Ph.D. Preliminary Examination **Code Number ___________**
Fall 2009

Instructions:

1. Please check to ensure that you have a complete exam booklet. There are 25 numbered problems. Note that **Problem 2 occupies 2 pages**, **Problem 4 occupies 2 pages**, **Problem 11 occupies 2 pages**, and **Problem 20 occupies 2 pages**. Including the cover sheet, you should have **30 pages**. There should be no blank pages in the booklet.
2. The examination is closed book and closed notes. No reference material is allowed at your desk. A calculator is permitted.
3. All wireless devices must be turned off for the entire duration of the exam.
4. You may work a problem directly on the problem statement (if there is room) or on blank sheets of paper available from the exam proctor. Do not write on the back side of any sheet.
5. Your examination code number **MUST APPEAR ON EVERY SHEET.** This includes this cover sheet, the problem statement sheets, and any additional work sheets you turn in. **DO NOT** write your name on any of these sheets. Use the preprinted numbers whenever possible, or **WRITE LEGIBLY!!!**
6. Under the rules of the examination, you must choose 8 problems to be handed in for grading. Each problem to be graded should be separated from the rest of the materials, stapled to the associated worksheets, and placed on the top of the appropriate envelope in the front of the exam room. **DO NOT TURN IN ANY SHEETS FOR THE OTHER 17 PROBLEMS!!**
7. The examination lasts 4 hours, from 9:30 AM to 1:30 PM.
8. When you hand in the exam:
   (a) Separate the 8 problems to be graded as explained above.
   (b) Check to see that your Code Number is in **EVERY** sheet you are turning in.
   (c) On the section at the bottom of this page, **CIRCLE** the problem numbers that you are turning in for grading.
   (d) Turn in this cover sheet (containing your code number) and the 8 problems to be graded.
   (e) All other material is to be placed in the discard box at the front of the room. You are not allowed to take any of the exam booklet pages from the room!

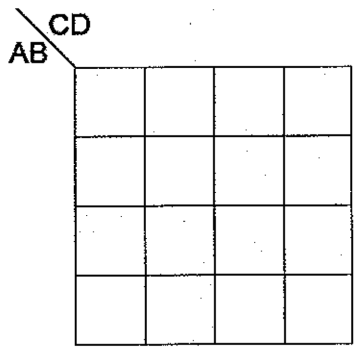
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
19	**20**	**21**	**22**	**23**	**24**	**25**		

Problem 1 (Core: CompE-ECE2030)   Code Number:_________

Use CMOS technology (nMOS and pMOS FETs) to implement the function below as a minimized complex gate (with a minimum number of transistors). Assume that the variables and their complements are available as inputs to your circuit.

F(A,B,C,D) = AB'C + CD + BC'D'

(a) Use a four-variable Karnaugh-Map (K-Map) to show that this expression is in the **minimum-sum-of-products** form.



(b) Write the **complement** of the function (i.e. F') as a **product-of-sums** form

(c) Draw a minimized transistor-level schematic for the function, using standard symbols to represent the nMOS and pMOS transistors.

Problem 2 (Core: CompE-ECE2030) Code Number:_________

a. (3pts) Express the following function as a Sum-of-Minterms. Write your answer in the box below.

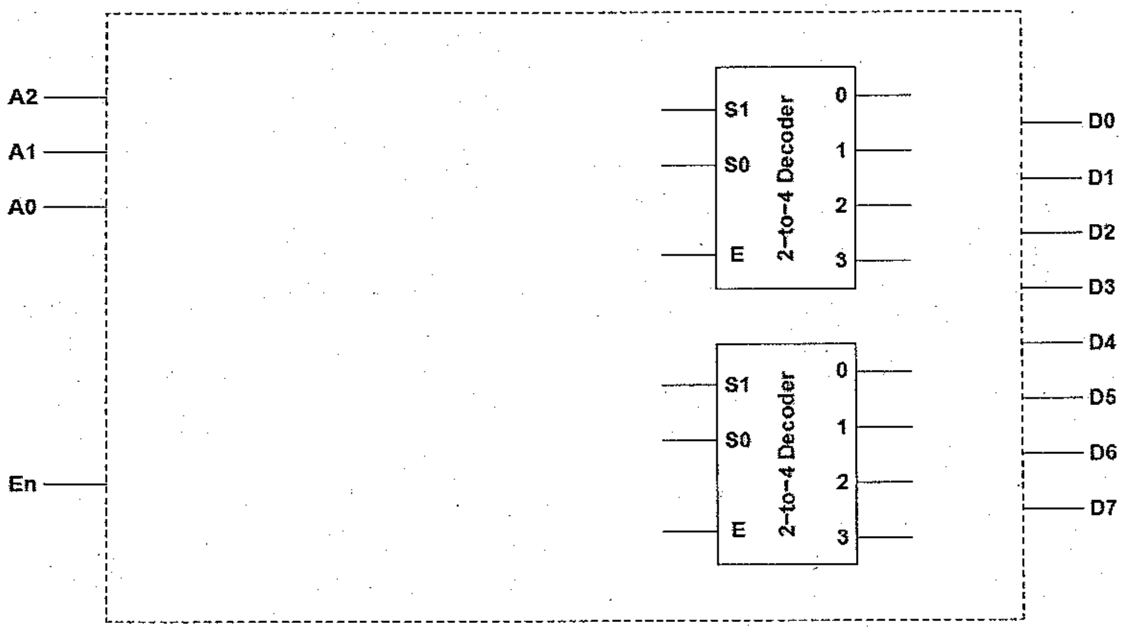
$$F = AB + \overline{B}(\overline{A} + \overline{C})$$

b. (3pts) Express the following function as a Product-of-Maxterms. Write your answer in the box below.

$$F = AB + \overline{B}(\overline{A} + \overline{C})$$

Problem 2 (Core: CompE-ECE2030) **Code Number:__________**

c. (4pts) Make the appropriate additions to the two decoders shown below to make the entire system act like a 3-to-8 bit decoder. All necessary lines must be shown (except power and ground) and the lines should be clear and neat—you may also use labels in place of drawing wires. You may add inverters and AND or OR gates as needed. Note, when the enable line is low, all outputs are low.



Problem 3 (Core: CompE-ECE3055) Code Number:________

Given a computer system with a single-level data cache and 1GB system memory. The direct-mapped 16KB writeback data cache employs 32-byte cache lines and is indexed by the virtual address. The OS running on the system manages memory with an "inverted page table" and its page size is 8KB. Given an access sequence (using virtual addresses) below when the inverted page table and data cache are completely empty, please answer the following questions.

```
(1) load  0x0012AF00
(2) load  0x0012AF20
(3) load  0x0012BF00
(4) store 0x0012AF10
(5) store 0x0012EF00
```

a) What is the total number of entries required for the inverted page table?

b) For the above execution, how many entries will be allocated in the inverted page table? What values are recorded in the table for translation? (Please write the values in Hex.)

c) At the end of execution, how many lines are present in the data cache? What are the indices (or set number) of these entries and their associated cache tag values? (Please write the values in Hex.)

Problem 4 (Core: CompE-ECE3060) Code Number:_________

Consider the function $f = \overline{(a+b).(b+c).d}$

Implement the above function using a static-CMOS logic using NO MORE THAN 8 transistors.

(a) Show the reduced functional form that you will implement.

(b) Draw the transistor level circuit diagram for the reduced functional obtained from part-a. You need to ensure that the junction capacitance connected to the output node is as small as possible.

Size the NMOS and PMOS devices in the figure so that the worst-case pull-up and pull-down resistances are same as that of an inverter with width of NMOS=W and PMOS=$2W$ (the channel length of NMOS and PMOS are assumed to be same). You can show the answer in the circuit diagram.

Problem 4 (Core: CompE-ECE3060) Code Number:__________

(c) Consider a step input and only **one input is allowed to make a transition** at one time. What are the input patterns that give the worst case high-to-low delay (i.e. output switches from '1' to '0'). State clearly what is the initial input pattern and what is the final pattern in the table below. For full-credit you need to consider the capacitances at the intermediate node.

	A	B	C	D
INITIAL				
FINAL				

Problem 5 (Core: E&M-ECE3025) **Code Number:__________**

A coaxial transmission line is constructed from two conducting cylindrical shells, one of radius 2 mm and the other of radius 5 mm, centered along the z-axis and separated by a material with $\mu_r = 1.0$ and $\varepsilon_r = 2.2$. When charged from a DC source, the electric field between the cylinders is

$$\bar{E} = \frac{1.637}{\rho}\hat{\rho} \qquad \text{(V/m)}$$

where ρ is in units of meters. You may use $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m. Where possible, provide numerical answers for the following:

(a) What is the voltage difference between the inner and outer conductors?

(b) What is the displacement field (electric flux density) $\bar{D}$ between the cylinders?

(c) Find the magnitude of the surface charge density ρ_S on either cylinder.

(d) What is the capacitance per unit length of the coaxial line?

(e) What is the total energy per unit length stored in this field?

Problem 6 (Core: E&M-ECE3065) **Code Number:__________**

A lossless transmission line of electrical length $l = 0.35\ \lambda$ and characteristic impedance $Z_o = 100\ \Omega$ is terminated in a load impedance $Z_L = 60\ \Omega$.

(a) Find the reflection coefficient Γ and the standing wave ratio S at the load

(b) Assuming that the incident power density to Z_L is 0.15 W/m^2, what is the reflected power density?

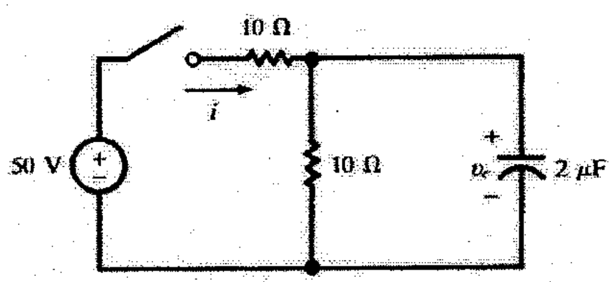
(c) Find the input impedance Z_{in} at the input of the transmission line [Formula: $Z_{in} = Z_o \times (Z_L + jZ_o \tan(\beta l))/(Z_o + jZ_L \tan(\beta l)$]

(d) Design a quarter-wavelength transformer matching the Z_L to Z_o. Give the electrical length, the physical length and the characteristic impedance Z_l of the transformer. Assume that the transformer will be fabricated by a material with phase velocity $u_p = 1.5 \times 10^8$ m/sec and will operate at the frequency of 150 MHz.

(e) If Z_L gets replaced by $Z_L = j\ 60\ \Omega$, can you still match it to Z_o with a quarter-wavelength transformer and why?

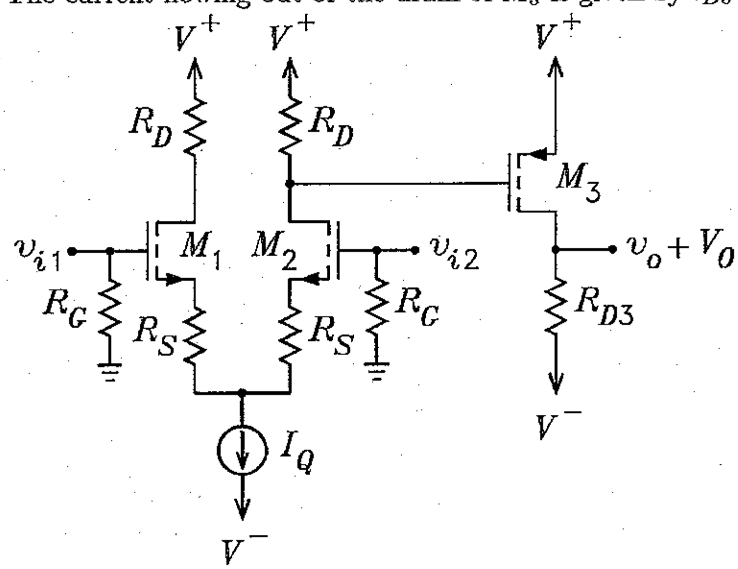
Problem 7 (Core: EDA-ECE2040) **Code Number:__________**

In the figure below, the switch is closed at $t=0$. Obtain the current i and capacitor voltage v_c, for $t > 0$. Assume $v_c(0+) = 0V$, t is measured in μs.



Problem 8 (Core: EDA-ECE3050) **Code Number:__________**

Given $V^+ = +15\,\text{V}$, $V^- = -15\,\text{V}$, $I_Q = 2.5\,\text{mA}$, $R_G = 10\,\text{M}\Omega$, $R_D = 1.6\,\text{k}\Omega$, $R_S = 100\,\Omega$, $R_{D3} = 12\,\text{k}\Omega$. The current flowing into the drains of M_1 and M_2 is given by $i_D = 0.004\,(v_{GS} - 1.5)^2$ The current flowing out of the drain of M_3 is given by $i_{D3} = 0.004\,(v_{SG} - 1.5)^2$.



(a) With $v_{i1} = v_{i2} = 0$, solve for the dc output voltage V_O.

(b) Solve for the small-signal ac output voltage v_o as a function of the small-signal input voltages v_{i1} and v_{i2}.

Problem 9 (Core: Power-ECE3070) **Code Number:_________**

An automotive plant is fed from a balanced 3 phase line-line voltage of 13.8 kV rms at 60 Hertz. The transmission line conductors are rated at 1000 A rms.

a. The present load of the plant is 15 MW @ 0.8 pf lagging. Calculate the apparent and reactive power drawn by the load.
b. What is the maximum delta connected load that can be added at 0.70 pf lagging, to ensure that the line current rating is not exceeded.
c. At the new operating point, calculate the delta connected capacitance in microfarads that must be used to improve the plant power factor to unity.

Problem 10 (Core: Power-ECE3070) **Code Number:_________**

A 3-phase, 2-pole, Y-connected synchronous machine has the following parameters: nominal capacity 7,500 kVA, nominal inter-phase voltage 2,300 V, nominal frequency 60 Hz, synchronous reactance 1.95 Ohms/phase, per phase resistance is zero.

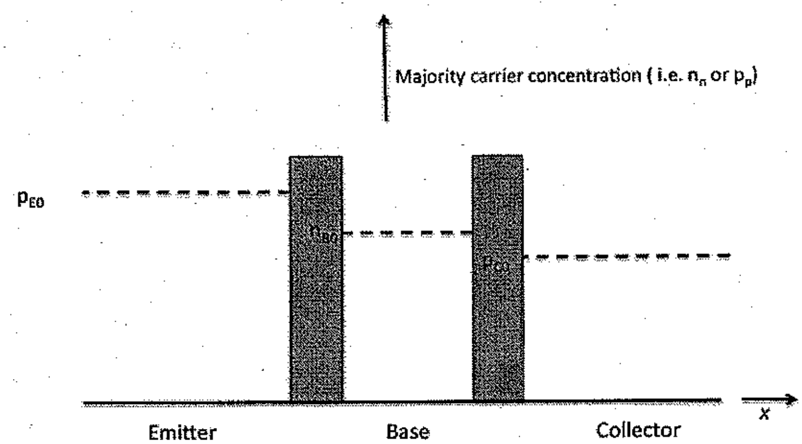
A) Machine is synchronized to a power network. Field current is 100 A at synchronization. The active power is increased until active power reaches 300 kW. Find the power angle δ, stator current I_S, and power factor in this operating condition.

B) Without any other changes, rotor current is being increased to 180 A. Find the power angle δ, stator current I_S, power factor and generated reactive power in this operating condition.

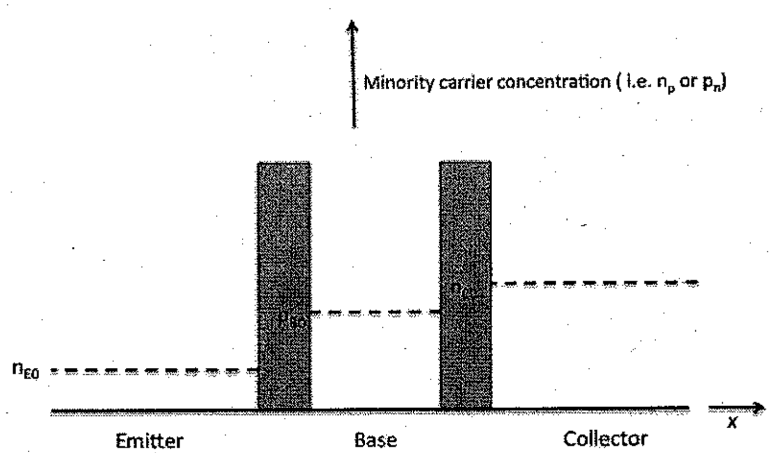
Problem 11 (Core: Microsystems-ECE3040) Code Number:_________

In this problem, you will be asked to show qualitatively the steady state majority or minority carrier concentration in the quasi-neutral region of a bipolar junction transistor (BJT) on a given set of plots. Please note that the x and y axis on these plots have a linear scale. The y-axis is carrier concentration and the x-axis represents the position in the BJT. The regions in grey represent the depletion regions around each junction. The carrier concentrations are not drawn to proper scale, but only reflect the fact that doping concentration in the emitter (N_E), base (N_B), and the collector (N_C) have the following relationship: $N_E >> N_B > N_C$. You may assume that the biasing allows for a low-level injection approximation to carrier dynamics, and that the equilibrium majority (p_{E0}, n_{B0}, p_{C0}) and the minority (n_{E0}, p_{B0}, and n_{C0}) concentrations are represented by dashed lines in the below plots.

a) Please assume that the BJT is in forward active mode of biasing. On the following plot, draw the approximate steady state **majority** carrier concentrations in the quasi-neutral regions.

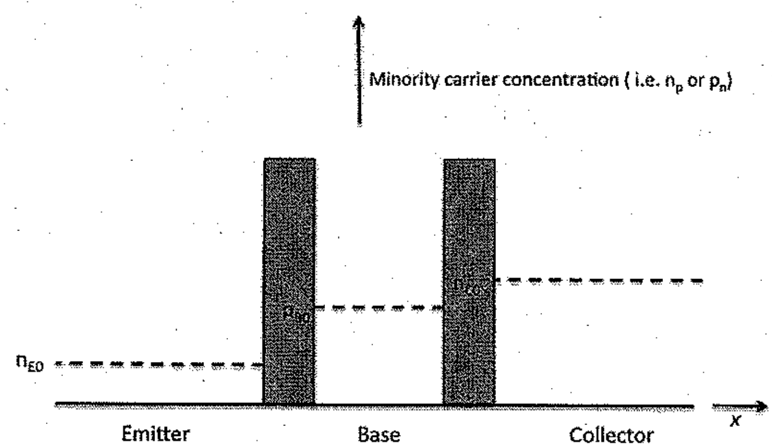


b) Please assume that the BJT is in forward active mode of biasing. On the following plot, draw the approximate steady state **minority** carrier concentrations in the quasi-neutral regions.



Problem 11 (Core: Microsystems-ECE3040) Code Number:________

c) Please assume that the BJT is in saturation mode of biasing. On the following plot, draw the approximate steady state **minority** carrier concentrations in the quasi-neutral regions.



d) From the given description so far in this problem, please indicate whether this is a *pnp* or *npn* BJT.

e) In a typical BJT, please comment on why the emitter doping is much higher than the base doping.

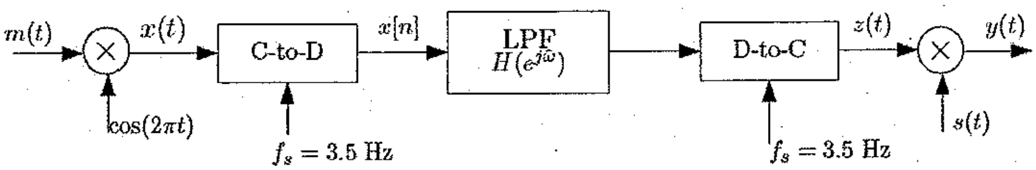
Problem 12 (Core: Microsystems-ECE3080) Code Number:__________

a) Draw the energy band diagram of a p-n homojunction diode at zero bias AND biased into forward bias at 0.6 volts. Be sure to indicate and label the position of the quasi-Fermi levels (qualitatively with respect to the bands), the conduction band, valence band, and position of the dopants.

b) Indicate the direction of motion due to electron drift, electron diffusion, hole drift, and hole diffusion as well as the direction of all four currents related to these motions.

c) What is the difference (numeric answer) in the quasi-Fermi levels?

Problem 13 (Core: DSP-ECE2025) Code Number:_________

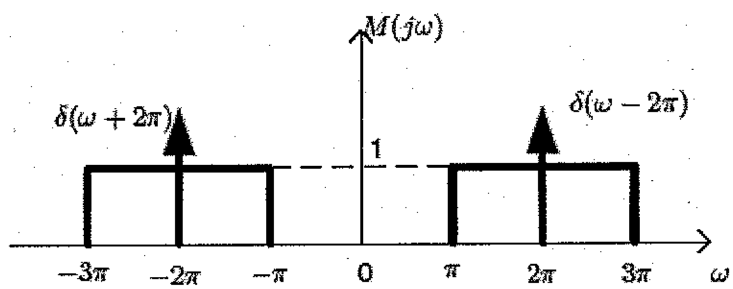


The input $m(t)$ multiplies a sinusoid signal $cos(2\pi t)$ and then is sampled by an ideal continuous-to-discrete (C-to-D) converter operating at a rate of $f_s = 3.5$ Hz. The resulting discrete-time signal $x[n]$ goes through a low-pass filter (LPF) given as

$$H(e^{j\hat{\omega}}) = \begin{cases} 1 & |\hat{\omega}| \le \hat{\omega}_p \\ 0 & |\hat{\omega}| > \hat{\omega}_p \end{cases}, \; for \quad \hat{\omega} \in [-\pi, \pi]$$

The output of the LPF goes through an ideal discrete-to-continuous (D-to-C) converter and then multiplies another signal $s(t)$ to generate $y(t)$.

The spectrum of the input signal $m(t)$ is given as follows (two rectangulars and two impulses):



where $\delta(\omega)$ is defined as $\delta(\omega) = 0$ when $\omega \neq 0$ and $\int_{-\infty}^{\infty} \delta(\omega) d\omega = 1$

(a) Based on the spectrum $M(j\omega)$, find the time domain signal $m(t)$.
(b) Plot the spectrum of $x(t)$, $X(j\omega)$. Label all axis carefully.
(c) Plot the spectrum of $x[n]$, $\hat{X}(e^{j\hat{\omega}})$ where $\hat{\omega} \in [-\pi, \pi]$ (Note that aliasing may happen here). Label all axis carefully.
(d) Determine the range of the cut-off frequency of LPF $\hat{\omega}_p$ and the mixing signal $s(t)$ so that $y(t) = m(t)$.

Problem 14 (Core: DSP-ECE3075) Code Number:__________

Let X and Y be *i.i.d.* $\mathcal{N}(0, 1)$ random variables, and let $Z = \frac{X}{Y}$ be the ratio.

(a) Y and Z are [positively correlated][negatively correlated][uncorrelated]. (circle one)
Explain.

(b) Find $P(X > 2Y)$.

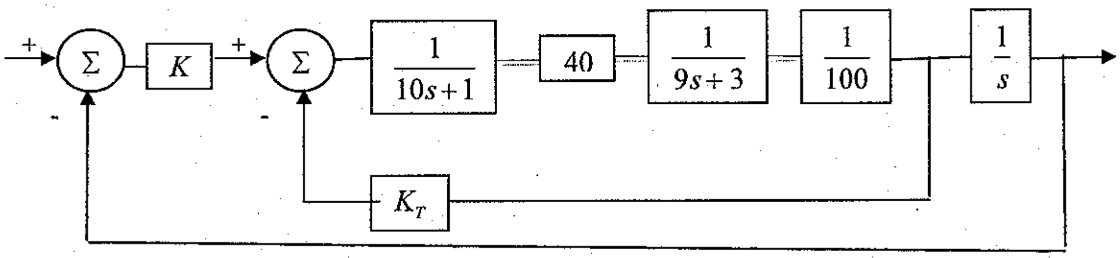
(c) Find $E(\cos(X))$.

(d) Find and sketch the conditional pdf $f(z \mid y)$, carefully <u>labeling</u> both axes.

(e) Find $P(Z > 1)$.

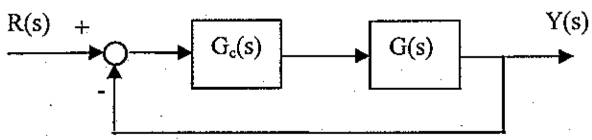
Problem 15 (Core: S&C-ECE3085)   **Code Number:__________**

Determine the conditions for which the feedback control system, shown by the following block diagram, is stable:



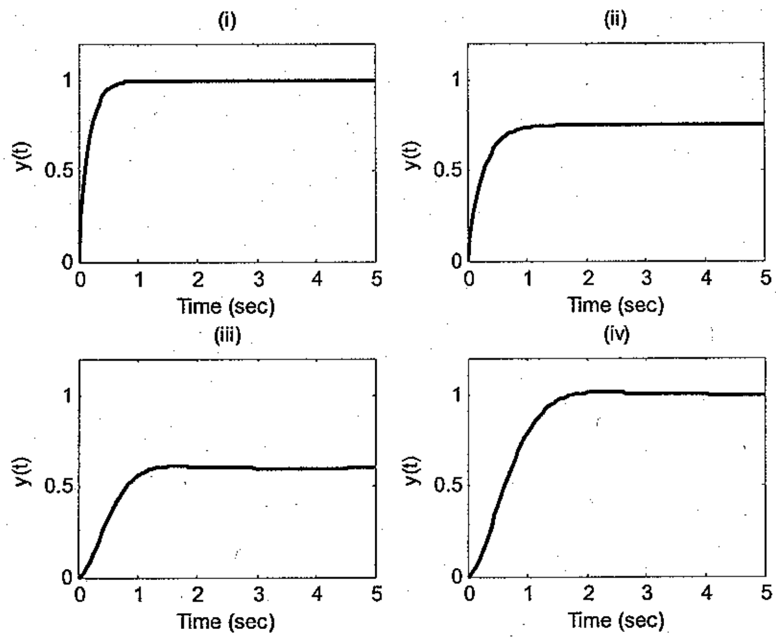
Problem 16 (Core: S&C-ECE3085) Code Number:__________

Consider a unity feedback system in the figure.

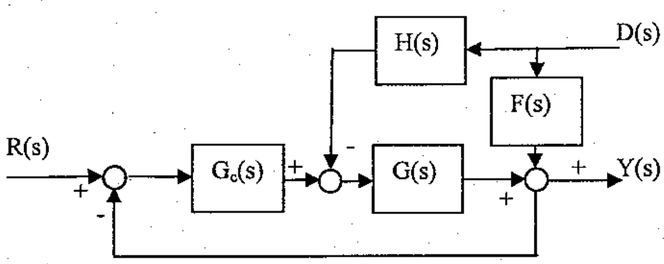


where $G_c(s)$ represents the compensator and G(s) is the plant to be controlled. G(s) has two stable, non-zero, distinct, real poles and no zero.

a) The unit step responses of the closed loop system with four different compensators: P, PD, PI, and PID, are shown below. Identify each of the figures with the corresponding compensator. Justify your answer.



b) Now consider the addition of a feedforward controller, H(s), as shown in the figure where D(s) is an unwanted but measurable disturbance. Determine a form for H(s) to reduce the effect of the disturbance on the output Y(s).



Problem 17 (Specialized: Comp Science-CS3210) Code Number:______

Consider a system with 20-bit virtual byte addresses, 15-bit physical byte addresses, and a page size of 4,096 bytes. For the memory trace given below consisting of a sequence of virtual addresses, indicate which memory accesses cause page faults. Also, for each physical page frame, list the virtual page residing in it at the end of the trace. Assume physical memory is initially empty and FIFO replacement is used. Make sure to show your work to ensure partial credit.

Virtual Address	*Page Fault? (Yes/No)*
2A000	____________
2A004	____________
C5328	____________
2A008	____________
E73AC	____________
2A00C	____________
2A010	____________
C7118	____________
2D200	____________
2D204	____________
9A388	____________
2D208	____________
9A38C	____________
2D20C	____________
2D210	____________
B329C	____________
27358	____________
2735C	____________
9B400	____________
27360	____________
B89AC	____________

Problem 18 (Specialized: Software Sys- ECE3035) Code Number: _____

Below is a snapshot of heap storage. Values that are pointers are denoted with a "$". The heap pointer is $6160. The heap has been allocated contiguously beginning at $6000, with no gaps between objects.

addr	value	addr	value	addr	value	addr	value	addr	value	addr	value
6000	12	6032	$6080	6064	$6148	6096	12	6128	12	6160	0
6004	48	6036	8	6068	4	6100	$6080	6132	8	6164	0
6008	$6080	6040	24	6072	12	6104	$6136	6136	4	6168	0
6012	16	6044	4	6076	8	6108	$6148	6140	$6100	6172	0
6016	8	6048	8	6080	$6032	6112	16	6144	12	6176	0
6020	8	6052	$6136	6084	0	6116	8	6148	4	6180	0
6024	24	6056	$6020	6088	4	6120	16	6152	8	6184	0
6028	4	6060	12	6092	$6004	6124	8	6156	12	6188	0

Part A Suppose the stack holds a local variable whose value is the memory address $6052 and a local variable whose value is $6004. No other registers or static variables currently hold heap memory addresses. List the addresses of all objects in the heap that are *not* garbage.

Addresses of Non-Garbage Objects: ________________________________

Part B Create a *sorted* (by size) free list by scanning the memory for garbage, starting at address $6000 and inserting each garbage object into the free list in increasing size order. List the *base address* of each object (not the address of its header) on the free list (in order) at the end of the scan.

Free List: ________________________________

Part C If the local variable whose value is the address $6052 is popped from the stack, which addresses will be reclaimed by each of the following strategies? If none, write "none." (You do not have to list addresses already on the free list from part B.)

Reference Counting:	
Mark and Sweep:	
Old-New Space (copying):	

Problem 19 (Specialized: Telecom-ECE3076) Code Number:__________

How does a reliable transport protocol (e.g. TCP) overcome the following problems:

1. Lost packet?

____

2. Bit error in packet?

____

3. Packets arrive in wrong order?

____

4. Packets from receiver lost?

____

5. Flow control?

____

6. What network device forwards IP datagrams? ______________________

7. What network device protects a network from harmful IP datagrams?

____

Name two Internet or Web parameters that must be assigned by a central organization, or coordinated organizations, to prevent duplication?

8. ____

9. ____

10. If signals travel at 2×10^8 m/s through 100 Mb/s fiber and wire connections, what is the maximum data transfer rate for a single TCP connection between a host in Atlanta and a host in Oregon (3600 km apart, 65,000 byte TCP window size)).

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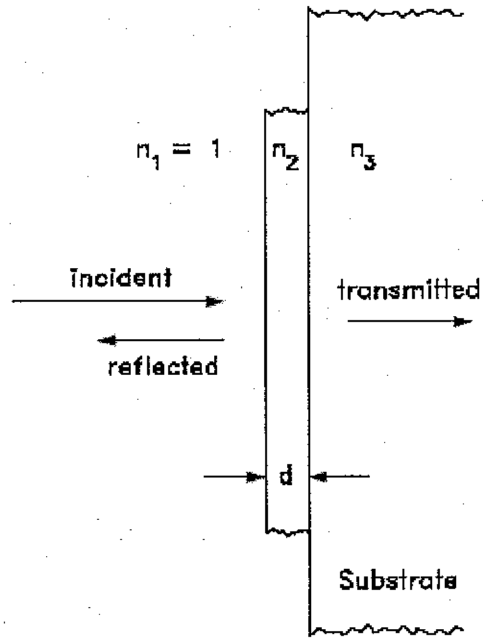
____

____

____

Problem 20 (Specialized: Optics-ECE4500) Code Number:_________

A thin dielectric film is deposited on an optically flat dielectric substrate. The thin film is lossless. The index of refraction of this film is n_2 and the thickness is d. Both n_2 and d can be varied. The substrate has a fixed refractive index of n_3. Laser light of freespace wavelength λ is incident upon the thin film/substrate combination in air. The light impinges at normal incidence as shown in the figure below.



A fraction of the incident light power is transmitted through the thin film into the substrate and a fraction of the power is reflected from the thin film/substrate combination as shown in the figure.

Part 1

Specify, in terms of the parameters given, the minimum thickness d and the refractive index n_2 for which this thin film/substrate combination *transmits* the maximum amount of optical power. Put your answers in the space provided.

d(*maximum transmission*) = ______________________________
(analytical expression)

n_2(*maximum transmission*) = ______________________________
(analytical expression)

Problem 20 (Specialized: Optics-ECE4500) Code Number:__________

In a particular case, the freespace wavelength is $\lambda = 1.000 \mu m$ and the substrate has a refractive index of $n_3 = 2.000$. For this case, calculate the minimum thickness d and the refractive index n_2 for *maximum transmission*. Select your answers from the list of possible answers given at the end of this problem.

d(*maximum transmission*) = ______________________________
(select from list below)

n_2(*maximum transmission*) = ______________________________
(select from list below)

Part 2

In another application, it is desired to have the thin film/substrate combination be *highly reflecting*. Note that this is opposite of the above highly *transmitting* case. For this application, the freespace wavelength is again $\lambda = 1.000\ \mu m$ the substrate again has a refractive index of $n_3 = 2.000$. For this case, from the possible answers given at the end of this problem, select the minimum thickness d and the corresponding refractive index n_2 for *maximum reflection*.

d(*maximum reflection*) = ______________________
(select from list below)

n_2(*maximum reflection*) = ______________________
(select from list below)

Possible Answers for Part 2

(a) 4.000	(h) 1.250	(o) 1.414 μm	(v) 0.250 μm
(b) 3.000	(i) 1.000	(p) 1.250 μm	(w) 0.1768 μm
(c) 2.828	(j) 0.833	(q) 1.000 μm	(x) 0.150 μm
(d) 2.500	(k) 0.7071	(r) 0.833 μm	(y) 0.1443 μm
(e) 2.000	(l) 0.5774	(s) 0.7071 μm	(z) 0.125 μm
(f) 1.732	(m) 0.500	(t) 0.5774 μm	(aa) 0.0833 μm
(g) 1.414	(n) 0.250	(u) 0.500 μm	(ab) 0.0625 μm

Problem 21 (Specialized: Optics-ECE4501) Code Number:_________

A point-to-point optical fiber communication link is to be constructed to join transmitter and receiver stations that are 100 km apart. The link consists of three segments that are end-to-end joined. The first segment is 25 km of old fiber whose quadratic dispersion is $D_1 = 16.0$ ps/nm-km, and whose decibel loss coefficient is $\alpha_1 = 0.30$ dB/km. The second segment is newer fiber, having dispersion $D_2 = 6.0$ ps/nm-km, loss coefficient $\alpha_2 = 0.15$ dB/km, and length L_2. The final segment (completing the 100 km overall distance) is dispersion-compensating fiber, having $D_3 = -100$ ps/nm-km, loss coefficient $\alpha_3 = 1.50$ dB/km, and length L_3. Assume all splice losses are negligible.

a. Determine the required lengths L_2 and L_3 such that the 100-km link has exactly zero net quadratic dispersion.

b. Suppose the receiver sensitivity is -30.0 dBm. What is the minimum required power input to the link from the transmitter. Express your result in *both* dBm and mW.

c. Suppose that a path-average dispersion of $D_{avg} = 3$ ps/nm-km could in fact be tolerated for this link. Keeping the 25-km old fiber segment as is, what new choices could be made for L_2 and L_3 to reduce the overall loss, and what would the new minimum transmitter power be? (in dBm only)

Problem 22 (Specialized: Microsystems-ECE4752) Code Number:_____

A one hour dry oxidation at 1000°C is followed by a five hour wet oxidation at 1100°C. Calculate the thickness after each step

Table 4.1 Oxidation coefficients for silicon

	Dry			Wet (640 torr)	
Temperature (°C)	**A (μm)**	**B (μm²/hr)**	**τ (hr)**	**A (μm)**	**B (μm²/hr)**
800	0.370	0.0011	9	—	—
920	0.235	0.0049	1.4	0.50	0.203
1000	0.165	0.0117	0.37	0.226	0.287
1100	0.090	0.027	0.076	0.11	0.510
1200	0.040	0.045	0.027	0.05	0.720

The τ parameter is used to compensate for the rapid growth regime for thin oxides. *(After Deal and Grove.)*

Problem 23 (Specialized: Bio Eng-ECE4784) Code Number:_________

a)(3pts)Describe the proper sequence of firing events for the heart. Be detailed in your description and draw a sketch of the heart to illustrate your description.

b)(3pts)Sketch the anticipated ECG/EKG in the case where there is an AV block, i.e. the atrial muscle and the AV node lose their electrical connection.

c)(4pts)Explain, using mathematical arguments why the p wave in the case where the SA node fails to fire will be inverted. Be sure to use the curve for the membrane voltage of the atrial muscle as a function of distance in your answer.

Problem 24 (Specialized: Bio Eng-ECE4782) Code Number:_________

Norbert Wiener used a zero-mean, Gaussian, white-noise stimulus to characterize nonlinear systems via an integral expansion containing kernels, which are now referred to as Wiener kernels. Write an equation that defines the first-order Wiener kernel (3 points). What are some of the good and bad features of Wiener kernels (4 points). How would you create a white-noise light stimulus suitable for characterizing the human Visual Evoked Response (3 points).

Problem 25 (Specialized: Bio Eng-ECE4781) Code Number:_________

Pretend that you are working for a medical diagnostics company that is designing a new product which will measure the human ERG response to periodic flashes of light. The RMS signal-to-noise is approximately 1/1000 with two difficult noise components, i.e. spikes of noise coming from eye blinks and low-frequency (i.e. .1 – 1 Hz) bias drifting due to unavoidable electrode movements. How would you deal with these two noise components without using an analog high-pass filter, since an analog high-pass filter would produce significant phase shifts at frequencies of interest (i.e. 1 – 30 Hz).