$$i_t = g_{m2}v_2 + (v_t + v_2)/r_{02}$$

$$= v_t/r_{02} + (g_{m2} + 1/r_{02})v_2 \simeq v_t/r_{02} + g_{m2}v_2$$

$$v_2 = -i_t R_{eff}$$

$$\Rightarrow i_t = v_t/r_{02} - g_{m2}R_{eff}i_t$$

$$\Rightarrow R_0 = v_t/i_t = r_{02}(1 + g_{m2}R_{eff})$$

- This is a ***Golden Equation***, which would be ***used frequently***
  - ***Carefully note the topology that produces this result***
- ***Exercise***: ***Reverse v_2 and show that the expression for R_0 remains invariant***

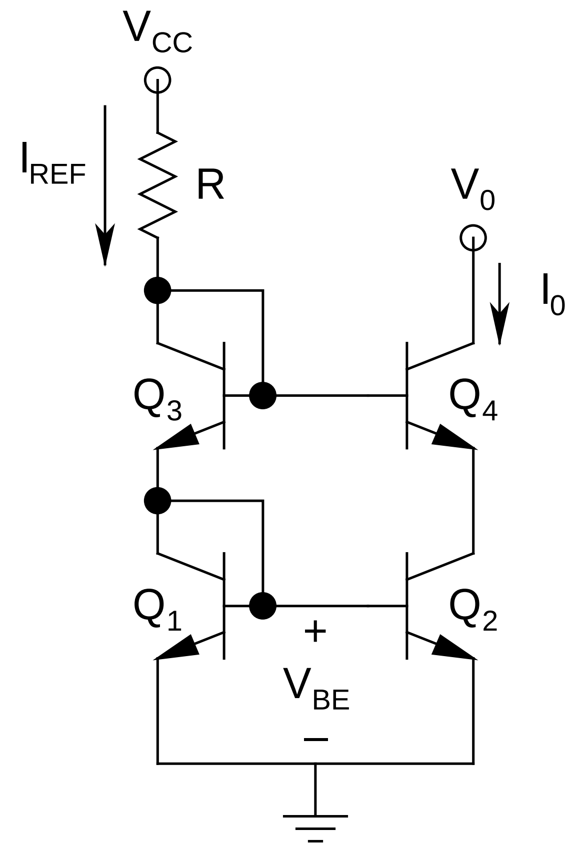
- If $r_{\pi 2} >> R_2$, $R_0 = r_{02}(1 + g_{m2}R_2)$
- If $R_2 >> r_{\pi 2}$, $R_0 \approx \beta_2 r_{02}$ (since $\beta = g_m r_\pi >> 1$)
- ***Under the second condition, the circuit produces enormously large value of R_0 ~ 10s of $M\Omega$ or greater***
  - ***Almost approaches a constant current source***!
- ***It's good to check the relative values of R_2 and $r_{\pi 2}$ before using either of the equations***
- ***This circuit does not have any MOS counterpart for obvious reasons***!

- ***Cascode Current Source***:
  - ***The best and most widely used***
  - ***Almost universal choice for biasing IC stages***
  - ***Produces extremely high R_0***
  - ***Original cascode needs higher values of $V_{0,min}$***
  - ***Modified cascode gets rid of this problem and pushes $V_{0,min}$ down***
  - ***The topology is basically two simple CMs stacked one upon the other***
  - ***Both npn and NMOS implementations exist***

- ***npn Cascode***:
  - ***All Qs are perfectly matched***
  - ***Neglecting I_B and V_A***:

    $I_0 = I_{REF} = (V_{CC} - 2V_{BE})/R$
  - Show that if ***I_B can't be neglected***, but ***all Qs have same β***:

    $$I_0 = \frac{I_{REF}}{1 + (4\beta + 2)/\beta^2}$$



  - Thus, ***β immunity is not that pronounced***

- ***All Qs operate with the same V_{BE}***

  $\Rightarrow V_{B1} = V_{B2} = V_{BE}, V_{B3} = V_{B4} = 2V_{BE}$

  $\Rightarrow V_{E4} = V_{C2} = V_{BE}$

  $\Rightarrow V_{BE2} = V_{CE2}$

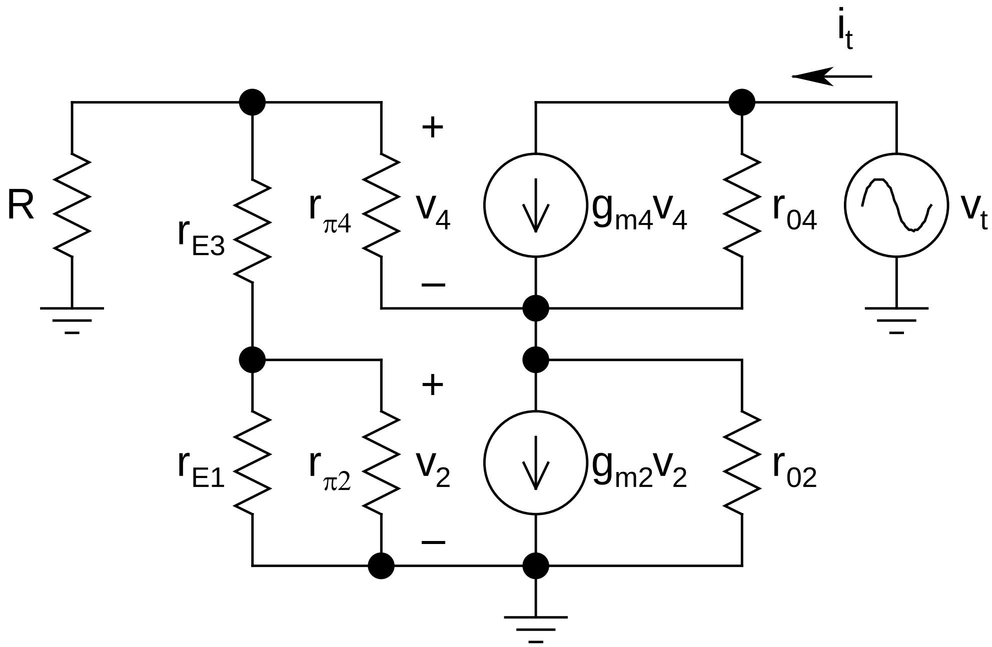
  $\Rightarrow$ ***Q_2 can never saturate, but Q_4 can***!

  $\Rightarrow V_{0,min} = V_{BE} + V_{CE4}(SS) = 0.7 + 0.2 = 0.9\ V$

- ***The output voltage swing is sacrificed quite a bit***!

- ***However, the main advantage of this circuit is enormously large R_0***

➢ *Calculation of R_0:*



Exact Equivalent

- *Q_1 and Q_3 diode-connected* $\Rightarrow r_{E1}$ and r_{E3}

- Note that to a ***first-order estimate***, ***bases of Q_1-Q_2 and Q_3-Q_4*** can be considered to be at a ***fixed DC potential***, and thus, ***ac ground***

  $\Rightarrow v_2 = 0 \Rightarrow g_{m2}v_2 = 0$

  $\Rightarrow$ Leads to the ***simplified equivalent*** (looks familiar?)

- ***By inspection***:

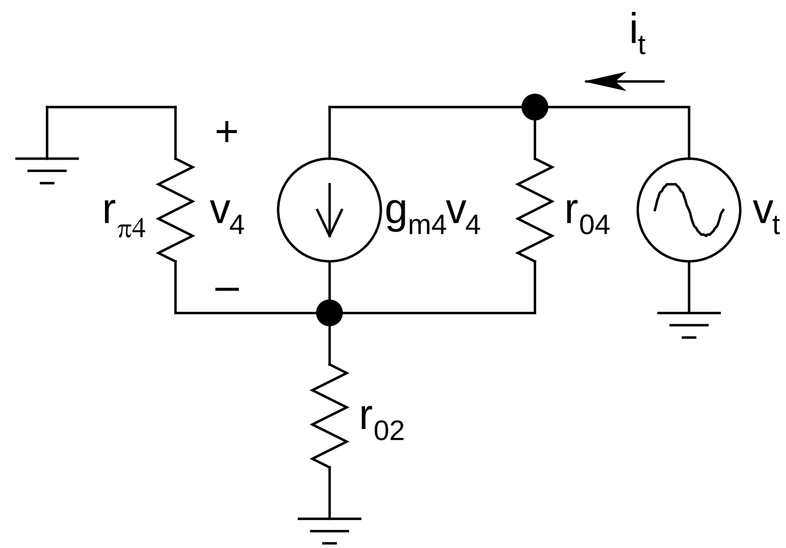
  $R_0 \approx r_{o4}(1 + g_{m4}r_{\pi 4})$

  $\approx \beta_4 r_{04}$

  (***assuming $r_{o2} >> r_{\pi 4}$***)

- ***Actual analysis gives***:

  $R_0 = \beta_4 r_{04}/2$ (***large error***!)



Simplified Equivalent