
DIGITAL DESIGN

Through Embedded Programming

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Introduction

This book introduces digital design through using the arduino framework.

Chapter 1

Installation

1.1. Termux

1. On your android device, install fdroid apk from

```
https://www.f-droid.org/
```

2. Install Termux from apkpure

3. Install basic packages on termux

```
#Give termux access to your user directory in android  
termux-setup-storage  
  
#Upgrade packages  
apt update && apt upgrade  
apt install build-essential openssh  
  
#Mandatory packages  
apt install curl git wget subversion proot proot-distro python nmap neovim ranger  
#-----End Install Termux
```

4. Install Ubuntu on termux

```
proot-distro install ubuntu  
proot-distro login ubuntu
```

1.2. Platformio

1. Install Packages

```
apt update && apt upgrade  
apt install apt-utils build-essential cmake neovim  
apt install git wget subversion imagemagick nano  
apt install avra avrdude gcc-avr avr-libc  
#-----End Installing ubuntu on termux  
  
#----- Installing python3 on termuxubuntu  
  
apt install python3-pip python3-numpy python3-scipy python3-matplotlib  
    python3-mpmath python3-sympy python3-cvxopt  
#----- End installing python3 on termuxubuntu  
  
#----- Installing platformio on termuxubuntu
```

```
-----  
pip3 install platformio  
#----- End installing python3 on termuxubuntu  
-----
```

2. Execute the following on ubuntu

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

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

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

4. 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/firmwarehex
```

for uploading hex file to the Arduino Uno

5. The LED beside pin 13 will start blinking

Chapter 2

Seven Segment Display

We show how to control a seven segment display.

2.1. Components

Component	Value	Quantity
Breadboard		1
Resistor	$\geq 220\Omega$	1
Arduino	Uno	1
Seven Segment Display	Common Anode	1
Jumper Wires		20

Table 2.1:

2.1.1. Breadboard

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.

2.1.2. 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.

2.1.3. 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.

Arduino	Breadboard
5V	Top Green
GND	Bottom Green

Table 2.2: Supply for Bread board

2. Make the connections in Table 2.3.
3. Connect the Arduino to the computer. The DOT led should glow.



Figure 2.1: Bread board connnections

Breadboard		Display
5V	Resistor	COM
GND		DOT

Table 2.3: Connecting Seven segment display on Bread board

2.2.2. Controlling the Display

Fig. 2.3 explains how to get decimal digits using the seven segment display. GND=0.

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:



Figure 2.2: Seven Segment pins

2.3. Display Control through Software

1. Make connections according to Table 2.5



Figure 2.3: Seven Segment connections

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

Table 2.5:

2. Download the following code using the arduino IDE and execute

```
ide/sevenseg/codes/sevenseg/sevenseg.ino
```

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

Chapter 3

7447

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

3.1. Components

Component	Value	Quantity
Resistor	220 Ohm	1
Arduino	UNO	1
Seven Segment Display		1
Decoder	7447	1
Jumper Wires	M-M	20
Breadboard		1

Table 3.1:

3.2. 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 3.2

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

Table 3.2:

2. Make connections to the lower pins of the 7447 according to Table 3.3 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 3.3:

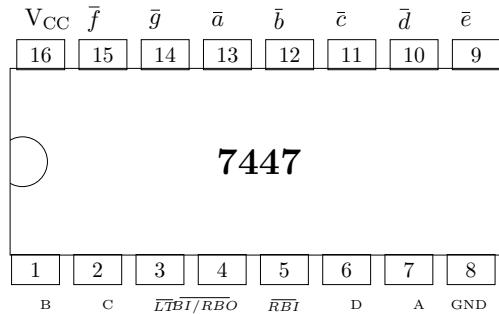


Figure 3.1:

3. Complete Table 3.3 by generating all numbers between 0-9.

3.3. Software

1. Now make the connections as per Table 3.4 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 3.4:

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 3.5: Truth table for incrementing Decoder.

In the truth table in Table 3.5, 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 3.5. Write the logic for A and verify.

ide/7447/codes/inc_dec/inc_dec.ino

3. Now make additional connections as shown in Table 3.6 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 3.6:

4. Verify the above code for all inputs from 0-9.
5. Now write a program where
 - (a) the binary inputs are given by connecting to 0 and 1 on the breadboard
 - (b) incremented by 1 using Table 3.5and
 - (c) 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.

3.4. Problems

1. Obtain the Boolean Expression for the Logic circuit shown below (CBSE 2013)



2. Verify the Boolean Expression

(CBSE 2013)

$$A + C = A + A'C + BC \quad (3.2)$$

3. Draw the Logic Circuit for the following Boolean Expression

(CBSE 2015)

$$f(x, y, z, w) = (x' + y)z + w' \quad (3.3)$$

4. Verify the following

(CBSE 2015)

$$U' + V = U'V' + U'V + UV \quad (3.4)$$

5. Draw the Logic Circuit for the given Boolean Expression

(CBSE 2015)

$$(U + V')W' + Z \quad (3.5)$$

6. Verify the following using Boolean Laws

(CBSE 2015)

$$X + Y' = XY + XY' + X'Y' \quad (3.6)$$

7. Write the Boolean Expression for the result of the Logic Circuit as shown in Fig. 3.2

(CBSE 2016)



Figure 3.2:

8. Draw the logic circuit of the following Boolean Expression using only NAND Gates.

(CBSE 2017)

$$XY + YZ \quad (3.7)$$

9. Draw the Logic Circuit of the following Boolean Expression using only NOR Gates

(CBSE 2017)

$$(A + B)(C + D) \quad (3.8)$$

10. Draw the Logic Circuit of the following Boolean Expression

(CBSE 2018)

$$(U' + V)(V' + W') \quad (3.9)$$

11. Derive a Canonical POS expression for a Boolean function F, represented by Table 3.7 (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 3.7:

12. For the logic circuit shown in Fig.3.3, find the simplified Boolean expression for the output. (GATE EC 2000)



Figure 3.3:

13. Obtain the Boolean Expression for the Logic circuit shown below (GATE EC 1993)



14. Implement Table 3.8 using XNOR logic. (GATE EC 1993)

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

Table 3.8:

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. 3.4 (GATE EC 2007)

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. 3.5 (GATE EC 2010)

19. Find the logic function implemented by the circuit given below in Fig. 3.6 (GATE EC 2011)



Figure 3.4:

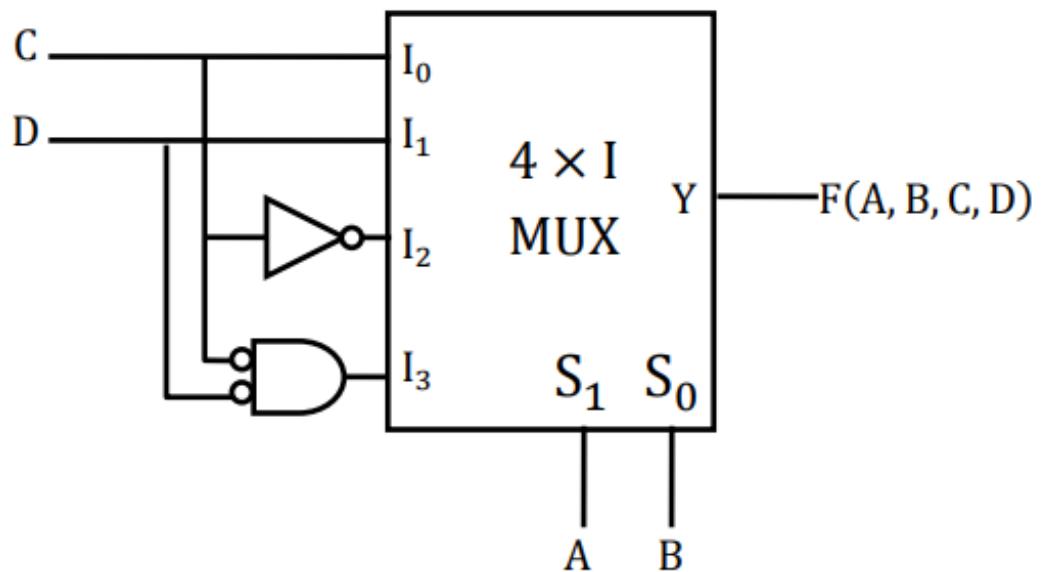


Figure 3.5:

20. Find F in the Digital Circuit given in the figure below in Fig. 3.7. (GATE IN 2016)

21. Find the logic function implemented by the circuit given below in Fig. 3.8 (GATE



Figure 3.6:

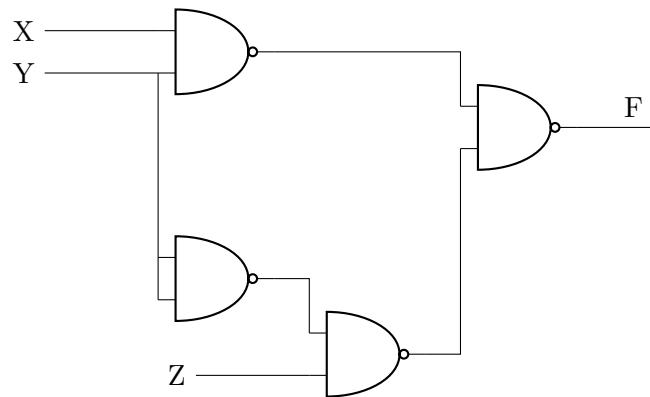


Figure 3.7:

EC 2017)

22. Find the logic function implemented by the circuit given below in Fig. 3.9 (GATE EC 2018)
23. Find the logic function implemented by the circuit given below in Fig. 3.10 (GATE EE 2018)



Figure 3.8:

24. Find the logic function implemented by the circuit given below in Fig. 3.11 (GATE EE 2019)



Figure 3.9:



Figure 3.10:



Figure 3.11:

Chapter 4

Karnaugh Map

4.1. Introduction

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

4.2. Incrementing Decoder

The incrementing decoder takes the numbers $0, 1, \dots, 9$ in binary as inputs and generates the consecutive number as output. The corresponding truth table is available in Table 3.5.

4.3. Karnaugh Map

Using Boolean logic, output A in Table 3.5 can be expressed in terms of the inputs W, X, Y, Z as

$$\begin{aligned} A = & W'X'Y'Z' + W'XY'Z' + W'X'YZ' \\ & + W'XYZ' + W'X'Y'Z \end{aligned} \quad (4.1)$$

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

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 4.2, (4.1) can be expressed as

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

Using the fact that

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

derive (4.2) from (4.1) algebraically

2. K-Map for B : From Table 3.5, 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

3. Derive (4.5) from (4.4) algebraically using (4.3)

4. K-Map for C : From Table 3.5, using boolean logic,

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

Show that (4.6) can be reduced to



Figure 4.1: K-map for A

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

using Fig 4.3

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



Figure 4.2: K-map for B

6. K-Map for D : From Table 3.5, using boolean logic,

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

7. Minimize (4.8) using Fig 4.4

ZY	XW_{00}	01	11	10
00	0	0	1	0
01	1	1	0	1
11	0	0	0	0
10	0	0	0	0

Figure 4.3: K-map for C

8. 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

9. 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



Figure 4.4: K-map for D

with and without don't care conditions

4.4. Dont Care

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

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.

4.5. 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 0-5 This phenomenon can be addressed by revising the truth table in Table 4.1 to obtain Table 4.2
2. The revised K-map for A is available in Fig 4.5. Show that

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

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

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

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:

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

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

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

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

6. Verify the incrementing decoder with don't care conditions using the arduino



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

7. Display Decoder: 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
8. Verify the display decoder with don't care conditions using arduino



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

4.6. Problems

1. Obtain the Minimal Form for the Boolean Expression (CBSE 2013)

$$H(P, Q, R, S) = \sum(0, 1, 2, 3, 5, 7, 8, 9, 10, 14, 15) \quad (4.13)$$

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



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

3. Reduce the following Boolean Expression to its simplest form using K-Map (CBSE 2015)

$$F(X, Y, Z, W) = (0, 1, 4, 5, 6, 7, 8, 9, 11, 15) \quad (4.14)$$

4. Derive a Canonical POS expression for a Boolean function F , represented by the



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

following truth table

(CBSE 2015)

5. (CBSE 2015) Reduce the following Boolean Expression to its simplest form using K-map

$$F(X, Y, Z, W) = \sum(0, 1, 6, 8, 9, 10, 11, 12, 15) \quad (4.15)$$

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:

X	Y	Z	F
0	0	0	1
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1

Table 4.4:

6. Reduce the following Boolean Expression to its simplest form using K-map. (CBSE 2016)

$$F(X, Y, Z, W) = \sum(2, 6, 7, 8, 9, 10, 11, 13, 14, 15) \quad (4.16)$$

7. Derive a Canonical POS expression for a Boolean function F, represented in Table 4.5 (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 4.5:

8. Verify the following (CBSE 2016)

$$A' + B'C = A'B'C' + A'BC' + A'BC + A'B'C + AB'C \quad (4.17)$$

9. Reduce the following boolean expression to it's simplest form using K-Map (CBSE 2017)

$$F(X, Y, Z, W) = \sum(0, 1, 2, 3, 4, 5, 10, 11, 14) \quad (4.18)$$

10. Reduce the following Boolean Expression to its simplest form using K-Map. (CBSE 2017)

$$E(U, V, Z, W) = (2, 3, 6, 8, 9, 10, 11, 12, 13) \quad (4.19)$$

11. Derive a canonical POS expression for a Boolean function G , represented by Table 4.6 (CBSE 2017)

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

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 4.6:

4.7.

(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 4.7:

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

$$F(P, Q, R, S) = \sum(0, 1, 2, 3, 5, 6, 7, 10, 14, 15) \quad (4.20)$$

(CBSE 2019)

14. 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(P,Q,R) is the output. Find the boolean

expression for output F as function of inputs P,Q,R using K-map. (GATE EC 2020)



Figure 4.9:

15. The four variable function f is given in terms of min-terms as

$$f(A, B, C, D) = \sum m(2, 3, 8, 10, 11, 12, 14, 15) \quad (4.21)$$

Using the K-map minimize the function in the sum of products form. (GATE EC 1991)

16. Find the logic realized by the circuit in Fig. 4.10.

(GATE EC 1992)

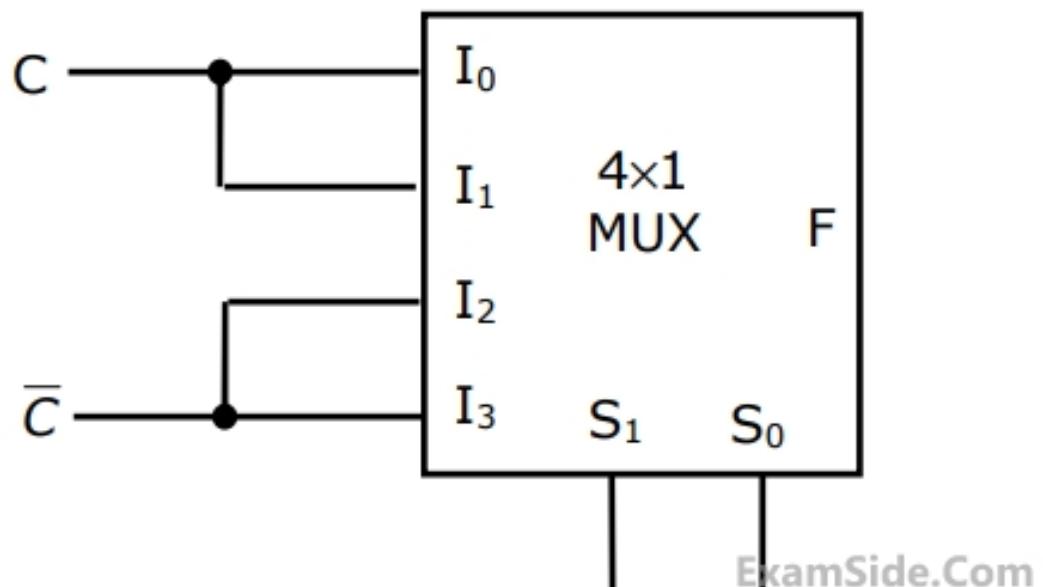


Figure 4.10:

17. 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
- (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.

18. Draw the logic circuit for Table 4.8 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 4.8:

19. Implement the following Boolean function in a 8x1 multiplexer. (GATE EC 1993)

$$Q = BC + ABD' + A'C'D \quad (4.22)$$

20. Minimize the following Boolean function in 4.23.

$$F = A'B'C' + A'BC' + A'BC + ABC' \quad (4.23)$$

21. Find the Boolean expression for Table 4.9. (GATE EC 2005)

22. Minimize the logic function represented by the following Karnaugh map. (CBSE)

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 4.9:

		YZ				
		00	01	11	10	
X		0	1	1	1	0
		1	0	0	1	0

2021)

23. Find the output for the Karnaugh map shown below

PQ

		PQ				
		00	01	11	10	
RS		00	0	1	1	0
		01	1	1	1	1
		11	1	1	1	1
		10	0	0	0	0

24. The propagation delays of the XOR gate, AND gate and multiplexer (MUX) in the

circuit shown in the Fig. 4.11 are 4 ns, 2 ns and 1 ns, respectively. If all the inputs P, Q, R, S and T are applied simultaneously and held constant, the maximum propagation delay of the circuit is
(Gate EC-2021)

- (a) 3 ns
- (b) 5 ns
- (c) 6 ns
- (d) 7 ns

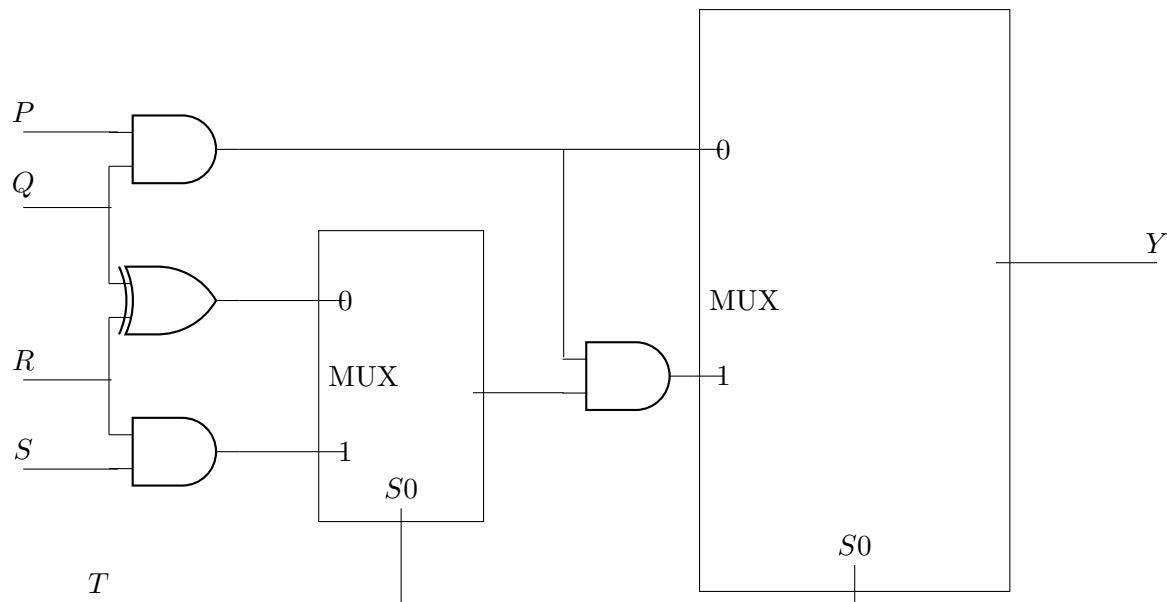


Figure 4.11:

25. Consider the 2-bit multiplexer(MUX) shown in the figure. 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) $W = 1, X = 0, Y = 1, Z = 0$

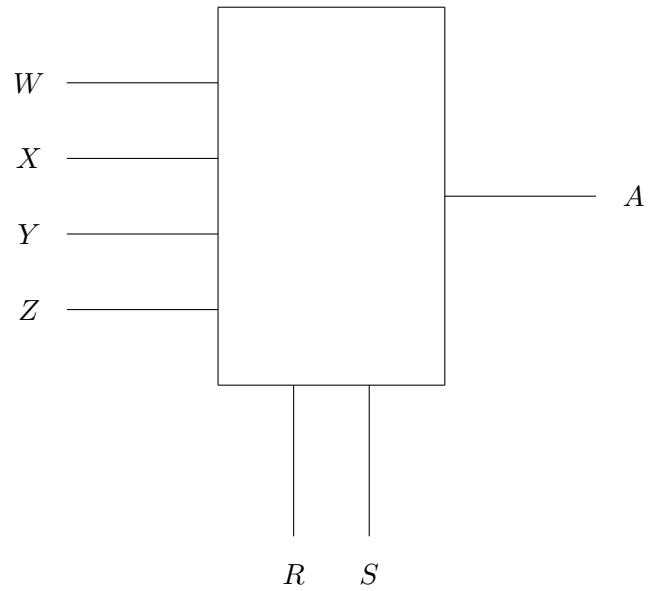


Figure 4.12:

(c) $W = 0, X = 1, Y = 1, Z = 0$

(d) $W = 1, X = 1, Y = 0, Z = 0$

Chapter 5

7474

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
Breadboard		1
Resistor	$\geq 220\Omega$	1
Arduino	Uno	1
Seven Segment Display	Common Anode	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.

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

Table 5.2:

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

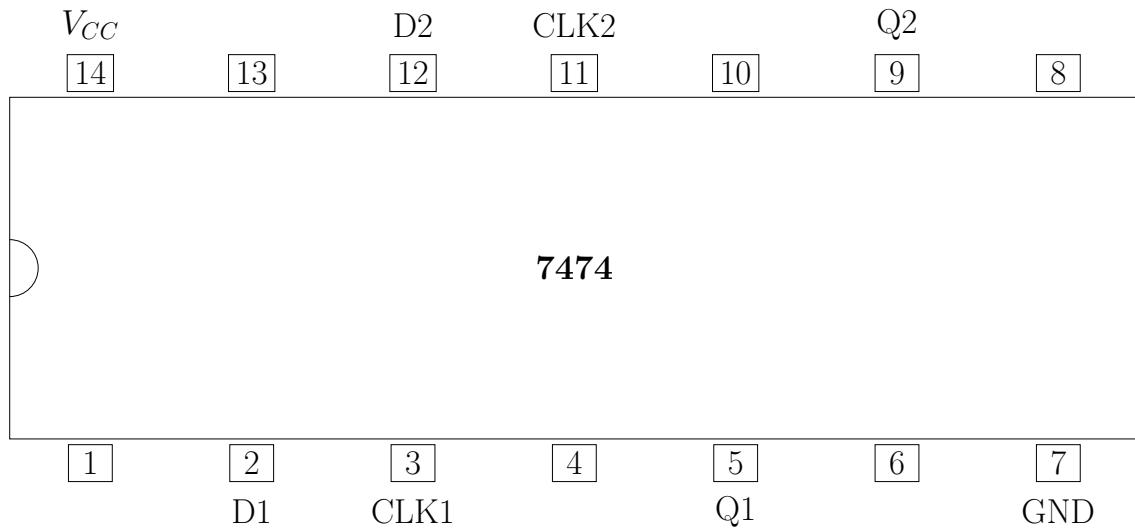


Figure 5.1:

3. Realize the decade counter in Fig. 5.2.

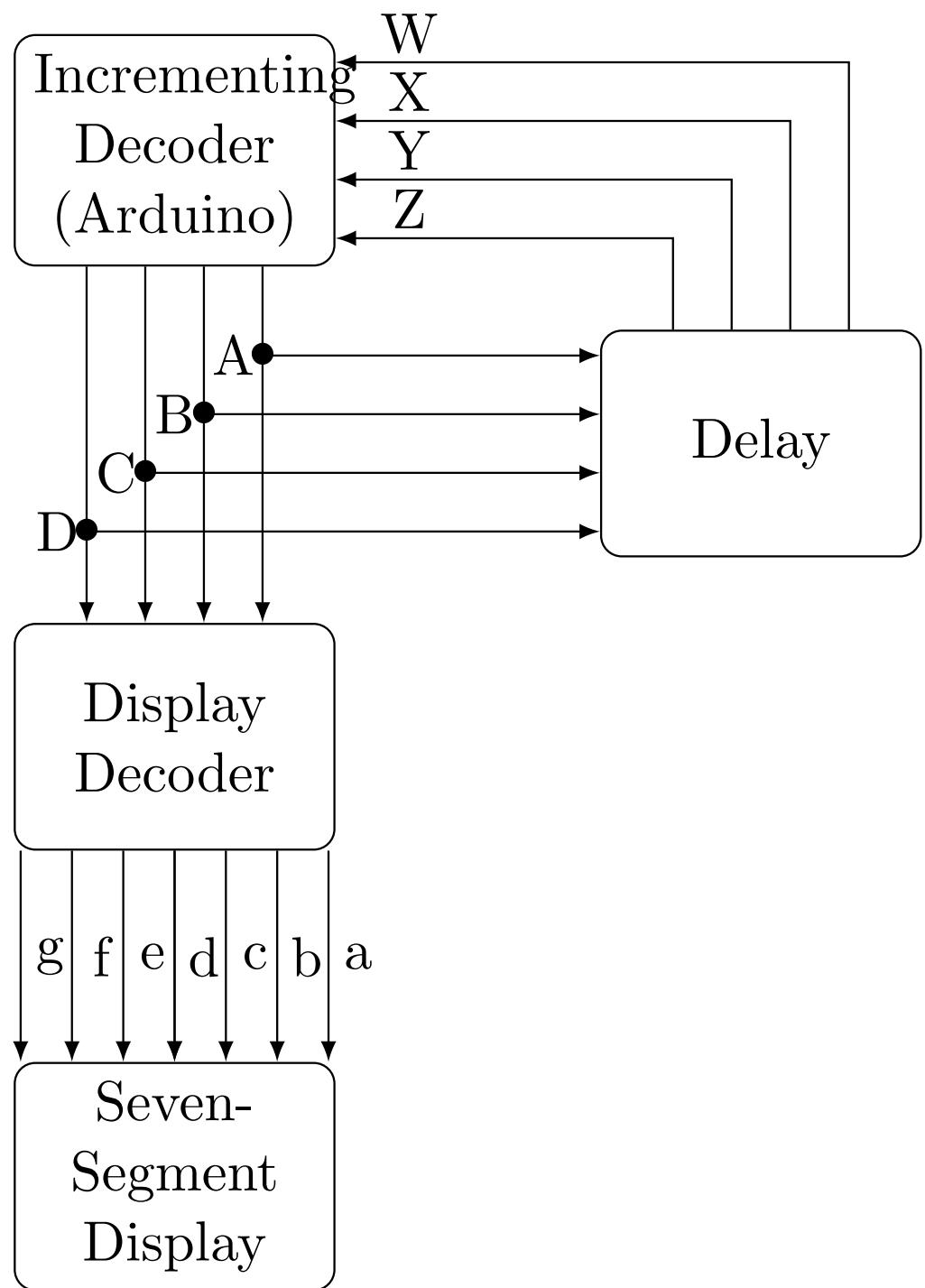


Figure 5.2:

Chapter 6

Finite State Machine

We explain a state machine by deconstructing the decade counter

6.1. 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

6.2. Finite State Machine

1. 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 3.5, where the present state is denoted by the variables W, X, Y, Z and the next state by A, B, C, D .
2. 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



Figure 6.1: FSM for the decade counter

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

6.3. Problems

1. The digital circuit shown in Fig. 6.3 generates a modified clockpulse at the output.
Sketch the output waveform. (GATE EE 2004)



Figure 6.2: Decade counter FSM implementation using D-Flip Flops

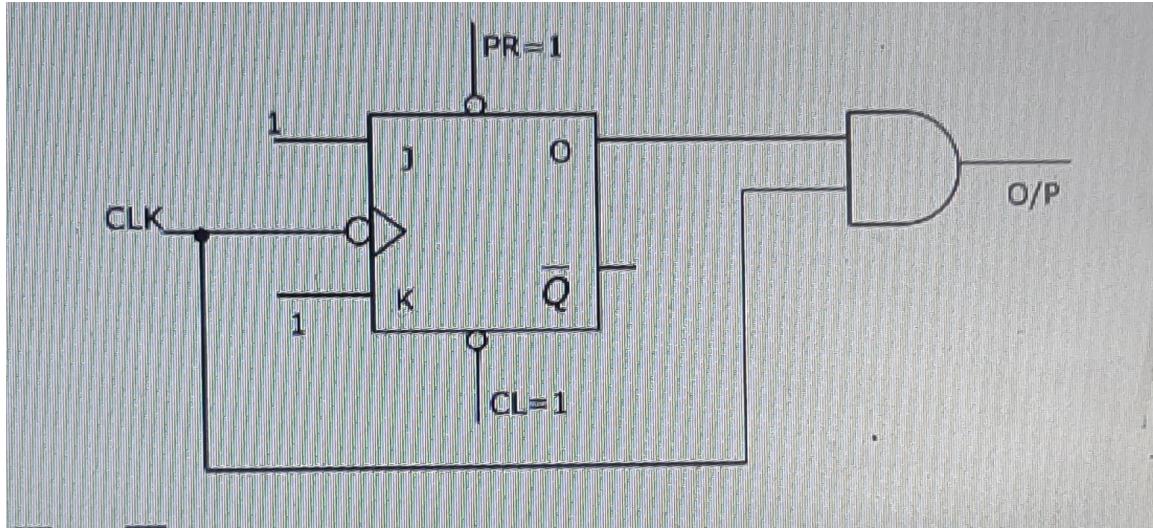


Figure 6.3:

2. The circuit shown in the figure 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)



Figure 6.4:

3. The state diagram of a sequence detector is shown in Fig. 6.5 . State S_0 is the initial state of the sequence detector. If the output is 1, then (GATE EC 2020)

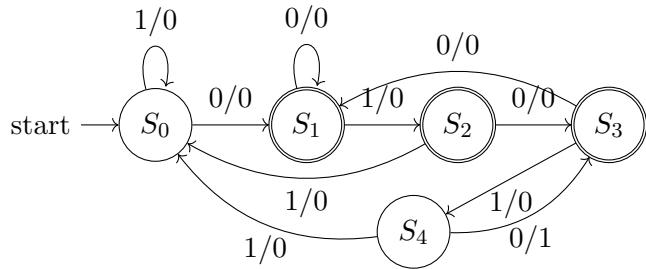


Figure 6.5: State diagram

- (a) the sequence 01010 is detected
 - (b) the sequence 01011 is detected
 - (c) the sequence 01110 is detected
 - (d) the sequence 01001 is detected
4. 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)

5. For the circuit shown in Fig. 6.6, the clock frequency is f_0 and the duty cycle is 25%. For the signal at the Q output of the Flip-Flop,

- (a) frequency of $\frac{f_0}{4}$ and duty cycle is 50%
- (b) frequency of $\frac{f_0}{4}$ and duty cycle is 25%
- (c) frequency of $\frac{f_0}{2}$ and duty cycle is 50%

(d) frequency of f_0 and duty cycle is 25%

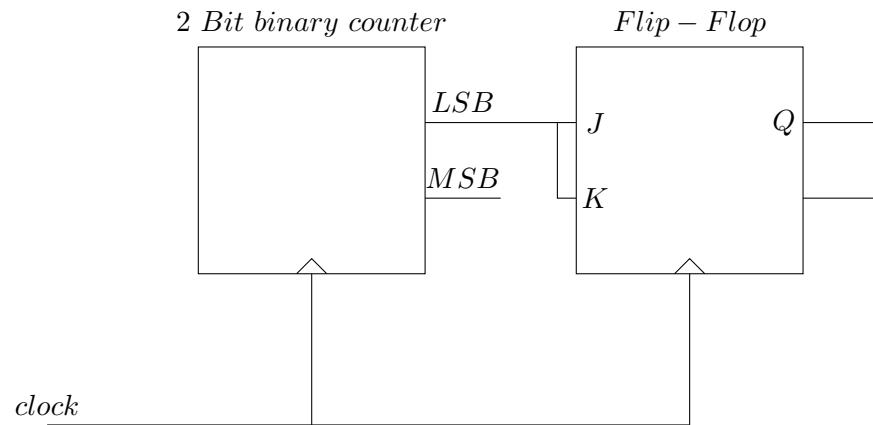


Figure 6.6:

(GATE EC-2022)

Chapter 7

Assembly Programming

This manual shows how to setup the assembly programming environment for the arduino.

7.1. Software Installation

1. Find the USB port to which arduino is connected.

```
%Finding the port  
  
sudo dmesg | grep tty  
  
%The output will be something like  
[ 6.153362] cdc_acm 1-1.2:1.0: ttyACM0: USB ACM device  
  
%and your port number is ttyACM0
```

2. Copy the .inc file to your home directory

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

3. Execute

```
avr assemly/setup/codes/hello.asm
```

as

4. Then flash the .hex file

```
hello.hex
```

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

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

```
ldi r17,0b00000000
```

Save and execute. The led should turn off.

7. 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).

8. What do the following instructions do?

```
ldi r17,0b00100000
```

```
out PortB,r17
```

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

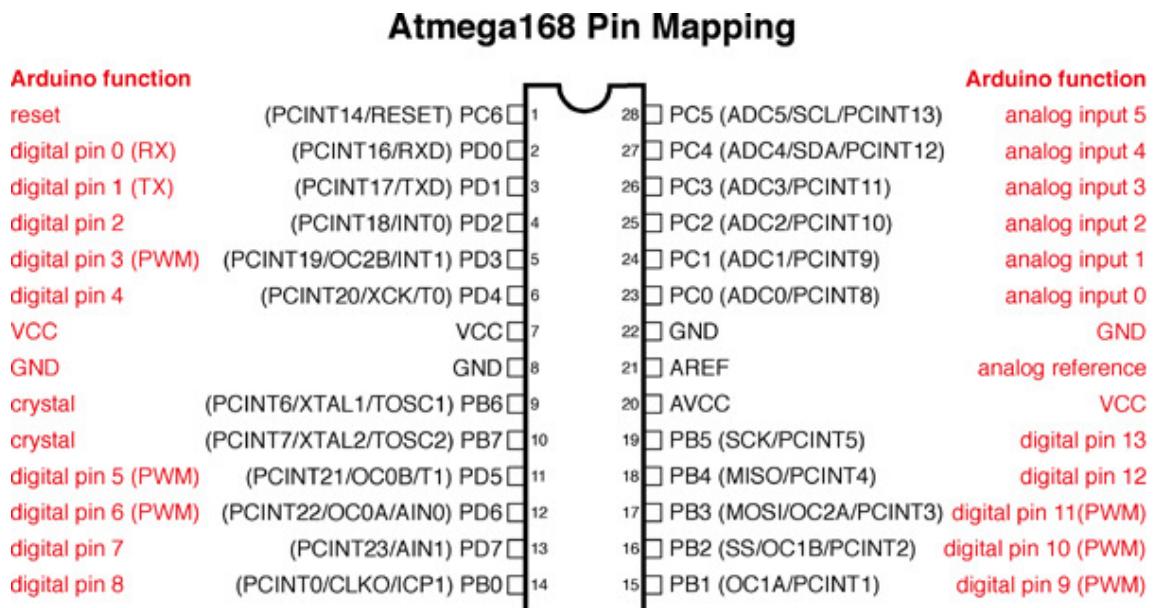
The objective of this manual is to show how to control a seven segment display through the AVR-Assembly.

7.2. Seven Segment Display

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

Port Pin	Digital Pin
PD2	2
PB5	13

Table 2:



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.

Figure 2:

3. Make connections according to Table 3.

Arduino	2	3	4	5	6	7	8
	PD2	PD3	PD4	PD5	PD6	PD7	PB0
Display	a	b	c	d	e	f	g
2	0	0	1	0	0	1	0

Table 3:

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

```
;using assembly language for
;displaying number on
;seven segment display

.include "/home/gadepall/m328Pdef.inc"

;Configuring pins 2–7 (PD2–PD7) of Arduino
;as output
ldi r16,0b11111100
out DDRD,r16

;Configuring pin 8 (PB0) of Arduino
;as output
ldi r16,0b00000001
out DDRB,r16

;Writing the number 2 on the
;seven segment display
ldi r17,0b10010000
out PortD,r17
```

```

ldi r17,0b00000000
out PortB,r17
Start:
rjmp Start

```

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

7.3. 7447

This manual shows how to program the 7447 BCD-Seven segment display decoder through AVR-Assembly.

7.3.1. Components

Component	Value	Quantity
Resistor	220 Ohm	1
Arduino	UNO	1
Seven Segment Display		1
Decoder	7447	1
Jumper Wires	M-M	20
Breadboard		1

7.3.2. Boolean Operations

- 7.3.2.1. Verify the AND,OR and XOR operations in assembly using the following code and making pin connections according to Table 7.3.2.1.1.

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

7447	D	C	B	A
Arduino	5	4	3	2

Table 7.3.2.1.1: Arduino and 7447 IC connections

- 7.3.2.2. 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.

- 7.3.2.3. 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.

- 7.3.2.4. 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
```

7.3.2.5. 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.

$$A = W' \quad (7.3.2.5.1)$$

$$B = WX'Z' + W'X \quad (7.3.2.5.2)$$

$$C = WXY' + X'Y + W'Y \quad (7.3.2.5.3)$$

$$D = WXY + W'Z \quad (7.3.2.5.4)$$

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

This manual shows how to program the 7447 BCD-Seven segment display decoder through AVR-Assembly.

7.3.3. Controlling the Display

1. Connect the 7447 IC to the seven segment display.
2. Make connections between the 7447 and the arduino according to Table 7.3.2.1.1
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 5. 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 5:

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.

7.4. Timer

T:his manual shows how to use the Atmega328p timer to blink the builtn led with a delay.

7.4.1. Components

Component	Value	Quantity
Arduino	UNO	1

7.4.2. Blink through TIMER

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

$$TCCR0B = 0b101 \quad (3.1)$$

$$\Rightarrow CLK = \frac{SYSCLK}{1024} \quad (3.2)$$

$$= \frac{16M}{1K} = 16kHz. \quad (3.3)$$

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=0bxxxxxx10 after every 256 cycles. PAUSE routine waits till TIFR0=0bxxxxxx10, 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

$$delay = \frac{CLK}{lp2 \times PAUSE} \text{seconds} \quad (6.1)$$

$$= \frac{16 \times 1024}{64 \times 256} \text{seconds} = 1 \text{second} \quad (6.2)$$

7.4.3. 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

$$delay \approx 80 \times 256 \times 256 \text{cycles} \quad (2.1)$$

$$= \frac{80 \times 256 \times 256}{2^4 \times 2^{20}} \text{seconds} \quad (2.2)$$

$$= 0.3125 \text{seconds} \quad (2.3)$$

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.

7.5. 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.

Chapter 8

Embedded C

8.1. Blink

This manual shows how to control an led using AVR-GCC. AVR-GCC is a C compiler for the Atmega328p.

8.1.1. Components

Component	Value	Quantity
Arduino	UNO	1

8.1.2. Blink

1. Execute the following

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

```
make
```

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

```
PORTB = ((0 << PB5));
```

```
_delay_ms(500);  
//turn led on  
PORTB = ((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.

This manual shows how to control a seven segment display using AVR-GCC with arduino

8.2. Display Control

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.

This manual shows how to control a seven segment display using AVR-GCC with arduino

8.3. Input

1. Connect the arduino to the seven segment display through 7447.

2. Execute the following code

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

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

8.4. GCC-Assembly

This manual shows 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.

8.4.1. Components

Component	Value	Quantity
Breadboard		1
Resistor	$\geq 220\Omega$	1
Arduino	Uno	1
Seven Segment Display	Common Anode	1
Jumper Wires		10

Table 3:

8.4.2. GCC with Assembly

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 4. 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 4: 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.

8.5. LCD

This manual shows 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.

Component	Value	Quantity
Breadboard		1
Arduino	Uno	1
LCD	16×2	1
Jumper Wires		20

Table 6:

8.5.1. Components

8.5.2. Display Number on LCD

8.5.2.1. Plug the LCD in Fig. 8.5.2.2.1 to the breadboard.

8.5.2.2. Connect the Arduino pins to LCD pins as per Table 8.5.2.2.1.



Figure 8.5.2.2.1: LCD

8.5.2.3. Execute

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

Table 8.5.2.2.1: 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
D8	4	RS	Register Select
GND	5	R/W	Read/Write
D9	6	EN	Enable
D10	11	DB4	Serial Connection
D11	12	DB5	Serial Connection
D12	13	DB6	Serial Connection
D13	14	DB7	Serial Connection
5V	15	LED+	Backlight
GND	16	LED-	Backlight

8.5.2.4. Modify the above code to display a string.

8.5.2.5. Modify the above code to obtain a decade counter so that the numbers from 0 to 9 are displayed on the lcd repeatedly.

8.5.2.6. Repeat the above exercises to display a string on the first line and a number on the second line of the lcd.

8.5.2.7. Write assembly routines for driving the lcd.

Chapter 9

Vaman-ESP32

9.1. Software

All codes used in this document are available in the following directory

```
vaman/esp32/codes
```

9.2. Flash Vaman-ESP32 using Arduino

9.2.1. Do not power any devices. Make connections as shown in Table 9.2.1.1 and Fig. 9.2.1.1.

The Vaman pin diagram is available in Fig. 9.2.1.2

VAMAN LC PINS	ARDUINO PINS
3.3	3.3
GND	GND
TXD0	TXD
RXD0	RXD
0	GND
EN	GND

Table 9.2.1.1:

9.2.2. For compiling and generating the bin file

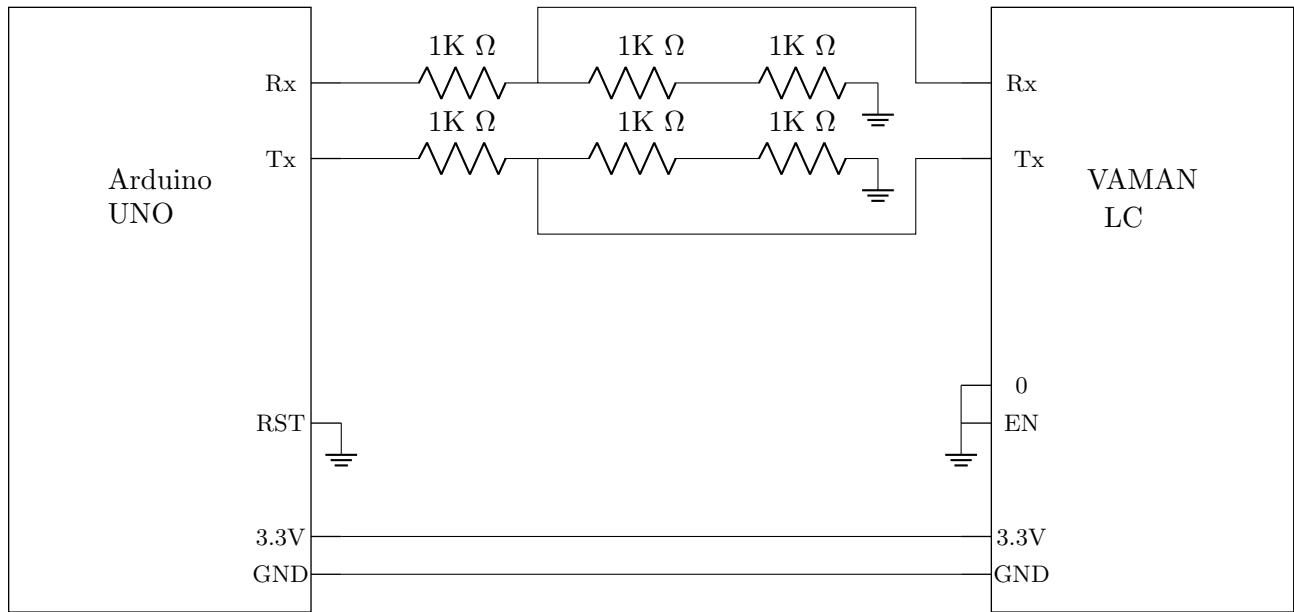
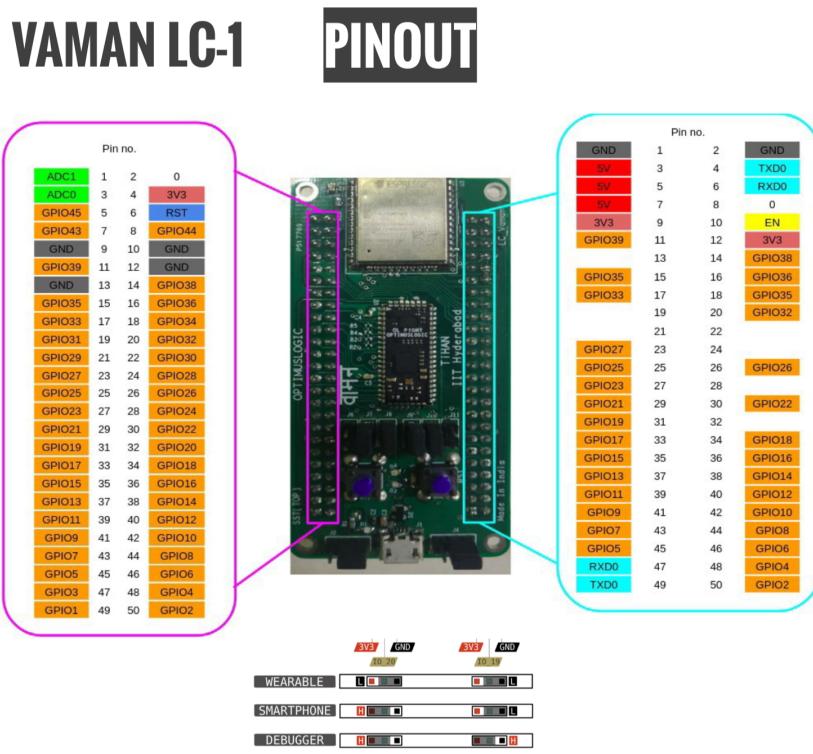


Figure 9.2.1.1: Circuit Connections

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

9.2.3. make sure that platformio.ini file contains these lines

```
[env:esp32doit-devkit-v1]
platform = espressif32
board = esp32doit-devkit-v1
framework = arduino
platform_packages = toolchain-xtensa-esp32@https://github.com/esphome/
    esphome-docker-base/releases/download/v1.4.0/toolchain-xtensa32.tar.gz
framework_arduinoespressif32@<3.10006.210326
```



sure that the Vaman board is not powering any device while flashing. The Vaman-ESP should now flash.

9.2.5. After flashing, disconnect pin 0 on Vaman-ESP from GND. Power on Vaman and the appropriate LED will blink.

9.2.6. Open

```
vaman/esp32/codes/ide/blink/src/main.cpp
```

and change the delay to

```
delay(2000);
```

and execute the code by following the steps above.

9.3. OTA

9.3.1. Flash the following code through USB-UART.

```
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

9.3.2. 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

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

```
vaman/esp32/codes/ide/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.

9.3.4. Connect pin 2 to an LED to see it blinking.

9.4. Onboard LED

9.4.1. Connect the pins between Vaman-ESP32 and Vaman-PYGMY as per Table 9.4.1.1

ESP32	Vaman
GPIO2	GPIO18
GPIO4	GPIO21
GPIO5	GPIO22

Table 9.4.1.1:

9.4.2. Flash the following code OTA

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

You should see the onboard green LED blinking.

9.4.3. Change the blink duration to 100 ms.

Chapter 10

Vaman-FPGA

10.1. Setup

This document provides a simple introduction to software and hardware using the Vaman FPGA/microcontroller board. The exercises provided here are suitable for students from primary school till college.

10.1.1. Software

The codes are available at

```
vaman/fpga/setup/codes/
```

10.1.2. Setup

10.1.2.1. Follow the instructions in

```
vaman/installation/termuxdebian/termux_debian_fpga.txt
```

10.1.3. Frequency

10.1.3.1. In the following verilog program,

```
codes/blink/helloworldfpga.v
```

pay attention to the following lines

```
delay = delay+1;  
if(delay > 20000000)  
begin  
delay=27'b0;  
led=!led;  
end
```

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

10.1.3.2. In instruction 10.1.3.1, replace

```
if(delay > 20000000)
```

with

```
if(delay==27'b100110001001011010000000)
```

and execute the verilog code.

10.1.3.3. Since the delay is 20 MHz, the blink period is 1 second. Modify the verilog code so that the blink period becomes 0.5s.

10.1.3.4. Find the bit length of 20 MHz.

Type	Vaman Pin	Connection
Input	IO_28	GND
Output	IO_11	LED

Table 10.1.3.8.1: Vaman Input/Output.

Solution:

$$\log_2(20000000) \approx 27 \quad (10.1.3.4.1)$$

10.1.3.5. Obtain the above answer using a Python code.

Solution: Execute the following code and compare with instruction 10.1.3.2.

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

10.1.3.6. Replace the following line in the code in instruction 10.1.3.1

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

with

```
assign blueled = led;
```

and execute the code.

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

Solution: Execute the following code

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

10.1.3.8. Using Table 10.1.3.8.1 and Fig. 9.2.1.2, control the onboard LED through an external input. Connect an external LED and control it using an output pin as well.

Solution: Execute the following code and take out the input pin connect to GND.

Plug it again. Do this repeatedly.

```
vaman/setup/codes/input/blink.ip.v  
vaman/setup/codes/input/pygmy.pcf
```

10.2. Seven Segment Display

We show how to use Vaman as a decade counter.

10.2.1. Software

All codes used in this manual are available at the following link.

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

10.2.2. Setup

10.2.2.1. The pin sheet for the Vaman is available in Fig. 9.2.1.2. Connect the pins in the bank

J5 of the Vaman with the seven segment display shown in Fig. 2.2 according to Table

10.2.2.1.1. Ensure that the COM pin is connected to 3.3V through a resistor.

10.2.2.2. Now execute the following code.

```
codes/static/sevenseg.v
```

Flash the helloworldfpga.bin file to Vaman. You should see the number 5 displayed.

The following lines are used for generating numbers on the display.

Display	Pygmy
a	IO_4
b	IO_5
c	IO_6
d	IO_7
e	IO_8
f	IO_10
g	IO_11
COM	3.3 V

Table 10.2.2.1.1: Seven segment display - Vaman connection.

```

assign a=0;
assign b=1;
assign c=0;
assign d=0;
assign e=1;
assign f=0;
assign g=0;

```

- 10.2.2.3. Modify the above code appropriately with the help of Table 10.2.2.3.1 and Fig. 2.3 to generate the numbers from 0-9 on the display.

a	b	c	d	e	f	g	decimal
1	0	0	1	1	1	1	1
0	0	1	0	0	1	0	2

Table 10.2.2.3.1: Pin values used for generating decimal numbers on the seven segment display.

10.2.3. Examples

10.2.3.1. Table 10.2.2.1.1 and the PU 64 table in Fig. 10.2.3.2.1 explain the pin numbering in the following file.

```
codes/static/Vaman.pcf
```

10.2.3.2. Execute the code below. All the pins in the display are controlled using a 7 bit word.

```
codes/static/sevenseg_word.v
```

The above file is used for generating the number 4 on the display. The process is explained by the completion of Table 10.2.2.3.1.

```
gpio_out=7'b0100100;
```

10.2.3.3. Use a verilog function that takes a decimal input and display it on the seven segment display.

Solution: Execute the following code.

```
codes/static/sevenseg_dec.v
```

10.2.3.4. Use the Vaman as a decade counter.

Solution: Execute the following code.

```
codes/loop/decade_counter.v
```

10.3. Boolean Logic

In this document we show how to design a decade counter using Vaman and boolean logic.

10.3.1. Software

All codes used in this manual are available at the following link.

```
vaman/fpga/boolean/codes
```

10.3.2. Setup

10.3.2.1. Fig. 9.2.1.2 shows the pin diagram for the Vaman. Using the bank J5, connect the pins of the seven segment display in Fig. 2.2 to the Vaman according to Table 10.3.2.1.1. Make sure that the COM pin is connected to 3.3V through a resistor.

10.3.2.2. Implement Table 4.1 using the Vaman and the display.

Solution: In Table 4.1, the output variables a, b, c, d, e, f, g can be expressed in terms

Display	Pygmy
a	IO_4
b	IO_5
c	IO_6
d	IO_7
e	IO_8
f	IO_10
g	IO_11
COM	3.3 V

Input Variable	Pin
W	IO_28
X	IO_23
Y	IO_31
Z	IO_12

Table 10.3.2.1.1: Pin connections between Vaman and the display.

of the input variables W, X, Y, Z as

$$a = WX'Y'Z' + W'X'YZ' \quad (10.3.2.2.1)$$

$$b = WX'YZ' + W'XYZ' \quad (10.3.2.2.2)$$

$$c = Z'Y'XW' \quad (10.3.2.2.3)$$

$$d = WX'Y'Z' + W'X'YZ' + WXYZ' + WX'Y'Z \quad (10.3.2.2.4)$$

$$e = WX'Y'Z' + WXY'Z' + W'X'YZ' + WX'YZ' + WXYZ' + WX'Y'Z \quad (10.3.2.2.5)$$

$$f = WX'Y'Z' + W'XY'Z' + WXY'Z' + WXYZ' \quad (10.3.2.2.6)$$

$$g = W'X'Y'Z' + WX'Y'Z' + WXYZ' \quad (10.3.2.2.7)$$

Execute the following program.

```
vaman/fpga/boolean/codes/decoders/dispdec.v
vaman/fpga/boolean/codes/decoders/Vaman.pcf
```

Connect W, X, Y, Z to GND. For different values of the input variables, verify the output in on the display using Table 4.1.

10.3.2.3. Table 3.5 describes the properties of the incrementing decoder. Using Boolean logic, express A, B, C, D in terms of W, X, Y, Z . Subsequently, implement this decoder by implementing the the expressions so obtained in the Vaman using verilog.

Solution: The following equations contain the desired expressions.

$$A = W'X'Y'Z' + W'XY'Z' + W'X'YZ' + W'X'Y'Z \quad (10.3.2.3.1)$$

$$B = WX'Y'Z' + W'XY'Z' + WX'YZ' + W'XYZ' \quad (10.3.2.3.2)$$

$$C = WXY'Z' + W'X'YZ' + WX'YZ' + W'XYZ' \quad (10.3.2.3.3)$$

$$D = WXYZ' + W'X'Y'Z \quad (10.3.2.3.4)$$

Execute the following code. The next number should be displayed.

```
vaman/fpga/boolean/codes/decoders/incdec.v
```

10.3.3. Decade Counter

10.3.3.1. Using Fig. 5.2 and modifying the code in Problem 10.3.2.3, design the decade counter.

10.3.3.2. Design and implement the down counter.

10.4. LCD

This manual shows how to interface a 16×2 LCD display to Vaman and verilog code for addition of two numbers and display the output on the LCD display.

Pygmy pins	LCD Pins	LCD Pin Label	LCD Pin Description
GND	1	GND	
5V	2	Vcc	
GND	3	Vee	Contrast
10	4	RS	Register Select
GND	5	R/W	Read/Write
9	6	EN	Enable
14	11	DB4	Serial Connection
13	12	DB5	Serial Connection
12	13	DB6	Serial Connection
11	14	DB7	Serial Connection
5V	15	LED+	Backlight
GND	16	LED-	Backlight

Table 10.4.1.2.1: Pin connections between Vaman and the display.

10.4.1. Display the addition of two numbers on LCD

10.4.1.1. Plug the LCD in Fig. 8.5.2.2.1 to the breadboard.

10.4.1.2. Connect the Vaman Pygmy pins to LCD pins as per Table 10.4.1.2.1.

10.4.1.3. The below code is for displaying the output of addition of two numbers

10.4.1.4. Now execute the following code.

```
cd vaman/fpga/lcd/codes/lcd.v
```

10.4.1.5. Flash the helloworldfpga.bin file to Vaman. You should see the result of addition of two numbers

10.4.1.6. Modify the above code to obtain addition of different numbers of two digits.

10.4.1.7. Repeat the above exercises to add three digit numbers and display the output.

10.4.1.8. Write verilog code for different arithmetic operations.

PD64			PU64			WR42		
IO Location	Alias	IO Type	IO Location	Alias	IO type	IO Location	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			

Figure 10.2.3.2.1: Pin Definitions

Chapter 11

Vaman-ARM

11.1. Setup

11.1.1. Software

All codes used in this document are available at

```
vaman/arm/codes/setup
```

11.1.2. Setup

11.1.2.1. Follow the instructions at

```
vaman/installation/termuxdebian/termuxdebian_arm.txt
```

11.1.3. Delay

11.1.3.1. 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.

11.1.3.2. Replace the following line in 11.1.3.1

```
HAL_DelayUSec(2000000);
```

with

```
HAL_DelayUSec(1000000);
```

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

11.1.3.3. To obtain red colour, execute the following code.

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

Now obtain blue colour.

11.1.3.4. Now obtain green colour without blink.

Solution: Execute the following code.

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

Type	Pin	Destination
Input	IO_5	GND

Table 11.1.3.5.1: Vaman control through external input.

11.1.3.5. Using Table 11.1.3.5.1 and Fig. 9.2.1.2, use an input pin to control the onboard LED.

Solution: Execute the following code. You should see the LED blinking pink. Disconnecting the wire from GND will result in the LED blinking white and green alternately.

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

11.2. Seven Segment Display

This document shows how to implement a decade counter using arm-gcc on Vaman.

11.2.1. Software

All codes used in this document are available at the following link

```
https://github.com/gadepall/vaman/tree/master/arm/vaman/arm/codes/sevenseg/
```

11.2.2. Setup

11.2.2.1. Fig.9.2.1.2 shows all the pin banks of the Vaman. Connect the pins of the display in Fig. 2.2 to bank J5 of the Vaman using Table 11.2.2.1.1. The COM pin should be connected to 3.3V through a resistor.

11.2.2.2. Now execute the following code

Display	Vaman
a	IO_4
b	IO_5
c	IO_6
d	IO_7
e	IO_8
f	IO_10
g	IO_11
COM	3.3 V

Table 11.2.2.1.1: Display-Vaman connection.

```
vaman/arm/codes/sevenseg/static/src/main.c
```

Flash static.bin obtained upon execution of the above code to the Vaman. You should see the number 7 on the display. The following function generates this number.

```
sevenseg(0,0,0,1,1,1,1);

void sevenseg(int a, int b, int c, int d, int e, int f, int g)
{
    //Seven Segment GPIO
    PyHal_GPIO_Set(4,a);//a
    PyHal_GPIO_Set(5,b);//b
    PyHal_GPIO_Set(6,c);//c
    PyHal_GPIO_Set(7,d);//d
```

```

    PyHal_GPIO_Set(8,e); //e
    PyHal_GPIO_Set(10,f); //f
    PyHal_GPIO_Set(11,g); //g
}
}

```

11.2.2.3. Modify the above program using Table 10.2.2.3.1 and Fig. 2.3 to display 0-9.

11.2.3. Examples

11.2.3.1. Table 11.2.2.1.1 and PU 64 Table in Fig. 10.2.3.2.1 show how to use the pins of the Vaman to drive the seven segment display.

11.2.3.2. Use a function taking decimal input in the code in 11.2.2.2 to generate numbers on the display.

Solution: Execute the following file.

```
vaman/arm/codes/sevenseg/decimal/main.c
```

11.2.3.3. Program the Vaman to function as a decade counter.

Solution: Execute the following code.

```
vaman/arm/codes/sevenseg/loop/main.c
```

11.3. FSM

This document shows how to use the Vaman to design a decade counter using a finite state machine (FSM).

11.3.1. Software

All codes in this document are available at the following links.

<https://github.com/gadepall/vaman/tree/master/arm/codes/decoders>

<https://github.com/gadepall/vaman/tree/master/arm/codes/fsm>

11.3.2. Setup

11.3.2.1. Execute Table 4.1 using the Vaman and a seven segment display.

Solution: The outputs a, b, c, d, e, f, g in Table 4.1 are expressed in terms of the inputs A, B, C, D through the following equations.

$$a = AB'C'D' + A'B'CD' \quad (11.3.2.1.1)$$

$$b = AB'CD' + A'BCD' \quad (11.3.2.1.2)$$

$$c = D'C'BA' \quad (11.3.2.1.3)$$

$$d = AB'C'D' + A'B'CD' + ABCD' + AB'C'D \quad (11.3.2.1.4)$$

$$e = AB'C'D' + ABC'D' + A'B'CD' + AB'CD' + ABCD' + AB'C'D \quad (11.3.2.1.5)$$

$$f = AB'C'D' + A'BC'D' + ABC'D' + ABCD' \quad (11.3.2.1.6)$$

$$g = A'B'C'D' + AB'C'D' + ABCD' \quad (11.3.2.1.7)$$

Now execute the following code.

`codes/decoders/dispdec/main.c`

For different values of A, B, C, D , execute the above code to verify Table 4.1.

11.3.2.2. Table 3.5 shows the logic for the incrementing decoder. Express A, B, C, D in terms of W, X, Y, Z .

Solution: The desired expressions are available below.

$$\begin{aligned} A = & W'X'Y'Z' + W'XY'Z' + W'X'YZ' \\ & + W'XYZ' + W'X'Y'Z \end{aligned} \quad (11.3.2.2.1)$$

$$\begin{aligned} B = & WX'Y'Z' + W'XY'Z' \\ & + WX'YZ' + W'XYZ' \end{aligned} \quad (11.3.2.2.2)$$

$$\begin{aligned} C = & WXY'Z' + W'X'YZ' \\ & + WX'YZ' + W'XYZ' \end{aligned} \quad (11.3.2.2.3)$$

$$D = WXYZ' + W'X'Y'Z \quad (11.3.2.2.4)$$

Execute the following code. You should see the next number displayed.

```
codes/decoders/incdec/main.c
```

11.3.2.3. Fig. 9.2.1.2 shows the pin diagram for the Vaman. Connect the pins in bank J5 to the seven segment display using Fig. 2.2 and Table 10.3.2.1.1. Do not forget to put a resistor between COM and 3.3V. Then execute the following code

```
codes/fsm/dispdec/main.c
```

11.3.2.4. Modify the above code to obtain a decade counter.

11.3.3. Decade Counter

11.3.3.1. Use the Vaman to implement all the decoders in Fig. 5.2. Implement the delay using a flip flop. This is an example of an FSM which is implemented using a sequential circuit.

Chapter 12

STM-32

12.1. Setup

This manual shows how to program an STM32 board using USB-UART.

12.1.1. Software

12.1.1.1. Make the connections as per the Table 12.1.1.1.1

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

Table 12.1.1.1.1: STM32 to USB-UART connections

12.1.1.2. Basic onchip led blink program is available at

```
cd stm32/setup/codes/src/blink.c
```

12.1.1.3. Make sure that platformio.ini file has these below lines

```
[env:bluepill_f103c8]
platform = ststm32
framework = arduino
board = bluepill_f103c8
platform_packages=platformio/toolchain-gccarmnoneabi@^1.90201.0
```

12.1.1.4. Now, compile the blink program

```
cd codes
pio run
```

12.1.1.5. By this .bin file will be generated and all the necessary packages will be installed

12.1.1.6. Before flashing, make sure that STM32 board is in Programming mode

12.1.1.7. To make the stm32 board into Programming mode, by setting the aligners to programming mode as shown in Fig 12.1.1.7.1. This configuration will ensure that the microcontroller enters the system memory programmer on reset.

12.1.1.8. After executing

```
Install STM-Utils from playstore
Give the necessary permissions
Now connect the USB-UART to OTG
Automatically the the USB will be detected
Now upload the .bin file to the STM32 board
```

12.1.1.9. By these above mentioned steps the blink code will be flashed to the STM32 board

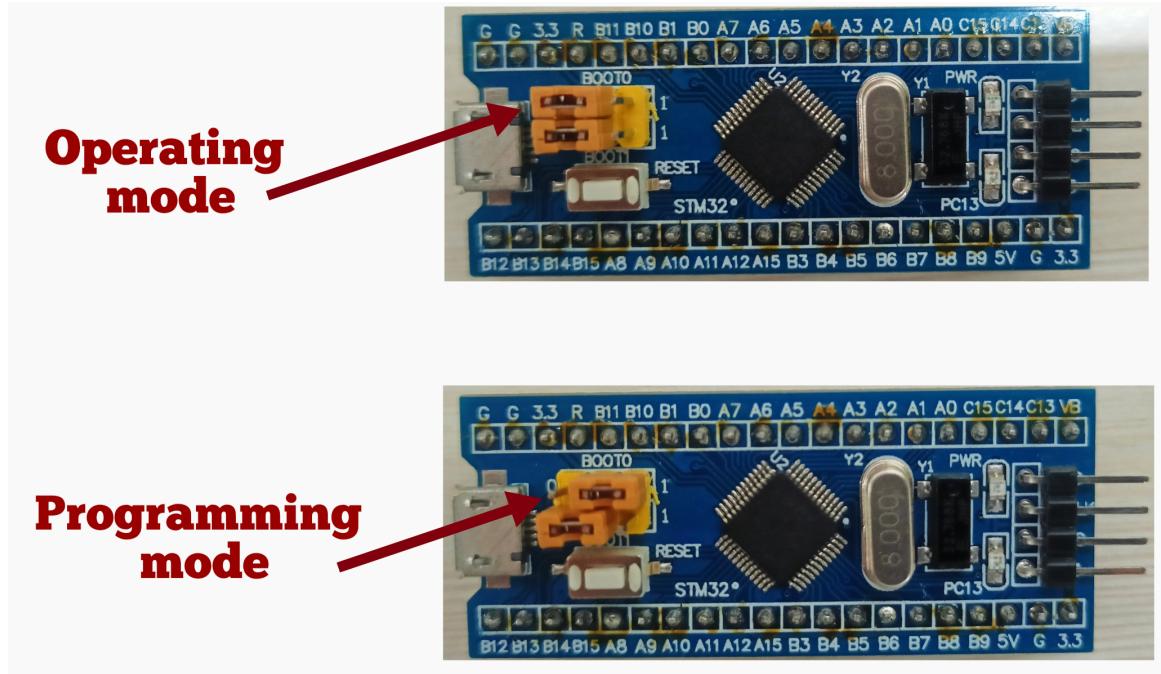


Figure 12.1.1.7.1: STM32 Operating and Programming mode

12.1.1.10. The inbuilt LED present on the stm32f103c8 will start blinking.

12.1.1.11. After flashing, the inbuilt LED present on the stm32f103c8 will start blinking and then change the STM32 board to operating mode as shown in Fig 12.1.1.7.1 inorder run your code from the main flash memory.

12.2. Seven Segment Display

The objective of this manual is to introduce beginners to arm embedded programming by powering a seven segment display.

12.2.1. Components

12.2.1.1. The necessary components for this manual are listed in Table 12.2.1.1.1.

Component	Value	Quantity
Breadboard		1
Resistor	220Ω	1
STM32F103C8T6		1
Seven Segment Display	Common Anode	1
Jumper Wires		20

Table 12.2.1.1.1: Components

12.2.2. Hardware

12.2.2.2. 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.

12.2.2.3. Connect one end of the 1K resistor to the COM pin of the display and the other end to an extreme pin of the breadboard.

12.2.2.4. The STM32F103C8T6 micro-controller in Fig. 12.2.2.5.1 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.

12.2.2.5. Make the pin connections in Table 12.2.2.5.2 using Figs. 2.2 and 12.2.2.5.1.

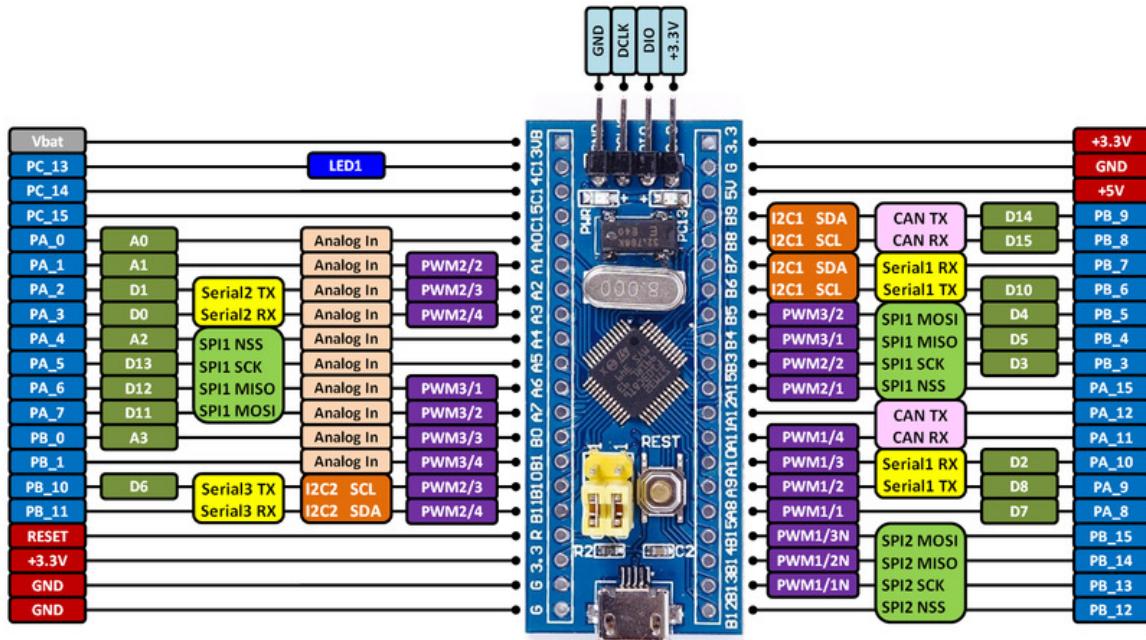


Figure 12.2.2.5.1: Pin Connections of STM-32

12.2.3. Software

12.2.3.6. Before flashing code to STM32 set the STM32 board to Programming mode as shown in Fig. 12.1.1.7.1, then change the mode to Operating mode as shown in Fig. 12.1.1.7.1 after flashing the code inorder to run your program from main memory.

12.2.3.7. Execute the following code

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

12.2.3.8. 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

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 12.2.2.5.2: STM-32 and Seven Segment Display Connections

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 12.2.2.5.2.

12.2.3.9. Repeat the above exercise to generate the numbers 1-9 on the display.

12.2.3.10. 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)
```

12.2.3.11. 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.

```
cd codes/bin2dec_example.c
```

12.3. Timers

This manual shows how to program timers in arm using STM32F103C8T6.

12.3.1. Components

12.3.1.1. The necessary components for this manual are listed in Table 12.3.1.1.1.

Component	Value	Quantity
Breadboard		1
Resistor	220 Ω	1
STM32F103C8T6		1
Seven Segment Display	Common Anode	1
Jumper Wires		20

Table 12.3.1.1.1: Components

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

Solution: See Table 12.3.1.2.1

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

Table 12.3.1.2.1: STM32F103C8T6 Timer Types.

12.3.2. Systick timer

12.3.2.3. The Systick timer is the default timer available on all ARM chips.

12.3.2.4. Make connections as shown in Table 12.3.2.4.1.

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

Table 12.3.2.4.1: Pin Connections

12.3.2.5. Before flashing code to STM32 set the STM32 board to Programming mode as shown in Fig. 12.1.1.7.1, then change the mode to Operating mode as shown in Fig. 12.1.1.7.1 after flashing the code inorder to run your program from main memory.

12.3.2.6. Execute the program in

```
cd timers/blink_systick.c
```

12.3.2.7. 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

$$T = \frac{1}{8} \mu s = 1 \text{ cycle} \quad (12.3.2.7.1)$$

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

$$1 \text{ second} = 8000000 \text{ cycles} \quad (12.3.2.7.2)$$

12.3.2.8. List the SysTick registers.

Solution: See Table 12.3.2.8.1.

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 12.3.2.8.1: Systick Registers

12.3.2.9. What do the following instructions do?

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

Solution: See Table 12.3.2.8.1 for details. These two instructions ask the SysTick timer to count down from 4000000 to 0.

12.3.2.10. Explain the following instruction.

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

Solution: Fig. 12.3.2.10.1 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.

12.3.2.11. What does the following instruciton do?

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	COUNT FLAG		
Reserved																		
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	rw		
Reserved																		
																CLKSO URCE	TICK INT	EN ABLE
																rw	rw	rw

Figure 12.3.2.10.1: Control Register (CTRL)

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

Solution: From Fig. 12.3.2.10.1, ENABLE = 1 enables the counter (for delay) and CLKSOURCE = 1 enables the 8 MHz internal RC clock.

12.3.2.12. 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

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

12.3.3. TIMER-1

12.3.3.14. Make the connections according to Table 12.3.2.4.1. Execute the following program

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

12.3.3.15. Enable Timer1 through RCC.

Solution:

RCC→APB2ENR = RCC_APB2ENR_TIM1EN;

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

Solution: See Fig. 12.3.3.16.1 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

Figure 12.3.3.16.1: Slave Mode Control Register (SMCR)

12.3.3.17. What does the following instruction do?

TIM1→CR1 = 0x0001;

Solution: Fig. 12.3.3.17.1 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

Figure 12.3.3.17.1: Control Register 1 (CR1)

12.3.3.18. Make TIM1 clock = 2 KHz.

Solution: Through the following command,

TIM1→PSC = 3999;

$$TIM1_CLK = \frac{HSI_CLK}{TIM1->PSC + 1} = \frac{8000000}{4000} \quad (12.3.3.18.1)$$

Fig. 12.3.3.18.1 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

Figure 12.3.3.18.1: Prescalar (PSC)

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

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

Solution:

TIM1->ARR = 999;

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

12.3.3.22. What do the following instructions do?

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

Solution: Once the TIM1 counter counts from 0 to TIM1->ARR=999, it resets and starts counting again to 999. At the time of reset, the LSB of TIM1->SR = 1. The if command checks this and when this condition is satisfied, TIM1->SR is cleared

and PA1 is toggled. This process keeps repeating. This results in a PA1 output of 1 and 0 with frequency

$$\frac{HSI_CLK}{(TIM1->PSC + 1)(TIM1->ARR + 1)} = \frac{8000000}{4000 \times 1000} = 2 \text{ Hz} \quad (12.3.3.22.1)$$

12.3.3.23. 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

$$\frac{HSI_CLK}{(TIM1->PSC + 1)(TIM1->ARR + 1)(TIM1->RCR + 1)} = \frac{8000000}{4000 \times 1000} = 2 \text{ Hz} \quad (12.3.3.23.1)$$

TIM1->RCR keeps track of the number of times the counter has overflowed. Fig. 12.3.3.23.1 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

Figure 12.3.3.23.1: Repition Counter (RCR)

12.3.3.24. What is the maximum value of TIM1->RCR?

12.3.3.25. What is the function of TIM1->SR?

Solution: The status register (SR) is shown in Fig. 12.3.3.25.1. The UIF flag is 1 if the RCR overflows.

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

Figure 12.3.3.25.1: Status Register (SR)

12.3.4. TIMER-2

12.3.4.26. Blink an LED with TIM2.

Solution:

```
cd timers/timer2_blink.c
```

12.3.4.27. 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 12.3.3.14. 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.

12.3.4.28. 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.

12.3.5. Master-Slave Configuration

12.3.5.1. Blink

12.3.5.29. Execute the following program.

```
cd timers/master1_slave2_blink.c
```

12.3.5.30. 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. 12.3.5.30.1.

The TS and SMS bits are visible in the SMCR register in Fig. 12.3.3.16.1.

```
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				Reserved		
					rw	rw	rw	rw	rw						

Figure 12.3.5.30.1: Control Register 2 (CR2)

12.3.5.2. Decade Counter

12.3.5.31. Execute the following program.

```
cd timers/decade_counter.c
```

12.3.5.32. If $\text{TIM2} \rightarrow \text{ARR} = 9$, $\text{TIM2} \rightarrow \text{CNT} = ?$

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

12.4. Clocks

This manual shows how to manage clocks in arm using STM32F103C8T6.

12.4.1. Components

12.4.1.1. The necessary components for this manual are listed in Table 12.4.1.1.1.

Component	Value	Quantity
Breadboard		1
Resistor	220Ω	1
STM32F103C8T6		1
Seven Segment Display	Common Anode	1
Jumper Wires		20

Table 12.4.1.1.1: Components

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

Solution: See Table 12.4.1.2.1.

12.4.1.3. Make connections as shown in Table 12.4.1.3.1.

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

Table 12.4.1.2.1: STM32F103C8T6 Clock Types

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

Table 12.4.1.3.1: Pin Connections

12.4.2. HSE

12.4.2.4. Before flashing code to STM32 set the STM32 board to Programming mode as shown in Fig. 12.1.1.7.1, then change the mode to Operating mode as shown in Fig. 12.1.1.7.1 after flashing the code inorder to run your program from main memory.

12.4.2.5. Execute the following program

```
cd /clocks/hse_systick_blink.c
```

12.4.2.6. Explain the following instruction

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

Solution: Fig. 12.4.2.6.1 shows the RCC->CR register. The above instruction enables the HSE crystal, which is 8 MHz for the STM32F103C8T6.

12.4.2.7. Explain the following instruction

```
RCC->CFGR =0x00000001;
```

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reserved				PLL RDY	PL隆ON	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	

Figure 12.4.2.6.1: RCC Clock Control Register (RCC->CR)

Solution: Fig. 12.4.2.7.1 shows the RCC->CFGR 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	
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

Figure 12.4.2.7.1: RCC clock Configuration Register (RCC->CFGR)

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

12.4.3. PLL

12.4.3.9. Make the PLL as the system clock.

Solution:

RCC->CFGR =0x00000010;

12.4.3.10. Choose the PLL input as HSE.

```
RCC->CFGR =0x00010010;
```

12.4.3.11. Enable PLL

Solution:

```
RCC->CR =0x01010000;
```

12.4.3.12. Execute the following code.

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

12.4.3.13. Make the PLL output = 24 MHz.

12.5. GPIO

This manual shows how to use the GPIO pins on the STM32F103C8T6 to control an LED.

12.5.1. Components

12.5.1.1. The necessary components for this manual are listed in Table 12.5.1.1.1.

12.5.2. Hardware Setup

12.5.2.2. Connect the USB-UART to STM32. Fig. 12.2.2.5.1 shows the blue pill board. The hardware connections between the USB-UART, STM32 and LED are available in Table 12.5.2.2.1. Make sure that the LED is connected to PB4 through the resistor.

Component	Quantity
STM32F103C8T6	1
USB-UART	1
Female-Female Jumper Wires	4
Female-Male Jumper Wires	4
Resistor ($> 220\Omega$)	1
LED	1

Table 12.5.1.1.1: Components

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

Table 12.5.2.2.1: USB-UART to STM32 connections

12.5.3. GPIO Output

12.5.3.3. Before flashing code to STM32 set the STM32 board to Programming mode as shown in Fig. 12.1.1.7.1, then change the mode to Operating mode as shown in Fig. 12.1.1.7.1 after flashing the code inorder to run your program from main memory.

12.5.3.4. Execute

```
cd /gpio/gpio_example.c
```

12.5.3.5. Modify the above program to turn the LED off.

12.5.3.6. 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.

12.5.3.7. 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 12.5.3.7.2.

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

Table 12.5.3.7.2: GPIO Enable pins

12.5.3.8. Explain the significance of the number (nibble) 0x3 corresponding to PB4 in Table 12.5.3.7.2.

Solution: The nibble $0x3 = 0b0011$. From Table 12.5.3.8.1, 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.

12.5.3.9. 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

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 12.5.3.8.1: GPIO Output configuration

atomically clear pin values to VDD. The above command clears PB4.

12.5.3.10. 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.

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

12.5.4. GPIO Input

12.5.4.12. Connect PB7 to GND and execute the following code

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

12.5.4.13. What does the following instruction do?

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

Solution: This instruction declares PB7 as an input pin. $0x8=0b1000$. According to Table 12.5.4.13.1, the mode 00 is used only for input and the first two bits 10 are used for pull-up/pull-down.

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

Table 12.5.4.13.1: GPIO Input configuration

12.5.4.14. Explain the following instruction.

```
#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 $\text{GPIOB} \rightarrow \text{IDR}$, i.e. the input from PB7 is 0. If so, then the LED connected to PB4 should be ON.

12.6. LCD

This manual shows how to interface the 16×2 HD44780-controlled LCD using STM32F103C8T6.

12.6.1. Components

12.6.1.1. The necessary components for this manual are listed in Table 12.6.1.1.1.

Component	Value	Quantity
Breadboard		1
STM32F103C8T6		1
LCD	16 × 2 HD44780	1
Jumper Wires	F-F	20
Jumper Wires	M-F	20

Table 12.6.1.1.1: Components

12.6.2. Hardware

12.6.2.2. Make connections as shown in Table 12.6.2.2.2.

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 12.6.2.2.2: Pin Connections

12.6.3. Software

12.6.3.3. Before flashing code to STM32 set the STM32 board to Programming mode as shown in Fig. 12.1.1.7.1, then change the mode to Operating mode as shown in Fig. 12.1.1.7.1 after flashing the code inorder to run your program from main memory. Execute the following program

```
cd /lcd/lcd_example.c
```

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

12.6.3.4. Write the ASCII code for the 0 character.

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

12.6.3.5. 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
}
```

12.6.3.6. 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

$$\begin{aligned}
 GPIOA -> BSRR &= (data << 2) \& 0b00111100 \\
 &= 0b00001100. \quad (12.6.3.6.1)
 \end{aligned}$$

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

Similarly,

$$GPIOA -> BRR = (data << 2) \& 0b00111100 \quad (12.6.3.6.2)$$

12.6.3.7. ensures that 00 is written to the pins A4-A5. PulseEnableLine() provides a clock pulse used to write the nibble 0011 to the LCD.

12.6.3.8. 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.

12.6.3.9. 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.

12.6.4. Project

12.6.4.10. Develop an arithmetic calculator using the STM32 along with the LCD.

12.7. ADC

This manual shows how to interface the 16x2 HD44780-controlled LCD using STM32F103C8T6.

12.7.1. Components

Component	Value	Quantity
Resistor	220 Ohm	1
	1K	1
Breadboard		1
STM32F103C8T6		1
LCD	16 x 2 HD44780	1
Jumper Wires	M-F	20
	F-F	5
	M-M	5

Table 10.1: Components

12.7.2. Internal Temperature Sensor

12.7.2.1. Make connections as shown in Table 12.6.2.2.2.

12.7.2.2. Make sure to set the STM32 board to Programming mode as shown in Fig. 12.1.1.7.1

then after flashing the code set the STM32 board to Operating mode as shown in Fig. 12.1.1.7.1 to run your program from main memory.

12.7.2.3. Execute the following program

```
cd /adc/internal_temp.c
```

12.7.2.4. What do you observe?

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

12.7.2.5. Find an expression for V_{SENSE}

Solution:

$$V_{SENSE} = 3.3 \times \frac{ADC1 - > DR}{4095} \quad (12.7.2.5.1)$$

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

Solution: The desired formula is

$$T = (V_{25} - V_{SENSE}) / AvgSlope + 25 \quad (12.7.2.6.1)$$

where the typical values of the above parameters are

V_{25}	AvgSlope
1.43	4.3

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
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
SMP 15_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

Figure 12.7.2.8.1: SMPR1

12.7.2.7. 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.

12.7.2.8. 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. 12.7.2.8.1. 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.

12.7.2.9. What is the sampling time?

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

$$T_s = 239.5 \times \frac{1}{14} \mu s = 17.1 \mu s \quad (12.7.2.9.1)$$

12.7.2.10. Explain the following instruction.

```
ADC1->SQR3 |= ADC_SQR3_SQ1_4;
```

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]			
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

Figure 12.7.2.10.1: SQR3

Solution: $ADC_SQR3_SQ1_4 = 0x00000010$. This implies that $SQ1=0b10000$ in the ADC regular sequence register 3 ($ADC1- > SQR3$) shown in Fig. 12.7.2.10.1. Since $SQ1=16$, 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.

12.7.3. Measuring an Unknown Resistance

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

Solution: This implies that $SQ2=1001$. Thus,

$$ADC1- > SQR3 = 0x000000120 \quad (12.7.3.11.1)$$

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

Solution: See Fig. 12.7.3.12.1

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

Table 12.7.3.12.1: ADC Analog Input Pins

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

Solution: Connect PB1 (Fig. 12.7.3.12.1) to 3.3 V of the STM 32 and execute the following code.

12.7.3.14. Before flashing code to STM32 set the STM32 board to Programming mode as shown in Fig. 12.1.1.7.1, then change the mode to Operating mode as shown in Fig. 12.1.1.7.1 after flashing the code inorder to run your program from main memory.

```
cd /adc/3_3V.c
```

12.7.3.15. Measure an unkown resistance using the STM32 and display the result on the LCD.

12.7.3.16. Display the output of the internal temperature sensor as well the unknown resistance on the LCD.

