Chapter 5 - Problems

5.1)  

a) Find $\omega_{-3dB} = \frac{1}{R_{outCeq}} = \frac{1}{R_{os2}\parallel R_{os4} \times C_L (1+A_2)}$

where $R_{os4} = \frac{8000L}{I_{Ds}} = \frac{8000 \times 1.2}{0.05} = 192 \, k\Omega$

$R_{os2} = \frac{12000L}{I_{Ds}} = \frac{12000 \times 1.2}{0.05} = 288 \, k\Omega$

$\therefore R_{os4} \parallel R_{os2} = 115 \, k\Omega$

$A_2 = g_m (r_{ps6}\parallel r_{ps7})$

$R_{ps6} = \frac{12000 \times 1.2}{0.1} = 144 \, k\Omega$

$R_{ps7} = \frac{8000 \times 1.2}{0.1} = 96 \, k\Omega$

$\therefore R_{ps6} \parallel R_{ps7} = 58 \, k\Omega$

$g_m = \sqrt{2mW/L \times I_{Ds}} = (2 \times 92 \times 10^{-6} \times 30 \times 1.2 \times 0.1 \times 10^{-3})^{\frac{1}{2}}$

$= 2.15 \, mA/V$

$\therefore A_2 = 2.15 \times 10^{-3} \times 58 \times 10^{3} = 124$

$\therefore \omega_{-3dB} = \frac{1}{115 \times 10^{3} \times 10^{-12} \times 125} = \frac{2\pi}{1.1 \, kHz}$

b) Find unity-gain frequency, $\omega_t$.

$\omega_t = g_m/c_c$ where $g_m = \sqrt{2 \times 30 \times 10^{-6} \times \frac{300}{1.2 \times 50 \times 10^{-6}}}$

$= 0.866 \, mA/V$

$\therefore \omega_t = \frac{0.866 \times 10^{-3}}{10 \times 10^{-12}} = \frac{2\pi}{14 \, MHz}$

C) Find slew rate.

$SR = \frac{2I_{Ds}}{C_c} = \frac{2 \times 50 \, mA}{10 \, pF} = 10 \, V/\mu sec$
5.2) With $C_c = 4\mu F$, 
\[ SR = \frac{2I_{in} \cdot C_c}{4\mu F} = 2 \times \frac{50\mu A}{4\mu F} = 25 \text{ V/msec} \]

To double the slew rate while maintaining $C_c$, we need to double $I_{in}$ by doubling the width of $Q_5$. In order to prevent this from changing $g_{m1}$ and $g_{m2}$ and hence $W_L$, we need to reduce the widths of $Q_1$ and $Q_2$ by half.

5.3) Referring to Problem 5.2, if we scale the widths of $Q_1$ and $Q_2$ by half, we need to maintain the equality
\[ \frac{W/L_4}{W/L_5} = 2 \frac{W/L_6}{W/L_7} \quad (5.28) \]

\[ \frac{\frac{(W/L)_7}{(W/L)_6}}{2 \frac{(W/L)_4}{(W/L)_5}} = 2 \frac{(150/1.2)}{(600/1.2)} = \frac{1}{2} \]

2 possibilities are:

1) If bias current at output stage remains unchanged =) 
\[ (\frac{W}{L})_6 = \frac{300}{1.2} \quad \text{and} \quad (\frac{W}{L})_7 = \frac{150}{1.2} \]

2) If bias current at output stage is doubled =) 
\[ (\frac{W}{L})_6 = \frac{600}{1.2} \quad \text{and} \quad (\frac{W}{L})_7 = \frac{300}{1.2} \]
To remove the inherent, systematic offset, the widths of $Q_3$ and $Q_4$ should become 150 µm. In that case,

$$ V_{eff7} = V_{eff4} = \sqrt{\frac{2 I_{OS}}{W/L}} = \sqrt{\frac{2 \times 100 \times 10^{-6}}{92 \times 10^{-6} \times 300 / 1.6}} $$

$$ = 0.1077 \text{V} $$

However, with the current circuit,

$$ V_{eff4} = \sqrt{\frac{2 \times 50 \times 10^{-6}}{92 \times 10^{-6} \times 50 / 6}} = 0.1865 \text{V} $$

So, an input offset voltage will have to be applied in order to decrease $V_{gs7}$ by

$$ \Delta V_{gs7} = 0.1865 - 0.1077 = 78.8 \text{ mV} $$

For the input-referred offset voltage $V_{i\text{off}},$

$$ V_{i\text{off}} = \Delta V_{gs7} / A_1 $$

where $A_1$ is the first stage's voltage gain,

$$ A_1 = g_{m1} \times R_{os2} / R_{os4} $$

$$ g_{m1} = \sqrt{2 \times 30 \times 10^{-6} \times 300 / 1.6 \times 50 \times 10^{-6}} = 0.75 \text{ mA/V} $$

$$ R_{os4} = 8000 \times 1.6 / 0.05 \text{ mA} = 256 \text{ kΩ} $$

$$ R_{os2} = 12000 \times 1.6 / 0.05 \text{ mA} = 384 \text{ kΩ} $$

So, $A_1 = 0.75 \times (256 / 384) = 115$

And $$ V_{i\text{off}} = \frac{78.8 \text{ mV}}{115} = 0.7 \text{ mV} \text{ (applied to } V_+ \text{ input)}.$$
5.5) Find max. and min \( V_{out} \) and \( V_{in} \) (common mode)

\[
V_{out\ max} = V_{DO} - V_{eff6} - V_{in6} - V_{eff8} \\
V_{out\ min} = V_{SS} + V_{eff9}
\]

\[
V_{in\ cm\ max} = V_{DO} - V_{eff5} - V_{eff1} + V_{tp1} \\
V_{in\ cm\ min} = V_{SS} + V_{eff3} + V_{tn3} + V_{tp1}
\]

Calculating all values,

\[
V_{eff5} = V_{eff6} = \sqrt{\frac{2I_{DS}}{MN_{ox} W/L}} = \sqrt{\frac{2 \times 100 \times 10^{-6}}{30 \times 10^{-6} \times 300 \times 6}} = 0.189 V
\]

Similarly,

\[
V_{eff1} = V_{eff2} = 0.133 V \\
V_{eff3} = V_{eff4} = 0.108 V \\
V_{eff8} = V_{eff9} = 0.108 V
\]

\[
\begin{align*}
V_{out\ max} &= 5 - 0.189 - 0.8 - 0.108 = 3.9 V \\
V_{out\ min} &= -5 + 0.108 = -4.9 V \\
V_{in\ cm\ max} &= 5 - 0.189 - 0.133 - 0.9 = 3.8 V \\
V_{in\ cm\ min} &= -5 + 0.108 + 0.8 - 0.9 = -4.99 V
\end{align*}
\]
Bad design of compensation network:

In order to understand why oscillations occur on account of this arrangement, we have to keep in mind our use of $Q_{16}$, operated in the triode region, as a substitute for a feed-forward resistor. When $\text{Nout}$ is large and positive, $\text{N}_2$ is similarly so. Should the voltage across $C_C$ happen to be small, a large voltage would appear across the drain and source of $Q_{16}$. If this voltage were large enough to put $Q_{16}$ into the active mode, capacitor $C_C$ would effectively become disconnected from the output. The result would be an uncompensated op amp that is prone to oscillations.

By keeping $Q_{16}$ connected to the input of the second stage, most of the large signal swings will appear across the capacitor instead. As such, $Q_{16}$ will more reliably remain in the triode region of operation.
5.7) The body effect changes the threshold voltages of Q₈, Q₁ and Q₂. The change in V₄₈ affects only Vout_max while the changes in V₃₈ and V₄₈ affect both Vin_cm_max and Vin_cm_min.

From Problem 5.5, \( V_{\text{out}}_{\text{min}} = -4.9 \text{V} \)

The other values must be solved iteratively as the threshold voltages are dependent on \( V_{\text{ss}} \)’s.

For \( V_{\text{out}}_{\text{max}} \):

Assume \( V_{\text{tn}₈} = 0.8 \text{V} \) for first iteration

\[ V_{\text{ss}₈} = V_{\text{out}}_{\text{max}} - V_{\text{ss}} = V₀₀ - V_{\text{eff}₆} - V_{\text{tn}₈} - V_{\text{eff}₈} - V_{\text{ss}} \]
\[ = 5 - 0.189 - 0.8 - 0.108 - (-5 \text{V}) \]
\[ = 8.9 \text{V} \]

\[ V_{\text{tn}₈} = V_{\text{tn}₀} + 0.5 \left( \sqrt{V_{\text{ss}₈} + 2\Phi_F} - \sqrt{2\Phi_F} \right) \]
\[ = 0.8 \text{V} + 0.5 \left( \sqrt{8.9 + 0.7} - \sqrt{0.7} \right) \]
\[ = 1.93 \text{V} \]

\[ V_{\text{ss}₈} = 5 - 0.189 - 1.93 - 0.108 - (-5 \text{V}) \]
\[ = 7.77 \text{V} \]

\[ V_{\text{tn}₈} = 0.8 + 0.5 \left( \sqrt{7.77 - 0.7} - \sqrt{0.7} \right) \]
\[ V_{\text{tn}₈} = 1.84 \text{V} \]

1st iteration

2nd iteration

\[ V_{\text{out}}_{\text{max}} = V₀₀ - V_{\text{eff}₆} - V_{\text{tn}₈} - V_{\text{eff}₈} = 5 - 0.189 - 1.84 - 0.108 \]

\[ V_{\text{out}}_{\text{max}} = 2.9 \text{V} \text{ which is almost 1 volt lower than our original result in PS.5.} \]

For \( V_{\text{in}}_{\text{cm}}_{\text{max}} \):

\[ V_{\text{ss}₁} = V_{\text{eff}₅} = 0.189 \text{V} \]

(no iterations required)

\[ V_{\text{tn}₁} = V_{\text{tn}₀} - 0.5 \left( \sqrt{V_{\text{ss}₁} + 2\Phi_F} - \sqrt{2\Phi_F} \right) \]
\[ = -0.9 - 0.8 \left( \sqrt{0.189 + 0.7} - \sqrt{0.7} \right) \]
\[ = -0.98 \text{V} \]

\[ V_{\text{in}}_{\text{cm}}_{\text{max}} = V₀₀ - V_{\text{eff}₅} - V_{\text{eff}₁} + V_{\text{tn}₁} = 5 - 0.189 - 0.133 - 0.98 \]
\[ V_{\text{in}}_{\text{cm}}_{\text{max}} = 3.7 \text{V} \]

(cont.)
5.7) (cont.)

For $V_{\text{in}c_{\text{min}}}$:

Assume $V_{\text{tp}1} = -0.9V$

$V_{\text{bs}1} = V_{\text{DD}} - (V_{\text{in}c_{\text{min}}} + V_{\text{th}1} - V_{\text{tp}1})$

$= V_{\text{DD}} - (V_{SS} + V_{\text{th}3} + V_{\text{tn}3} + V_{\text{tp}1} + V_{\text{th}1} - V_{\text{tp}1})$

$= V_{\text{DD}} - V_{SS} - V_{\text{th}3} - V_{\text{tn}3} - V_{\text{th}1} = 5 - 2.5 - 0.108 - 0.8 - 0.138$

$= 8.96V$

$\therefore V_{\text{tp}1} = \sqrt{V_{\text{bs}1} + 2\Phi} - \sqrt{2\Phi}$

$= -0.9 - 0.8(\sqrt{8.96 + 0.7} - \sqrt{0.7})$

$= -2.7V$

$\therefore V_{\text{in}c_{\text{min}}} = V_{SS} + V_{\text{th}3} + V_{\text{tn}3} + V_{\text{tp}1} = 5 + 0.108 + 0.8 - 2.7$

$= 6.8V$

Note that the min common-mode input voltage is lower than the -5 V supply.

5.8) Show that $V_{\text{weg}} = \Sigma \frac{1}{\lambda_{\text{pi}}} - \Sigma \frac{1}{\lambda_{\text{zi}}}$.

We are given that

$A[H(j\omega t)] \approx A[H_{\text{app}}(j\omega t)]$

$L_S = A[H(j\omega t)] \approx A[\frac{\pi (1 + j\omega \kappa )}{\pi (1 + j\kappa \lambda /\omega_{\text{pi}})}]$

$= \tan^{-1} \left( \frac{\omega_{\text{pi}}}{\omega_{\text{zi}}} \right) + \tan^{-1} \left( \frac{\omega_{\text{ni}}}{\omega_{\text{zi}}} \right) + \ldots + \tan^{-1} \left( \frac{\omega_{\text{t}}}{\omega_{\text{ni}}} \right) - \tan^{-1} \left( \frac{\omega_{\text{t}}}{\omega_{\text{ni}}} \right) + \ldots - \tan^{-1} \left( \frac{\omega_{\text{t}}}{\omega_{\text{pi}}} \right)$

But the Taylor Series expansion for $\tan^{-1} x = x - \frac{x^3}{3} + \frac{x^5}{5} - \ldots$

$\approx x$ for $x << 1$

If the op amp is compensated such that the unity gain frequency, $\omega_{\text{t}}$, is much lower than all higher order poles and zeros but much higher than $\omega_{\text{pi}}$.

$L_S \approx \omega_{\text{t}} \omega_{\text{zi}} + \cdots + \frac{\omega_{\text{t}} \omega_{\text{ni}}}{\omega_{\text{zi}}} - 90^\circ \frac{\omega_{\text{t}}}{\omega_{\text{pi}}} \cdots - \omega_{\text{t}} \omega_{\text{ni}} = \omega_{\text{t}} \left( \Sigma \frac{1}{\lambda_{\text{zi}}} - \Sigma \frac{1}{\lambda_{\text{pi}}} \right) - 90^\circ$

Similarly, $R_S = A[H_{\text{app}}(j\omega t)] = -\tan^{-1} \left( \frac{\omega_{\text{pi}}}{\omega_{\text{weg}}} \right) - 90^\circ = -\omega_{\text{weg}} - 90^\circ$

$\therefore \omega_{\text{t}} \left( \Sigma \frac{1}{\lambda_{\text{zi}}} - \Sigma \frac{1}{\lambda_{\text{pi}}} \right) \approx -\omega_{\text{t}} \omega_{\text{weg}}$

or $\frac{1}{\omega_{\text{weg}}} = \Sigma \frac{1}{\lambda_{\text{pi}}} - \Sigma \frac{1}{\lambda_{\text{zi}}} \quad Q.E.D.$
5.9) **Given**:

\[
H(s) = \frac{K}{(1 + \frac{s}{\omega_1})(1 + \frac{s}{\omega_2})(1 + \frac{s}{\omega_3})(1 + \frac{s}{\omega_4})}
\]

where \( \omega_1 = 2\pi \times 3 \text{ kHz} \), \( \omega_2 = 2\pi \times 130 \text{ MHz} \)
\( \omega_3 = 2\pi \times 160 \text{ MHz} \), \( \omega_4 = 2\pi \times 180 \text{ MHz} \)

\[\phi H(i\omega) = -90^\circ - \tan^{-1}\left(\frac{\omega_1}{130}\right) - \tan^{-1}\left(\frac{\omega_2}{160}\right) - \tan^{-1}\left(\frac{\omega_3}{180}\right)\]

Given that \( \phi H(i\omega_{eq}) = -135^\circ \) then trial and error gives \( \omega_{eq} \approx 2\pi \times 41.3 \text{ MHz} \)

Using Eq. (5.45),

\[
\frac{1}{\omega_{eq}} = \frac{1}{\omega_2} + \frac{1}{\omega_3} + \frac{1}{\omega_4} = \frac{1}{2\pi} \left( \frac{1}{130 \times 10^6} + \frac{1}{160 \times 10^6} + \frac{1}{180 \times 10^6} \right)
\]

\( \therefore \omega_{eq} \approx 2\pi \times 51.3 \text{ MHz} \)

This estimate is about 24% above the true value.

5.10) **Two stage Opamp**

\[g_m = 0.775 \text{ mA/V} \]
\( \omega_{p2} = 60 \text{ MHz} \)

\( \omega_{oc} \) is defined as the frequency at which the loop gain, \( A_{\phi} \), is unity.

(cont.)
For a closed loop phase margin of 55°, eqn (5.53) states

\[ W_t = \tan (90° - \Phi_M) \arcsin \]

\[ W_t = \tan (90° - 55°) \arcsin \]

\[ W_t = 0.7 \arcsin \]

For \( \arcsin = 25 \times 60 \text{MHz} \), \( W_t = 25 \times 42 \text{MHz} \)

Now including a feedback factor \( \beta \) into eqn (5.46), we have

\[ A(s) = \frac{W_t \beta}{s(1 + 5\arcsin)} = \frac{\beta}{s(1 + 5\arcsin)} \]

Here \( \beta = \frac{R_1}{R_1 + R_2} = \frac{1}{6} \)

We require that \(|A(iW_t)| = 1\) leading to

\[ |A(iW_t)| = 1 = \frac{\beta}{\sqrt{1 + \left(\frac{W_t}{\arcsin}\right)^2}} \]

\[ C_c = \frac{\frac{\beta}{\sqrt{1 + 0.7^2}}}{\frac{0.775 \times 10^{-3} \times 1.6}{25 \times 42 \times 10^6 \times 1.221}} = 0.4 \text{ pF} \]
5.11) Find $C_2$ that provides compensation.

In Problem 5.10, we found that

$$\beta = \frac{R_1}{R_1 + R_2}. $$

This can be generalized to $\beta = \frac{Z_1}{Z_1 + Z_2}$. We now wish to use the feedback network for compensation.

For $Z_1 = R_1$, $Z_1 = R_2$ and $\frac{1}{sC_2} = \frac{R_2}{1 + sR_2C_2}$,

$$\beta = \frac{\frac{R_1}{R_1 + \frac{R_2}{1 + sR_2C_2}}}{\frac{R_1}{R_1 + \frac{R_2}{1 + sR_2C_2}}} = \frac{R_1(1 + sR_2C_2)}{sR_1R_2C_2 + R_1 + R_2} \quad \text{new zero added}$$

From Section 5.2, lead compensation is achieved by placing a zero at 1.2 times the unity loop gain frequency, $\omega_t$.

$$\omega_z = \frac{1}{R_3C_2} \equiv 1.2 \times \omega_t$$

$$C_2 = \frac{1}{1.2 \times 0.7 \times \omega_2 \times R_2}$$

$$= 63\text{fF}$$
5.12) Find \( \omega_1 \) and \( \omega_t \).

\[
|H(\omega)| = 10^6
\]

\[
\omega_2 = \omega_t
\]

\[
H(s) = \frac{A_0 (1 + \frac{s}{\omega_t})}{(1 + \frac{s}{\omega_2}) (1 + \frac{s}{\omega_t})}
\]

and \( \angle H(j\omega_t) = 180^\circ - PM = -100^\circ = 45^\circ - \tan^{-1}\left(\frac{\omega_t}{\omega_1}\right) - \tan^{-1}\left(\frac{\omega_t}{\omega_2}\right) \)

\[
\therefore A_0 >> 1
\]

\[
\omega_t >> \omega_1 \quad \text{by the constant gain bandwidth}
\]

\[
\tan^{-1}\left(\frac{\omega_t}{\omega_1}\right) \approx 90^\circ \quad \text{product}
\]

\[
-100^\circ \approx 45^\circ - 90^\circ - \tan^{-1}\left(\frac{\omega_t}{\omega_2}\right)
\]

\[
\frac{\omega_t}{\omega_2} \approx \tan(55^\circ)
\]

\[
\omega_t \approx 1.43 \omega_2 = 1.43 \times 10^6 \text{ rad/sec}
\]

\[
|H(j\omega_t)| = A_0 \left\{ \frac{1}{\sqrt{1 + \left(\frac{\omega_2}{\omega_1}\right)^2} \sqrt{1 + \left(\frac{\omega_t}{\omega_2}\right)^2}} \right\} = 1
\]

\[
\left[ 1 + \left(\frac{\omega_t}{\omega_1}\right)^2\right]\left[ 1 + \left(\frac{\omega_2}{\omega_1}\right)^2\right] = 2 A_0^2
\]

\[
1 + \left(\frac{\omega_t}{\omega_1}\right)^2 = \frac{2 \times 10^8}{1 + 1.43^2}
\]

\[
\omega_1 = \frac{1.43 \times 10^6 \text{ rad/sec}}{8.1 \times 10^3}
\]

\[
\omega_1 = 1.8 \times 10^4 \text{ rad/sec}
\]
Given \( A(s) \approx \frac{A_0 (1 + s \tau_2)}{s \tau_1 (1 + s \tau_2)} \), the closed loop transfer function is given by

\[ A_{CL}(s) = \frac{A(s)}{1 + A(s) \beta} \approx \frac{A_0 (1 + s \tau_2)/(s \tau_1 (1 + s \tau_2))}{1 + A_0 \beta (1 + s \tau_2)/(s \tau_1 (1 + s \tau_2))} \]

\[ = \frac{A_0 (1 + s \tau_2)}{s \tau_1 (1 + s \tau_2) + A_0 \beta (1 + s \tau_2)} \]

\[ = \frac{A_0 (1 + s \tau_2)}{s \tau_1 \tau_2 \left[ s^2 + s \left( \frac{1}{\tau_2} + A_0 \beta \frac{\tau_2}{\tau_1 \tau_2} \right) + \frac{A_0 \beta}{\tau_1 \tau_2} \right]} \]

Equating the coefficients of the denominator polynomial to the standard second-order pole polynomial,

\[ s^2 + \frac{\omega_0}{Q} s + \omega_0^2, \]

we find that

\[ \frac{\omega_0}{Q} = \frac{1}{\tau_2} + A_0 \beta \frac{\tau_2}{\tau_1 \tau_2}, \quad \omega_0^2 = \frac{A_0 \beta}{\tau_1 \tau_2} \]

\[ \therefore \omega_0 = \sqrt{\frac{A_0 \beta}{\tau_1 \tau_2}} \]

\[ Q = \frac{\frac{\omega_0}{\tau_2} + A_0 \beta \frac{\tau_2}{\tau_1 \tau_2}}{\frac{\omega_0 \tau_2}{1 + A_0 \beta \tau_2 / \tau_1}} \]

Since \( \tau_2 \) is roughly \( \tau_1 / A_0 \) we cannot make any approximations here.
Given $R_c = 0$, Equations (5.66) – (5.68) describe the denominator polynomial $D(s)$, as

$$D(s) = 1 + sa + s^2b$$

where

$$a = (C_2 \cdot C_0)R_1 + (C_1 \cdot C_0)R_1 + gm_R R_1 R_2 C_c$$

$$b = R_1 R_2 (C_1 C_2 + C_1 C_0 + C_2 C_0)$$

When $R_c \neq 0$, the admittance $sC_c$ becomes $\frac{SC_c}{1 + SRC_c}$. Thus, we can obtain the new denominator polynomial $D'(s)$, by simply substituting $C_c$ with $\frac{CC_c}{1 + SBC_c}$.

$$a' = (C_2 + \frac{C_0}{1 + SRC_c})R_2 + (C_1 + \frac{C_0}{1 + SRC_c})R_1 + gm_R R_1 R_2 \frac{CC_c}{1 + SRC_c}$$

$$b' = R_1 R_2 \left[ C_1 C_2 + C_1 \frac{CC_c}{1 + SRC_c} + C_2 \frac{CC_c}{1 + SRC_c} \right]$$

$$D'(s) = 1 + sa' + s^2b' = \frac{1}{1 + SRC_c} \left[ (1 + SRC_c) + s(a + s(R_c C_c + R_1 C_c C_0) + s^2(b + s R_1 C_1 R_2 C_2 C_0) \right]$$

The poles of the system are determined by the roots of $D''(s)$.

$$D''(s) = 1 + s(a + R_c C_c) + s^2(b + R_c C_0 R_c C_c + R_1 C_1 C_0 C_c) + s^3 R_1 C_1 R_2 C_2 C_0 C_c$$

- $R_c \ll R_1$ or $R_2$
- Any time constant with $R_c$ is much less than time constants with $R_1$ or $R_2$
- $a \gg R_c C_c$ and $b \gg R_2 C_c + R_1 C_c C_0 C_c$

(cont.)
5.14 (cont.)

\[ 0^* \quad 0^* \quad 0^* \quad 0^* \]

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Equating these coefficients, we have the original approximations,

\[ w_{p1} \approx 1/a \]
\[ w_{p2} \approx a/b \]

Equations (5.70) and (5.71) still hold true.

Q.E.D.

5.15) Find \( R_B \) and \( V_{eff} \) at 70°C.

From Eq. (5.108)

\[ R_B = \frac{1}{g_m} = \frac{1}{(W_0 C_{ox W} V_{eff})} = \frac{1}{(92 \times 10^{-6} \times 10^4 \times 0.25)} \]
\[ R_B = 5.2 \text{ kΩ} \]

To determine the effect of temperature on \( V_{eff} \), note that

\[ M_n \propto T^{-3/2} \] (see pg 250)

Also \( R_B \propto \frac{1}{M_n V_{eff}} \propto \frac{1}{T^{-3/2} V_{eff}} \) and \( R_B \) is a constant

\[ T_1^{-3/2} V_{eff1} = T_2^{-3/2} V_{eff2} \]

Let \( T_1 = 300 K \), \( T_2 = 343 K \), \( V_{eff1} = 0.25 V \)

(27°C) (70°C)

\[ V_{eff2} = 0.25 \times \left( \frac{300}{343} \right)^{-3/2} = 0.31 V \]

Results from HSpice:

at 27°C: \( V_{eff} = V_{osat} = 0.26 V \)
at 70°C: \( V_{eff} = V_{osat} = 0.31 V \)

Results are consistent with our calculations.