EE 140/240A  Linear Integrated Circuits  
Spring 2020 

Homework 6

1. K2-W

Check out the datasheet for the K2-W tube op-amp: http://philbrickarchive.org/k2-w_operational_amplifier_later.htm. This op-amp, released in 1952, was the first production op-amp. It runs from a ±300V supply, and has a bandwidth of 300kHz (or k-cycles/s, as they said back then—the unit Hertz not having been established yet). There’s a schematic on page 2. Pins 1, 2, and 6 on the bottom of the figure are \( V_+ \), \( V_- \), and \( V_{\text{out}} \). \( V_{R1} \) and \( V_{R2} \) are neon bulbs that provide a low impedance level shift of roughly 100V to center the output between the rails. Identify (circle and label):

(a) input differential pair
(b) diff-pair load resistor
(c) tail current resistor
(d) Estimate the common mode gain and write it near the tail resistor
(e) Common-cathode gain stage (like CS or CE)
(f) Cathode-follower output stage (like source-follower or emitter follower, CD, CC)
(g) Miller-multiplied compensation capacitor from the output back to the input of the gain stage
(h) (BONUS) positive feedback in this amplifier, designed to increase the low frequency gain (which ended up at about 20,000)

Solution:
You can find more info on the K2-W here: https://www.electronicdesign.com/analog/whats-all-k2-w-stuff-anyhow

Rubric: (8 Points)

• +1: For each correct marking (with no extra devices)

2. More Single-Pole Amplifiers

You have an opamp with a low-frequency gain of 1000 and a single pole at 1Mrad/s. Plot the location of the pole as a function of the feedback factor \( f \) from \( f = [0, 1] \).

Solution:

\[
\begin{array}{c|c}
\text{f = 1} & \text{f = 0} \\
1000.0\text{Mrad/s} & 1\text{Mrad/s}
\end{array}
\]

Rubric: (3 Points)

• +1: Pole location with \( f = 0 \)
• +1: Pole location with \( f = 1 \)
• +1: Trajectory of pole location correct

(a) From now on, assume \( f = 0.1 \). Sketch the Bode plot of the closed-loop amplifier.

Solution:

\[
\begin{array}{c}
\text{Gain (V/V)} \\
10^0 - 10^0 \\
\omega_{\text{rad}/s}
\end{array}
\]

\( A_{v,CL} = 10\text{V/V} \)

\( \omega_{p,CL} = 100\text{Mrad/s} \)

\( \omega_{u,CL} = 1000.0\text{Mrad/s} \)
Rubric: (2 Points)
• +1: Correct 3dB frequency
• +1: Correct closed-loop gain

(b) What is the fractional gain error?

Solution: Following the equation for fractional gain error:

\[
- \frac{1}{Af}
\]

-1 \cdot 10^{-2}

Rubric: (2 Points)
• +1: Correct equation
• +1: Correct numerical answer

(c) What is the time constant of the step response? How does it compare to the open-loop time constant?

Solution:

\[
\tau_{OL} = \frac{1}{\omega_{p,OL}} \quad \tau_{CL} = \frac{1}{\omega_{p,OL}A_0f}
\]

\[
\tau_{OL} = 1\mu s \\
\tau_{CL} = 1 \cdot 10^{-2}\mu s
\]

The closed loop time constant is faster than the open-loop time constant by a factor of the loop gain \(A_0f\)
Rubric: (2 Points)
• +1: Correct closed-loop time constant
• +1: Correct comparison to open-loop time constant

(d) What is the unity gain frequency? How does it compare to the open-loop unity gain frequency?

Solution:

The unity gain frequency stays constant
\[ \omega_u = 1000.0 \text{ Mrad/s} \]

Rubric: (2 Points)
• +1: Correct \( \omega_u \)
• +1: Correct comparison between closed-loop and open-loop unity gain frequency

3. Now With Three Poles!
You have an opamp with a low-frequency gain of 1000 and three poles at 1Mrad/s.

(a) Plot the location of the three poles as a function of the feedback factor \( f \).

Solution: First, define \( \omega_p \) as the open loop pole frequency.

The open-loop transfer function:
\[ A_{\text{OL}}(s) = \frac{A_0 \omega_p^3}{(s + \omega_p)^3} \]

And plug this into the closed loop transfer function equation:
\[ A_{\text{CL}}(s) = \frac{A_{\text{OL}}(s)}{1 + A_{\text{OL}}(s)f} = \frac{A_0 \omega_p^3}{(s + \omega_p)^3 + A_0 f \omega_p^3} \]

The poles of the characteristic equation can be found by setting the denominator to 0:
\[(s + \omega_p)^3 + A_0 f \omega_p^3 = 0\]
\[s + \omega_p = \sqrt[3]{A_0 f} \omega_p \cdot \exp(j\phi), \phi = 180 \pm 60^\circ\]
\[s = -\omega_p \left(1 + \sqrt[3]{A_0 f} e^{\pm j\frac{\pi}{3}}\right)\]

where the portion of the expression above with the complex exponential gives the angle and magnitude of the vector which progresses from the initial pole location.
Rubric: (9 Points)

• +1: Calculated correct pole location in terms of \( f \) (×3)
• +1: Correct starting point when \( f = 0 \) (×3)
• +1: Correct angle of trajectory for each pole as \( f \) changes (×3)

(b) At the point where the poles cross the \( j\omega \) axis, annotate the plot with the value of \( f \) that gives this pole location.

Solution:
Using our answer to the previous part and with some triangle geometry, at the \( j\omega \) axis, the real part is 0, so

\[
2\omega_p = \sqrt{A_0 f \omega_p}
\]

\[
f = \frac{8}{A_0}
\]

\[
= 0.008
\]

See the plot above for the annotation.

Rubric: (2 Points)

• +1: Set real portion to 0 in expression for poles in previous part (don’t double-penalize yourself—even if your expression for the pole location earlier was incorrect, you should still give yourself credit if you went through the correct process here)
• +1: Correctly calculated \( f \) given the expression from the previous part

(c) Using this value for \( f \), draw a Bode plot of the loop gain \( A_f \)

Solution:

\[
A_{OL} f = \frac{8}{\left(1 + \frac{s}{\omega_p}\right)^3}
\]
Rubric: (3 Points)
• +1: Correct DC $A_f$
• +1: Correct pole location and $-60$dB/decade slope
• +1: $\omega_u$ of $A_f < 10^7 \text{rad}/s$

4. Compensating for Something
A two-stage CMOS op-amp running at a particular bias point has the following parameters:

- $G_{m1} = 1\text{mS}$
- $R_{o1} = 1\text{M}\Omega$
- $C_1 = 0.1\text{pF}$
- $C_C = 0\text{pF}$
- $G_{m2} = 1\text{mS}$
- $R_{o2} = 100\text{k}\Omega$
- $C_2 = 10\text{pF}$

(a) Plot the magnitude and phase of the overall gain of this uncompensated amplifier.

Solution:
The poles of the uncompensated amplifier can be found by solving for the roots of the characteristic equation. The poles are determined by the given equations:

$$\omega_{p1} = \frac{1}{R_{o1}C_1} = 10^7 \text{ rad/s}$$

$$\omega_{p2} = \frac{1}{R_{o2}C_2} = 10^6 \text{ rad/s}$$

The DC gain of the amplifier is:

$$A_v0 = G_m R_{o1} G_m2 R_{o1} = 10^5 \frac{V}{V}$$

The rubric for this problem is as follows:

Rubric: (6 Points)
- +1: Correct pole frequency (2×)
- +1: Correct DC gain
- +1: Correct phase relationship about pole frequencies (2×)
- +1: Correct unity gain frequency

(b) Where are the poles of the uncompensated amplifier? Is it unity-gain stable?

Solution: See the plot in part (a)
\[ \omega_{p,1} = 10^{7}\text{rad/s}, \omega_{p,2} = 10^{6}\text{rad/s} \]

No, the amplifier is not unity gain stable.

**Rubric:** (1 Points)
- +1: Correct answer of if the amplifier is unity gain stable

5. **Continuing... For the same amplifier above, we now add** \( C_c = 1\text{pF} \). You may ignore the RHP zero that this introduces. On the figures provided below,

(a) Plot the magnitude of the second stage gain vs. frequency.

**Rubric:** (3 Points)
- +1: Correct DC gain
- +1: Correct pole frequency
- +1: 20dB/decade drop-off

(b) Plot the magnitude of the input *capacitance* of the second stage (including \( C_c \)) vs. frequency.

**Rubric:** (4 Points)
- +1: Correct DC capacitance (if you didn’t include \( C_1 \) that’s fine)
- +1: Correct high-frequency capacitance (fine if you didn’t include \( C_1 \))
- +1: Correct pole location for gain dropping the capacitance
- +1: Correct \( \omega_u \) location where \( C_c \) no longer Millerizes

(c) Plot the magnitude of the input *impedance* of the second stage vs. frequency. Add a line for the output impedance of the first stage.

**Rubric:** (4 Points)
- +1: Correct low frequency \( R_{o1} \)
- +1: Correct impedance line for Millerized \( C_c \)
- +1: Correct zero location in the impedance when Miller effect begins to decrease
- +1: Correct impedance line for non-Millerized \( C_c \)

(d) Now plot the magnitude of the gain of the first stage on the top plot, and the magnitude of the overall gain of the amplifier.

**Rubric:** (9 Points)
- +1: Correct DC gain of first stage
- +1: Correct pole and zero locations of the first stage gain (3×)
- +1: Correct DC gain of combined stages
- +1: Correct pole locations and slope of combined stages (4×)

(e) What are the compensated poles of the amplifier? If \( C_c \) were 0pF, where would the poles of the amplifier be?

**Solution:**
Rubric: (4 Points)

• +1: Correct compensated poles of the amplifier (2×)
• +1: Correct uncompensated poles of the amplifier (2×)
Second stage gain – |A_{2,1}|, and first stage and overall gains

\[ |A_{2,1}| \]

\[
\begin{array}{c|c|c|c|c|c}
1 & 1k & 1M & 1G & \text{rad/s} \\
\hline
100 & \text{ } & \text{ } & \text{ } & \text{ } \\
1 & \text{ } & \text{ } & \text{ } & \text{ }
\end{array}
\]

magnitude of second stage input (Miller) capacitance

\[ C \]

\[
\begin{array}{c|c|c|c|c|c}
1 & 1k & 1M & 1G & \text{rad/s} \\
\hline
10pF & \text{ } & \text{ } & \text{ } & \text{ } \\
1pF & \text{ } & \text{ } & \text{ } & \text{ }
\end{array}
\]

second stage input impedance, and \( R_{c1} \)

\[ Z_{ac2} \]

\[
\begin{array}{c|c|c|c|c|c}
1 & 1k & 1M & 1G & \text{rad/s} \\
\hline
1M & \text{ } & \text{ } & \text{ } & \text{ } \\
100k & \text{ } & \text{ } & \text{ } & \text{ } \\
10k & \text{ } & \text{ } & \text{ } & \text{ } \\
1k & \text{ } & \text{ } & \text{ } & \text{ } 
\end{array}
\]
6. Biasing

For our standard 2-stage NMOS-input CMOS op-amp (e.g. lecture notes W6L1P4LL) once the device sizes are picked the resistor sets the overdrive voltage in all of the transistors. If

- $\mu_n C_{ox} = 200 \mu A/V^2$
- $\mu_p C_{ox} = 100 \mu A/V^2$
- $\lambda = 0.1 \text{V}^{-1}$
- $V_{in} = -V_{tp} = 0.5 \text{V}$
- $V_{DD} = 2 \text{V}$
- $(W/L)_1 = 100$
• \((W/L)_2 = 200\)
• \((W/L)_4 = 400\)

\[ (W/L)_{3,5,6} = 200 \]

\[ (W/L)_{2,4} = 400 \]

Figure 1: Our standard 2-stage NMOS-input CMOS op amp, duplicated here for convenience

(a) What is the reference current \(I_{REF}\) necessary for each of the following biasing conditions? You may assume \(\lambda = 0\) to make these calculations easier.

**Rubric:** (6 Points)

• +2: Per correct answer \((\times 3)\)

i. \(V_{ov} = 100\)mV

**Solution:**

Note that all the PMOS devices relative to their corresponding NMOS devices in the same branch are twice as large to have the same overdrive (since they’re half as strong per \(W/L\)).

\[ I_{D6} = I_{REF} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{ov}^2 \]
\[ = 0.2\text{mA} \]

\[ I_{REF} = 0.2\text{mA} \]

ii. \(V_{ov} = 500\)mV

**Solution:**

Note that all the PMOS devices relative to their corresponding NMOS devices in the same branch are twice as large to have the same overdrive (since they’re half as strong per \(W/L\)).

\[ I_{D6} = I_{REF} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{ov}^2 \]
\[ = 5\text{mA} \]
\( I_{REF} = 5\text{mA} \)

iii. \( V_{ov} = -80\text{mV} \) (assuming that subthreshold and inversion currents are equal when \( V_{ov} = 10\text{mV} \), and \( n = 1.5 \))

**Solution:**
Setting subthreshold and inversion currents equal:

\[
\frac{1}{2} \mu_n C_{ox} \frac{W}{L} (10\text{mV})^2 = 2\mu\text{A}
\]

From here, we know we need 90mV/decade of current in subthreshold, so when \( V_{ov} = -80\text{mV} \), that’s 1 decade(s) of current less than the previous value.

0.2\mu\text{A}

(b) What are the bias resistor values needed to produce the bias conditions above?

**Solution:**
We’ve already found the current through the resistors from above, so

\[
R = \frac{V_{DD} - V_{GS6}}{I_{REF}} = \frac{V_{DD} - (V_n + V_{ov6})}{I_{REF}}
\]

Going in order,

| 7k\Omega |
| 200\Omega |
| 79M\Omega |

**Rubric:** (6 Points)
- +3: Correct method
- +1: Per correct numerical value (\( \times 3 \))

(c) Looking back at HW3 Problem 3, on a single plot sketch the gain and bandwidth of this amplifier vs. bias resistor value.

**Solution:**
This is an n-input common source amplifier with the same process parameters as above.

For the gain

\[
|A_v| = g_{mv} (\frac{1}{r_{on}}) \\
= \frac{2I_D}{V_{ov}} \cdot \frac{1}{2\lambda I_D} \\
= \frac{1}{\lambda V_{ov}}
\]
For the bandwidth

\[ \omega_{3dB} = \frac{1}{R_o C_L} \]

\[ = \frac{1}{(r_{op})|r_{on}| C_L} \]

\[ = \frac{2\lambda I_D}{C_L} \]

Remember that

\[ \frac{V_{DD} - (V_t + V_{ov})}{R} = \frac{1}{2} \mu_n C_{ox} V_{ov}^2 \]

so solving for \( V_{ov} \) in terms of \( R \) isn’t trivial. However, we can go the other direction and plot overdrive vs. resistance:

And from there we can calculate the gain and bandwidth using the equations we described above:
Rubric: (4 Points)
- +1: Correct equation for gain
- +1: Correct equation for bandwidth
- +2: Reasonable attempt at plotting

7. Output Range
You have three op-amp topologies: single stage active load (our standard 5 transistor opamp), the two stage version of that, and the current mirror op-amp. Each topology can either have NMOS or PMOS inputs, for six different op-amps. Sketch the output swing vs. common mode input range for the PMOS versions.

Rubric: (12 Points)
- +2: Per correct amplifier (6×)

Solution:
5 transistor opamp with pmos input:

two-stage opamp with pmos input
8. Razavi’s equations

Figure 6.15 in Razavi is a model of a two-stage amplifier. [For ee247A students: Fig 9.18 in GHLM, and equations 9.27 and 9.33 for parts b and c]

(a) Re-draw it using our terminology from class: \( G_{m1}, G_{m2}, R_{o1}, R_{o2}, C_1, C_2, C_c \).

Solution:

\[
\begin{align*}
\text{Rubric: } & \quad \text{(2 Points)} \\
& \quad \text{• +2: Correct}
\end{align*}
\]

(b) Equation 6.30 is the transfer function of the amplifier. Re-write that with our terminology.

Solution: [2 pts]

\[
\frac{V_o(s)}{V_i(s)} = \frac{(C_c s - G_{m2}) R_{o2}}{R_{o1} R_{o2} C_c s^2 + R_{o1} (1 + G_{m1} R_{o2}) C_c + C_i + R_{o2} (C_c s + 1)}
\]

Where, \( \xi = C_c C_e + C_c C_z + C_z C_e \)

Rubric: (2 Points)
• +2: Correct rewrite

(c) Equation 6.39 is the simplified expression for the 2nd pole location, assuming the first pole is given by Miller-multiplied $C_c$.

i. Re-write that with our terminology

Solution: [1 pts]

\[ \omega_{p2} = \frac{1}{\omega_{p1} \frac{R_1 R_2}{R_1 + R_2} \left( C_1 C_2 + C_1 C_c + C_2 C_c \right)} \]

\[ = \frac{R_1 \left( 1 + G_m R_2 C_c + C_1 + R_2 \left( C_c + C_2 \right) \right)}{R_1 R_2 \left( C_1 C_2 + C_1 C_c + C_2 C_c \right)} \]

ii. Assuming that the 2nd stage gain is much larger than 1, the Miller capacitance is all that matters in the compensated first stage pole $\omega_{p1,c}$, write the expression for the compensated second stage pole $\omega_{p2,c}$ in terms of only capacitors and the transconductance of the second stage.

Solution: [1 pts]

\[ \omega_{p2} \approx \frac{G_m}{C_2} \]

iii. With those same assumptions, and ignoring any other poles and zeros, what is the constraint on transconductance and capacitance that insures a unity gain phase margin of at least 45°?

Solution: [1 pts]

To make $PM \geq 45°$, $\omega_d \leq \omega_{p2}$. Then,

\[ \frac{G_m C_c}{G_m C_2} \geq 1 \]

Rubric: (3 Points)

• +1: Per correct subpart

9. [Not Graded] Virtual Ground Doesn’t Fly

Estimate the output resistance of a CMOS differential amplifier with current mirror load.

You may assume that $g_m r_o \gg 1$ for all combinations of $g_m$ and $r_o$. The following steps may help:

(a) Estimate the impedance seen looking into the source of M1A

Solution:

\[ R_a = \frac{1}{\frac{1}{g_m a} + r_o} \]

\[ \approx \frac{r_o}{g_{m1a} r_o} \]
Rubric: (1 Points)
• +1: Correct impedance estimate

(b) Estimate the impedance seen looking down from the source of M1B

Solution:

\[ R_b \approx \frac{1}{g_{m1a}} \]

Rubric: (1 Points)
• +1: Correct impedance estimate

(c) Estimate the impedance seen looking into the drain of M1B

Solution:

\[ R_c = R_b + r_o (1 + g_m R_b) \]
\[ \approx r_o (1 + g_m R_b) \]
\[ \approx 2r_o \]

Rubric: (1 Points)
• +1: Correct impedance estimate

(d) For the \( R_o \) calculation, estimate \( i_{d1B} \) as a function of \( v_o \).

Solution:

\[ i_{d1B} = \frac{v_o}{R_{out}} = \frac{v_o}{2r_o 1B} \]

Rubric: (1 Points)
• +1: Correct relationship between $i_{d1B}$ and $v_o$

(e) The current $i_{d2B}$ is due to both the output resistance and the mirrored current. Estimate both parts.

Solution:

\[ i_{d2B} = (\text{mirrored current}) + (\text{current due to output resistance}) \]
\[ \approx i_{d1B} + \frac{v_o}{r_{o2B}} \]
\[ = \frac{3v_o}{2r_o} \]

\[ i_{d2B} = \frac{3v_o}{2r_o}, r_o = r_{o1B} = r_{o2B} \]

Rubric: (2 Points)
• +1: Correct mirrored current
• +1: Correct current due to output resistance

(f) Estimate the total output current $i_o = i_{d1B} + i_{d2B}$.

Solution:

\[ i_o = i_{d1B} + i_{d2B} \]
\[ \approx \frac{v_o}{2r_{o1B}} + \frac{v_o}{2r_{o1B}} + \frac{v_o}{r_{o2B}} \]
\[ = v_o \left( \frac{1}{r_{o1B} + r_{o2B}} \right) \]

\[ i_o \approx v_o \left( \frac{1}{r_{o1B} + r_{o2B}} \right) \]

Rubric: (1 Points)
• +1: Correct total output current given previous answers (don’t double-penalize)

(g) Show that $R_o \approx r_{o1B} || r_{o2B}$. Magic!

Solution:

\[ R_o = \frac{v_o}{i_o} \]
\[ \approx \frac{1}{\left( \frac{1}{r_{o1B}} + \frac{1}{r_{o2B}} \right)} \]
\[ = r_{o1B} || r_{o2B} \]

\[ R_o \approx r_{o1B} || r_{o2B} \]

Rubric: (1 Points)

A single-stage op-amp has a low frequency gain of 200 and a dominant pole at 10\text{Mrad/s}.

(a) Draw the s-plane with the real axis from $-10^7$ to 0, and the imaginary axis from 0 to $10^7$. Mark the pole location and draw a dot at 10$^7 j$.

\textbf{Solution:} See the solution for part (c)

\textbf{Rubric:} (2 Points)

\begin{itemize}
  \item +1: Correct imaginary and real axes
  \item +1: Correct pole location
\end{itemize}

(b) Draw the vector from the pole to 10$^7 j$. Calculate the magnitude and phase of this vector.

\textbf{Solution:}

\begin{align*}
\text{magnitude} &= \sqrt{2} \cdot 10^7 \\
\text{phase} &= -\arctan \left( \frac{10^7}{10^7} \right) \\
&= 45^\circ
\end{align*}

See the solution for part (c) for the plot.

\begin{align*}
\text{magnitude} &= \sqrt{2} \cdot 10^7 \\
\text{phase} &= 45^\circ
\end{align*}

\textbf{Rubric:} (3 Points)

\begin{itemize}
  \item +1: Drew vector
  \item +1: Correct magnitude
  \item +1: Correct phase
\end{itemize}

(c) Draw a dot at 10$^6 j$. Draw the vector from the pole to 10$^6 j$. Calculate the magnitude and phase of this vector.

\textbf{Solution:}

\begin{align*}
\text{magnitude} &= \sqrt{(10^7)^2 + (10^6)^2} \\
&\approx 10^7 \\
\text{phase} &= -\arctan \left( \frac{10^6}{10^7} \right) \\
&\approx 0.1 \text{ rad} \quad \text{small angle approximation} \\
&\approx 5.73^\circ
\end{align*}
Rubric: (3 Points)
- +1: Drew vector and dot
- +1: Correct magnitude
- +1: Correct phase

(d) Repeat parts (a) and (b), but with the imaginary axis from 0 to $10^8$ and the dot at $10^8 j$. Keep the pole in the same location.

Solution:

\[
\text{magnitude} = \sqrt{(10^7)^2 + (10^8)^2} \\
\approx 10^8 \\
\]

\[
\text{phase} = -\arctan\left(\frac{10^8}{10^7}\right) \\
\approx 1.47\text{rad} \\
\approx 84.3^\circ
\]
Rubric: (3 Points)
• +1: Drew vector
• +1: Correct magnitude
• +1: Correct phase

(e) Draw a Bode plot of the gain of your amplifier, with frequency running from $10^5$ to $10^9$ rad/s. Use the straight-line approximations for the Bode plot, and then add dots showing the results of parts (b), (c), and (d).

Solution:

Rubric: (4 Points)
• +1: Correct DC magnitude
• +1: Correct pole frequency
• +1: Correct magnitude slope
• +1: Correct phase start and end values

11. [Not Graded] Virtual Ground Is A Lie

For a standard 5 transistor CMOS differential amplifier show that the gain from a differential input to the (so called virtual ground!) tail voltage is \( \frac{1}{4} \). You can assume that \( g_m r_o \gg 1 \) for all combinations of \( g_m \) and \( r_o \). You can win bets with experienced IC designers with this knowledge!

Solution:

Estimating \( G_m \):

\[
\begin{align*}
  v_{\text{mirr}} &\approx -\frac{v_i}{2} \\
  v_d &\approx g_m v_i \left( \frac{r_o}{2} \right) \\
  i_o &\approx -\frac{v_x}{r_o} - \frac{v_d}{r_o} \\
  &\approx -\frac{v_i}{2r_o} - \frac{g_m}{2} v_i \\
  G_m &\approx -\frac{g_m}{2}
\end{align*}
\]

Estimating \( R_o \)

\[
R_o \approx r_o \left| \frac{r_o + \frac{1}{g_m}}{1 + g_m r_o} \right| \frac{r_o + r_o}{1 + g_m r_o} \\
\approx r_o \left| \frac{1}{g_m} \right| \frac{2}{g_m} \\
\approx \frac{2}{3g_m} \\
\approx \frac{1}{2g_m} \text{ if you ignore the additional } r_o \text{ on the non-diode connected branch}
\]

Rubric: (4 Points)

• +1: Correct \( G_m \) estimate with correct sign
• +1: Correct \( R_o \) estimate (using \( \frac{2}{3g_m} \) is acceptable)
• +2: Correct gain with correct sign