Design of Embedded Systems with RaspberryPI

Version 1.0

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1. Acronyms

CPU
Central Processing Unit

EABI
Extended Application Binary Interface

EHCI
Enhanced Host Controller Interface

GPU
Graphical Processing Unit

I/O
Input and Output

MMC
Multimedia card

NAND
Flash memory type for fast sequential read and write

OS
Operating system

PCI
Peripheral Component Interconnect – computer bus standard

PCI Express
Peripheral Component Interconnect Express

UART
Universal Asynchronous Receiver Transmitter

USB
Universal Serial Bus

2. Getting started with RPI

This document describes the essential steps students have to follow to boot the Raspberry Pi with a Linux-based distribution such as Raspberry PI OS. After performing the operating system installation, the student must investigate the software tools installed and their potential. Finally, the student must implement a software application that measures 3D acceleration using a transducer. The following variants of application are proposed to the student:

1. Develop a simple console program developed in the C language.

2. (Optional) Develop an equivalent application using Python.

Note

[Time to complete the laboratory]: The time necessary to complete steps 1 to 3 in this tutorial is approximately 4 hours.

2.1. Reference Documentation

The following documentation has to be read and checked.

1. http://www.raspberrypi.org/help/. This web contains some guides and documents covering a lot of topics

2. https://projects.raspberrypi.org/en . RPI application examples

3. http://www.python.org. Phyton resources, tutorial, and reference

4. https://www.raspberrypi.org/courses/learn-python

5. http://i2c.info/i2c-bus-specification

2.2. Operating System Installation

2.2.1. Downloading and installing Raspberry PI OS

Several Linux and Android distributions can be installed on the Raspberry Pi platform. These Operating System distributions also include multiple software applications and tools such as text editors, music players, video editing and playing, games, development tools, etc.

Follow the steps below to install the Raspbian Operating System:

1. Download the Raspberry PI Imager tool for your specific OS.

2. Execute the application, and a window will be displayed (see Fig. 2.1). First choose the Raspberry PI hardware (see Fig. 2.2) and then, choose the Operating System (see Fig. 2.3) and Storage options (CHOOSE STORAGE) to burn an SD card with the Raspberry PI OS 32 bits version. Click on the NEXT button and you will have the options (see Fig. 2.4, Fig. 2.5, Fig. 2.6, Fig. 2.7) to apply your specific customization (**enable SSH**, Username (rpi-student) and Password (rpi) , WIFI SSID and passkey, and your keyboard language configuration). Save the configuration and continue to write the micro SD Card.

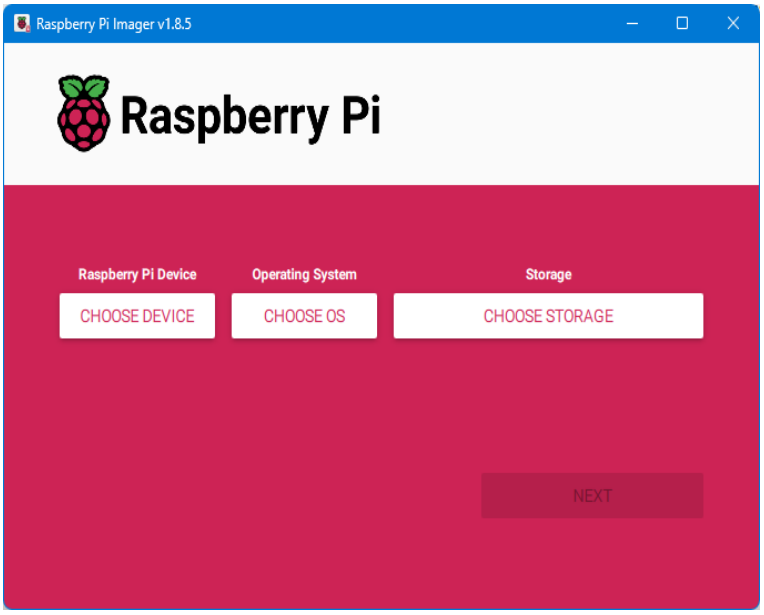


Fig. 2.1 Raspberry Pi Imager main screen

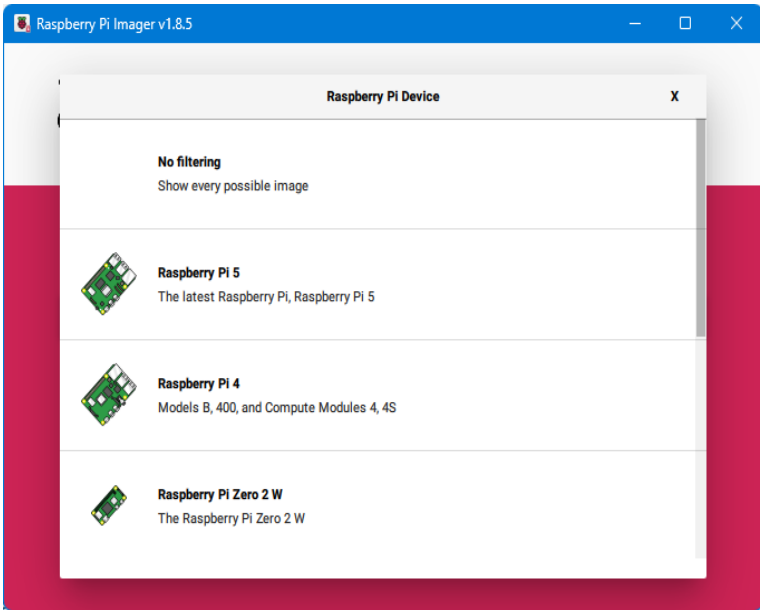


Fig. 2.2 Raspberry Pi Imager HW model

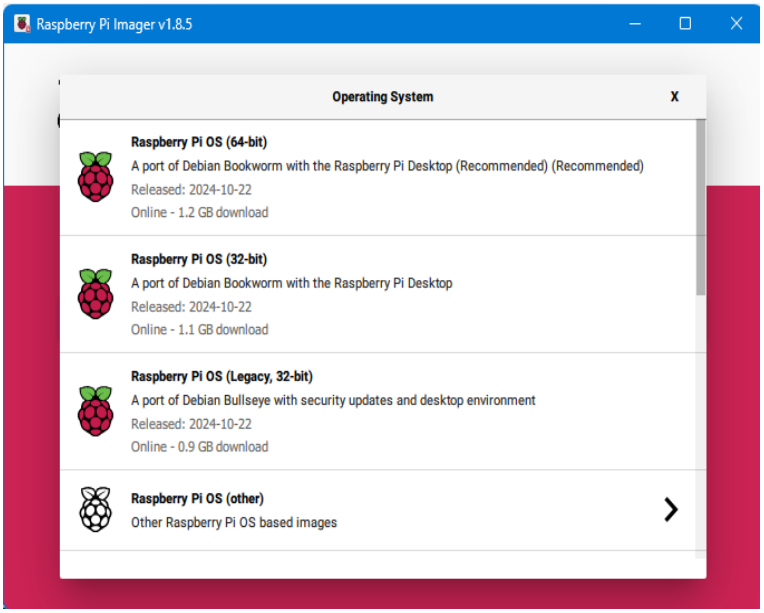


Fig. 2.3 Raspberry Pi Imager OS selection

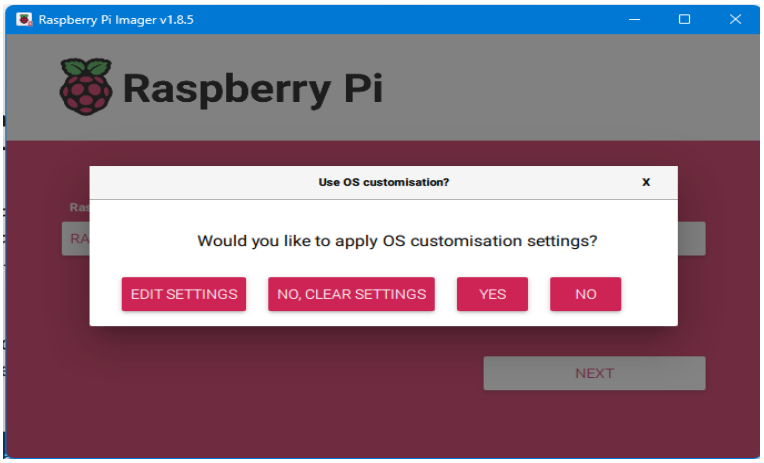


Fig. 2.4 Raspberry Pi Imager Settings (more info from RPI official documentation)

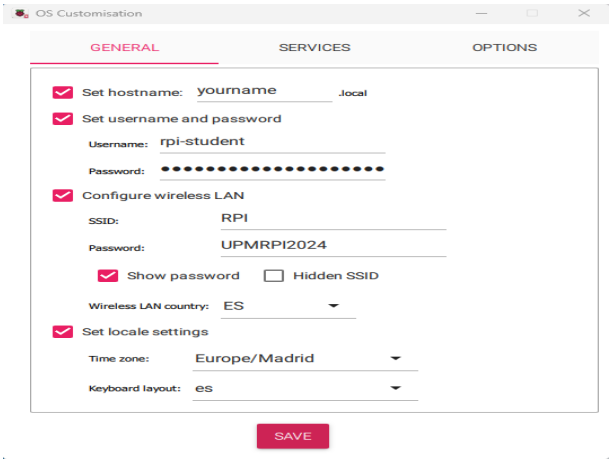


Fig. 2.5 Raspberry Pi Imager General Settings

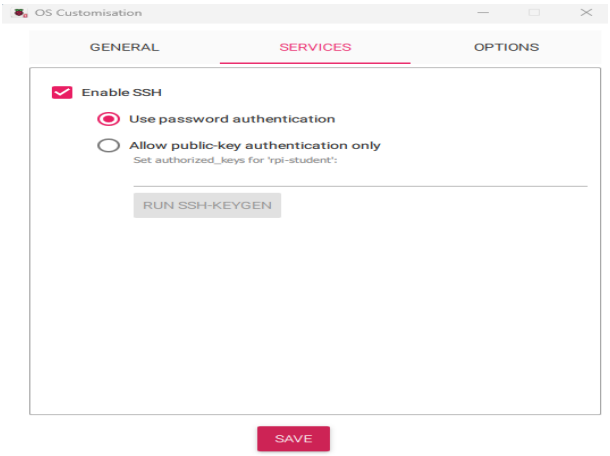


Fig. 2.6 Raspberry Pi Imager OS Services

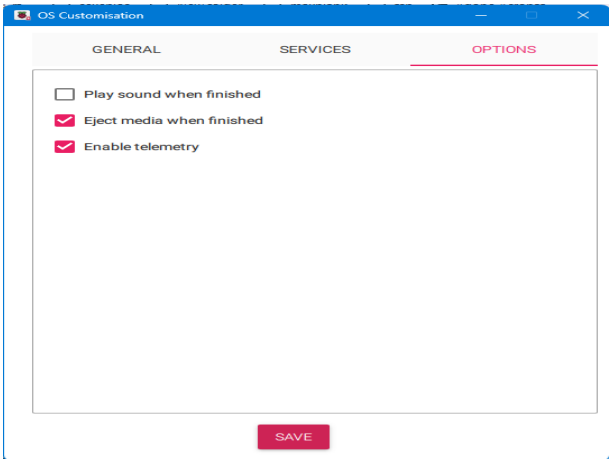


Fig. 2.7 Raspberry Pi Imager OS Options

⚠ Warning

[VERY IMPORTANT]: Be careful in the destination device where the image is burned because this information is not recoverable

1. Wait until the program ends writing the SD Card **(this can take up to one hour depending on your SD card category and model)**.

2.2.2. Setting up the Raspberry Pi

We need to interact with the Raspberry Pi for the activities described in this document. There are three ways to establish this interaction:

- The easiest one is connecting an HDMI monitor, a USB keyboard, and a USB mouse. This configuration allows us to use the Raspberry Pi as we would with a regular computer. Once the RPI is booted, we can set the WiFi connections and other settings such as enable the use of a serial line.
- Opening an SSH session between your computer and the Raspberry Pi without connecting additional peripherals. This kind of configuration is known as headless start (use the *rpi-student* login).
- Use the serial USB-TTL cable that you need to connect to the GPIO expansion connector. This requires first to enable the serial line in the Raspberry PI OS using the raspi-config tool. The connection of the USB-TTL cable is depicted in Fig. 2.8.

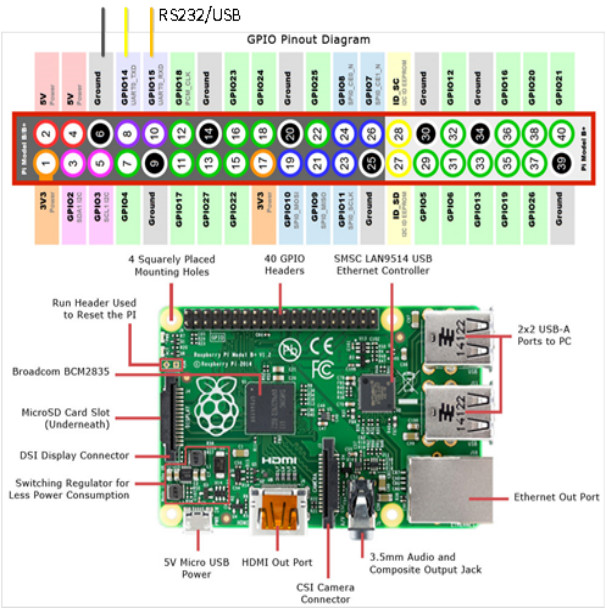


Fig. 2.8 Detail of expansion connector highlighting the USB-TTL RS232

2.2.3. Reviewing the SD card content

1. Plug in the SD card into the computer.

2. You should now see one new drive in the System Explorer (Windows)/Nautilus (Ubuntu) named “boot”. In Linux you will see two partitions mounted in your system. Open the partition/unit identified as “boot”.

Note

[VERY IMPORTANT]: This is the partition used by Raspberry to make the necessary hardware configuration before starting the operating system. Beware of not deleting or modifying files other than those described in this manual, or the Raspberry may not boot.

1. List the content of the boot partition (FAT32) and identify the files as in Fig. 2.9 (Ubuntu Linux).

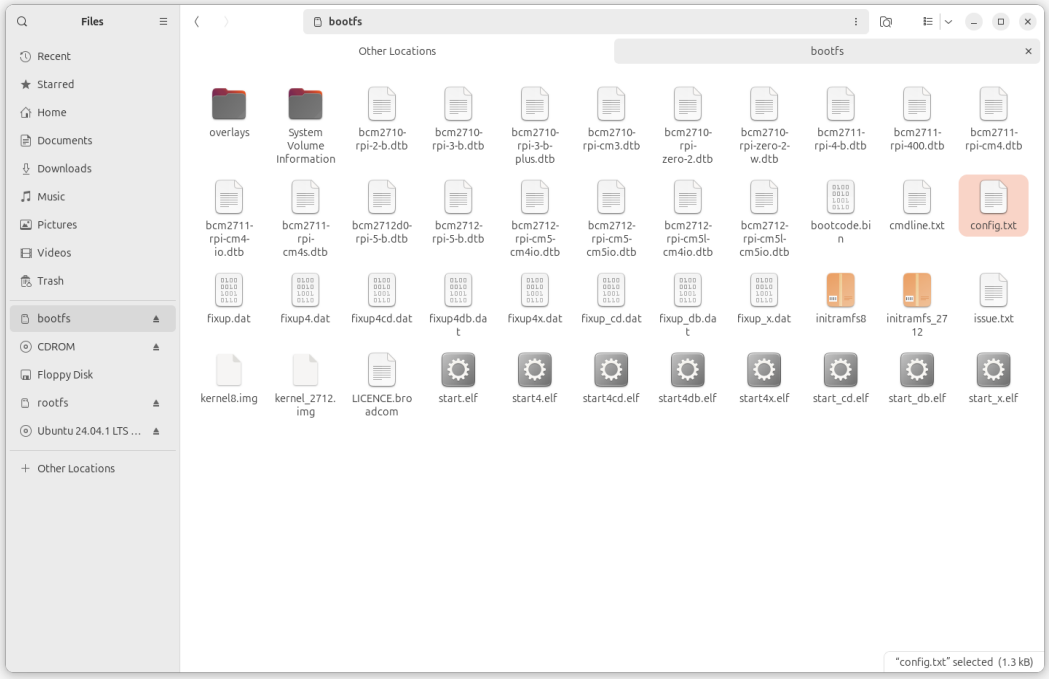


Fig. 2.9 Files available in the FAT32 partition

2.2.4. Booting the RPI

Insert the SD card and connect the power supply and all other cables needed. The first time you boot your RPI you will see how the RPI is configured (this information is only displayed in the

HDMI monitor) and rebooted. Wait 1 or 2 minutes (this depends again on your SD card category) until the RPI is completely booted.

Note

[Security]: Having the default user and password supposes a security issue, more if the SSH sessions are enabled. You can always change the password by executing the command passwd once logged in.

2.2.5. Discovering the RPI IP address

To open an SSH session from your computer to the Raspberry Pi you need to know its IP address. There are multiple ways to discover the Raspberry Pi IP address:

1. Use an IP Scanner utility, and scan in the range of your network. For example, you can quickly identify a Raspberry Pi as they use the hostname "raspberrypi.local" by default. This tool cannot be used at the UPM lab.
2. If you know your Raspberry Pi MAC address, you can set the DHCP server to assign a static IP to the Raspberry Pi MAC. This is typically done in the router configuration. Please, consider that Ethernet and WiFi ports have different MAC addresses. In the laboratory, your Raspberry can have only a dynamically assigned IP in the WIFI network with SSID RPI (ask your instructor to verify the configuration).
3. You could open an RS232 serial connection in the Raspberry Pi GPIO ports and use the command line (*ifconfig* command) to obtain the IP or set the desired IP and netmask.

2.2.6. Raspberry Pi OS Update

You can update and upgrade the OS if you have an internet connection. Please, do not update the OS during the classes, as this operation will require some time. You can update the OS by running the following commands:

Listing 2.1 RPI OS update

```
$ sudo apt update
$ sudo apt upgrade
```

2.3. Integration of a 3-axis accelerometer with Raspberry-Pi

2.3.1. Specifications

The student must investigate functions and commands and implement a C program to get the following requirements:

1. Show the values of the 3-axis acceleration obtained from the MPU-6000 I2C sensor.

2. The measurement readings are shown every 3 seconds.

2.3.2. Suggested Improvements

- Analyses the problem of offsets in the values returned. Define and implement a method to get corrected values
- Get stop the program if “CRTL-C” is typed.

2.3.3. Optional: Python Script

For advanced students, the implementation of this exercise in Python is proposed. For this, you can use any of the multiple Python modules that gain access to I2C interface in the Raspberry Pi.

2.4. Compiling & linking C program in Linux

In Linux, C/c++ programs are compiled and linked using the “make” command. This command searches a “Makefile”. A “Makefile” is a text file with the necessary information to compile and link and must be in the same directory of *myprogram.c*. The result will be *myprogram.o* and *myprogram* (executable).

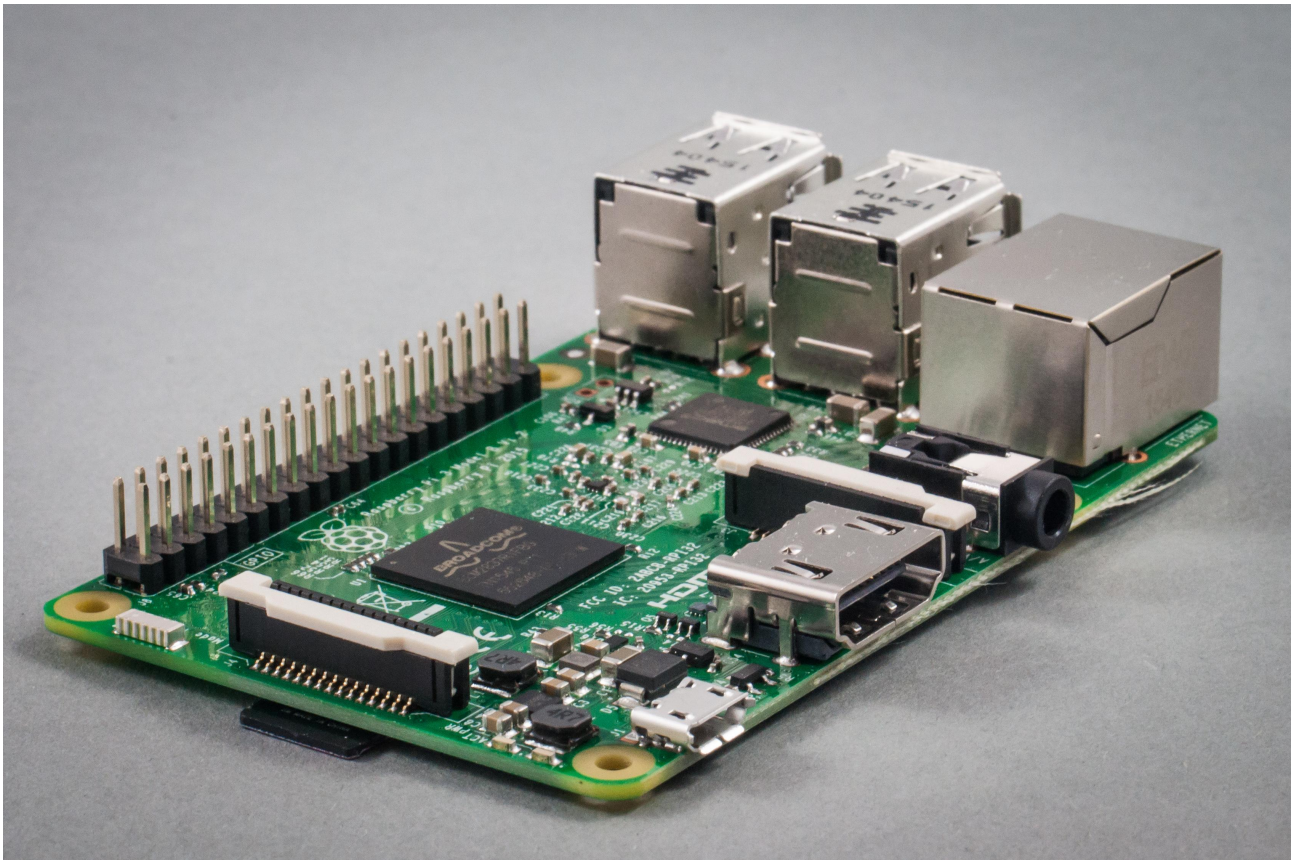
Listing 2.2 Detail Makefile

```
DEBUG= -O2 #Debugging Level

CC= gcc #Compiler command
INCLUDE= -I/usr/local/include #Include directory
CFLAGS= $(DEBUG) -Wall $(INCLUDE) -Winline #Compiler Flags
LDFLAGS= -L/usr/local/lib #Linker Flags
```

```
LIBS= -lpthread -lm #Libraries used if needed

SRC = myprogram.c

OBJ  = $(SRC:.c=.o)
BIN  = $(SRC:.c=)

$(BIN):       $(OBJ)
     @echo [link] $@
     $(CC) -o $@ $< $(LDFLAGS) $(LIBS)
.c.o:
     @echo [Compile] $<
     $(CC) -c $(CFLAGS) $< -o $@

clean:
     @rm -f $(OBJ) $(BIN)
```

2.5. Questions to be reported to instructors

1. Explain the content of the *config.txt* file in the FAT32 partition of the uSDCARD of your RPI
2. How the I2C interface is enabled? Is there any change in the config.txt file?
3. Could you describe the commands used to compile a C/C++ program in Linux?
4. What is a library? What is the difference between a static and a shared library?
5. Summarize the utility of the *makefile* file and the make command.
6. What is the preferred utility to debug a C program in Linux?
7. How can you obtain the serial number of your Raspberry Pi? Is there any relation between the serial number and the MAC address?



3. Embedded Linux With RPI

3.1. Document Overview

This document describes the steps to develop an embedded Linux-based system using the Raspberry PI board. The document has been specifically written to use a Raspberry PI development system based on the BCM2837 processor. All the software elements used have a GPL license.

Note

The time necessary to complete all the tutorial steps is approximately 8 hours.

Read all the instructions carefully before executing the practical part; Otherwise, you will find errors, which are probably unpredicted. In parallel, you need to review the slides available at the Moodle site or at [RD1]

3.2. References

1. Embedded Linux system development. Slides
2. https://bootlin.com/training/embedded-linux/
3. Mastering Embedded Linux Programming - Second Edition. Packt. https://www.packtpub.com/product/mastering-embedded-linux-programming-second-edition/9781787283282
4. Raspberry-Pi User Guide. Reference Manual.

   www.myraspberry-pi.org/wp-content/.../Raspberry.Pi_.User_.Guide_.pdf

3.3. Building Linux using buildroot

3.3.1. Elements needed for the execution of these LABS

In order to execute this lab properly, you need the following elements:

1. The VMware player software version 17.6.1 or above. Available at Broadcom website (free download and use but you need to register). This software has already been installed on the laboratory desktop computer.

2. A VMWare virtual machine with Ubuntu 24.04 and all the software packages installed is already available on the Desktop. This virtual machine is available for your personal use. If you want to set up your virtual machine by yourself, follow the instructions provided in Annex I.

3. A Raspberry Pi, accessories and a USB cable are available at the laboratory.

4. Basic knowledge of Linux commands.

3.4. Starting the VMware

Start VMware Player and open the RPI Virtual Machine. Wait until the welcome screen is displayed (see Fig. 3.1 and Fig. 3.2). Login as "*ubuntu*" user using the password "ubuntu".

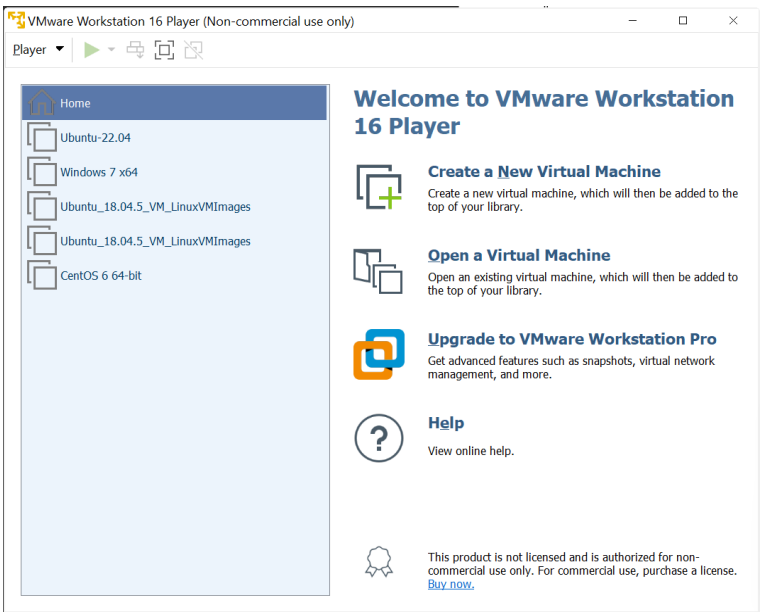


Fig. 3.1 Main screen of VMware player with some VM available to be executed

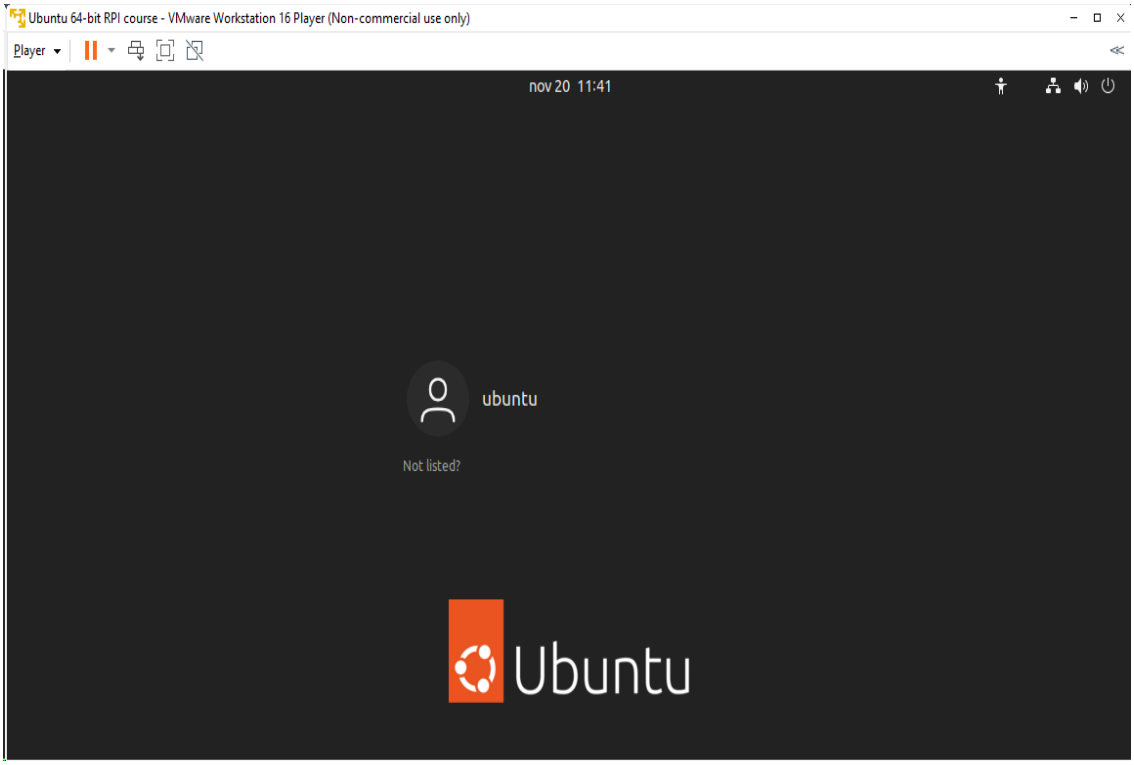
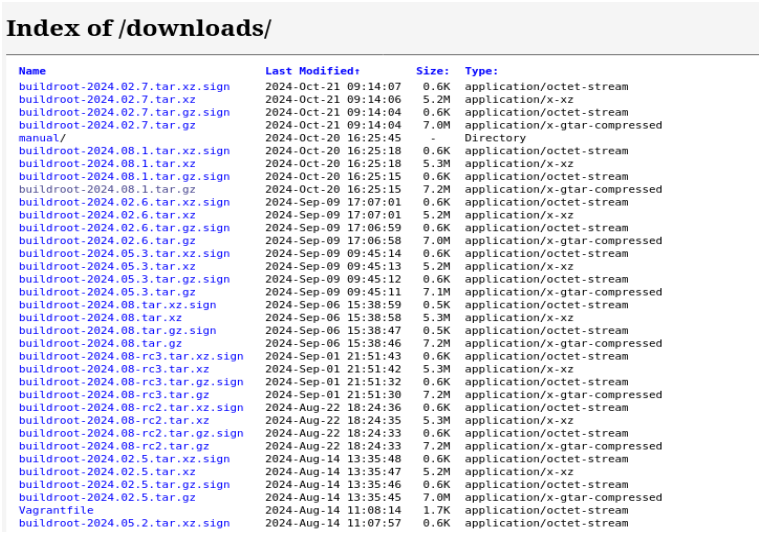


Fig. 3.2 Ubuntu Virtual Machine login screen.

Open the **Firefox** web browser and download from https://buildroot.org/, the version identified as **buidlroot2024-08-1** (use the download link, see Fig. 3.3, and navigate searching for earlier releases if necessary, https://buildroot.org/downloads/). Save the file to the **Documents** folder in your account (Fig. 3.4).

Fig. 3.3 Buildroot home page.

Buildroot is a tool to generate embedded Linux systems in our PC, and then this Linux will be installed in the target.



Index of /downloads/

Name	Last Modified↑	Size:	Type:
buildroot-2024.02.7.tar.xz.sign	2024-Oct-21 09:14:07	0.6K	application/octet-stream
buildroot-2024.02.7.tar.xz	2024-Oct-21 09:14:06	5.2M	application/x-xz
buildroot-2024.02.7.tar.gz.sign	2024-Oct-21 09:14:04	0.6K	application/octet-stream
buildroot-2024.02.7.tar.gz	2024-Oct-21 09:14:04	7.0M	application/x-gtar-compressed
manual/	2024-Oct-20 16:25:45	-	Directory
buildroot-2024.08.1.tar.xz.sign	2024-Oct-20 16:25:18	0.6K	application/octet-stream
buildroot-2024.08.1.tar.xz	2024-Oct-20 16:25:18	5.3M	application/x-xz
buildroot-2024.08.1.tar.gz.sign	2024-Oct-20 16:25:15	0.6K	application/octet-stream
buildroot-2024.08.1.tar.gz	2024-Oct-20 16:25:15	7.2M	application/x-gtar-compressed
buildroot-2024.02.6.tar.xz.sign	2024-Sep-09 17:07:01	0.6K	application/octet-stream
buildroot-2024.02.6.tar.xz	2024-Sep-09 17:07:01	5.2M	application/x-xz
buildroot-2024.02.6.tar.gz.sign	2024-Sep-09 17:06:59	0.6K	application/octet-stream
buildroot-2024.02.6.tar.gz	2024-Sep-09 17:06:58	7.0M	application/x-gtar-compressed
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buildroot-2024.08.tar.gz	2024-Sep-06 15:38:46	7.2M	application/x-gtar-compressed
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buildroot-2024.08-rc3.tar.gz.sign	2024-Sep-01 21:51:32	0.6K	application/octet-stream
buildroot-2024.08-rc3.tar.gz	2024-Sep-01 21:51:30	7.2M	application/x-gtar-compressed
buildroot-2024.08-rc2.tar.xz.sign	2024-Aug-22 18:24:36	0.6K	application/octet-stream
buildroot-2024.08-rc2.tar.xz	2024-Aug-22 18:24:35	5.3M	application/x-xz
buildroot-2024.08-rc2.tar.gz.sign	2024-Aug-22 18:24:33	0.6K	application/octet-stream
buildroot-2024.08-rc2.tar.gz	2024-Aug-22 18:24:33	7.2M	application/x-gtar-compressed
buildroot-2024.02.5.tar.xz.sign	2024-Aug-14 13:35:48	0.6K	application/octet-stream
buildroot-2024.02.5.tar.xz	2024-Aug-14 13:35:47	5.2M	application/x-xz
buildroot-2024.02.5.tar.gz.sign	2024-Aug-14 13:35:46	0.6K	application/octet-stream
buildroot-2024.02.5.tar.gz	2024-Aug-14 13:35:45	7.0M	application/x-gtar-compressed
Vagrantfile	2024-Aug-14 11:08:14	1.7K	application/octet-stream
buildroot-2024.05.2.tar.xz.sign	2024-Aug-14 11:07:57	0.6K	application/octet-stream

Fig. 3.4 Example of Downloading Buildroot source code.

Create a folder “rpi” in “Documents”. Copy the file to the “Documents/rpi” folder and decompress the file (Fig. 3.5).

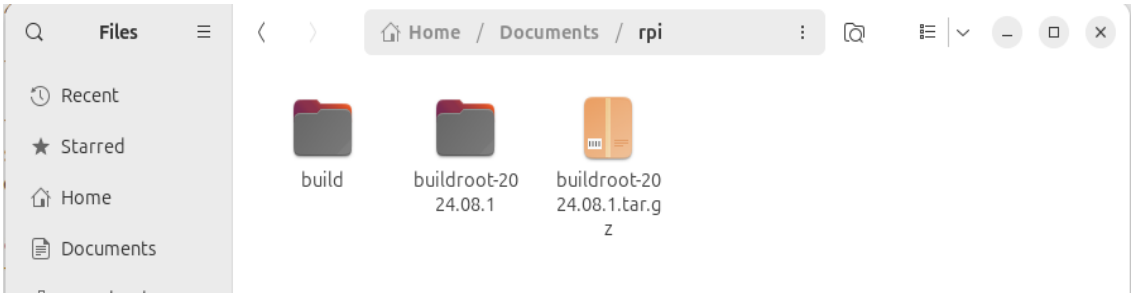


Fig. 3.5 Buildroot folder (the folder name depends on the version downloaded).

Right-click in the window and execute “Open in Terminal” or execute the Terminal application from Dash home as shown in Fig. 3.6 (if “Open in Terminal” is not available, search how to install it in Ubuntu).

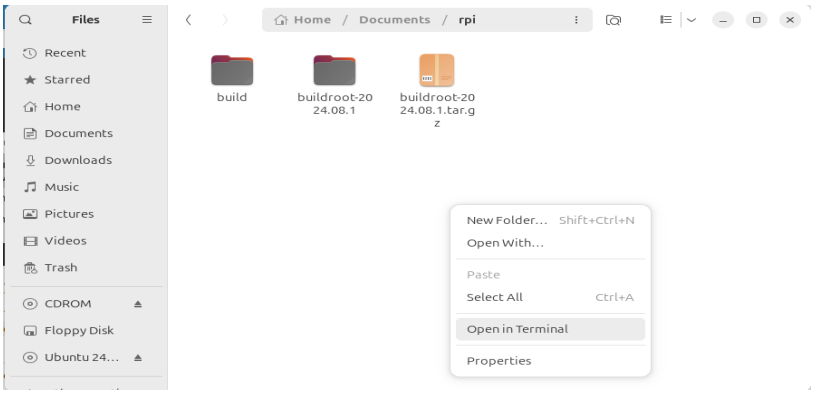


Fig. 3.6 Terminal application

In some seconds, a command window is displayed. Then, execute these commands:

```
$ mkdir build
$ cd build
```

```
$ make O=$PWD -C /home/ubuntu/Documents/rpi/buildroot-2025.02.9/
menuconfig
```

Important

The **build** folder will contain all the compilation of the embedded Linux generated. Remember to change to this folder before doing any operation with buildroot

Important

For this course, you will need to become familiar with the Linux Terminal use. On the Moodle site of this course, you can find a cheat sheet with the basic Linux commands.

Tip

In a Linux terminal, the “TAB” key helps you to autocomplete the commands, folders, and file names.

In some seconds, you will see a new window similar to Fig. 3.7.

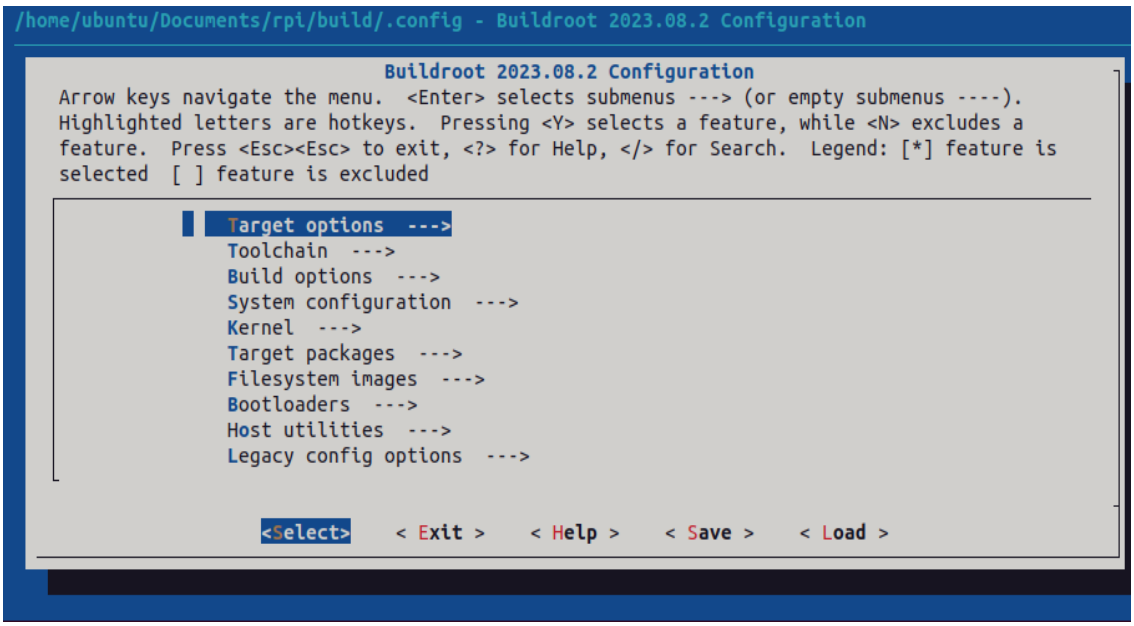


Fig. 3.7 Buildroot setup screen.

3.5. Configuring Buildroot for RPI4

Once the **Buildroot** configuration is started, it is necessary to configure the different items. You need to navigate the different menus and select the installation elements. Table I contains the specific configuration of **Buildroot** for installing it in the Raspberry Pi. Depending on the downloaded version, the organization and the items displayed can differ. If an item of buildroot configuration does not appear in the Table I leaves it with its default value.

Important

The Buildroot configuration is an iterative process. In order to set up your embedded Linux system, you will need to execute the configuration several times.

Warning

The tables have three colums. Check that you understnad all the content shown.

3.5.1. Target Options

This is the selection of the processor to use (Table 3.1).

Table 3.1 Target Options

Target Architecture	AArch64 (little endian)	ARM 64 bits
Target Architecture Variants.	Cortex-A72	
Floating Point Strategy	VFPv4	
MMU Page Size	4KB	
Target Binary Format	ELF	

3.5.2. Toolchain

Cross Compiler, linker, and libraries to be built to compile our embedded application. Select the options shown in the following table (Table 3.2).

Table 3.2 Toolchain

Toolchain type	Buildroot toolchain	The Embedded Linux System will be compiled with tools integrated into Buildroot
Custom toolchain vendor name.	buildroot	
C library	glib	Library containing the typical C libraries used in Linux environments (stdlib, stdio, etc)
Kernel Headers	Same as kernel being built	Include files for kernel
Kernel Header Options	6.6.x kernel headers	
Binutils Version	2.43.1	Binutils contains tools to manage the binary files obtained in the compilation of the different applications
GCC compiler Version	gcc 13.x	GCC tools version to be installed
Enable C++ support	Yes.	Including support for C++ programming, compiling, and linking.
Build cross gdb for the host	Yes.	Includes the support for GDB.

Add Python support	Yes
GDB debugger version	gdb 15.x

3.5.3. Build options

How Buidlroot will build the code. Leave the default values.

3.5.4. System Configuration

Here you can define the basic configuration of the embedded Linux to generate and specific scripts to add additional functionality (Table 3.3).

Table 3.3 System-configuration

Root FS skeleton	Default target skeleton.	Linux folder filesystem organization for skeleton the embedded system
System hostname	**buildroot**	Name of the embedded system
System Banner	**Linux RPI 4**	Banner.
Passwords encoding	sha 256	
Init System	Busybox	
/dev management	Dynamic using devtmpfs + mdev	
Path to permissions for table	**system/device_table.txt**	
	yes	

Enable root login with password		
Root password	rpi	
Busybox' default shell	/bin/sh	
Run a getty after boot	tty PORT: **console**. Baudrate: keep kernel default. TERM environment variable: vt100	
remount root filesystem read write during boot	Yes	
Network interface to configure through DHCP	eth0	
Set the system's default PATH	/bin:/sbin:/usr/bin:/usr/sbin	
Purge unwanted locales	yes	
Leave the default values for all others		
Custom scripts to run path **before** creating filesystem images	**your path**/buildroot-2025.02.9/board/raspberrypi4-64/post-build.sh	your path -> "/home/...." os where you have decompressed buildroot
Custom scripts to run inside the fakeroot environment		

Custom scripts to run **after** creating filesystem images	**your path**/buildroot-2025.02.9/board/raspberrypi4-64/post-image.sh

3.5.5. Linux Kernel

This is the configuration of the Linux kernel. The specific location and version is specified among other parameters (Table 3.4). See thrird column for details of git repor to use.

Table 3.4 kernel-configuration

Kernel Version	Custom tarball.	$(call github,raspberrypi,linux,576cc10e1ed50a9eacffc7a05c796051d7343ea4)/linux-576cc10e1ed50a9eacffc7a05c796051d7343ea4.tar.gz
Kernel configuration	Using and intree defconfig file	
Defconfigname	bcm2711	This file contains the specific configuration of the kernel for the RPI
Kernel binary format	Image	
Kernel compression format	gzip compression	
Build a Device Tree Blob (DTB)	Yes	
Intree Device Tree Source file name	broadcom/bcm2711-rpi-4-b broadcom/bcm2711-rpi-400	

	broadcom/bcm2711-rpi-cm4 broadcom/bcm2711-rpi-cm4s
Need host OpenSSL	Yes
Linux kernel Extensions	Nothing
Linux Kernel Tools	Nothing

3.5.6. Target Packages

Target packages option allows to select the software elements that will be installed in the filesystem of the embedded Linux. Additionaly, this option install the busybox package that contains the basic Linux commands (Table 3.5). Buildroot creates the filesystem hierarchy following the Linux standard organization.

Table 3.5 Busybox and target packages

Busybox	yes
Busybox configuration file to use	package/busybox/busybox.config
Show packages that are also provided by busybox	Yes
Audio and video applications	Default values

Compresssors and decompressors	xz-utils	
Debugging, profiling and benchmark	**gdb, gdbserver, full debugger**	
Developments tools	Default values	
Filesystem and flash utilities	Default values	
Games	Default values	
Graphic libraries and applications (graphic/text)	Default values	
Hardware handling	**Firmware>rpifirmware rpi4 (default)**	Path to a file stores as boot/config.txt: **your path**/board/raspberrypi4-64/config_4_64bit.txt
Hardware handling	**Firmware>rpifirmware**	Path to a file stored as boot/cmdline.txt: **your path**/board/raspberrypi4-64/cmdline.txt
Hardware handling	**Firmware>rpifirmware**	**install DTB overlays**
Interpreters language and scripting Libraries	Python3	
Miscellaneous	Default Values	
Libraries	Default Values	

Networking applications	**ifupdown openssh**	**scripts,**
Package Managers	Default values	
Real Time, Shell and utilities	Default Values	
System Tools	kmod, kmod utilities	
Text Editor and Viewers	Default Values	

3.5.7. File System Images

This option selects the format of the root filesystem and the size (Table 3.6).

Table 3.6 Filesystem images

ext2/3/4 root filesystem	ext4	
filesystem label	rootfs	
exact size	**400M** Leave the other default values	Update this value with your specific needs
Compression method	No compression	

3.5.8. Boot-loaders

The Raspberry PI does not need an specific bootloader becuase it is incorporated in the firmware provided by Broadcom.

3.5.9. Host Utilities

Additional tools needed for ubuntu to create all the embedded images (Table 3.7).

Table 3.7 Host utilities

host environment setup	Yes
host genimage	Yes
host dosfstools	Yes
host kmod	Yes, support **xz-compressed modules**
host mtools	Yes

Once you have configured all the menus, you need to exit, saving the values (File->Quit).

3.6. Compiling buildroot

In the Terminal Window executes the following command (Listing 3.1):

Listing 3.1 Build Buildroot

```
$ make O=$PWD -C /home/ubuntu/Documents/rpi/buildroot-2025.02.9/
```

If everything is correct, you will see a final window similar to the one represented in Fig. 3.8.

⚠ Warning

In this step, buildroot will connect, using the internet, to different repositories. After downloading the code, Buildroot will compile the applications and generate a lot of files and folders. Depending on your internet speed access and the configuration chosen, this step could take up to **two hours**. If you have errors in the buildroot configuration, you could obtain errors in this compilation phase. Check your configuration correctly. Use “make O=$PWD -C /

home/ubuntu/Documents/rpi/buildroot-2025.02.9/ clean" to clean up your partial compilation.

Note

dl subfolder in your buildroot folder contains all the packages downloaded for the internet. If you want to move your buildroot configuration from one computer to another, avoiding the copy of the virtual machine, you can copy this folder. |

Warning

If your building process fails different reasons could be the origin. consider to use the following actions. Make a copy of your *.config* file (hidden file in Linux) to save your configuration.

Table 3.8 actions

make O=$PWD -C /home/ubuntu/Documents/rpi/ buildroot-2025.02.9/ clean	Build again buildroot
make O=$PWD -C /home/ubuntu/Documents/rpi/ buildroot-2025.02.9/ distclean	configure and build again buildroot

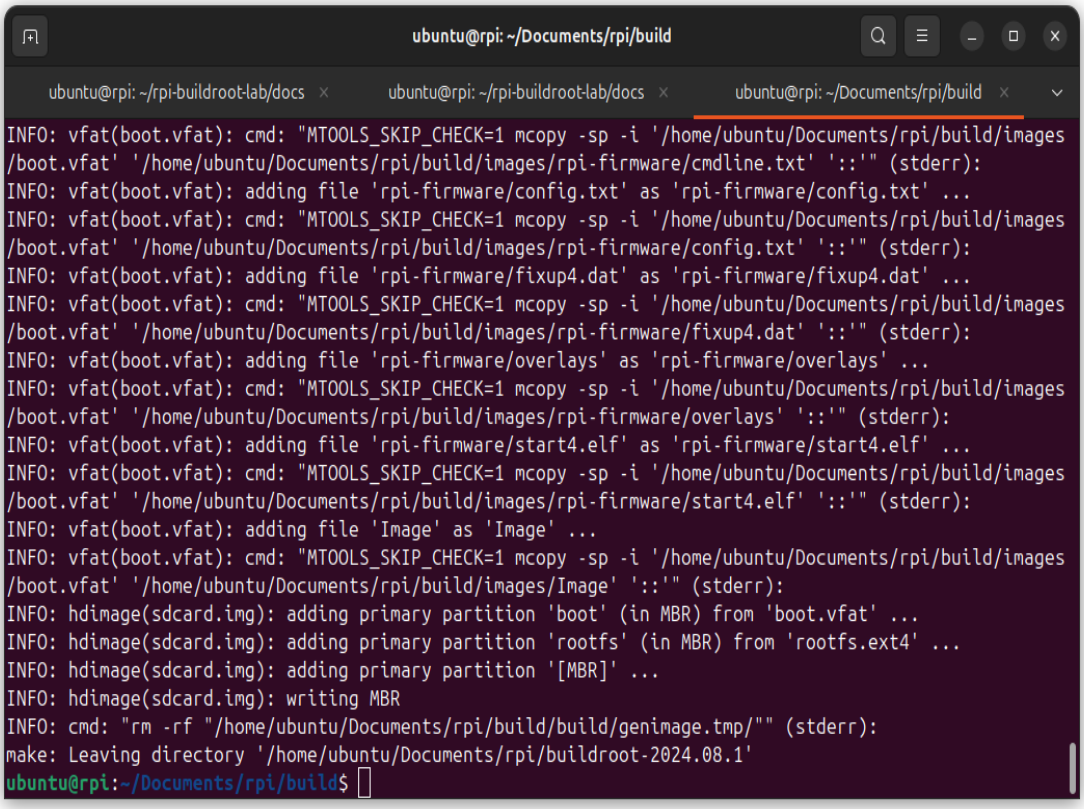


Fig. 3.8 Successful compilation and installation of Buildroot

Buildroot has generated some folders with different files and subfolders containing the tools for generating your Embedded Linux System. The next paragraph explains the main outputs obtained,

3.7. Buildroot Output.

The main output files of the execution of the previous steps can be located in the folder “build/images”. Fig. 3.9 summarizes the use of **Buildroot**. Buildroot generates a bootloader, a kernel image, and a file system.

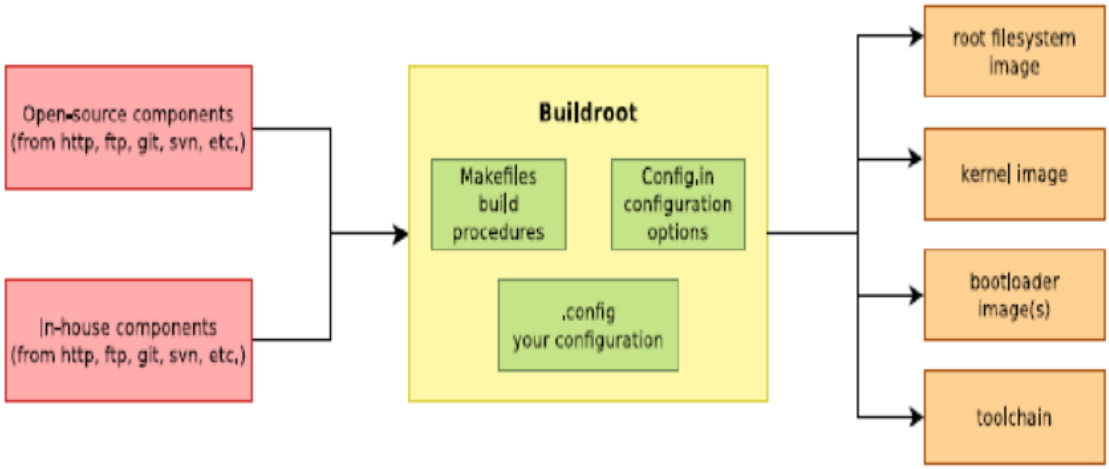


Fig. 3.9 Schematic representation of the Buildroot tool. Buildroot generates the root file system, the kernel image, the bootloader, and the toolchain. Figure copied from "Bootlin" training materials (http://bootlin.com/training/)

In our specific case, the folder content is shown in Fig. 3.10

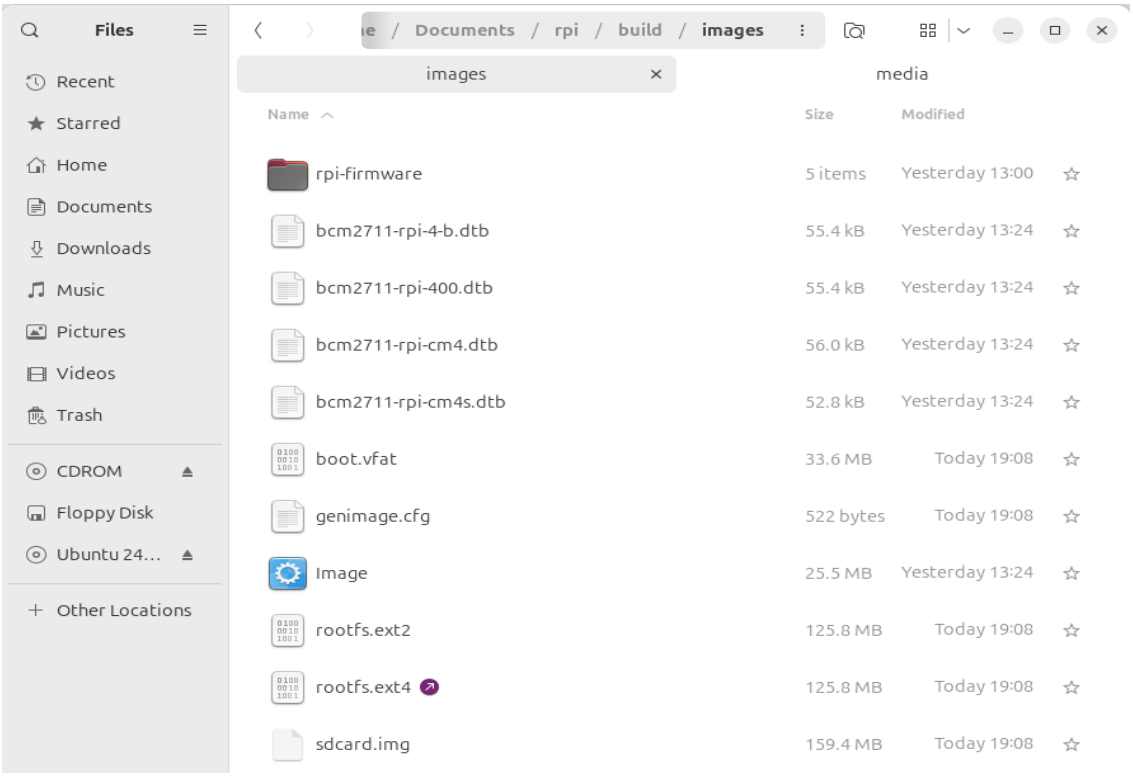


Fig. 3.10 The images folder contains the binary files for our embedded system.

Copy the *sdcard.img* file to your SDcard using this Linux command in the Buildroot folder (*sdb* is typically the device assigned to the sdcard, unless you have other removable devices connected to the system):

```
$ sudo dd if=./images/sdcard.img of=/dev/sd<x> bs=10M
```

Warning

<x> is the identification used by Linux for your microSD card, tipically "b" or "c". **Never** use "a" because this is the operating system hardisk

Remember to format again the microSDcard if you need to repeat this process otherwise you will have errors when Linux is booting.

See also

Linux *gparted* is an excellent tool for partitioning and formatting the SD card.

3.8. Booting the Raspberry Pi.

Fig. 3.11 displays a Raspberry Pi. The description of this card, its functionalities, interfaces, and connectors are explained in the ref [RD2]. The fundamental connection requires:

1. To connect a USB to RS232 adapter (provided) to the raspberry-pi expansion header (see Fig. 3.12, and Fig. 3.13). This adapter provides the serial line interface as a console in the Linux host operating system.
2. To connect the power supply with the micro-USB connector provided (5 v).
3. To connect the Ethernet cable to the RJ45 port if it is available (at home, not the case of UPM's Lab).

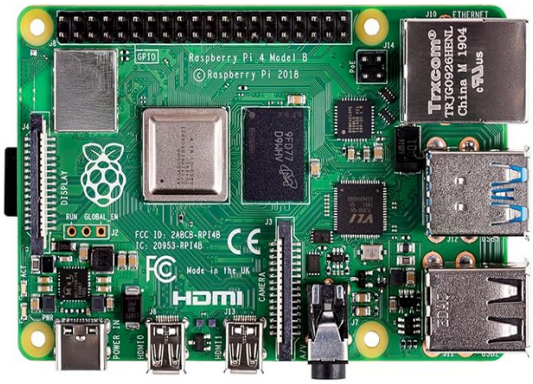
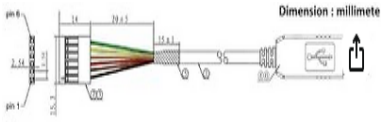


Fig. 3.11 RaspBerry-Pi 4 Model B hardware with main elements identified

Fig. 3.12 Raspberry-PI 4 header terminal identification.



① PVC Jacket
② 2.54mm 1*6p female terminal, single row
③ 2.54mm pitch socket
④ USB A male, FT232RL TTL 3.3V PCBA inside
⑤ Heat shrink tube, black, OD=5.0
⑥ ABS Housing

1*6P Female Socket	Name	Colour	Description
Pin 1	GND	Black	Device ground supply
Pin 2	CTS	Brown	Clear to Send Control/Handshake signal
Pin 3	VCC	Red	+5V
Pin 4	TXD	Orange	Transmit Asynchronous Data
Pin 5	RXD	Yellow	Receive Asynchronous Data
Pin 6	RTS	Green	Request To Send Control/Handshake signal

Fig. 3.13 Identification of the terminals in the USB-RS232 adapter

Table 3.9 FDTI Terminals

RPI connector	FDTI Terminal
RXD UART (GPIO16) Pin 10	Terminal 4 (Orange)
TXD UART (GPIO15) Pin 8	Terminal 5 (Yellow)
Ground (GND) Pin 6	Pin 1

The booting process of the Raspberry Pi BCM2711 BCM2711 processor is depicted in Fig. 3.14. Take into account that this System On Chip (SoC), the BCM2711, contains two different processors: a GPU and an ARM CPU. The programs *bootcode.bin* and *start.elf* are written explicitly for the GPU, and the source code is unavailable. Broadcom only provides details of this to customers who sign a commercial agreement. The last executable (*start.elf*) boots the ARM processor and allows the execution of ARM programs such as Linux OS kernel or other binaries such as u-boot bootloader.

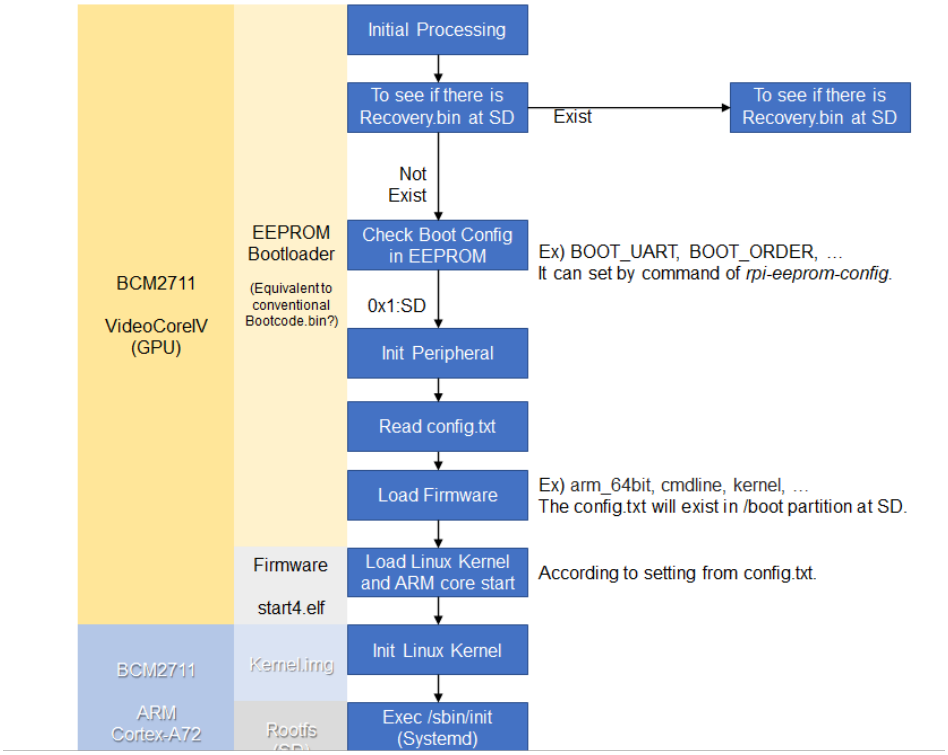


Fig. 3.14 Booting process for BCM2711 processor in the raspberry-pi.

The config.txt file contains essential information to boot the Linux OS and perform the configuration of different hardware elements (look at http://elinux.org/RPiconfig and check the meaning of the different configuration parameters). Verify the content of the config.txt file generated by buildroot and complete it as depicted below (Listing 3.2).

Listing 3.2 config.txt file

```
# Please note that this is only a sample, we recommend you to change
it to fit
# your needs.# You should override this file using
BR2_PACKAGE_RPI_FIRMWARE_CONFIG_FILE.
# See http://buildroot.org/manual.html#rootfs-custom
# and http://elinux.org/RPiconfig for a description of config.txt
syntax

start_file=start4.elf
fixup_file=fixup4.dat

kernel=**Image**

# To use an external initramfs file
#initramfs rootfs.cpio.gz
# Disable overscan assuming the display supports displaying the full
resolution
# If the text shown on the screen disappears off the edge, comment
this out

disable_overscan=1

# How much memory in MB to assign to the GPU on Pi models having
# 256, 512 or 1024 MB total memory
gpu_mem_256=100
gpu_mem_512=100
gpu_mem_1024=100

# Enable UART0 for serial console on ttyAMA0
dtoverlay=miniuart-bt

# enable autoprobing of Bluetooth driver without need of hciattach/
btattach
dtparam=krnbt=on
```

In this example, once the ARM is released from reset, it executes the Image application. This binary application is the Linux Kernel in Image format. The parameters passed to the application specified in the *kernel=<....>* are detailed in the *cmdline.txt* file. For instance, by default, Buildroot generates this one (Listing 3.3):

Listing 3.3 cmdline.txt file

```
root=/dev/mmcblk0p2 rootwait console=tty1 console=ttyAMA0,115200
```

In the Linux machine, open a Terminal and execute the program *sudo putty* with **sudo rights** (sudo putty), in a second a window appears. Configure the parameters using the information displayed

in Fig. 3.15 (for the specific case of *putty*), and then press "Open". **Apply the power to the Raspberry PI,** and you will see the booting messages.

Tip

[Serial interface identification in Linux]: In Linux the serial devices are identified typically with the names /dev/ttyS0, /dev/ttyS1, etc. In the figure, the example has been checked with a serial port implemented with a USB-RS232 converter. This is the reason why the name is **/dev/ttyUSB0**. In your computer, you need to find the identification of your serial port. Use Linux **dmesg** command to do this.

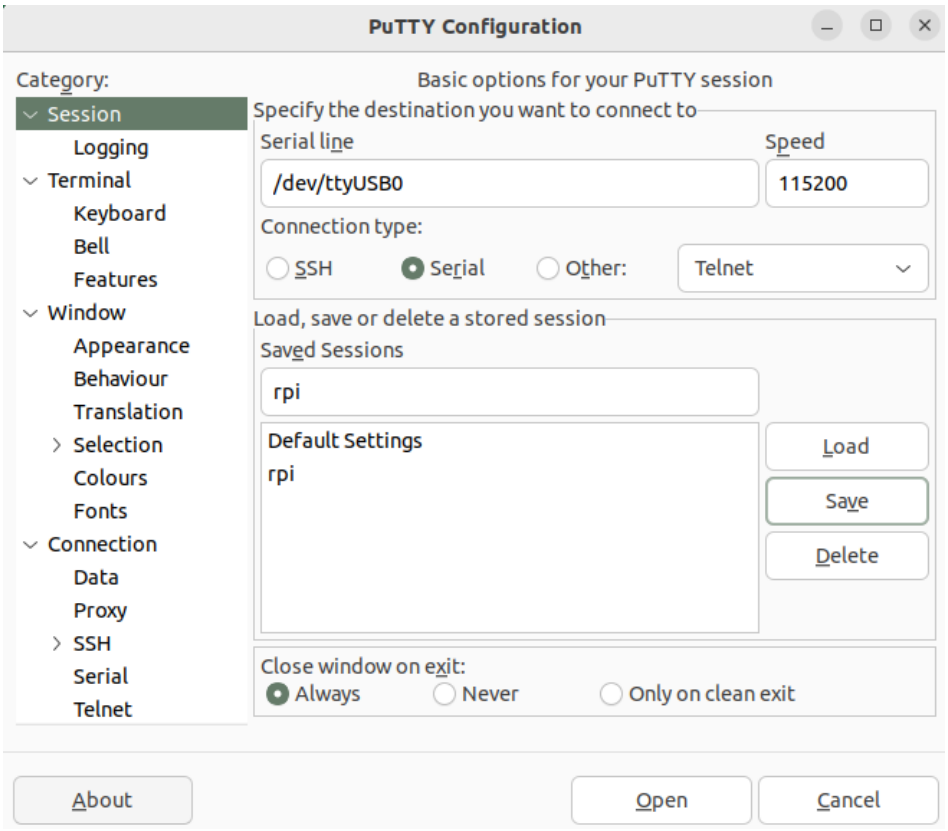


Fig. 3.15 Putty program main window.

After a few seconds, you will see a lot of messages displayed on the terminal. Linux kernel is booting, and the operating system is running its configuration and initial daemons. If the system boots correctly, you will see an output like the one represented in Fig. 3.16. Introduce the username *root* (password in case you have configured it), and the Linux shell will be available for you.

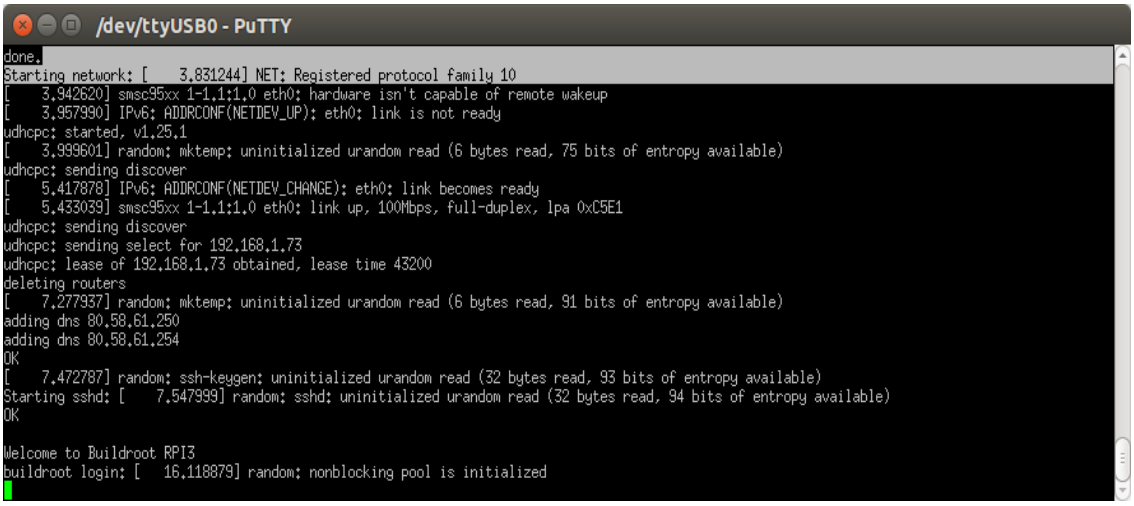


Fig. 3.16 Linux Running in the RaspBerry Pi

Tip

[DHCP Server]: The DHCP server providing the IP address to the RPI should be active in your network. In the UPM ETSIST labs, there is no cabled network, only WIFI. If you are using the RPI at home, the DHCP server is running in your router. The method used to assing IP addresses is different from one manufactures to others. If you want to know the IP address assigned, you have two options: use a serial cable connected to the RPI (*ifconfig* command) or check the router status web page and display the table of the DHCP clients connected. Looking for the MAC in the list, you will obtain the IP address.

3.9. Connecting the RPI to the cabled ethernet network

3.9.1. Inspecting the configuration of the network interface generated automatically by Buildroot

Inspect the content of */etc/network/interfaces* and */etc/init.d/S40network*. You will see content similar to this in the *interfaces* file:

```
# interface file auto-generated by buildroot

auto lo
iface lo inet loopback

auto eth0
```

```
iface eth0 inet dhcp
     pre-up /etc/network/nfs_check
     wait-delay 15
     hostname $(hostname)
```

This configuration activates the use of eth0 with DHCP support. Test the connectivity, trying to connect to another computer in the laboratory. Use the ping command.

Note

[Help]: If you run the ping command in the Raspberry trying to connect with a computer in the laboratory, you probably obtain a connection timeout. Consider that computers running Windows could have the firewall activated. You can also try to run the ping on a windows computer or on Linux virtual machine. In this case, the RPI does not have a firewall running, and the connection should be successful.

Question

What is the MAC address of your RPI interface? Use the *dmesg* command to see the kernel boot parameters and identify the method used to get the MAC address from the hardware.

3.10. Adding WIFI support

3.10.1. Adding mdev support to Embedded Linux

The folder <buildroot-folder>*/package/busybox* contains two files named S10mdev and mdev.conf. These files have to be added to the target filesystem. This step is done by adding these commands to the *<buildroot-folder>/board/raspberrypi4-64/post-build.sh* script:

```
cp <buildroot-folder>/package/busybox/S10mdev ${TARGET_DIR}/etc/
init.d/S10mdev
chmod 755 ${TARGET_DIR}/etc/init.d/S10mdev
cp <buildroot-folder>/package/busybox/mdev.conf ${TARGET_DIR}/etc/
mdev.conf
```

Note

[mdev] mdev provides a method to add or remove hotplug devices in Linux.

3.10.2. Adding the Broadcom firmware support for Wireless hardware

The hardware element included in the RPI-4 for the Wireless communication is implemented with the BCM43438 chip. It is needed to include the software packages with the firmware's chip and the wireless utilities.

1. Execute "make ..... menuconfig". Navigate to "Target Packages->Hardware Handling->Firmware-> bcrmfmac-sdio-firmware-rpi" and select the "bcrmfmac-sdio-firmware-rpi-wifi".
2. Before compiling Buildroot we need to add more software supporting the configuration of the WIFI.
    1. Navigate to "Target Packages->Networking Applications" and select
        - "crda"
        - "ifupdown scripts"
        - "iw"
        - "wireless-regdb"
        - "wireless tools"
        - "wpa_supplicant"
            1. "Enable EAP"
            2. "Enable WPS"
            3. "Install wpa_cli binary"
            4. "Install wpa_client shared library"
            5. "Instal wpa_passphrase binary"
    2. Add these lines to ./board/rapsberrypi4-64/post-build.sh.

```
cp <buildroot-folder>/board/raspberrypi4-64/interfaces ${TARGET_DIR}/
etc/network/interfaces
```

```
cp <buildroot-folder>/board/raspberrypi4-64/wpa_supplicant.conf ${TARGET_DIR}/etc/wpa_supplicant.conf
```

1. Create the file **<buildroot-folder>*/board/raspberrypi4-64/interfaces* adding the highlighted content:

```
auto lo
iface lo inet loopback

auto eth0
iface eth0 inet dhcp
     pre-up /etc/network/nfs_check
     wait-delay 15
     hostname $(hostname)

auto wlan0
iface wlan0 inet dhcp
       pre-up wpa_supplicant -B -iwlan0 -c/etc/wpa_supplicant.conf
       post-down killall -q wpa_supplicant
       wait-delay 15
```

1. Create the file **<buildroot-folder>*/board/raspberrypi4-64/wpa_supplicant.conf* with this content (ask professors about the values to be provided as SSID and Key-passwd). You can define as many WIFIs as you want.

```
network={
    ssid="SSID"
    key_mgmt=WPA-PSK
    psk="PASSWORD"
    priority=9
}
```

1. Perform a **make** and burn again the new image in the micro SDcard. Boot the Raspberry and check that you can connect to the wireless network.

3.11. Customizing the Linux kernel

3.11.1. Kernel configuration

Execute the following command to configure the Linux Kernel in Buildroot

```
$ make  O=$PWD -C /home/ubuntu/Documents/rpi/buildroot-2025.02.9/
linux-menuconfig
```

Using the different menus you can configure specific kernel features, add support for specific device drivers and multiple additional functionalities. The compilation of the Linux kernel package is done with this command:

```
$ make  O=$PWD -C /home/ubuntu/Documents/rpi/buildroot-2025.02.9/
linux-rebuild
```

In order to get the new sdcard.img file execute:

```
$ make  O=$PWD -C /home/ubuntu/Documents/rpi/
buildroot-2025.02.9/
```

4. Using the integrated development environment Eclipse/CDT

4.1. Eclipse IDE for C/C++ developers

The Eclipse IDE CDT is installed in the virtual machine. You can execute it running eclipse in a window terminal.

4.2. Cross-Compiling applications using Eclipse

How will a program be compiled and linked? Remember that we are developing cross applications. We are developing and compiling the code in a Linux x86_64 architecture, and we are executing it on an ARM one (see Fig. 4.1).

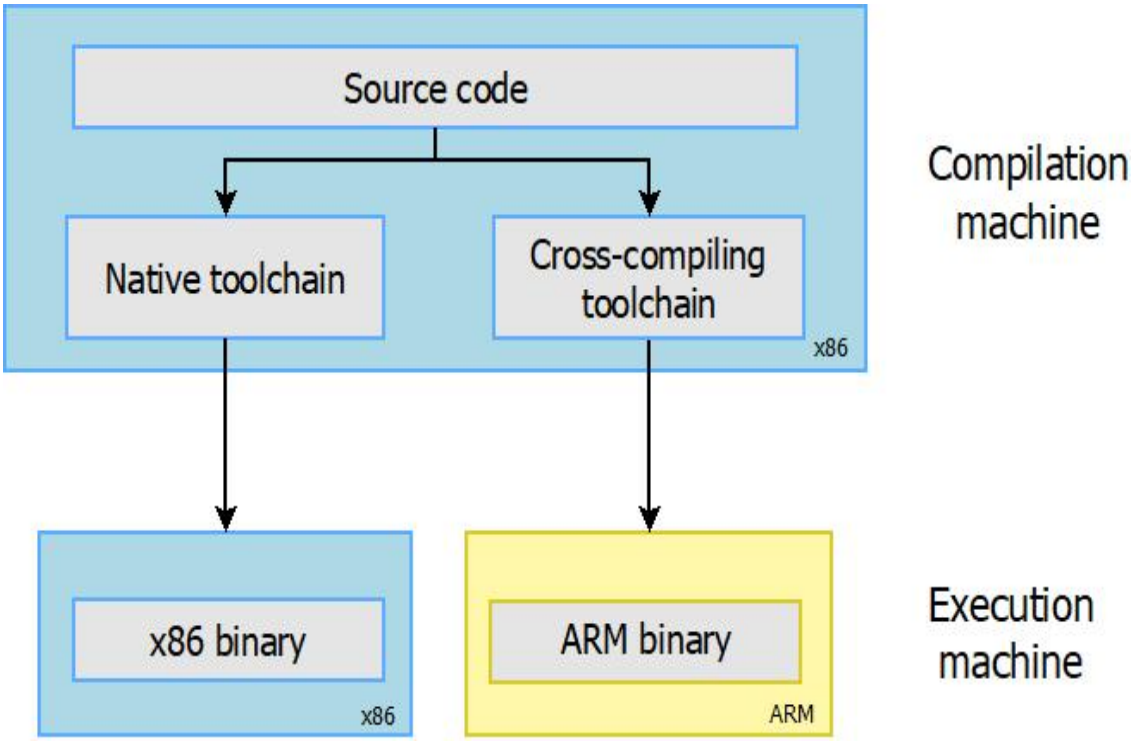


Fig. 4.1 Cross Toolchain. Figure copied from “Free Electrons” training materials (http://free-electrons.com/training/)

The first question is where the cross-compiler and other cross-tools are located. The answer is this: in the folder *build/host/usr/bin*. If you inspect this folder’s content, you can see the entire

compiling, linking, and debugging tools (see Fig. 4.2). These programs are executed in your x86_64 computer, but they generate code for the ARM processor.

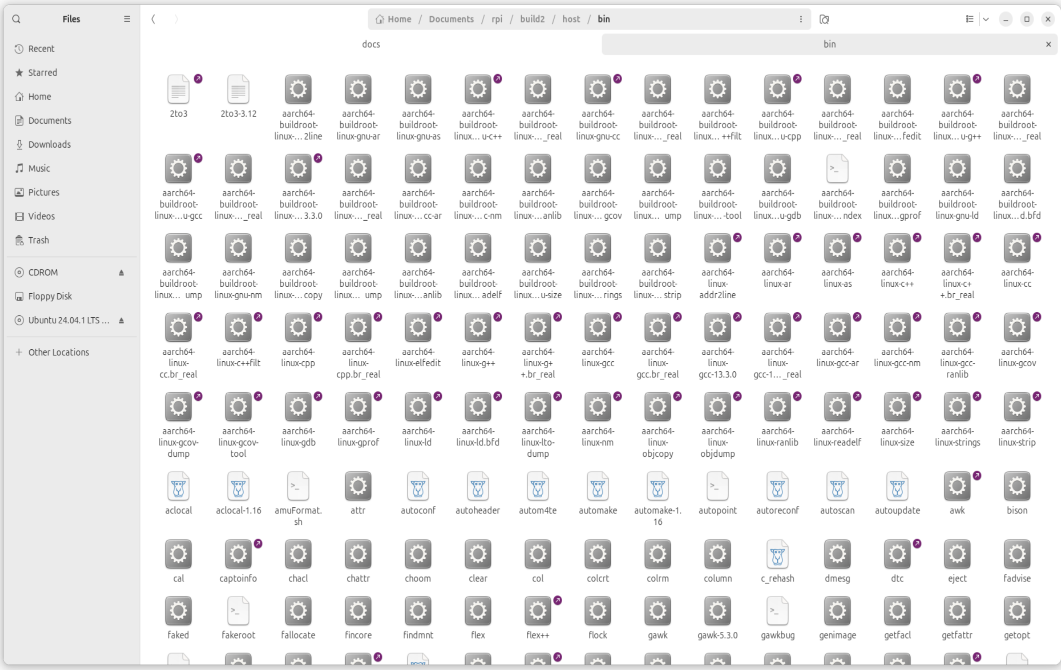


Fig. 4.2 Cross-compiling tools installed in the host computer

In a Terminal window execute the following commands:

```
# change the directory to the folder where `build` directory is
$ cd ./build/host
$ source environment-setup
# run eclipse in the same terminal. In this case eclipse is available
in your ubuntu user folder
$ /home/ubuntu/eclipse/cpp-2024-09/eclipse/eclipse &
```

The **environment-setup** file contains the code listed below.

```
cat <<'EOF'
 _           _ _     _                _
| |__  _   _(_) | __| |_ __ ___   ___ | |_
| '_ \| | | | | |/ _` | '__/ _ \ / _ \| __|
| |_) | |_| | | | (_| | | | (_) | (_) | |_
|_.__/ \__,_|_|_|\__,_|_|  \___/ \___/ \__|

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Some tips:
* PATH now contains the SDK utilities
* Standard autotools variables (CC, LD, CFLAGS) are exported
* Kernel compilation variables (ARCH, CROSS_COMPILE, KERNELDIR) are
```

```
exported
* To configure do "./configure $CONFIGURE_FLAGS" or use
  the "configure" alias
* To build CMake-based projects, use the "cmake" alias

EOF
if [ x"$BASH_VERSION" != x"" ] ; then
     SDK_PATH=$(dirname $(realpath "${BASH_SOURCE[0]}"))
elif [ x"$ZSH_VERSION" != x"" ] ; then
     SDK_PATH=$(dirname $(realpath $0))
else
     echo "unsupported shell"
fi
export "AR=aarch64-buildroot-linux-gnu-gcc-ar"
export "AS=aarch64-buildroot-linux-gnu-as"
export "LD=aarch64-buildroot-linux-gnu-ld"
export "NM=aarch64-buildroot-linux-gnu-gcc-nm"
export "CC=aarch64-buildroot-linux-gnu-gcc"
export "GCC=aarch64-buildroot-linux-gnu-gcc"
export "CPP=aarch64-buildroot-linux-gnu-cpp"
export "CXX=aarch64-buildroot-linux-gnu-g++"
export "FC=aarch64-buildroot-linux-gnu-gfortran"
export "F77=aarch64-buildroot-linux-gnu-gfortran"
export "RANLIB=aarch64-buildroot-linux-gnu-gcc-ranlib"
export "READELF=aarch64-buildroot-linux-gnu-readelf"
export "STRIP=aarch64-buildroot-linux-gnu-strip"
export "OBJCOPY=aarch64-buildroot-linux-gnu-objcopy"
export "OBJDUMP=aarch64-buildroot-linux-gnu-objdump"
export "AR_FOR_BUILD=/usr/bin/ar"
export "AS_FOR_BUILD=/usr/bin/as"
export "CC_FOR_BUILD=/usr/bin/gcc"
export "GCC_FOR_BUILD=/usr/bin/gcc"
export "CXX_FOR_BUILD=/usr/bin/g++"
export "LD_FOR_BUILD=/usr/bin/ld"
export "CPPFLAGS_FOR_BUILD=-I$SDK_PATH/include"
export "CFLAGS_FOR_BUILD=-O2 -I$SDK_PATH/include"
export "CXXFLAGS_FOR_BUILD=-O2 -I$SDK_PATH/include"
export "LDFLAGS_FOR_BUILD=-L$SDK_PATH/lib -Wl,-rpath,$SDK_PATH/lib"
export "FCFLAGS_FOR_BUILD="
export "DEFAULT_ASSEMBLER=aarch64-buildroot-linux-gnu-as"
export "DEFAULT_LINKER=aarch64-buildroot-linux-gnu-ld"
export "CPPFLAGS=-D_LARGEFILE_SOURCE -D_LARGEFILE64_SOURCE -
D_FILE_OFFSET_BITS=64"
export "CFLAGS=-D_LARGEFILE_SOURCE -D_LARGEFILE64_SOURCE -
D_FILE_OFFSET_BITS=64  -Os -g0 -D_FORTIFY_SOURCE=1"
export "CXXFLAGS=-D_LARGEFILE_SOURCE -D_LARGEFILE64_SOURCE -
D_FILE_OFFSET_BITS=64  -Os -g0 -D_FORTIFY_SOURCE=1"
export "LDFLAGS="
export "FCFLAGS= -Os -g0"
export "FFLAGS= -Os -g0"
export "PKG_CONFIG=pkg-config"
export "STAGING_DIR=$SDK_PATH/aarch64-buildroot-linux-gnu/sysroot"
```

```
export "INTLTOOL_PERL=/usr/bin/perl"
export "ARCH=arm64"
export "CROSS_COMPILE=aarch64-buildroot-linux-gnu-"
export "CONFIGURE_FLAGS=--target=aarch64-buildroot-linux-gnu --
host=aarch64-buildroot-linux-gnu --build=x86_64-pc-linux-gnu --
prefix=/usr --exec-prefix=/usr --sysconfdir=/etc --localstatedir=/var
--program-prefix="
alias configure="./configure ${CONFIGURE_FLAGS}"
alias cmake="cmake -DCMAKE_TOOLCHAIN_FILE=$SDK_PATH/share/buildroot/
toolchainfile.cmake -DCMAKE_INSTALL_PREFIX=/usr"
export "PATH=$SDK_PATH/bin:$SDK_PATH/sbin:$PATH"
export "KERNELDIR=/home/ubuntu/Documents/rpi/build/build/linux-
custom/"
```

This script when is sourced in a terminal window sets all the environment variables needed to use the cross-compilation tools and adds the folder of cross-tools to the Linux *PATH* variable.

The execution of eclipse popups a window inviting you to enter the workspace (see Fig. 4.3). The workspace is the folder that contain eclipse projects created by the user. You can have as many workspaces as you want. Please specify a folder in your account.

Tip

The figures displayed in the following paragraphs can be different depending on the Eclipse version installed

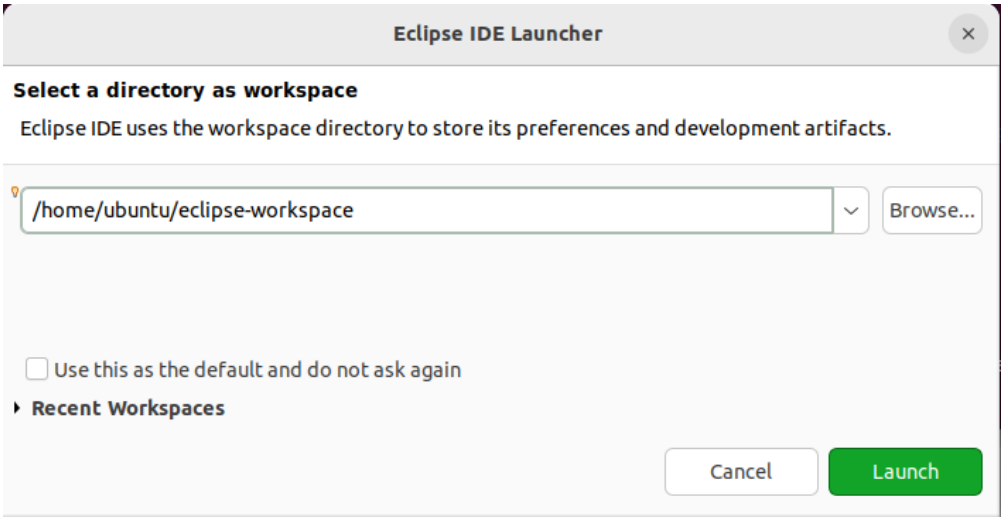

Fig. 4.3 Selection of the workspace for Eclipse. Use a folder in your account.

Select Ok, and the welcome window of Eclipse will be shown (see Fig. 4.4).Next, close the welcome window and the main eclipse window will be displayed (see Fig. 4.5).

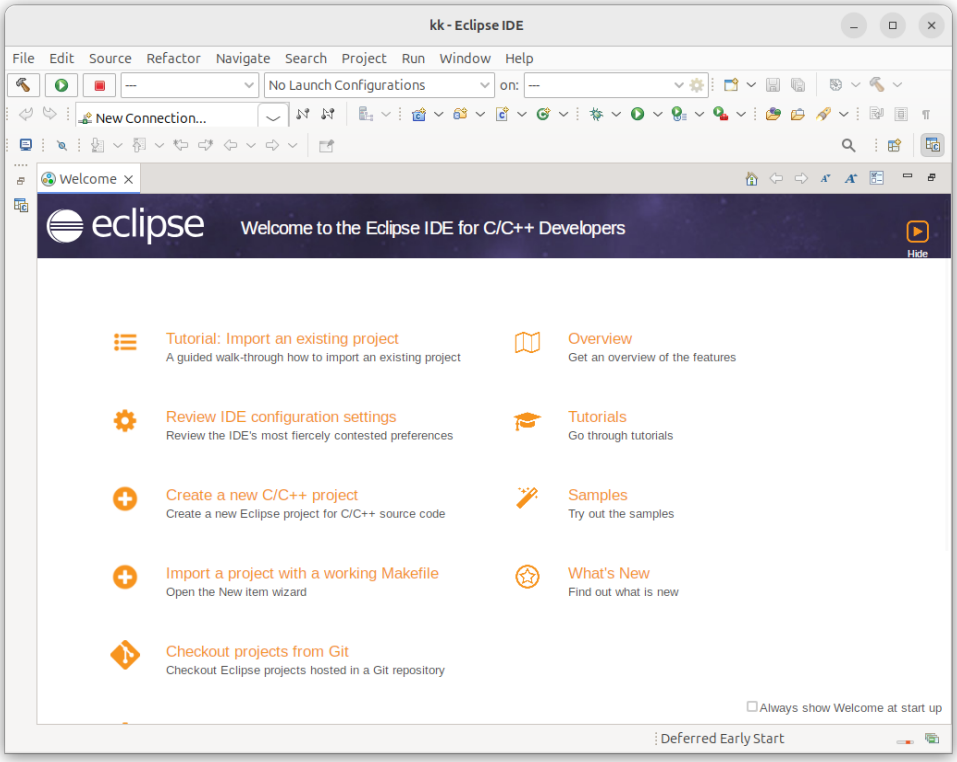

Fig. 4.4 Eclipse welcome window.

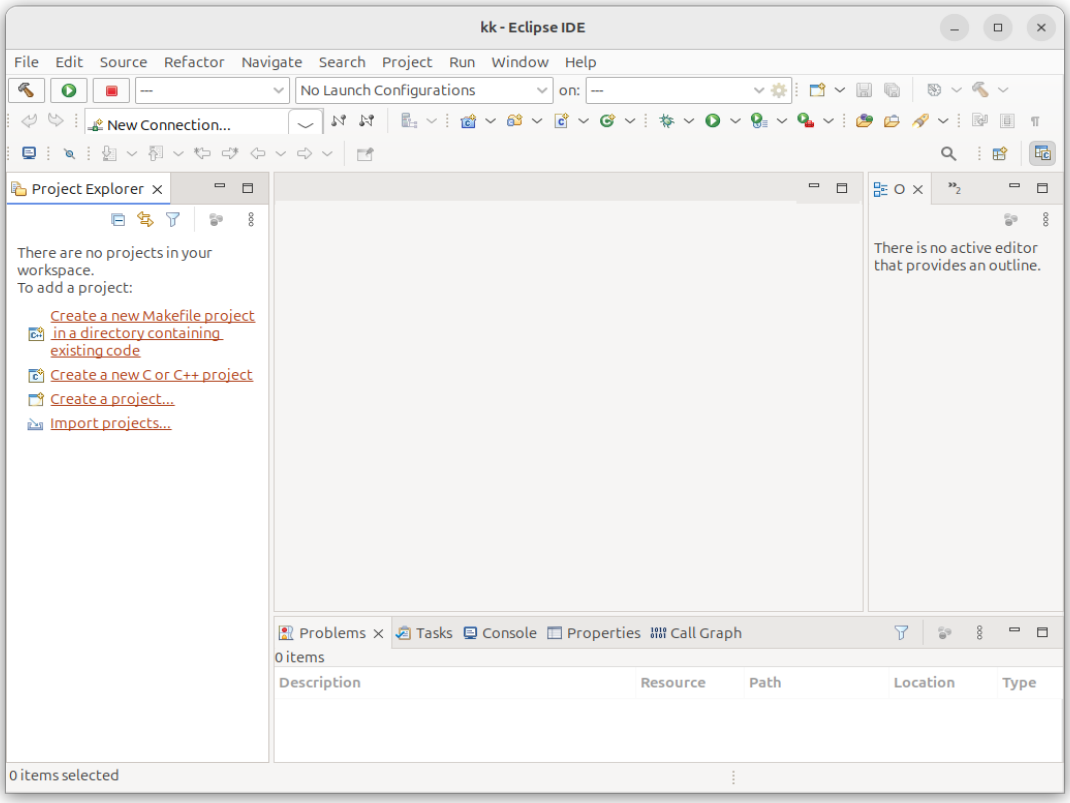

Fig. 4.5 Eclipse main window.

In a terminal window create an empty folder. In this folder create the following files with the content described in Listing 4.1, Listing 4.2 , Listing 4.3, and Listing 4.4. The Makefile uses the environment variables that are defined in the environment where the *makefile* is run.

Listing 4.1 Makefile

```
LIBS= -lpthread -lm #Libraries used if needed
SRCS= main.cpp func.cpp
BIN=app
CFLAGS+= -g -O0
OBJS=$(subst .cpp,.o,$(SRCS))
all : $(BIN)
$(BIN): $(OBJS)
    @echo [link] $@
    $(CXX) -o $@ $(OBJS) $(LDFLAGS) $(LIBS)
%.o: %.cpp
    @echo [Compile] $<
    $(CXX) -c $(CFLAGS) $< -o $@
clean:
    @rm -f $(OBJS) $(BIN)
```

Listing 4.2 main.cpp

```
#include "func.h"
#include <iostream>
int main(void){
    int b=2;
    std::cout<<"A is: "<< fun(b) << std::endl;
}
```

Listing 4.3 func.h

```
#ifndef __FUNC_H
#define __FUNC_H
    int fun(int);
#endif
```

Listing 4.4 func.cpp

```
int fun(int b){
    int a=b*2;
    return a;
}
```

In Eclipse select in the left part of the windows *Import projects*. A new window is popup, select then *C/C++* and the option *Existing Code as Makefile Project*. The window shown in Fig. 4.6 is displayed. Complete the name of the project, select the folder with the code and check *Cross GCC in Toolchain for Indexer Settings*.

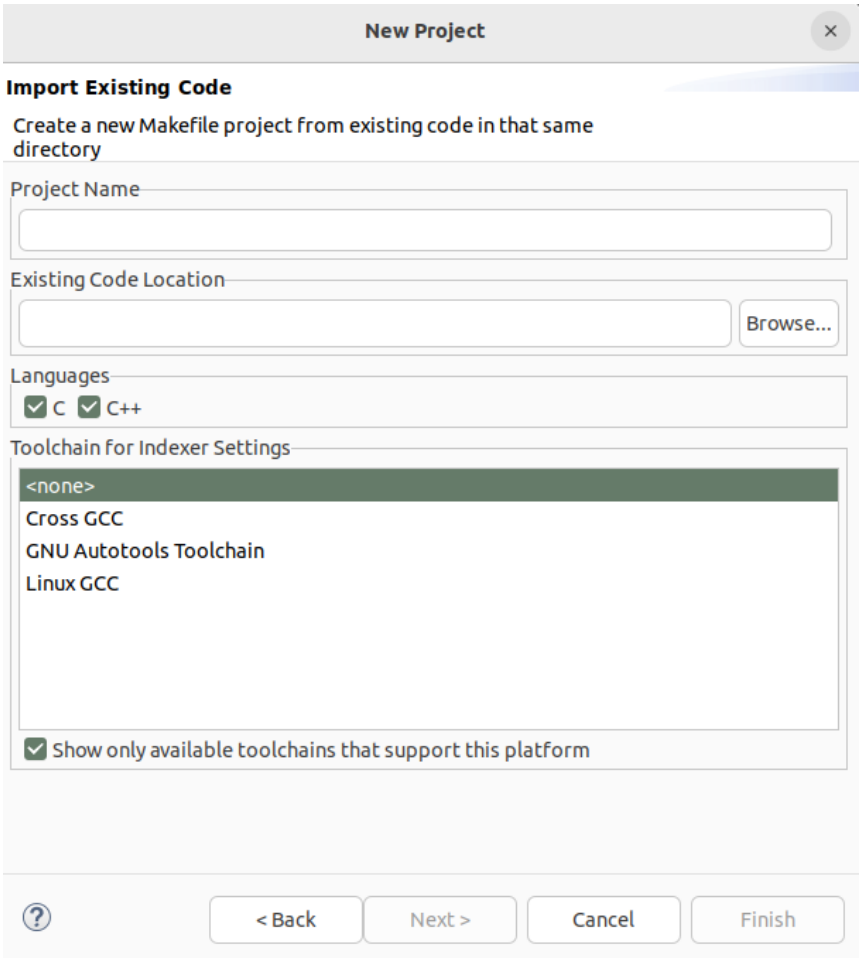

Fig. 4.6 Importing the code.

4.3. Building a project

Once you have configured the cross-chain in Eclipse you can build your project using Project->Build Project. If everything is correct, you will see the eclipse project as represented in Fig. 4.7 . You can clean the project (remove the executable and objects) with *Clean*.

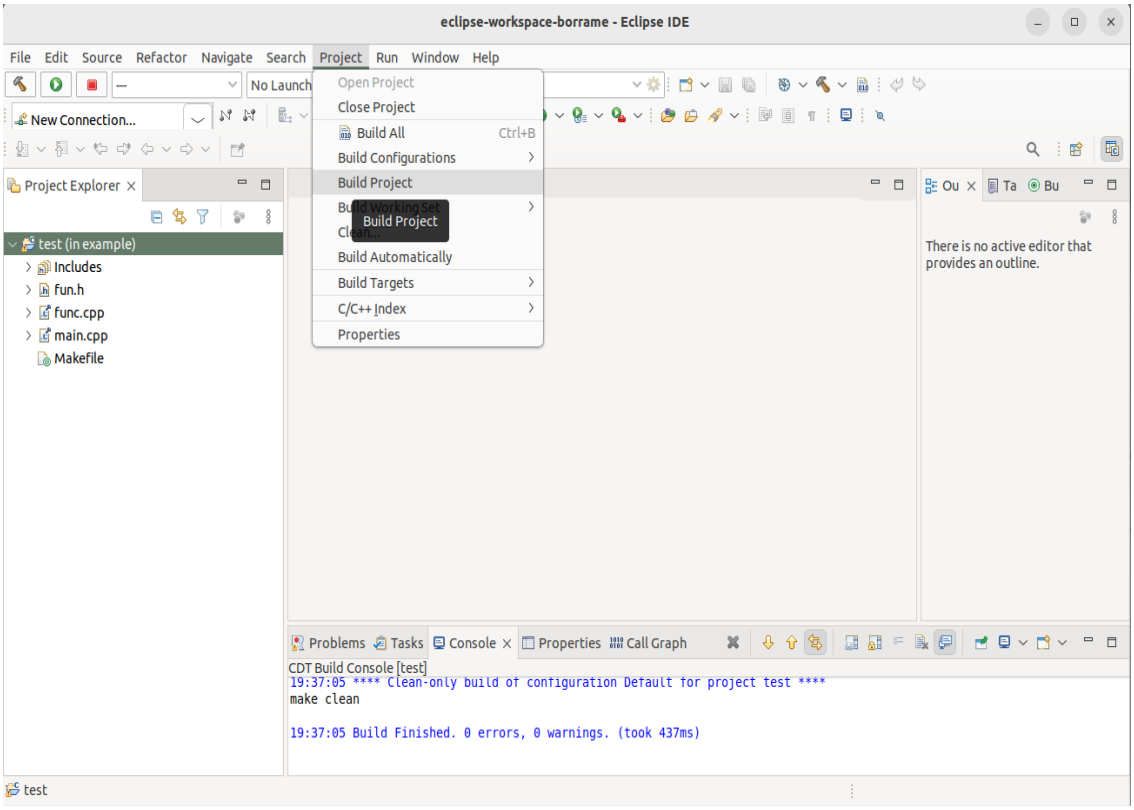

Fig. 4.7 Eclipse project compiled (Binaries has been generated)

Note

[Console in Eclipse]: Have a look at the messages displayed in the Console. You will see how eclipse is calling the cross compiler with different parameters.

4.4. Moving the binary to the target

In order to copy the executable to the target, you have different options. You can use the Linux application called *scp* or other similar applications. In our case, we are going to use the "Other Locations...." utility included in the nautilus explorer (Fig. 4.8). Specify in Server Address *ssh://<ip address>*

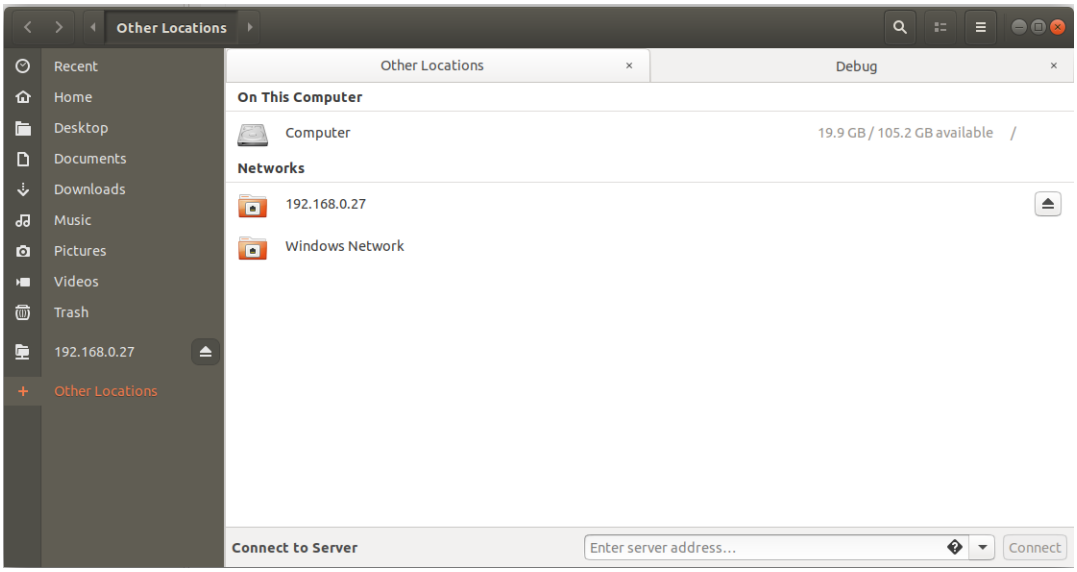

Fig. 4.8 Connect to Server" option in Nautilus explorer

4.5. Executing the application

You can run the Raspberry PI program using putty (remember that once you have a network connection available in the RPI you can also use putty to connect to it).

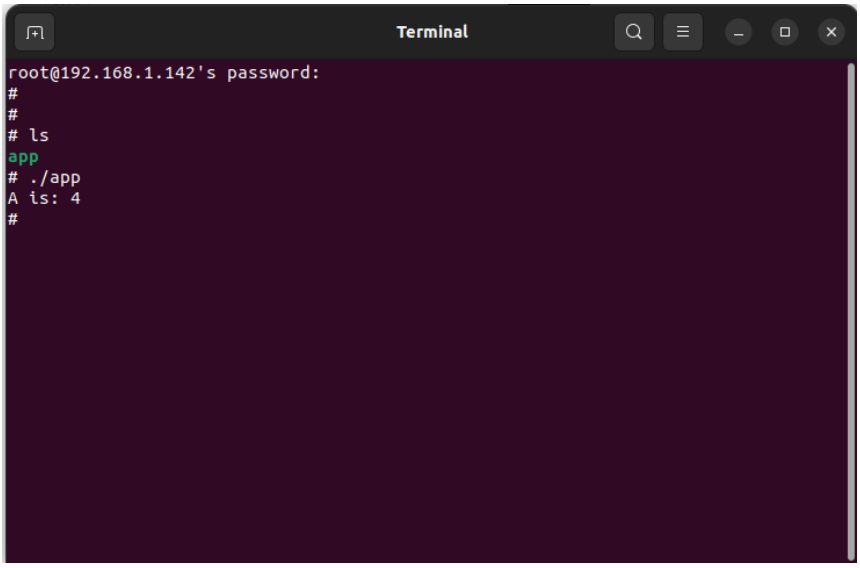

Fig. 4.9 Run test program in Raspberry Pi

⚠ Warning

Warning. If you experiment problems using ssh, delete the *.ssh* folder in your home directory.

4.6. Automatic debugging using gdb and gdbserver

You can directly debug the program running in the RPI using Eclipse. There are two methods to do it: manually and automatically. In the manual method, firstly, you need to copy the executable program to the RPI, change the file permissions to “executable” and execute the program to be debugged using *gdbserver* utility. Of course, this is a time-consuming process and very inefficient. The alternative solution is to use automatic debugging. In order to debug your applications, we need to define a debug session and configure it. Firstly, *Select Run->Debug Configurations* and generate a new configuration under *C/C++ Remote Application*. You need to complete the different tabs available in this window. The first one is the main tab (see Fig. 33). You need to configure here the path to the C/C++ application to be debugged, the project name, the connection with the target (you will need to create a new one using the IP address of your RPI), the remote path where your executable file will be downloaded, and the mode for the debugging (Automatic Remote Debugging Launcher). Secondly, in the argument tab, you can specify the arguments of your executable program. It is very important here that you can also specify the working directory path where the executable will be copied and launched (you need to have rights in this folder).

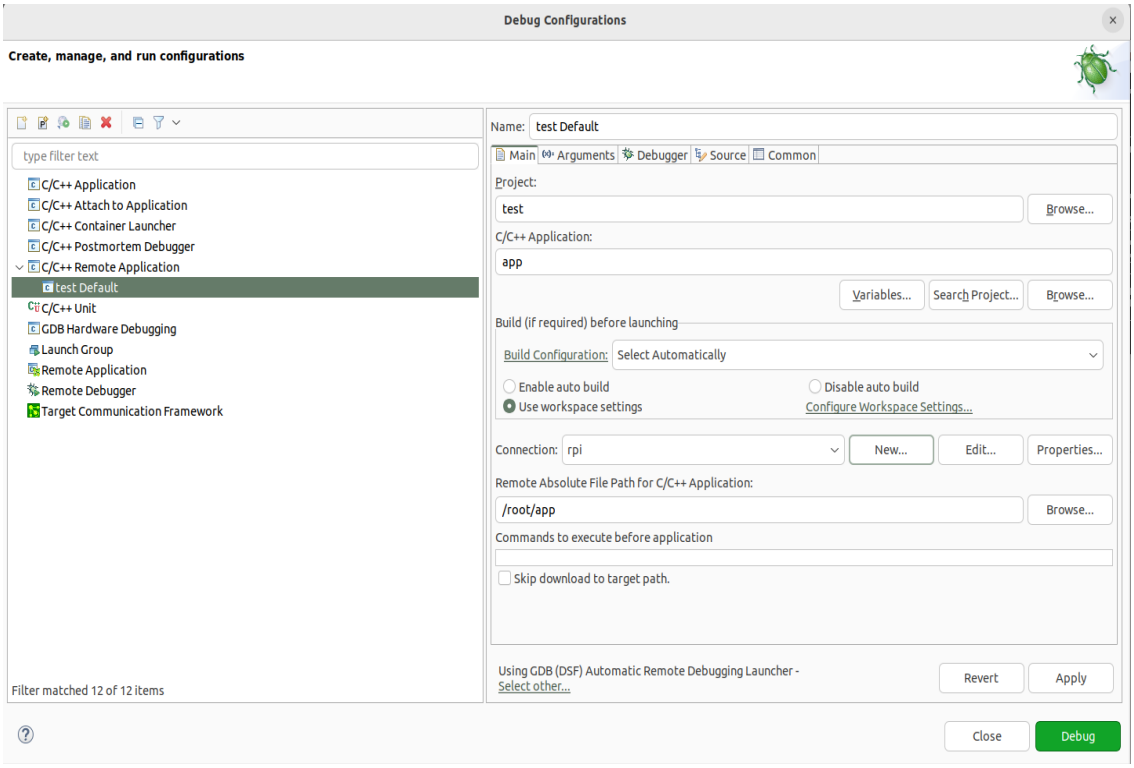

Fig. 4.10 Creating a Debug Configuration

In the debugger window you need to configure the path of your cross gdb application. Remember that we are working with a cross-compiler, cross debugging. Therefore, you need to provide here the correct path of your gdb. The GDB command file (.gdbinit) must be specified, providing a path with an empty file. In the Gdbserver settings tab, you need to provide the path to the gdbserver in the target and the TCP/IP port used (by default 2345).

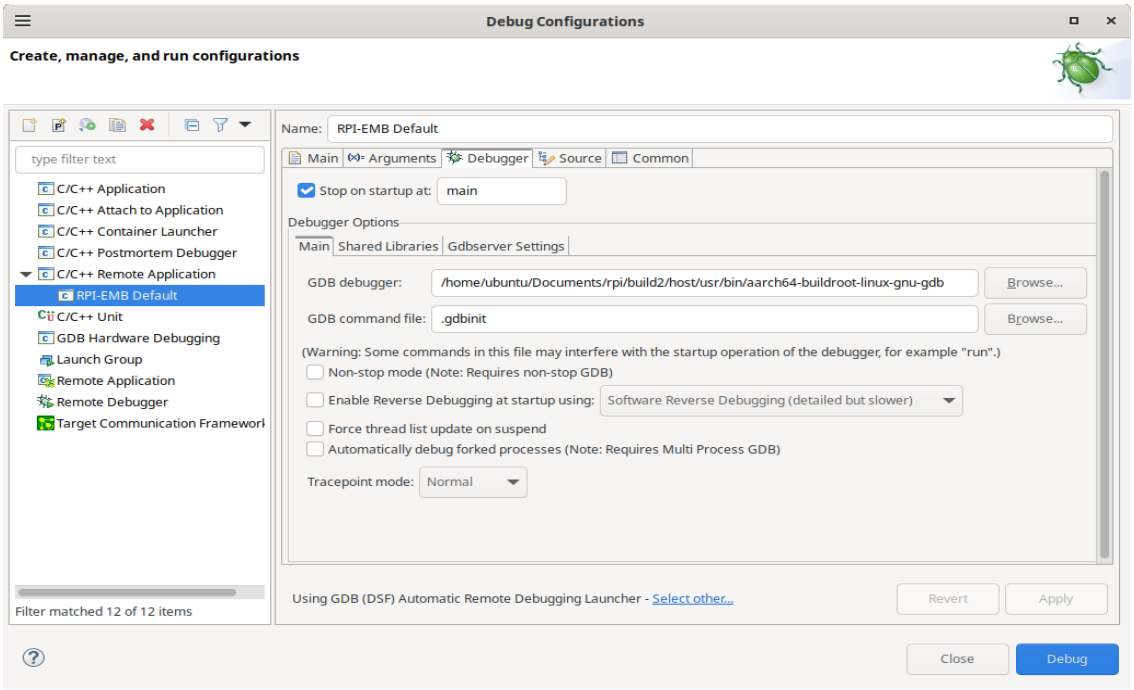

Fig. 4.11 Debug configuration, including the path to locate the cross gdb tool.

Now, press Debug in Eclipse window, and you can debug your application remotely.

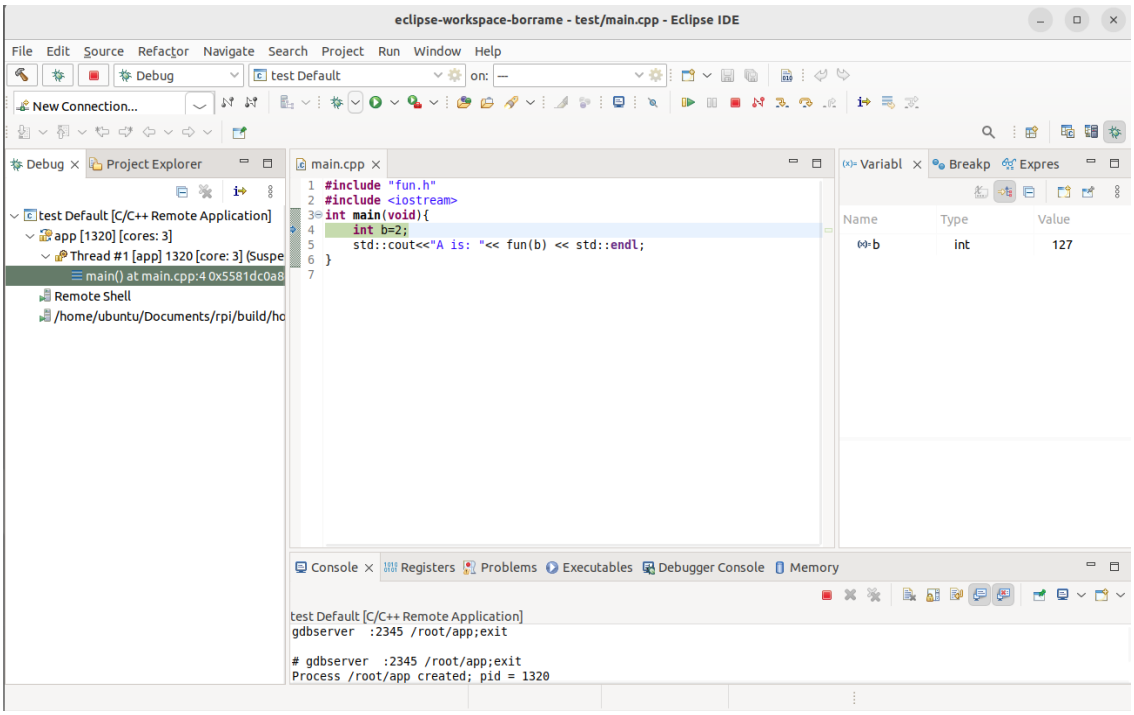

Fig. 4.12 Debugging session on the RPI remotely

5. Preparing the VMware Ubuntu Virtual Machine.

5.1. Download VMware Workstation Player.

The software can be downloaded from this link. Follow the instructions to set up the application on your computer.

5.2. Installing Ubuntu 24.04.01 LTS as a virtual machine.

Note

It is mandatory to install Ubuntu 24.04.01 LTS version. Use this link to download it http://ftp.rediris.es/sites/releases.ubuntu.com/noble

The first step is to download Ubuntu. You will download an ISO image with this Linux operating System. Run WMware player and install Ubuntu using the VMWare player instructions. Select the *Typical* configuration and reserve at least 100G/150G for the hard disk. In the hardware configuration select 8GByte of RAM, if possible 4 processors, and the USB 3.1 support. The installation time will be half an hour, more or less, depending on your computer. Moving a virtual machine from one computer to another is a time-consuming task; therefore, take this into account to minimize the development time.

5.3. Installing synaptic

If you need to install software packages, you can do it using the linux terminal command *apt-get*. Another alternative process is the use of the synaptic utility. In order to use it, you need to install it using this command:

```
$ sudo apt-get install synaptic
```

Once installed, you can search and execute the synaptic program. When you click two times over the package, it will show all the dependent packages that would be installed (see Fig. 5.1).

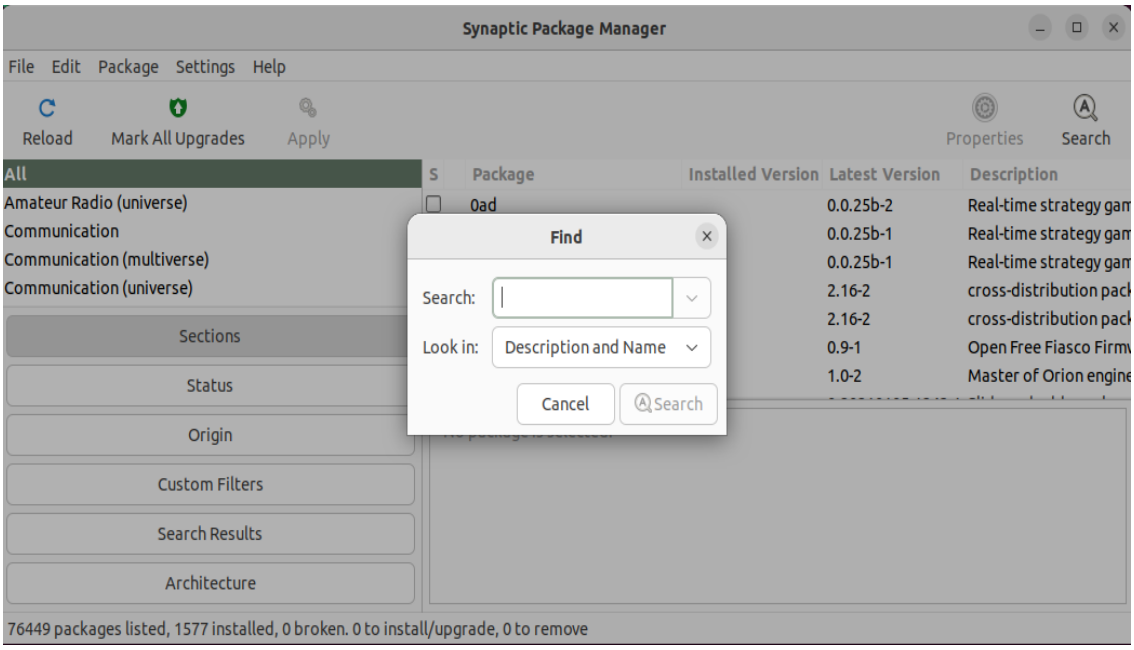

Fig. 5.1 Synaptic window

5.4. Installing putty

You need to execute:

- sudo apt-get install putty

5.5. Installing packages for supporting Buildroot.

Using buildroot requires some software packages that have to be installed in the VM. These are listed in this link http://buildroot.uclibc.org/downloads/manual/manual.html#requirement. You need to install at least:

- build-essential
- git
- libncurses-dev

5.6. Installing packages supporting Eclipse

Follow the instructions of this link to install Eclipse. Use the Eclipse C/C++ or the Eclipse for Embedded C/C++ developers.

Indices and tables

Created using Sphinx 8.2.3.