Analogue Electronics II (E2-2) — SOLUTION

① (a) (i) Circuit shown is a "digital" inverter. Should identify that this is in fact two CS amps. 1

$\therefore A_V = -G_m R_{out}$ where $G_m = g_{m1} + g_{m2}$

2 or $G_m = 2g_{m1}$ (assuming g_m's are matched)

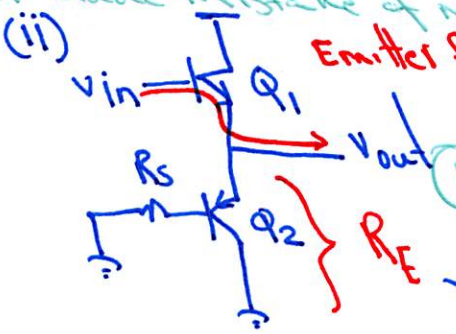
$R_{out} = r_{o1} \| r_{o2}$

2

$\therefore A_V = -2g_{m1}(r_{o1} \| r_{o2})$ if both devices are in sat.

Most students realised this was 2 CS amplifiers in parallel but several made mistake of multiplying gms instead of adding

(ii)



1

Emitter follower → from formula sheet

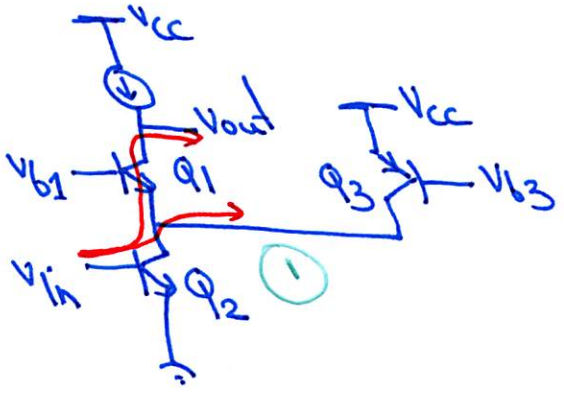
$$A_V = \frac{R_E \| r_o}{\frac{1}{g_m} + R_E \| r_o} \quad 1$$

R_E → from formula sheet 1

$$R_E = \frac{1}{g_m} + \frac{R_S}{\beta + 1}$$

$$\therefore A_V = \frac{\left(\frac{1}{g_{m2}} + \frac{R_S}{\beta+1}\right) \| r_{o1}}{\left(\frac{1}{g_{m2}} + \frac{R_S}{\beta+1}\right) \| r_{o1} + \frac{1}{g_{m1}}} \quad 2$$

(iii)



1

Use $A_V = -G_m R_{out}$

for G_m → $v_{in} = v_{be2}$

$i_{out} \neq i_{c2}$

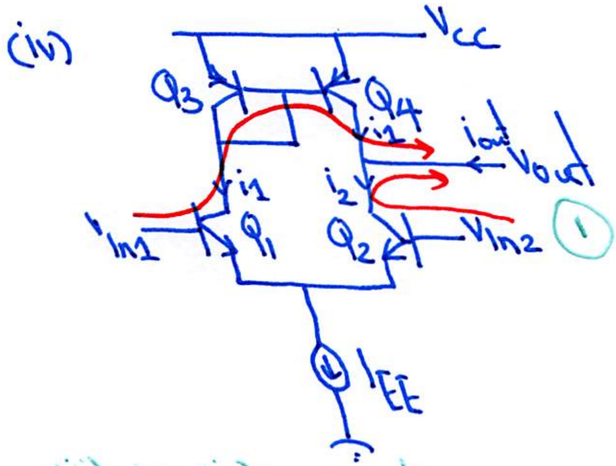
$\therefore$ need $\frac{i_{out}}{i_{c2}}$ → current splitter

$$G_m = \frac{r_{o2} \| r_{o3}}{r_{o2} \| r_{o3} + 1/g_{m1}} (g_{m2}) \quad 2$$

$$R_{out} = g_{m1} r_{o1} (r_{o2} \| r_{o3} \| r_{\pi 1}) + r_{o1} + (r_{o2} \| r_{o3} \| r_{\pi 1})$$

2

(iv)



(1)

use $A_v = -G_m R_{out}$

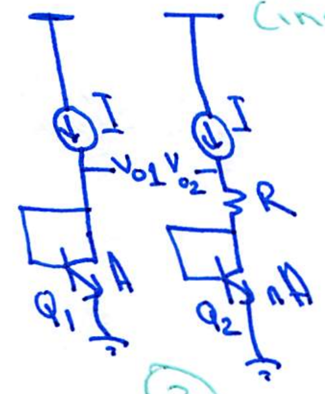
$G_m = g_{m1}$ (if $g_{m1} = g_{m2}$ and $v_{in} = v_{in2} - v_{in1}$) (2)

$R_{out} = r_{o2} || r_{o4}$

$\therefore\ A_v = -g_{m1}(r_{o2}||r_{o4})$ (2)

(ii) to (iv) generally answered well. In (iv) some students applied (incorrectly ½ cct assumption)

(b)



(2)

Bandgap voltage reference uses the fact that $V_T \left(=\frac{KT}{q}\right)$ has a +ve TC and V_{BE} has a -ve TC in order to generate a voltage that is independent of temperature. (2)

On cct on left if $V_{o1} = V_{o2}$

$V_{BE1} = IR + V_{BE2}$ then $IR = V_{BE1} - V_{BE2}$
$= V_T \ln(n)$

$V_{o2} = V_{BE2} + V_T \ln(n)$ (1)

$\rightarrow$ need to design n.

(c) (i) $CMRR = \dfrac{A_{VDM}}{A_{VCM}}$ (1)

- A_{VDM} is $-G_m R_{out}$ so increasing bias current or o/p R will improve (2)
- A_{VCM} is affected by how good current source the bias sink is (ideally ∞ r_{out}). (2)

$\therefore$ so transconductance (or bias current magnitude) affect A_{VDM} whereas current sink r_o affects A_{VCM}

answered well

(ii) input offset voltage has two components (systematic offset and random offset). (1)

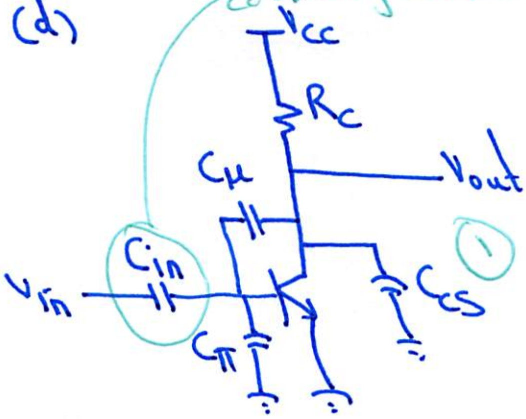
only a few students got this

Systematic offset is affected by an unbalanced o/p, i.e. ideally $V_{out} = A_o(V_+ - V_-)$ so if $(V_+ - V_-) = \emptyset\ \therefore\ V_{out} = \emptyset$. (2)

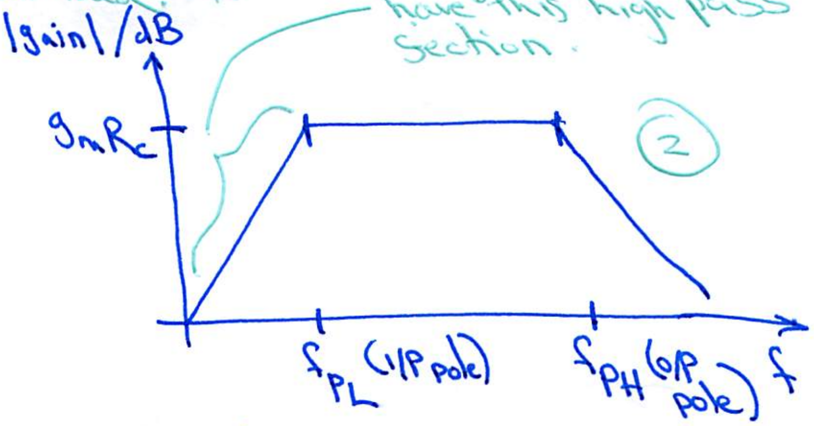
Random offset is due to mismatch between diff. pair. (2)

(d)

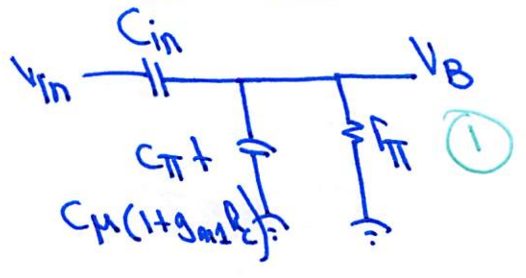
Cin was in many cases not series coupling but parallel load.



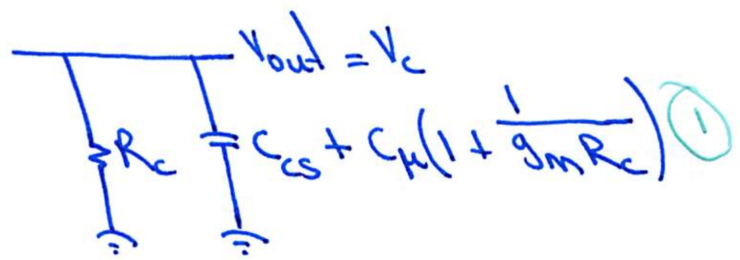
many students did not have this high pass section.



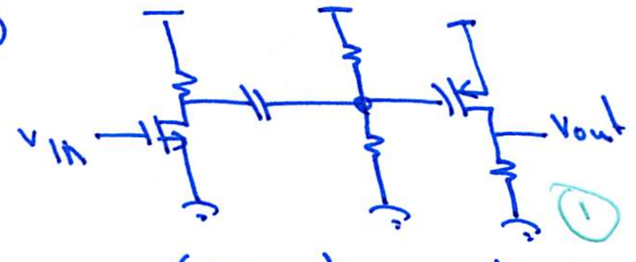
At input



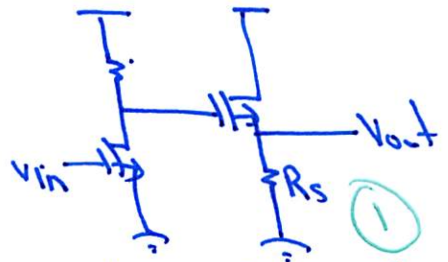
At output



(e)



(Capacitive coupling)



(Direct coupling)

In capacitive coupling each amplifier stage in independently biased and subsequent stages are cascaded using an AC coupling capacitor.

Direct coupling is when amplifier stages are directly cascaded and thus biasing is all dependant.

In IC design large capacitors are unfeasible ∴ capacitive coupling is undesirable for LF signals.

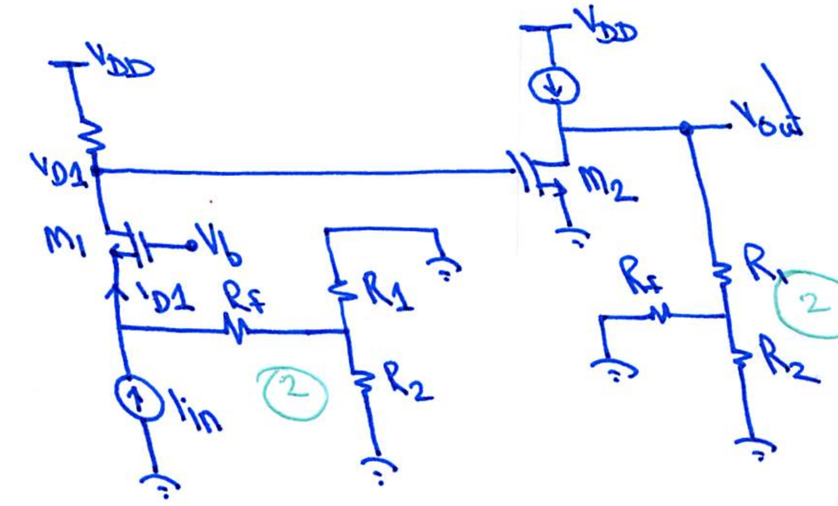
(e) answered well

(2) (a) Since input = current, output = voltage $\therefore$ Transimpedance amplifier (1)
(units of gain = Ohms)

almost all got this.

ideally $R_{in} = \phi$ (1), $R_{out} = \phi$ (1).

(b) (i) To determine open loop gain, i.e $\left(\frac{V_{out}}{I_{in}}\right)_{OL}$ need to break feedback loop.



$$A_{OL} = \frac{V_{out}}{i_{in}} = \frac{i_{D1}}{i_{in}} \times \frac{V_{D1}}{i_{D1}} \times \frac{V_{out}}{V_{D1}}$$

$$\frac{i_{D1}}{i_{in}} = \frac{(R_f + R_1 \| R_2)}{(R_f + R_1 \| R_2) + 1/g_{m1}} \quad (1)$$

several students assumed $i_{in} = i_{D1}$

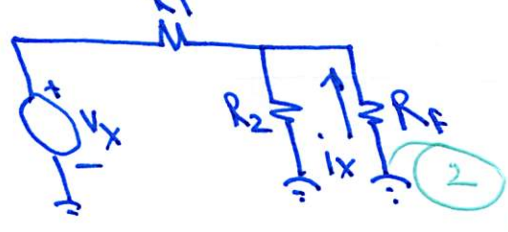
$$V_{D1} = i_{D1} R_{D1} \quad (1)$$

$$\frac{V_{out}}{V_{D1}} = -g_{m2}\left(r_{o2} \| (R_1 + R_f \| R_2)\right) \quad (1)$$

$$\therefore A_{OL} = -g_{m2}\left[r_{o2} \| (R_1 + R_2 \| R_f)\right] R_{D1} \frac{R_f + R_1 \| R_2}{\frac{1}{g_{m1}} + R_f + R_1 \| R_2}$$

(3)

(ii)



$$K = \frac{i_x}{v_x}$$

generally macromodel provided by most

$$K = \frac{i_x}{v_x} = \frac{-R_2}{(R_1 + R_2 \| R_f)(R_2 + R_f)} = \frac{-R_2 \| R_f}{R_f (R_1 + R_2 \| R_f)} \quad 3$$

about 1/2 students got this

(iii) $R_{in,open} = \frac{1}{g_{m1}} \| (R_f + R_1 \| R_2)$ 3

$R_{out,open} = r_{o2} \| (R_1 + R_2 \| R_f)$ 2

answered very well

(iv) $$\frac{V_{out}}{I_{in}} = - \frac{g_{m2}[r_{o2} \| (R_1 + R_2 \| R_f)] R_{D1} \dfrac{R_f + R_1 \| R_2}{\frac{1}{g_{m1}} + R_f + R_1 \| R_2}}{1 + \left\{ g_{m2}[r_{o2} \| (R_1 + R_2 \| R_f)] R_{D1} \dfrac{R_f + R_1 \| R_2}{\frac{1}{g_{m1}} + R_f + R_1 \| R_2} \right\} \left\{ \dfrac{R_2 \| R_f}{R_f (R_1 + R_2 \| R_f)} \right\}} \quad 3$$

$$R_{in,closed} = \frac{\frac{1}{g_{m1}} \| (R_f + R_1 \| R_2)}{1 + A_{OL} K} \quad 2$$

$$R_{out,closed} = \frac{r_{o2} \| (R_1 + R_2 \| R_f)}{1 + A_{OL} K} \quad 2$$

$1 + A_{OL} K =$

few student got complete, correct expressions

3 (a) $P_{total} = V_{DD} \times I_{total}$

$I_{total} = I_{ref} + I_{D7} + I_{D8} + I_{D9}$ 2

from $\frac{W}{L}$'s ratio $(I_{ref} : I_{D7} : I_{D8} : I_{D9}) = 1 : 4 : 8 : 40$

$\therefore I_{total} = I_{ref}(1 + 4 + 8 + 40) = 0.25\,mA\,(53) = 13.25\,mA$

$\therefore P_{total} = \underline{23.85\,mW}$ 2 ← most obtained correct value.

(b) $$A_V = \frac{V_{out}}{V_{in2} - V_{in1}} = \frac{V_{out}}{V_z} \times \frac{V_z}{V_y} \times \frac{V_y}{V_{in2} - V_{in1}}$$

$$\frac{V_y}{V_{in2} - V_{in1}} = -g_{m1}(r_{o2} \| r_{o4}) \quad \text{(assuming good matching)}$$

$$\frac{v_z}{v_y} = -g_{m5}(r_{o5} \| r_{o8})$$

$$\frac{V_{out}}{V_z} = \frac{r_{o6} \| r_{o9}}{r_{o6} \| r_{o9} + 1/g_{m6}}$$

$$\therefore A_v = g_{m1} g_{m5} (r_{o2} \| r_{o4})(r_{o5} \| r_{o8}) \frac{r_{o6} \| r_{o9}}{r_{o6} \| r_{o9} + 1/g_{m6}}$$ 5

answered very well !!

$$g_{m1} = \sqrt{2 \mu_n C_{ox} \left(\frac{W}{L}\right)_1 I_{D1}} = \sqrt{2(200\mu)(250)(0.5m)} = 7.07 mS$$

$$g_{m5} = \sqrt{2(100\mu)50(2m)} = 4.47 mS$$

$$g_{m6} = \sqrt{2(200\mu)50(10m)} = 14.14 mS$$

$$r_{o2} = \frac{1}{\lambda_n I_{D2}} = \frac{1}{(0.1)(0.5m)} = 20k\Omega$$

$$r_{o4} = \frac{1}{(0.2)(0.5m)} = 10k\Omega$$

$$r_{o5} = \frac{1}{(0.2)(2m)} = \cancel{10k\Omega}\ 2.5k\Omega \qquad r_{o6} = \frac{1}{(0.1)(10m)} = 1k\Omega$$

$$r_{o8} = \frac{1}{(0.1)(2m)} = 5k\Omega \qquad r_{o9} = \frac{1}{(0.1)(10m)} = 1k\Omega$$

3 Some rounding errors or incorrect expression but generally most followed correct method

$$A_v = \underbrace{(7.07m)(4.47m)}_{31.60\mu}\underbrace{(20k \| 10k)}_{6.6k}\underbrace{(2.5k \| 5k)}_{1.6k}\underbrace{\frac{1k \| 1k}{1k \| 1k + \frac{1}{14.14m}}}_{0.88}$$

$$= 293.65 = \underline{49.36 dB}$$ 2

(c) $R_{out} = \frac{1}{g_{m6}} \| r_{o6} \| r_{o9} = \frac{1}{14.14m} \| 1k \| 1k = \underline{61.96\Omega}$ 2 2

(d) Nodes in signal path : V_{in1}, V_{in2}, V_x, V_y, V_{out}, V_z

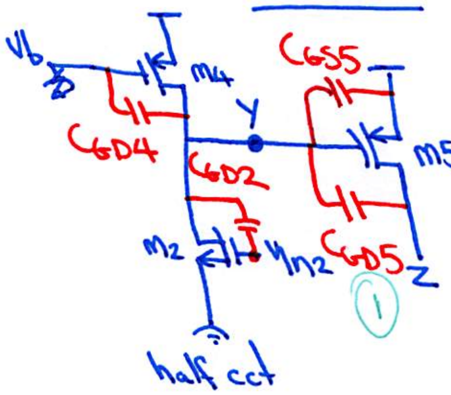
However can exclude low Z nodes (source connections) such as V_x, V_{out}. 1

$\therefore$ Remaining high Z nodes V_y and V_z 4

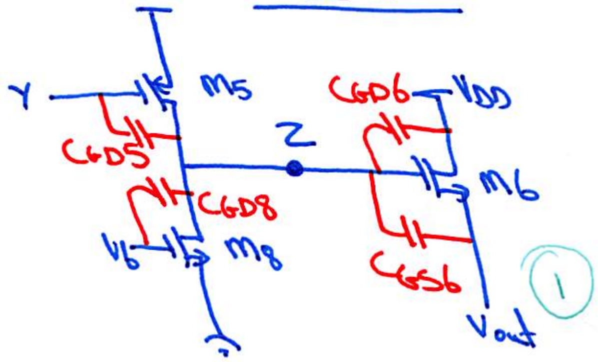
many incorrectly identified Vout as high Z

(e) Need to determine RCs at nodes Y and Z.

Node Y



Node Z



$R_y = r_{o4} \| r_{o2} = 10k\Omega \| 20k\Omega$
$= \underline{6.6k\Omega}$ 1

$R_Z = r_{o5} \| r_{o8} = 2.5k\Omega \| 5k\Omega$
$= \underline{1.6k\Omega}$ 1

$C_y = C_{GD4} + C_{GD2}\left(1 - \frac{1}{A_{v2}}\right) + C_{GS5} + C_{GD5}(1 - A_{v5})$
$= 0.5f(5) + \overset{0.5f}{\cancel{20f}}(250)(21) + 20f(50)(1) + 0.5f(50)(1+7.45)$
$= 1.34pf$ 2

$C_Z = C_{GD5}\left(1 - \frac{1}{A_{v5}}\right) + C_{GD8} + C_{GD6} + C_{GS6}(1 - A_{v6})$
$= 0.5f(50)\left(1 + \cancel{\frac{1}{7.45}}\right) + 0.5f(16) + 0.5f(50) + 20f(50)(1-0.88)$
$= 178ff$ 2

$f_{py} = \frac{1}{2\pi R_y C_y} = \underline{17.82 MHz}$ 1

$f_{pZ} = \frac{1}{2\pi R_Z C_Z} = \underline{536.69MHz}$ ✓

Although method followed correctly by many, either due to selecting wrong nodes, or incorrect calculation of capacitances, final pole frequencies were incorrect.

Most students however received credit for correct method.