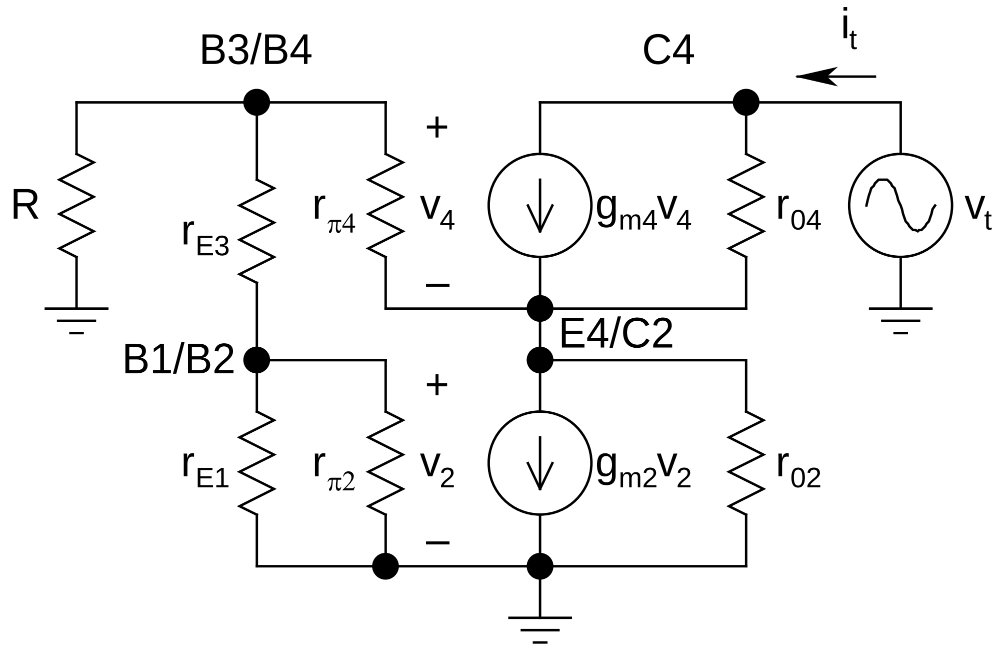
➢ *Calculation of R_0:*

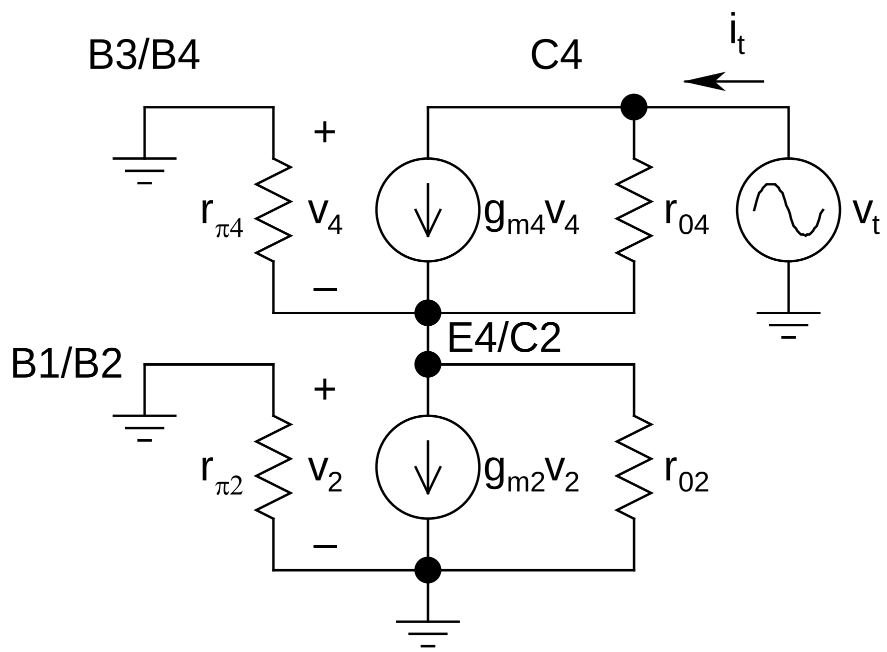


Exact Equivalent

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

➢ *Simplification*:

- *Bases of Q_1-Q_2 and Q_3-Q_4 can be approximated to be at ac ground* (*a first-order estimate*)



Equivalent after First-Order Simplification

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

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

- ***By inspection***:

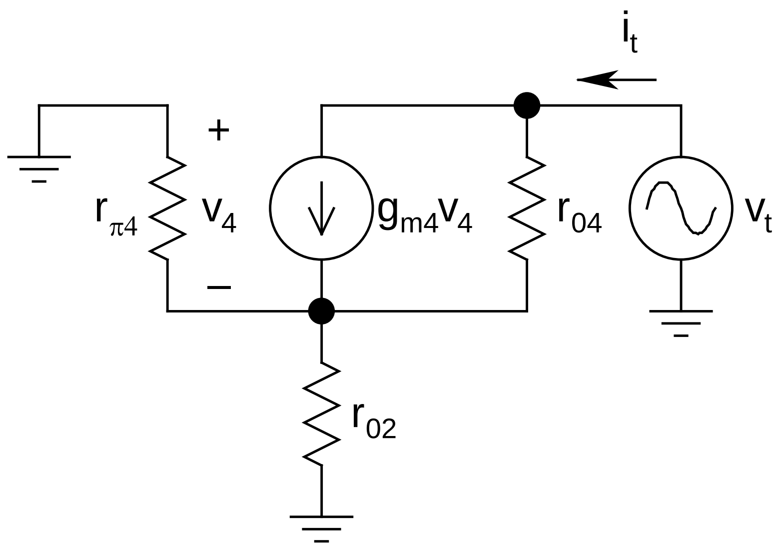
  $R_0 \approx r_{o4}(1 + g_{m4}r_{\pi 4})$

  $\approx \beta_4 r_{04}$

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

- ***Actual analysis gives***:

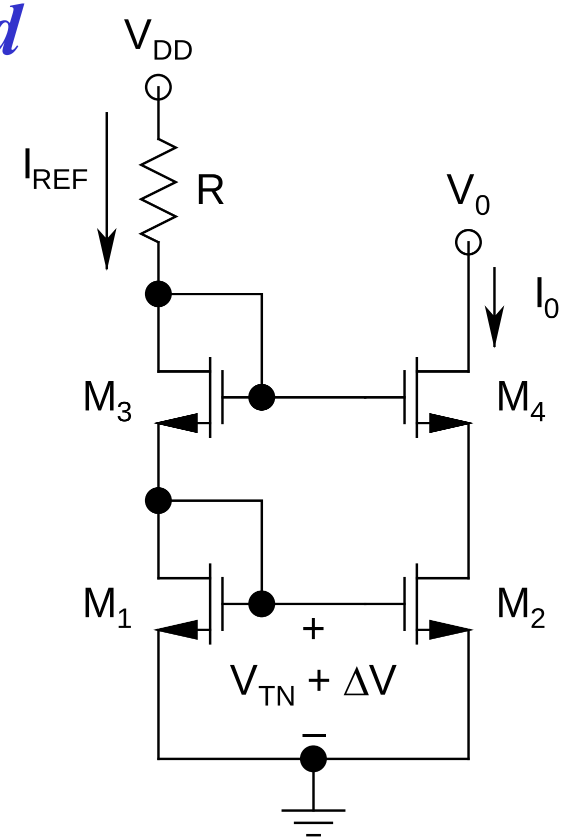
  $R_0 = \beta_4 r_{04}/2$ (***large error***!)



Simplified Equivalent

- ***NMOS Cascode***:
  - ***All Ms perfectly matched***
  - ***All bodies connected to ground***
    - ***M_1-M_2 does not have body effect***, ***but M_3-M_4 does***!
    - ***Makes hand analysis quite tedious***

      $\Rightarrow$ ***Neglect body effect***
  - ***All Ms operate with same V_{GS}***
  - Define $\Delta V = V_{GS} - V_{TN} = V_{GT}$
    - ΔV = ***Gate Overdrive***



- ***The reference current***:

$$I_{REF} = \frac{V_{DD} - 2V_{GS}}{R} = \frac{k_N}{2} V_{GT}^2 \quad (\textit{\textbf{neglecting}}\ \boldsymbol{\lambda})$$

- ***V_{GS} and I_{REF} can be found*** $\Rightarrow I_0 = I_{REF}$
- $V_{G1} = V_{G2} = V_{GS} = V_{TN} + \Delta V$
- $V_{G3} = V_{G4} = 2V_{GS} = 2(V_{TN} + \Delta V)$
- $V_{S4} = V_{D2} = V_{TN} + \Delta V$

$\Rightarrow V_{GS2} = V_{DS2}$

$\Rightarrow$ ***M_2 can never enter linear region***

$\Rightarrow V_{0,min} = V_{DS2} + V_{DS4} = V_{TN} + 2\Delta V$