University of Toronto

Faculty of Applied Science and Engineering

Final Examination

Date - Monday, April 23rd, 2001

Duration: 2 hours 30 mins.

ECE530S — Analog Electronics
Examiner - K. Phang

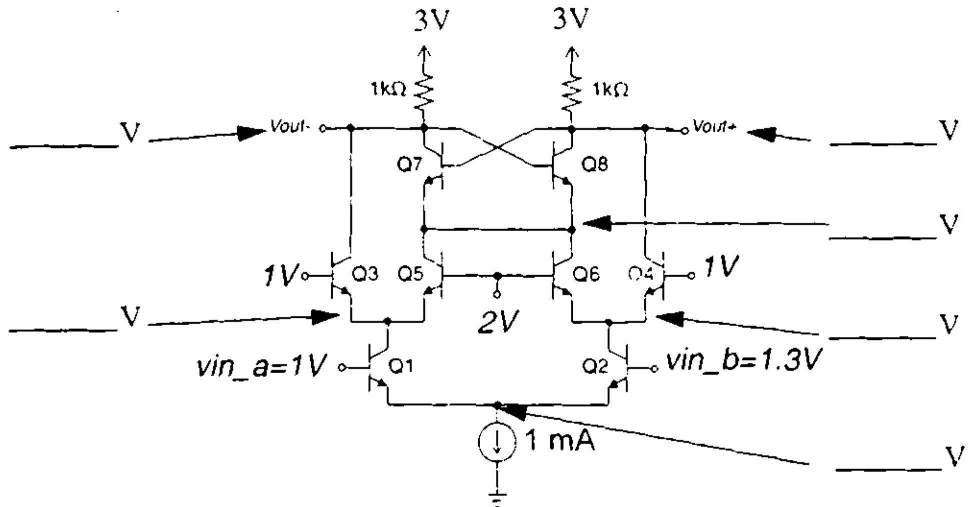
ANSWER QUESTIONS ON THESE SHEETS **USING BACKS IF NECESSARY**

1. Two, double-sided aid-sheets are allowed.
2. Grading is indicated by [ ]. Attempt all questions since a blank answer will certainly get 0.
3. Unless otherwise stated, use the device equations and parameter values found at the back of this exam paper.

Last Name: ____________________
First Name: ____________________
Student #: ____________________

Question	Mark
1	/8
2	/10
3	/10
4	/6
5	/8
6	/8
Total	/50

Question 1: [8] For the latched comparator circuit shown below



a) Circle what mode the latched comparator is currently in.

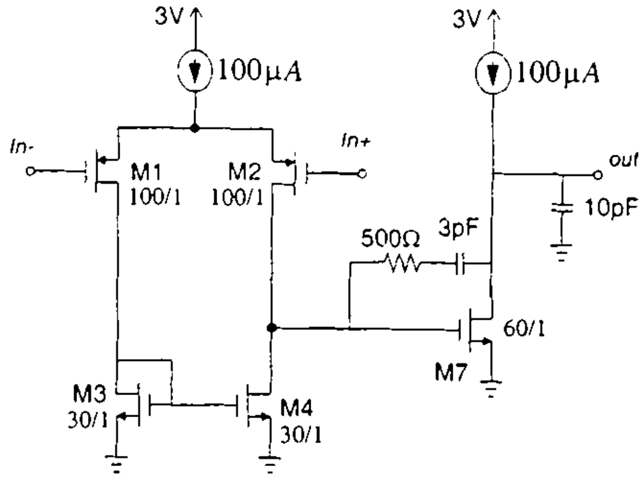
Latched Tracking

b) Assuming the input voltages are fixed, circle below the devices that are currently OFF.

Q1 Q2 Q3 Q4 Q5 Q6 Q7 Q8

c) Determine the SIX marked node voltages, assuming that $V_{BE} = 0.7V$ when a bipolar transistor is on and that $V_{CE} = 0.2V$ when the transistor is saturated.

Question 2: [10] For the following op amp circuit, assume $r_{ds} = 100k\Omega/\mu m \times L(\mu m)$, but otherwise use the process parameters for the 0.5um process found on equation summary sheet. Device W/L ratios are given in the diagram beside each device.



a) Give the expression for the small-signal gain, and calculate its value. Assume all current sources are ideal.

Last Name: ______________

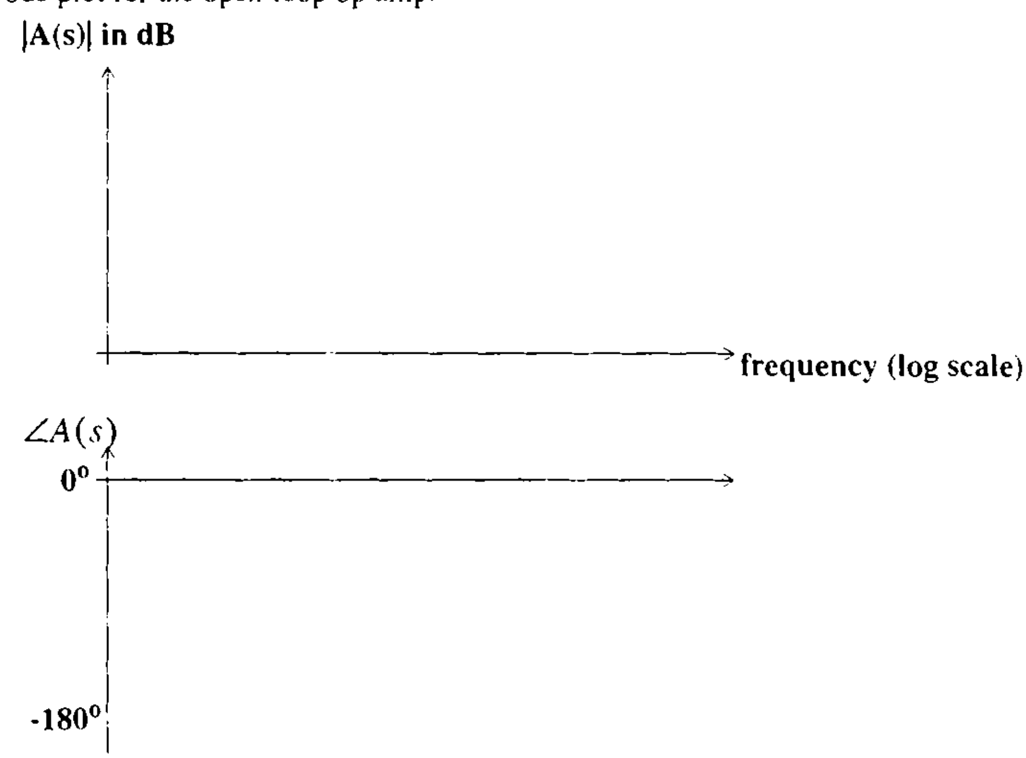
b) What is the slew rate of the amplifier? Is the op amp limited by its postive or negative slew rate? Assume the device parasitic capacitances are negligible.

Question 3: [10] You are given an op amp IC that has not been compensated to allow for unity-feedback operation. The op amp has the following frequency response

$$A(s) = \frac{A_o}{(1 + s/\omega_{p1})(1 + s/\omega_{p2})}$$

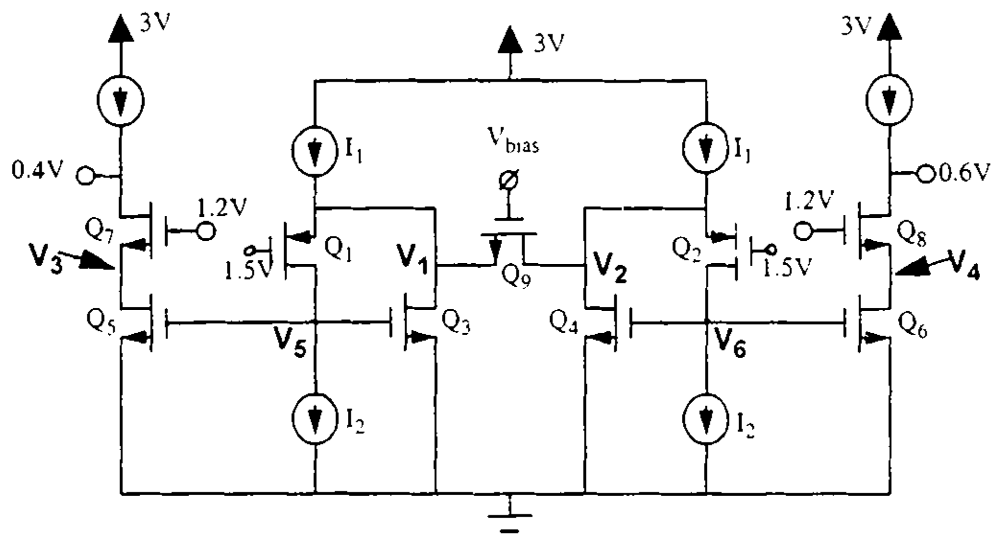
where $A_o = 3.16 \times 10^5$, $\omega_{p1} = 2\pi \times 500Hz$, $\omega_{p2} = 2\pi \times 15.8MHz$.

a) Sketch the Bode plot for the open-loop op amp.



b) If we want to ensure a step response with no overshoot, what is the maximum feedback factor, β, that can be used for this op amp in closed-loop configuration? (Hint: no overshoot occurs if the phase margin is greater than 75 degrees)

Question 4: [6] In the circuit below, all MOSFETs are biased with an effective voltage that is 0.2V in magnitude.



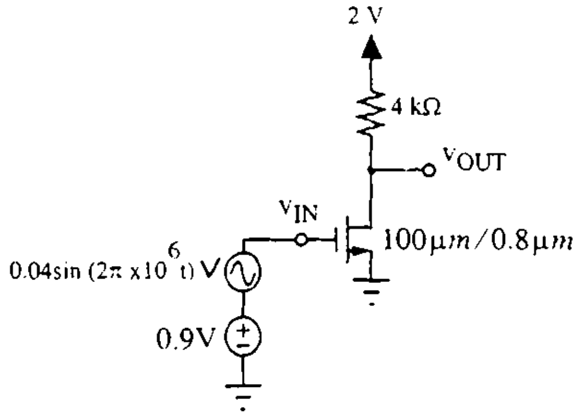
a) Determine the remaining node voltages in the circuit. Ignore the body effect.

Node	Voltage (V)
V_1	
V_2	
V_3	
V_4	
V_5	
V_6	

b) Circle the operating region that each MOSFET is in:

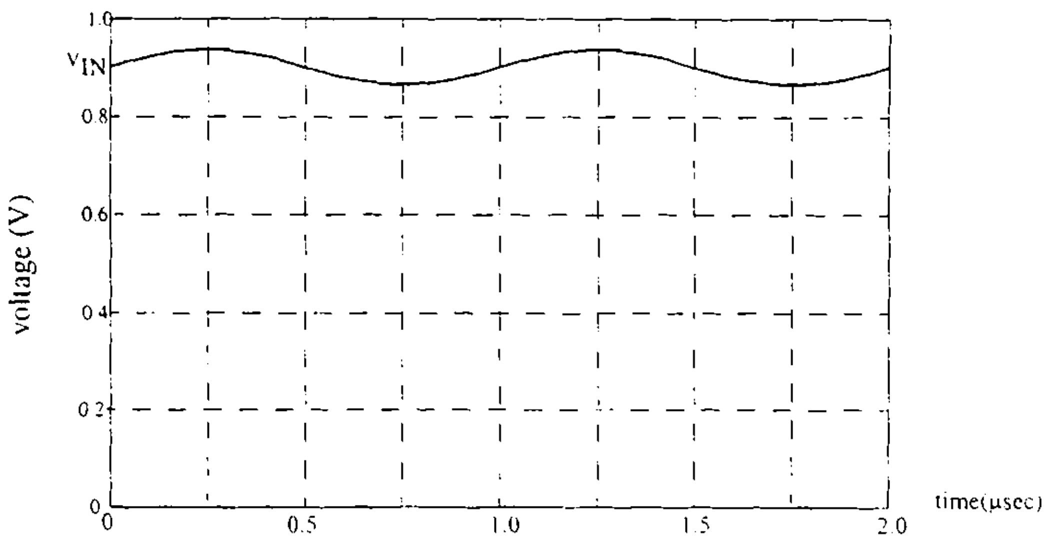
MOSFET	Operating Region	
Q1	Triode	Active
Q2	Triode	Active
Q3	Triode	Active
Q4	Triode	Active
Q5	Triode	Active
Q6	Triode	Active
Q7	Triode	Active
Q8	Triode	Active
Q9	Triode	Active

Question 5: [8] For the following amplifier circuit

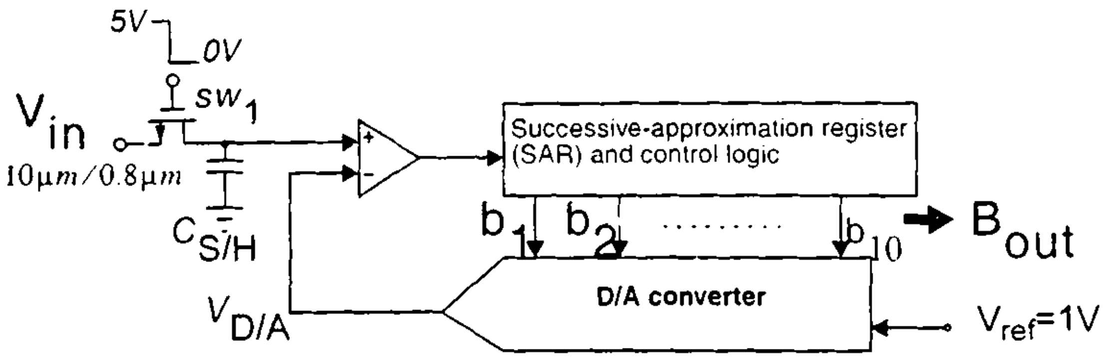


a) Find the small-signal gain. Assume $\lambda = 0$.

b) Given the input waveform, v_{IN}, sketch the approximate output waveform, v_{OUT}, on the same graph. Assume the parasitic capacitances are negligible.



Question 6: [8] The unipolar, 10-bit, successive-approximation (binary-search) A/D converter shown below uses a sample-and-hold circuit at the input. The input range is from 0V to 1V.



a) What is the maximum allowable voltage error of the sample-and-hold circuit in order to maintain 1/2 LSB accuracy?

b) Assuming the allowable voltage error due to charge injection and clock feedthrough of the S/H circuit is $\pm 1mV$, determine the minimum required size of capacitor $C_{S/H}$. Use the process parameters for the 0.5um process found on equation summary sheet. Ignore the body effect on SW_1, and assume that the portion of channel charge that is transferred to $C_{S/H}$ when SW_1 is opened may vary from 30% to 70%. (Hint: identify the worst-case scenario)

Question 6 (cont.)

Device Modelling Summary

Constants

$q = 1.602 \times 10^{-19}$ C	$k = 1.38 \times 10^{-23}$ JK^{-1}
$n_i = 1.1 \times 10^{16}$ carriers/m^3 at $T = 300$ °K	$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m
$K_{ox} \cong 3.9$	$K_s \cong 11.8$
$\mu_n = 0.05$ m^2/V·s	$\mu_p = 0.02$ m^2/V·s

Diode Equations

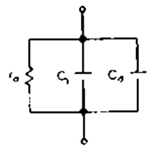
Reverse-Biased Diode (Abrupt Junction)

$C_j = \dfrac{C_{j0}}{\sqrt{1 + \dfrac{V_R}{\Phi_0}}}$	$Q = 2C_{j0}\Phi_0\sqrt{1 + \dfrac{V_R}{\Phi_0}}$
$C_{j0} = \sqrt{\dfrac{qK_s\varepsilon_0}{2\Phi_0}\dfrac{N_D N_A}{N_A + N_D}}$	$C_{j0} = \sqrt{\dfrac{qK_s\varepsilon_0 N_D}{2\Phi_0}}$ if $N_A \gg N_D$
$\Phi_0 = \dfrac{kT}{q}\ln\left(\dfrac{N_A N_D}{n_i^2}\right)$	

Forward-Biased Diode

$I_D = I_S e^{V_D/V_T}$	$I_S = A_D q n_i^2\left(\dfrac{D_n}{L_n N_A} + \dfrac{D_p}{L_p N_D}\right)$
$V_T = \dfrac{kT}{q} \cong 26$ mV at 300 °K	

Small-Signal Model of Forward-Biased Diode



$r_d = \dfrac{V_T}{I_D}$	$C_T = C_d + C_j$
$C_d = \tau_T\dfrac{I_D}{V_T}$	$C_j \cong 2C_{j0}$
$\tau_T = \dfrac{L_n^2}{D_n}$	

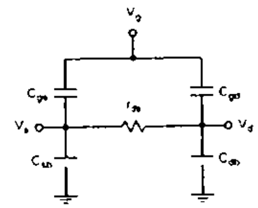
MOS Transistor Equations

The following equations are for n-channel devices—for p-channel devices, put negative signs in front of all voltages. These equations do not account for short-channel effects (i.e., $L < 2L_{min}$)

Triode Region ($V_{GS} > V_{tn}$, $V_{DS} \le V_{eff}$)

$I_D = \mu_n C_{ox}\left(\dfrac{W}{L}\right)\left[(V_{GS} - V_{tn})V_{DS} - \dfrac{V_{DS}^2}{2}\right]$	
$V_{eff} = V_{GS} - V_{tn}$	$V_{tn} = V_{tn-0} + \gamma\left(\sqrt{V_{SB} + 2\phi_F} - \sqrt{2\phi_F}\right)$
$\phi_F = \dfrac{kT}{q}\ln\left(\dfrac{N_A}{n_i}\right)$	$\gamma = \dfrac{\sqrt{2qK_{si}\varepsilon_0 N_A}}{C_{ox}}$
$C_{ox} = \dfrac{K_{ox}\varepsilon_0}{t_{ox}}$	

Small-Signal Model in Triode Region (for $V_{DS} \ll V_{eff}$)

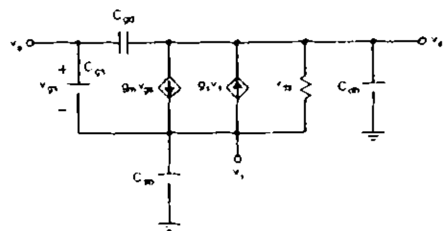


$r_{ds} = \dfrac{1}{\mu_n C_{ox}\left(\dfrac{W}{L}\right)V_{eff}}$	
$C_{gd} = C_{gs} \cong \dfrac{1}{2}WLC_{ox} + WL_{ov}C_{ox}$	$C_{sb} = C_{db} = \dfrac{C_{j0}(A_s + WL/2)}{\sqrt{1 + \dfrac{V_{sb}}{\Phi_0}}}$

Active (or Pinch-Off) Region ($V_{GS} > V_{tn}$, $V_{DS} \ge V_{eff}$)

$I_D = \dfrac{\mu_n C_{ox}}{2}\dfrac{W}{L}(V_{GS} - V_{tn})^2[1 + \lambda(V_{DS} - V_{eff})]$	
$\lambda \cong \dfrac{1}{L\sqrt{V_{DS} - V_{eff} + \Phi_0}}$	$V_{tn} = V_{tn-0} + \gamma\left(\sqrt{V_{SB} + 2\phi_F} - \sqrt{2\phi_F}\right)$
$V_{eff} = V_{GS} - V_{tn} = \sqrt{\dfrac{2I_D}{\mu_n C_{ox} W/L}}$	

Small-Signal Model (Active Region)



$g_m = \mu_n C_{ox}\left(\frac{W}{L}\right)V_{eff}$	$g_m = \sqrt{2\mu_n C_{ox}(W/L)I_D}$
$g_m = \frac{2I_D}{V_{eff}}$	$g_s = \frac{\gamma g_m}{2\sqrt{V_{SB} + 2\phi_F}}$
$r_{ds} = \frac{1}{\lambda I_D}$	$g_s \approx 0.2 g_m$
$\lambda = \frac{k_{rds}}{2L\sqrt{V_{DS} - V_{eff} + \Phi_0}}$	$k_{rds} = \sqrt{\frac{2K_s\epsilon_0}{qN_A}}$
$C_{gs} = \frac{2}{3}WLC_{ox} + WL_{ov}C_{ox}$	$C_{gd} = WL_{ov}C_{ox}$
$C_{sb} = (A_s + WL)C_{js} + P_sC_{j\text{-}sw}$	$C_{js} = \frac{C_{j0}}{\sqrt{1 + V_{SB}/\Phi_0}}$
$C_{db} = A_dC_{jd} + P_dC_{j\text{-}sw}$	$C_{jd} = \frac{C_{j0}}{\sqrt{1 + V_{DB}/\Phi_0}}$

Typical Values for a 0.5-μm Process

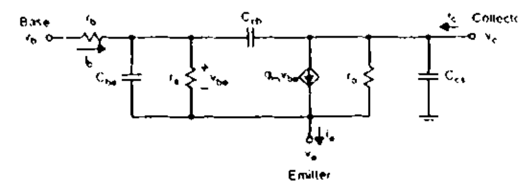
$V_{tn} = 0.7\ V$	$V_{tp} = -0.8\ V$
$\mu_n C_{ox} = 120\ \mu A/V^2$	$\mu_p C_{ox} = 60\ \mu A/V^2$
$C_{ox} = 3.4 \times 10^{-3}\ pF/(\mu m)^2$	$C_j = 5.4 \times 10^{-4}\ pF/(\mu m)^2$
$C_{j\text{-}sw} = 1.5 \times 10^{-4}\ pF/\mu m$	$C_{gs(overlap)} = 1.2 \times 10^{-4}\ pF/\mu m$
$\phi_F = 0.42\ V$	$\Phi_0 = 0.99\ V$
$\gamma = 0.6\ V^{1/2}$	$t_{ox} = 0.01\ \mu m$
$N_A \approx 1.3 \times 10^{17}$ impurities/cm^3	

Bipolar-Junction Transistors

Active Transistor

$I_C = I_{CS}e^{V_{BE}/V_T}$	$V_T = \frac{kT}{q} \cong 26\ mV$ at 300 °K
For more accuracy, $I_C = I_{CS}e^{V_{BE}/V_T}\left(1 + \frac{V_{CE}}{V_A}\right)$	
$I_{CS} = \frac{A_E q D_n n_i^2}{WN_A}$	$I_B = \frac{I_C}{\beta}$
$I_E = \left(1 + \frac{1}{\beta}\right)I_C = \frac{1}{\alpha}I_C = (\beta + 1)I_B$	$\beta = \frac{I_C}{I_B} = \frac{D_n N_D L_p}{D_p N_A W} \cong 2.5\frac{N_D L_p}{N_A W}$
$\alpha = \frac{\beta}{1 + \beta}$	

Small-Signal Model of an Active BJT



$g_m = \frac{I_C}{V_T}$	$r_\pi = \frac{V_T}{I_B} = \frac{\beta}{g_m}$
$r_e = \frac{\alpha}{g_m}$	$r_o = \frac{V_A}{I_C}$
$g_m r_o = \frac{V_A}{V_T}$	$C_d = \tau_b\frac{I_C}{V_T} = g_m\tau_b$
$C_{be} = C_j + C_d$	$C_{cs} = \frac{A_T C_{js0}}{\left(1 + \frac{V_{CS}}{\Phi_{s0}}\right)^{1/2}}$
$C_{cb} = \frac{A_C C_{jc0}}{\left(1 + \frac{V_{CB}}{\Phi_{c0}}\right)^{1/3}}$	