Final Exam, ECE 137A

Wednesday March 20, 2019, Noon - 3 p.m.

Name: _____

Closed Book Exam:

Class Crib-Sheet and 2 pages (4 surfaces) of student notes permitted Do not open this exam until instructed to do so. Use any and all reasonable approximations (5% accuracy), *after stating & justifying them*.

Show your work:

Full credit will not be given for correct answers if supporting work is missing. Good luck

Time function	LaPlace Transform
$\delta(t)$ impulse	1
U(t) unit step-function	1/ <i>s</i>
$e^{-\alpha t}U(t)$	$\frac{1}{s+\alpha} = \frac{1/\alpha}{1+s/\alpha}$
$e^{-\alpha t}\cos(\omega_d t)U(t)$	$\frac{s+\alpha}{\left(s+\alpha\right)^2+\omega_d^2}$
$e^{-\alpha t}\sin(\omega_d t)U(t)$	$\frac{\omega_d}{\left(s+\alpha\right)^2+\omega_d^2}$

Part	Points	Points	Part	Points	Points
	Received	Possible		Received	Possible
1a		6	2c		15
1b		5	2d		10
1c		4	3a		7
1d		10	3b		8
1e		10	3c		7
2a		10	3d		8
2b		10			
total		100			

Problem 1, 35 points

This is an NOT an Op-Amp: Analyze under the assumption that the differential and common mode input voltages are at zero volts



All the transistors have the same (matched) I_s , have $\beta = 100$, and $V_A = \infty$ Volts.

$$V_{CE(sat)} = 0.5 V$$

 V_{be} is approximately 0.7 V,

but use $V_{be} = (kT/q) \ln(I_E/I_S)$ when necessary or appropriate.

The supplies are +4 Volts and -4 Volts.

All transistors (and diodes) have the same I_s

Q1A,1B,5,11 are biased at 10mA collector current.

Q6 is biased at 25mA collector current.

Q7 and Q10 are biased at 3mA collector current.

The DC voltage drops across RE5 and RE14 are both 400mV.

RB1A=RB1B=2kOhm. RE1A=RE1B=44.8Ohm. RL11=1.1kOhm. RL=1kOhm.

Part a, 6 points DC bias---to simplify ,assume $\beta = \infty$ for the DC analysis only.

Find the value of the following resistors:

Re5=	Re14=	Re4=
Re15=	Re12=	Re3=
Re7=	Re10=	

4

Part b, 5 points





On the circuit diagram above, label the DC voltages at ALL nodes, and the DC collector currents of all transistors. Label the values of all resistors (except RC5).

6

Part c, 4 points

find the following

device	Q1AB	11	12	4	6	15	7	10
gm,								
mS								

Part d, 10 points.

Find the following, *using the actual value of* β , *i.e.* $\beta = 100$

	Voltage Gain	Input impedance
Q1AB		
Q11		
Q6		
Q7		
Overall differential		
Vout/Vin		

Note: with some insight, you can find the combined gain of Q1AB/11 in a single step. If would would like to do so, omit the separate answers for Q1AB and Q11 in the table above, and instead fill in the table below,

	Voltage Gain	Input impedance
Q1AB/Q11 combination.		

9

Part e, 10 points

Maximum peak-peak output voltage (*show all your work*)

For this, you must use the full circuit diagram, not the half circuit diagram.

	magnitude and sign of	magnitude and sign of
	maximum output signal	maximum output signal
	swing due to <i>cutoff</i>	swing due to <i>saturation</i>
Transistor Q7		
Transistor Q10		
Transistor Q6		
Transistor Q15		
Transistor Q4		
Transistor Q11		
Transistor Q1A		
Transistor Q1B		

Be warned: In some cases a limit is not relevant at all. Mark those answers "not relevant". But, give a 1-sentence statement below as to why it is not relevant. Q7/10 form a push pull stage, so be careful about your answer there.

Problem 2, 35 points

This is an Op-Amp---analyze the bias under the assumption that DC output voltage is zero volts, that the positive input Vi+ is zero volts, and that we must determine the DC value of the negative input voltage (Vi-) necessary to obtain this.



The NMOSFETs have $K_{\mu} = \mu c_{gs} W_g / 2L_g = 0.55 \text{mA/V}^2 \cdot (W_g / 1\mu\text{m})$ $K_{\nu} = c_{gs} v_{inj} W_g = 0.69 \text{mA/V} \cdot (W_g / 1\mu\text{m}), \ \Delta V = v_{inj} L_g / \mu = 0.625 \text{V}, \ V_{ih} = 0.25 \text{V},$ $1 / \lambda = 20 \text{V}$

The PMOS have identical parameters, except, of course, V_{th} is negative.

 $V_{DD} = +1 \text{ V}, -V_{SS} = -1 \text{ V}, R_{L} = 50 \text{ kOhm}$

All transistors have |Vgs|=0.35V, *except for M7 and M15*, which have |Vgs|=0.45V, *and except for M8,9,10,11*, which have |Vgs|=0.30V

M12,13 are biased at I_D =25 µA.

M5,7,15 are biased at $I_D = 50 \mu A$.

M8,9,10,11 are biased at $I_D = 50 \ \mu$ A.

Part a, 10 points DC bias. Analyze the bias under the assumption that DC output voltage is zero volts, that the positive input Vi+ is zero volts, and that we must determine the DC value of the negative input voltage (Vi-) necessary to obtain this. (Hint, this should give Vi- = 0V)

Find the following: Gate widths of M12 and M13 = _____ Gate width of M7 = _____ Gate width of M8 = _____ Gate width of M9 = _____

Part b, 10 points

DC bias



On the circuit diagram above, label the DC voltages at ALL nodes, the drain currents of ALL transistors, and the gate widths of ALL transistors

19

Part c, 15 points.

You will now compute the op-amp differential gain. Find the following

	Voltage Gain	Input impedance
Transistor combination		
M1,2,13, 13		
M5,6 combination		
Q9 or Q12.		
Q8 or Q15		
Overall differential		
Vout/Vin		

Notes:

1) You can analye M5 and M6 as separate stages, or as a combined stage using Norton/Thevenin methods. Don't ask for hints as to how to do this.

2) For M8/9and for M10/11, you can assume that M8 and M9 are on for the positive signal swing and M10 and M11 are on for the negative signal swing. More accurately, you can assume, for the signal swing near zero volts, that all are on. If you take the latter approach (and do it correctly), you will receive a couple of extra credit points. One hint (don't ask for any other hints): use symmetry.

Part d, 10 points

Maximum peak-peak output voltage at the positive output Vo+ (*show all your work*)

	magnitude and sign of	magnitude and sign of
	maximum output signal	maximum output signal
	swing due to <i>cutoff</i>	swing due to:
		<i>knee voltage</i> (saturation)
Transistor M9		
Transistor M11		
Transistor M8		
Transistor M10		
Transistor M4		
Transistor M19		
Transistor M6		
Transistor M14		

Be warned: in some cases a limit is not relevant. Mark those answers "not relevant".

Problem 3, 30 points



Part a, 7 points

Draw a small-signal equivalent circuit of the circuit.

Part b, 8 points

gm=10 mS. C=1pF. R= 1000 Ohms

Find, by nodal analysis, a small-signal expression for Vout/Vin. Be sure to give the answer with **correct units** and in ratio-of-polynomials form, i.e.

$$\frac{V_{out}(s)}{V_{gen}(s)} = K \cdot \frac{1 + b_1 s + b_2 s^2 + \dots}{1 + a_1 s + a_2 s^2 + \dots} \text{ or (as appropriat e)} \frac{V_{out}(s)}{V_{gen}(s)} = K \cdot (s\tau)^n \cdot \frac{1 + b_1 s + b_2 s^2 + \dots}{1 + a_1 s + a_2 s^2 + \dots}$$

Note that an expression like

 $\frac{V_{out}(s)}{V_{gen}(s)} = \frac{1}{1 + (3 \cdot 10^{-6})s}$ is dimensionally wrong; $\frac{1}{1 + (3 \cdot 10^{-6} \text{ seconds})s}$ is dimensionally correct

Vout(s)/Vin(s)=_____

Part c, 7 points

Find any/all pole and zero frequencies of the transfer function, in Hz:

Draw a clean Bode Plot of Vout/Vin,

LABEL AXES, LABEL all relevant gains and pole or zero frequencies, Label Slopes

	I						I						1							I						1						ı.						I	
_			-	-	\square	+++		 				111	ļ				_	\square	++		 -	-	-	_	\square	Ш	 			-					_			++	_
		1.0	$\mathbf{r} = \mathbf{r}$	÷.,	с÷,		i	i	1.1	i - 1	÷ 1		(C)	1.1		i	÷.,	i i	1.1	ю.	1.1	1.1		1	с÷.	e e i	1 - E	1.1	i	1		сн. – I			1.1	1.1			
_		202	1	ч.,	L L	υü	с. ц.	 с с.	1 -	ц. I	L L	οu	сц.			1 L	ц.,	L L	сı,	эc	 с.,	. г.	- 1-	L.	LС	ωų	 ы. ц	1	с.)	. L	οo	сці. П	1	1	. L 14	L 1	L L I	귀는	-
		1.1	1.1	1	1.1		1.1		1.1	1.1			1.1	1.1		١., I	۰.				1.1	11	1	1			1.1	1.1		1			1		1.1	1.1		11	
_		- 14 -	44	Ъ.	11	22	Ş. 2.	 2.2	44	24	14	222	ļ)		4 -	Ь.	11	25	44	 5.5	. ÷ .	- 1-	4	22	23	 2.4	4.4	23	4	213)		Ja	4	14	귀	_
		100	1.1	11	11	111	1		1.1	11		111		- 1		1	1		11	11	1.	11	4	11			1.1	1.1	11	1	111				- 1	11		н	
_		a la la	4.4	14	L L	1.1.4	6.0	 	4.2	1-1		in the	È L I			11	i	11	1.1	4.6	 1.	. i .	- i-	4	1.1	14.4	 14.14	4.4	i. i	÷.	1.1.4	1 H - H	1		i.	4.1		4	_
		1.0	$\mathbf{r} = \mathbf{r}$	£.,	с (r.	0.00	1.1	н. — — — — — — — — — — — — — — — — — — —	1.1	() (с н.	(1,1,1)	(i i i i	1.1		н I.	÷.,	с i	0.1	ю.	$\mathbf{r} = \mathbf{r}$	1.1	1	1.1	с÷,		1.1	$\mathbf{r} = \mathbf{r}$	с. I	1		с (° –			1.1	1.1			
_		202	2.2	<u>12</u>	1.1	5.02	5.5	 <u>u 1</u> .	1.1	12.3	1.1	9.92	512.5			1.1	Q.,	11	23	2.5	 12.1	11.	12	12	5.5	12.5	 12.12	L = L	93	1.1	9.9	12.2	$z \in X$	1	1212	12.1	5.51	24	_
		1.1	1.1	1			1.1	1. Star	1.1	1.1			1. State	1.1		١	١.,			11	1.1	1	1	1			1.00	1.1		1			1		1.1	1.1		11	
_			1.	5		111	2.2	 	1	2.1		111	<u>.</u>	!		<u>.</u> _	5		11		 L .			1			 2.2	1	2	. 1	111		!			1		11	_
		10.0	1.1	11	11	111	1.1		1.1	1.1		222		- 1		1	1	11	11	11	1.1	11	4	÷.	11	:::	1.1	1.1	11	11	111				- 1	11		11	
		di di	i	λ.	ιi.	66	i	 	i	1.1	L L	ЦÚ.				i	ί.	i i	Ш.	Зù	ί.	. i .	. i.,	÷.	i i	ыi	i	i	L i	÷.	ωü					1.1		JI.	
		-67	17	÷.	сī.	ΰŐ	67	 67	17	ē i	сĩ.	úñ,	671	11	-	۰Ť	ē.,	сī.	66	ωĩ	 11	17.	17	÷.	ωĩ	ωi	 67	17	6.	÷.	66	ωĒ.	17	- 1	- 77	1.1	ιū	٦F	
		1.0	1.1	۰.	с (r.	0.00	1.1	н. — — — — — — — — — — — — — — — — — — —	1.1	1.1	÷ 1	1.1.1	1 - C	1.1		н. – I	÷.,	с (1.1	1.1	1.1	1.	1	1	с (r		1.1	1.1	0.0	1		н — —			1.1	1.1		1	
	T	- C C	7.7	с.	τ.τ.	60	6.5	сε.	7.7	<u>e 1</u>	τ.	60	6.5.3	1.00		T 7.	с.	7.7	59	2.6	 6.2	11	10	π.	Г. C.	0.0	 6.5	7.7	6.9	17	60	ю÷.	2.24		196	1.1	6.63	٦F	-
		1.1	1.1	1.1		111	1		1.1	1.1		111		1		1	1	11	11	11	1.1	1	1	1		111	1.1	1.1	1	1	111				1			11	
_			17	Ζ.			27	 	27	2.1		222	5 - 1			17	2		1.1		 11	11	17	1			 2.5	17	2.1	12			1			11		7.5	-
		4.1	÷.,	11	11	111	i		1.1	1.1		111	i	- 1		1.	1.	11	11	11	1.1	11	4	4.1	11	111	1.1	÷.,	1.1	4	111				- 1	11			
-		16.5	7.7	С.	77	66	6.5	 6.5.	7.7	- T (17	66	6.5.3	177		77	С.	77	77	57	 17.1	17.1	17	÷7.	77	67	 6.5	7.7	6.6	17	66	67.7	2.27		100	111	77,	71	-
		1.0	$\mathbf{U}_{i} = \mathbf{U}_{i}$	۰.	с. I.	0.00	1 - C	н. — — — — — — — — — — — — — — — — — — —	1.1	1.1	÷ 1	0.00	1 - C	1.1		н. – с	÷.,	с (0.0	1.1	\mathbf{r}_{i+1}	1.1	1	1	с (1.1	\mathbf{r}_{i+1}	0.0	1		с (¹	1.1		1.1	1.1		1	
_	t		7.7	Π.	г г.	C (1)	5.5	 с т.	7.7	12.1	с г.	0.0		1.5.5		T 7	σ.	r r	с I.	7.5	 - C - C	1.1	1.17	Π.		17.0	 5.5	7.7	с.)	с. т.	0.0	с с.	2.23		1.0	- F - 1		٦Ē	-
		1	1	1		111	1		1.1	1.1		111		1		1	1		11	11	1	1	1	1.1			1.1	1.1	1	1	111				1			11	
_	t	- 21-2	27	а.		222	27	 2.2	27	21		222	5	123		17	а.		22	20	 2.1	111	17	÷.		22.2	 2.5	27	23	12	210	1.5	2.23		127	1.1		1 F	-
		1.1	1.1	i.	i i	1.1.1	i i		i.	1.1		111	i			1.1	i.	i i	i i	ii.	i.	1.	÷.	÷.	i i		1.1	i.	1.1	÷.	i i i				- i	1.1		1	
-	+	- e e	7.7	с.	тτ	0.0	6.5	 с. т.	7.7	C_{1}	τ.	0.0	6.5.5	1.7.6		7.7	с.	7.7	$T \in C$	5.6	 6.0	17.1	10	7	τr	0.7	 0.0	7.7	с.;	17	6.0	07.7	7,73		100	7.1	с с i	٦h	-
		1.0	1.1	۰.	с (r)	0.00	1 - C	н. — — — — — — — — — — — — — — — — — — —	1.1	1.1	÷ 1	0.00	1 - C	1.1		н. – I	÷.,	с (1.1	1.1	1.1	1.1	1	1	с (r		1.1	1.1	0.0	1		с (¹	1.1		1.1	1.1		1	
-	+		+ -	14		ы на 1	н н.	 	÷ -	1-1			5 - 1			÷ -	÷-		ь.		 14		- 1-	4		-	 1	÷ -	- 1	1		н н. С	1		- 1-	ь.,		ᅻ┝	-
		1.1	1.1	11	11	111	1		1.1	1.1		111	1	1		1	1	11	11	11	1.1	11	1	1		111	1.1	1.1	11	1	111				11			11	
-		- 2.5	÷ r	Ъ.	÷÷.	28	2.5	 2.2	÷ r	2.3	11	223	2.5.5	12)		÷-	Ъ.	11	÷2	12	 21	t fili	÷	÷.	11	23	 2.5	÷ r	23	÷÷.	233	2.5	5 E }		- 12	11		÷E	-
		1.1	i.	i.	i i	1.1.1	i		1.1	i i		111	i.			i	i.	i i	i i	ii.	i.	1	÷.	÷.	i i	i i i	1.1	i.	i i	÷.	1.1.1				÷.	i.			
-		10.5	$\tau = \tau$	(T_{i})	r r	σ (σ	e = 1	 e =	τ. τ	(τ_{i})	r r	e ini	e = 1	1.5		τ. τ	e.	r r	$\sigma_{\rm e}$	n e	 $\sigma_{\rm eff}$	с т . (1.0	Π.	r r	in r	 σ_{i}, σ_{i}	τ. Τ	e i	÷,	e in	0.0	7,7,6		1.0	F 3	n ni	٦ŀ	-
		1.0	1.1	۰.	с (),	1.1.1	1.1	1 - C	1.1	1.1	÷ 1	1.1.1	1 - C	1.1		۱. I	÷.,	с I	1.1	11	1.1	1.1	1	1	с (1.00	1.1		1		0	1.1		1.1	1.1		1	
-		- 5 -	1 -	5	L L	υu	6.2	 99	1 -	12.1	L L	сю,	5			± -	5	LL	<u>с</u> ,	J L	 5.5	- <u>+</u> -	- 1-	L	LЦ	9.6	 5.5	1 -	51	- L	C D	ц –	}	4		L 1	L L I	란남	-
		1.1	1.1	11		111	1		1.1	11		111		- 1		1	1		22	11	1.1	11	1	11		:::	1.1	1.1	11	1	111				- 1			11	
_		- in -	÷-	÷.	÷÷.	66	èн.	 6.5	÷-	ie i	÷÷.	86	2	i		÷-	÷.	÷ ÷	Ϋ́	֏	 ÷.	÷÷.	- i-	÷	÷ è	67	 6.5	÷-	h i	÷÷	26	T	j		je	÷		÷ŀ	-
		1.0	1.1	÷.,	сi.	1.1.1	i	i	1.1	i i	сi.	111	i	1		i	÷	сi.	ъŝ,	цÌ.	1.1	1.	÷.	1	сi.	нù	i	1.1	1.1	÷.	1.1.1	ст. —			1	1.1			
_			+ -	њ.,	e e	њ (т.)	н. н	 	4 -	i		ы (н н н			÷ -	i		ы.		 н.		- 1-	н.		64.6	 њ. –	÷ -	(÷ .)		6.14	н н. Н)		- 1-	н.	e e i	⊣⊢	-
		1.0	1.1	۰.	1.1	1.1.1	1.1	1. S.	1.1	0.0	1.1		1 - C	1.1		1	÷.,		1.1	11	1	11	1	1	с (1.1	1.1	1.1	1		0.00	1.1	1.1	1.1	1		1	
-	+	- 5	÷ -	5	5.5	22	5.5	 5.5	÷ ÷	53	94	88	5-5	}		÷ ÷	5	<u>+</u> +	55	45	 5.5	- ÷ -	÷÷	÷.	5.5	23	 동문	÷ -	23	÷ ÷	22	5 -	}	}	- 5	19	99	÷F	-
		11	1.1	11	11	111	1		11	11		111	1	- 1		1	1	11	11	11	1	11	4	1		11	1.1	1.1	11	1	111				1			11	
_		·	÷-	÷	 				÷-							· 		· ·		· · ·	 ·	· ·	· ·	·	 		 -	· ·										++	_
	1			1	11	111	1			1 1		1.1.1	1			1	I	11	11	11				1	L L	111		1	1 1	- L	111							- 1	

Part d, 8 points

Vin(t) is a 0.1 V amplitude step-function.

Find Vout(t)=_____

Plot it below. Label axes, show initial and final values, show time constants.

	1					ı	I		1	 1						I	1			
-	 					 			 	 	 		 							Γ
-	 					 			 	 	 		 							F
-	 		1111	200	1000	 			 	 	 	1	 					1		F
-	 ÷					 2.5.5	222		 	 	 200		 				200			F
-	 					 			 	 	 		 							\vdash
_	 					 			 	 	 		 							\vdash
_	 					 			 	 	 		 							
		1	1	1	1								1							
				100	100	<u> </u>														Γ
			1000	12.2.2	100	555	575										222			Γ
-	 			1.1.1	1.1.1	 			 	 	 		 							F
-	 					 			 	 	 		 							F
-	 					 			 	 	 		 							\vdash
-	 <u></u>					 	222		 	 	 	1)	222	F
_	 	; ·				 			 	 	 		 							\vdash
_	 					 			 	 	 		 							F
_	 					 				 	 		 	_						
				277	100	<u> </u>														Γ
-	Г — — — — — — — — — — — — — — — — — — —	1	1	l – – – – – – – – – – – – – – – – – – –		l – –		Г — Т												F