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Practical Audio DSP Projects with the ESP32

Easy and Affordable Digital Signal Processing

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Preface

Digital Signal Processing (DSP) is the process of capturing, analyzing, and manipulating analog or digital signals by any type of digital processor including digital computers and microcontrollers.

The theory of DSP is quite complex and requires a good understanding of higher-level mathematics and discrete time systems. Students new to DSP are usually taught the theory in great detail with very few or no practical applications. For example, in many cases a student can derive complex equations for digital filters or Fast Fourier Transforms (FFT) but is unable to implement a simple digital filter in real life. Some institutions use tools such as MATLAB to derive the coefficients of digital filters and then to simulate the behavior of these filters on a PC. Although simulation can be an invaluable tool in teaching, it is never the same as real-time or real-life implementations.

The aim of this book is to teach the basic principles of DSP and to introduce DSP from a practical point of view using the bare minimum of mathematics. The level of discrete-time systems theory is sufficient to permit implementing DSP applications in real time. The emphasis of the book is on practical aspects of DSP such as design issues and real-time implementation issues. The practical implementation is described using the highly popular and widely available, low-cost, ESP32 DevKitC microcontroller development board enabling readers to easily and quickly design as well as implement DSP applications running in real time. The architectures of dedicated DSP processors are complex and this adds additional exertion to students who may want to implement DSP applications using such tools.

Using the ESP32 microcontroller, readers should be able to implement DSP applications with sampling frequencies within the audio range. Programming is accomplished using the well-liked and widely available Arduino IDE and the C language compiler. The DSP projects given in the book are based on using the I^{2}S bus. The standard ESP32 processor is equipped with two independent I^{2}S bus modules that can easily be interfaced to I^{2}S-compatible digital microphones or amplifiers.

The early sections of the book include simple projects using basic electronic components such as LEDs, LCD, sensors, and pushbuttons. These sections are aimed to provide a review of the basic programming concepts of the ESP32 processor using the Arduino IDE.

Later sections of the book include audio-based sound and DSP projects, including the following:

- Using I^{2}S-based digital microphone to capture audio sound
- Using I^{2}S-based class D audio amplifier and speaker
- Playing MP3 music stored on an SD card via I^{2}S-based amplifier and speaker
- Playing a list of MP3 music files stored on an SD card via I^{2}S-based amplifier and speaker
- Playing MP3 music files stored in ESP32 flash memory via I^{2}S-based amplifier and speaker

- Internet radio with I^{2}S-based amplifier and speaker
- Internet radio in stereo with dual I^{2}S-based amplifiers and speakers
- Text-to-speech with I^{2}S-based amplifier and speaker
- Using volume control in I^{2}S-based amplifier and speaker systems
- Speaking event counter with I^{2}S-based amplifier and speaker
- Sinewave generator with desired frequency on I^{2}S-based amplifier and speaker
- Digital low-pass and band-pass FIR design using external ADC and DAC
- Digital low-pass and band-pass IIR filter design using external ADC and DAC
- Fast Fourier Transform (FFT)

This book is primarily intended for students and practicing engineers who may want to learn the practical implementation of audio sound projects and DSPs in real time. Some working knowledge of MATLAB will be useful, especially in understanding the theory of discrete-time systems, Z-transforms, digital filters, and FFT. Previous knowledge of advanced electronics is not necessary but readers should have a basic understanding of electronics and electronic systems. Also, previous knowledge of the C programming language, especially in an Arduino IDE environment with an ESP32 processor will be invaluable.

We hope that you find the book useful and enjoyable, and swiftly get to developing your next audio-based projects based on the ideas given in this book.

Prof Dr Dogan Ibrahim, BSc MSc PhD CEng FIET
Ahmet Ibrahim, BSc MSc
London, June 2023

Chapter 1 • The ESP32 Processor

1.1 Overview

The ESP8266 from Espressif has been a highly popular processor costing less than $10. It is basically a WiFi enabled microcontroller with GPIOs that can be used in small monitoring and control applications. The ESP8266 has been developed by Shanghai-based Chinese manufacturer Espressif Systems and incorporates a full TCP/IP stack. There is a vast amount of information, tutorials, datasheets, applications notes, books, and projects based on the ESP8266. Several companies have created small development boards based on this processor, such as the ESP8266 Arduino and NodeMCU series.

Espressif has released a new and more powerful processor than the ESP8266, called the ESP32. Although ESP32 has not been developed to replace the ESP8266, it improves on it in many aspects. The new ESP32 processor not only has WiFi support but it also has a Bluetooth communications module, making the processor communicate with Bluetooth-compatible devices. The ESP32 CPU is the 32-bit Xtensa LX6 which is very similar to the ESP8266 CPU, but in addition it has two cores, more data memory, more GPIOs, higher CPU speed, ADC converters with higher resolution, DAC converter, and CAN bus connectivity.

The basic specifications of the ESP32 processor are summarized below:

- 32-bit Xtensa RISC CPU: Tensilica Xtensa LX6 dual-core microcontroller
- Operation speed 160 to 240 MHz
- 520 KB SRAM memory
- 448 KB ROM
- 16 KB SRAM (in RTC)
- IEEE 802.11 b/g/ne/I Wi-Fi
- Bluetooth 4.2
- 18 12-bit ADC channels
- 2 8-bit DAC channels
- 10 touch sensors
- Temperature sensor
- 36 GPIOs
- 4 × SPI
- 2 × I^2C
- 2 × I^2S
- 3 × UART
- 1 × CAN bus 2.0
- SD memory card support
- 2.2 V – 3.36 V operation
- RTC timer and watchdog
- Hall sensor
- 16 channels PWM
- Ethernet interface
- Internal 8 MHz, and RC oscillator
- External 2 MHz – 60 MHz and 32 kHz oscillator
- Cryptographic hardware acceleration (AES, HASH, RSA, ECC, RNG)

- IEEE 802.11 security features
- 5 μA sleep current

Table 1.1 shows comparison of the basic features of ESP32 and ESP8266 processors.

Specifications	ESP32	ESP8266
CPU	32-bit Xtensa L106 dual-core	32-bit Xtensa LX6 dual-core
Operating frequency	160 MHz	80 MHz
Bluetooth	Bluetooth 4.2	None
Wi-Fi	Yes (HT40)	Yes (HT20)
SRAM	512 KB	160 KB
GPIOs	36	17
Hardware PWM	1	None
Software PWM	16	8
SPI/I2C/I2S/UART	4/2/2/2	2/1/2/2
CAN	1	None
ADC	12-bit	10-bit
Touch sensor	10	None
Temperature sensor	1	None
Ethernet MAC interface	1	None

1.2 The ESP32 architecture

Figure 1.1 shows the functional block diagram of the ESP32 processor (see **ESP32 Datasheet**, *Espressif Systems*). At the heart of the block is the dual-core Xtensa LX6 processor and memory. On the left-hand side, you can see the peripheral interface blocks such as SPI, I^{2}C, I^{2}S, SDIO, UART, CAN, ETH, IR, PWM, temperature sensor, touch sensor, DAC, and ADC. The Bluetooth and WiFi modules are situated on the top middle part of the block diagram. The clock generator and the RF transceiver are located on the top right-hand of the block. The middle right hand is reserved for the cryptographic hardware accelerator modules such as the SHA, RSA, AES, and RNG. Finally, the bottom middle part is where the RTC, PMU, co-processor, and the recovery memory are.

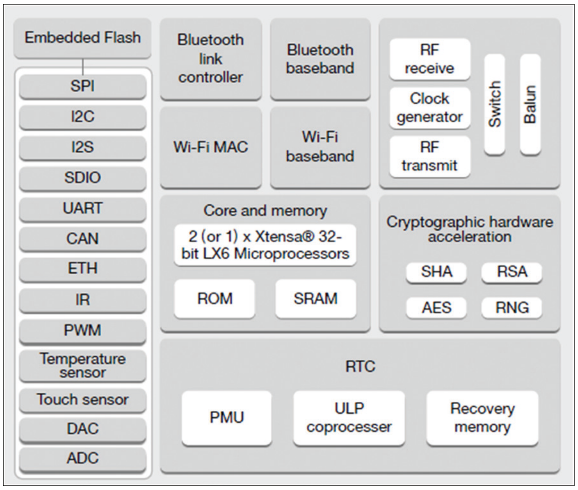


Figure 1.1: Functional block diagram of the ESP32 processor.

Figure 1.2 shows the system structure, consisting of two core Harvard architecture CPUs named PRO_CPU (for Protocol CPU) and APP_CPU (for Application CPU). The modules in the middle of the two CPUs are common to both CPUs. Detailed information about the internal architecture of the ESP32 can be obtained from the **ESP32 Technical Reference Manual,** *Espressif Systems*. Some information about the internal modules is given below.

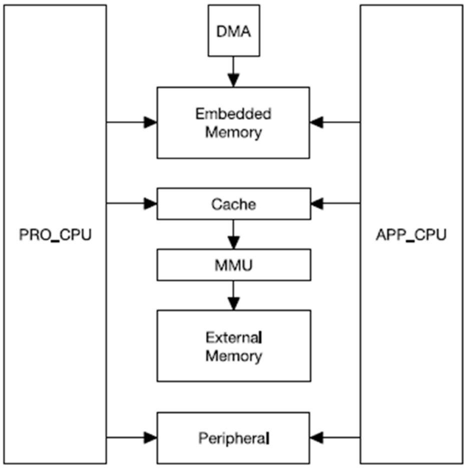


Figure 1.2: System structure.

1.2.1 The CPU

The CPU can operate at up to 240 MHz and supports 7-stage pipelining with a 16/24-bit instruction set. Floating-Point Unit and DSP instructions such as a 32-bit multiplier, 32-bit divider, and 40-bit MAC are supported. Up to 70 external and internal interrupt sources with 32 interrupt vectors are available. Debugging can be done with the JTAG interface.

1.2.2 Internal memory

In terms of memory, 520 KB SRAM and 448 KB ROM (for booting) are available on-chip. The Real-Time Clock module contains 8 KB slow memory and 8 KB fast memory. 1 Kbit of eFuse is available with 256 bits used for the MAC address and chip configuration, and the remaining 768 bits reserved for customer applications.

1.2.3 External memory

Up to four 16 MB external flash and SRAM memory devices are supported which can be accessed through a high-speed cache. Up to 16 MB of the external flash are mapped onto the CPU code space and up to 8 MB of the external flash/SRAM are mapped onto the CPU data space. Although data reading is supported both on flash and SRAM, data writing is supported on SRAM only.

1.2.4 General purpose timers

Four 64-bit general purpose software controllable timers are supported by the ESP32 processor. The timers have 16-bit prescalers (2 to 65535) and auto-reload up/down counters. The timers can generate interrupts if configured.

1.2.5 Watchdog timers

Three watchdog timers with programmable timeout values are available. Two watchdog timers, called the main Watchdog Timers are inside the general purpose timers, while the third one, called the RTC Watchdog Timer, is inside the RTC module. The actions taken when a watchdog timer resets can be one of: interrupt, CPU reset, core reset, and system reset.

1.2.6 The system clock

An external crystal clock controls the system timing when the processor is reset. The clock frequency is typically 160 MHz configured with the help of a PLL.

An 8 MHz accurate internal clock is also available. The programmer can either select the external or the internal clock.

1.2.7 Real-time clock (RTC)

An RTC is provided that can be clocked using an external 32 kHz crystal, an internal RC oscillator (typically 150 kHz), an internal 8 MHz oscillator, or an internal 31.25 kHz clock derived by dividing the 8 MHz internal oscillator by 256.

1.2.8 General purpose input-outputs (GPIOs)

There are 34 GPIOs that can be configured as digital, analog, or as a capacitive touch screen. Digital GPIOs can be configured to have internal pull-up resistors or pull-down resistors or set to a high impedance state. Input pins can be configured to accept interrupts on either edge or on level changes.

1.2.9 Analog to digital converter (ADC)

The ESP32 processor includes 18 channels of 12-bit ADC. Small analog voltages can be measured by configuring some of the pins as programmable gain amplifiers.

1.2.10 Digital to analog converter (DAC)

The ESP32 processor includes two independent 8-bit DACs.

1.2.11 Hall sensor

A Hall effect sensor is available on the processor based on a resistor. A small voltage that can be measured by the ADC is developed when the sensor is inside a magnetic field.

1.2.12 Built-in temperature sensor

An analog internal temperature sensor is available that can measure the temperature in the range of –40 ºC to +125 ºC. The measured temperature is converted into digital form using an ADC. The measurement is affected by the temperature of the chip and the modules active inside the chip and thus, the temperature sensor is only suitable to measure temperature changes rather than measuring the absolute temperature.

1.2.13 Touch sensor

Up to 10 capacitive touch sensors are provided that can detect the capacitive changes when a GPIO pin is in direct contact with a finger or any other suitable object.

1.2.14 UART

Three UARTs with speeds up to 5 Mbps are provided for RS232, RS485 and IrDA serial communications.

1.2 15 I^{2}C interface

The ESP32 processor supports up to two I^{2}C bus interfaces that can be configured in "master" or "slave" modes. The interface supports 400 Kbits/s fast transfer mode with 7-bit/10-bit addressing mode. External devices compatible with the I^{2}C bus can be connected to these pins.

1.2.16 I^{2}S interface

ESP32 processor supports up to two I^{2}S bus interfaces that can be configured in master or slave modes, in full or half duplex. The clock frequency can be from 10 kHz to 40 MHz. The I^{2}S interface is used in digital audio processing applications and will be used in all of the audio DSP projects in this book.

1.2.17 Infrared controller

Up to 8 channels of programmable infrared remote controller transmissions are supported by ESP32. The transmitting and receiving waveforms can be stored in shared 512 × 32-bit memory.

1.2.18 Pulse width modulation

Pulse Width Modulation (PWM) is used to control devices such as motors, electric heaters, smart lights and so on. ESP32 offers one programmable hardware PWM module and 16 software configurable PWM modules.

1.2.19 LED PWM

The LED PWM can be used to generate up to 16 independent digital waveforms with configurable duty cycles and periods. The duty cycle can be changed by software in a step-by-step mode.

1.2.20 Pulse counter

Up to 8 channels of pulse counters are provided to capture pulses and count pulse edges. An interrupt can be generated when the count reaches a pre-defined value.

1.2.21 SPI interface

Up to 4 SPI interfaces are supported by ESP32 in master and slave modes. External devices compatible with the SPI bus interface can be connected to these pins.

1.2.22 Hardware accelerators

ESP32 supports hardware accelerators for implementing mathematical operations on algorithms such as AES, SHA, RSA and ECC. These accelerators help to increase the operation speed and also reduce the software complexity.

1.2.23 Wi-Fi

ESP32 includes a WiFi module that can be used in projects to communicate with other WiFi devices, such as mobile phones, PCs, laptops, iPads, etc., through a network router.

1.2.24 Bluetooth

A Bluetooth module is included on the ESP32 processor. With the help of this module, you can develop projects to communicate with other Bluetooth-compatible devices, such as mobile phones, PCs, iPads, and others.

1.2.25 Controller area network (CAN)

ESP32 includes a CAN bus controller that can be programmed to communicate with other ESP32 processors or other CAN bus-compatible devices.

1.2.26 SD card support

ESP32 supports SD memory cards, thus making it possible to store data, for example, on a memory card.

1.3 ESP32 development boards

The ESP32 chip is highly complex and cannot easily be used on its own. There are several development boards available in the marketplace based on the ESP32 chip. These development boards incorporate the ESP32 chip and associated hardware to simplify the task of project development based on the ESP32.

Some popular ESP32 development boards available at the time of authoring this book include:

- SparkFun ESP32 thing
- Geekcreit ESP32 Development Board
- HiLetgo ESP-WROOM-32 Development Board
- LoLin32 ESP32 Development Board
- Pycom LoPy Development Board
- ESP32 OLED Development Board
- Makerfocus ESP32 Development Board
- ESPS32 Test Board
- ESP32-EVB
- ESP32 Development Board by Pesky Products
- MakerHawk ESP32 Development Board
- Huzzah32 Development Board
- ESPea32
- NodeMCU-32s
- Node32S
- ESP32 DevKitC

Chapter 2 • The ESP32 DevKitC Development Board

2.1 Overview

In the last chapter, you had a look at the architecture of the ESP32 processor and its basic features and advantages. You have also read about some of the popular ESP32 development boards available in the marketplace.

Currently, ESP32 DevKitC is one of the most popular development boards based on the ESP32 processor. In this book, all projects to replicate at home or in your lab are based on this development board. It is therefore important that you learn the architecture and the features of this board in detail.

In this chapter, you will be looking at the features of the ESP32 DevKitC development board in greater detail.

2.2 ESP32 DevKitC hardware

The ESP32 DevKitC is a small ESP32 processor-based board developed manufactured by Espressif. As shown in Figure 2.1, the board is breadboard compatible and has the dimensions 55 mm × 27.9 mm. The one used in this book had the marking **ESPRESSIF ESP32-WROOM-32D** on its metal plate.

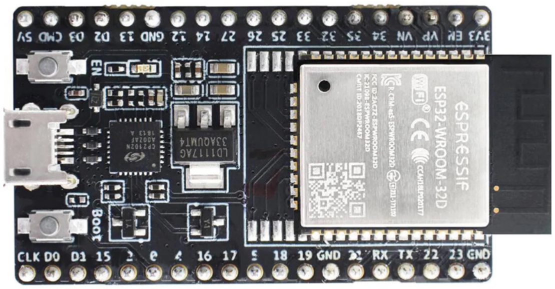


Figure 2.1: ESP32 DevKitC development board.

The board has two connectors located along each side of the board for GPIO, clock, and power line interfaces. Each connector has 19 pins. As shown in Figure 2.2, the two connectors carry the following signals:

Left Connector	**Right Connector**
+3.3V	GND
EN	IO23
SVP	IO22
SVN	TXD0
IO34	RXD0
IO35	IO21
IO32	GND
IO33	IO19
IO25	IO18

IO26	IO5
IO27	IO17
IO14	IO16
IO12	IO4
GND	IO0
IO13	IO2
SD2	IO15
SD3	SD1
CMD	SD0
+5V	CLK

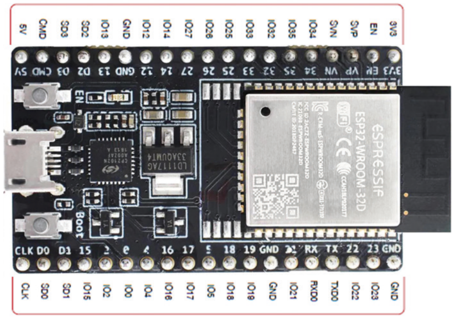


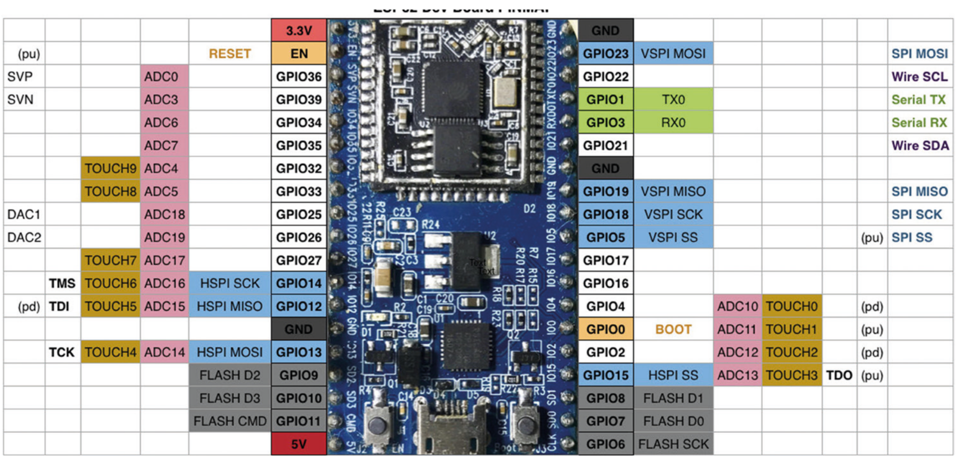
Figure 2.2: ESP32 DevKitC connectors.

The board has a mini USB connector for connection to a PC. The board also receives its power from the USB port. Standard +5 V from the USB port is converted into +3.3 V on the board. In addition, two buttons are provided on the board named EN and BOOT, with the following functions:

EN: This is the Reset button. Pressing this button resets the board.

BOOT: This is the Download button. The board is normally in operation mode where the button is not pressed. Pressing and holding down this button and at the same time pressing the EN button starts the firmware download mode allowing firmware to be downloaded to the processor through the USB serial port.

The pins on the ESP32 DevKitC board have multiple functions. Figure 2.3 shows the functions of each pin. For example, pin 10 is shared with functions GPIO port 26, DAC channel 2, ADC channel 19, RTC channel 7, and RX01.



					3.3V	GND						
(pu)				RESET	EN	GPIO23	VSPI MOSI					SPI MOSI
SVP			ADC0		GPIO36	GPIO22						Wire SCL
SVN			ADC3		GPIO39	GPIO1	TX0					Serial TX
			ADC6		GPIO34	GPIO3	RX0					Serial RX
			ADC7		GPIO35	GPIO21						Wire SDA
		TOUCH9	ADC4		GPIO32	GND						
		TOUCH8	ADC5		GPIO33	GPIO19	VSPI MISO					SPI MISO
DAC1			ADC18		GPIO25	GPIO18	VSPI SCK					SPI SCK
DAC2			ADC19		GPIO26	GPIO5	VSPI SS				(pu)	SPI SS
		TOUCH7	ADC17		GPIO27	GPIO17						
	TMS	TOUCH6	ADC16	HSPI SCK	GPIO14	GPIO16						
(pd)	TDI	TOUCH5	ADC15	HSPI MISO	GPIO12	GPIO4		ADC10	TOUCH0		(pd)	
					GND	GPIO0	BOOT	ADC11	TOUCH1		(pu)	
	TCK	TOUCH4	ADC14	HSPI MOSI	GPIO13	GPIO2		ADC12	TOUCH2		(pd)	
				FLASH D2	GPIO9	GPIO15	HSPI SS	ADC13	TOUCH3	TDO	(pu)	
				FLASH D3	GPIO10	GPIO8	FLASH D1					
				FLASH CMD	GPIO11	GPIO7	FLASH D0					
					5V	GPIO6	FLASH SCK					

Figure 2.3: Multiple functions of each pin. Source: www.cnx-software.com

Note that GPIO34, GPIO35, GPIO36, GPIO37, GPIO38 and GPIO39 ports are input only and cannot be used as output ports (GPIO37 and GPIO38 are not available on the ESP32 board).

The board operates at a typical power supply of +3.3 V although the absolute maximum is specified as +3.6 V. It is recommended that the current capacity of each pin should not exceed 6 mA, although the absolute maximum current capacity is specified as 12 mA. It is therefore important to use current limiting resistors while driving external loads such as LEDs. Depending upon the configuration, the RF power consumption during reception is around 80 mA, and it can be in excess of 200 mA during a transmission.

Programming of the ESP32 DevKitC requires the board to be connected to a PC through its mini USB port. The communication between the board and the PC takes place using the standard serial communication protocol. ESP32 DevKitC is preloaded with firmware that can be used to test the board. This firmware is activated by default when power is applied to the board. Before communicating with this firmware you have to run a terminal emulation program on your PC, such as the HyperTerm, Putty, X-CTU, and others.

Chapter 3 • Using the Arduino IDE with the ESP32 DevKitC

3.1 Overview

By default, the ESP32 DevKitC is distributed with no programming firmware installed. It is therefore necessary to install a programming language firmware on the processor permitting user programs to be developed and uploaded to the processor. Just like the ESP8266, the ESP32 processor is compatible with various programming languages such as C, MicroPython, and others.

The Arduino IDE is currently one of the most commonly used development environments for microcontrollers, especially for the Arduino family of microcontrollers. This IDE is easy to use, supports many microcontrollers, and includes a very rich library of functions that make programming easier. Most electrical/electronic engineering students and people whose hobbies are electronics are familiar with the Arduino IDE. In this chapter, you will be learning how to incorporate the ESP32 processor software interface into the Arduino IDE running on a Windows PC.

3.2 Installing the Arduino IDE for the ESP32 DevKitC

At the time of writing this book, the Arduino IDE had two current versions: Version 1 (more specifically 1.8.19), and Version 2 (more specifically 2.0.4). The steps for installing the ESP32 support on both versions of the Arduino IDE on a Windows PC are given in this section. If you already have installed ESP32 on Arduino IDE, then you must delete the **Espressif** folder from your Arduino directory before re-installing it.

Installing on version 1.8.19 of Arduino IDE

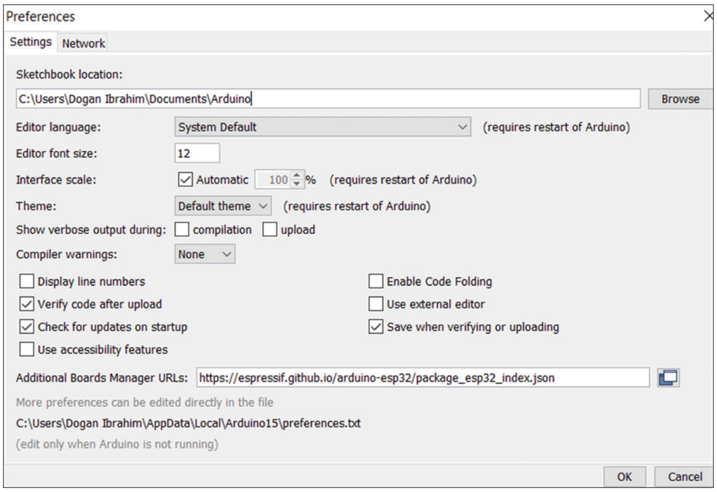
The steps to install the ESP32 on Arduino IDE version 1.8.19 are as follows.

- Download and install the latest version of Arduino IDE 1.8.19 from the following website:

  https://www.arduino.cc/en/Main/Software

- Open your Arduino IDE and click **File → Preferences** to open the Preferences window. Locate the text box **Additional Board Manager URLs** at the bottom of the window and enter the following text as shown in Figure 3.1. If the text box contains another URL, add the new URL after separating it with a comma:

  https://espressif.github.io/arduino-esp32/package_esp32_index.json


Preferences

Settings | Network

Sketchbook location: C:\Users\Dogan Ibrahim\Documents\Arduino

Editor language: System Default (requires restart of Arduino)

Editor font size: 12

Interface scale: ☑ Automatic 100 % (requires restart of Arduino)

Theme: Default theme (requires restart of Arduino)

Show verbose output during: ☐ compilation ☐ upload

Compiler warnings: None

☐ Display line numbers
☑ Verify code after upload
☑ Check for updates on startup
☐ Use accessibility features
☐ Enable Code Folding
☐ Use external editor
☑ Save when verifying or uploading

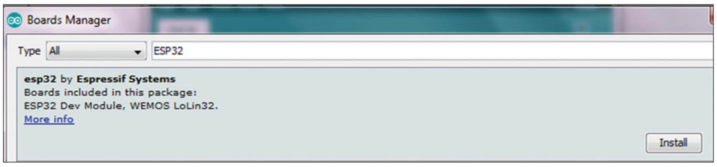
Additional Boards Manager URLs: https://espressif.github.io/arduino-esp32/package_esp32_index.json

More preferences can be edited directly in the file
C:\Users\Dogan Ibrahim\AppData\Local\Arduino15\preferences.txt
(edit only when Arduino is not running)

Figure 3.1: Preferences window.

- Click **OK**.

- Click **Tools → Boards → Board Managers** window and search for ESP32 as shown in Figure 3.2. Select the latest version.

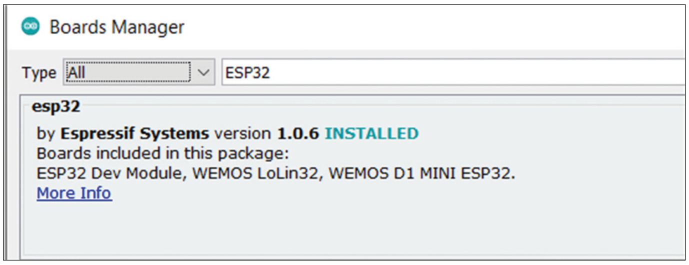

Boards Manager

Type All ESP32

esp32 by **Espressif Systems**
Boards included in this package:
ESP32 Dev Module, WEMOS LoLin32.
More info

Figure 3.2: Search for ESP32.

- Click **Install** button. You should see the Installed message as shown in Figure 3.3. **Close** the window. At the time of writing this book, the version was 2.09.


Boards Manager

Type All ESP32

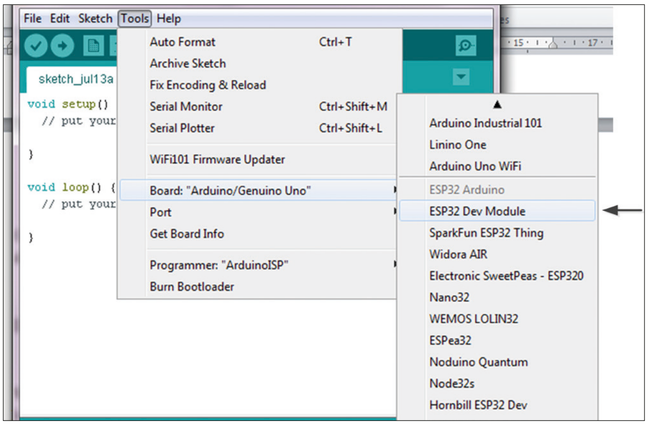
esp32
by **Espressif Systems** version **1.0.6** **INSTALLED**
Boards included in this package:
ESP32 Dev Module, WEMOS LoLin32, WEMOS D1 MINI ESP32.
More Info

Figure 3.3: ESP32 installed.

- You should now test the installation to make sure that all the necessary files have been loaded. You can make use of one of the supplied example applications to make sure that a program can be uploaded to the ESP32 processor and is working correctly.

- Plug in your ESP32 DevKitC to your PC. You should see the red power LED on the development board to turn ON. Start the Arduino IDE.

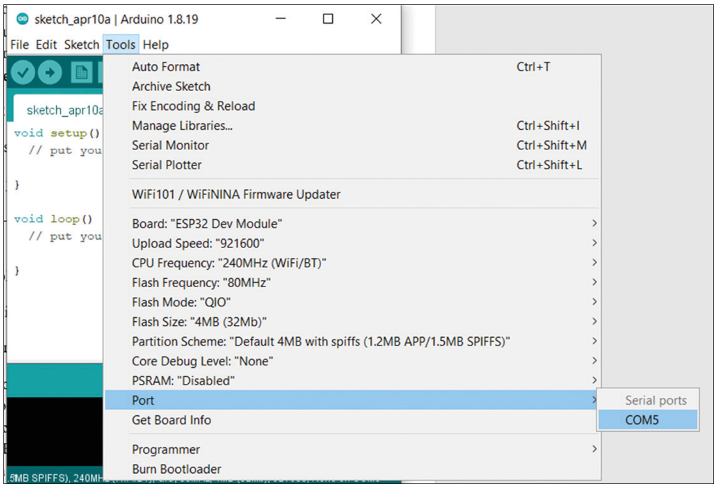
- Select **Tools → Board → ESP32 Dev Module** as shown in Figure 3.4.



```
void setup() {
  // put your

}

void loop() {
  // put your

}
```

Figure 3.4: Select the ESP32 Dev Module.

- Select the serial port number (**Tools → Port**). In this example, this is **COM5** as shown in Figure 3.5.


sketch_apr10a | Arduino 1.8.19
File Edit Sketch Tools Help
sketch_apr10a
Auto Format Ctrl+T
Archive Sketch
Fix Encoding & Reload
Manage Libraries... Ctrl+Shift+I
Serial Monitor Ctrl+Shift+M
Serial Plotter Ctrl+Shift+L
WiFi101 / WiFiNINA Firmware Updater
Port
Get Board Info
Programmer
Burn Bootloader
Serial ports
COM5

Board: "ESP32 Dev Module"
Upload Speed: "921600"
CPU Frequency: "240MHz (WiFi/BT)"
Flash Frequency: "80MHz"
Flash Mode: "QIO"
Flash Size: "4MB (32Mb)"
Partition Scheme: "Default 4MB with spiffs (1.2MB APP/1.5MB SPIFFS)"
Core Debug Level: "None"
PSRAM: "Disabled"

Figure 3.5: Select the serial port.

- Open the example program in **File → Examples → WiFi (in ESP32) → WiFi Scan** as shown in Figure 3.6.