MODULE 5

- **ARM Based System**

Introduction - ARM family, ARM 7 register architecture, ARM programmer's model. Raspberry pi 4 board – introduction and brief description. Applications – Portable Bluetooth speaker, remote controlled car, Photo Booth, IoT weather station, Home automation centre, Portable Digital eBook Library

Course Outcome

- After completion of the module the student will be able to
  - Familiarize the building blocks of RISC Processors and ARM microcontrollers

Introduction

ARM stands for Advanced RISC Machines. The ARM processor is a key component of many successful 32-bit embedded systems. These processors are widely used in mobile phones, and multitude of other everyday portable consumer devices.

ARM is a processor architecture based on a 32-bit reduced instruction set computer. ARM was originally developed at Acorn Computers Limited of Cambridge, between 1983 and 1985. ARM is designed to meet the requirement for **low power and cost sensitive embedded applications**. ARM designers have came a long way from the first ARM1 prototype in 1985. The ARM Company bases their success on a simple and powerful original design which continues to improve today through constant technical innovations. The ARM7TDMI is ARM's most successful core processor.

Features of ARM Processors

1. **All of the instructions are 32-bit length instructions.**
2. **Load Store Architecture:** ARM processor operates on data held in registers. Separate load and store instructions transfer data between the register bank and external memory. Except the load and store instructions, all other instructions operate on data held in registers. Since data from a register can be accessed much quickly than from memory, instruction execution will be faster in ARM.
3. ARM limited has incorporated a novel mechanism, called the **Thumb Architecture,** into some versions of the ARM processor. Thumb instruction set is a 16-bit compressed form of the original 32-bit ARM instruction set. This feature will reduce the memory requirement to store the program because in Thump architecture, instructions are of length 16 bit only. ARM employs dynamic decompression hardware to convert it into 32-bit original instructions during program execution.
4. ARM processors have a good **speed of execution to power consumption ratio.**
5. They have a wide range of clock frequency ranging from 1MHz to few GHz.
6. They support direct execution of Java bytecodes using ARM's Java Jazelle DBX(Direct Bytecode Execution) – this will improve speed of execution, thereby improving the performance by 5x-10x.

7. ARM processors have built in hardware for debugging.
8. It supports enhanced instructions for DSP operations.
9. ARM has three instruction set states: a. 32-bit ARM instruction set in which instructions will be of length 32-bit and this is the normal mode of instruction execution state of the ARM processor. b. 16-bit Thumb instruction set in which the instructions will be of length 16-bits. c. 8 bit Jazelle instruction set in which ARM processor will be executing a program written in JAVA. Using this hardware feature, ARM processor can directly execute a program written using JAVA codes.

Processor Operating Modes

ARM processor has seven processor modes. Out of this, six are privileged modes and one is Non- privileged mode. They are

- o Privileged modes: Abort, Fast interrupt Request, Interrupt Request, Supervisor, System, Undefined.
- o Non- Privileged mode: User.

User Mode: This is the normal mode of operation of an ARM processor. In this mode, processor will be executing the instructions written by the user.

FIQ Mode (Fast Interrupt Request): Processor will enter into this mode when a high priority interrupt is raised.

IRQ Mode (Interrupt Request Mode): Processor will enter into the interrupt request Mode when a low priority interrupt is raised.

Supervisor Mode: Processor will enter into this mode upon on RESET and when a software interrupt instruction is executed.

Abort Mode: Processor will enter into this mode whenever a memory access violation occurs.

Undefined (Undef) Mode: Processor will enter into this mode whenever an undefined instruction is executed.

System Mode: It is a privileged user mode for the operating system. Whenever the processor is running under the control of an Operating System, it will be in System Mode.

Name Description of ARM Processors

- **The letters or words after 'ARM' are used to indicate the features of a processor.**

- **T – Thumb instruction set -** ARM processor which has the Thump Architecture. If T is found in the name description of an ARM processor, then that ARM Processor can work in Thump Mode apart from the Normal mode of execution.
- **D – JTAG Debug –** ARM processor which has built-in Debug facility. JTAG is a serial protocol used by ARM to transfer the debug information between the ARM and the test equipment.
- **M – Fast Multiplier –** ARM processor which has a fast multiplier unit in it. Using this fast multiplier unit available in such ARM processors, multiplication operation can be completed in a single clock cycle itself.
- **I – Embedded ICE Macro cell**
- **E – Enhanced Instructions –** ARM processor which contains enhanced instructions suitable for DSP operations.
- **J – Jazelle –** ARM processor which has the Jazelle feature. Such processors are able to execute JAVA code directly.
- **F – Vector Floating-point Unit –** ARM processor which has a floating point unit thereby enabling it to do floating point arithmetic operations on an array (vector) of data.
- **S – Synthesizable –** ARM Holdings, the current owner of ARM never produces a processor in the market. Instead they are developing the architectures of Processors. The companies like Apple, Samsung etc. buy the license of these processors from ARM holdings and produces a System on Chip(SoC) using this core. This is what you mean by the Synthesizable feature of ARM. So ARM holdings don't manufacture a Processor of its own; they are only selling their technology.

One example of an ARM processor is ARM7TDMI.Its their first successful family of Processor. It supports Thumb mode of execution, Debug facility, Fast multiplication etc.

ARM Processors Family

ARM processor family can be divided into

1. ARM Classic Processors
2. Cortex Processors

ARM Classic Processors

ARM Classic processors include ARM7, ARM9 and ARM11 families. Each family is developed as a separate version. ARM7 family belongs to Version 4, ARM9 belongs to Version 5 and ARM 11 belongs to Version 6. ARM7 based processors are still used in many small and simple 32-bit devices.ARM9 and ARM 11 are like ARM7 with more complex architectural features. For example the number of pipelines stages in ARM7 is 3. It is increased to 5 in ARM9 and to 8 in ARM11.

CPU Architecture Version	**ARMv4**	**ARMv5**	**ARMv6**
Family	ARM7	ARM9	ARM11
Processors	ARM7TDMI	ARM946	ARM1156T2
	ASC 100	ARM968	ARM1136J
		ARM926	ARM1176JZ
No. of Pipeline Stages	3	5	8

Cortex Family

Cortex family of ARM processors includes ARM Embedded Processors and ARM Application Processors.

ARM Embedded Processors: CORTEX M and R Series processors come under this family.

ARM Application Processors: CORTEX A Series processors come under this family

ARM Embedded Processors

Cortex R and M family of processors comes under this class. R stands for Real Time profile and M stands for Microcontroller profile. Cortex R family of processors are employed in time critical applications and M family of processors are used as a Microprocessor in a Microcontroller. Table below lists some of the processors in the Cortex M and R family.

Cortex – M0	**Microcontroller Profile**
Cortex – M3	
Cortex – M4	
Cortex – M7	
Cortex – R4	**Real Time Profile**
Cortex – R5	
Cortex – R7	
Cortex – R8	

Cortex R family of processors finds applications in time critical or real time applications. They are widely employed in automobile industry. For example in the airbag system in modern cars. The airbag should open whenever a collision occurs. A delay in the airbag action will lead to casuality for the passenger.

Cortex M processors are processors which can be used as processors in a Microcontroller. They find applications in Home security systems, IoT and other various embedded applications.

ARM Application Processors

ARM Application processors or Cortex A family of processors are used in applications where the processor is used along with an Operating System. They are commonly used in Mobiles and

Tabs. If you look at the processors in a Mobile, about 90% of them are using Cortex – A series as the Processor which is working with an Android OS.

Cortex A Series processors again falls into High performance, High Efficiency and Ultra-high efficiency processors. Some of the processors under each category is listed below.

High Performance	High Efficiency	Ultra-High Efficiency
Cortex-A73	Cortex-A53	Cortex-A35
Cortex-A72	Cortex-A9	Cortex-A32
Cortex-A57	Cortex-A8	Cortex-A7
Cortex-A17		Cortex-A5

ARM7 Register Architecture

Registers are temporary locations present in a processor. Total available registers in ARM7 is divided into Visible registers and Invisible registers (also known as Banked Registers). Visible registers are those which are available for the programmer. Invisible registers are those which are not available for the programmer, but processors use it internally during program execution.

ARM register set includes 37 registers, each of 32-bit in length. Out of these 37 registers, 20 registers are not available for the programmer. These registers are called banked registers. So in user mode, 17 registers are available for the programmer. They are r0 to r12, r13, r14, r15 and CPSR (Current Program Status Register). The remaining 20 registers are available only in Privileged modes for handling interrupts and system level programming.

So in User mode, out of the 17 of the visible registers, r0 to r12 are called as General Purpose Registers. Register r13, r14 and r15 are special purpose registers – r13 is Stack Pointer, r14 is Link register and r15 is Program Counter. CPSR (Current Program Status Register) contains different flags that reflect the status of the processor after the execution of an arithmetic instruction.

General purpose registers hold either data or an address. They are identified with the letter ‘r’ prefixed to the register number. For example, register 4 is given the label r4.

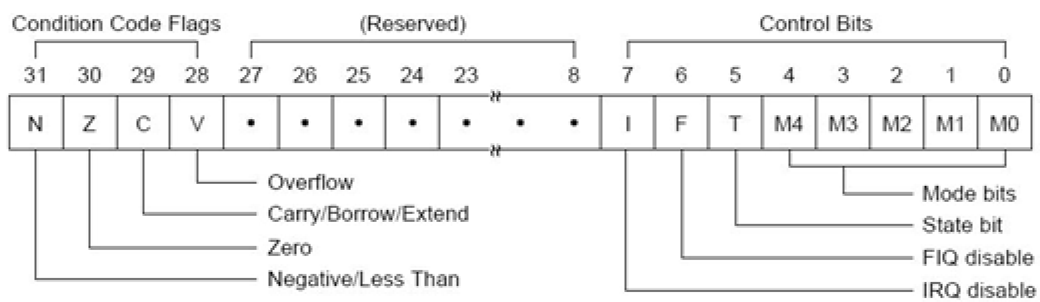
Special Purpose Registers are

● r13 – stack pointer (SP) and stores the top of the stack

● r14 – link register (LR) where the processor puts the return address whenever it calls a subroutine.

● r15 – program counter (PC) and contains the address of the next instruction to be fetched by the processor.

CPSR (Current Program Status Register)



CPSR is a 32-bit register. Bit number 31 to 28 reflect the status of the processor after the execution of an arithmetic operation. Bit 31 is Negative Flag (N), Bit 30 is Zero flag (Z), Bit 29 is Carry flag(C) and Bit 28 is Overflow flag (V).

N: Negative Flag: is set if the result of the ALU operation is negative

Z- Zero Flag: is set if the result of the ALU operation is zero

C-Carry Flag: is set if result of ALU is generating carry

V-Overflow Flag: is set if result of ALU generates an overflow.ie, if a carry is generated into the 31th bit

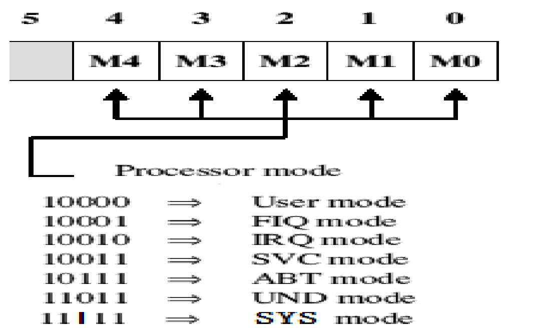
Bit number 27th to 8th bits are reserved for future.

Bit number 7th - I — used to enable or disable Interrupt (1-enables Interrupt, 0-disables Interrupt)

Bit number 6th – F – used to enable or disable Fast Interrupt (1-enables Interrupt, 0-disables Interrupt)

Bit number 5th - T –State Bit – If set to 1, Thumb mode is selected. If set to 0, ARM mode(normal mode) is selected.

Bit number 4th to 0th - Mode bits(M4-M0) - used to select the Processor Modes



Banked Registers

The ARM maintains a few separate/ duplicate registers that are available only when the processor is operating in a certain mode. Modes have their own local/private SP, LR and PSR.

The FIQ mode has separate r8 to r14 registers. The IRQ, SVC, ABT and UNDEF mode has separate r13 and r14 registers. That means when the processor is operating in any mode other than user mode, if the processor is accessing r13, then it will be a separate register; not the r13 which is used in user mode. So you don't need to save the content of r13 register when you are moving from user mode to any other mode because r13 used in user mode is different from r13 used in an another mode. These Duplicate registers make mode and context switching faster and more efficient. Also help decrease the amount of work required to do proper context switching when changing modes. SPSR (Saved Program Status Register) is the duplicate register of CPSR in different modes.

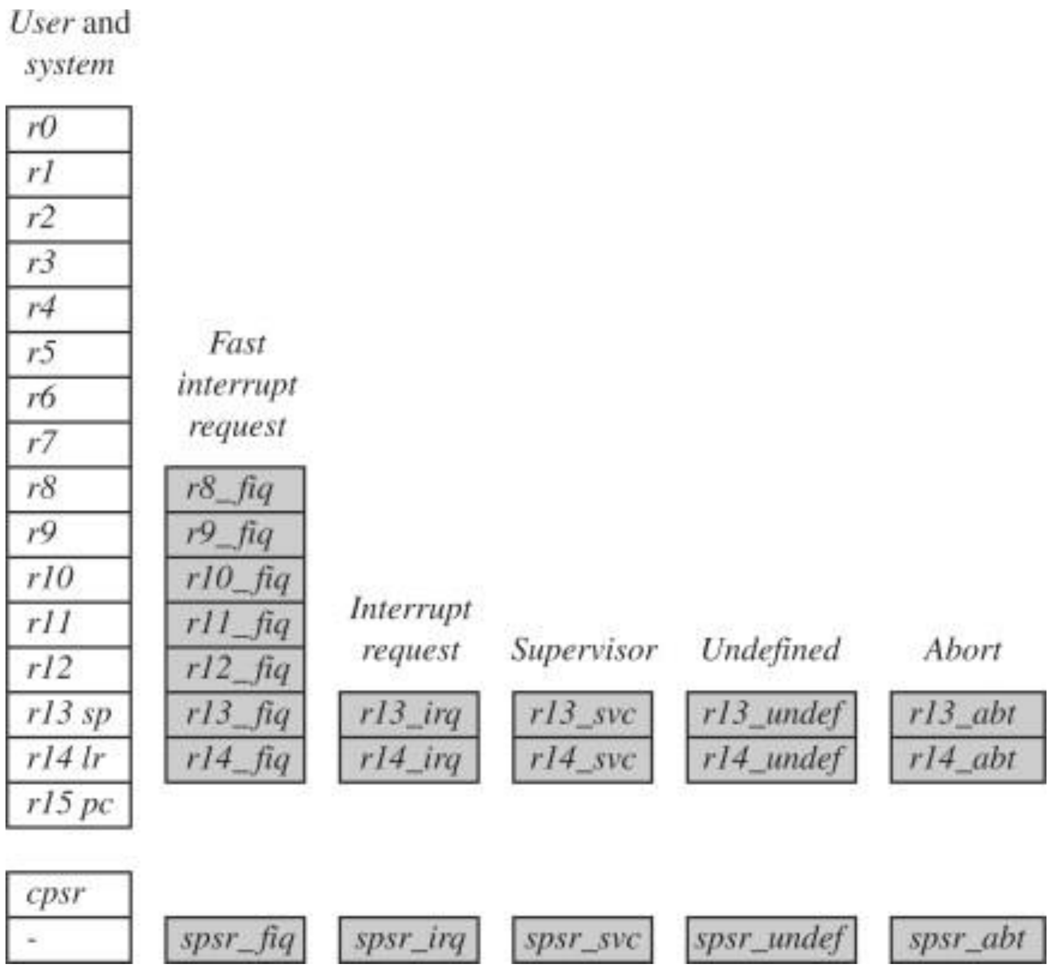


Fig: Register Bank

The above figure shows all 37 registers in the register file. Of those, 20 registers are hidden from a program at different times. These registers are called banked registers and are identified by the shading in the diagram. Banked registers of a particular mode are denoted by an underline character post-fixed to the mode mnemonic or _mode. For example, when the processor is in the interrupt request mode, the instructions you execute still access registers named r13 and r14. However, these registers are the banked registers r13_irq and r14_irq. The user mode registers r13_usr and r14_usr are not affected by the instruction referencing these registers. A program still has normal access to the other registers r0 to r12.

ARM Programmers Model

Programmers model of a processor help the programmer to use the core component of the processor to program it. Programmer's model of ARM processor includes the details of the main core, registers of the processor, operating modes and the instruction set. Understanding Programmers model is important for the reusability of the processor, and software development tools.

Registers: In the application level view, an ARM processor has:

- 13 general purpose 32-bit registers, r0 to r12.
- Three 32-bit registers with special uses, SP, LR and PC, that can be described as r13 to r15.
- Special purpose registers are :
    - SP, Stack Pointer
    - LR, Link Register
    - PC, Program Counter

General Registers and Program Counter Modes

User32	FIQ32	Supervisor32	Abort32	IRQ32	Undefined32
R0	R0	R0	R0	R0	R0
R1	R1	R1	R1	R1	R1
R2	R2	R2	R2	R2	R2
R3	R3	R3	R3	R3	R3
R4	R4	R4	R4	R4	R4
R5	R5	R5	R5	R5	R5
R6	R6	R6	R6	R6	R6
R7	R7	R7	R7	R7	R7
R8	R8_fiq	R8	R8	R8	R8
R9	R9_fiq	R9	R9	R9	R9
R10	R10_fiq	R10	R10	R10	R10
R11	R11_fiq	R11	R11	R11	R11
R12	R12_fiq	R12	R12	R12	R12
R13	R13_fiq	R13_svc	R13_abt	R13_irq	R13_und
R14	R14_fiq	R14_svc	R14_abt	R14_irq	R14_und
R15 (PC)	R15 (PC)	R15 (PC)	R15 (PC)	R15 (PC)	R15 (PC)

Program Status Registers

CPSR	CPSR	CPSR	CPSR	CPSR	CPSR
	SPSR_fiq	SPSR_svc	SPSR_abt	SPSR_irq	SPSR_und

Modes of Operation: Processor can operate in seven different modes of operation namely user(USR) mode, Fast Interrupt Request(FIQ) mode, Interrupt Request (IRQ) mode, Supervisory(SVC) mode, Undefined (UNDEF) mode and Abort (ABT) mode. The bits 0 to 4 in the CPSR register decide the mode of operation of the processor at any point of time.

M[4:0]	Mode	Accessible Registers
10000	User	r0 – r14,PC,CPSR
10001	FIQ	r0 – r7,r8_fiq – r14_fiq,PC,SPSR_fiq
10010	IRQ	r0 – r12,r13_irq – r14_irq,PC,SPSR_irq
10011	Supervisor	r0 – r12,r13_svc – r14_svc,PC,SPSR_svc
10111	Abort	r0 – r12,r13_abt – r14_abt,PC,SPSR_abt
11011	Undef	r0 – r12,r13_und – r14_und,PC,SPSR_und

Memory: ARM 7 is having Von-Neumann, load-store architecture. The width of the data and address bus is 32 bit. Since the address bus width is 32 bits, the addressable memory is 2^{32}. Also only the load/store instructions access memory; all other instructions accesses registers to fetch data for execution, thereby making execution faster. Data type can be 8-bit bytes, 16-bit half words or 32-bit words.

Raspberry Pi 4 Board

Introduction

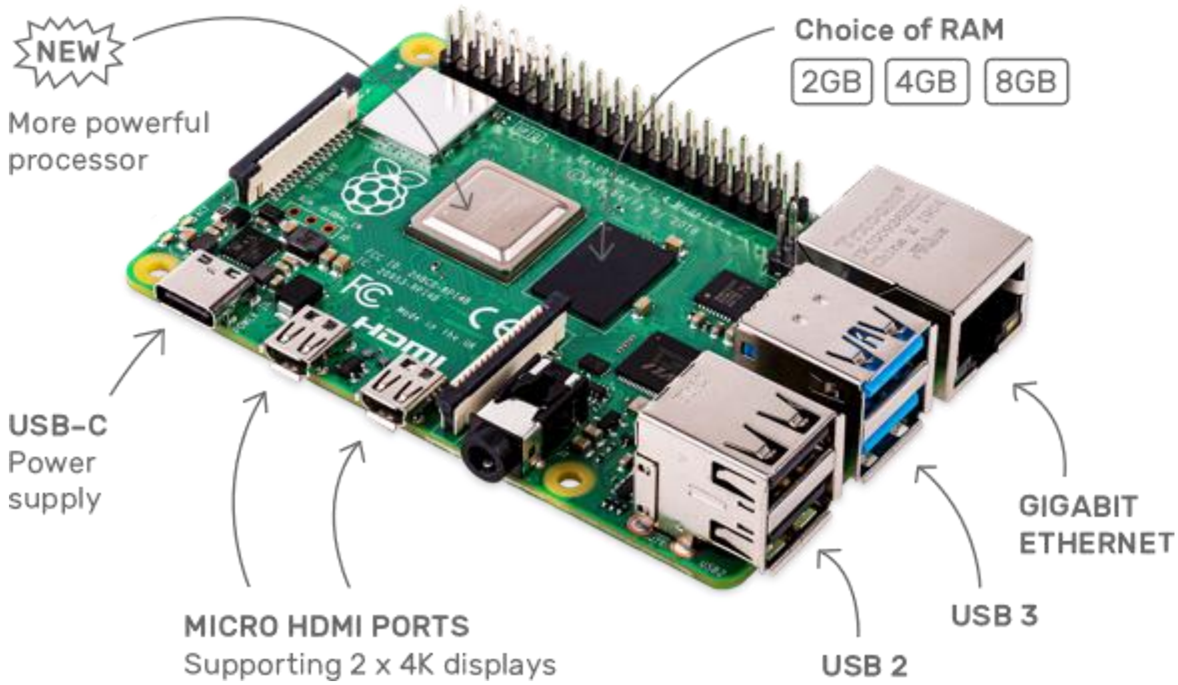
Raspberry Pi is a series of small single-board computers developed in the United Kingdom by the Raspberry Pi Foundation in association with Broadcom. The Raspberry Pi project originally leaned towards the promotion of teaching basic computer science in schools and in developing countries.

The first generation (Raspberry Pi Model B) was released in February 2012. In 2014, the Foundation released a board with an improved design, Raspberry Pi Model B+. The Raspberry Pi 2 was released in February 2015 and initially featured a 900 MHz 32-bit quad-core ARM Cortex-A7 processor with 1 GB RAM. Raspberry Pi 3 Model B was released in February 2016 with a 1.2 GHz 64-bit quad core ARM Cortex-A53 processor, on-board 802.11n Wi-Fi, Bluetooth and USB boot capabilities. Raspberry Pi 4 Model B was released in June 2019 with a 1.5 GHz 64-bit quad core ARM Cortex-A72 processor, on-board 802.11ac Wi-Fi, Bluetooth 5, full gigabit Ethernet (throughput not limited), two USB 2.0 ports, two USB 3.0 ports, 2-8 GB of RAM, and dual-monitor support via a pair of micro HDMI (HDMI Type D) ports for up to 4K resolution. The Pi 4 is also powered via a USB-C port, enabling additional power to be provided to downstream peripherals.

Brief Description of Raspberry Pi 4 Board

Raspberry Pi 4 Model B is the latest product in the popular Raspberry Pi range of computers. It offers ground-breaking increases in processor speed, multimedia performance, memory, and connectivity compared to the prior-generation Raspberry Pi 3 Model B+, while retaining backwards compatibility and similar power consumption. For the end user, Raspberry Pi 4 Model B provides desktop performance comparable to entry-level x86 PC systems.

This product's key features include a high-performance 64-bit quad-core processor, dual-display support at resolutions up to 4K via a pair of micro-HDMI ports, up to 8GB of RAM, dual-band 2.4/5.0 GHz wireless LAN, Bluetooth 5.0, Gigabit Ethernet and four USB ports.



Specifications

Processor	: Quad-core Cortex-A72 (ARM v8) 64-bit @ 1.5GHz
Memory	: 2GB, 4GB or 8GB
Connectivity	: 2.4 GHz and 5.0 GHz wireless LAN, Bluetooth 5.0 Gigabit Ethernet 2 × USB 3.0 ports 2 × USB 2.0 ports.
GPIO	: Standard 40-pin GPIO header
Video & sound	: 2 × micro HDMI ports (up to 4Kp60 supported)

SD card support : Micro SD card slot for loading operating system and data storage

Input power : 5V DC via USB-C connector

Applications of Raspberry Pi

Portable Bluetooth Speaker

Raspberry Pi is a palm sized computer having in-built Bluetooth, Wi-Fi, Ethernet port, Camera port etc. Here we will see how a Raspberry Pi can convert a normal speaker into a wireless Bluetooth speaker.

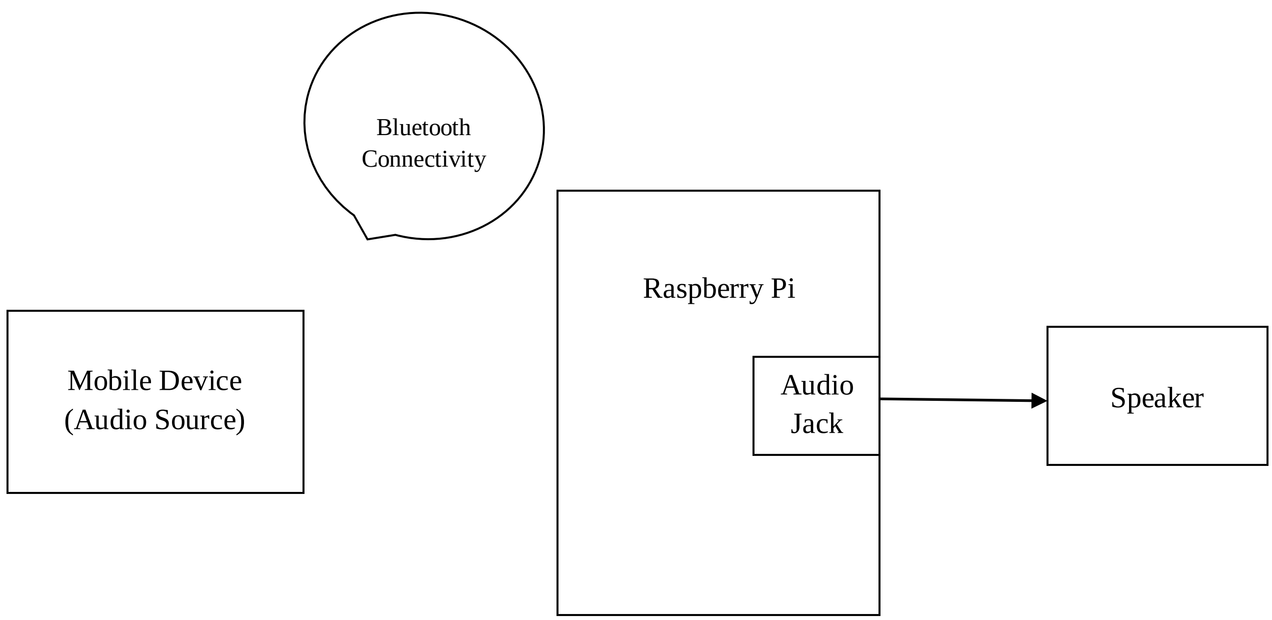


Fig: Portable Bluetooth Speaker using Raspberry Pi

Here using the Bluetooth facility available in Raspberry Pi, our mobile device can be paired to the Raspberry Pi. From the Raspberry Pi, make a connection to Speaker through the Audio Jack out of the Raspberry Pi. In this set up, our mobile device will act as the audio source and speaker act as the audio sink. Once our mobile and Raspberry Pi are paired through Bluetooth, whenever we play music in mobile, it will be played on the Speaker. So we can make use of this set up as a portable Bluetooth Speaker.

Photo Booth

A photo booth is a vending machine or modern kiosk that contains an automated, usually coin-operated, camera and film processor. Today, the vast majority of photo booths are digital. We can use the Raspberry Pi to make it easy to roll your own standalone photo booth that can connect to the internet with no help from your precious PC. Here's a simple build that's based on the Raspberry Pi minicomputer and Pi Camera Module. It can automatically emails your photos (if you wish) and uploads them to Google Photos where anyone with the password can see and share. All the software is open source.

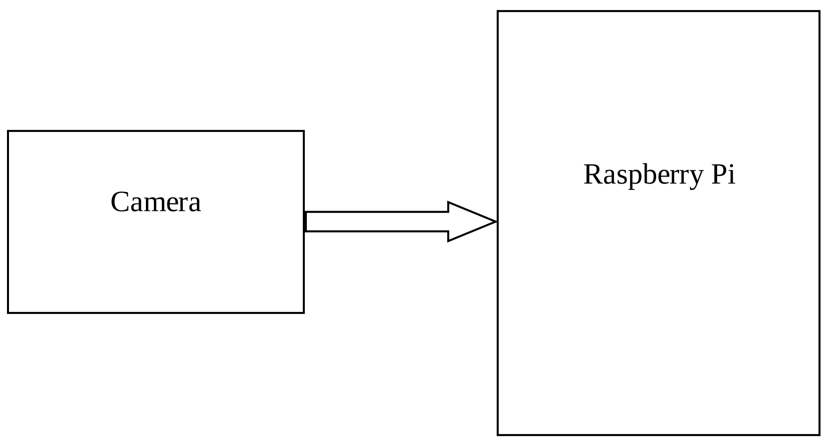


Fig: Photo Booth using Raspberry Pi

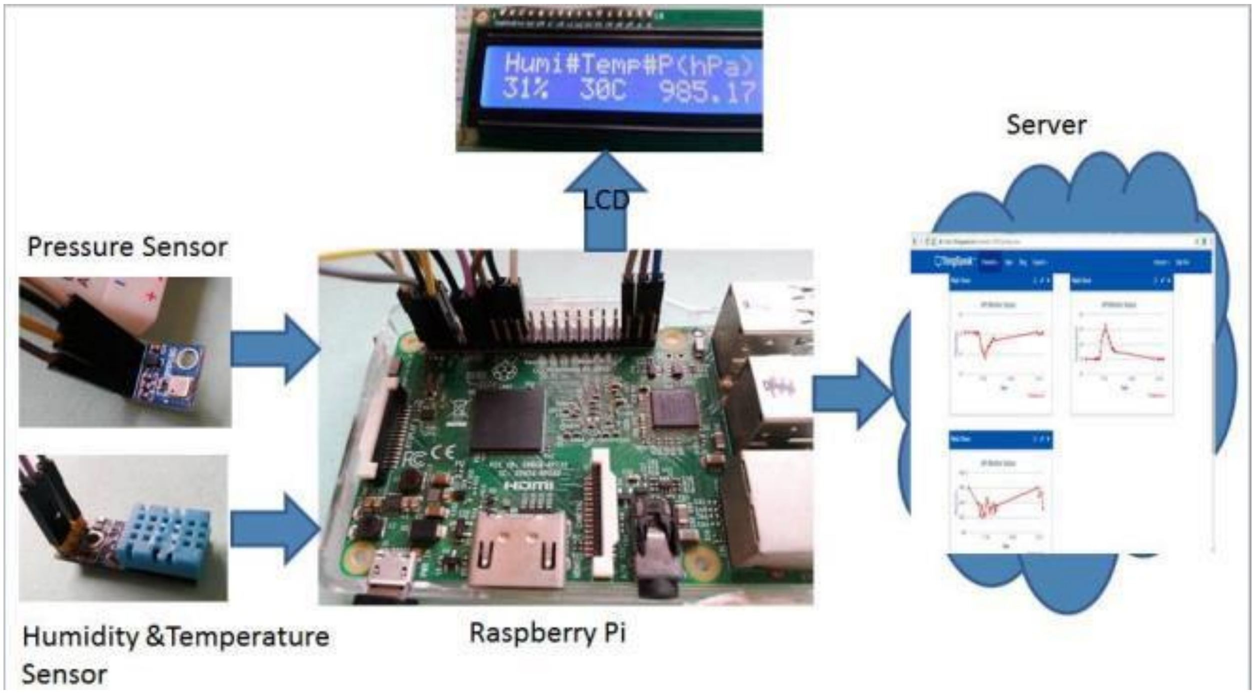
Raspberry Pi Remote Controlled Car

We can use Raspberry Pi to control a remote control car in a remote location. The car can be driven remotely through your mobile using Bluetooth. Connect the 2 DC motors to the Pi using GPIO pins on a car chasis. Now you need to pair your mobile to the Pi using Bluetooth. When you press the keys in your mobile, the car will move in the forward/backward or left/right directions.

IoT Weather Station

Humidity, Temperature and Pressure are three basic parameters to build any Weather Station and to measure environmental conditions. This IoT based set up aims to show the current Humidity, Temperature and Pressure parameters on the LCD as well on the Internet server using Raspberry Pi**,** which makes it a Raspberry Pi Weather Station. You can install this setup anywhere and can monitor the weather conditions of that place from anywhere in the world over the internet, it will not only show the current data but can also show the past values in the form of Graphs.

We can use Humidity & temperature sensor for sensing the temperature and Pressure sensor module for measuring barometric pressure. This Celsius scale Thermometer and percentage scale Humidity meter displays the ambient temperature and humidity through a LCD display and barometric pressure is displayed in millibar or hPa (hectopascal). All this data is sent to ThingSpeak server for live monitoring from anywhere in the world over internet.



Working and ThingSpeak Setup:

This IoT based set up has four sections. Firstly Humidity & temperature sensor senses the Humidity & Temperature Data and pressure sensor measures the atmospheric pressure. Secondly Raspberry Pi reads the Humidity & temperature sensor module's output and pressure sensor's output by using I2C protocol and extracts both sensors values into a suitable number in percentage (humidity), Celsius scale (temperature), hectoPascal or millibar (pressure). Thirdly, these values are sent to ThingSpeak server by using inbuilt Wi-Fi of Raspberry Pi 4. And finally ThingSpeak analyses the data and shows it in a Graph form. An LCD is also used to display these values locally.

We can create an account in ThingSpeak and give the account details in the Pi code to send the various parameters received by the Pi to the ThingSpeak Server which everyone can access from anywhere in the world.

Portable digital e-book library

How to turn a Raspberry Pi into an eBook server?

The Calibre eBook management software makes it easy to set up an eBook server on a Raspberry Pi 3, even in low-connectivity areas.

eBooks are a great way for teachers, librarians, and others to share books, classroom materials, or other documents with students—provided you have ready and reliable access to broadband. But even if you have low or no connectivity, there's an easy solution: Create an eBook server with the open source Calibre eBook management software running on a Raspberry Pi 4.

To set up the Calibre e-book management software, you need to download the software into your Pi. Once set up is finished, we can start downloading books. Once downloaded, you can start reading them offline.

You can also add books to the library from other content providers, not in Calibre's list. For example, a teacher could share open educational resources in eBook format with students through this content server. This is how you can convert your Raspberry Pi as a Portable digital e-book library.

Another highlight of this software is that you can share the e-books in your Pi to the rest of the systems in your network. For that you just need to share the IP address of your machine and others can get access to your system using that IP address.