Q-1) [19pts]
a) [6pts. 2pts each for mag and phase plot of Av1, Av2 & Av. 1pt for shape of the plot and 1 for correct numerical calculation of pole values.]

b) [2pts. 1pt for the reason and 1pt for stable/unstable]
As shown above, at \( \omega = 10^7 \), the gain of the amplifier is 20dB but the phase shift almost hits 180°. Hence, the amplifier is not stable.

c) ) [2pts. 1pt for DC gain and 1 for value of ‘f’]
PM = 45° is achieved at \( \omega = 10^6 \). The DC gain is 60dB here. Thus, the \( A_{CL} \) can only be lowered to 60dB by a feedback factor, \( f = 0.001 \).

d) [2pts. 1pt for correct expression and 1 for numerical value]
The second stage pole, \( \omega_{p2,c} \), is given by:
\[
\omega_{p2,c} = -\frac{g_{m2}C_c}{(C_cC_1 + C_1C_2 + C_cC_2)} \approx -\frac{g_{m2}}{C_2} = 10\text{Mrad/sec}
\]

e) [1pts]
To achieve at the PM = 45°, the unit gain frequency, \( \omega_u \), should be made equal to \( \omega_{p2,c} \) calculated above. Thus, \( \omega_u = \omega_{p2,c} \) ensures PM = 45°

f) [2pts. 1pt for correct expression and 1 for numerical value]
The value of required compensation capacitor \( C_c \) can be calculated by solving \( \omega_u = \omega_{p2,c} \),
\[
g_{m1}/C_c = g_{m2}/C_2 \Rightarrow C_c = g_{m1}C_2/g_{m2} = 0.1 \times 100pF = 10pF
\]
The assumption in part-d) was that \( C_c > C_1 \) which is still correct as \( C_1 = 1pF \).
g) [2pts. 1pt for expression and 1 for numerical value]
The compensated first stage pole is \( \omega_{p1,c} = \frac{1}{R_{o1}g_{m2}R_{o2}C_c} = 1 \text{krad/sec} \)

h) [2pts. 1pt for mag and 1pt for phase plot]
Bode plot of compensated amplifier:
Simulation of Q-1)
Test-bench

Simulation Results: Before Compensation Vo1 and Vo2 individual Magnitude and Phase plots.

Vout Uncompensated Magnitude and Phase plot:
After Compensation:
Q-2) [9 pts. a) 5pts, b) 1pts, c) 2pts, d) 1pts]

a) The series resistor limits current through the Zener diode.

b) The series resistor limits current through the Zener diode.

c) $I_{\text{Tail}} = \frac{V_{\text{Zener}} - V_{\text{BE}}}{R_{\text{Tail}}} = \frac{3.5 - 0.7}{1000} = 2.8\text{mA}$

In the equation above, both $V_{\text{Zener}}$ and $V_{\text{BE}}$ do not depend upon supply. Hence, $I_{\text{Tail}}$ is relatively independent of supply.

d) Shown above in the figure.

Q-3) [6 pts. a) 2 pts, 1 each for rising and falling slew rates. b) 2 pts, 1 for finding output current limit, 1 for saying it is not output slew limited. c) 2 pts, 1 for tail current as limiting factor, 1 for calculating $C_c$]

a) Rising-edge slew rate = $1.75\text{V}/5.0\mu\text{s} = 0.35\text{V}/\mu\text{s}$ (Values read: 0.5V at 5us and 2.25V at 10us). Falling-edge slew rate = $2.0\text{V}/5.0\mu\text{s} = 0.4\text{V}/\mu\text{s}$ (Values read: 3.0V at 20us and 1V at 25us).

b) Minimum output stage current is 1mA. Thus the slew-rate limit of the output stage = $I/C_L = 1\text{mA}/50\text{pF} = 20\text{V}/\mu\text{s}$, which is much greater than the values calculated above. Hence, the slew rate is not limited by the output stage.

c) The slew rate must then be due to the compensation capacitor, which on both rising and falling edges has a current limit of $6\mu\text{A}$ due to the $6\mu\text{A}$ diff pair current source. $C = \frac{I}{(dv/dt)}$. Taking the average of the rise/fall slew rates, $C = \frac{6\mu\text{A}}{(0.375\text{V}/\mu\text{s})} = 16\text{pF}$.

Q-4) [5 pts. a) 3 pts, 1 each $A_{\text{vo}}$, $f_{\text{pi}}$, $f_{\text{u}}$. b) 2 pts, 1 for $\text{PM}=45^\circ$, 1 for $w_{\text{pi}}=w_{\text{u}}$]
a) $A_{vo} = 100k, f_{p1} = 5Hz$ and $f_{pu} = 1MHz$

b) As LM324 is a 2-stage amplifier, it is fair to assume that the non-dominant pole, $f_{p2}$, is governed by load cap, $C_L$. As shown in fig-4, as the value of the phase margin, $PM = 45^\circ$ at load capacitance is 1000pF. This means that the phase-shift of -135$^\circ$ occurs when $|Af| = 1$, indicating the presence of non-dominant pole $f_{p2}$. Thus, $f_{p2} = f_{pu} = 1MHz$.

Q-5) [7 pts. a) 3 pts, 1 for gain error, 1 each for the two poles in (ii). b) 4 pts, 1 for min gain and 1 for bandwidth, for both values of $C_F$]

a) For this part we use the fig-1 shown below:

i) At $f = 0.1Hz$, the DC gain $A_{vo} = 130dB \rightarrow 3200K$. Given that closed loop gain $A_{CL} = 1000$, the feedback factor $f = 0.001$. Thus, the fractional gain error $= -1/A_{vo}f = 31.6e-3$

ii) For $C_S = 10pF$ open-loop 3dB pole, $\omega_{3dB} = 5Hz$ and for $C_F = 30pF$ open-loop 3dB pole, $\omega_{3dB} = 0.2Hz$. We know that the closed-loop pole is related to the open-loop pole by $A_{vo}\omega_{3dB}/A_{CL}$. Thus, the closed-loop pole for the two cases are $3200*5 = 16kHz$ and $3200*0.2 = 640Hz$.

b) For this part the fig-2 shown above is used:

For both part PM = 60$^\circ$ is desired.

For $C_F = 3pF$, the minimum gain is 25dB (marked by the arrow) at max bandwidth of 300kHz $\rightarrow$ The resulting feedback factor is $f = 1/A_{CL} = 0.056$
For $C_F = 30\text{pF}$, the minimum gain is 0dB. It is unity gain stable as $PM = 60^\circ$ is ensured beyond $U_{GB} = 1\text{MHz}$. Thus, maximum feedback factor, $f = 1$ with maximum $BW = 1\text{MHz}$.

Q-6) [7 pts. a) 2 pts for correctly redrawing. b) 2 pts c) 3 pts, 1 for each subpart]
a, b) Small signal equivalent circuit for a 2-stage amplifier and its voltage transfer function:

\[
\frac{V_o(s)}{V_i(s)} = \frac{(C_c S - G_{mnz}) R_{oz}}{R_{o1} R_{o2} G_c s^2 + R_{o1} ((1+G_{m2} R_{o2}) C_s + C_c) + R_{o2} (C_c R_c S + 1)}
\]

Where, $G_c = G_{c1} + G_{c2} + G_{c3}$

c)

\[
W_{p2} = \frac{1}{W_{p1}} \cdot \frac{1}{R_{o1} R_{o2} (C_{c1} + C_{c2} + C_{c3})}
\]

\[
W_{p1, C} = \frac{1}{G_{m2} R_{o2} C_c}
\]

and $W_{p2, C} = \frac{G_{m2} C_c}{C_{c1} + C_{c2} + C_{c3}} \approx \frac{G_{m1}}{C_c}$

$W_{p2} > W_{p1}$ ensures $PM > 45^\circ$

\[
\frac{W_{p2}}{W_{p1}} > 1 \Rightarrow \frac{G_{m2} C_c}{G_{m1} C_c} > 1
\]

approximately

\[
\frac{G_{m2}}{G_{m1}} \cdot \frac{C_c}{(C_{c1} + C_{c2} + C_{c3})} \approx 1
\]

Exact
**Grading rubric:**

First, please identify whether you belong to EE140/240a.

Rubric for EE140:
Max. points: 53
Q-1) Total points 19
   a) 6 b) 2 c) 2 d) 2 e) 1 f) 2 g) 2 h) 2

Q-2) Total points: 9
   a) 5 b) 1 c) 2 d) 1

Q-3) Total points: 6
   a) 2 b) 2 c) 2

Q-4) Total points: 5
   a) 3 b) 2

Q-5) Total points: 7
   a) 3 b) 4

Q-6) Total points: 7
   a) 2 b) 2 c) 3

Rubric for EE240a:
Max. points: 78
Q-7) 25 pts
   a) 15 b) 10

**Grading guidelines:**

1) It important to get the approach right. You should grade a right approach at 60% for grade.  
   E.g. 3/5

2) Next, important point is to get right numerical answer. Full grade is reserved for this purpose.

3) Numerical error should cost you 20%  
   E.g. 1 numerical error in a 5pt problem is 4/5

4) If approach is correct and problem has multiple numerical error, you at least get 60%  
   E.g. 3 numerical error in a 5pt problem is 3/5