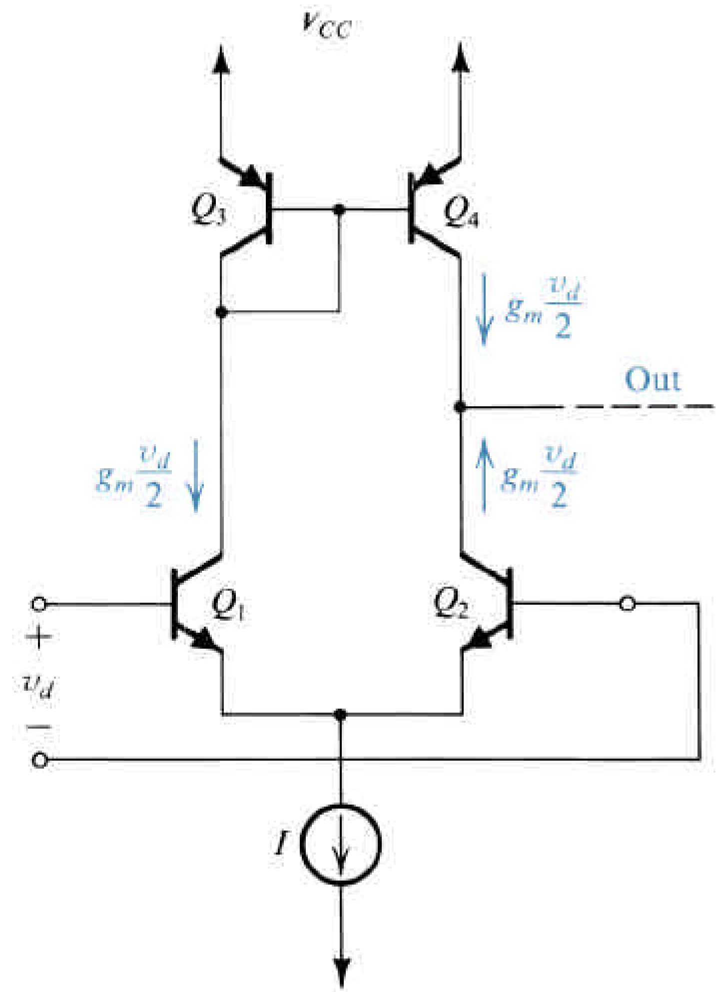
The BJT differential AMP with an active load

- Many IC amplifiers use BJT loads in place of the load resistance, R_C.
- BJT load resistor is usually connected as a constant-current source with a very high resistance load (output resistance of the current source)
- Higher load resistance, higher output gain.



Left figure shows an AMP with active load (consisting of Q3 and Q4).

- Q3 and Q4 are connected in a current mirror configuration.
- If no input signal is applied, that is, both bases are grounded. I is split into equal between Q1 and Q2.
- Assume $\beta >> 1$, the mirror supplies an equal current I/2 through the collector of Q4.
- Since this current is equal to the current through Q2, no output current flows through the output terminal.
- When a differential signal v_d is applied, current signal $g_m(v_d/2)$ will result in the collectors Q1 and Q2.
- The mirror supplies generate the same current $g_m(v_d/2)$ through the collector of Q4.
- The overall current at the output terminal is $g_m v_d$.
- The output voltage is $v_0 = g_m v_d R_o$, where R_o is the output resistance of the AMP.
- R_o is the parallel of output resistances of Q2 and Q4:

$$R_o = r_{o2} // r_{o4}$$

In case $r_{o2} = r_{o4} = r_o$, we have

$$R_o = r_0 / 2$$

The output voltage: $v_0 = g_m v_d \left(r_o / 2 \right)$

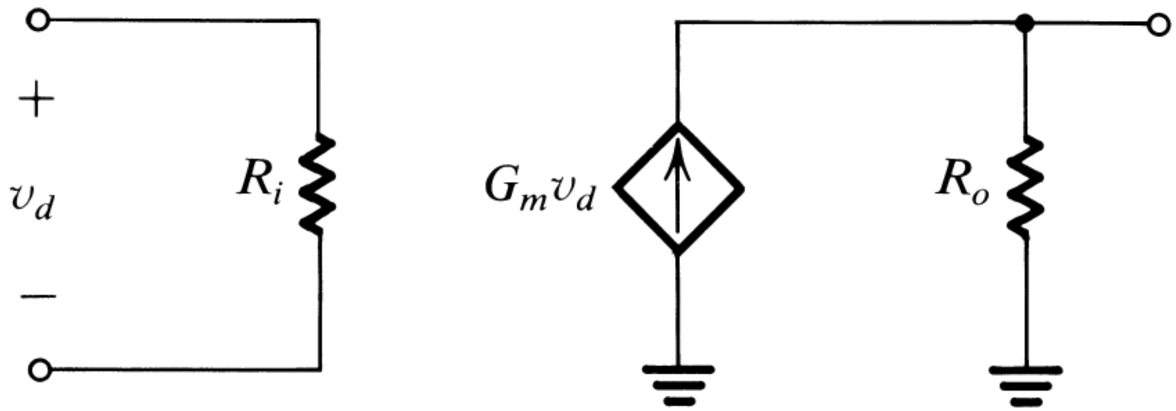
The voltage gain: $A_d = \frac{v_0}{v_d} = g_m \left(r_o / 2 \right)$

Considering $g_m = I_C / V_T$, and $r_0 = \frac{V_A}{I_C}$, we have

$$A_d = \frac{V_A}{2V_T}$$

In some cases the input resistance of the subsequent amplifier stage may be of the same order as R_o and must be taken into account in determining voltage gain.

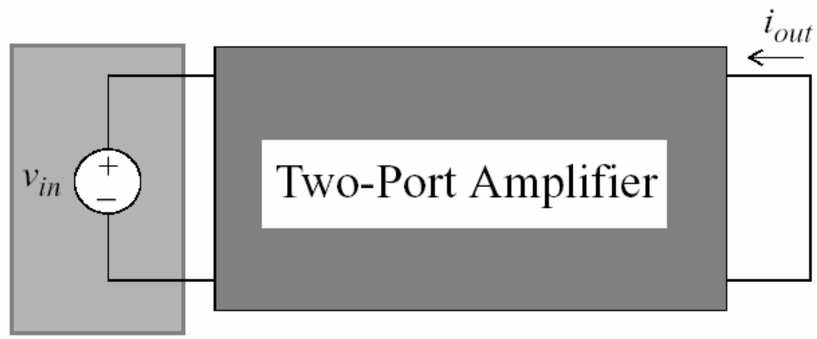
In such situations, the amplifier with active load may be represented by the transconductance amplifier model shown below:



Here $R_i = 2r_\pi$ is differential input resistance. The amplifier transconductance G_m is the short-circuit transconductance,

$$G_m = g_m = \frac{I/2}{V_T}$$

Short-circuit the input resistance ($R_S = 0\ \Omega$) and short-circuit the output port ($R_L = 0\ \Omega$) to find the transconductance G_m:



$$G_m = \left.\frac{i_{out}}{v_{in}}\right|_{R_S = 0,\ R_L = 0}$$

Example: if $V_A = 100V$ and $V_T = 25mV$, we have

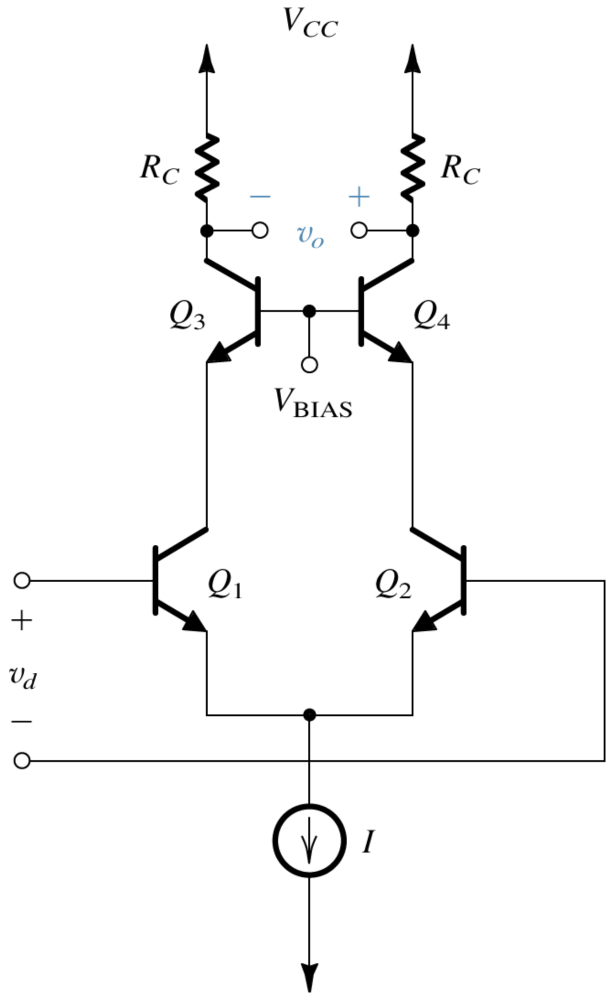
$$A_d = \frac{V_A}{2V_T} = \frac{100V}{2 \times 25mV} = 2000\ V/V$$

The gain is much higher than differential amplifiers using a resistor load.

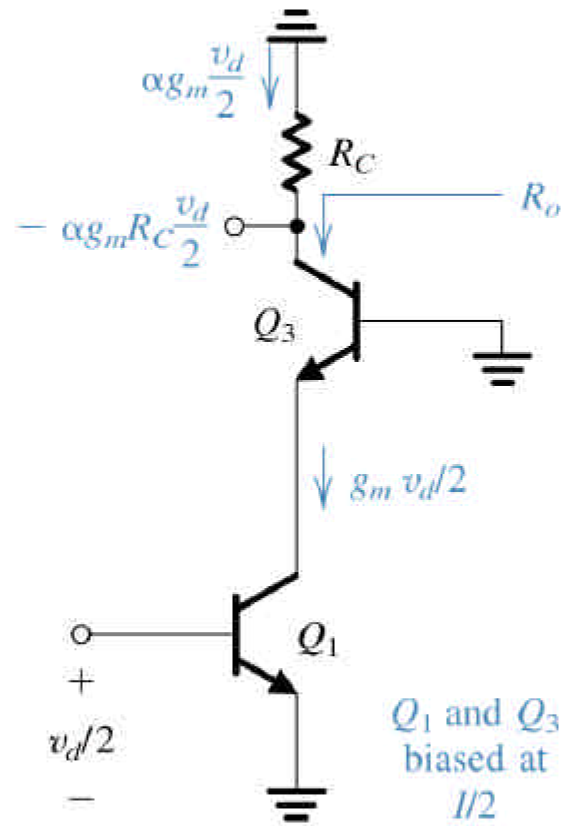
The Cascode Configuration

Cascode configuration: a common emitter (CE) stage followed by a common base (CB) stage.

- Q1 and Q2 form a basic differential AMP.



(a)



(b)

- Q3 and Q4 form a differential common-base stage.

- The differential half-circuit is shown in (b). The load resistance seen by CE transistor Q1 is no longer Rc, but is the much lower input resistance of the CB transistor, namely r_e (reduction of the effective load resistance of Q1 will lead to a tremendous improvement in the AMP frequency response.)

- The function of the CB stage acts as a current buffer; it accepts a current $g_m(v_d/2)$ from Q2 at a low input resistance (r_e) and delivers almost equal current $\alpha g_m(v_d/2)$ to the load at a very high output resistance R_o.

- The high output resistance constitutes the 2nd important feature of the cascode configuration.

- Q3 has an emitter resistance equal to r_0 of Q1.

- Using the output resistance equation for the Wilson current mirror, we have

$$R_0 = (1 + g_{m3} R'_E) r_{03} \approx (1 + g_{m3} r_{\pi 3}) r_{03}$$

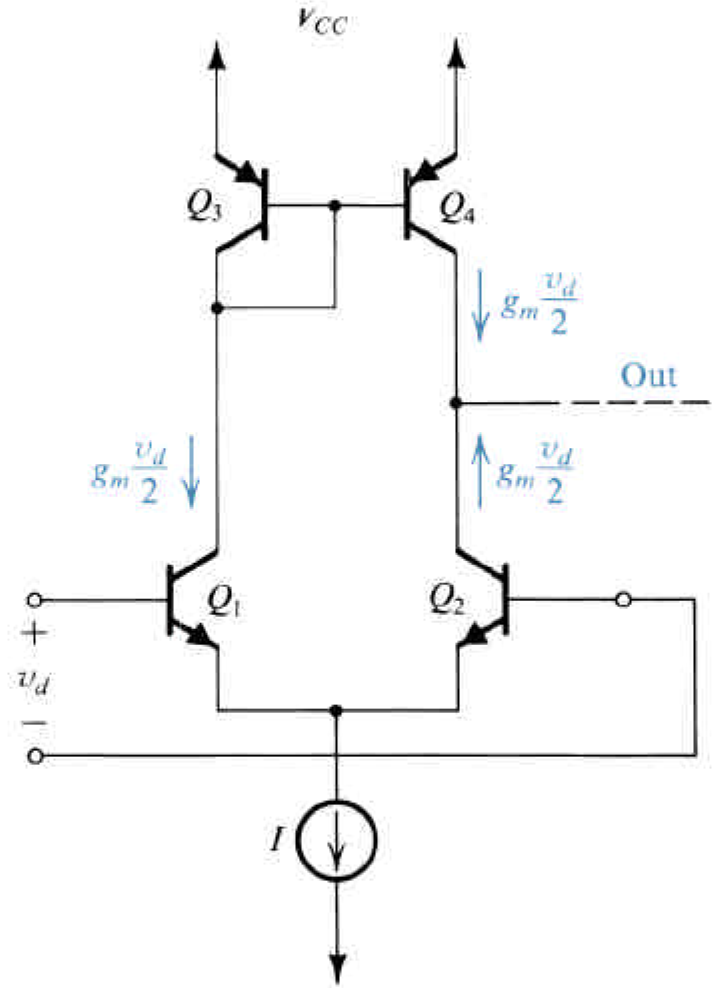
$$= (1 + \beta) r_{03} \approx \beta r_{03}$$

where $R'_E = r_{\pi 3} // r_{01} \approx r_{\pi 3}$

Since the BJTs are biased at the same current I/2, so the their small-signal parameters are equal and thus we can drop the subscript and express R_0

$$R_0 = \beta r_0$$

The output resistance of Cascode configuration is β times greater than that of the common-emitter amplifier.



Example 1: For an active-loaded differential amplifier when biased with $I = 0.2$ mA, and if $\beta = 200$, and V_A=100 V, find the values of R_i, G_m, R_0 and the open-circuit voltage gain.

Solution:

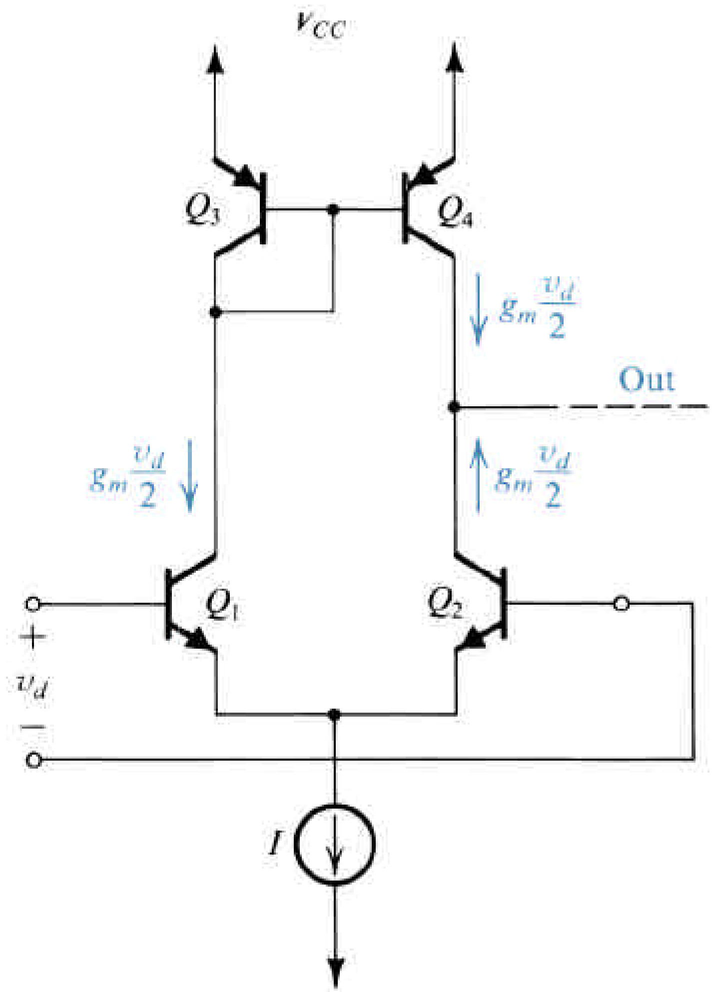
$$g_m = \frac{I/2}{V_T} = \frac{0.1mA}{25mV} = 4mA/V$$

$$R_i = 2r_\pi = 2\beta/g_m = \frac{2\times 200}{4\ mA/V} = 100\,k\Omega$$

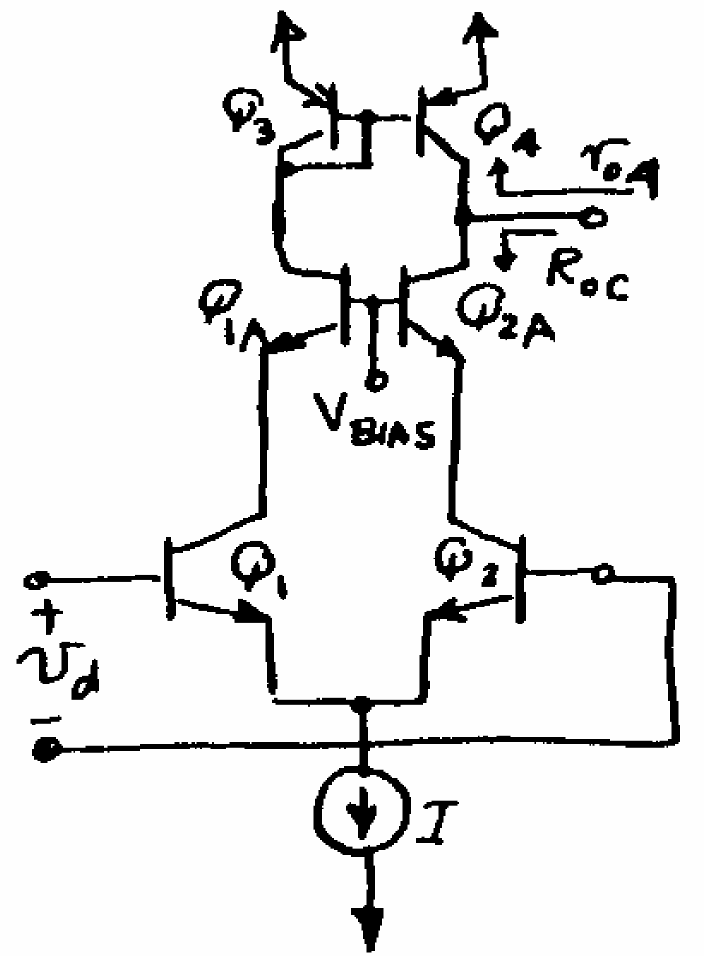
$$G_m = g_m = 4mA/V$$

$$R_0 = \frac{r_0}{2} = \frac{V_A/(I/2)}{2} = 500\,k\Omega$$

$$A_d = \frac{V_A}{2V_T} = \frac{100V}{2\times 25mV} = 2000\ V/V$$



Example 2: Repeat the Example 1. If the differential pair is replaced with a differential cascode amplifier.



Solution:

$$R_i = 2r_\pi = 2\beta / g_m = \frac{2\times 200}{4\ mA/V} = 100\,k\Omega$$

$$G_m = g_m = 4\,mA/V$$

$$R_0 = R_{0c} // r_{04}$$

R_{0c} is the output resistance of the cascode amplifier:

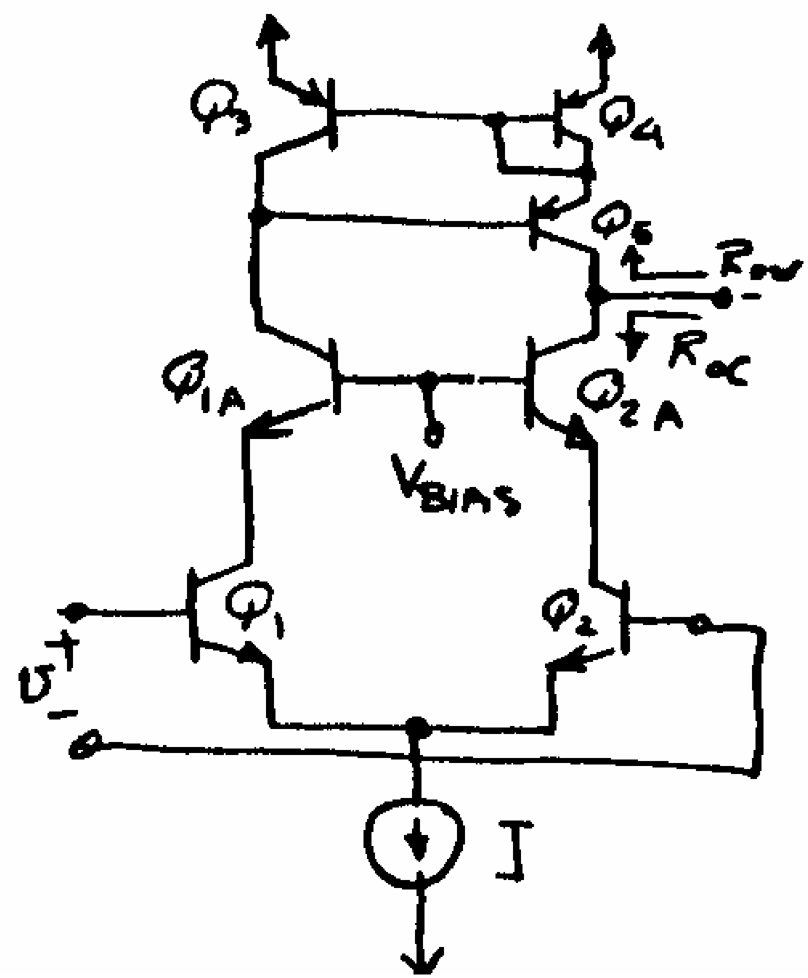
$$R_{0c} = r_{o2A}\beta_{2A} = \frac{V_A}{I/2}\beta = 200\,M\Omega$$

$$r_{04} = \frac{V_A}{I/2} = \frac{100V}{0.2/2\,mA} = 1\,M\Omega$$

$$R_0 = R_{0c} // r_{04} = 200 // 1 \approx 1\,M\Omega$$

$$A_{v0} = G_m R_0 = 4\times 1000 = 4000\,V/V$$

Example 3: Repeat Example 1 if the differential pair is replaced with a cascode amplifier and the basic current mirror load replaced with a Wilson current mirror.



Solution:

$$R_i = 2r_\pi = 2\beta / g_m = \frac{2\times 200}{4\ mA/V} = 100\,k\Omega$$

$$G_m = g_m = 4\,mA/V$$

$$R_0 = R_{0c} \,//\, R_{oW}$$

$$R_{0c} = \beta r_0 = 200\,M\Omega$$

$$R_{oW} = \beta r_0 / 2 = 100\ M\Omega$$

$$R_0 = R_{0c} \,//\, R_{oW} = 100 // 200 = 66.7\,M\Omega$$

$$A_{v0} = G_m R_0 = 4\times 66.7\times 10^3 = 2.67\times 10^5\,V/V$$