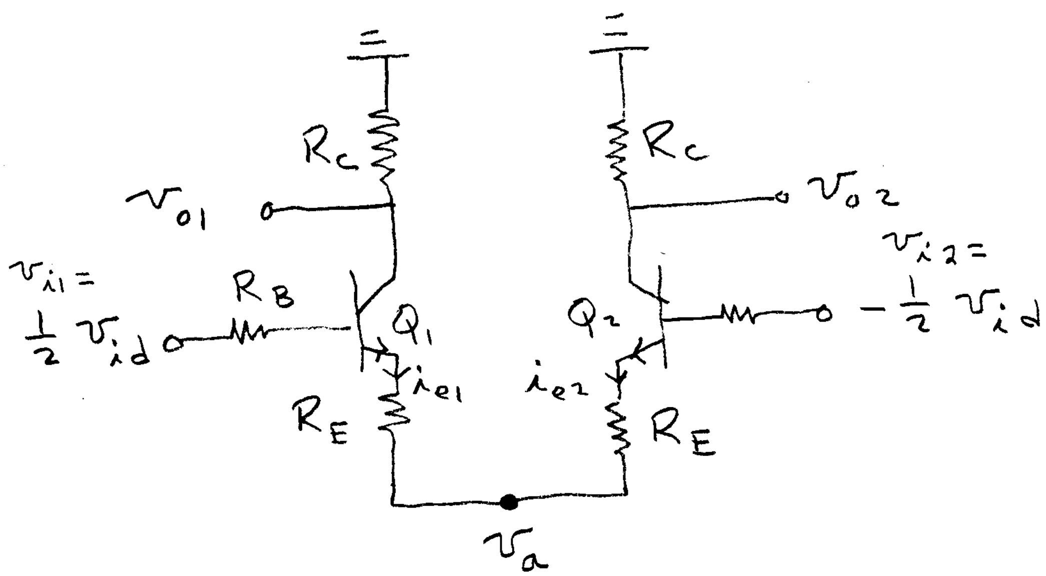


We can use superposition of v_{id} and v_{icm} to solve for v_{o1} and v_{o2}.

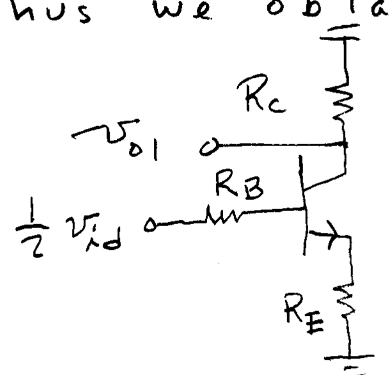
First let $v_{icm} = 0$

$\Rightarrow \quad v_{i1} = \frac{1}{2} v_{id} \qquad v_{i2} = -\frac{1}{2} v_{id}$

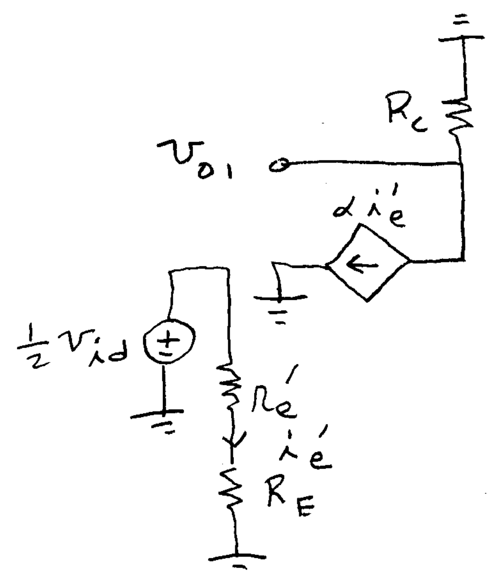
The ac signal circuit is



v_{i1} forces v_a to increase while v_{i2} forces v_a to decrease. The net effect is $v_a = 0$. Thus we obtain the equivalent circuit.



The simplified T model is



$$i_e' = \frac{1}{2} v_{id} \frac{1}{r_e' + R_E}$$

$$v_{o1} = -\alpha i_e' R_C$$

$$= -\frac{\alpha R_C}{2(r_e' + R_E)} (v_{i1} - v_{i2})$$

This is the same answer.
By symmetry $v_{o1} = -v_{o2}$
Now, let $v_{i1} = v_{i2} = v_{icm}$. By symmetry $i_{e1} = i_{e2}$. But by KCL $i_{e1} + i_{e2} = 0 \Rightarrow i_{e1} = i_{e2} = 0$. There is no output voltage due to v_{icm}.

Now suppose $R_E = 0$. Because $v_a = 0$ for the differential inputs, one side of r_o is grounded for both Q_1 and Q_2. In this case, r_o combines in parallel with R_C and we have

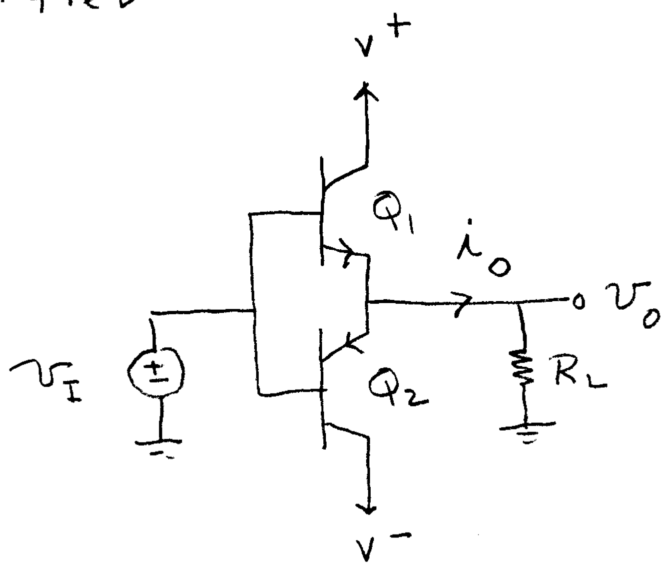
$$v_{o1} = -\frac{\alpha(r_0 \| R_C)}{r_e'}(v_{i1} - v_{i2})$$

$$= -\frac{\alpha(r_0 \| R_C)}{\frac{R_B}{1+\beta} + r_e}(v_{i1} - v_{i2})$$

$$v_{o2} = -v_{o1}$$

These are the same solutions obtained from the original circuit. The common-mode solution is zero because there is no resistor from the v_a node to ground. If such a resistor is present, the differential solution does not change but the common-mode solution is no longer zero.

The Complementary Common-Collector Amplifier

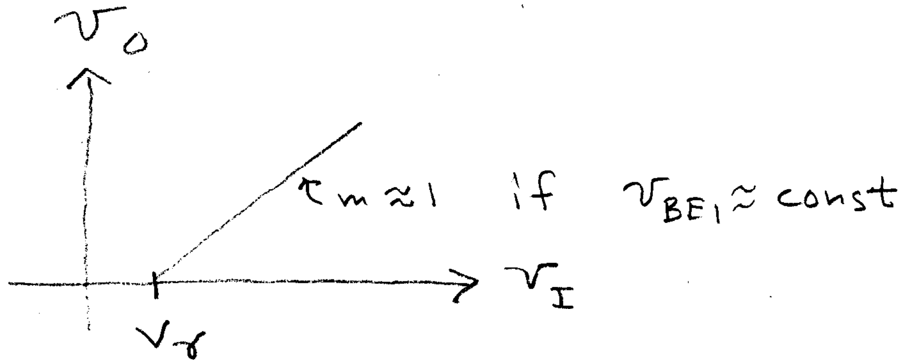


This stage is commonly used as the output stage in an op amp. It acts as a buffer stage. Q_1 supplies positive i_O and Q_2 supplies negative i_O.

For $-V_\gamma < v_I < +V_\gamma$, both Q_1 and Q_2 are cut off. In this case $v_O = 0$. For $v_I > V_\gamma$, Q_1 cuts on and Q_2 remains off. The output voltage is given by

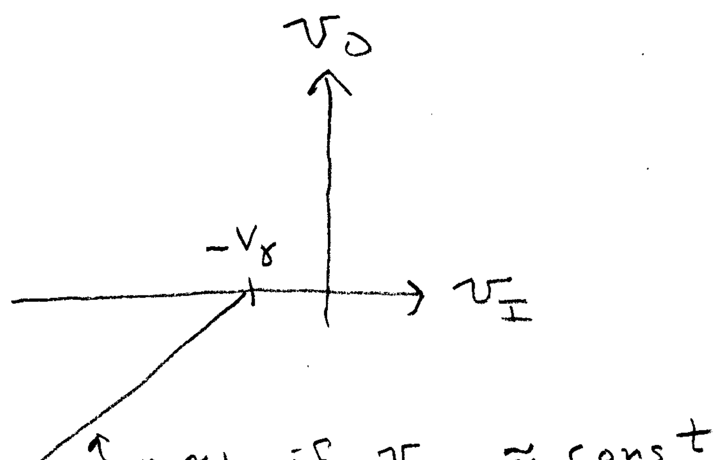
$$v_O = v_I - v_{BE1}$$

If we assume $v_{BE1} \approx$ constant, the plot of v_O versus v_I is

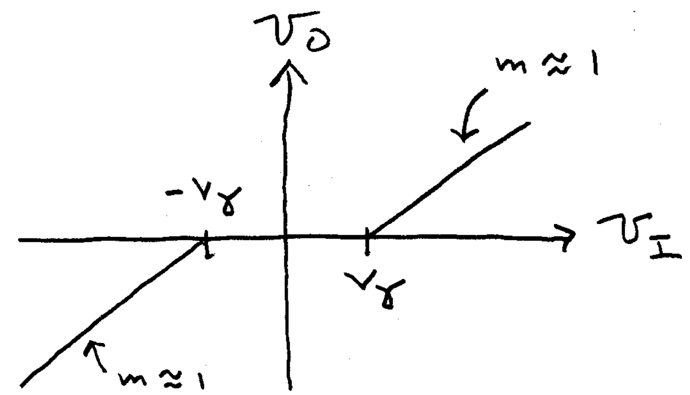


Now, for $v_I < -V_\gamma$, Q_2 cuts on and Q_1 remains off. In this case

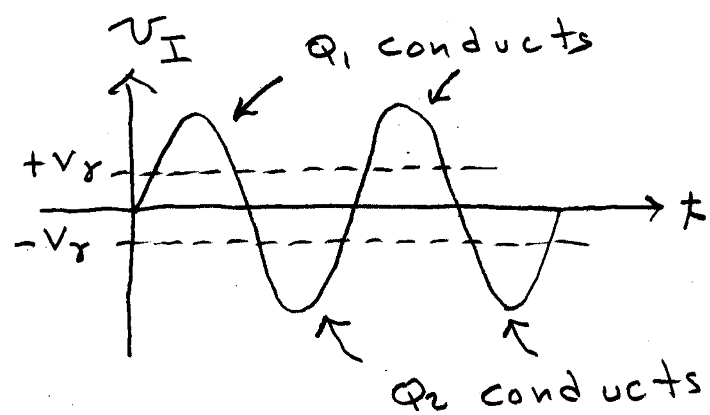
$$v_O = v_I + v_{EB2}$$



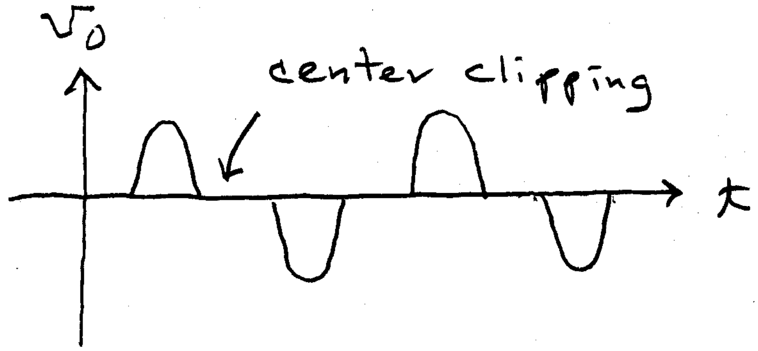
Putting the two curves together, we get



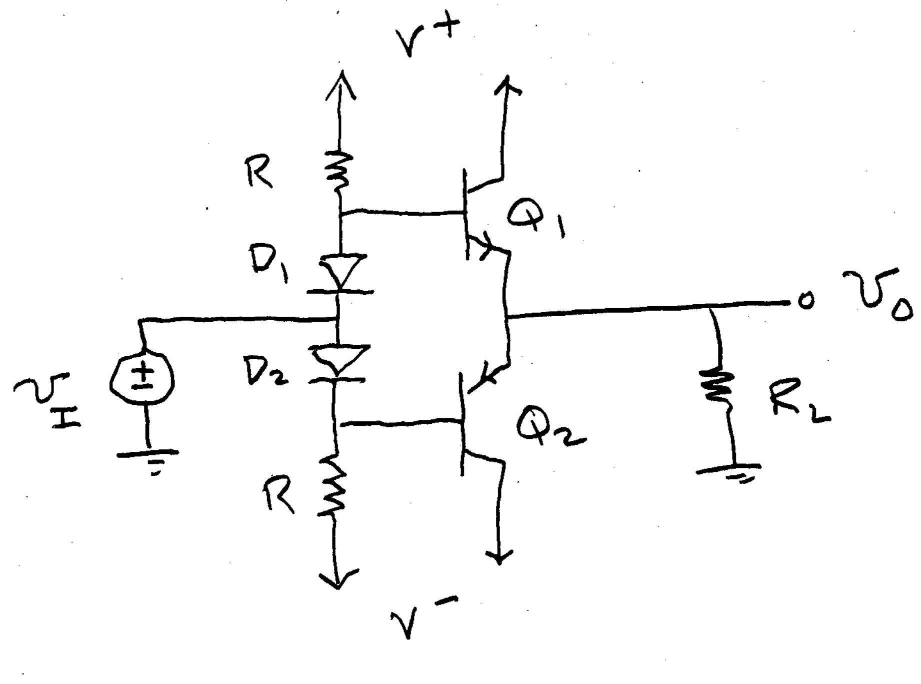
Now, suppose v_I is a sine wave.



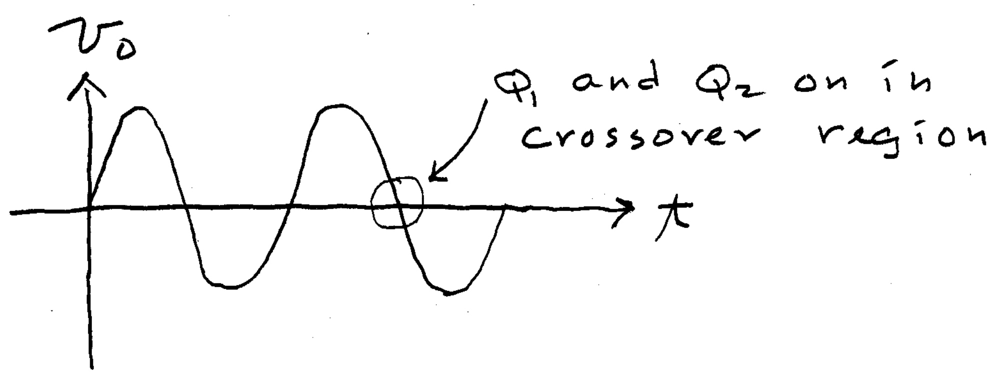
The output voltage appears as follows:



To minimize the center clipping, Q_1 and Q_2 must be biased on when $v_I = 0$. A possible circuit is



The resistors supply current to D_1 and D_2. The voltages across the diodes turn Q_1 and Q_2 on when $v_I = 0$. Thus the graph for v_O becomes



The ac small signal gain of the circuit is less than but close to unity. It is often approximated by unity.