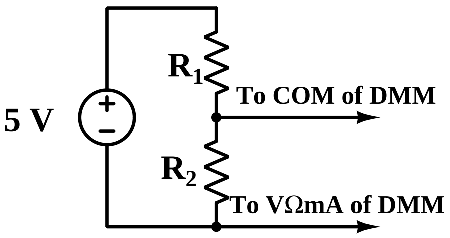
INDIAN INSTITUTE OF TECHNOLOGY BOMBAY
ELECTRICAL ENGINEERING DEPARTMENT

Solution to EE-Midsem: Autumn 2023

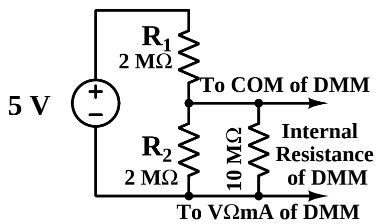
Q–1 In the circuit shown below, two resistors R_1 and R_2 are connected to the 5 V DC output of the Keithley DC Power Supply.



$R_1 = R_2 = 2$ MΩ. (Note: 1 MΩ $= 10^6$ Ω).
The voltage across R_2 was measured using a DMM, by putting it in the DC Voltage range.

The DMM in the chosen voltage range can show two decimal places and has an internal resistance of 10 MΩ.

What reading will you see on the DMM?



R2 comes in parallel with internal resistance of DMM (= 10 MΩ).

Effective value of lower resistance in potential divider is (2×10)/(2+10) = 5/3 MΩ. So the Voltage seen by DMM is:

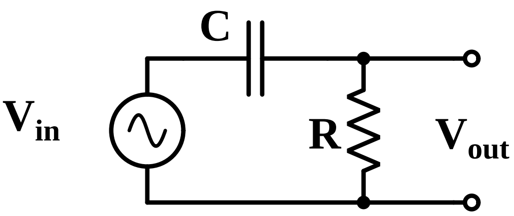
$$\frac{5}{2+5/3} \times \frac{5}{3} = \frac{25}{11} \approx 2.27 \text{ V, to 2 Decimal places.}$$

Since the output is connected to DMM common, reported value will be negative.

Answer: $\boxed{-2.27 \text{ V}}$

– [**2**]

Q–2 Circuit diagram of an RC high-pass filter is shown below in the figure.
$R = 2$ kΩ and $C = 0.01$ μF.



The input-output expression for this filter can be written as:

$$\frac{V_{out}}{V_{in}} = \frac{R}{R + (1/j\omega C)} = \frac{1}{1 + (1/j\omega RC)}$$

A) What is the cut-off frequency f_c in Hz of this RC filter? ($\omega RC = 1$ at f_c).

Answer: $\boxed{f_c = 1/(2\pi RC) \approx 7957.75 \text{ Hz}}$ – [**1**]

B) Find the magnitude of V_{out}/V_{in}

i) at $f_c := |1/(1+j)| = 1/\sqrt{2}$

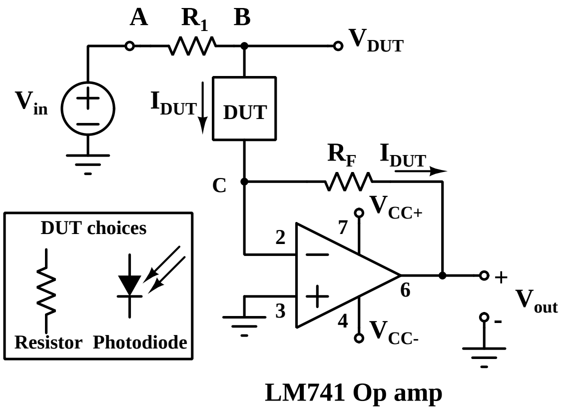
Answer: $\boxed{V_{out}/V_{in} \text{ at } f_c = 1/1.4142 = 0.7071}$

ii) at 2 kHz: $\omega RC =$
$2 \times 3.1416 \times 2000 \times 2000 \times 10^{-8} = 0.2513$
$|1/(1 + 1/0.2513j)| = |1/(1 - 3.9789j)|$
$= 1/\sqrt{1 + 3.9789^2} = 0.2437$

$\boxed{V_{out}/V_{in} \text{ at 2 kHz} = 0.2437}$

– [**1 + 2**]

Q–3 Circuit diagram of the op amp I-to-V converter used in Expt 2 is shown below.



The device under test (DUT) is connected between terminals B and C. Assume the op amp is ideal.

$V_{cc+} = +12$ V, $V_{cc-} = -12$ V;
$R_1 = 1.5$ kΩ, $R_F = 2$ $k\Omega$.

Also assume that the maximum and minimum V_{out} levels are V_{cc+} and V_{cc-} respectively.

Calculation steps must be shown with your answer. No marks will be awarded without proper steps.

a) A 3 kΩ resistor is connected as the DUT. If $V_{in} = +6$ V, what will be the values of V_{DUT} and V_{out}?

Calculation Steps: C is at virtual ground
$I_{DUT} = 6/(1.5 + 3) = 4/3$ mA.
$V_{DUT} = 3$ kΩ $\times$ $4/3$ mA $= 4$ V.
$V_{out} = -$ 2 kΩ $\times$ $4/3$ mA $= -8/3$ V.

Answer:

$\boxed{V_{DUT} = 4 \text{ V}}$

$\boxed{V_{out} = -8/3\ V = -2.667 \text{ V}}$

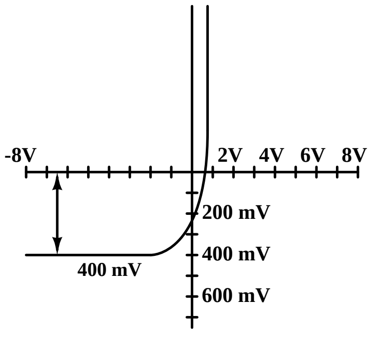
– **[1 + 1]**

b) A photodiode (similar to the one used in the lab) is connected as the DUT with its anode at terminal B and cathode at terminal C. Assume that light from a mobile flashlight is made to fall on the photodiode and the corresponding photocurrent is 200 μA. V_{in} is a triangular wave of 200 Hz with +ve and −ve peaks of +8 V and −8 V respectively.

i) Sketch the I-V characteristic of this photodiode as seen on the DSO when it is put in the X-Y mode with V_{DUT} as X and I_{DUT} as Y and with the Y channel inverted. Indicate appropriate voltage and current values.

Anode is connected to B and cathode to C. The diode will be forward biased when V_{in} is positive and reverse biased when it is negative. Photocurrent flows when the diode is reverse biased. A negative voltage at B will reverse bias the diode and will produce a positive voltage at V_{out}. However, because of channel inversion, it will show up as a negative value on the scope. Photocurrent of 200 μA will show up as
$-$ 200 μA $\times 2$ kΩ $= -400$ mV.

Sketch:



– **[2]**

ii) Based on the I-V characteristic of the photodiode in the reverse biased region, comment with justification whether the photodiode is working as a voltage source or as a current source.

Comment with justification:

Photocurrent remains constant even as the reverse voltage across the diode is changed. Since it supplies constant current irrespective of voltage across its terminals, it is acting as a current source. – [**2**]

Q–4 **a)** A sine wave with peak to peak amplitude of approximately 200 mV is superimposed on a DC value of about 10 V.
Choose the correct coupling mode (AC or DC) for accurately measuring:

i) the average value of this waveform $\boxed{\text{DC}}$ (AC coupling reduces average voltage to 0).

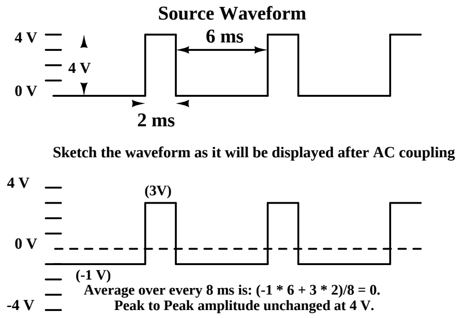
and

ii) the peak to peak value of the sine wave. $\boxed{\text{AC}}$ (High sensitivity required to see low AC voltage. DC coupling at this sensitivity will take the trace out of the window.)

– [**2**]

b) Consider a source waveform as shown in the figure below. This wave is displayed on an oscilloscope using AC coupling.

Sketch how the waveform will appear on the oscilloscope. (The waveform after AC coupling should be drawn with an identical time scale as used for the source waveform and should show the voltage levels at the bottom and top of the waveform in text).



– [**3**]

Q–5 Using 3 bits, we can represent unsigned numbers in the range (0-7). We want to design a combinational digital circuit with a 3 bit input whose output is '1' if the number represented by the input bits is a prime number and '0' otherwise.
(Numbers 2, 3, 5 and 7 are prime numbers in this range).

a) Using the table on the right (where A, B and C are inputs with A as the most significant bit), fill in the truth table entries for the function F whose output should be '1' whenever the input number is a prime number.

A	B	C	F
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

b) Express the function F in canonical form as a sum of products.

Answer:
$F = \overline{A}B\overline{C} + \overline{A}BC + A\overline{B}C + ABC$

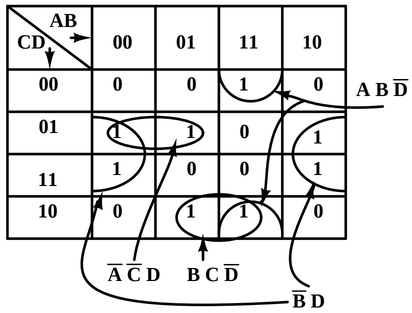
– [**3**]

(Just for information: The function can be simplified to
$\overline{A}B(\overline{C} + C) + AC(\overline{B} + B) = \overline{A}B + AC$
This is a multiplexer choosing one of B and C based on the value of A.)

Q–6 A function is specified in canonical sum of products form as

$$F = \overline{A}\,\overline{B}\,\overline{C}D + \overline{A}\,\overline{B}\,C\,D + \overline{A}\,B\,\overline{C}\,D + \overline{A}\,B\,C\,\overline{D} + A\,\overline{B}\,\overline{C}D + A\,\overline{B}\,CD + A\,B\,\overline{C}\,\overline{D} + A\,B\,C\overline{D}$$

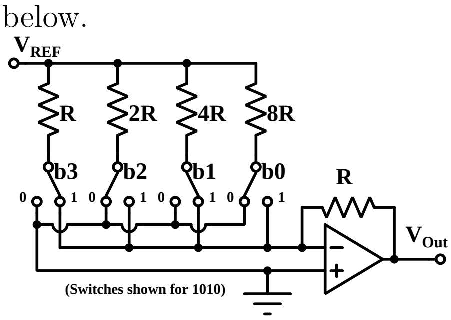
Fill in entries for this function in the Karnaugh map given on the right.
Find the minimal expression for this function using the Karnaugh minimisation procedure.



Answer: $F = A\ B\ \overline{D} + \overline{A}\ \overline{C}\ D + B\ C\ \overline{D} + \overline{B}\ D$ – [**5**]

Q–7 An n bit A-D converter divides a given range of analog values in 2^n equal intervals and represents any analog value in the range by the interval number enclosing it. This involves a possible inaccuracy of half the size of the interval in the worst case. This is called quantization error.
What is the least number of bits that one should use for digital representation of analog voltages in the range 0 to 5 V such that the worst case quantization error is less than 5 mV.
Answer: For worst case quantization error of 5 mV, interval width should be ≤ 10 mV.
We must divide the range (0 to 5) V in $\geq \frac{5}{(10\times10^{-3})} = 500$ intervals.
Nearest power of 2 is 512, which is 2^9. Therefore we need 9 bit resolution to ensure that quantization error is ≤ 5 mV. – [**2**]

Q–8 Consider a 4 bit D-A converter using binary weighted resistors as shown in the figure below.



Each switch is controlled by a bit of the digital word being converted to analog and steers the current through the resistor (to which it is connected) to ground or to virtual ground depending on the bit being ‘0’ or ‘1’.
For $V_{REF} = 4V$, Fill in the output voltage V_{out} for the given digital values in the table below:

Inverting gain through the four input resistors of $R,\ 2R,\ 4R$ and $8R$ is $-1,\ -1/2,\ -1/4,\ -1/8$ respectively with an input voltage of 4, when the corresponding switch is connected to the inverting input.

Digital Word $b_3b_2b_1b_0$	Output voltage V_{out} in V
1100	$-4-2-0-0=-6$ V
1010	$-4-0-1-0=-5$ V
0111	$-0-2-1-0.5=-3.5$ V

(Output = Digital value represented by $b_3b_2b_1b_0 \times -0.5$ V.) – [**3**]