Problem 1: You have an amplifier with a gain of 1000 and a single pole at $10^7$ rad/s. You put it into feedback with a feedback factor of exactly $f=0.1$.

A. What is the closed-loop pole location?
B. What is the low-frequency closed-loop gain, exactly?
C. If the amplifier gain varies from 1000 to 5000 over process, voltage, and temperature variation, what is the range of the closed-loop gain?
D. What is the low-frequency closed-loop gain error? (Define closed-loop gain error as the % difference between the actual closed-loop gain, and the closed-loop gain if the amplifier were an ideal op-amp with infinite gain).
E. What is the closed-loop gain error at $10^8$ rad/sec, $10^9$ rad/sec, $10^{10}$ rad/sec?

Problem 2: Use spice to simulate your oscillator from the project. Turn in the schematic of your circuit, your spice deck, your hand analysis of the operating point and Bode plot of open loop gain, and your spice simulations of the operating point, Bode plot of open loop gain, and transient analysis showing oscillation. Compare your hand calcs to spice. (note: All of this goes directly into your final project report as well.)

Problem 3: Amplifier or Oscillator?
The circuit below consists of three CMOS inverters, and can be used as an amplifier or an oscillator, depending on the load capacitance. If we make the inverters such that $(W/L)_{PMOS} / (W/L)_{NMOS}$ is the same as the ratio of the N and P mobilities, then the inverters will switch at mid-rail ($V_{DD}/2$). The low-frequency gain through this amplifier is big and negative (180 degrees of phase shift). There are at least 4 poles (can you estimate their magnitude? With $t_{ox}=6.9$nm, $C_{ox}=5$F/um²). At some frequency those poles will give us another 180 degrees of phase shift, for a total of 360, or 0.

A) Using the spice deck below, plot the open loop gain (magnitude and phase) from $V_{IN}$ to $V_{FB}$. With $C_{FB}=0$, what is the unity gain frequency, $\omega_1$? What is the gain when the phase shift around the loop is 360? What is the frequency, $\omega_{360}$? Try the same with $C_{FB}$ set to 50pF, 100pF, and 1nF, and fill in the following table.

<table>
<thead>
<tr>
<th>$C_{FB}$</th>
<th>$\omega_1$</th>
<th>$\omega_{360}$</th>
<th>$A(f \omega_{360})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50pF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100pF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1nF</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The circuit diagram is as follows:

- $V_{SRC}$
- $R_{SRC}$
- $V_{IN}$
- $V_{FB}$
- $R_{FB}$
- $C_{FB}$
- $V_{out3}$

The output is connected to a 10u/0.5u and 5u/0.5u.
B1) Using spice, connect the feedback node to the input node (IN) with a 0 Ohm resistor. Let V\textsubscript{SRC} float (spice will give you a warning about node src – that’s fine). This circuit is a ring oscillator. With CFB=0, do a transient analysis from 0 to 10ns. What’s the period? Does it match what you would expect from part A?

B2) Repeat for C\textsubscript{FB}=50pF. Simulate from 0 to 1us, and make sure to plot all four nodes: in, out1, out2, out3. Why do we need to simulate for so much longer? Think about what it takes to get the circuit into the high-gain region.

B3) Repeat for C\textsubscript{FB}=100pF. What operating point does the circuit settle to after ~0.8us? Smoothly, or with bumps? Zoom in to find the frequency of the bumps.

B4) Repeat for C\textsubscript{FB}=1nF. You will need to simulator for ~1us for this one (why so much longer?).

B5) Fill in the table with your measured period. Do the numbers match? Why does the oscillation not continue with larger capacitors?

<table>
<thead>
<tr>
<th>C\textsubscript{FB}</th>
<th>(\omega_{360}) (from part A)</th>
<th>Oscillation frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50pF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100pF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1nF</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C) Now using the same circuit from part B, with C\textsubscript{FB}=1nF, and VSRC connected, use spice to generate a closed-loop bode plot of the amplifier. The closed-loop amplifier has a gain of \(-R\text{fb}/R\text{src}\), or -1 in this case. What is the pole frequency of the closed-loop amplifier? How does that compare to the pole frequency that you measured in B5? What has feedback done to the pole frequency?

C2) Now plot the transient response of the amplifier to a step input. Does Vout3 faithfully reproduce -1 V\text{src} (note that “AC gnd” in this case is the equilibrium point of 1.5V)?