

Digital Design Through Arduino



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ABOUT THIS BOOK

This book provides a simple introduction to digital design using the Arduino framework, assembly and embedded C. It is suitable for students ranging from primary school to college. The content is sufficient for industry jobs. There is no copyright, so readers are free to print and share.

All the boards introduced in this book are well supported by linux toolchains on termux-debian, allowing readers to explore the power of free software and low cost hardware on their android phones.

This book is dedicated to my teachers at IIT Guwahati, Prof. Anil Mahanta and Prof. Anup Gogoi. They somehow managed to teach me circuits.

September 11, 2024

Github:<https://github.com/gadepall/digital-design>

License: <https://creativecommons.org/licenses/by-sa/3.0/>

and

<https://www.gnu.org/licenses/fdl-1.3.en.html>

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In this edition, content on the vaman board has been added. This covers ESP 32, ARM Cortex-M4 as well as the Quiclogic EOS-S3 FPGA. In addition, some content on getting started with the Raspberry Pi Pico has been added. Also, the STM32F103C8T6 (blue pill) has been introduced in some detail.

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1 INSTALLATION

1.1 Termux

1. On your android device, follow the instructions in

```
https://github.com/gadepall/fwc-1
```

to setup and install Debian on Termux.

1.2 Platformio

1. Install Packages

```
apt install avra avrdude gcc-avr avr-libc
```

2. Follow the instructions in

```
https://docs.platformio.org/en/stable/core/installation/methods/installer-script.html#super-quick-macos-linux
```

to install platformio.

3. Execute the following on debian

```
cd ide/piosetup/codes  
pio run
```

4. Connect your arduino to the laptop/rpi and type

```
pio run -t nobuild -t upload
```

5. The LED beside pin 13 will start blinking

1.3 Arduino Droid

1. Install ArduinoDroid from apkpure
2. Open ArduinoDroid and grant all permissions
3. Connect the Arduino to your phone via USB-OTG
4. For flashing the bin files, in ArduinoDroid,

```
Actions->Upload->Upload Precompiled
```

then go to your working directory and select

```
pio/build/uno/firmware.hex
```

for uploading hex file to the Arduino Uno

5. The LED beside pin 13 will start blinking

2 SEVEN SEGMENT DISPLAY

We show how to control a seven segment display.

2.1 Components

Component	Value	Quantity
Resistor	220 Ohm	1
Arduino		1
Seven Segment Display		1
Decoder	7447	1
Flip Flop	7474	2
Jumper Wires		20

TABLE 2.1: Components

1. Breadboard:

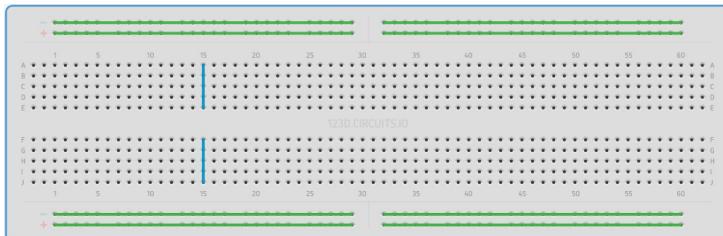


Fig. 2.1: Bread board connnections

The breadboard can be divided into 5 segments. In each of the green segments, the pins are internally connected so as to have the same voltage. Similarly, in the central segments, the pins in each column are internally connected in the same fashion as the blue columns.

2. Seven Segment Display: The seven segment display in Fig. 2.2 has eight pins, a, b, c, d, e, f, g and *dot* that take an active LOW input, i.e. the LED will glow only if the input is connected to ground. Each of these pins is connected to an LED segment. The *dot* pin is reserved for the · LED.
3. Arduino: The Arduino Uno has some ground pins, analog input pins A0-A3 and digital pins D1-D13 that can be used for both input as well as output. It also has two power pins that can generate 3.3V and 5V. In the following exercises, only the GND, 5V and digital pins will be used.

2.2 Display Control through Hardware

2.2.1 Powering the Display:

1. Plug the display to the breadboard in Fig. 2.1 and make the connections in Table 2.2. Henceforth, all 5V and GND connections will be made from the breadboard.

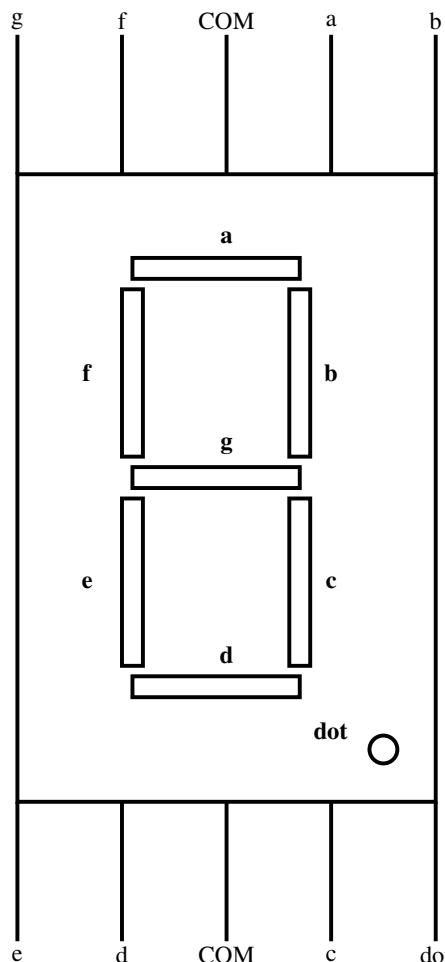


Fig. 2.2: Seven Segment pins

Arduino	Breadboard
5V	Top Green
GND	Bottom Green

TABLE 2.2: Supply for Bread board

2. Make the connections in Table 2.3.

Breadboard		Display
5V	Resistor	COM
GND		DOT

TABLE 2.3: Connecting Seven segment display on Bread board

Arduino	2	3	4	5	6	7	8	8
Display	a	b	c	d	e	f	g	

TABLE 2.5

3. Connect the Arduino to the computer. The DOT led should glow.

2.2.2 *Controlling the Display*: Fig. 2.3 explains how to get decimal digits using the seven segment display. GND=0.

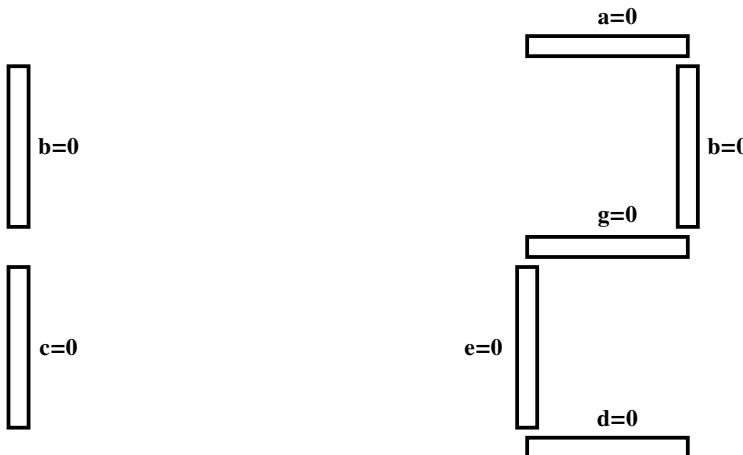


Fig. 2.3: Seven Segment connections

1. Generate the number 1 on the display by connecting only the pins *b* and *c* to GND (=0). This corresponds to the first row of 2.4. 1 means not connecting to GND.
2. Repeat the above exercise to generate the number 2 on the display.
3. Draw the numbers 0-9 as in Fig. 2.3 and complete Table 2.4

a	b	c	d	e	f	g	decimal
0	0	0	0	0	0	1	0

TABLE 2.4

2.3 Display Control through Software

1. Make connections according to Table 2.5
2. Download the following code using the arduino IDE and execute

```
ide/sevenseg/codes/sevenseg/sevenseg.cpp
```
3. Now generate the numbers 0-9 by modifying the above program.

3 7447

Here we show how to use the 7447 BCD-Seven Segment Display decoder to learn Boolean logic.

3.1 Hardware

1. Make connections between the seven segment display in Fig. 2.2 and the 7447 IC in Fig. 3.1 as shown in Table 3.1

7447	\bar{a}	\bar{b}	\bar{c}	\bar{d}	\bar{e}	\bar{f}	\bar{g}
Display	a	b	c	d	e	f	g

TABLE 3.1

2. Make connections to the lower pins of the 7447 according to Table 3.2 and connect $V_{CC} = 5V$. You should see the number 0 displayed for 0000 and 1 for 0001.

D	C	B	A	Decimal
0	0	0	0	0
0	0	0	1	1

TABLE 3.2



Fig. 3.1: 7447 IC

3. Complete Table 3.2 by generating all numbers between 0-9.

3.2 Software

1. Now make the connections as per Table 3.3 and execute the following program

```
ide/7447/codes/gvv_ard_7447/gvv_ard_7447.cpp
```

7447	D	C	B	A
Arduino	5	4	3	2

TABLE 3.3

Z	Y	X	W	D	C	B	A
0	0	0	0	0	0	0	1
0	0	0	1	0	0	1	0
0	0	1	0	0	0	1	1
0	0	1	1	0	1	0	0
0	1	0	0	0	1	0	1
0	1	0	1	0	1	1	0
0	1	1	0	0	1	1	1
0	1	1	1	1	0	0	0
1	0	0	0	1	0	0	1
1	0	0	1	0	0	0	0

TABLE 3.4: Truth table for incrementing Decoder.

In the truth table in Table 3.4, W, X, Y, Z are the inputs and A, B, C, D are the outputs. This table represents the system that increments the numbers 0-8 by 1 and resets the number 9 to 0 Note that $D = 1$ for the inputs 0111 and 1000. Using *boolean* logic,

$$D = WXYZ' + W'X'Y'Z \quad (3.1)$$

Note that 0111 results in the expression $WXYZ'$ and 1000 yields $W'X'Y'Z$.

2. The code below realizes the Boolean logic for B, C and D in Table 3.4. Write the logic for A and verify.

```
ide/7447/codes/inc_dec/inc_dec.ino
```

3. Now make additional connections as shown in Table 3.5 and execute the following code. Comment.

```
ide/7447/codes/ip_inc_dec/ip_inc_dec.cpp
```

Solution: In this exercise, we are taking the number 5 as input to the arduino and displaying it on the seven segment display using the 7447 IC.

	Z	Y	X	W
Input	0	1	0	1
Arduino	9	8	7	6

TABLE 3.5

4. Verify the above code for all inputs from 0-9.
5. Now write a program where
 - the binary inputs are given by connecting to 0 and 1 on the breadboard
 - incremented by 1 using Table 3.4 and
 - the incremented value is displayed on the seven segment display.

6. Write the truth table for the 7447 IC and obtain the corresponding boolean logic equations.
7. Implement the 7447 logic in the arudino. Verify that your arduino now behaves like the 7447 IC.

3.3 Problems

Verify all logic using the Arduino

1. Obtain the Boolean Expression for the logic circuit shown below in Fig. 3.2.
(CBSE 2013)

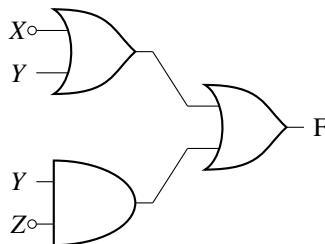


Fig. 3.2

2. Verify the Boolean Expression (CBSE 2013)

$$A + C = A + A'C + BC$$

3. Draw the logic circuit for the following Boolean Expression (CBSE 2015)

$$f(x, y, z, w) = (x' + y)z + w'$$

4. Verify the following (CBSE 2015)

$$U' + V = U'V' + U'V + UV$$

5. Draw the logic circuit for the given Boolean Expression (CBSE 2015)

$$(U + V')W' + Z$$

6. Verify the following using Boolean Laws (CBSE 2015)

$$X + Y' = XY + XY' + X'Y'$$

7. Write the Boolean Expression for the result of the logic circuit as shown in Fig. 3.3 (CBSE 2016)

8. Draw the logic circuit of the following Boolean Expression using only NAND Gates. (CBSE 2017)

$$XY + YZ$$

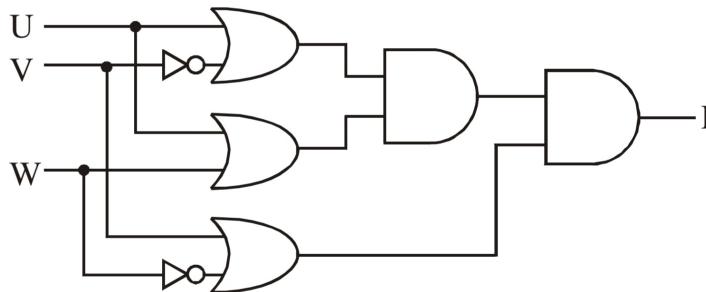


Fig. 3.3

9. Draw the logic circuit of the following Boolean Expression using only NOR Gates (CBSE 2017)

$$(A + B)(C + D)$$

10. Draw the logic circuit of the following Boolean Expression (CBSE 2018)

$$(U' + V')(V' + W')$$

11. Derive a Canonical POS expression for a Boolean function F, represented by Table 3.6 (CBSE 2019)

X	Y	Z	F(X,Y,Z)
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	0

TABLE 3.6

12. For the logic circuit shown in Fig. 3.4, find the simplified Boolean expression for the output. (GATE EC 2000)

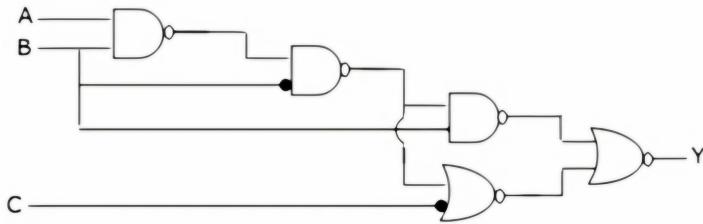


Fig. 3.4

13. Obtain the Boolean Expression for the logic circuit shown below in Fig. 3.5.

(GATE EC 1993)

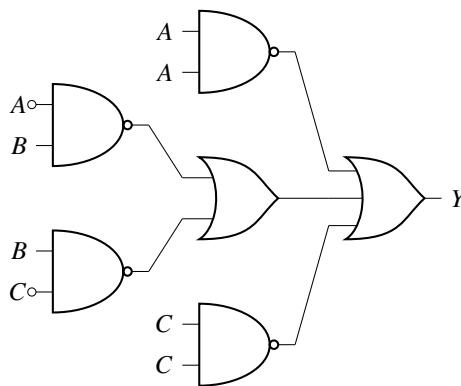


Fig. 3.5

14. Implement Table 3.7 using XNOR logic.

(GATE EC 1993)

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	1

TABLE 3.7

15. For a binary half-sub-tractor having two inputs A and B, find the correct set of logical expressions for the outputs $D = A$ minus B and X =borrow. (GATE EC 1999)
16. Find X in the following circuit in Fig. 3.6 (GATE EC 2007)

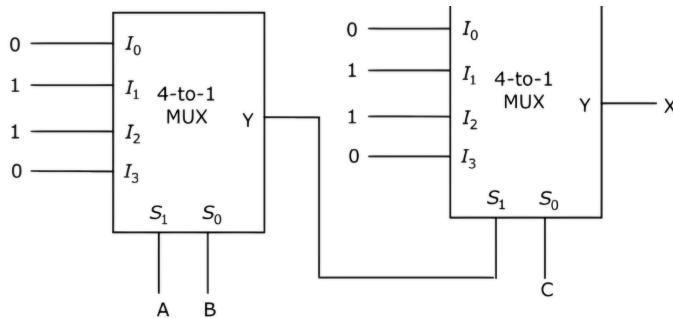


Fig. 3.6

17. A logic circuit implements the boolean function $F = X' \cdot Y + X \cdot Y' \cdot Z'$. It is found that the input combination $X = Y = 1$ can never occur. Taking this into account, find a simplified expression for F .
(GATE IN 2007)
18. Find the Boolean logic realised by the following circuit in Fig. 3.7.
(GATE EC 2010)

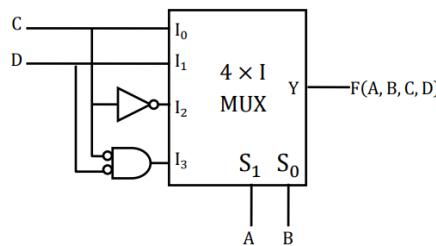


Fig. 3.7

19. Find the logic function implemented by the circuit given below in Fig. 3.8.
(GATE EC 2011)

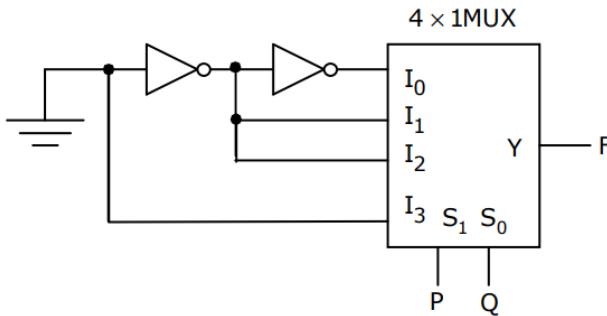


Fig. 3.8

20. Find F in the Digital Circuit given in the figure below in Fig. 3.9. (GATE IN 2016)

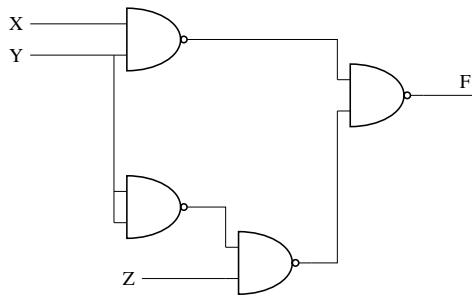


Fig. 3.9

21. Find the logic function implemented by the circuit given below in Fig. 3.10.

(GATE EC 2017)

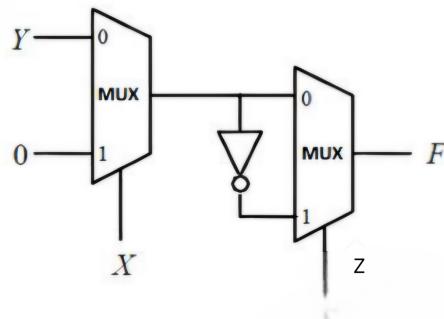


Fig. 3.10

22. Find the logic function implemented by the circuit given below in Fig. 3.11

(GATE EE 2018)

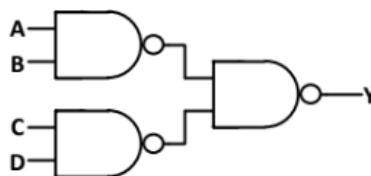


Fig. 3.11

23. Let \oplus and \odot denote the Exclusive OR and Exclusive NOR operations, respectively. Which one of the following is NOT CORRECT ?

(GATE CS 2018)

(A) $\overline{P \oplus Q} = P \odot Q$

- (B) $\overline{P} \oplus \underline{Q} = P \odot Q$
 (C) $\overline{P} \oplus \overline{Q} = P \oplus Q$
 (D) $(P \oplus \overline{P}) \oplus Q = (P \odot \overline{P}) \odot \overline{Q}$

24. Find the logic function implemented by the circuit given below in Fig. 3.12
 (GATE EE 2019)

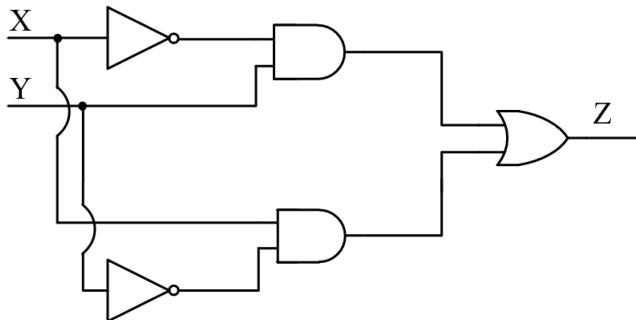


Fig. 3.12

25. Find the logic function implemented by the circuit given below in Fig. 3.13
 (GATE EC 2018)

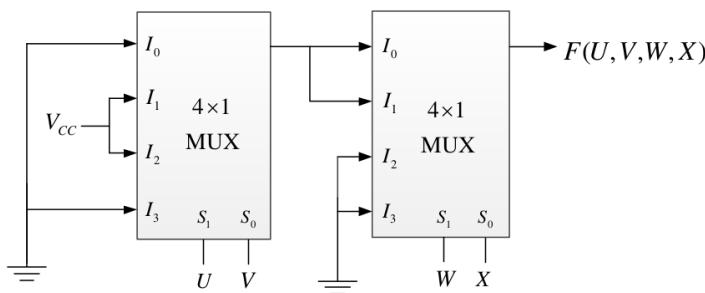


Fig. 3.13

26. A Boolean digital circuit is composed using two 4-input multiplexers $M1$ and $M2$ and one 2-input multiplexer $M3$ as shown in the Fig. 3.14. $X0-X7$ are the inputs of the multiplexers $M1$ and $M2$ and could be connected to either 0 or 1. The select lines of the multiplexers are connected to Boolean variables A, B and C as shown. Which one of the following set of values of $(X0, X1, X2, X3, X4, X5, X6, X7)$ will realise the Boolean function $\overline{A} + \overline{AC} + A\overline{BC}$?
 (GATE CS 2023)

- a) (1, 1, 0, 0, 1, 1, 1, 0)
- b) (1, 1, 0, 0, 1, 1, 0, 1)
- c) (1, 1, 0, 1, 1, 1, 0, 0)

- d) (0, 0, 1, 1, 0, 1, 1, 1)

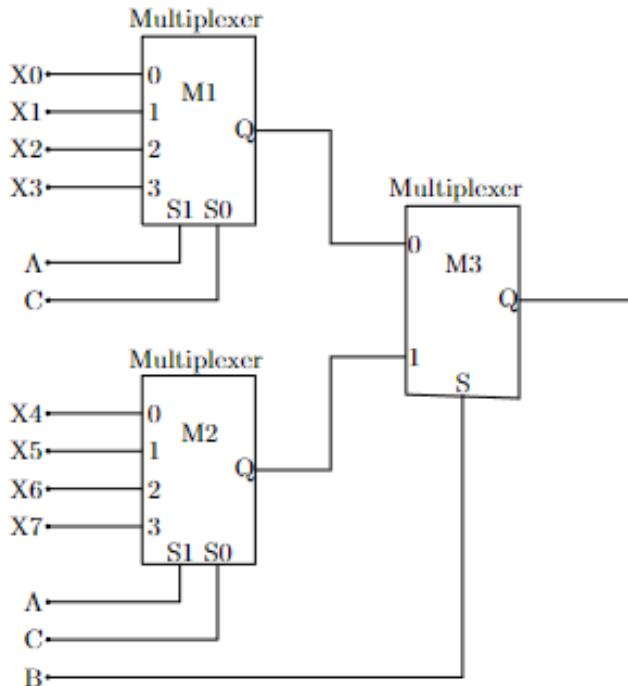


Fig. 3.14: Digital Circuit

27. Select the Boolean function(s) equivalent to $x + yz$, where x, y , and z are Boolean variables, and $+$ denotes logical OR operation. (GATE EC 2022)

- (A) $x + z + xy$
- (B) $(x + y)(x + z)$
- (C) $x + xy + yz$
- (D) $x + xz + xy$

28. Which one of the following options is CORRECT for the given circuit in Fig. 3.15? (GATE PHYSICS 2023)

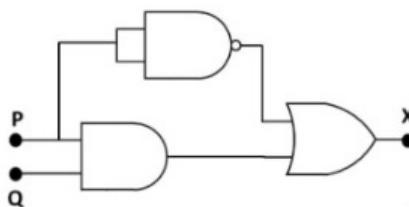


Fig. 3.15

- (A) $P = 1, Q = 1 ; X = 0$
 (B) $P = 1, Q = 0 ; X = 1$
 (C) $P = 0, Q = 1 ; X = 0$
 (D) $P = 0, Q = 0 ; X = 1$

29. Consider a Boolean gate D where the output Y is related to the inputs A and B as $Y = A + B$, where $+$ denotes logical OR operation. The Boolean inputs 0 and 1 are also available separately. Using instances of only D gates and inputs 0 and 1, select the correct option(s). (GATE EC 2022)

- a) NAND logic can be implemented
- b) OR logic cannot be implemented
- c) NOR logic can be implemented
- d) AND logic cannot be implemented.

30. Let $R1$ and $R2$ be two 4-bit registers that store numbers in 2's complement form. For the operation $R1 + R2$, which one of the following values of $R1$ and $R2$ gives an arithmetic overflow? (GATE CS 2022)

- a) $R1 = 1011$ and $R2 = 1110$
- b) $R1 = 1100$ and $R2 = 1010$
- c) $R1 = 0011$ and $R2 = 0100$
- d) $R1 = 1001$ and $R2 = 1111$

31. The logic block shown in Fig. 3.16 has an output F given by _____.

- a) $A + B$
- b) $A\bar{B}$
- c) $A + \bar{B}$
- d) \bar{B}

(GATE IN 2021)

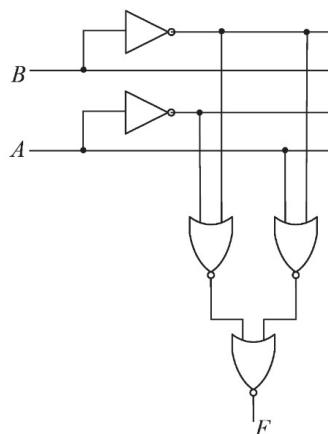


Fig. 3.16

32. Consider the following Boolean expression

$$F = (X + Y + Z)(\bar{X} + Y)(\bar{Y} + Z)$$

Which of the following Boolean expressions is/are equivalent to \bar{F} ?

- a) $(\bar{X} + \bar{Y} + \bar{Z})(X + \bar{Y})(Y + \bar{Z})$
- b) $X\bar{Y} + \bar{Z}$
- c) $(X + \bar{Z})(\bar{Y} + \bar{Z})$
- d) $X\bar{Y} + Y\bar{Z} + \bar{X}\bar{Y}\bar{Z}$

(GATE CS 2021)

33. The circuit shown in Fig. 3.17 comprises of XOR, AND gates and multiplexers. If all the inputs P, Q, R, S and T are applied simultaneously and held constant, find Y .

(GATE EC 2021)

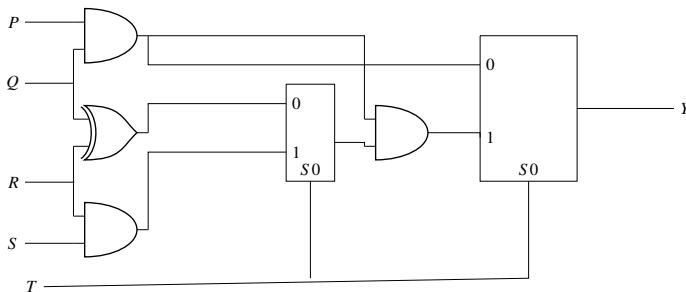


Fig. 3.17

34. The following combination of logic gates in Fig. 3.18 represents the operation

- a) OR
- b) NAND
- c) AND
- d) NOR

(GATE PH 2021)

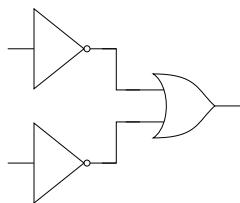


Fig. 3.18

35. Consider the boolean Function $z(a, b, c)$ from Fig. 3.19 below. Which of the following minterm lists represent the circuit given above?

- a) $z = \Sigma(0, 1, 3, 7)$
- b) $z = \Sigma(1, 4, 5, 6, 7)$

c) $z = \Sigma(2, 4, 5, 6, 7)$

d) $z = \Sigma(2, 3, 5)$

(GATE CS 2020)

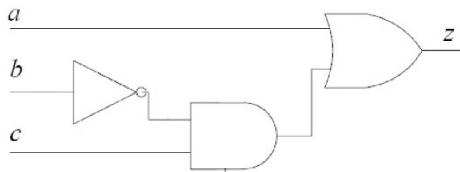


Fig. 3.19

36. Consider three 4-variable functions f_1, f_2 , and f_3 , which are expressed in sum-of-minterms as

$$f_1 = \sum(0, 2, 5, 8, 14), f_2 = \sum(2, 3, 6, 8, 14, 15), f_3 = \sum(2, 7, 11, 14)$$

. For the following circuit in Fig. 3.20, with one AND gate and one XOR gate, the output function f can be expressed as

- a) $\sum(7, 8, 11)$
- b) $\sum(2, 7, 8, 11, 14)$
- c) $\sum(2, 14)$
- d) $\sum(0, 2, 3, 5, 6, 7, 8, 11, 14, 15)$

(GATE-CS2019,30)

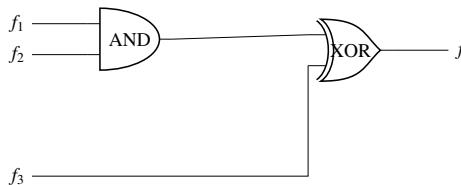


Fig. 3.20

37. In the circuit shown in Fig. 3.21, what are the values of F for $EN = 0$ and $EN = 1$, respectively?

- a) 0 and D
- b) $Hi-Z$ and D
- c) 0 and 1
- d) $Hi-Z$ and \bar{D}

(GATE EC 2019)

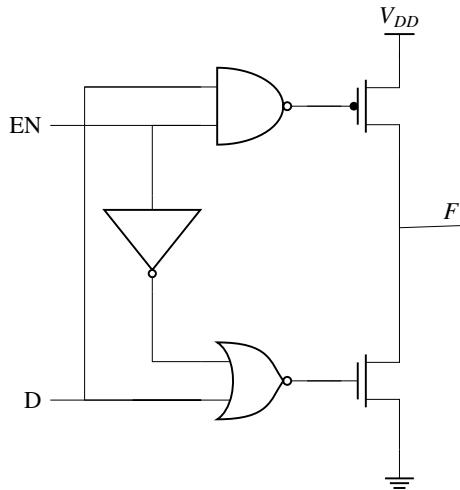


Fig. 3.21: Circuit Diagram

38. In the circuit shown below in Fig. 3.22, assume that the comparators are ideal and all components have zero propagation delay. In one period of the input signal $V_{in} = 6 \sin(\omega t)$, the fraction of the time for which the output OUT is in logic HIGH is
- $\frac{1}{12}$
 - $\frac{1}{2}$
 - $\frac{2}{3}$
 - $\frac{5}{6}$

(GATE IN 2019)

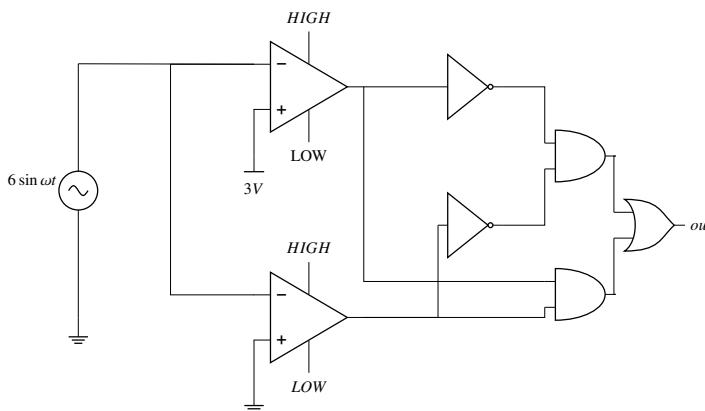


Fig. 3.22: Circuit Diagram

39. Fig. 3.23 shows the i th full-adder block of a binary adder circuit. C_i is the input

carry and C_{i+1} is the output carry of the circuit. If the inputs A_i, B_i ; are available and stable throughout the carry propagation, find the outputs S_i and C_{i+1} .

(GATE IN 2019)

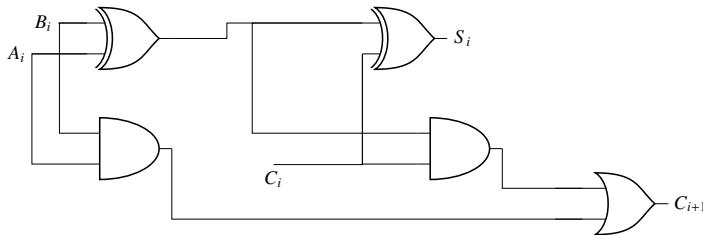


Fig. 3.23: Full Adder

40. The Boolean operation performed by the following circuit in Fig. 3.24 at the output O is _____.

- a) $O = S_1 \oplus S_0$
- b) $O = S_1 \overline{S_0}$
- c) $O = S_1 + S_0$
- d) $O = S_0 \overline{S_1}$

(GATE IN 2020)

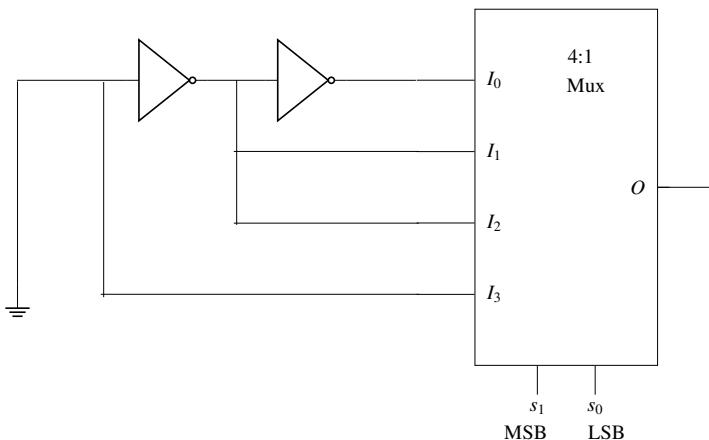


Fig. 3.24

41. The chip select logic for a certain DRAM chip in a memory system design is shown below in Fig. 3.25. Assume that the memory system has 16 address lines denoted by A_{15} to A_0 . What is the range of addresses (in hexadecimal) of the memory system that can get enabled by the chip select (CS) signal?

- a) C800 to CFFF
- b) CA00 to CAFF

- c) CA00 to C8FF
 d) DA00 to DFFF

(GATE CS 2019)

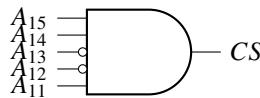
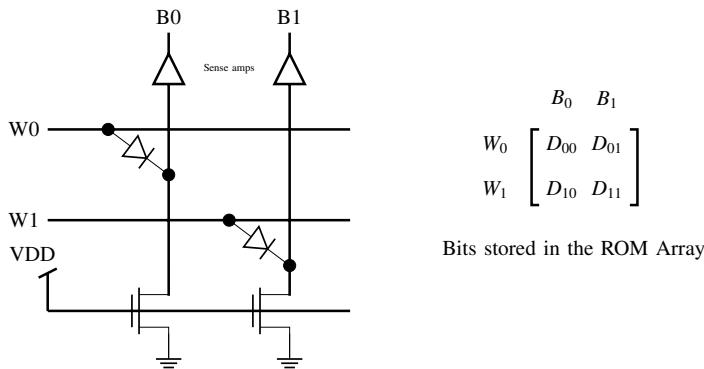


Fig. 3.25

42. A 2×2 ROM array is built with the help of diodes as shown in the circuit below in Fig. 3.26. Here W_0 and W_1 are signals that select the word lines and B_0 and B_1 are signals that are output of the sense amps based on the stored data corresponding to the bit lines during the read operation.

Fig. 3.26: 2×2 ROM array

During the read operation, the selected word line goes high and the other word line is in a high impedance state. As per the implementation shown in the circuit diagram above, what are the bits corresponding to D_{ij} (where $i = 0$ or 1 and $j = 0$ or 1) stored in the ROM?

(GATE EC 2018)

- a) $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ b) $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ c) $\begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix}$ d) $\begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix}$

43. Which one the following is not a valid identity?

- a) $(x \oplus y) \oplus z = x \oplus (y \oplus z)$
 b) $(x + y) \oplus z = x \oplus (y + z)$
 c) $x \oplus y = x + y, xy = 0$
 d) $x \oplus y = (xy + x'y')'$

(GATE CS 2019)

44. Let p and q be two propositions. Consider the following two formulae in propositional logic.

$$S_1 : (\neg p \vee (p \wedge q)) \rightarrow q$$

$$S_2 : q \rightarrow (\neg p \vee (p \wedge q))$$

Which one of the following choices is correct?

- a) Both S_1 and S_2 are tautologies.
- b) S_1 is a tautology but S_2 is not a tautology.
- c) S_1 is not a tautology but S_2 is a tautology.
- d) Neither S_1 nor S_2 is a tautology.

(GATE CS 2021)

45. A 3-input majority gate is defined by the logic function

$$M(a, b, c) = ab + bc + ca.$$

Which one of the following gates is represented by the function

$$\overline{M(\overline{M(a, b, c)}, M(a, b, \bar{c}), c)}?$$

- a) 3-input NAND gate
- b) 3-input XOR gate
- c) 3-input NOR gate
- d) 3-input XNOR gate

(GATE EC 2015)

46. A and B are logical inputs and X is the logical output shown in Fig. 3.27. The output X is related to A and B by

- a) $X = \overline{AB} + \overline{BA}$
- b) $X = AB + \overline{BA}$
- c) $X = \overline{AB} + \overline{BA}$
- d) $X = \overline{AB} + BA$

(GATE IN 2017)

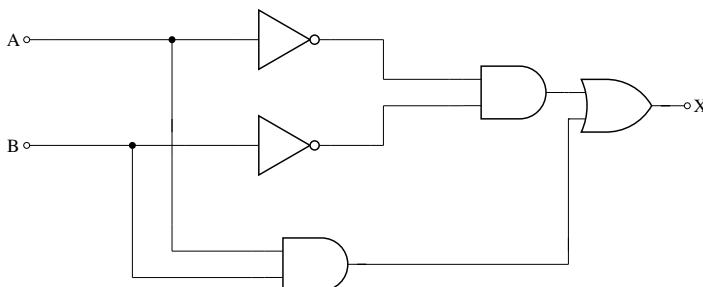


Fig. 3.27

47. The functionality implemented by the circuit below in Fig. 3.28 is

- a) 2-to-1 multiplexer

- b) 4-to-1 multiplexer
- c) 7-to-1 multiplexer
- d) 6-to-1 multiplexer

(GATE 2016 EC)

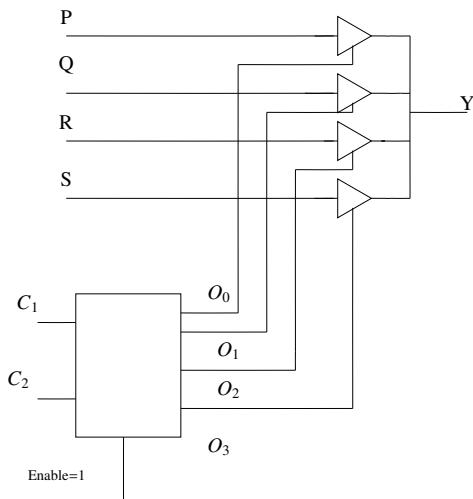


Fig. 3.28: Multiplexer

48. Consider the Boolean function $Z(a, b, c)$. Which one of the following minterm lists represents the circuit given below in Fig. 3.29?

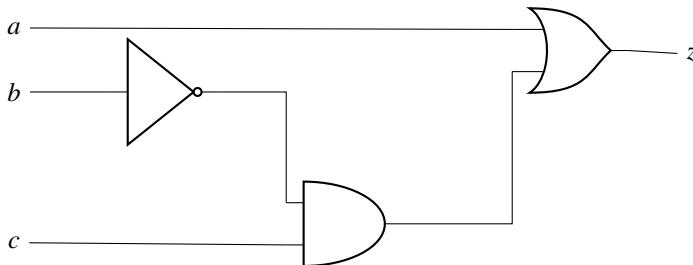


Fig. 3.29

- A. $z = \sum (0, 1, 3, 7)$
- B. $z = \sum (1, 4, 5, 6, 7)$
- C. $z = \sum (2, 4, 5, 6, 7)$
- D. $z = \sum (2, 3, 5)$

(GATE CS 2020)

49. A 2-bit flash Analog to Digital Converter (ADC) is given in Fig. 3.30. The input is $0 \leq V_{IN} \leq 3$ Volts. The expression of the LSB of the output B_0 as a boolean function of X_2 , X_1 , and X_0 is

- a) $X_0 \left[\overline{X_2 \oplus X_1} \right]$
 b) $\overline{X_0} \left[\overline{X_2 \oplus X_1} \right]$
 c) $X_0 [X_2 \oplus X_1]$
 d) $\overline{X_0} [X_2 \oplus X_1]$

(GATE EE 2016)

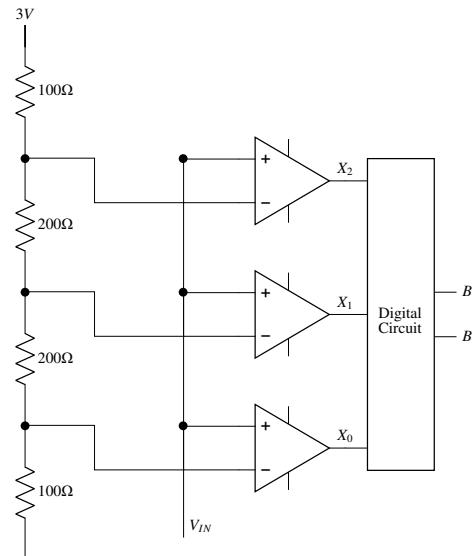


Fig. 3.30

50. In Fig. 3.31, the number of distinct values of $X_3X_2X_1X_0$ (out of the 16 possible values) that give $Y = 1$ is _____. (GATE EC 2018)

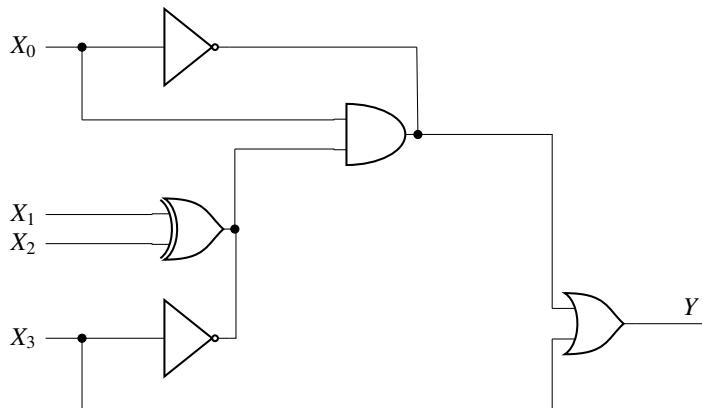


Fig. 3.31

51. In the logic circuit shown in Fig. 3.32, Y is given by

(GATE EE 2018)

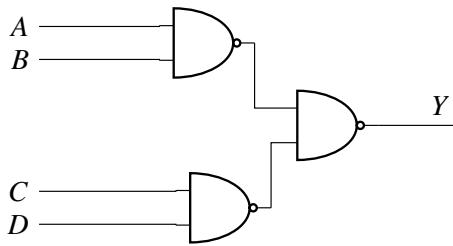


Fig. 3.32

- a) $Y = ABCD$
 b) $Y = (A + B)(C + D)$
 c) $Y = A + B + C + D$
 d) $Y = AB + CD$
52. In the circuit shown in Fig. 3.33, if $C = 0$, the expression for Y is

(GATE EC 2014)

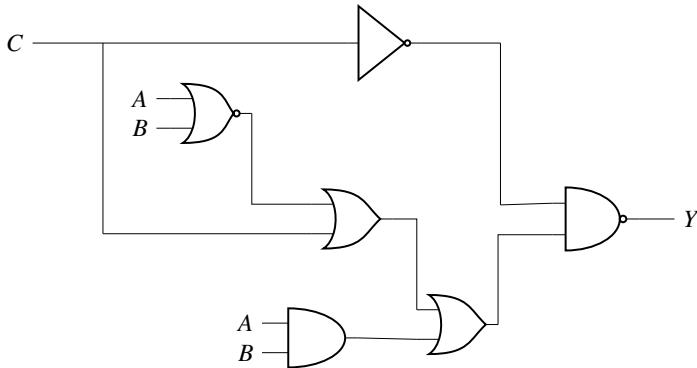


Fig. 3.33

- a) $Y = A\bar{B} + \bar{A}B$
 b) $Y = A + B$
 c) $Y = \bar{A} + \bar{B}$
 d) $Y = AB$
53. The logic function $f(X, Y)$ realised by the given circuit in Fig. 3.34 is (GATE EC 2018)

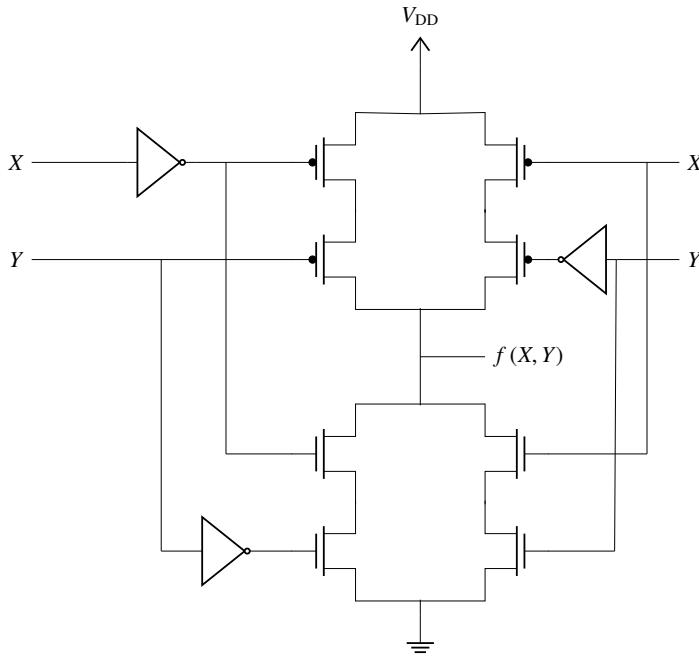


Fig. 3.34

- a) NOR
- b) AND
- c) NAND
- d) XOR

54. P, Q and R are the decimal integers corresponding to the 4-bit binary number 1100 considered in single magnitude, 1's complement and 2's complement representations, respectively. The 6-bit 2's complement representation of $(P + Q + R)$ is

- a) 110101
- b) 110010
- c) 111101
- d) 111001

(GATE EC 2020)

55. The Boolean expression $F(X, Y, Z) = \overline{XY\bar{Z}} + X\overline{Y\bar{Z}} + XY\bar{Z} + XYZ$ converted into the canonical product of sum (POS) form is

- a) $(X + Y + Z)(X + Y + \bar{Z})(X + \bar{Y} + \bar{Z})(\bar{X} + Y + \bar{Z})$
- b) $(X + \bar{Y} + Z)(\bar{X} + Y + \bar{Z})(\bar{X} + \bar{Y} + Z)(\bar{X} + \bar{Y} + \bar{Z})$
- c) $(X + Y + Z)(\bar{X} + Y + \bar{Z})(X + \bar{Y} + Z)(\bar{X} + \bar{Y} + \bar{Z})$
- d) $(X + \bar{Y} + \bar{Z})(\bar{X} + Y + Z)(\bar{X} + \bar{Y} + Z)(X + Y + Z)$

(GATE EC 2015)

4 KARNAUGH MAP

4.1 Incrementing Decoder

We explain Karnaugh maps (K-map) by finding the logic functions for the incrementing decoder

1. The incrementing decoder takes the numbers $0, \dots, 9$ in binary as inputs and generates the consecutive number as output. The corresponding truth table is available in Table 3.4
2. Using Boolean logic, output A in Table 3.4 can be expressed in terms of the inputs W, X, Y, Z as

$$A = W'X'Y'Z' + W'XY'Z' + W'X'YZ' + W'XYZ' + W'X'Y'Z \quad (4.1)$$

3. K-Map for A : The expression in (4.1) can be minimized using the K-map in Fig. 4.1

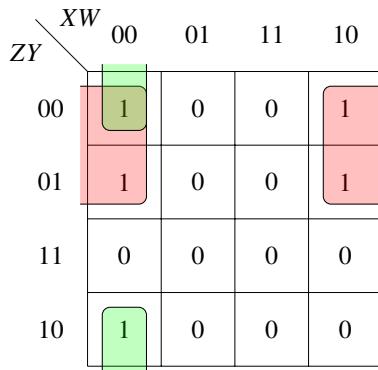


Fig. 4.1: K-map for A

In Fig. 4.1, the *implicants* in boxes 0,2,4,6 result in $W'Z'$. The implicants in boxes 0,8 result in $W'X'Y'$. Thus, after minimization using Fig. 4.1, (4.1) can be expressed as

$$A = W'Z' + W'X'Y' \quad (4.2)$$

Using the fact that

$$\begin{aligned} X + X' &= 1 \\ XX' &= 0, \end{aligned} \quad (4.3)$$

derive (4.2) from (4.1) algebraically

4. K-Map for B : From Table 3.4, using boolean logic,

$$B = WX'Y'Z' + W'XY'Z' + WX'YZ' + W'XYZ' \quad (4.4)$$

Show that (4.4) can be reduced to

$$B = WX'Z' + W'XZ' \quad (4.5)$$

using Fig 4.2

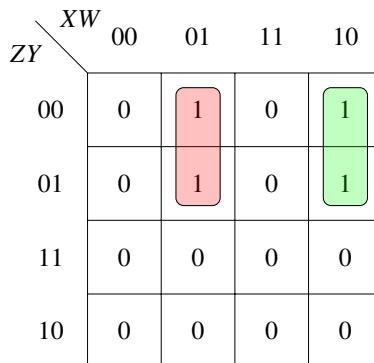


Fig. 4.2: K-map for B

5. Derive (4.5) from (4.4) algebraically using (4.3)
6. K-Map for C : From Table 3.4, using boolean logic,

$$C = WXY'Z' + W'X'YZ' + WX'YZ' + W'XYZ' \quad (4.6)$$

Show that (4.6) can be reduced to

$$C = WXY'Z' + X'YZ' + W'YZ' \quad (4.7)$$

using Fig. 4.3.

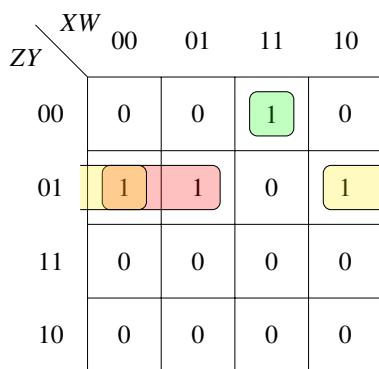


Fig. 4.3: K-map for C

7. Derive (4.7) from (4.6) algebraically using (4.3)

8. K-Map for D : From Table 3.4, using boolean logic,

$$D = WXYZ' + W'X'Y'Z \quad (4.8)$$

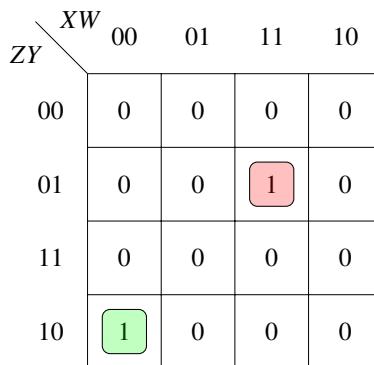


Fig. 4.4: K-map for D

9. Minimize (4.8) using Fig 4.4

10. Execute the code in

ide/7447/codes/inc_dec/inc_dec.cpp

and modify it using the K-Map equations for A, B, C and D . Execute and verify for each case.

11. Display Decoder: Table 4.1 is the truth table for the display decoder in Fig. 3.1. Use K-maps to obtain the minimized expressions for a, b, c, d, e, f, g in terms of A, B, C, D .

D	C	B	A	a	b	c	d	e	f	g	Decimal
0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	1	1	0	0	1	1	1	1	1
0	0	1	0	0	0	1	0	0	1	0	2
0	0	1	1	0	0	0	0	1	1	0	3
0	1	0	0	1	0	0	1	1	0	0	4
0	1	0	1	0	1	0	0	1	0	0	5
0	1	1	0	0	1	0	0	0	0	0	6
0	1	1	1	0	0	0	1	1	1	1	7
1	0	0	0	0	0	0	0	0	0	0	8
1	0	0	1	0	0	0	1	1	0	0	9

TABLE 4.1: Truth table for display decoder.

4.2 Dont Care

We explain Karnaugh maps (K-map) using don't care conditions

1. Don't Care Conditions: 4 binary digits are used in the incrementing decoder in Table 4.1. However, only the numbers from 0-9 are used as input/output in the decoder and we *don't care* about the numbers from 10-15. This phenomenon can be addressed by revising the truth table in Table 4.1 to obtain Table 4.2.

Z	Y	X	W	D	C	B	A
0	0	0	0	0	0	0	1
0	0	0	1	0	0	1	0
0	0	1	0	0	0	1	1
0	0	1	1	0	1	0	0
0	1	0	0	0	1	0	1
0	1	0	1	0	1	1	0
0	1	1	0	0	1	1	1
0	1	1	1	1	0	0	0
1	0	0	0	1	0	0	1
1	0	0	1	0	0	0	0
1	0	1	0	-	-	-	-
1	0	1	1	-	-	-	-
1	1	0	0	-	-	-	-
1	1	0	1	-	-	-	-
1	1	1	0	-	-	-	-
1	1	1	1	-	-	-	-

TABLE 4.2

2. The revised K-map for A is available in Fig 4.5. Show that

$$A = W' \quad (4.9)$$

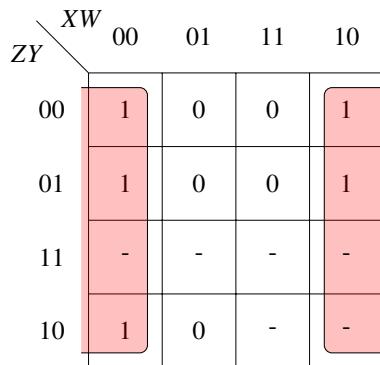


Fig. 4.5: K-map for A with don't cares

3. The revised K-map for B is available in Fig 4.6. Show that

$$B = WX'Z' + W'X \quad (4.10)$$

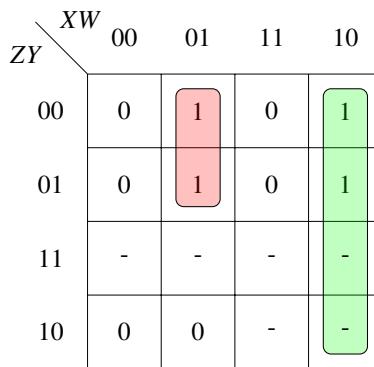


Fig. 4.6: K-map for B with don't cares

4. The revised K-map for C is available in Fig 4.7. Show that

$$C = X'Y + W'Y + WXY' \quad (4.11)$$

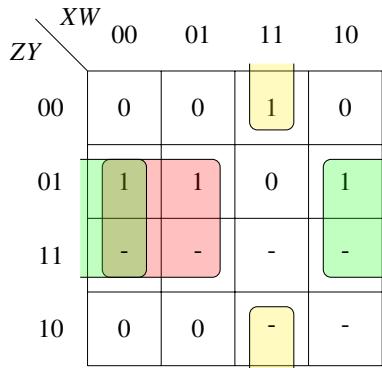


Fig. 4.7: K-map for C with don't cares

5. The revised K-map for D is available in Fig 4.8. Show that

$$D = W'Z + WXY \quad (4.12)$$

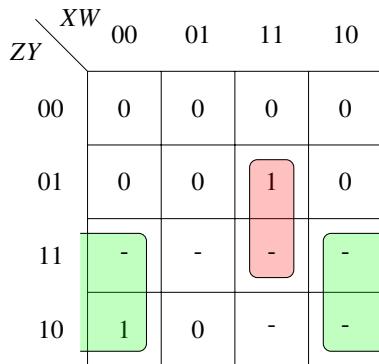


Fig. 4.8: K-map for D with don't cares

6. Verify the incrementing decoder with don't care conditions using the arduino.
7. Display Decoder: In Table 4.1, use K-maps to obtain the minimized expressions for a, b, c, d, e, f, g in terms of A, B, C, D with don't care conditions. Verify using arduino.

4.3 Problems

Verify all your solutions using arduino.

1. Obtain the minimal form for the Boolean expression (CBSE 2013)

$$H(P, Q, R, S) = \sum(0, 1, 2, 3, 5, 7, 8, 9, 10, 14, 15)$$

2. Write the POS form for the function G shown in Table 4.3. (CBSE 2013)

U	V	W	G
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1

TABLE 4.3

3. Reduce the following Boolean Expression to its simplest form using K-Map.

$$F(X, Y, Z, W) = (0, 1, 4, 5, 6, 7, 8, 9, 11, 15)$$

(CBSE 2015)

4. Reduce the following Boolean Expression to its simplest form using K-map

$$F(X, Y, Z, W) = \sum(0, 1, 6, 8, 9, 10, 11, 12, 15)$$

5. Reduce the following Boolean Expression to its simplest form using K-map.

$$F(X, Y, Z, W) = \sum(2, 6, 7, 8, 9, 10, 11, 13, 14, 15)$$

(CBSE 2016)

6. Derive a Canonical POS expression for a Boolean function F , represented in Table 4.4.

(CBSE 2016)

P	Q	R	$F(P, Q, R)$
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

TABLE 4.4

7. Verify the following (CBSE 2016)

$$A' + B'C = A'B'C' + A'BC' + A'BC + A'B'C + AB'C$$

8. Reduce the following boolean expression to its simplest form using K-Map.

$$F(X, Y, Z, W) = \sum(0, 1, 2, 3, 4, 5, 10, 11, 14)$$

(CBSE 2017)

9. Reduce the following Boolean Expression to its simplest form using K-Map.

$$E(U, V, Z, W) = (2, 3, 6, 8, 9, 10, 11, 12, 13)$$

(CBSE 2017)

10. Derive a canonical POS expression for a Boolean function G , represented by Table 4.5.

(CBSE 2017)

X	Y	Z	$G(X, Y, Z)$
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	1

TABLE 4.5

11. Derive a canonical POS expression for a Boolean function FN , represented by Table 4.6.

(CBSE 2018)

X	Y	Z	FN(X,Y,Z)
0	0	0	1
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1

TABLE 4.6

12. Reduce the following Boolean expression in the simplest form using K-Map.

$$F(P, Q, R, S) = \sum(0, 1, 2, 3, 5, 6, 7, 10, 14, 15)$$

(CBSE 2019)

13. Fig. 4.9 below shows a multiplexer where S0 and S1 are the select lines, I0 to I3 are the input lines, EN is the enable line and F is the output. Find the boolean expression for output F as function of inputs P, Q, R using K-map. (GATE EC 2020)

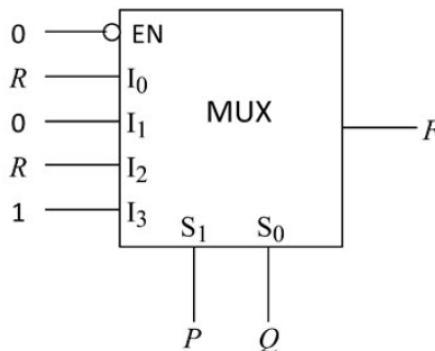


Fig. 4.9

14. The four variable function f is given in terms of min-terms as (GATE EC 1991)

$$f(A, B, C, D) = \sum m(2, 3, 8, 10, 11, 12, 14, 15)$$

Using the K-map minimize the function in the sum of products form.

15. Find the logic realized by the circuit in Fig. 4.10. (GATE EC 1992)

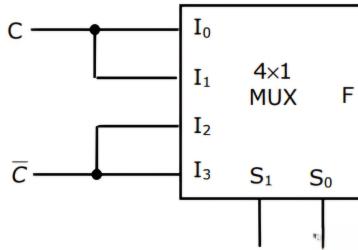


Fig. 4.10

16. A combinational circuit has three inputs A, B and C and an output F. F is true only for the following input combinations. (GATE EC 1992)

- a) A is false and B is true
- b) A is false and C is true
- c) A, B and C are all false
- d) A, B and C are all true

Now, do the following.

- a) Write the truth table for F. use the convention, true = 1 and false = 0.
- b) Write the simplified expression for F as a sum of products.
- c) Write the simplified expression for F as a product of Sums.

17. Draw the logic circuit for Table 4.7 using only NOR gates. (GATE EC 1993)

C	B	A	Y
0	0	0	1
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

TABLE 4.7

18. Implement the following Boolean function in a 8×1 multiplexer. (GATE EC 1993)

$$Q = BC + ABD' + A'C'D$$

19. Minimize the following Boolean function.

$$F = A'B'C' + A'BC' + A'BC + ABC' \quad (4.13)$$

20. Find the Boolean expression for Table 4.8. (GATE EC 2005)

A	B	C	X
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	0

TABLE 4.8

21. Minimize the logic function represented by the following Karnaugh map in Fig. 4.11. (CBSE 2021)

		<i>YZ</i>	00	01	11	10
		<i>X</i>	0	1	1	0
<i>X</i>	<i>Y</i>	0	1	1	1	0
		1	0	0	1	0

Fig. 4.11

22. Find the output for the Karnaugh map shown below in Fig. 4.12 (GATE EE 2019)

		<i>PQ</i>	00	01	11	10
		<i>RS</i>	00	1	1	0
<i>RS</i>	<i>P</i>	00	0	1	1	0
		01	1	1	1	1
<i>RS</i>	<i>Q</i>	11	1	1	1	1
		10	0	0	0	0

Fig. 4.12

23. If all the inputs P, Q, R, S and T are applied simultaneously and held constant in Fig. 4.13, find the output Y . (GATE EC 2021)

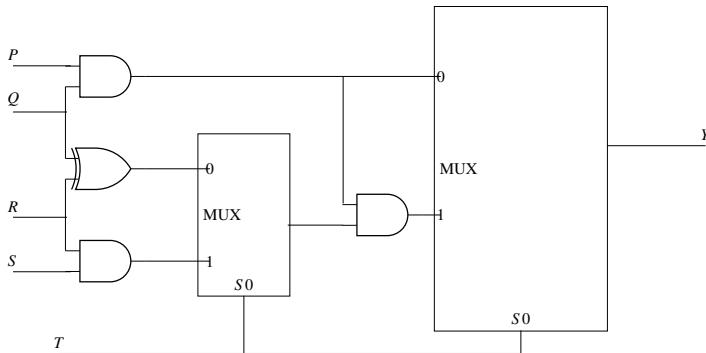


Fig. 4.13

24. Consider the 2-bit multiplexer (MUX) shown in Fig. 4.14. For output to be the XOR of R and S , the values for W, X, Y and Z are _____. (GATE EC-2022)

- a) $W = 0, X = 0, Y = 1, Z = 1$
- b) $W = 1, X = 0, Y = 1, Z = 0$
- c) $W = 0, X = 1, Y = 1, Z = 0$
- d) $W = 1, X = 1, Y = 0, Z = 0$

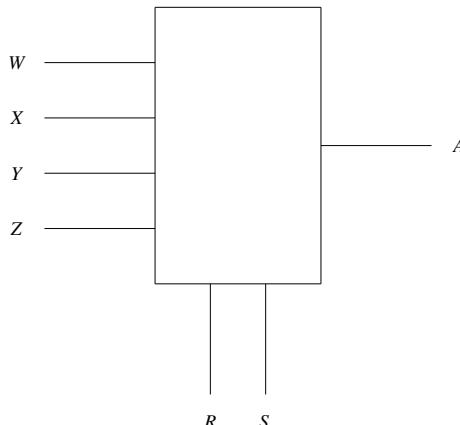


Fig. 4.14

25. $A = a_1a_0$ and $B = b_1b_0$ are two 2-bit unsigned binary numbers. If $F(a_1, a_0, b_1, b_0)$ is a Boolean function such that $F = 1$ only when $A > B$, and $F = 0$ otherwise, then F can be minimized to the form _____. (GATE IN-2022)
26. The logic block shown in Fig. 4.15 has an output F given by _____. (GATE IN 2022)

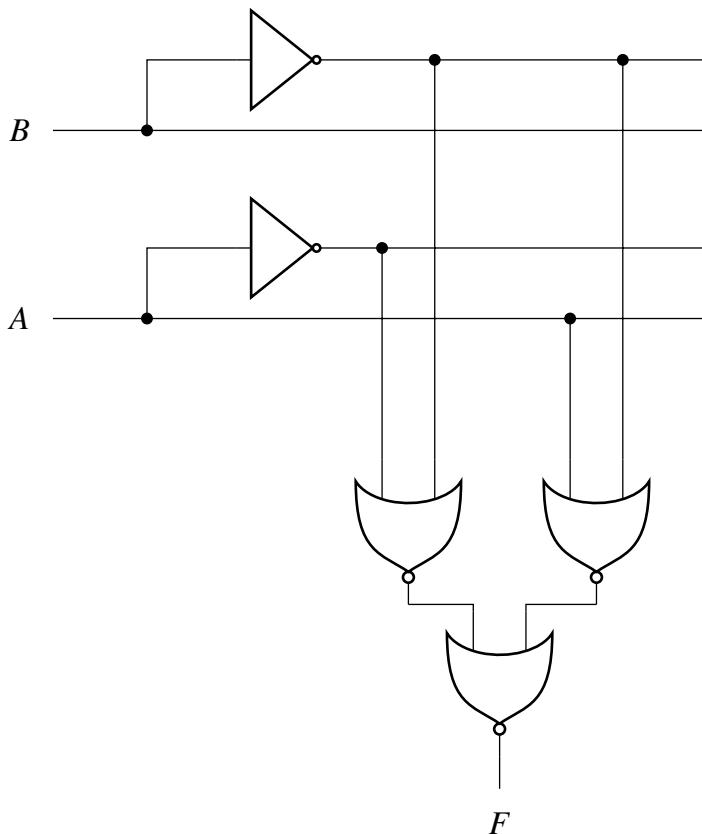


Fig. 4.15: Circuit

- a) $A + B$
 - b) $A \cdot \bar{B}$
 - c) $A + \bar{B}$
 - d) \bar{B}
27. A 4×1 multiplexer with two selector lines is used to realize a Boolean function F having four Boolean variables X, Y, Z , and W as shown below. S_0 and S_1 denote the least significant bit (LSB) and most significant bit (MSB) of the selector lines of the multiplexer, respectively. I_0, I_1, I_2, I_3 are the input lines of the multiplexer.

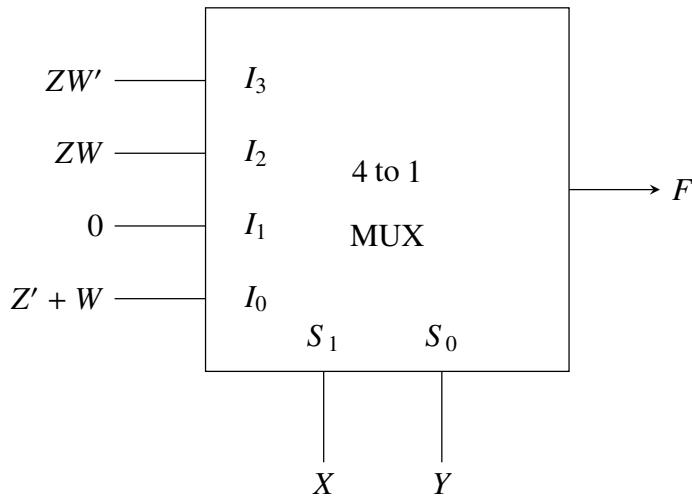


Fig. 4.16: 4×1 multiplexer

The canonical sum of product representation of F is:

(GATE IN-2021)

- (A) $F(X, Y, Z, W) = \Sigma m(0, 1, 3, 14, 15)$
 - (B) $F(X, Y, Z, W) = \Sigma m(0, 1, 3, 11, 14)$
 - (C) $F(X, Y, Z, W) = \Sigma m(2, 5, 9, 11, 14)$
 - (D) $F(X, Y, Z, W) = \Sigma m(1, 3, 7, 9, 15)$
28. The output expression for the Karnaugh map shown below in Fig. 4.17 is (GATE EE 2019)

PQ
RS

	00	01	11	10
00	0	1	1	0
01	1	1	1	1
11	1	1	1	1
10	0	0	0	0

Fig. 4.17

- a) $QR' + S$
 - b) $QR + S$
 - c) $QR' + S'$
 - d) $QR + S'$
29. In the circuit shown below in Fig. 4.18, X and Y are digital inputs, and Z is a digital output. The quivalent circuit is a (GATE EE 2019)

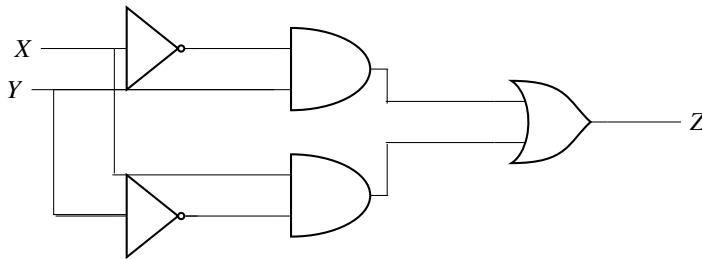


Fig. 4.18

- a) NAND gate
- b) NOR gate
- c) XOR gate

- d) XNOR gate
 30. The output F of the digital circuit shown in Fig. 4.19 can be written in the form(s) _____ (GATE IN 2022)

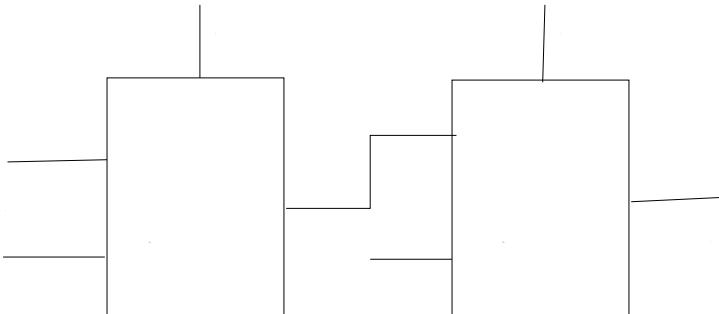


Fig. 4.19

- a) $\overline{A \cdot B}$
 b) $\overline{A+B}$
 c) $\overline{A + B}$
 d) $\overline{A \cdot \overline{B}}$
31. If $X = X_1X_0$ and $Y = Y_1Y_0$ are 2-bit binary numbers. The Boolean function S that satisfies the condition "If $X > Y$, then $S = 1$ ", in its minimized form, is ?
- a) $X_1Y_1 + X_0Y_0$
 b) $X_1\overline{Y_1} + X_0\overline{Y_0}Y_1 + X_0\overline{Y_0}X_1$
 c) $X_1\overline{Y_1}X_0\overline{Y_0}$
 d) $X_1Y_1 + X_0\overline{Y_0}Y_1 + X_0\overline{Y_0}X_1$
- (GATE IN 2019)
32. Fig. 4.20 below shows the i^{th} full-adder block of a binary adder circuit. C_i is the input carry and C_{i+1} is the output carry of the circuit. Assume that each logic gate has a delay of 2 nanosecond, with no additional time delay due to the interconnecting wires. Of the inputs A_i , B_i are available and stable throughout the carry propagation, the maximum time taken for an input C_i to produce a steady-state output C_{i+1} is _____ nanosecond.
- (GATE IN 2019)

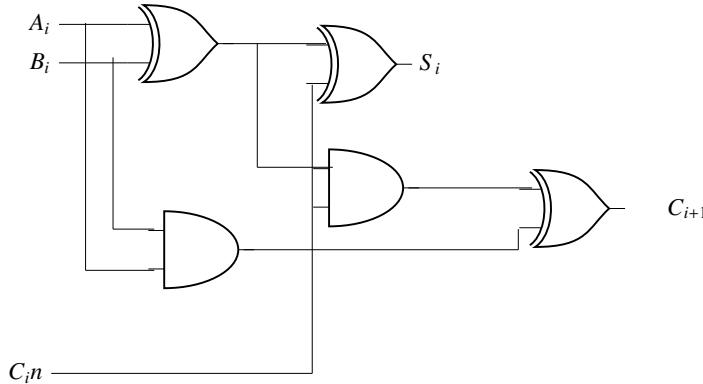


Fig. 4.20

33. The Product of sum expression of a Boolean function $F(A, B, C)$ three variables is given by

$$\begin{aligned} F(A, B, C) = & (A + B + \bar{C})(A + \bar{B} + \bar{C}) \\ & \times (\bar{A} + B + C)(\bar{A} + \bar{B} + \bar{C}) \quad (4.14) \end{aligned}$$

The canonical sum of product expression of $F(A, B, C)$ is given by

- a) $\bar{ABC} + \bar{ABC} + A\bar{BC} + ABC$
- b) $\bar{ABC} + \bar{ABC} + \bar{ABC} + \bar{ABC}$
- c) $\underline{ABC} + \underline{ABC} + \bar{ABC} + \underline{ABC}$
- d) $\bar{ABC} + \bar{ABC} + ABC + \bar{ABC}$

(GATE IN 2018)

34. A four-variable Boolean function is realized using 4×1 multiplexers as shown in the Fig. 4.21.

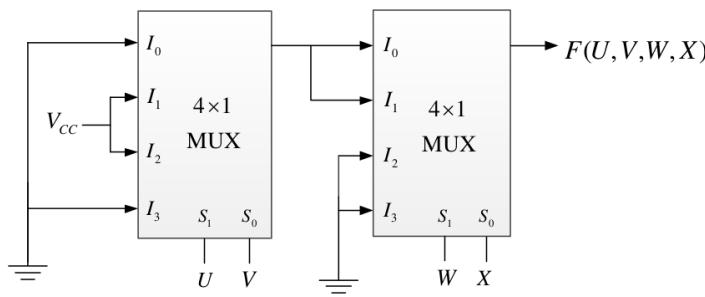


Fig. 4.21

The minimized expression for

- a) $(UV + \bar{U}\bar{V})\bar{W}$

- b) $(UV + \bar{U}\bar{V})(\bar{W}\bar{X} + \bar{W}X)$
 c) $(U\bar{V} + \bar{U}V)\bar{W}$
 d) $(U\bar{V} + \bar{U}V)(\bar{W}\bar{X} + \bar{W}X)$

(GATE EC 2018)

35. A function $F(A, B, C)$ defined by three Boolean variables A, B and C when expressed as sum of products is given by

$F = (\bar{A} \cdot \bar{B} \cdot \bar{C}) + (\bar{A} \cdot B \cdot \bar{C}) + (A \cdot \bar{B} \cdot \bar{C})$ where, \bar{A}, \bar{B} and \bar{C} are the complements of the respective variables. The product of sums (POS) form of the function F is

- (A) $(A + B + C) \cdot (\bar{A} + \bar{B} + C) \cdot (\bar{A} + B + C)$
 (B) $(\bar{A} + \bar{B} + \bar{C}) \cdot (\bar{A} + B + \bar{C}) \cdot (\bar{A} + \bar{B} + \bar{C})$
 (C) $(A + B + \bar{C}) \cdot (\bar{A} + \bar{B} + \bar{C}) \cdot (\bar{A} + B + \bar{C}) \cdot (\bar{A} + \bar{B} + C) \cdot (\bar{A} + \bar{B} + C)$
 (D) $(\bar{A} + \bar{B} + C) \cdot (\bar{A} + B + C) \cdot (\bar{A} + \bar{B} + C) \cdot (\bar{A} + B + \bar{C}) \cdot (A + B + C)$

(GATE EC 2018)

36. In the Karnaugh map shown below in Fig. 4.22, X denotes a don't care term. What is the minimal form of the function represented by the Karnaugh map?

		<i>ba</i>	
		00	01
		11	10
<i>cd</i>	00	1	1
	01	X	0
	11	X	0
	10	1	X

Fig. 4.22

- (A) $b'd' + a'd'$
 (B) $a'b' + b'd' + a'bd'$
 (C) $b'd' + a'bd'$

(D) $a'b' + b'd' + a'd'$

(GATE EC 2008)

37. Consider the minterm list form of a Boolean function given below.

$$F(P, Q, R, S) = \sum m(0, 2, 5, 7, 9, 11) + d(3, 8, 10, 12, 14)$$

Here, denotes a minterm and denotes a don't care term. The number of essential prime implicants of the function is (GATE CS 2018)

38. In the circuit shown below in Fig. 4.23, P and Q are the inputs. The logical function realized by the circuit shown below in Fig. 4.23 is

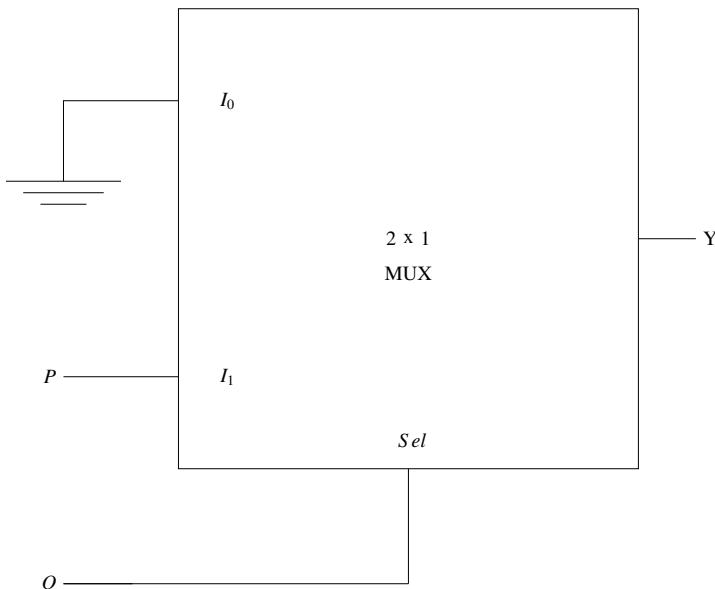


Fig. 4.23

- a) $Y = PQ$
- b) $Y = P + Q$
- c) $Y = \overline{P}Q$
- d) $Y = \overline{P} + \overline{Q}$

(GATE EC2023,23)

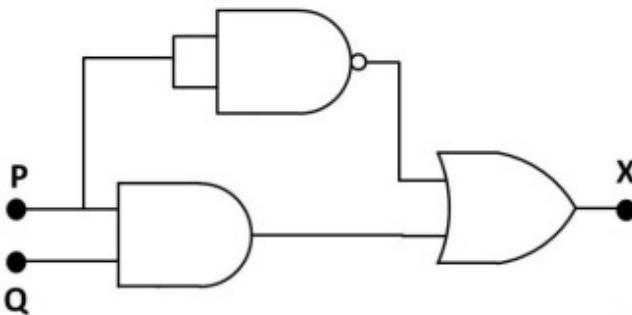


Fig. 4.24: k-maps

In Fig. 4.24, which of the following is correct?

- (a) $P = 1, Q = 1; X = 0$
- (b) $P = 1, Q = 0; X = 0$
- (c) $P = 0, Q = 1; X = 0$
- (d) $P = 0, Q = 0; X = 1$

(GATE PH2023,24)

39. Consider the 2-bit multiplexer(MUX) shown in Fig. 4.25. For OUTPUT to be the XOR of C and D, the values for A_0, A_1, A_2 and A_3 are _____ (GATE EC 2022)

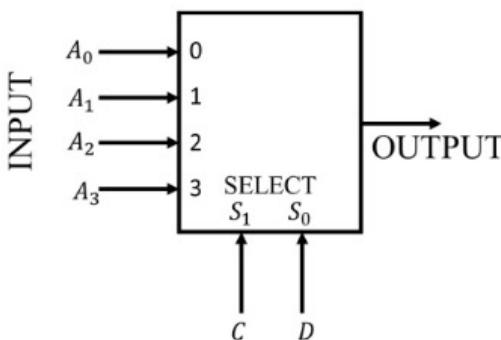


Fig. 4.25: MUX

- (A) $A_0 = 0, A_1 = 0, A_2 = 1, A_3 = 1$
 - (B) $A_0 = 1, A_1 = 0, A_2 = 1, A_3 = 0$
 - (C) $A_0 = 0, A_1 = 1, A_2 = 1, A_3 = 0$
 - (D) $A_0 = 1, A_1 = 1, A_2 = 0, A_3 = 0$
40. The simplified form of the Boolean function $F(W, X, Y, Z) = \sum(4, 5, 10, 11, 12, 13, 14, 15)$ with the minimum number of terms and smallest number of literals in each terms is _____

- a) $WX + \bar{W}X\bar{Y} + W\bar{X}Y$
- b) $WX + WY + X\bar{Y}$
- c) $X\bar{Y} + WY$
- d) $\bar{X}Y + \bar{W}\bar{Y}$

(GATE IN 2023)

41. Q, R, S are Boolean variables \oplus and is the XOR operator. Select the CORRECT option(s).

- a) $(Q \oplus R) \oplus S = Q \oplus (R \oplus S)$
- b) $(Q \oplus R) \oplus S = 0$ when any of the Boolean variables (Q, R, S) are 0 and the third variable is 1
- c) $(Q \oplus R) \oplus S = 1$ when $Q = R = S = 1$
- d) $((Q \oplus R) \oplus (R \oplus S)) \oplus (Q \oplus S) = 1$

(Gate BM 2023)

42. The output F of the digital circuit shown in Fig. 4.26 can be written in the form(s) _____

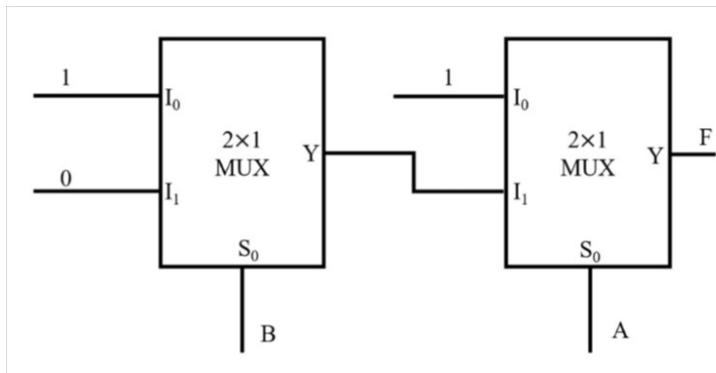


Fig. 4.26

- a) $\overline{A.B}$
- b) $\overline{\bar{A}+\bar{B}}$
- c) $A + B$
- d) $\bar{A}.\bar{B}$

(GATE IN 2022)

43. $\mathbf{A} = a_1a_0$ and $\mathbf{B} = b_1b_0$ are two 2-bit unsigned binary numbers. If $\mathbf{F}(a_1, a_0, b_1, b_0)$ is a Boolean function such that $\mathbf{F} = 1$ only when $\mathbf{A} > \mathbf{B}$, and $\mathbf{F} = 0$ otherwise, then \mathbf{F} can be minimized to the form _____

- a) $a_1\bar{b}_1 + a_1a_0\bar{b}_0$
- b) $a_1\bar{b}_1 + a_1a_0\bar{b}_0 + a_0\bar{b}_0\bar{b}_1$
- c) $a_1a_0\bar{b}_0 + a_0\bar{b}_0\bar{b}_1$
- d) $a_1\bar{b}_1 + a_1a_0\bar{b}_0 + a_0\bar{b}_0b_1$

(GATE IN-2022)

44. The minimum number of two-input NAND gates required to implement the following Boolean expression is _____

$$Y = [A\bar{B}(C + BD) + \bar{A}\bar{B}]C$$

(GATE-PH-2022)

45. In the circuit shown below in Fig. 4.27, Y is a 2-bit ($Y_1 Y_0$) output of the combinational logic. What is the maximum value of Y for any given digital inputs, $A_1 A_0$ and $B_1 B_0$?

(GATE-BM2021)

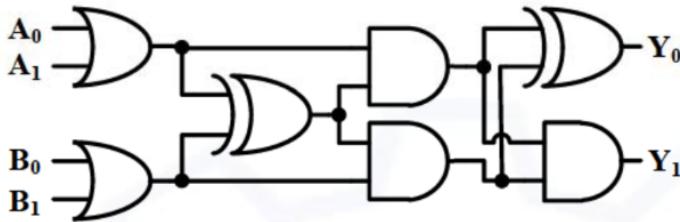


Fig. 4.27

- (A) 01
 (B) 10
 (C) 00
 (D) 11
46. Match the Boolean expression with its minimal realization in Table 4.9

	Boolean expression		Minimal realization
P	$\bar{X}YZ + \bar{X}\bar{Y}Z + \bar{X}Y\bar{Z}$	K	$\bar{X}(Y + Z)$
Q	$XYZ + X\bar{Y}Z + XY\bar{Z}$	L	$\bar{X}(Y + \bar{Z})$
R	$XY + XYZ + XY\bar{Z} + X\bar{Y}Z$	M	Z
S	$\bar{X}YZ + \bar{X}Y\bar{Z} + X\bar{Y}Z + XYZ$	N	$Y(\bar{X} + Z)$

TABLE 4.9

(GATE BM 2020)

- (A) $P - K, Q - L, R - N, S - M$
 (B) $P - L, Q - K, R - N, S - M$
 (C) $P - L, Q - N, R - M, S - K$
 (D) $P - M, Q - K, R - L, S - N$

47. A 4×1 multiplexer with two selector lines is used to realize a Boolean function F having four Boolean variables X, Y, Z and W as shown below in Fig. 4.28. S_0

and S_1 denote the least significant bit (*LSB*) and most significant bit (*MSB*) of the selector lines of the multiplexer respectively. I_0, I_1, I_2, I_3 Is are the input lines of the multiplexer. (GATE-IN2021,35)

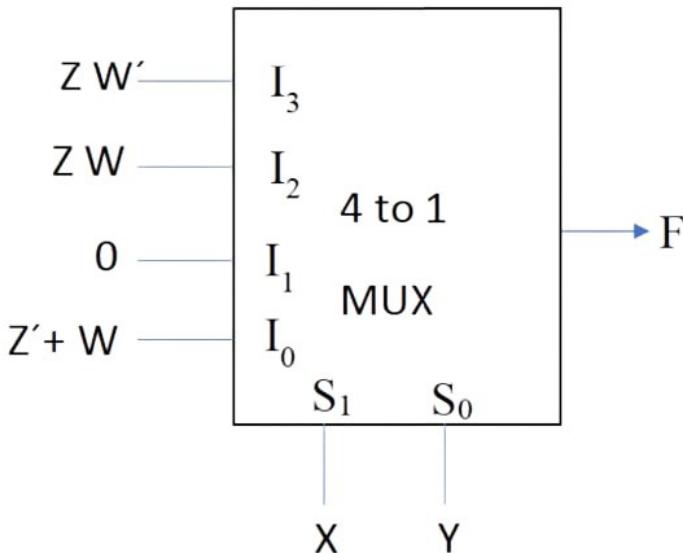


Fig. 4.28: Multiplexer

The canonical sum of product representations of F is

- a) $F(X, Y, Z, W) = \sum m(0, 1, 3, 14, 15)$
- b) $F(X, Y, Z, W) = \sum m(0, 1, 3, 11, 14)$
- c) $F(X, Y, Z, W) = \sum m(2, 5, 9, 11, 14)$
- d) $F(X, Y, Z, W) = \sum m(1, 3, 7, 9, 15)$

48. The output expression for the Karnaugh map shown below in Fig. 4.29 is (GATE-EE2019,35)

		00	01	11	10	
		00	0	1	1	0
		01	1	1	1	1
		11	1	1	1	1
		10	0	0	0	0

Fig. 4.29: K-MAP

- a) $Q\bar{R} + S$
 b) $Q\bar{R} + \bar{S}$
 c) $QR + S$
 d) $QR + \bar{S}$
49. The Boolean expression for the shaded regions as shown in Fig. 4.30 is _____.
 (GATE IN2020 – 11)

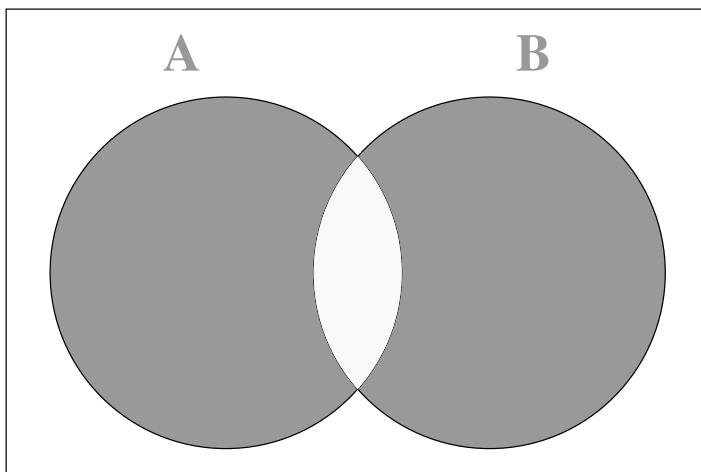


Fig. 4.30: Venn Diagram

- a) $(A + B) \bullet (\bar{A} + \bar{B})$
 b) $(A + \bar{B}) \bullet (\bar{A} + B)$
 c) $(\bar{A} + B) \bullet (\bar{A} + \bar{B})$

- d) $(\overline{A} + \overline{B}) \bullet (A + \overline{B})$
50. The output expression of the Karnaugh map shown below in Fig. 4.31 is (GATE EE-2017, 36)

		CD			
		00	01	11	10
AB	00	0	0	0	0
	01	1	0	0	1
11	1	0	1	1	
10	0	0	0	0	

Fig. 4.31

- A. $B\overline{D} + BCD$
 B. $B\overline{D} + AB$
 C. $\overline{B}\overline{D} + ABC$
 D. $B\overline{D} + ABC$
51. A Boolean function F of three variables X, Y , and Z is given as $F(X, Y, Z) = (X' + Y + Z) \cdot (X + Y' + Z') \cdot (X' + Y + Z') \cdot (X'Y'Z' + X'YZ' + XYZ')$. Which one of the following is true? (GATE IN2021,31)
- a) $F(X, Y, Z) = (X + Y + Z') \cdot (X' + Y' + Z')$
 b) $F(X, Y, Z) = (X' + Y) \cdot (X + Y' + Z')$
 c) $F(X, Y, Z) = X'Z' + YZ'$
 d) $F(X, Y, Z) = X'Y'Z + XYZ$
52. Fig. 4.32 below shows a multiplier where S_1 and S_0 are select lines, I_0 to I_3 are the input data lines, EN is the enable line, and $F(P, Q, R)$ is the output. F is (GATE EC 2020)

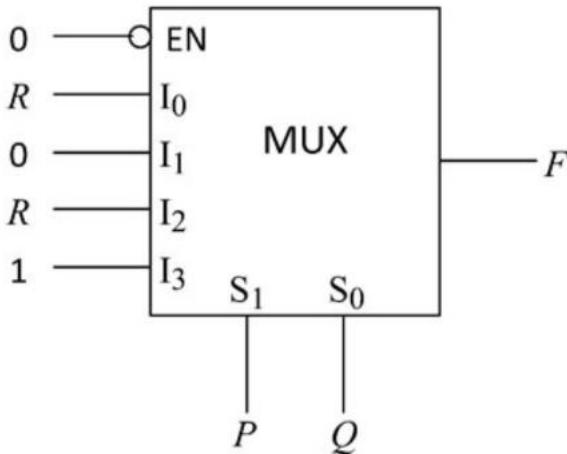


Fig. 4.32

- (A) $PQ + \bar{Q}R$.
 (B) $P + QR$.
 (C) $P\bar{Q}R + \bar{P}Q$.
 (D) $\bar{Q} + PR$.
53. The product of sum expression of a Boolean function $F(A, B, C)$ of three variables is given by
- $$F(A, B, C) = (A + B + \bar{C}) \cdot (A + \bar{B} + \bar{C}) \cdot (\bar{A} + B + C) \cdot (\bar{A} + \bar{B} + C) \quad (4.15)$$
- The canonical sum of product expression of $F(A, B, C)$ is given by (GATE IN 2018)
- (A) $\bar{A} \bar{B} C + \bar{A} B \bar{C} + A \bar{B} C + A B C$
 (B) $\bar{A} \bar{B} \bar{C} + \bar{A} B \bar{C} + A \bar{B} C + A B \bar{C}$
 (C) $A B \bar{C} + A \bar{B} \bar{C} + \bar{A} B C + \bar{A} B \bar{C} + \bar{A} \bar{B} \bar{C}$
 (D) $\bar{A} \bar{B} \bar{C} + \bar{A} B C + A B \bar{C} + A B \bar{C} + A B C$
54. Digital input signals A, B, C with A as the MSB and C as the LSB are used to realize the Boolean function $F = m_0 + m_2 + m_3 + m_5 + m_7$, where m_i denotes the i^{th} minterm. In addition, F has a don't care for m_1 . The simplified expression for F is given by (GATE-2018,EE,37)
- a) $\bar{A}\bar{C} + \bar{B}C + AC$
 b) $\bar{A} + C$
 c) $\bar{C} + A$
 d) $\bar{A}\bar{C} + BC + A\bar{C}$

55. Consider the minterm list form of a Boolean function F given below.

$$F(P, Q, R, S) = \sum m(0, 2, 5, 7, 9, 11) + d(3, 8, 10, 12, 14)$$

Here, m denotes a minterm and d denotes a don't care term. The number of essential prime implicants of the function F is _____ . (GATE-2018,CS,49)

We show how to use the 7474 D-Flip Flop ICs in a sequential circuit to realize a decade counter.

5.1 Components

Component	Value	Quantity
Resistor	220 Ohm	1
Arduino		1
Seven Segment Display		1
Decoder	7447	1
Flip Flop	7474	2
Jumper Wires		20

TABLE 5.1

5.2 Decade Counter

1. Generate the CLOCK signal using the **blink** program.
2. Connect the Arduino, 7447 and the two 7474 ICs according to Table 5.2 and Fig. 5.2. The pin diagram for 7474 is available in Fig. 5.1

	INPUT				OUTPUT				CLOCK		5V			
	W	X	Y	Z	A	B	C	D						
Ardu- ino	D6	D7	D8	D9	D2	D3	D4	D5	D13		5V			
7474	5	9			2	12								
7474			5	9			2	12	CLK1	CLK2	1	4	10	13
7447					7	1	2	6	CLK1	CLK2	1	4	10	13
														16

TABLE 5.2

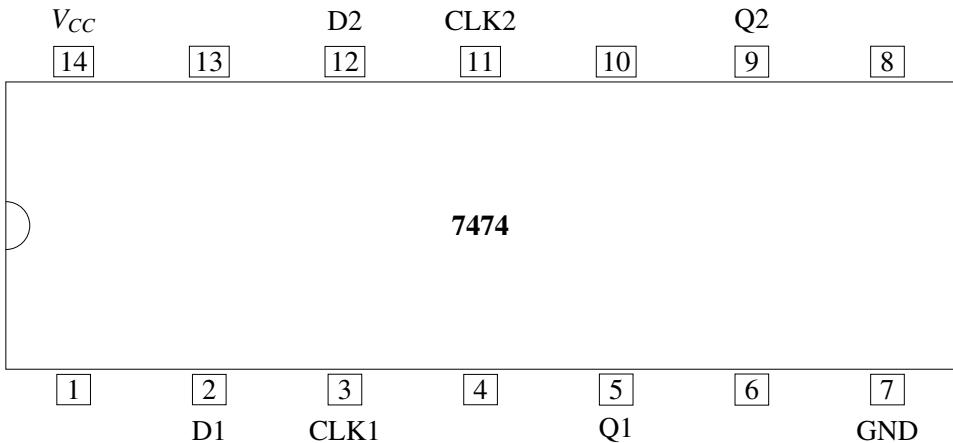


Fig. 5.1

3. Realize the decade counter in Fig. 5.2.

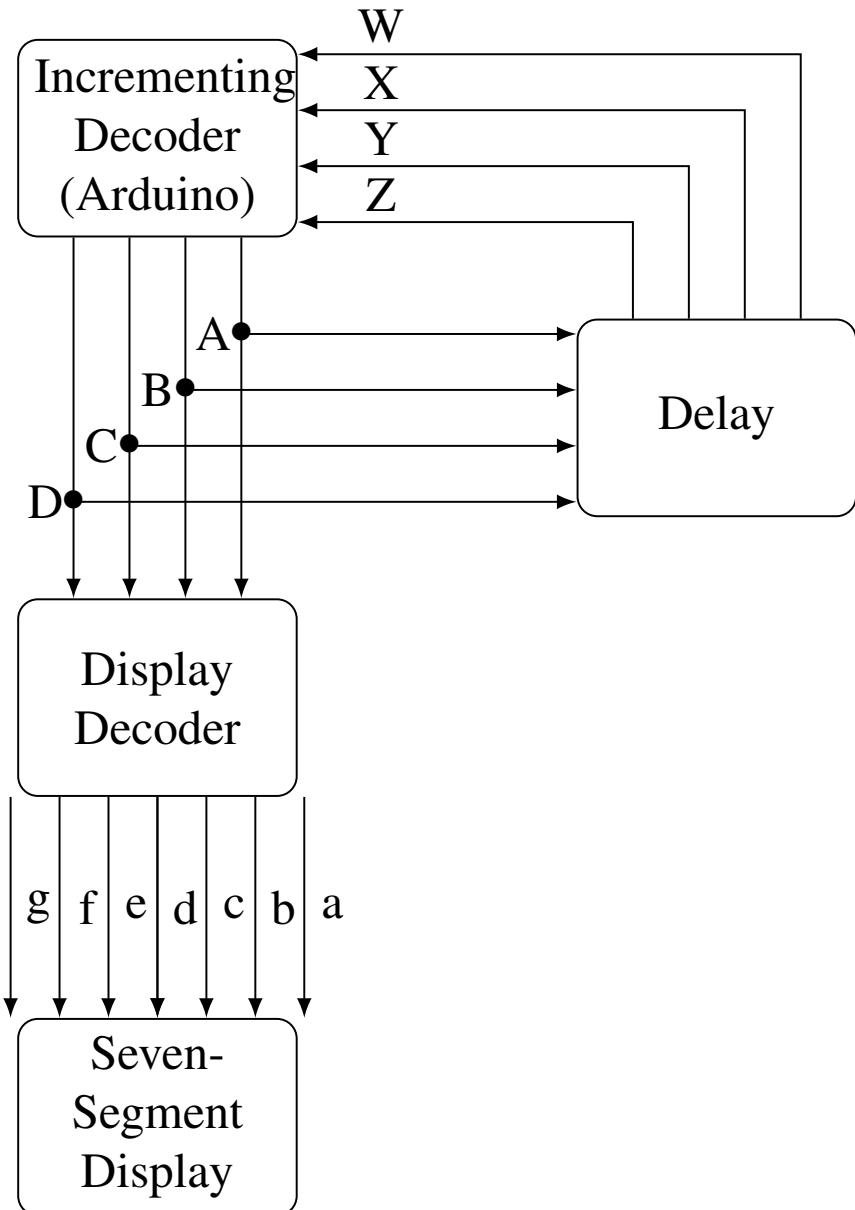


Fig. 5.2

5.3 Problems

1. A counter is constructed with three D flip-flops. The input-output pairs are named (D_0, Q_0) , (D_1, Q_1) , and (D_2, Q_2) , where the subscript 0 denotes the least

significant bit. The output sequence is desired to be the Gray-code sequence 000, 001, 011, 010, 110, 111, 101, and 100, repeating periodically. Note that the bits are listed in the $Q_2\ Q_1\ Q_0$ format. The combinational logic expression for D_1 is (GATE-EE2021,37)

- $Q_2Q_1Q_0$
 - $Q_2Q_0 + Q_1\bar{Q}_0$
 - $\bar{Q}_2Q_0 + Q_1\bar{Q}_0$
 - $Q_2Q_1 + \bar{Q}_2\bar{Q}_1$
2. The propagation delay of the exclusive- OR(XOR) gate in the circuit in Fig. 5.3 is 3 ns. The propagation delay of all the flip-flops is assumed to be zero. The Clock(clk) frequency provided to the circuit is 500 MHz.

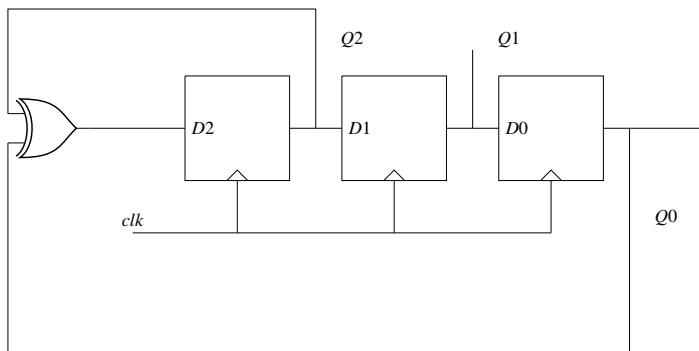


Fig. 5.3: Propagation Delay

Starting from the initial value of the flip-flop outputs $Q_2Q_1Q_0 = 111$ with $D_2 = 1$, the minimum number of triggering clock edges after which the flip-flop outputs $Q_2Q_1Q_0$ becomes 1 0 0(in integer) is _____

(GATE-EC2021,46)

- The maximum clock frequency in MHz of a 4-stage ripple counter, utilizing flip-flops, with each flip-flop having a propagation delay of 20 ns, is _____. (round off to one decimal place) (GATE EE 2022)
- The digital circuit shown in Fig. 5.4

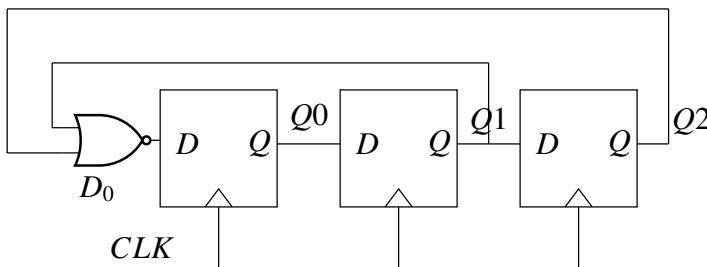


Fig. 5.4

- (A) is a divide-by-5 counter
- (B) is a divide-by-7 counter
- (C) is a divide-by-8 counter
- (D) does not function as a counter due to disjoint cycles of states

GATE IN 2022

5. The propagation delay of the exclusive-OR(XOR) gate in the circuit in Fig. 5.5 is 3ns. The propagation delay of all the flip-flops is assumed to be zero. The clock(Clk) frequency provided to the circuit is 500MHz.

(GATE EC 2021)

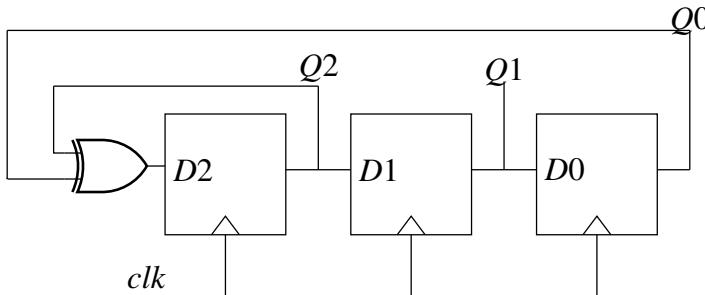


Fig. 5.5

Starting from the initial value of the flip-flop outputs $Q2Q1Q0 = 111$ with $D2 = 1$, the minimum number of triggering clock edges after which the flip-flop outputs $Q2Q1Q0$ becomes 1 0 0 (*in integer*) is ____

6. For the 3-bit binary counter shown in Fig. 5.6, the output increments at every positive transition in the clock (CLK). Assume ideal diodes and the starting state of the counter as 000. If output high is 1V and output low is 0V, the current I (in mA) flowing through the 50Ω resistor during the 5th clock cycle is (up to one decimal place) (GATE IN 2018)

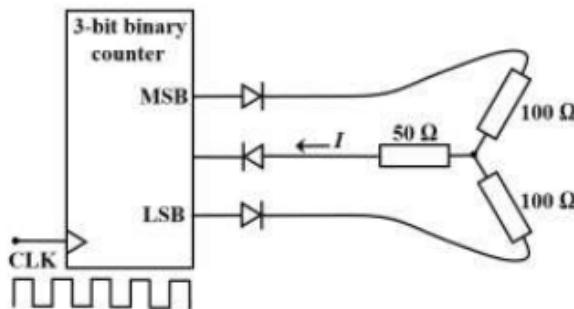


Fig. 5.6

7. Consider the sequential circuit shown in Fig. 5.7, where both flip-flops used are positive edge-triggered D flip-flops.

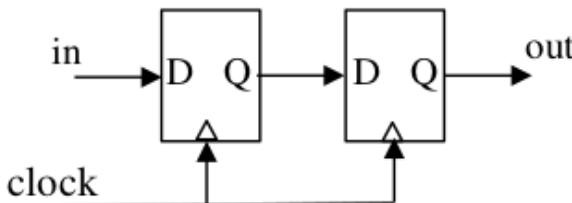


Fig. 5.7

The number of states in the state transition diagram of this circuit that have a transition back to the same state on some value of "in" is _____. (GATE IN 2018)

8. The synchronous sequential circuit shown below in Fig. 5.8 works at a clock frequency of $1GHz$. The throughput, in $Mbits/s$, and the latency, in ns , respectively, are

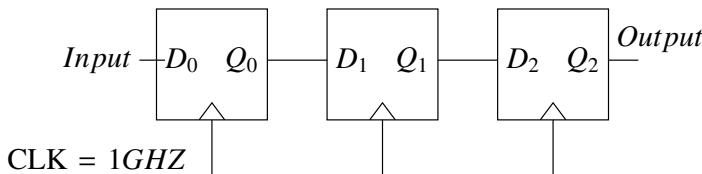


Fig. 5.8

- a) 1000, 3
- b) 333.33, 1
- c) 2000, 3
- d) 333.33, 3

(GATE EC 2023)

9. In a given sequential circuit in Fig. 5.9, initial states are $Q1 = 1$ and $Q2 = 0$. For a clock frequency of $1MHz$, the frequency of signal $Q2$ in kHz, is (rounded off to the nearest integer)

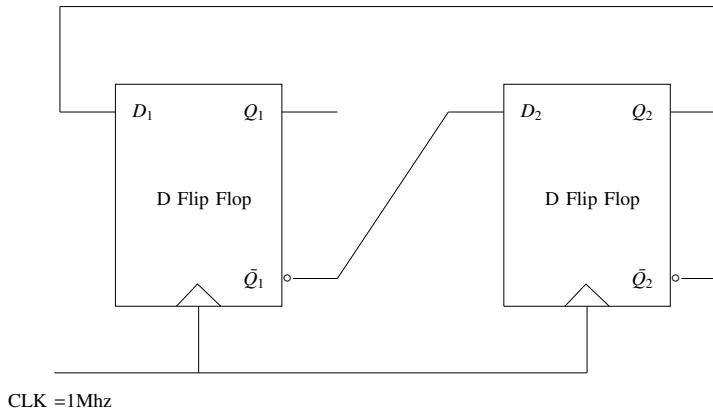


Fig. 5.9

(GATE EC 2023)

10. Neglecting the delays due to the logic gates in the circuit shown in Fig. 5.10, the decimal equivalent of the binary sequence [ABCD] of initial logic states, which will not change with clock, is _____.

(EE GATE 2023)

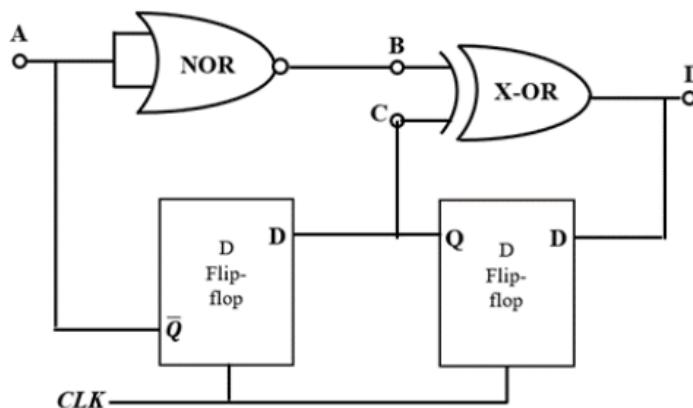


Fig. 5.10

11. Consider a sequential digital circuit consisting of T flip-flops and D flip-flops as shown in Fig. 5.11. CLKIN is the clock input to the circuit. At the beginning, Q₁, Q₂ and Q₃ have values 0, 1 and 1, respectively.

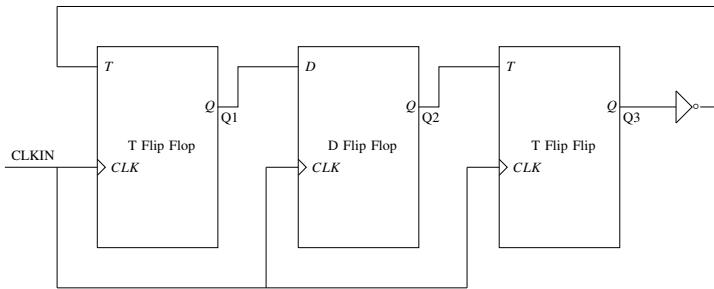


Fig. 5.11

Which of the given values of (Q_1, Q_2, Q_3) can NEVER be obtained with this digital circuit?

- a) (0, 0, 1)
- b) (1, 0, 0)
- c) (1, 0, 1)
- d) (1, 1, 1)

(GATE CS2023,43)

12. In the circuit shifter in Fig. 5.12, the initial binary content of the shift register A 1101 and that of shift register B is 1010. The shift registers are positive edge triggered, and the gates have no delay. When the shift control is high, what will be the binary content of the shift registers A and B after clock pulses?

(GATE IN 2023)

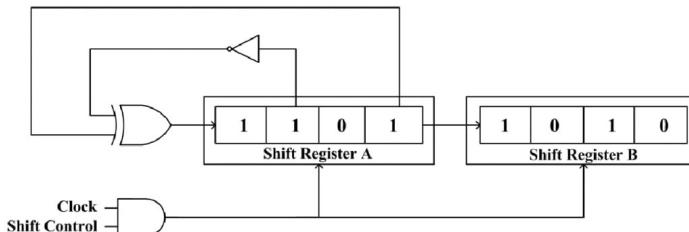


Fig. 5.12: circuit Diagram

- a) $A = 1101, B = 1101$
 - b) $A = 1110, B = 1001$
 - c) $A = 0101, B = 1101$
 - d) $A = 1010, B = 1111$
13. For the circuit shown in Fig. 5.13, the clock frequency is f_0 and the duty cycle is 25%. For the signal at the Q output of the Flip-Flop, (GATE EC 2022)

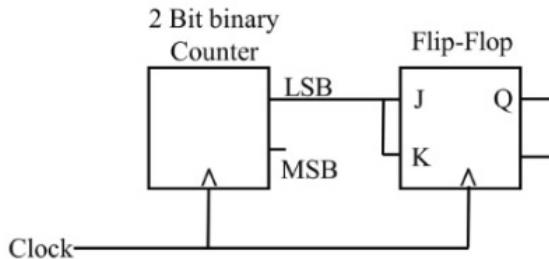


Fig. 5.13: Circuit

- a) frequency is $\frac{f_0}{4}$ and duty cycle is 50%
 - b) frequency is $\frac{f_0}{4}$ and duty cycle is 25%
 - c) frequency is $\frac{f_0}{2}$ and duty cycle is 50%
 - d) frequency is f_0 and duty cycle is 25%
14. The digital circuit shown in Fig. 5.14

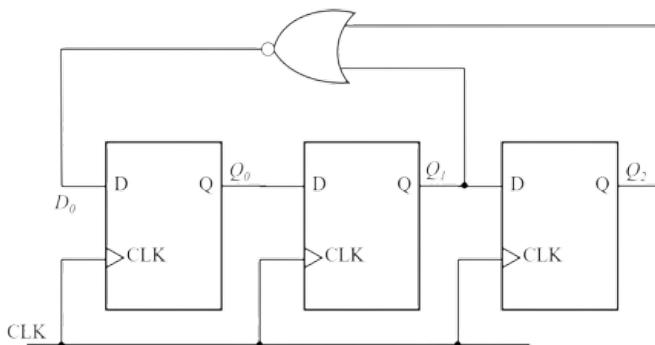


Fig. 5.14

- a) is a divide-by-5 counter
- b) is a divide-by-7 counter
- c) is a divide-by-8 counter
- d) does not function as a counter due to disjoint cycles of states

(GATE-IN-2022)

15. Given below in Fig. 5.15 is the diagram of a synchronous sequential circuit with one $J-K$ flip-flop and one T flip-flop with their outputs denoted as A and B respectively, with $J_A = (A' + B')$, $K_A = (A+B)$ and $T_B = A$. Starting from the initial state ($AB = 00$), the sequence of states (AB) visited by the circuit is

(GATE-IN2021)

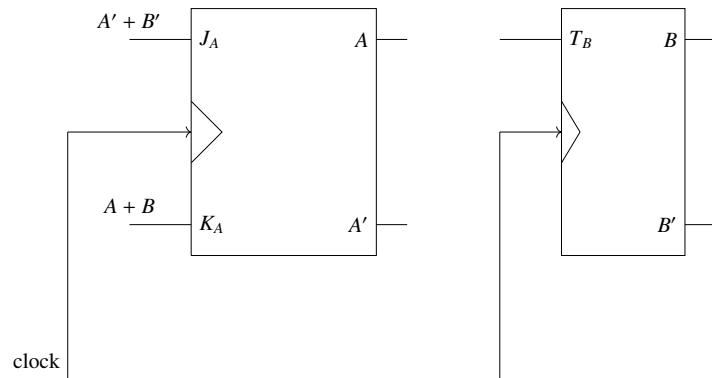


Fig. 5.15

- a) $00 \rightarrow 01 \rightarrow 10 \rightarrow 11 \rightarrow 00 \dots$
- b) $00 \rightarrow 10 \rightarrow 01 \rightarrow 11 \rightarrow 00 \dots$
- c) $00 \rightarrow 10 \rightarrow 11 \rightarrow 01 \rightarrow 00 \dots$
- d) $00 \rightarrow 01 \rightarrow 11 \rightarrow 00 \dots$

16. Consider the D -Latch shown in Fig. 5.16, which is transparent when its clock input CK is high and has zero propagation delay. In the figure, the clock signal $CLK1$ has 50% duty cycle and $CLK2$ is a one fifth period delayed version of $CLK1$. The duty cycle at the output of the latch in percentage is _____. (GATE-EC2017)

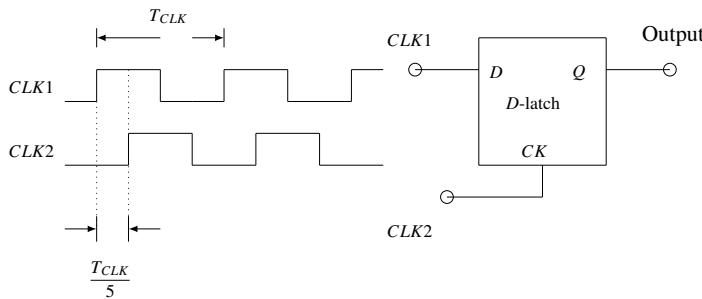


Fig. 5.16

17. A 4-bit shift register circuit configured for right-shift operation, i.e. $D_{in} \rightarrow A, A \rightarrow B, B \rightarrow C, C \rightarrow D$, is shown in Fig. 5.17. If the present state of the shift register is $ABCD = 1101$, the number of clock cycles required to reach the state $ABCD = 1111$ is _____.

(GATE-EC 2017)

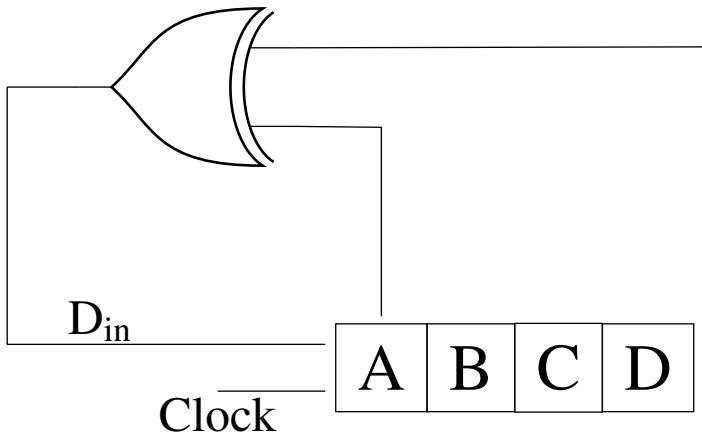


Fig. 5.17

18. In the circuit shown in Fig. 5.18, the clock frequency, i.e., the frequency of the clk signal, is 12 KHz. The frequency of the signal at **Q2** is ____ KHz. (GATE-EC2019,25)

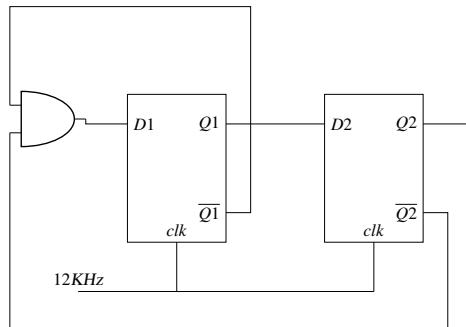


Fig. 5.18

19. The circuit shown in Fig. 5.19 below uses ideal positive edge-triggered synchronous $J - K$ flip flops with outputs X and Y . If the initial state of the output is $X = 0$ and $Y = 0$ just before the arrival of the first clock pulse, the state of the output just before the arrival of the second clock pulse is _____ (GATE-IN2019,12)

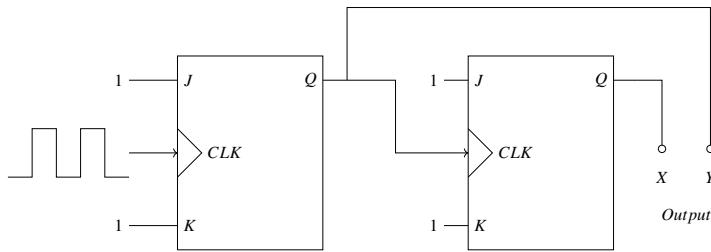


Fig. 5.19

- a) $X = 0, Y = 0$
 b) $X = 0, Y = 1$
 c) $X = 1, Y = 0$
 d) $X = 1, Y = 1$

20. Consider a 4-bit counter constructed out of four flip-flops. It is formed by connecting the J and K inputs to logic high and feeding the Q output to the clock input of the following flip-flop (see Fig. 5.20). The input signal to the counter is a series of square pulses and the change of state is triggered by the falling edge. At time $t=t0$ the outputs are in logic low state ($Q_0 = Q_1 = Q_2 = Q_3 = 0$). Then at $t=t1$, the logic state of the outputs is (GATE-PH2020,30)

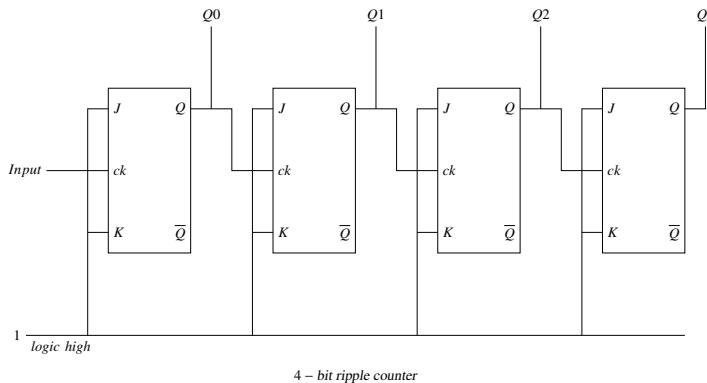


Fig. 5.20

- a) $Q_0 = 1$, $Q_1 = 0$, $Q_2 = 0$ and $Q_3 = 0$
 - b) $Q_0 = 0$, $Q_1 = 0$, $Q_2 = 0$ and $Q_3 = 1$
 - c) $Q_0 = 1$, $Q_1 = 0$, $Q_2 = 1$ and $Q_3 = 0$
 - d) $Q_0 = 0$, $Q_1 = 1$, $Q_2 = 1$ and $Q_3 = 1$

21. Two T-flip flops are interconnected as shown in Fig. 5.21. The present state of the flip flops are: A = 1, B = 1. The input x is given as 1, 0, 1 in the next three clock cycles. The decimal equivalent of $(ABy)_2$ with A being the MSB and y being the LSB, after the 3_{rd} clock cycle is _____. (GATE IN2020 – 40)

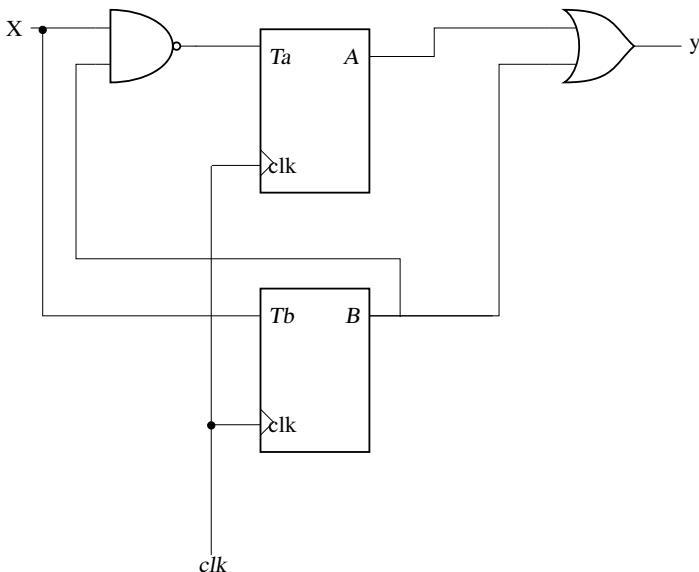


Fig. 5.21

22. For the components in the sequential circuit shown in Fig. 5.22 below, t_{pd} is the propagation delay, t_{setup} is the setup time, and t_{hold} is the hold time. The maximum clock frequency (rounded off to the nearest integer) at which the given circuit can operate reliably is _____ MHZ. (GATE EC2020 – 50)

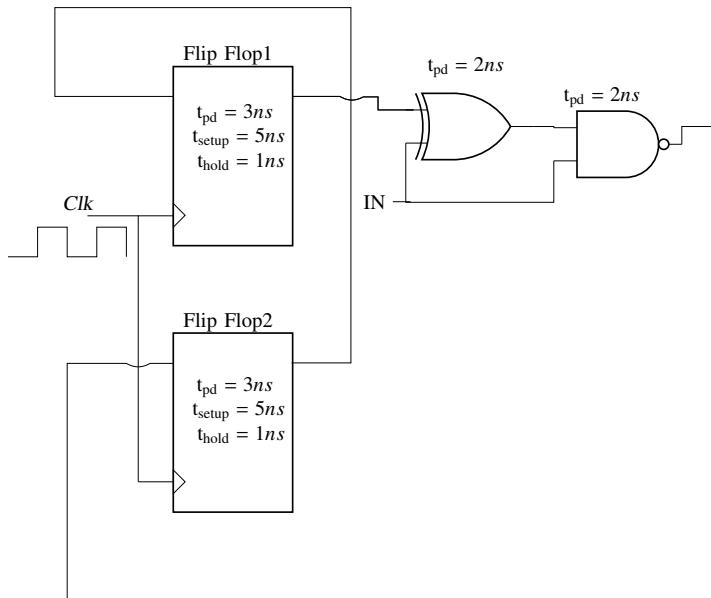


Fig. 5.22

23. A 2-bit synchronous counter using two J-K flip flops is shown in Fig. 5.23. The expression for the inputs to the J-K flip flops are also shown in the figure. The output sequence of the counter starting from $Q_1 Q_2 = 00$ is GATE-IN2018,44

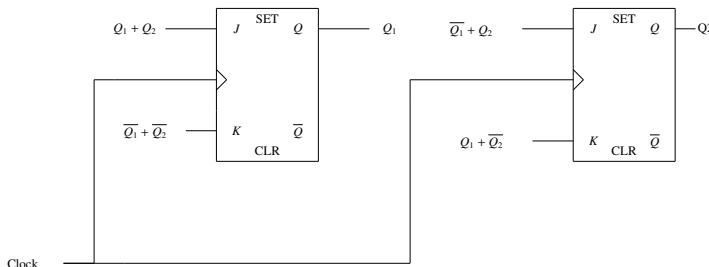


Fig. 5.23

- A. $00 \rightarrow 11 \rightarrow 10 \rightarrow 01 \rightarrow 00\dots$
B. $00 \rightarrow 01 \rightarrow 10 \rightarrow 11 \rightarrow 00\dots$
C. $00 \rightarrow 01 \rightarrow 11 \rightarrow 10 \rightarrow 00\dots$
D. $00 \rightarrow 10 \rightarrow 11 \rightarrow 01 \rightarrow 00\dots$

24. Which of the following statements is true about digital circuits shown in Fig. 5.24?
(Gate EE-2018,36)

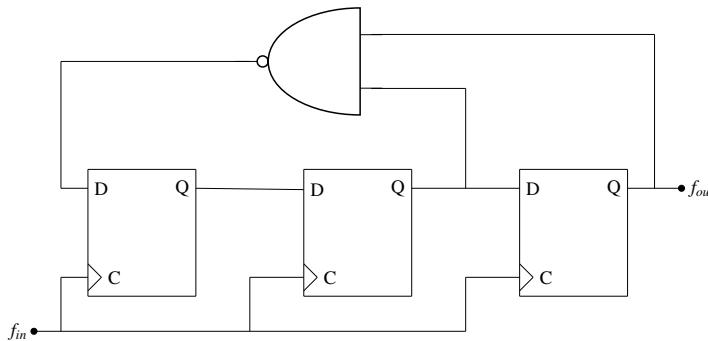


Fig. 5.24

- a) It can be used for dividing the input frequency by 3 .
 - b) It can be used for dividing the input frequency by 5 .
 - c) It can be used for dividing the input frequency by 7 .
 - d) It cannot be reliably used as frequency divider due to disjoint internal cycles .
25. In the circuit shown below, a positive edge-triggered D Flip-Flop is used for sampling input data D_{in} using clock CK . The XOR gate outputs 3.3 volts for logic HIGH and 0 volts for logic LOW levels. The data bit and clock periods are equal and the value of $\Delta T/T_{CK} = 0.15$, where the parameters ΔT and T_{CK} are shown in Fig. 5.25. Assume that the Flip-Flop and the XOR gate are ideal. If the probability of input data bit (D_{in}) transition in each clock period is 0.3, the average value (in volts, accurate to two decimal places) of the voltage at node X , is

(GATE-EC 2018,46)

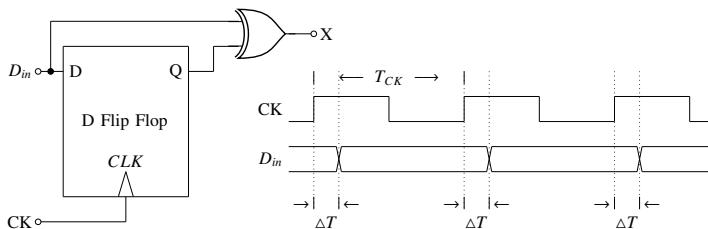


Fig. 5.25

26. Assume that all the digital gates in the circuit shown in Fig. 5.26 are ideal, the resistor $R=10k\Omega$ and the supply voltages is 5V. The D flip-flops D_1, D_2, D_3, D_4 and D_5 are initialized with logic values 0, 1, 0, 1, and 0, respectively. The clock has a 30% duty cycle.

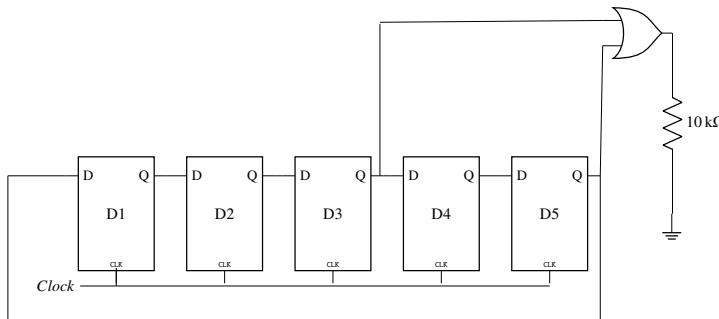


Fig. 5.26

The average power dissipated ($inmW$) in the resistor R is _____.

(GATE EC 2016)

27. The digital circuit shown in Fig. 5.27 generates a modified clockpulse at the output. Sketch the output waveform.
(GATE EE 2004)

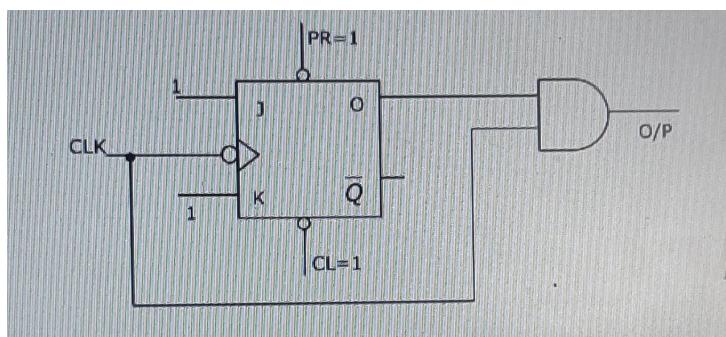


Fig. 5.27

28. The circuit shown in Fig. 5.28 below uses ideal positive edge-triggered synchronous J-K flip flops with outputs X and Y. If the initial state of the output is $X=0$ and $Y=0$, just before the arrival of the first clock pulse, the state of the output just before the arrival of the second clock pulse is _____
(GATE IN 2019)

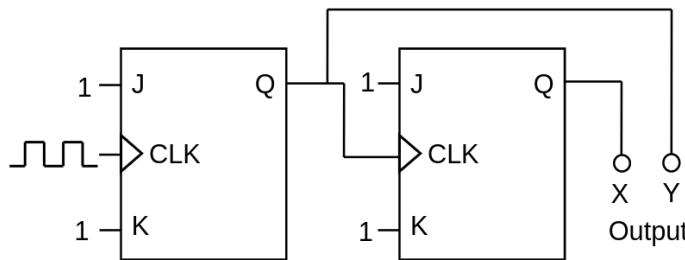


Fig. 5.28

29. A counter is constructed with three D flip-flops. The input-output pairs are named (D0, Q0), (D1, Q1), and (D2, Q2), where the subscript 0 denotes the least significant bit. The output sequence is desired to be the Gray-code sequence 000, 001, 011, 010, 110, 111, 101, and 100, repeating periodically. Note that the bits are listed in the Q2 Q1 Q0 format. Find the combinational logic expression for D1. (GATE EE 2021)
30. For the circuit shown in Fig. 5.29, the clock frequency is f_0 and the duty cycle is 25%. For the signal at the Q output of the Flip-Flop,
- frequency of $\frac{f_0}{4}$ and duty cycle is 50%
 - frequency of $\frac{f_0}{4}$ and duty cycle is 25%
 - frequency of $\frac{f_0}{2}$ and duty cycle is 50%
 - frequency of f_0 and duty cycle is 25%

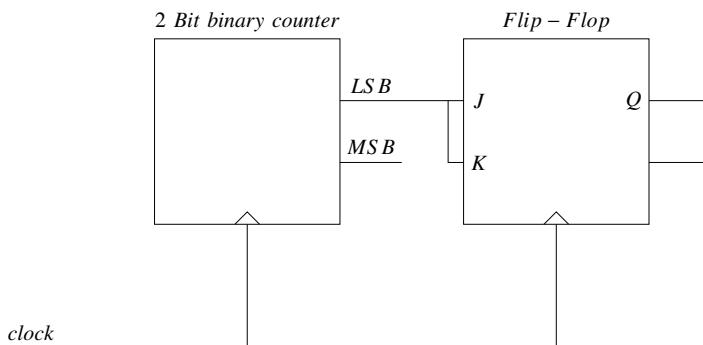


Fig. 5.29

(GATE EC-2022)

31. Two T-flip flops are interconnected as shown in Fig. 5.30. The present state of the flip flops are: $A = 1, B = 1$. The input x is given as 1, 0, 1 in the next three clock cycles. The decimal equivalent of $(ABy)_2$ with A being the MSB and y being the LSB, after the 3rd clock cycle is _____

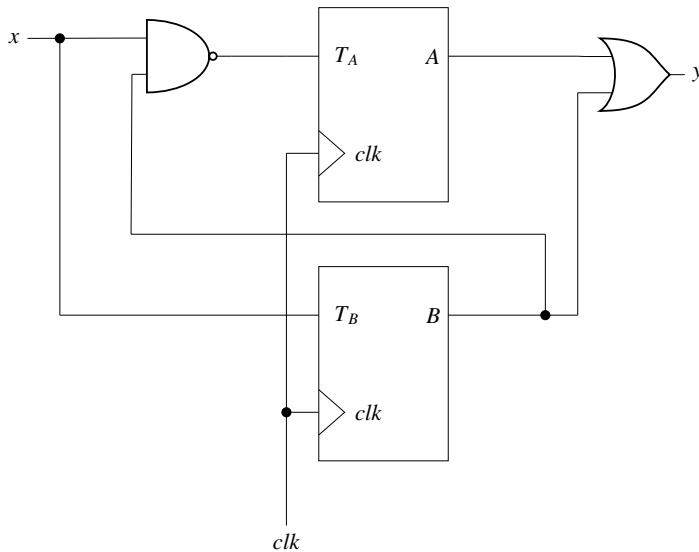


Fig. 5.30

(GATE IN 2020)

32. In the circuit shown below in Fig. 5.31 a positive edge-triggered D flip-flop is used for sampling input data using clock CK. The XOR gate outputs 3.3 volts for logic HIGH and 0 volts for logic LOW levels. The data bit and clock periods are equal and the value of $\Delta T/T_{ck} = 0.15$, where the parameters ΔT and T_{ck} are shown in the figure. Assume that the Flip and the XOR gate are ideal.

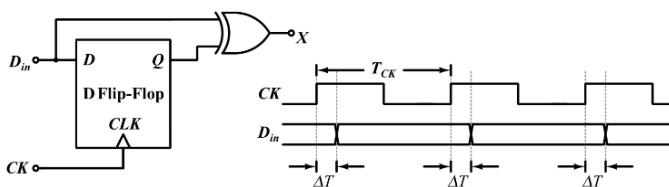


Fig. 5.31

(GATE EC 2018)

33. A 2-bit synchronous counter using two J-K flip flops is shown in Fig. 5.32. The expressions for the inputs to the J-K flip flops are also shown in the figure. The output sequence of the counter starting from $Q_1Q_2 = 00$ is

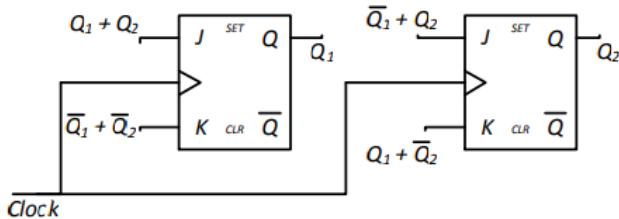


Fig. 5.32

- a) $00 \rightarrow 11 \rightarrow 10 \rightarrow 01 \rightarrow 00\dots$
- b) $00 \rightarrow 01 \rightarrow 10 \rightarrow 11 \rightarrow 00\dots$
- c) $00 \rightarrow 01 \rightarrow 11 \rightarrow 10 \rightarrow 00\dots$
- d) $00 \rightarrow 10 \rightarrow 11 \rightarrow 01 \rightarrow 00\dots$

(GATE IN 2018)

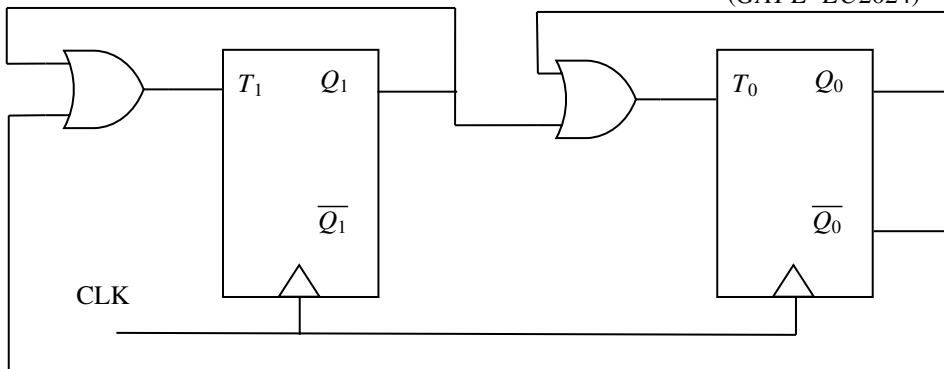
34. A 16-bit synchronous binary up-counter is clocked with the frequency f_{CLK} . The two most significant bits are OR-ed together to form an output Y . Measurements show that Y is periodic, and the duration for which Y remains high in each period is 24 ms. The clock frequency _____ MHz.

(Round off to 2 decimal places.)

(GATE EE2021 – 22)

35. The sequence of states (Q_1Q_0) of the given synchronous sequential circuit is _____.

(GATE EC2024)



- (A) $00 \rightarrow 10 \rightarrow 11 \rightarrow 00$
- (B) $11 \rightarrow 00 \rightarrow 10 \rightarrow 01 \rightarrow 00$
- (C) $01 \rightarrow 10 \rightarrow 11 \rightarrow 00 \rightarrow 01$
- (D) $00 \rightarrow 01 \rightarrow 10 \rightarrow 00$

36. The maximum clock frequency in MHz of a 4-stage ripple counter, utilizing flip-flops, with each flip-flop having a propagation delay of 20 ns, is _____.
(round off to one decimal place) (GATE EE 2022)
37. In the latch circuit shown in Fig. 5.33, the NAND gates have non-zero but unequal

propagation delays. The present input condition is: $P = Q = '0'$. If the input condition is changed simultaneously to $P = Q = '1'$, the outputs X and Y are

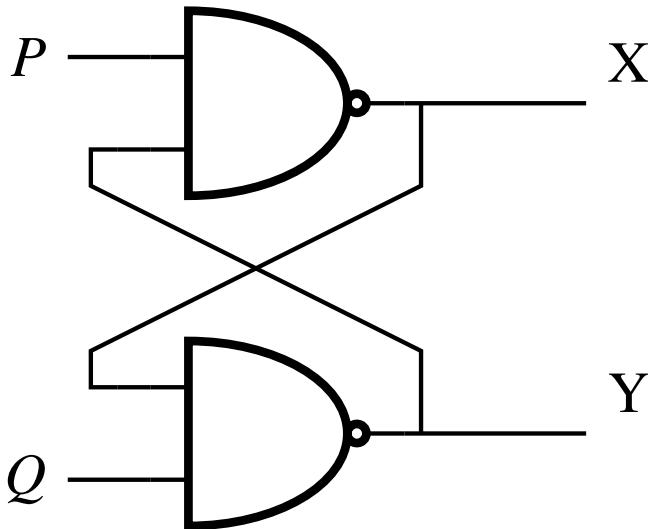


Fig. 5.33

- a) $X = '1', Y = '1'$
- b) either $X = '1', Y = '0'$ or $X = '0', Y = '1'$
- c) either $X = '1', Y = '1'$ or $X = '0', Y = '0'$
- d) $X = '0', Y = '0'$

(GATE EC 2017)

38. In the circuit shown in Fig. 5.34, A and B are the inputs and F is the output. What is the functionality of the circuit? (GATE-EC2019,15)

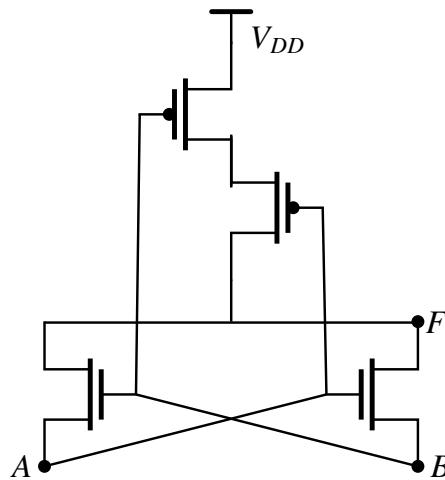


Fig. 5.34: Circuit Diagram

- a) Latch
 - b) XNOR
 - c) SRAM Cell
 - d) XOR
39. A $6\frac{1}{2}$ digit time counter is set in the time period mode of operation and range is set as 'ns'. For an input signal the time-counter displays 1000000. with the same input signal, The time counter is changed to 'frequency' mode of operation and the range is set as 'HZ'. The display will be show the number _____. (GATE IN2020 – 43)
40. The two inputs A and B are connected to an R-S latch via two AND gates as shown in Fig. 5.35. If $A = 1$ and $B = 0$, the output $Q\bar{Q}$ is

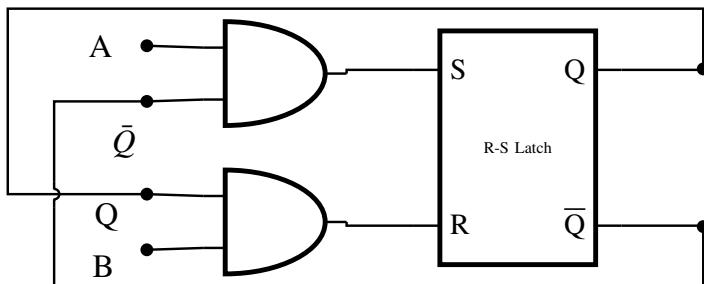


Fig. 5.35

(GATE IN2017,43)

- a) 00
- b) 10
- c) 01

d) 11

41. For the following circuit Fig. 5.36, the correct logic values for the entries X_2 and Y_2 in the truth table in Table 5.3 are
 (PH2019,36)

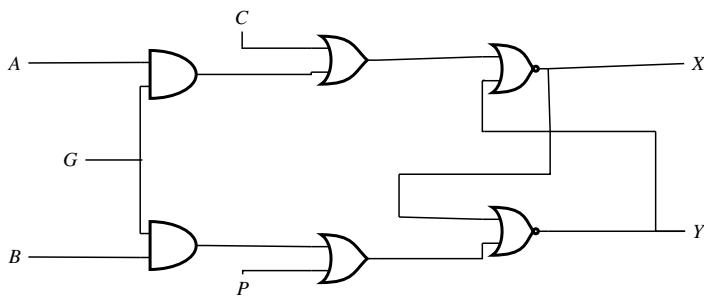


Fig. 5.36

G	A	B	P	C	X	Y
1	0	1	0	0	0	1
0	0	0	1	0	X2	Y2
1	0	0	0	1	0	1

TABLE 5.3

- a) 1 and 0
- b) 0 and 0
- c) 0 and 1
- d) 1 and 1

6 FINITE STATE MACHINE

We explain a state machine by deconstructing the decade counter

The block diagram of a decade counter (repeatedly counts up from 0 to 9) is available in Fig 5.2 The *incrementing* decoder and *display* decoder are part of *combinational* logic, while the *delay* is part of *sequential* logic

- Fig. 6.1 shows a *finite state machine* (FSM) diagram for the decade counter in Fig 5.2 s_0 is the state when the input to the incrementing decoder is 0 The *state transition table* for the FSM is Table 3.4, where the present state is denoted by the variables W, X, Y, Z and the next state by A, B, C, D .

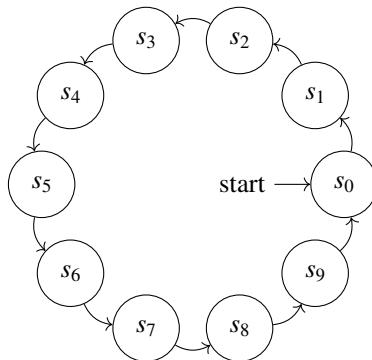


Fig. 6.1: FSM for the decade counter

- The FSM implementation is available in Fig 6.2 The *flip-flops* hold the input for the time that is given by the *clock* This is nothing but the implementation of the *Delay* block in Fig 5.2

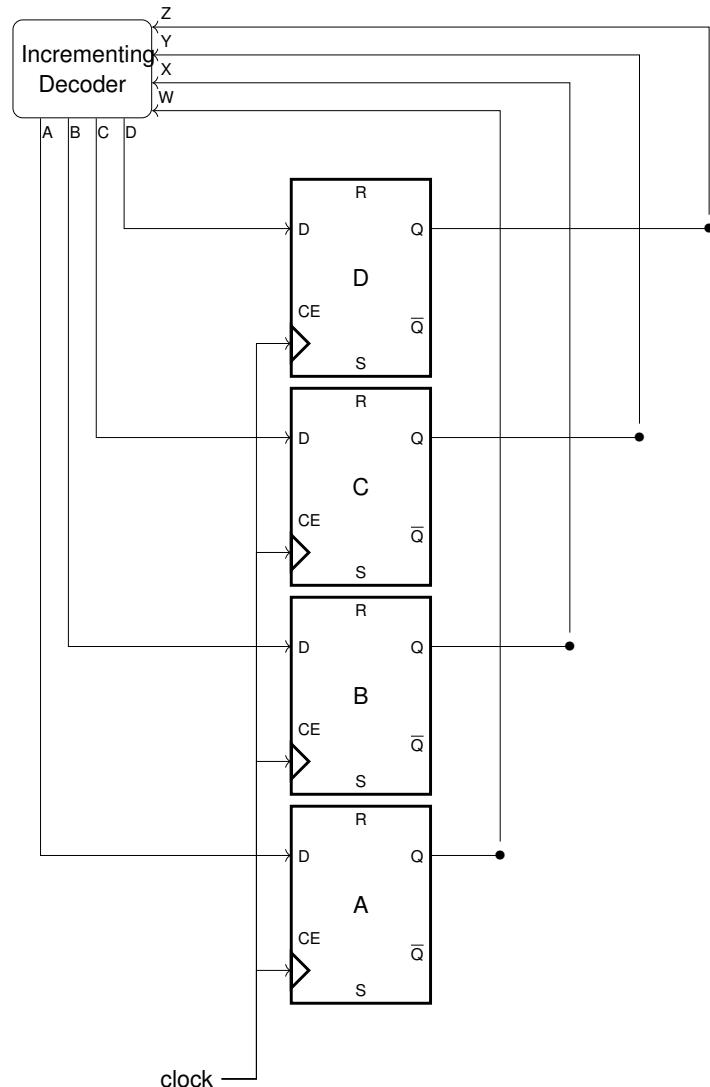


Fig. 6.2: Decade counter FSM implementation using D-Flip Flops

3. The hardware cost of the system is given by

$$\text{No of D Flip-Flops} = \lceil \log_2 (\text{No of States}) \rceil \quad (6.1)$$

For the FSM in Fig 6.1, the number of states is 9, hence the number flipflops required = 4

4. Draw the state transition diagram for a decade down counter (counts from 9 to 0 repeatedly) using an FSM
5. Write the state transition table for the down counter

6. Obtain the state transition equations with and without don't cares
7. Verify your design using an arduino

6.1 Problems

1. The state diagram of a sequence detector is shown in Fig. 6.3. State S_0 is the initial state of the sequence detector. If the output is 1, then (GATE EC 2020)

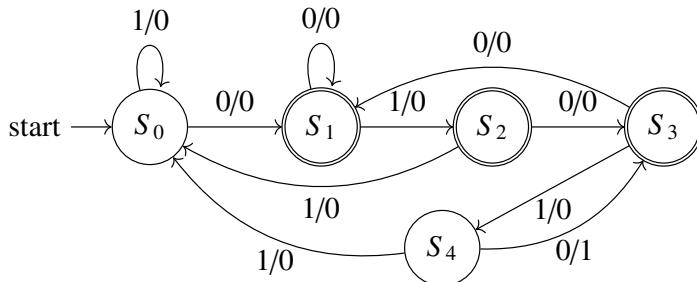


Fig. 6.3

- a) the sequence 01010 is detected
b) the sequence 01011 is detected
c) the sequence 01110 is detected
d) the sequence 01001 is detected
2. A sequence detector is designed to detect precisely 3 digital inputs, with overlapping sequences detectable. For the sequence (1,0,1) and input data (1,1,0,1,0,0,1,1,0,1,0,1,0,1,1,0), what is the output of this detector?
a) 1,1,0,0,0,0,1,1,0,1,0,0
b) 0,1,0,0,0,0,0,1,0,1,0,0
c) 0,1,0,0,0,0,0,1,0,1,1,0
d) 0,1,0,0,0,0,0,0,1,0,0,0

(GATE EE 2020)

3. Consider a 3-bit counter, designed using T flip-flops, as shown below in Fig. 6.4

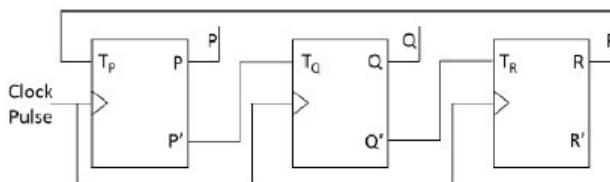


Fig. 6.4

Assuming the initial state of the counter given by PQR as 000, what are the next three states? (GATE-CS2021)

- (A) 011, 101, 000
 (B) 010, 101, 000
 (C) 010, 101, 000
 (D) 010, 101, 000
4. The state diagram of a sequence detector is shown below. State S_0 is the initial state of the sequence detector. If the output is 1, then (GATE-EC2020,39)

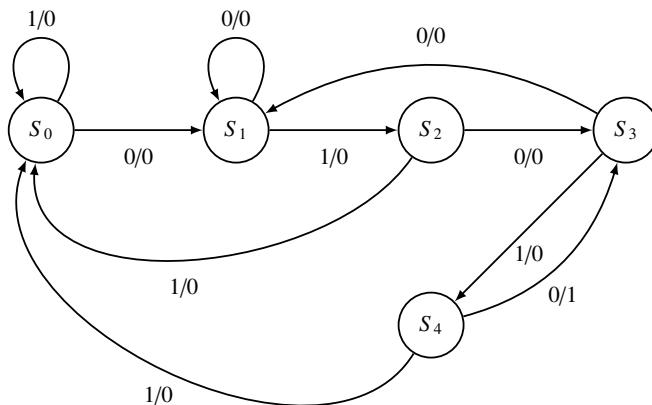


Fig. 6.5

- a) the sequence 01010 is detected.
 b) the sequence 01011 is detected.
 c) the sequence 01110 is detected.
 d) the sequence 01001 is detected.
5. The state transition diagram for the circuit shown in Fig. 6.6 is (GATE-IN2019,39)

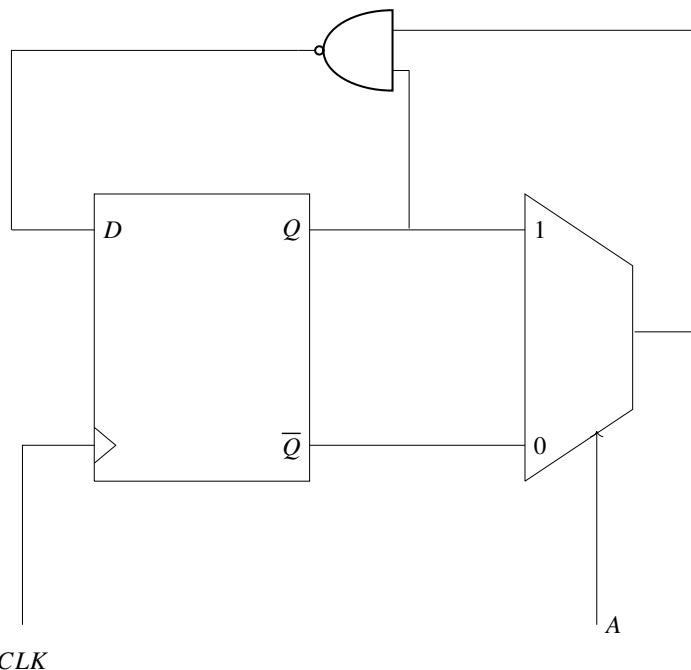
 CLK

Fig. 6.6

a) Fig. 6.7

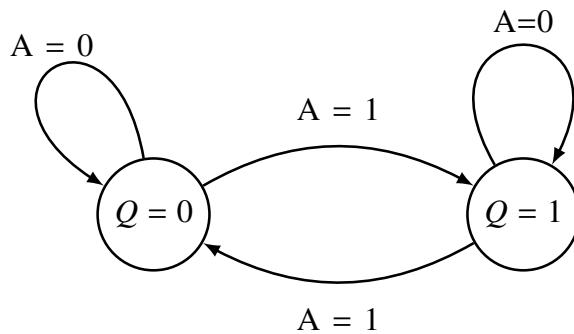


Fig. 6.7

b) Fig. 6.8

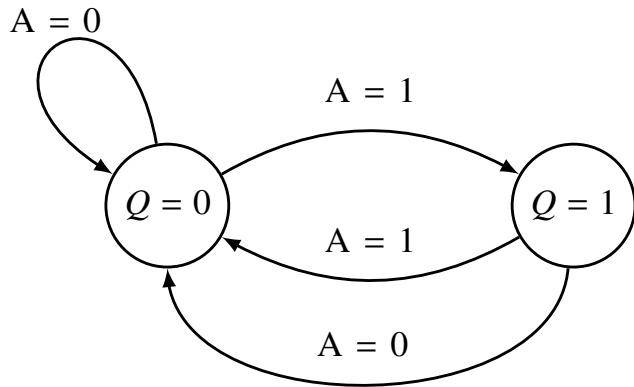


Fig. 6.8

c) Fig. 6.9

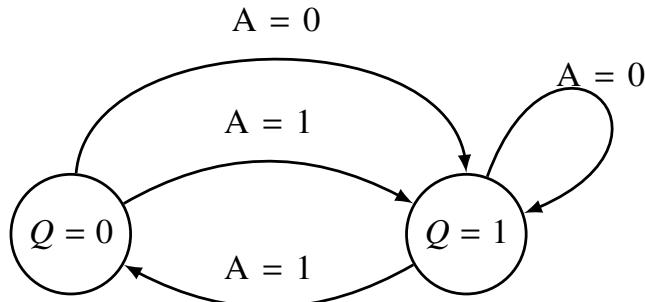


Fig. 6.9

d) Fig. 6.10

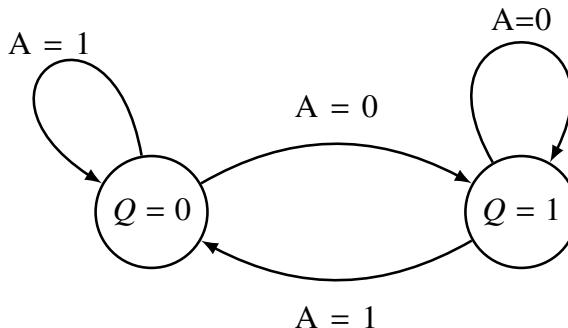


Fig. 6.10

6. A sequence detector is designed to detect precisely 3 digital inputs, with overlapping sequences detectable. For the sequence (1,0,1) and input data (1,1,0,1,0,0,1,1,0,1,0,1,1,0), the output sequence is (GATE EE2020 – 15)
- (1,1,0,0,0,1,1,0,1,0,0)
 - (0,1,0,0,0,0,1,0,1,0,0)
 - (0,1,0,0,0,0,0,1,0,1,1,0)
 - (0,1,0,0,0,0,0,1,0,0,0,0)
7. A finite state machine (FSM) is implemented using the D flip-flops A and B, and logic gates, as shown in Fig. 6.11 below. The four possible states of the FSM are $Q_A Q_B = 00, 01, 10 and }11.$

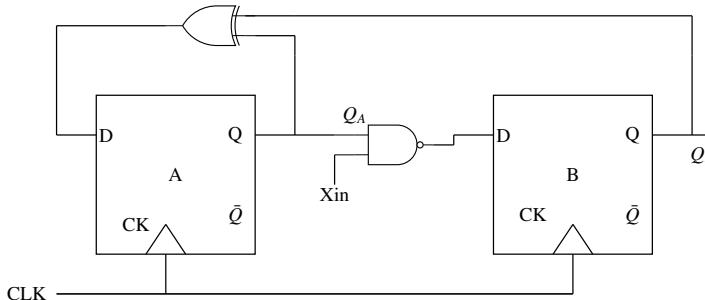


Fig. 6.11

Assume that X_{IN} is held at a constant logic level throughout the operation of the FSM. When the FSM is initialized to the state $Q_A Q_B = 00$ and clocked, after a few clock cycles, it starts cycling through

- all of the four possible states if $X_{IN} = 1$
- three of the four possible states if $X_{IN} = 0$
- only two of the four possible states if $X_{IN} = 1$
- only two of the four possible states if $X_{IN} = 0$

8. For the given digital circuit in Fig. 6.12, $A = B = 1$. Assume that AND, OR, and NOT gates have propagation delays of 10ns, 10ns, and 5ns respectively. All lines have zero propagation delay. Given that $C = 1$ when the circuit is turned on, the frequency of steady-state oscillation of the output Y is _____. (GATE IN 2023)

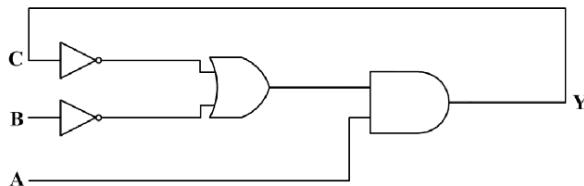


Fig. 6.12: Image

9. In the circuit diagram shown below in Fig. 6.13, the logic gates operate with a supply voltage of 1V. NAND and XNOR have 200ps and 400ps input-to-output delay, respectively.

At time $t = T$, $A(t) = 0$, $B(t) = 1$ and $Z(t) = 0$. When the inputs are changed to $A(t) = 1$, $B(t) = 0$ at $t = 2T$, a 1 V pulse is observed at Z. The pulse width of the 1V pulse is ps.

(GATE BM 2022)

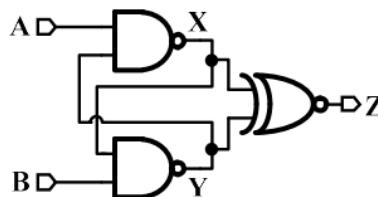


Fig. 6.13

- a) 100
- b) 200
- c) 400
- d) 600

7 ASSEMBLY PROGRAMMING

7.1 Setup

We show how to setup the assembly programming environment for the arduino.

1. Copy the .inc file to your home directory

```
cp assembly/setup/m328Pdef/m328Pdef.inc ~/
```

2. Execute

```
avr-assembly/setup/codes/hello.asm
```

3. Then flash the .hex file

```
hello.hex
```

4. You should see the led beside pin 13 light up.

5. Now edit **hello.asm** by modifying the line to

```
ldi r17,0b00000000
```

Save and execute. The led should turn off.

6. What do the following instructions do?

```
ldi r16,0b00100000
out DDRB,r16
```

Solution: The Atmega328p microcontroller for the arduino board has 32 internal 8-bit registers, R0-R31. R16-R31 can be used directly for i/o. The first instruction loads an 8-bit binary number into R16. The second instruction loads the value in R16 to the DDRB register. Each bit of the DDRB register corresponds to a pin on the arduino. The second instruction declares pin 13 to be an output port. Both the instructions are equivalent to `pinMode(13, OUTPUT)`.

7. What do the following instructions do?

```
ldi r17,0b00100000
out PortB,r17
```

Solution: The instructions are equivalent to `digitalWrite(13)`.

7.2 Seven Segment Display

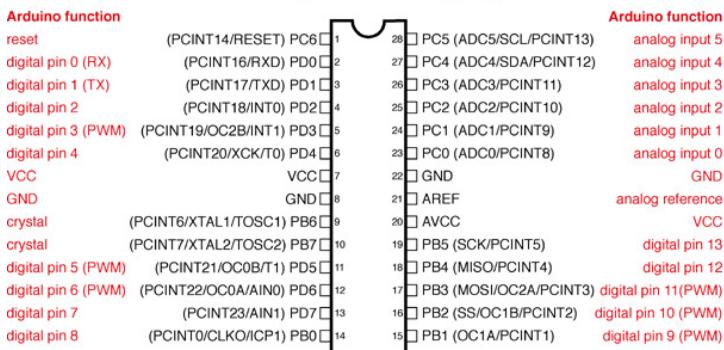
We show how to control a seven segment display through AVR-Assembly.

1. See Table 2.1 for components.
2. Complete Table 7.1 for all the digital pins using Fig. 7.1.

Port Pin	Digital Pin
PD2	2
PB5	13

TABLE 7.1

Atmega168 Pin Mapping



Digital Pins 11,12 & 13 are used by the ICSP header for MOSI,
MISO, SCK connections (Atmega168 pins 17,18 & 19). Avoid low-
impedance loads on these pins when using the ICSP header.

Fig. 7.1

3. Make connections according to Table 7.2.

Arduino	2	3	4	5	6	7	8
Display	a	b	c	d	e	f	g
0	0	0	0	0	0	0	1

TABLE 7.2

4. Execute the following code. The number 2 should be displayed.

```
assembly/sevenseg/codes/sevenseg.asm
```

5. Now generate the numbers 0-9 by modifying the above program.

7.3 7447

We show how to program the 7447 BCD-Seven segment display decoder through AVR-Assembly.

1. Verify the AND,OR and XOR operations in assembly using the following code and making pin connections according to Table 3.3

```
wget https://raw.githubusercontent.com/gadepall/arduino/master/assembly/7447/
count/codes/and_or_xor.asm
```

2. Suppose R20=0b00000010, R16=0b00000001. Explain the following routine

```
loopw: lsl r16 ;left shift
        dec r20 ;counter --
        brne loopw ;if counter != 0
        ret
```

Solution: The routine shifts R16 by 2 bits to the left (the count in R20=2). At the end of the routine, R16=0b00000100.

3. What do the following instructions do?

```
rcall loopw
out PORTD,r16 ;writing output to pins 2,3,4,5
```

Solution: **rcall** calls for execution of the **loopw** routine, which shifts R16 by 2 bits to the left and writes R16 to the display through PORTD.

4. Use the following routine for finding the complement of a number.

```
wget https://raw.githubusercontent.com/gadepall/arduino/master/assembly/7447/
      count/codes/complement.asm
```

5. Write an assembly program for implementing the following equations. Note that ZYXW is the input nibble and DCBA is the output nibble. Display DCBA on the seven segment display for each input ZYXW from 0-9.

$$A = W' \quad (7.1)$$

$$B = WX'Z' + W'X \quad (7.2)$$

$$C = WXY' + X'Y + W'Y \quad (7.3)$$

$$D = WXY + W'Z \quad (7.4)$$

6. Repeat the above exercise by getting ZYXW as manual inputs to the arduino from the GND and 5V pins on the breadboard.

7.4 Display Control

We show how to program the 7447 BCD-Seven segment display decoder through AVR-Assembly.

1. Connect the 7447 IC to the seven segment display.
2. Make connections between the 7447 and the arduino according to Table 3.3.
3. Execute the following program. The number 5 will be displayed.

```
assembly/7447/io/codes/op_7447.asm
```

4. Now generate the numbers 0-9 by modifying the above program.
5. Execute the following program after making the connections in Table 7.3. The number 3 will be displayed. What does the program do?

```
assembly/7447/io/codes/ip_7447.asm
```

	Z	Y	X	W
Input	0	0	1	1
Arduino	13	12	11	10

TABLE 7.3

Solution: The program reads from pins 10-13 and displays the equivalent decimal value on the display by writing to pins 2-5 of the arduino.

6. Explain the following instructions

```
ldi r17, 0b11000011 ; identifying input pins 10,11,12,13
ldi r17, 0b11111111 ;
out PORTB,r17 ;
in r17,PINB
```

Solution: First define pins 10,11,12 and 13 as input pins. Then ensure that these pins have the input 1 by default. Load the inputs from the pins in port B (which includes pins 10-13) into R17.

7.5 Blink through TIMER

We show how to use the Atmega328p timer to blink the builtin led with a delay.

1. Connect the Arduino to the computer and execute the following code

```
assembly/timer/codes/timer.asm
```

2. Explain the following instruction

```
sbi DDRB, 5
```

3. What do the following instructions do?

```
ldi r16, 0b00000101
out TCCR0B, r16
```

Solution: The system clock (SYSCLK) frequency of the Atmega328p is 16 MHz. TCCR0B is the Timer Counter Control Register. When

$$TCCR0B = 0b101 \quad (7.5)$$

$$\implies CLK = \frac{SYSCLK}{1024} \quad (7.6)$$

$$= \frac{16M}{1K} = 16kHz. \quad (7.7)$$

4. Explain the PAUSE routine.

```
ldi r19, 0b01000000 ;times to run the loop = 64 for 1 second delay
```

```
PAUSE: ;this is delay (function)
```

```
lp2: ;loop runs 64 times
```

```
    IN r16, TIFR0 ;tifr is timer interrupt flag (8 bit timer runs 256
    times)
```

```
    ldi r17, 0b00000010
```

```
    AND r16, r17 ;need second bit
```

```
    BREQ PAUSE
```

```
    OUT TIFR0, r17 ;set tifr flag high
```

```
    dec r19
```

```
brne lp2
ret
```

Solution: TIFR0 is the timer interrupt flag and TIFR0=0bxxxxx10 after every 256 cycles. PAUSE routine waits till TIFR0=0bxxxxx10, this checking is done by the AND and BREQ instructions above.

5. Explain the lp2 routine.

Solution: R19 = 64 and is used as a count for lp2. The lp2 routine returns after 64 PAUSE routines.

6. What is the blinking delay?

Solution: The blinking delay is given by

$$\text{delay} = \frac{\text{CLK}}{\text{lp2} \times \text{PAUSE}} \text{seconds} \quad (7.8)$$

$$= \frac{16 \times 1024}{64 \times 256} \text{seconds} = 1 \text{second} \quad (7.9)$$

7.6 Blink through Cycle Delays

1. Connect pin 8 of the Arduino to an led and execute the following code

```
assembly/timer/codes/cycle_delay.asm
```

2. Explain how the delay is obtained

```
ldi r16,0x50
ldi r17,0x00
ldi r18,0x00
```

w0:

```
dec r18
brne w0
dec r17
brne w0
dec r16
brne w0
pop r18
pop r17
pop r16
ret
```

Solution: The w0 loop is executed using the counts in $R16=2^6 + 2^4 = 80$, $R17=R18=2^8 = 256$. Thus

$$\text{delay} \approx 80 \times 256 \times 256 \text{cycles} \quad (7.10)$$

$$= \frac{80 \times 256 \times 256}{2^4 \times 2^{20}} \text{seconds} \quad (7.11)$$

$$= 0.3125 \text{seconds} \quad (7.12)$$

The actual time is slightly more since each instruction takes a few cycles to execute.

3. Should you use timer delay or cycle delay?

Solution: Timer delay is an accurate method for giving delays. Cycle delay is a crude method and should be avoided.

7.7 Memory

This manual shows how to use the Atmega328p internal memory for a decade counter through a loop.

1. Execute the following code by connecting the Arduino to 7447 through pins 2,3,4,5. The seven segment display should be connected to 7447.

```
assembly/memory/codes/mem.asm
```

2. Explain the following instructions

```
ldi xl,0x00
ldi xh,0x01
ldi r16,0b00000000
st x,r16
```

Solution: X=R27:R26, Y=R29:R28, and Z=R31:R30 where R27:R26 represents XH:XL. The above instructions load 0b00000000 into the memory location X=0x0100.

3. What does the **loop_cnt** routine do?

```
ldi r16,0b00000000
ldi r17,0x09
loop_cnt:
inc r16
inc xl
st x,r16
dec r17
brne loop_cnt
```

Solution: The routine loads the numbers 1-9 in memory locations 0x0101 - 0x0109.

4. Revise your code by using a timer for giving the delay.

7.8 Problems

1. In a given 8-bit general purpose micro-controller there are following flags. C-Carry, A-Auxiliary Carry, O-Overflow flag, P-Parity (0 for even, 1 for odd) R0 and R1 are the two general purpose registers of the micro-controller. After execution of the following instructions, the decimal equivalent of the binary sequence of the flag pattern [CAOP] will be _____.

```
MOV R0,+0x60
MOV R1,+0x46
ADD R0,R1
```

(EE GATE 2023)

2. Consider the given C-code and its corresponding assembly code, with a few operands U1-U4 being unknown. Some useful information as well as the semantics of each unique assembly instruction is annotated as inline comments in the code.

```
int a[10],b[10],i;
//int is 32-bit
for (i=0;i<10;i++)
a[i]=b[i]*8;
```

```
;r1–r5 are 32-bit integer registers
;initialize r1=0,r2=0
;initialize r3,r4 with base address of a,b

L01:jeq r1,r2,end ;if(r1==r2) goto end
L02:lw r5,0(r4) ;r5<-Memory[r4+0]
L03:shl r5,r5,U1 ;r5<-r5<<U1
L04:sw r5,0(r3) ;Memory[r3+0]<- r5
L05:add r3,r3,U2 ;r3<-r3+U2
L06:add r4,r4,U3
L07:add r1,r1,1
L08:jmp U4 ;goto U4
L09:end
```

3. Which one of the following options is a CORRECT replacement for operands in the position (U1,U2,U3,U4) in the above assembly code?
- (8,4,1,L02)
 - (3,4,4,L01)
 - (8,1,1,L02)
 - (3,1,1,L01)

4. An 8085 microprocessor accesses two memory locations (2001H) and (2002H), that contain 8-bit numbers 98H and B1H, respectively. The following program is executed:

```
LXI H,2001H
MVI A,21H
INX H
ADD M
INX H
MOV M,A
HLT
```

At the end of this program, the memory location 2003H contains the number in decimal (*base10*) form _____.

(GATE EE2020 – 54)

5. Which of the following is the correct binary equivalent of the hexadecimal F6C?
(GATE PH2020, 6)
 - a) 011011111100
 - b) 111101101100
 - c) 110001101111
 - d) 011011000111
6. A portion of an assembly language program written for an 8-bit microprocessor is given below along with explanations. The code is intended to introduce a software time delay. The processor is driven by a 5 MHz clock. The time delay (in μs) introduced by the program is

MVI B, 64H; Move immediate the given byte into register B. Takes 7 clock periods.

LOOP: DCR B ; Decrement register B. Affects Flags. Takes 4 clock periods.

JNZ LOOP ; Jump to address with Label LOOP if zero flag is not set. Takes 10 clock periods when jump is performed and 7 clock periods when jump is not performed.

(GATE IN 2018)

7. A $10\frac{1}{2}$ digit Counter-timer is set in the 'frequency mode' of operation (with $T_s = 1\text{s}$). For a specific input, the reading obtained is 1000. Without disconnecting this input, the Counter-timer is changed to operate in the 'Period mode' and the range selected is microseconds (μs , with $f_s = 1 \text{ MHz}$). The Counter Will then display (GATE IN 2021)
 - a) 0
 - b) 10
 - c) 100
 - d) 1000
8. Consider three registers **R1**, **R2**, **R3** that store numbers in IEEE – 754 single precision floating point format. Assume that **R1** and **R2** contain the values (in hexadecimal notation) 0x42200000 and 0xC1200000, respectively. If **R3** = $\frac{\text{R1}}{\text{R2}}$, what is the value stored in **R3**? (GATE-EC2021,31)
 - a) 0x40800000
 - b) 0xC0800000
 - c) 0x83400000
 - d) 0xC8500000
9. The content of the registers are $R_1 = 25H$, $R_2 = 30H$ and $R_3 = 40H$. The following

machine instructions are executed.

PUSH {R₂}
PUSH {R₂}
PUSH {R₃}
POP {R₁}
POP {R₂}
POP {R₃}

After execution, the content of registers R_1 , R_2 , R_3 are

(GATE-EC2021,32)

- a) $R_1 = 40H, R_2 = 30H, R_3 = 25H$
- b) $R_1 = 25H, R_2 = 30H, R_3 = 40H$
- c) $R_1 = 30H, R_2 = 40H, R_3 = 25H$
- d) $R_1 = 40H, R_2 = 25H, R_3 = 30H$

8 EMBEDDED C

8.1 Blink

We show how to control an led using AVR-GCC. AVR-GCC is a C compiler for the Atmega328p.

1. Execute the following

```
cd avr-gcc/setup/codes
make
```

2. Now open **main.c**. Explain the following lines.

```
PORTRB = ((0 << PB5));
    _delay_ms(500);
//turn led on
PORTRB = ((1 << PB5));
    _delay_ms(500);
```

Solution: $((0 << PB5))$ writes 0 to pin 13 (PB5). $_delay_ms(500)$ introduces a delay of 500 ms.

3. Modify the above code to keep the led on.
4. Repeat the above exercise to keep the led off.

8.2 Display Control

We show how to control a seven segment display using AVR-GCC with arduino

1. Connect the arduino to the seven segment display
2. Execute the following code

```
avr-gcc/sevenseg/codes/main.c
```

3. Modify the above code to generate numbers between 0-9.
4. Now connect the arduino to the seven segment display through 7447.
5. Execute the following code

```
avr-gcc/input/codes/main.c
```

6. Modify the above code to work without the 7447.

8.3 GCC-Assembly

We show how to write a function in assembly and call it in a C program while programming the ATMega328P microcontroller in the Arduino. This is done by controlling an LED.

1. Execute

```
cd avr-gcc/gcc-assembly/codes
make
```

2. Modify **main.c** and **Makefile** to turn the builtin led on.
3. Repeat the above exercise to turn the LED off.
4. Explain how the **disp_led(0)** function is related to **Register R24** in **disp_led** routine in **displedasm.S**.

Solution: The function argument 0 in **disp_led(0)** is passed on to R24 in the assembly routine for further operations. Also, the registers R18-R24 are available for storing more function arguments according to the Table 8.1. More details are available in official ATMEL AT1886 reference.

Register	r19	r18	r21	r20	r23	r22	r25	r24
Function Argument	b7	b6	b5	b4	b3	b2	b1	b0

TABLE 8.1: Relationship between Register in assembly and function argument in C

5. Write an assembly routine for controlling the seven segment display and call it in a C program.
6. Build a decade counter with **main.c** calling all functions from assembly routines.

8.4 LCD

We show how to interface an Arduino to a 16×2 LCD display using AVR-GCC. This framework provides a useful platform for displaying the output of AVR-Assembly programs.

1. The required components are listed in Table 8.2

Component	Value	Quantity
Resistor	220 Ohm	1
	1K	1
Arduino	Uno	1
Jumper Wires		20

TABLE 8.2

2. Plug the LCD in Fig. 8.1 to the breadboard.
3. Connect the Arduino pins to LCD pins as per Table 8.3.

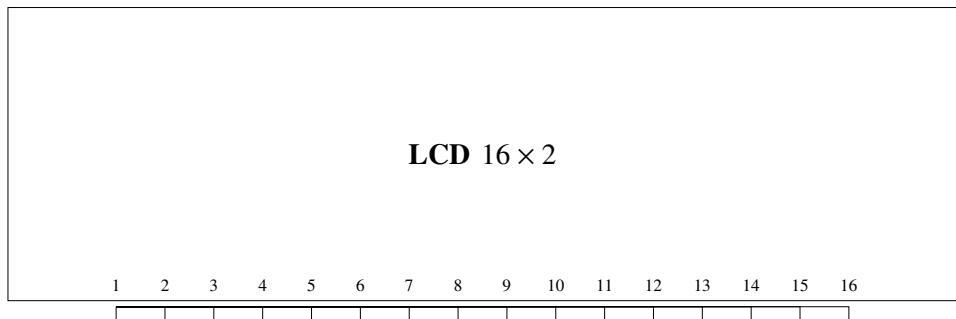


Fig. 8.1: LCD

TABLE 8.3: Arduino to LCD Pin Connection.

Arduino Pins	LCD Pins	LCD Pin Label	LCD Pin Description
GND	1	GND	
5V	2	Vcc	
GND	3	Vee	Contrast
D12	4	RS	Register Select
GND	5	R/W	Read/Write
D11	6	EN	Enable
D5	11	DB4	Serial Connection
D4	12	DB5	Serial Connection
D3	13	DB6	Serial Connection
D2	14	DB7	Serial Connection
5V	15	LED+	Backlight
GND	16	LED-	Backlight

4. Execute

```
cd avr-gcc/lcd/codes
make
```

5. Modify the above code to display a string.
6. Modify the above code to obtain a decade counter so that the numbers from 0 to 9 are displayed on the lcd repeatedly.
7. Repeat the above exercises to display a string on the first line and a number on the second line of the lcd.
8. Write assembly routines for driving the lcd.

8.5 Problems

- 1) The representation of the decimal number $(27.625)_{10}$ in base-2 number is
(A) 11011.110

- (B) 11101.101
- (C) 11011.101
- (D) 10111.110

(GATE IN 2018)

VAMAN LC-1

PINOUT

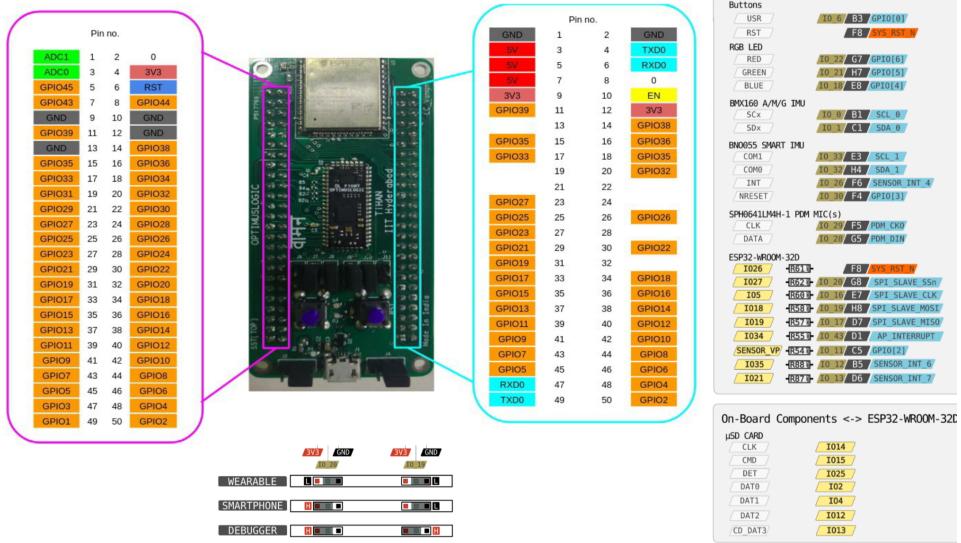


Fig. 9.1: Vaman pins. Right side represents ESP32 and left side M4-FPGA (Pygmy).

9 VAMAN

9.1 ESP

Here we show how to program the ESP32 on the Vaman using the Arduino framework.

1. Make sure that Vaman board does not power any devices.
2. Make connections as shown in Table 9.1.
3. The Vaman pin diagram is available in Figure 9.1.

VAMAN-ESP	UART PINS
5V	5V
GND	GND
TXD0	TXD
RXD0	RXD
0	GND

TABLE 9.1

4. Connect the UART to raspberry pi through USB.
5. Connect the pins between Vaman-ESP32 and Vaman-PYGMY as per Table 9.2
6. On termux on your phone,

ESP32	Vaman
GPIO2	GPIO18
GPIO4	GPIO21
GPIO5	GPIO22

TABLE 9.2

```
cd vaman/esp32/codes/ide/blink
pio run
```

7. Transfer the ini and bin files to the rpi

```
scp platformio.ini pi@192.168.50.252:./hi/platformio.ini
```

```
scp .pio/build/esp32doit-devkit-v1/firmware.bin pi@192.168.50.252:./hi/.pio/build/
esp32doit-devkit-v1/firmware.bin
```

8. On rpi,

```
cd /home/pi/hi
pio run -t nobuild -t upload
```

You should see the blue led blinking.

9. Now disconnect pin 2 from pin 18 and connect to pygmy GPIO pin 21.

10. Repeat the above exercise using GPIO pin 22.

11. On your phone, open

```
src/main.cpp
```

and change the delay to

```
delay(100);
```

and execute the code by following the steps above.

12. Flash the following code.

```
vaman/esp32/codes/ide/ota/setup
```

after entering your wifi username and password (in quotes below)

```
#define STASSID "..." // Add your network credentials
#define STAPSK "..."
```

in src/main.cpp file

13. You should be able to find the ip address of your vaman-esp using

```
ifconfig
nmap -sn 192.168.231.1/24
```

where your computer's ip address is the output of ifconfig and given by 192.168.231.x

14. Assuming that the username is gvv and password is abcd, flash the following code wirelessly

```
vaman/esp32/codes/ide/ota/blink
```

through

```
pio run
```

```
pio run -t nobuild -t upload --upload-port 192.168.231.245
```

where you may replace the above ip address with the ip address of your vaman-esp.

15. Flash the following code OTA

```
vaman/esp32/codes/ide/ota/blinkt
```

You should see the onboard LEDs blinking.

16. Change the blink duration to 100 ms.

17. Execute the code in

```
vaman/esp32/codes/ide/ota/sevenseg/static/
```

to control the seven segment display.

9.2 FPGA

We show how to program the Vaman FPGA/microcontroller board.

1. Follow the instructions available in the video at

```
https://github.com/whyakari/TermuxDisableProcces?tab=readme-ov-file
```

to ensure that termux is not killed during the following installation process.

2. On termux-debian,

```
wget https://raw.githubusercontent.com/gadepall/fwc-1/main/scripts/setup.sh  
bash setup.sh
```

3. Login to termux-debian on the android device and execute the following commands

```
cd vaman/fpga/setup/codes/blink
```

```
source ~/.vamenv/bin/activate
```

```
ql_symbiflow -compile -src vaman/fpga/setup/codes/blink -d ql-eos-s3 -P
```

```
PU64 -v helloworldfpga.v -t helloworldfpga -p pygmy.pcf -dump binary  
scp blink/helloworldfpga.bin pi@192.168.0.114:
```

Make sure that the appropriate IP address for the raspberry pi is given in the above command.

4. Put the Vaman board in download mode. For this, you need to first press the button to the right of the usb port and immediately press the button to the left. The green led should now flash and you can go to the next step.
5. Now execute the following commands on the raspberry pi.

```

python3 -m venv ~/.vamenv
source ~/.vamenv/bin/activate
git clone --recursive https://github.com/QuickLogic-Corp/TinyFPGA-
    Programmer-Application.git
pip3 install tinyfpgab
deactivate
sudo reboot
source ~/.vamenv/bin/activate
python3 TinyFPGA-Programmer-Application/tinyfpga-programmer-gui.py --
    port /dev/ttyACM0 --appfpga /home/pi/helloworldfpga.bin --mode fpga --
    reset

```

6. Make sure that the correct USB port address is given in the above command. After some time, the LED will start blinking red.
7. Replace the following line in the code in instruction 10

assign redled = led; //If you want to change led colour to red,

with

assign blueled = led;

and execute the code.

8. In the following .pcf file,

codes/blink/pygmy.pcf

the pin numbers for the 3 colour-leds are defined. See Table 9.2 and Figure 9.2. The IO locations in Figure 9.2 can be found in pygmy.pcf while the aliases (GPIO) are printed on the board.

9. Now modify the helloworldfpga.v file to get the green led blinking.
10. In the following verilog program,

codes/blink/helloworldfpga.v

pay attention to the following lines

```

delay = delay+1;
if(delay > 20000000)
begin
delay=25'b0;
led=!led;
end

```

It may be deduced from the above that the blink frequency is 20 MHz.

11. In instruction 10, replace

if(delay > 20000000)

Type	Vaman Pin	Connection
Input	IO_28	3.3V

TABLE 9.3: Vaman Input/Output.

with

```
if(delay==25'b1001100010010110100000000)
```

and execute the verilog code.

12. Since the delay is 20 MHz, the blink period is 1 second. Modify the verilog code so that the blink period becomes 0.5s.
13. Find the bit length of 20 MHz.

Solution:

$$\log_2(20000000) \approx 25 \quad (9.1)$$

14. Obtain the above answer using a Python code.

Solution: Execute the following code and compare with instruction 11.

```
codes/blink/freq_count.py
```

15. Ensure that the LED stays on in green colour.

Solution: Execute the following code

```
vaman/setup/codes/blink/onoff.v
```

16. Execute the following code and make pin connections as per Table 9.3. Take out the input pin connect to 3.3V. Plug it again. Do this repeatedly.

```
vaman/setup/codes/input/blink_ip.v
vaman/setup/codes/input/pygmy.pcf
```

17. Connect an external LED and repeat.

18. Execute the codes in

```
vaman/fpga/sevenseg/codes
```

to control the seven segment display.

9.3 ARM

We show how to control an LED using the M4 on Vaman.

1. Check your path

```
cd vaman/arm/setup/blink/GCC_Project
nvim config.mk
```

and

2. and modify so that you have the following lines

PD64			PU64			WR42		
IO Locatid	Alias	IO Type	IO Locatid	Alias	IO type	IO Locatid	Alias	IO Type
B1	IO_0	BIDIR	4	IO_0	BIDIR	A7	IO_0	BIDIR
C1	IO_1	BIDIR	5	IO_1	BIDIR	B7	IO_1	BIDIR
A1	IO_2	BIDIR	6	IO_2	BIDIR	C7	IO_3	BIDIR
A2	IO_3	BIDIR	2	IO_3	BIDIR	A6	IO_6	BIDIR
B2	IO_4	BIDIR	3	IO_4	BIDIR	B6	IO_8	BIDIR/CLOCK
C3	IO_5	BIDIR	64	IO_5	BIDIR	A5	IO_9	BIDIR
B3	IO_6	BIDIR	62	IO_6	BIDIR	B5	IO_10	BIDIR
A3	IO_7	BIDIR/CLOCK	63	IO_7	BIDIR/CLOCK	A4	IO_14	BIDIR
C4	IO_8	BIDIR/CLOCK	61	IO_8	BIDIR/CLOCK	B4	IO_15	BIDIR
B4	IO_9	BIDIR	60	IO_9	BIDIR	E1	IO_16	BIDIR
A4	IO_10	BIDIR	59	IO_10	BIDIR	D1	IO_17	BIDIR
C5	IO_11	BIDIR	57	IO_11	BIDIR	C1	IO_19	BIDIR
B5	IO_12	BIDIR	56	IO_12	BIDIR	F2	IO_20	BIDIR
D6	IO_13	BIDIR	55	IO_13	BIDIR	E2	IO_23	BIDIR/CLOCK
A5	IO_14	BIDIR	54	IO_14	BIDIR	D2	IO_24	BIDIR/CLOCK
C6	IO_15	BIDIR	53	IO_15	BIDIR	D3	IO_25	BIDIR
E7	IO_16	BIDIR	40	IO_16	BIDIR	F3	IO_28	BIDIR
D7	IO_17	BIDIR	42	IO_17	BIDIR	E3	IO_29	BIDIR
E8	IO_18	BIDIR	38	IO_18	BIDIR	F4	IO_30	BIDIR
H8	IO_19	BIDIR	36	IO_19	BIDIR	E4	IO_31	BIDIR
G8	IO_20	BIDIR	37	IO_20	BIDIR	D5	IO_34	SDIOMUX
H7	IO_21	BIDIR	39	IO_21	BIDIR	F5	IO_36	SDIOMUX
G7	IO_22	BIDIR/CLOCK	34	IO_22	BIDIR/CLOCK	E6	IO_38	SDIOMUX
H6	IO_23	BIDIR/CLOCK	33	IO_23	BIDIR/CLOCK	F6	IO_39	SDIOMUX
G6	IO_24	BIDIR/CLOCK	32	IO_24	BIDIR/CLOCK	D7	IO_43	SDIOMUX
F7	IO_25	BIDIR	31	IO_25	BIDIR	E7	IO_44	SDIOMUX
F6	IO_26	BIDIR	30	IO_26	BIDIR	F7	IO_45	SDIOMUX
H5	IO_27	BIDIR	28	IO_27	BIDIR			
G5	IO_28	BIDIR	27	IO_28	BIDIR			
F5	IO_29	BIDIR	26	IO_29	BIDIR			
F4	IO_30	BIDIR	25	IO_30	BIDIR			
G4	IO_31	BIDIR	23	IO_31	BIDIR			
H4	IO_32	SDIOMUX	22	IO_32	SDIOMUX			
E3	IO_33	SDIOMUX	21	IO_33	SDIOMUX			
F3	IO_34	SDIOMUX	20	IO_34	SDIOMUX			
F2	IO_35	SDIOMUX	18	IO_35	SDIOMUX			
H3	IO_36	SDIOMUX	17	IO_36	SDIOMUX			
G2	IO_37	SDIOMUX	15	IO_37	SDIOMUX			
E2	IO_38	SDIOMUX	16	IO_38	SDIOMUX			
H2	IO_39	SDIOMUX	11	IO_39	SDIOMUX			
D2	IO_40	SDIOMUX	13	IO_40	SDIOMUX			
F1	IO_41	SDIOMUX	14	IO_41	SDIOMUX			
H1	IO_42	SDIOMUX	10	IO_42	SDIOMUX			
D1	IO_43	SDIOMUX	7	IO_43	SDIOMUX			
E1	IO_44	SDIOMUX	8	IO_44	SDIOMUX			
G1	IO_45	SDIOMUX	9	IO_45	SDIOMUX			

Fig. 9.2: Pin Definitions

```
#export PROJ_ROOT=/data/data/com.termux/files/home/pygmy-dev/pygmy-sdk
export PROJ_ROOT=/root/pygmy-dev/pygmy-sdk
```

3. Now execute

```
cd vaman/arm/setup/blink/GCC_Project
make -j4
scp output/bin/blink.bin pi@192.168.0.114:
```

Appropriately modify the above ip address before sending blink.bin to the pi.

- Now log on to the RPi and execute the following

```
sudo python3 /home/pi/Vaman-dev/Vaman-sdk/TinyFPGA-Programmer-
Application/tinyfpga-programmer-gui.py --port /dev/ttyACM0 --m4app
blink.bin --mode m4-fpga
```

- Enter the appropriate USB device port above while executing. Press the button to the right after the above command is successfully executed. The LED will start blinking.
- See the following lines of the code below

codes/setup/blink/src/main.c

```
PyHal_Set_GPIO(18,1); //blue
PyHal_Set_GPIO(21,1); //green
PyHal_Set_GPIO(22,1); //red
    HAL_DelayUsec(2000000);
PyHal_Set_GPIO(18,0);
PyHal_Set_GPIO(21,0);
PyHal_Set_GPIO(22,0);
```

We may conclude that the blink delay is 2000 000us = 2 s.

- Replace the following line in 6

HAL_DelayUsec(2000000);

with

HAL_DelayUsec(1000000);

and execute. Can you see any difference in the blink period?

- To obtain red colour, execute the following code.

vaman/arm/codes/setup/red/src/main.c

Now obtain blue colour.

- Now obtain green colour without blink.

Solution: Execute the following code.

vaman/arm/codes/setup/onoff/src/main.c

- Using Table 9.4 and Fig. 9.1, use an input pin to control the onboard LED.

Solution: Execute the following code. You should see the green LED on. Connecting IO_5 to GND will turn the green LED off.

Type	Pin	Destination
Input	IO_5	5V

TABLE 9.4: Vaman control through external input.

vaman/arm/codes/setup/gpio/src/main.c

11. Execute the codes in

vaman/arm/codes/sevenseg/loop/

to control the seven segment display.

10.1 Setup

1. There is a button adjacent to the USB port of the pico. Keep this button (BOOTSEL) pressed while connecting the RPi to the Pico through the USB cable.
2. Login to termux-debian and execute the following commands.

```
cd pico/trunk/arm/codes/setup/blink
mkdir build #Only once
cd build
cmake ..
make -j4
scp main.uf2 pi@192.168.0.114:
```

Suitably modify the above ip address before sending main.uf2 .

3. Now login to the raspberry pi and execute the following commands.

```
sudo mkdir /mnt/pico #Only once
sudo fdisk -l
sudo mount /dev/sda1 /mnt/pico
sudo mv /mnt/pico
sudo umount /mnt/pico
```

You should now see the LED to the right of the USB port blinking.

4. Connect RUN on pico to GND. Keep pressing BOOTSEL while removing the RUN-GND wire from GND. The LED stops blinking. Pico is now ready to be flashed.

10.2 Delay

1. Note the followign lines in the C code below:

```
codes/setup/blink/main.c
```

```
gpio_put(LED_PIN, 1);
sleep_ms(250);
gpio_put(LED_PIN, 0);
sleep_ms(250);
```

It is obvious that the blink period is $500\text{ms} = 0.5\text{s}$

2. Replace the below instruction in the C program

```
sleep_ms(250);
```

with

```
sleep_ms(500);
```

Can you see any difference in the LED blinking frequency?

3. Now modify the above code to keep the LED on permanently.

Solution: Execute the following code.

pico/codes/setup/onoff/main.c

4. Use GP2 as an output pin and drive an LED.

Solution: Connect the LED to pico as per Table 10.1 and Fig. 10.1

pico/codes/setup/gpio/main.c

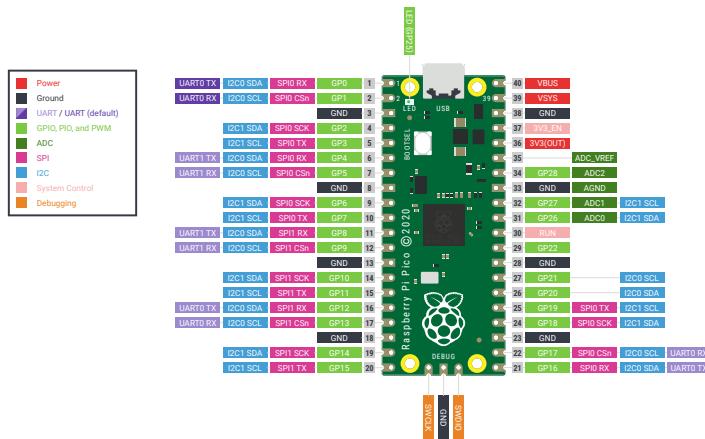
Type	pico pin	Destination
Output	3V3	LED
Output	GP2	LED

TABLE 10.1: Connection between LED and pico

5. Execute the following code. Connect a wire to GND and touch GP2 on the pico. The onboard LED will turn off. Repeat this exercise to blink the LED manually.

pico/codes/setup/input/main.c

Raspberry Pi Pico Pinout



Raspberry Pi

Fig. 10.1: Pin diagram

6. Execute the following code to drive the seven segment display.

pico/arm/codes/sevenseg/static/main.c

11 STM32

11.1 Arduino Framework

- The STM32F103C8T6 micro-controller in Fig. 11.1 has two ground pins, few analog input pins and few digital pins that can be used for both input as well as output. It has one Vcc (3.3V) pin that can generate 3.3V. In the following exercises, only the GND, 3.3V and digital pins will be used.

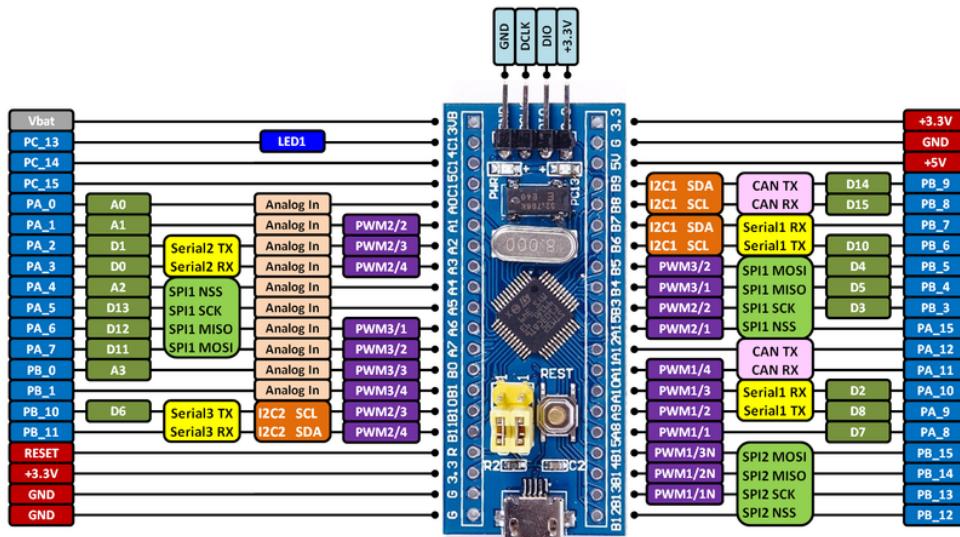


Fig. 11.1: Pin Connections of STM-32

- Make the connections as per the Table 11.1

STM32F103C8 PINS	USB2UART PINS
3.3	3.3
GND	GND
A9(TXD)	RXD
A10(RXD)	TXD

TABLE 11.1: STM32 to USB-UART connections

- Basic onchip led blink program is available at

stm32/setup/codes/src/blink.c

- Make sure that platformio.ini file has the following lines

```
[env:bluepill_f103c8]
platform = ststm32
framework = arduino
```

board = bluepill_f103c8

- Now, compile the blink program

```
cd stm32/ardsetup/codes  
pio run
```

- With this .bin file will be generated and all the necessary packages will be installed.
- Before flashing, make sure that STM32 board is in Programming mode
- See how to enable programming mode in Fig. 11.2. This configuration will ensure that the microcontroller enters the system memory programmer on reset.

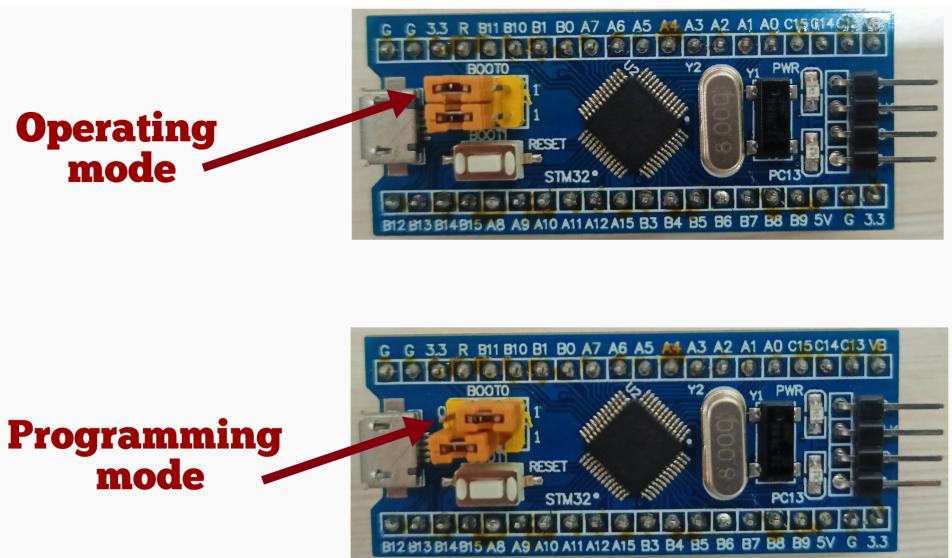


Fig. 11.2: STM32 Operating and Programming mode

- After executing

```
Install STM32-Utils app from playstore  
Give the necessary permissions  
Connect the USB-UART to OTG  
Upload the .bin file to the STM32 board
```

- The inbuilt LED present on the STM32F103C8T6 will start blinking.
- Change the STM32 board to operating mode as shown in Fig 11.2 in order to run your code from the main flash memory.

11.2 Embedded C

- Copy your codes directory to the termux-debian root directory.

```
cp -r STM32F103C8T6 ~/STM32F103C8T6/
cd ~/STM32F103C8T6
make bin
```

2. This will generate main.bin. Flash it using the android app or platformio.
3. Modify main.c in the STM32F103C8T6 directory and modify the code to keep the LED on. Flash it to the STM32 and verify.

11.3 Seven Segment Display

1. Make the pin connections in Table 11.3 using Figs. 2.2 and 11.1.

STM32	PB9	PB8	PB7	PB6	PB5	PB4	PB3	3.3V
DISPLAY	a	b	c	d	e	f	g	COM
0	0	0	0	0	0	0	1	
1	1	0	0	1	1	1	1	
2	0	0	1	0	0	1	0	
3	0	0	0	0	1	1	0	
4	1	0	0	1	1	0	0	
5	0	1	0	0	1	0	0	
6	0	1	0	0	0	0	0	
7	0	0	0	1	1	1	1	
8	0	0	0	0	0	0	0	
9	0	0	0	0	1	0	0	

TABLE 11.3: STM-32 and Seven Segment Display Connections

2. Execute the following code

```
stm32/sevenseg/codes/sevenseg_example.c
```

3. Explain the process of generating the number 0 using the following instruction.

```
GPIOB->ODR = 0xFC08;
```

Solution: ODR is the Output Data Register, which is used to write outputs to the GPIO pins. The 16 bit number 0xFC08 on the RHS represents the pin configuration for the pins of port B of STM32F103C8T6, which are numbered PB15-PB0 in that order. See Table 11.3.

4. Repeat the above exercise to generate the numbers 1-9 on the display.
5. The previous instructions set the bits in the unused ports PB15-PB10 and PB2-PB0. This may be undesirable in some cases. Generate 0 by not disturbing the unused pins.

Solution: The following instructions help accomplish this. The first instruction resets PB4-PB9. The second instruction sets the PB3 pin. The other pins are undisturbed.

```
GPIOB->BRR = (1<<4)|(1<<5)|(1<<6)|(1<<7)|(1<<8)|(1<<9); // (Led ON)
GPIOB->BSRR = (1<<3); // (Led OFF)
```

6. Write a program to take a 4-bit BCD as input from hardware (GND or VDD) and show the next number on the seven segment display.

Solution: The following program takes 4 bits as input from pins PB12-PB15 and displays the output on a seven segment display. The next number can be displayed by slightly modifying the code.

```
stm32/sevenseg/codes/bin2dec_example.c
```

11.4 GPIO Output

1. Connect the USB-UART to STM32. The hardware connections between the USB-UART, STM32 and LED are available in Table 11.4. Make sure that the LED is connected to PB4 through the resistor.

STM32	UART	LED
GND	GND	-
3.3V	3.3V	
A9(Txd)	Rxd	
A10(Rxd)	Txd	
PB4		+

TABLE 11.4: USB-UART to STM32 connections

2. Execute

```
gpio/codes/gpio_example.c
```

3. Modify the above program to turn the LED off.
4. Explain the following line.

```
AFIO->MAPR = AFIO_MAPR_SWJ_CFG_JTAGDISABLE;
```

Solution: By default, the PB3 and PB4 pins in the STM32F103C8T6 board cannot be used as GPIO pins. The above command allows these pins to be configured for GPIO.

5. What does the following command do?

```
GPIOB->CRL = 0x00030000;
```

Solution: The STM32F103C8T6 has ports A and B, each having 16 pins that can be used as GPIO output. The above command enables the pin B4 of port B as an output pin See Tables 11.6.

6. Explain the significance of the number (nibble) 0x3 corresponding to PB4 in Table 11.6.

Pin	PB7	PB6	PB5	PB4	PB3	PB2	PB1	PB70
Nibble	0	0	0	3	0	0	0	0

TABLE 11.6: GPIO Enable pins

Solution: The nibble $0x3 = 0b0011$. From Table 11.7, The first two bits are CNF1=0, CNF0=0 which means that PB4 is configured as a general purpose push-pull output. The last two bits are 11, denoting the mode, which says that PB4 is capable of a maximum output speed of 50 MHz.

Configuration Mode		CNF1	CNF0	Mode	Max Speed (MHz)
General Purpose Output	Push-pull	0	0	01	10
	Open-drain		1	10	2
				11	50
				00	reserved

TABLE 11.7: GPIO Output configuration

7. What does the following instruction do?

```
GPIOB->BRR = (1<<4);
```

Solution: BRR is the Bit Reset Register. The least significant 16 bits are used to atomically set pin values to GND whereas the most significant 16 bits are used to atomically clear pin values to VDD. The above command clears PB4.

8. What does the following instruction do?

```
GPIOB->BSRR = GPIO_BSRR_BR4;
```

Solution: BSRR is the Bit Set/Reset Register. GPIO_BSRR_BR4 is used to reset PB4. The result is the same as the previous problem.

9. Modify your program to control an LED using PA2.

11.5 GPIO Input

10. Connect PB7 to GND and execute the following code

```
cd /gpio/gpio_input_example.c
```

11. What does the following instruction do?

```
GPIOB->CRL = 0x80030000;
```

Solution: This instruction declares PB7 as an input pin. $0x8 = 0b1000$. According to Table 11.8, the mode 00 is used only for input and the first two bits 10 are used for pull-up/pull-down.

12. Explain the following instruction.

Configuration Mode		CNF1	CNF0	Mode
Input	Analog	0	0	00
	Input Floating		1	
	Input pull-down	1	0	
	Input pull-up			

TABLE 11.8: GPIO Input configuration

```
#define B7 0x0080
if (((GPIOB->IDR & B7) == 0 ))
    GPIOB->BRR = (1<<4); //PB4 = 0 (Led ON)
else
    GPIOB->BSRR = (1<<4); //PB4 = 1 (Led OFF)
```

Solution: The instruction checks whether the 8th bit of GPIOB->IDR, i.e. the input from PB7 is 0. If so, then the LED connected to PB4 should be ON.

11.6 Clocks

1. List all available clocks in the STM32F103C8T6 blue pill.

Solution: See Table 11.9.

Clock	Location	Type	Frequency
HSI	Internal	RC	8Mhz
LSI	Internal	RC	32.768 kHz
HSE	External	Crystal	8Mhz

TABLE 11.9: STM32F103C8T6 Clock Types

2. Make connections as shown in Table 11.10.

STM32	Seven Segment Display
3.3V	COM (through resistor)
PA1	DOT

TABLE 11.10: Pin Connections

11.7 HSE

3. Execute the following program

```
clocks/codes/hse_systick_blink.c
```

4. Explain the following instruction

```
RCC->CR =0x00010000;
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reserved				PLL RDY	PLLON	Reserved				CSS ON	HSE BYP	HSE RDY	HSE ON		
				r	rw					rw	rw	r	rw		
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
HSICAL[7:0]								HSITRIM[4:0]				Res.	HSI RDY	HSION	
r	r	r	r	r	r	r	r	rw	rw	rw	rw		r	rw	

Fig. 11.3: RCC Clock Control Register (RCC->CR)

Solution: Fig. 11.3 shows the RCC->CR register. The above instruction enables the HSE crystal, which is 8 MHz for the STM32F103C8T6.

5. Explain the following instruction

RCC->CFG =0x00000001;

Solution: Fig. 11.4 shows the RCC->CFG register. The above instruction makes the HSE as the system clock through SW = 01.

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reserved				MCO[2:0]			Res.	USB PRE	PLLMUL[3:0]				PLL XTPRE	PLL SRC	
				rw	rw	rw		rw	rw	rw	rw	rw	rw	rw	rw
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
ADCPRE[1:0]	PPRE2[2:0]		PPRE1[2:0]			HPRE[3:0]			SWS[1:0]		SW[1:0]				
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	r	r	rw	rw

Fig. 11.4: RCC clock Configuration Register (RCC->CFG)

6. Verify that HSE is the system clock by checking that SWS = 01.

11.8 PLL

7. Make the PLL as the system clock.

Solution:

RCC->CFG =0x00000010;

8. Choose the PLL input as HSE.

RCC->CFG =0x00010010;

9. Enable PLL

Solution:

RCC->CR =0x01010000;

10. Execute the following code.

```
cd /clocks/pll_systick_blink.c
```

11. Make the PLL output = 24 MHz.

11.9 Timers

1. List all the available timers in the STM32F103C8T6 blue pill.

Solution: See Table 11.11

Timer	Type	Counter Resolution
Systick	Default	24 bit
Independent	Watchdog	12 bit
Window	Watchdog	7 bit
TIM1	Advanced	
TIM2		
TIM3	General Purpose	16 bit
TIM4		

TABLE 11.11: STM32F103C8T6 Timer Types.

11.10 Systick timer

2. The Systick timer is the default timer available on all ARM chips.
3. Make connections as shown in Table 11.12.

STM32	Seven Segment Display
3.3V	COM (through resistor)
PA1	DOT

TABLE 11.12: Pin Connections

4. Execute the program in

```
timers/codes/blink_systick.c
```

5. The default clock is the HSI 8MHz RC. Find the number of clock cycles required for a 1 s delay.

Solution: The time period is

$$T = \frac{1}{8}\mu\text{s} = 1 \text{ cycle} \quad (11.1)$$

Thus, the number of cycles required for 1 s delay is

$$1 \text{ second} = 8000000 \text{ cycles} \quad (11.2)$$

6. List the SysTick registers.

Solution: See Table 11.13.

7. What do the following instructions do?

```
SysTick->LOAD = 4000000;  
SysTick->VAL = 0;
```

Solution: See Table 11.13 for details. These two instructions ask the SysTick timer to count down from 4000000 to 0.

8. Explain the following instruction.

Register	Command	Purpose
SysTick Control and Status	SysTick->CTRL	Timer control
SysTick Reload Value	SysTick->LOAD	Timer Count
SysTick Current Value	SysTick->VAL	Timer Initialize
SysTick Calibration Value		

TABLE 11.13: Systick Registers

```
while(!(SysTick->CTRL & 0x00010000));
```

Solution: Fig. 11.5 shows the SysTick CTRL register. 0x00010000 is used in the above command to mask all the bits except for bit 16, which is the COUNTFLAG. The **while** loop will stop once COUNTFLAG = 0. The while loop is used for the delay.

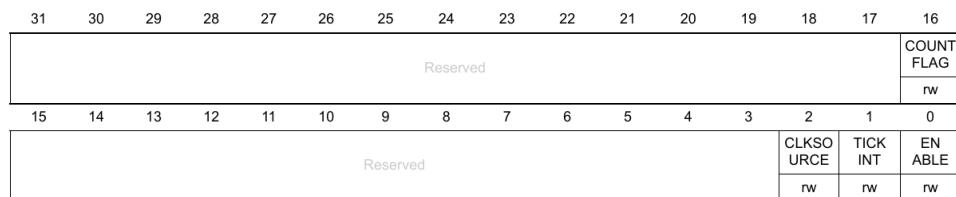


Fig. 11.5: Control Register (CTRL)

9. What does the following instruction do?

```
SysTick->CTRL = 0x00000005; //8MHz clock
```

Solution: From Fig. 11.5, ENABLE = 1 enables the counter (for delay) and CLKSOURCE = 1 enables the 8 MHz internal RC clock.

10. Obtain a 1 MHz clock.

Solution: CLKSOURCE = 1 results in the $\frac{\text{Processor Clock}}{8} = 1 \text{ MHz clock}$.

```
SysTick->CTRL = 0x00000001; //1MHz clock
```

11. Obtain a delay of 1 second using the 1 MHz clock.

11.11 TIMER-1

12. Make the connections according to Table 11.12. Execute the following program

```
cd /timers/timer1_blink.c
```

13. Enable Timer1 through RCC.

Solution:

```
RCC->APB2ENR |= RCC_APB2ENR_TIM1EN;
```

14. Select the HSI clock of 8 MHz as TIM1 clock.

Solution: See Fig. 11.6 for register. SMS=000 implies that the TIM1 will be controlled by the internal clock.

TIM1->SMCR = 0;

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
ETP	ECE	ETPS[1:0]		ETF[3:0]		MSM		TS[2:0]		Res.		SMS[2:0]			
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	res.	rw	rw	rw

Fig. 11.6: Slave Mode Control Register (SMCR)

15. What does the following instruction do?

TIM1->CR1 = 0x0001;

Solution: Fig. 11.7 shows the control register 1 (CR1). CEN=1 enables the counter.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Reserved						CKD[1:0]	ARPE	CMS[1:0]	DIR	OPM	URS	UDIS	CEN		
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw		rw

Fig. 11.7: Control Register 1 (CR1)

16. Make TIM1 clock = 2 KHz.

Solution: Through the following command,

TIM1->PSC = 3999;

$$TIM1_CLK = \frac{HSI_CLK}{TIM1->PSC + 1} = \frac{8000000}{4000} \quad (11.3)$$

Fig. 11.8 shows the TIM1->PSC (prescalar) register.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
PSC[15:0]															
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw

Fig. 11.8: Prescalar (PSC)

17. What is the maximum value that can be stored in TIM1->PSC?

18. Make TIM1 count 1000 cycles of the 2 KHz TIM1 clock.

Solution:

TIM1->ARR = 999;

19. Like the PSC, the ARR (auto reload register) is also of length 16 bits and used for factoring the clock.

20. What do the following instructions do?

```

if(TIM1->SR & 0x0001)//check if ARR count complete
{
    TIM1->SR &= ~0x0001;//clear status register SR
    GPIOA->ODR ^= (1 << 1); //blink LED through PA1
}

```

Solution: Once the TIM1 counter counts from 0 to $TIM1 \rightarrow ARR = 999$, it resets and starts counting again to 999. At the time of reset, the LSB of $TIM1 \rightarrow SR = 1$. The **if** command checks this and when this condition is satisfied, $TIM1 \rightarrow SR$ is cleared and PA1 is toggled. This process keeps repeating. This results in a PA1 output of 1 and 0 with frequency

$$\frac{HSI_CLK}{(TIM1 \rightarrow PSC + 1)(TIM1 \rightarrow ARR + 1)} = \frac{8000000}{4000 \times 1000} = 2 \text{ Hz} \quad (11.4)$$

21. How would you use the repetition counter (RCR) to do the above?

Solution: The following instructions

```

TIM1->SMCR = 0; //Internal clock, 8MHz
TIM1->PSC = 999; //Prescalar, dividing clock by 1000
TIM1->CR1 = 0x0001; //enable Timer1
TIM1->ARR = 999; //Load Count
TIM1->RCR = 3; //Load Repetition Count

```

lead to

$$\frac{HSI_CLK}{(TIM1 \rightarrow PSC + 1)(TIM1 \rightarrow ARR + 1)(TIM1 \rightarrow RCR + 1)} = \frac{8000000}{4000 \times 1000} = 2 \text{ Hz} \quad (11.5)$$

$TIM1 \rightarrow RCR$ keeps track of the number of times the counter has overflowed. Fig. 11.9 shows the repetition counter register.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Reserved								REP[7:0]							
								rw	rw	rw	rw	rw	rw	rw	rw

Fig. 11.9: Repition Counter (RCR)

22. What is the maximum value of $TIM1 \rightarrow RCR$?
 23. What is the function of $TIM1 \rightarrow SR$?

Solution: The status register (SR) is shown in Fig. 11.10. The UIF flag is 1 if the RCR overflows.

11.12 TIMER-2

24. Blink an LED with TIM2.

Solution:

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
				CC4OF	CC3OF	CC2OF	CC1OF	Res.	BIF	TIF	COMIF	CC4IF	CC3IF	CC2IF	CC1IF	UIF
Reserved				rc_w0	rc_w0	rc_w0	rc_w0	Res.	rc_w0							

Fig. 11.10: Status Register (SR)

timers/codes/timer2_blink.c

25. In the above code,

RCC->APB1ENR |= RCC_APB1ENR_TIM2EN;

is used for enabling TIM2. Note that for TIM1, APB2 was used instead of APB1 in Problem 12. Explain.

Solution: Advanced Peripheral Bus 1 (APB1) and Advanced Peripheral Bus 2 (APB2) are connected to the Direct Memory Access (DMA) module, SRAM, peripherals like GPIOs, ADC, timers, etc. and Cortex core. APB1 has a maximum operating frequency of 36MHz while the maximum operating frequency of APB2 is 72MHz. That is why GPIOs are connected to APB2 bus instead of APB1 or any other bus and STM32 GPIOs can achieve 50MHz switching speed. APB1 bus mostly serves communication and timer modules of the STM32.

26. Mention any major difference between TIM1 and TIM2.

Solution: TIM1 is an advanced timer while TIM2 is a general purpose timer. One major difference between the two is that TIM2 does not have RCR.

11.13 Master-Slave Configuration

27. Execute the following program.

timers/codes/master1_slave2_blink.c

28. List the instructions for setting up TIM1 as master and TIM2 as slave. TIM1 should be a prescalar for TIM2.

Solution: The MMS bits can be seen in the CR2 register is shown in Fig. 11.11. The TS and SMS bits are visible in the SMCR register in Fig. 11.6.

TIM1->CR2 = 0x0020;//MMS = 010

TIM2->SMCR = 0x0007;//TS = 000, SMS = 111

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
				Reserved				TI1S	MMS[2:0]	CCDS			Reserved		

Fig. 11.11: Control Register 2 (CR2)

29. Execute the following program.

```
timers/codes/decade_counter.c
```

30. If $\text{TIM2_ARR} = 9$, $\text{TIM2_CNT} = ?$

Solution: $\text{TIM2_CNT} = 0, 1, \dots, 9, 0, \dots, 9, \dots$ The counting rate depends on the PCR, ARR, RCR registers of TIM1 and the PCR and ARR registers of TIM2.

11.14 LCD

We show how to interface the 16×2 HD44780-controlled LCD using STM32F103C8T6.

1. Make connections as shown in Table 11.15.

STM32	LCD Pins	LCD Pin Label	LCD Pin Description
GND	1	GND	
3.3V	2	Vcc	
GND	3	Vee	Contrast
A0	4	RS	Register Select
GND	5	R/W	Read/Write
A1	6	EN	Enable
A2	11	DB4	Serial Connection
A3	12	DB5	Serial Connection
A4	13	DB6	Serial Connection
A5	14	DB7	Serial Connection
3.3V	15	LED+	Backlight
GND	16	LED-	Backlight

TABLE 11.15: Pin Connections

2. Execute the following program

```
lcd/codes/lcd_example.c
```

The following problems explain how to display the string **0** on the screen using the above code.

3. Write the ASCII code for the 0 character.

Solution: The code for 0 is **48 =0b00110000 = 0x30**.

4. How is 0 written by the STM32 to the LCD controller.

Solution: For the number 0, the upper nibble 0011 is first written followed by the lower nibble 0000. This is done by

```
void SendByte (byte data)
{
    SendNibble(data >> 4); // send upper 4 bits 0011
    SendNibble(data); // send lower 4 bits 0000
}
```

5. How is the nibble 0011 written to the LCD.

Solution: This is done by the following function where data = 0011.

```
void SendNibble(byte data)
{
    GPIOA->BRR = ~(data << 2) & 0b00111100;
    GPIOA->BSRR = (data << 2) & 0b00111100;

    PulseEnableLine(); // clock 4 bits into controller
}
```

The expression

$$GPIOA -> BSRR = (data << 2) \& 0b00111100 = 0b00001100. \quad (11.6)$$

This ensures that 11 is written to the pins A2-A3. Note that << indicates 2 left shifts.
Similarly,

$$GPIOA -> BRR = (data << 2) \& 0b00111100 \quad (11.7)$$

6. ensures that 00 is written to the pins A4-A5. PulseEnableLine() provides a clock pulse used to write the nibble 0011 to the LCD.
7. Which pins of the STM32 are used for what purpose?
- Solution:** The A2-A5 pins of the STM32 are used for pushing the upper/lower data nibble to the DB4-DB7 pins of the LCD using the BRR and BSRR registers. The A0-A1 pins are used for Register Select and EN for the LCD.
8. What is Register Select?
- Solution:** Register Select = 0 implies that LCD configuration commands are being written. For example, cursor on/off, clearing display, number of lines, etc... Register Select = 1 implies that characters are being written to the LCD.
9. Develop an arithmetic calculator using the STM32 along with the LCD.

11.15 ADC

We show how to use the Internal Temperature Sensor to measure the CPU temperature through the ADC.

1. Make connections as shown in Table 11.15.
2. Execute the following program

```
stm32adc/codes/internal_temp.c
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	122
Reserved								SMP17[2:0]		SMP16[2:0]		SMP15[2:1]				
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
SMP15_0	SMP14[2:0]			SMP13[2:0]			SMP12[2:0]			SMP11[2:0]			SMP10[2:0]			
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	

Fig. 11.12: SMPR1

3. What do you observe?

Solution: You should observe a number between 1750-1760. This is the output of the internal temperature sensor, captured in $ADC1- > DR$.

4. Find an expression for V_{SENSE}

Solution:

$$V_{SENSE} = 3.3 \times \frac{ADC1- > DR}{4095} \quad (11.8)$$

5. Obtain the formula for finding the temperature of the STM32 and list the values of the various parameters.

Solution: The desired formula is

$$T = (V_{25} - V_{SENSE})/\text{AvgSlope} + 25 \quad (11.9)$$

where the typical values of the above parameters are

V_{25}	AvgSlope
1.43	4.3

6. What is the default ADC frequency?

Solution: The ADC operates at 14 MHz by default and is independent of the processor frequency (8 MHz in this case). It can, however be synchronized with the processor clock for some real time applications.

7. Explain the significance of the following instruction

$ADC1->SMPR1 |= ADC_SMPR1_SMP16;$

Solution: Through this command, $ADC1- > SMPR1 = 0x001C0000$ where the SMPR1 register is shown in Fig. 11.12. Note that this makes $SMP16 = 111$ which means that channel 16 sample time = 239.5 cycles. Channel 16 is reserved for the internal temperature sensor and is connected to ADC1.

8. What is the sampling time?

Solution: Since the sample time is 239.5 cycles and the ADC frequency is 14 MHz,

$$T_s = 239.5 \times \frac{1}{14} \mu s = 17.1 \mu s \quad (11.10)$$

9. Explain the following instruction.

$ADC1->SQR3 |= ADC_SQR3_SQ1_4;$

Solution: $ADC_SQR3_SQ1_4 = 0x00000010$. This implies that SQ1=0b10000 in the ADC regular sequence register 3 ($ADC1- > SQR3$) shown in Fig. 11.13. Since

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reserved	SQ6[4:0]					SQ5[4:0]					SQ4[4:1]				
	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
SQ4_0	SQ3[4:0]					SQ2[4:0]					SQ1[4:0]				
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw

Fig. 11.13: SQR3

SQ1=16, this means that the ADC input in channel 16 will be the first in the queue for conversion. The ADC is capable of converting analog 16 inputs one after the other. The inputs are called *channels* and the sequence number corresponding to the channel is decided according to the 5 bit entry in SQ.

11.16 Measuring an Unknown Resistance

- Configure SQR3 so that the 9th channel for ADC1 is 2nd in sequence.

Solution: This implies that SQ2=1001. Thus,

$$ADC1 \rightarrow SQR3 = 0x000000120 \quad (11.11)$$

- List the various pin numbers corresponding to the different channels of the ADC.

Solution: See Fig. 11.16

TABLE 11.16: ADC Analog Input Pins

Channel	0	1	2	3	4	5	6	7	8	9
Pin	PA0	PA1	PA2	PA3	PA4	PA5	PA6	PA7	PB0	PB1

- Use the 9th channel of ADC1 in SQ2 to measure 3.3V.

Solution: Connect PB1 (Fig. 11.16) to 3.3 V of the STM 32 and execute the following code.

```
stm32adc/codes/3_3V.c
```

- Measure an unknown resistance using the STM32 and display the result on the LCD.
- Display the output of the internal temperature sensor as well the unknown resistance on the LCD.