Ground Rules:

- Closed book and notes; one formula sheet (both sides)
- Do all work on exam pages
- Answers accurate to within 10% will receive full credit
- Default bipolar transistor parameters:
  
  \[
  \text{nnp: } (\beta)^n = 100, \ V_{AN} = 50 \ V, \ I_{Sn} = 10^{-16} \ A. \\
  \text{pnp: } (\beta)^p = 50, \ V_{AP} = 25 \ V, \ I_{Sp} = 10^{-16} \ A. 
  \]

- Default MOS transistor parameters:

  \[
  \text{NMOS: } (\mu)^n \ C_{ox} = 50 (\mu)AV^{-2}, \ (\lambda)^n = 0.02V^{-1}, \ V_{Tn} = 1 \ V. \\
  \text{PMOS: } (\mu)^p \ C_{ox} = 25 (\mu)AV^{-2}, \ (\lambda)^p = 0.02V^{-1}, \ V_{Tp} = -1 \ V. 
  \]

**Problem #1. Matched Complementary Bipolar Transistor Design [12 points]**

The cross sections, minority carrier concentrations, and circuit schematics are shown for matched npn and pnp vertical BJTs, operated in the forward-active region.
Given: all doping levels are matched and the emitter areas are identical

- $N_{dE} (npn) = N_{aE} (pnp)$
- $N_{aB} (npn) = N_{dB} (pnp)$
- $N_{dC} (npn) = N_{aC} (pnp)$
- $A_E (npn) = A_E (pnp)$

Given: the bias voltages for the two transistors are matched and both are in the forward-active region

- $V_{BEn} = V_{EBp}$
- $V_{CEn} = V_{ECP}$

(a) [5 pts.] In order for the npn and the pnp transistors to have matched collector currents, $I_{Cn} = |I_{ Cp}|$, determine the numerical value of the base width of the pnp, $W_{Bp}$.

Given: the base width of the npn is $W_{Bn} = 0.2$ (mu)m, the electron diffusion coefficient (diffusivity) is $D_n = 20 \text{ cm}^2\text{s}^{-1}$, and the hole diffusivity is $D_p = 10 \text{ cm}^2\text{s}^{-1}$ -- these are valid for the emitter, base, and collector of each transistor.

(b) [5 pts.] In order for the npn and the pnp transistors to matched base currents, $I_{Bbn} = |I_{ Bp}|$, determine the numerical value of the emitter width of the pnp, $W_{Ep}$. This part is independent of part (a).

Given: the emitter width of the npn is $W_{En} = 0.1$ (mu)m, and $D_n = 20 \text{ cm}^2\text{s}^{-1}$, $D_p = 10 \text{ cm}^2\text{s}^{-1}$.

(c) [2 pts.] Which transistor has the smaller Early voltage, $V_A$? Explain why in one sentence.
Problem #2. Two-Stage Transconductance Amplifier [24 points]

Given: \( I_{\text{REF}} = 100 \ \mu\text{A} \), \( V_L = 0 \) (DC), \( R_S = 1 \ \text{k}\Omega \), \( R_L = 400 \ \text{k}\Omega \)
MOSEFTs: \((W/L)_{3,5,6,7} = 10\) and \((W/L)_4 = 25\)

(a) [4 pts.] Find the collector currents \( I_{C1} \) and \( I_{C2} \). You can neglect the base currents \( I_{B1} \) and \( I_{B2} \), as is customary for hand calculations.

(b) [4 pts.] Find the numerical value of the input resistance, \( R_i \) of this amplifier. If you couldn't answer part (a), you can assume that \( I_{C1} = 50 \ \mu\text{A} \) and that \( I_{C2} = 75 \ \mu\text{A} \) for this part.

(c) [4 pts.] Find the numerical answer value of the output resistance, \( R_o \) of this amplifier. If you couldn't answer part (a), you can assume that \( I_{C1} = 50 \ \mu\text{A} \) and that \( I_{C2} = 75 \ \mu\text{A} \) for this part.

(d) [4 pts.] Find the numerical value of the short-circuit transconductance \( G_m \) of the amplifier. Again, if you couldn't answer part (a), you can assume that \( I_{C1} = 50 \ \mu\text{A} \) and that \( I_{C2} = 75 \ \mu\text{A} \) for this part.

(e) [5 pts.] Find the numerical value of the load current \( i_l \), for a small-signal input voltage \( v_s = 2 \ \text{mV} \). If you couldn't solve parts (b), (c), and (d), assume for this part that \( R_i = 80 \ \text{k}\Omega \), \( R_o = 500 \ \text{k}\Omega \), and \( G_m = 7.5 \ \text{mS} \).

(f) [3 pts.] What is the DC voltage at the base \( Q_1 \)? You can assume that \( V_{BE} = 0.7\text{V} \) for the transistors in the forward-active region.

Problem #3. Current-Source Design [14 points]
Given: \((W/L)_1 = (W/L)_2 = (W/L)_3\)

(a) [5 pts.] Find \((W/L)_1\) such that \(I_{REF} = 20\) \((\mu A)\).

(b) [3 pts.] Find \((W/L)_4\) such that \(I_{OUT} = 50\) \((\mu A)\). If you couldn't solve part (a), assume that \((W/L)_1 = 10\).

(c) [3 pts.] Find the numerical value of \(r_{oc}\) for this current source, assuming that \(I_{OUT} = 50\) \((\mu A)\).

(d) [3 pts.] Assuming that the source-gate voltage for transistor \(M_4\) is \(V_{SG4} = 1.4V\). What is the largest DC output voltage \(V_{OUT}\) for which transistor \(M_4\) remains in the saturation region?