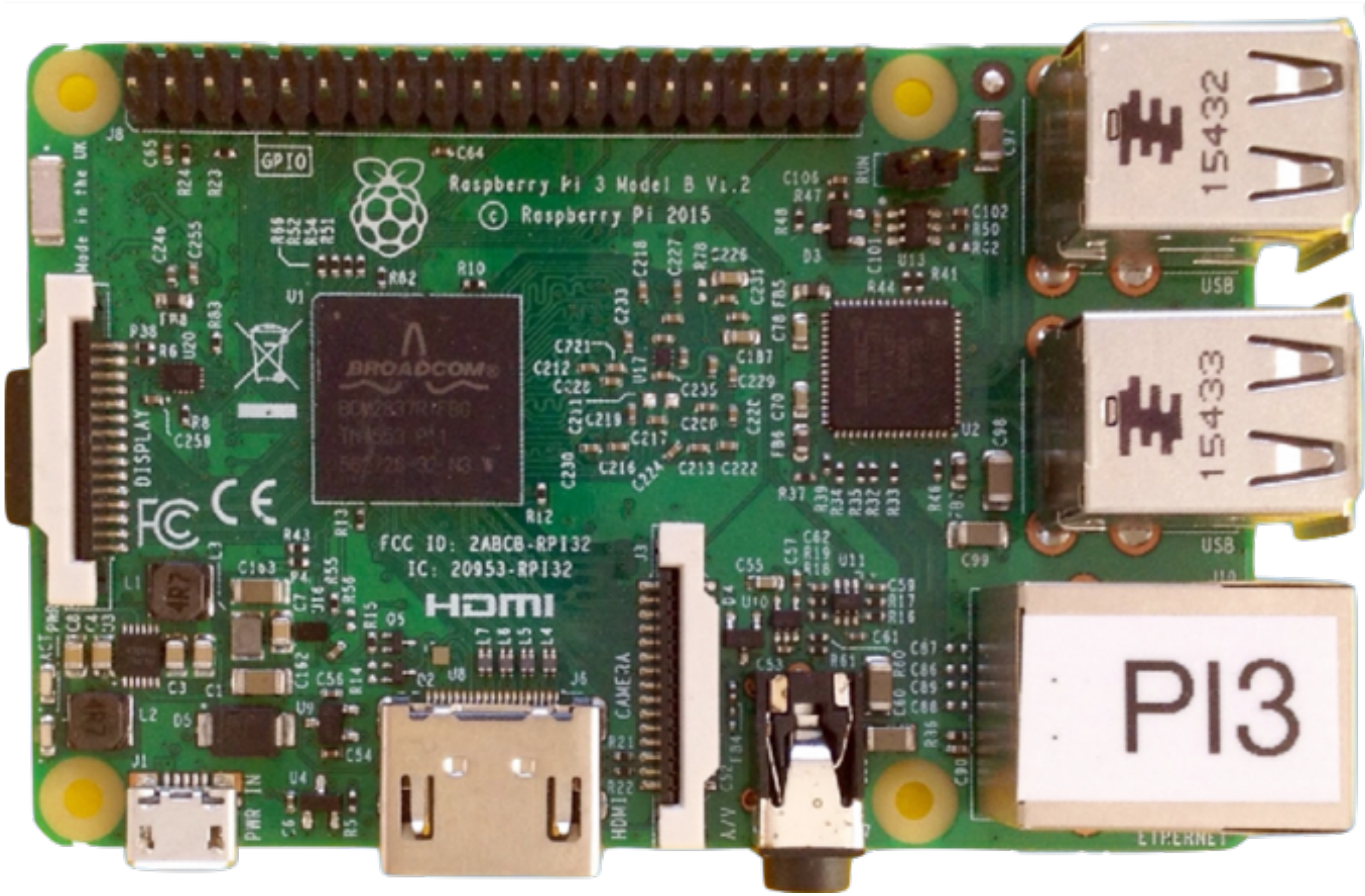

64 bit Bare Metal Programming on RPI-3

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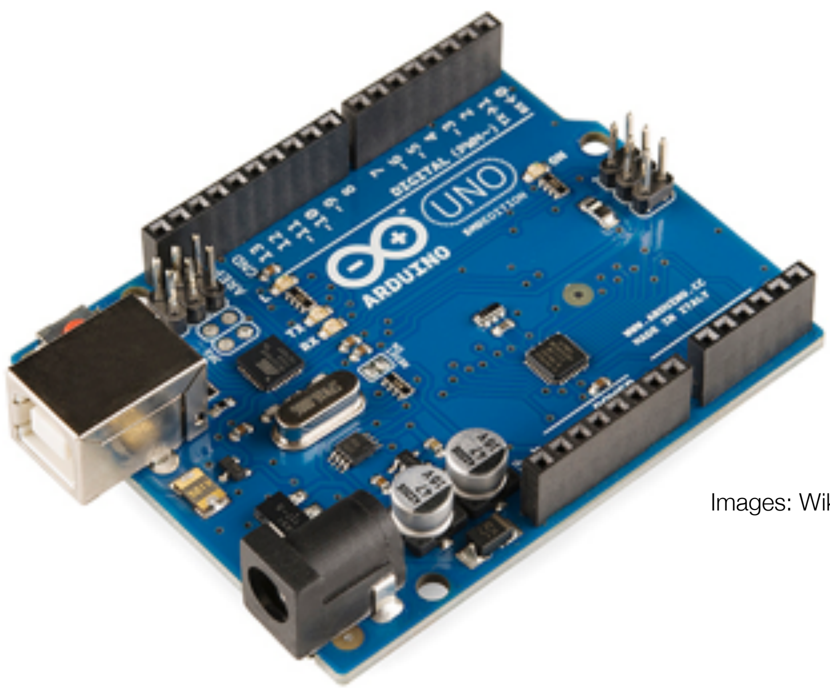
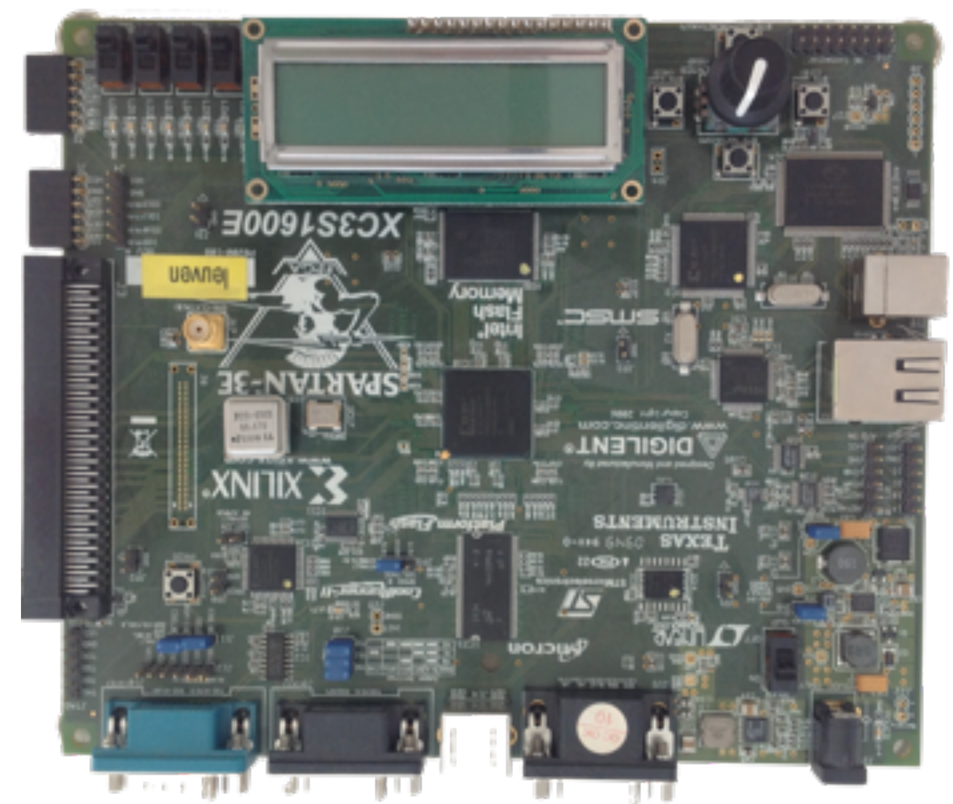
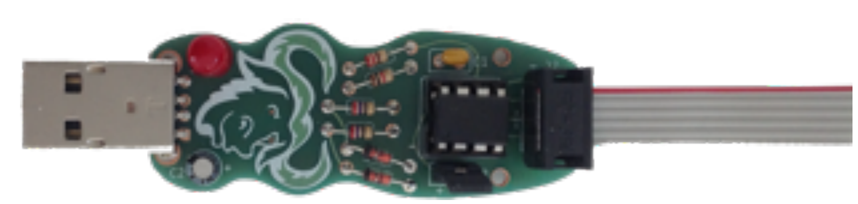
What is Bare Metal ?



Images: Wikipedia



- No box

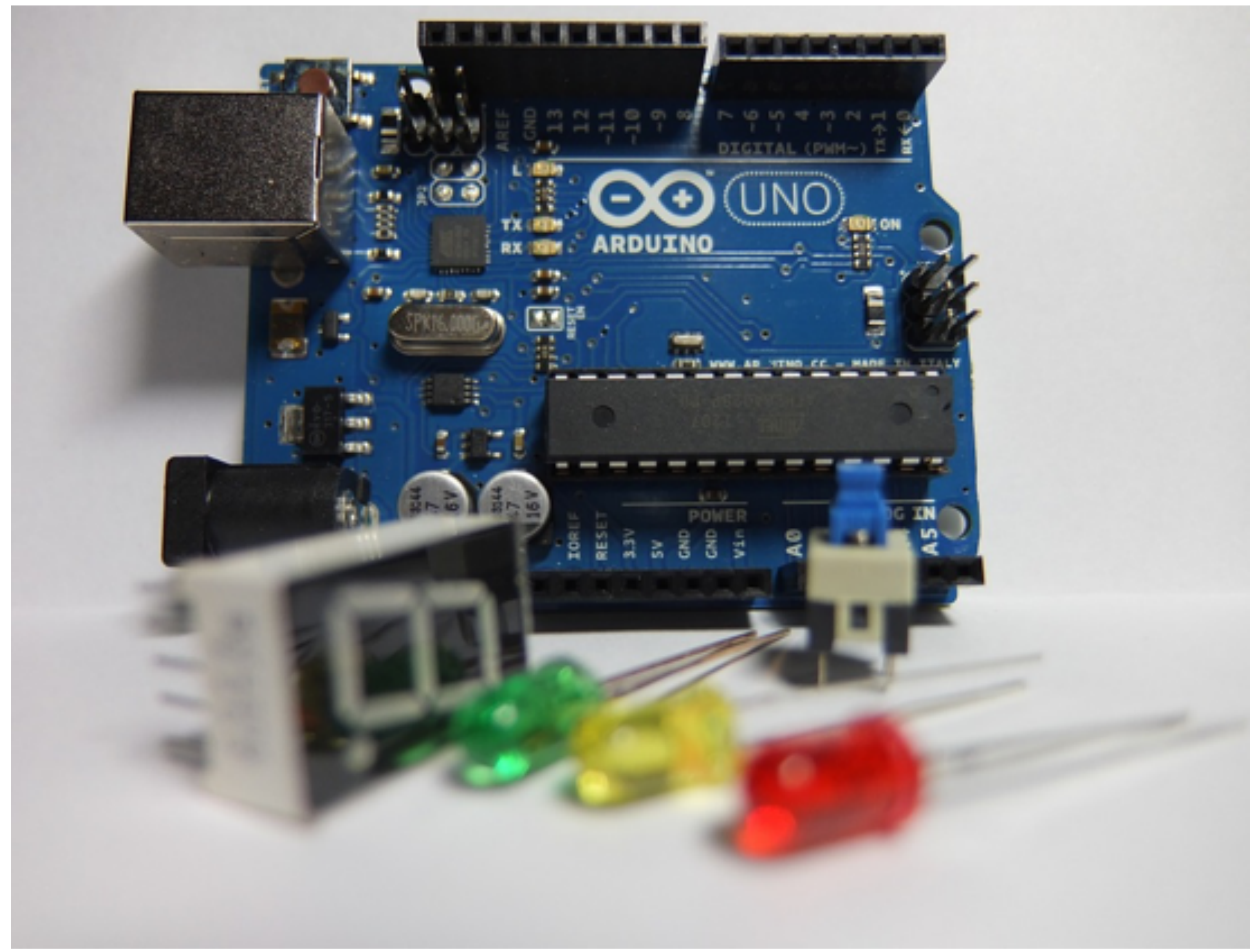


What is Bare Metal ?

Your application is the OS

Why Bare Board ?

Not enough ressources for an OS



Why Bare Board ?

It's fun
(YMMV)

Why Bare Board ?

To learn low-level stuff

Why Raspberry PI-3 ?

It’s popular:

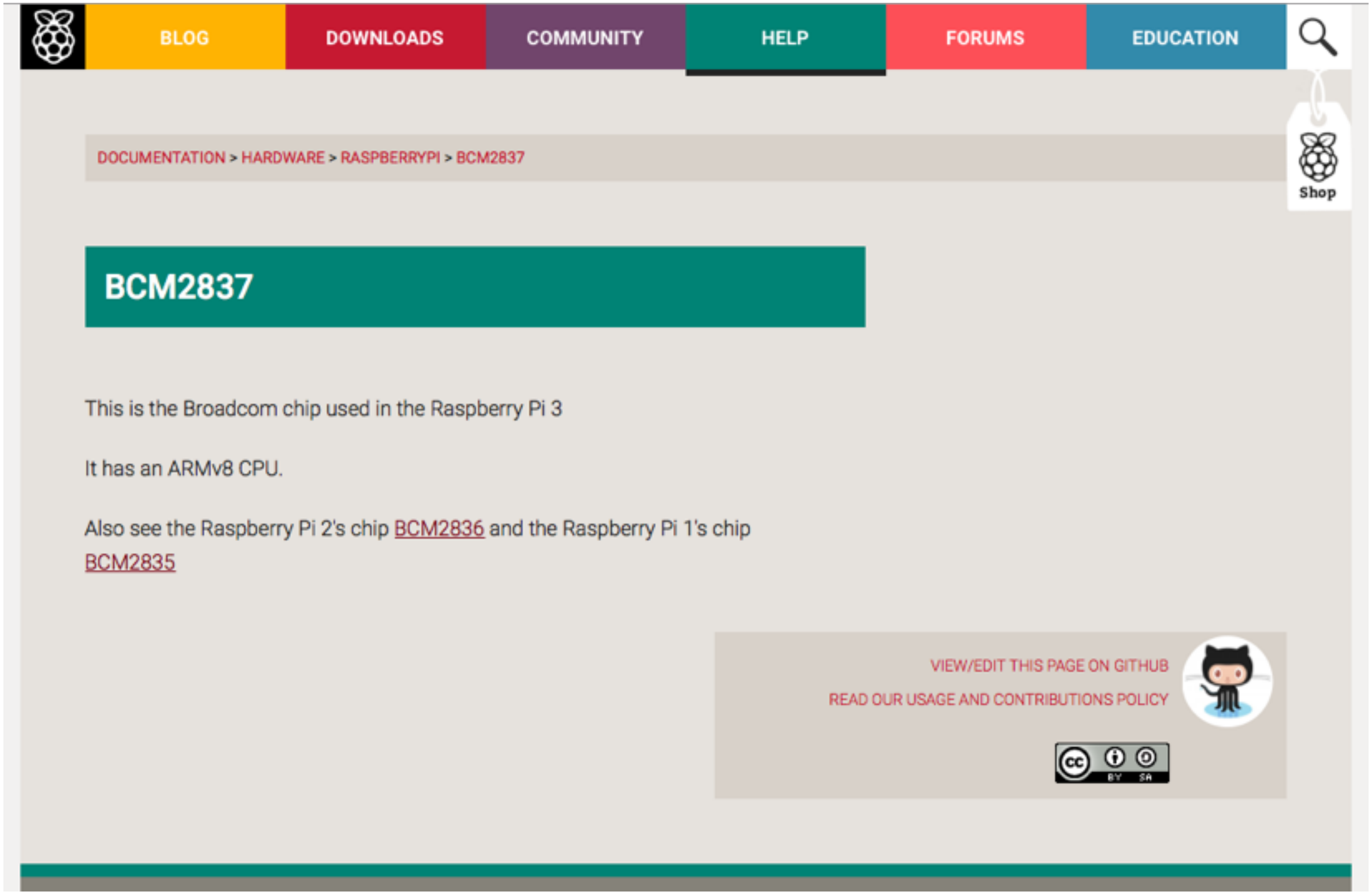
- Forums (https://www.raspberrypi.org/forums/ - Bare metal)
- Many tutorials (like github.com/dwelch67/raspberrypi.git)
- It’s safe (you cannot brick it)

Why Raspberry PI-3 ? But…

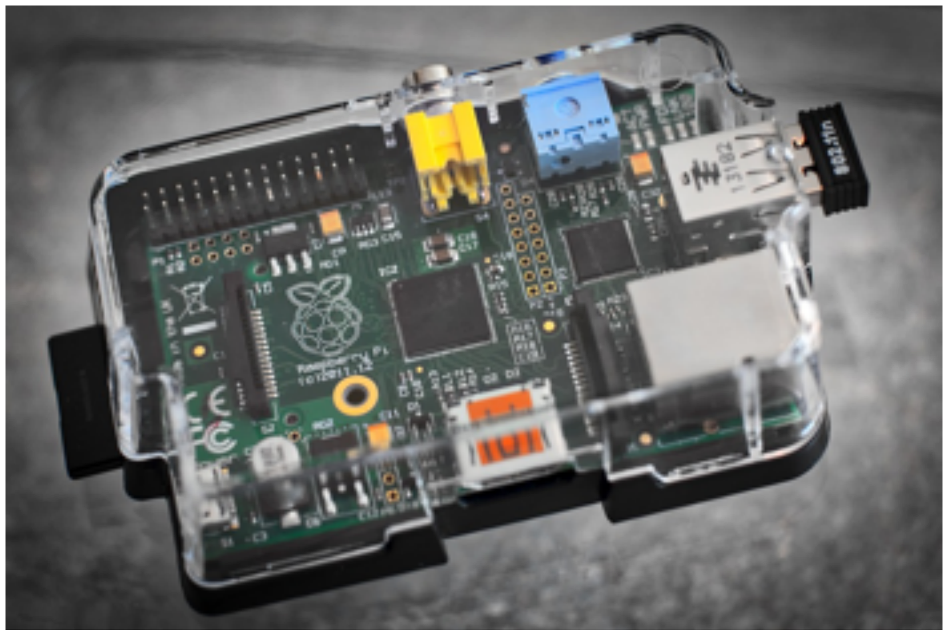
It’s poorly documented:

- It’s a Broadcom SOC
- Data sheet of BCM2835 is available
  - But it’s Raspberry Pi 1
  - It’s incomplete (watchdog ?)
- Differences between Pi 1 and Pi 2 are (partially) documented
- What about BCM2837 ? Wifi ? Bluetooth ?
- Only 1 page schematic of Pi 3 (IO)
- GPU is partially documented
- https://www.raspberrypi.org/documentation/hardware/raspberrypi/bcm2836/README.md

Why Raspberry PI-3 ? But…

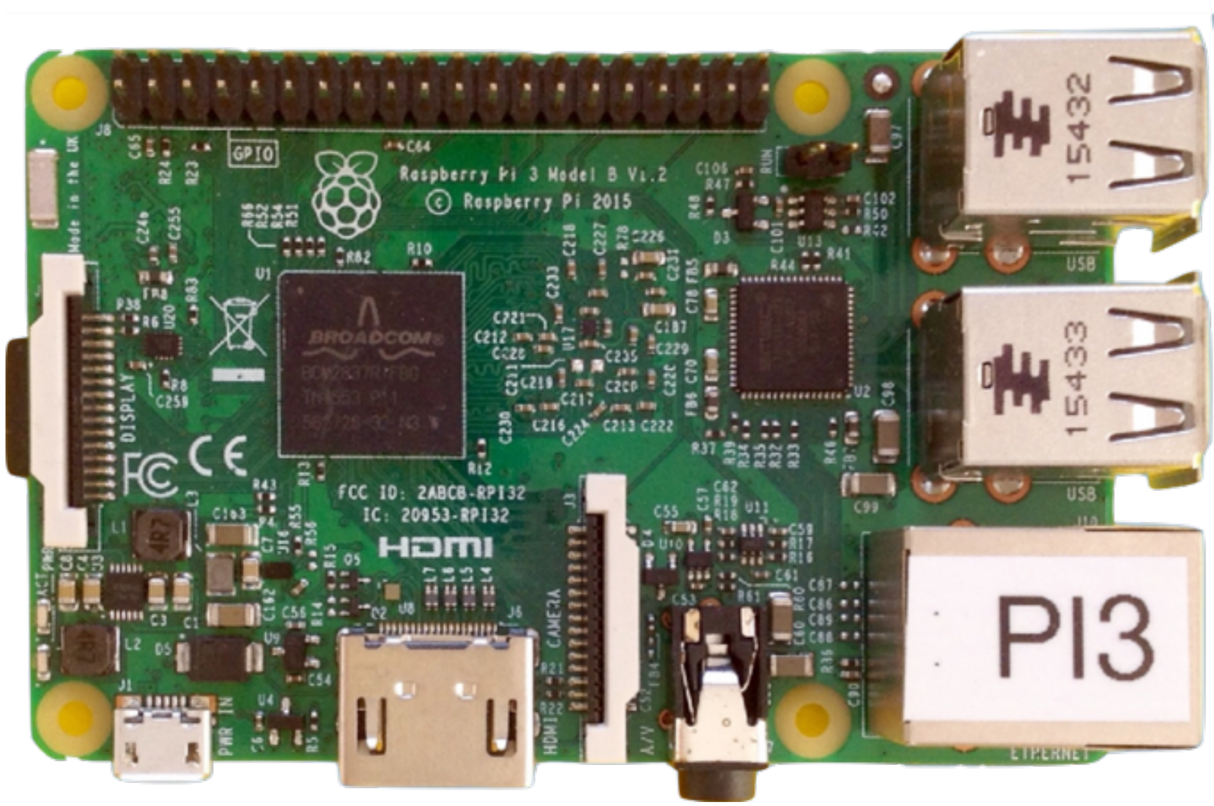


Raspberry PI-3 Platform



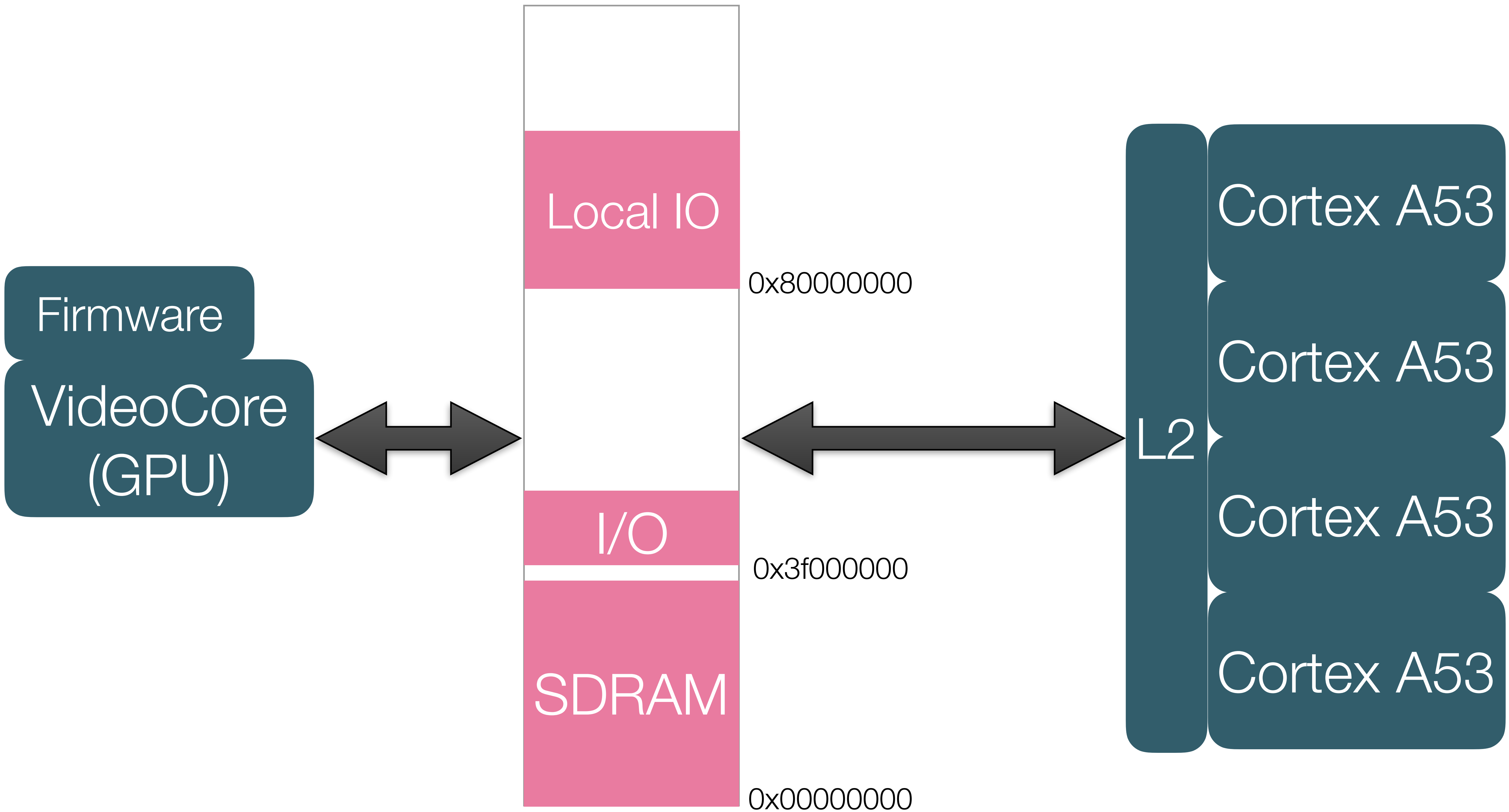
PI-1: ARM1176JZF

PI-2: 4 * Cortex A7



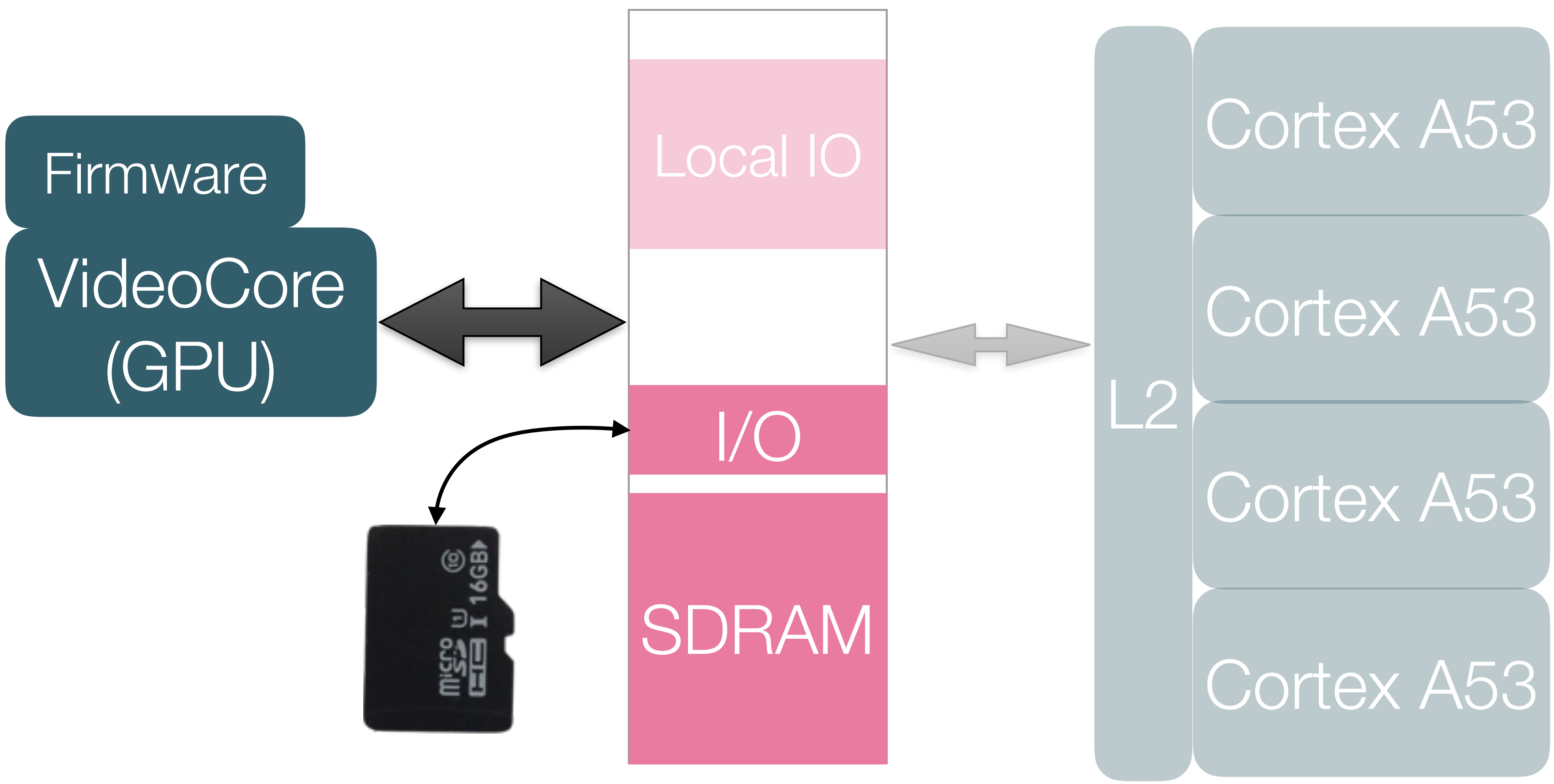
PI-3: 4 * Cortex A53
(Aarch-64)

Raspberry PI Architecture



Raspberry PI Boot (1/2)

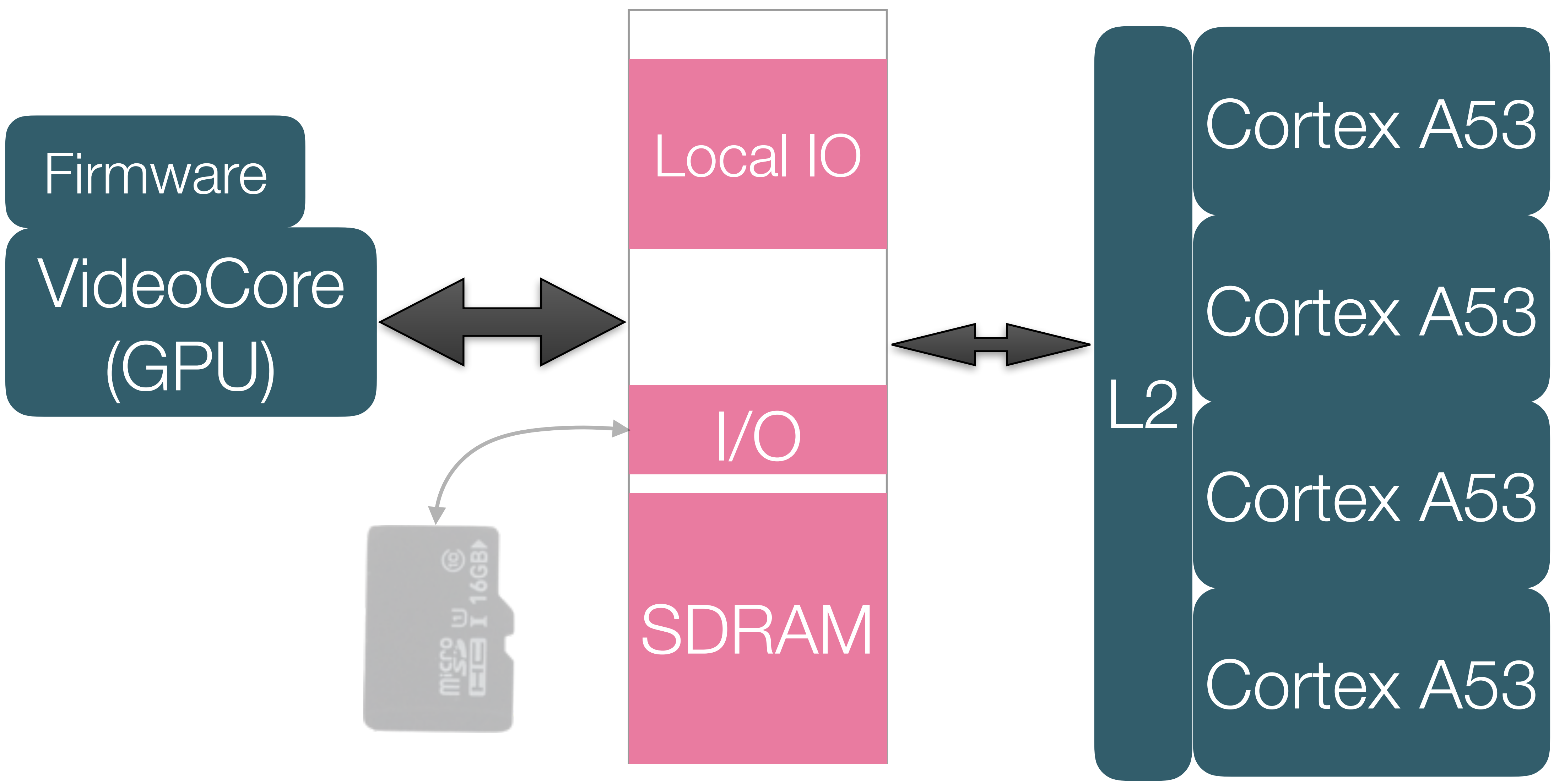
1. VideoCore GPU boots, Cortex cores are off
2. GPU initialise HW, load config and ELF file



Raspberry PI Boot (2/2)

3.GPU starts the cores (*)

Note: Boot process is very safe - you cannot brick the board



Files on the SD Card (FAT32)

- `bootcode.bin`
  First file read by the ROM. Enable SDRAM, and load…
  Boot loader: load start.elf
- `start.elf`
  GPU firmware, load the other files and start the CPUs
- `config.txt`
  configuration
- `fixup.dat`
  Needed to use 1GB of memory
- `kernel7.img`
  Your bare metal application (or the Linux kernel)
  https://github.com/raspberrypi/firmware/tree/master/boot

config.txt

Start in 64 bit mode!

```
arm_control=0x200
kernel_old=1
disable_commandline_tags=1
```

Load at address 0x0

Don't write ATAGS at 0x100

https://github.com/raspberrypi/documentation/blob/master/configuration/config-txt.md

Your First Bare Metal Program

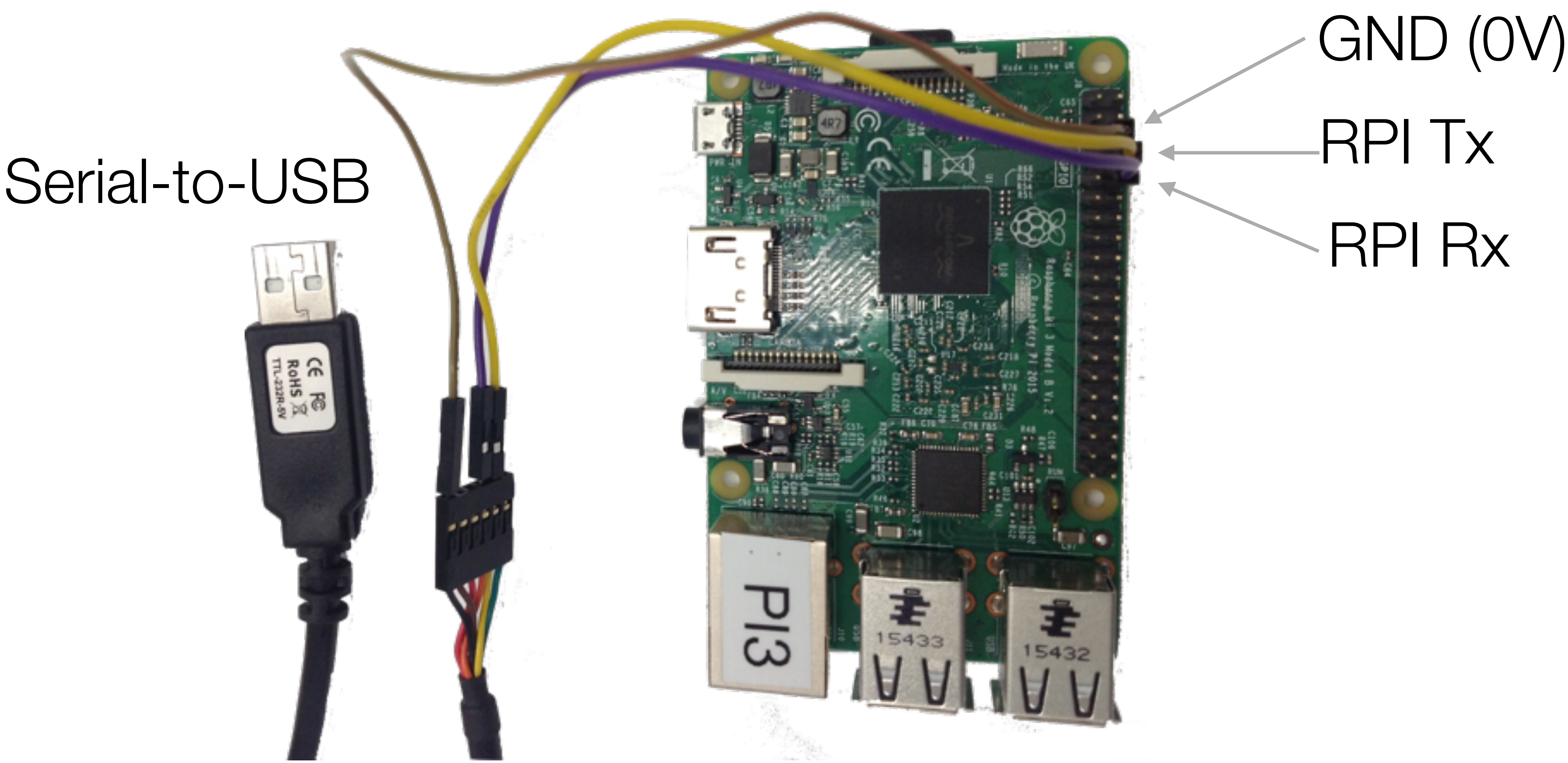
“Hello World” on the console

You need:

- A 3.3v to serial USB converter
- A terminal emulator

- https://github.com/gingold-adacore/rpi3-fosdem17.git

Console (Mini-UART)



Makefile

No libc

Linker map

Linker script

```
CROSS=aarch64-elf-
CC=$(CROSS)gcc
CFLAGS=-Wall -O -ffreestanding

HELLO_OBJS=crt0.o hello.o

all: hello.bin

hello.bin: hello.elf
	$(CROSS)objcopy -O binary $< $@

hello.elf: $(HELLO_OBJS) ram.ld
	$(CROSS)ld -o $@ $(HELLO_OBJS) -Tram.ld -Map hello.map

clean:
	rm -f $(HELLO_OBJS) *.bin *.elf *.map
```

Crt0

- C Run Time 0
    - Traditional name for the entry point file (before main)
- Generally written in assembly
- Has to initialise the board
- Simpler on RPI as the GPU does initialisation
- Still have to create a C friendly environment

Crt0: Setup (before calling main)

```
        .section .traps,"ax"
__start:
        b       __start_ram1

        .text
        .type   __start_ram1, %function
__start_ram1:
        # Read processor number, move slave processors to an infinite loop
        mrs     x7, mpidr_el1
        and     x7, x7, #3
        cbz     x7, __start_master
0:      wfe                             //  Busy loop
        b       0b

__start_master:
        # Load stack pointer (on 32bit)
        adrp    x2,__cpu0_stack_end
        add     x2, x2, #:lo12:__cpu0_stack_end
        mov     sp,x2

        # Clear BSS
        ldr     w0,bss_segment + 0
        ldr     w1,bss_segment + 4
0:      cbz     x1,1f
        str     xzr,[x0],#8
        sub     x1,x1,#1
        cbnz    x1,0b
1:
        bl      main    /* Call the main routine */
0:      b       0b      /* Wait forever in case of exit.  */
        .size   __start_ram1, . - __start_ram1

bss_segment:
        .word   __bss_start
        .word   __bss_dwords
```

Start point (at 0x00)

Keep only cpu #0

Set stack pointer

Clear bss

Call C main

No need for more assembly

C code

- Crt0 calls main()
- You can execute C code
- But no syscalls, you have to write your own IO code
- There might be no C library (you write all the code)
- Write your own drivers
  - Essentially writing and reading words at special addresses, with side effects
- First driver on RPI3: Serial port

Main()

```
void
raw_putc (char c)
{
  while (!(MU_LSR & 0x20))
    ;
  MU_IO = c;
}

void
putc (char c)
{
  if (c == '\n')
    raw_putc ('\r');
  raw_putc (c);
}

void
puts (const char *s)
{
  while (*s)
    putc (*s++);
}

int
main (void)
{
  init_uart ();

  puts ("Hello world!\n");

  return 0;
}
```

Wait until ready

Send one byte to the UART

Write to the TX shift register

Handle \n

Send a string

Next slide

UART init

```c
#define IO_BASE 0x3f000000
#define GP_BASE (IO_BASE + 0x200000)
#define MU_BASE (IO_BASE + 0x215000)

#define AUX_ENB (*(volatile unsigned *)(MU_BASE + 0x04))
#define MU_IO   (*(volatile unsigned *)(MU_BASE + 0x40))
#define MU_LCR  (*(volatile unsigned *)(MU_BASE + 0x4c))
#define MU_LSR  (*(volatile unsigned *)(MU_BASE + 0x54))
#define MU_CNTL (*(volatile unsigned *)(MU_BASE + 0x60))
#define MU_BAUD (*(volatile unsigned *)(MU_BASE + 0x68))

#define GPFSEL1 (*(volatile unsigned *)(GP_BASE + 0x04))
#define GPPUD   (*(volatile unsigned *)(GP_BASE + 0x94))
#define GPPUDCLK0   (*(volatile unsigned *)(GP_BASE + 0x98))

static void
init_uart (void)
{
  int i;

  AUX_ENB |= 1;         /* Enable mini-uart */
  MU_LCR = 3;           /* 8 bit.  */
  MU_BAUD = 270;        /* 115200 baud.  */
  GPFSEL1 &= ~((7 << 12) | (7 << 15)); /* GPIO14 & 15: alt5  */
  GPFSEL1 |= (2 << 12) | (2 << 15);

  /* Disable pull-up/down.  */
  GPPUD = 0;
  for (i = 0; i < 150; i++)
    asm volatile ("nop");
  GPPUDCLK0 = (2 << 14) | (2 << 15);
  for (i = 0; i < 150; i++)
    asm volatile ("nop");
  GPPUDCLK0 = 0;

  MU_CNTL = 3;          /* Enable Tx and Rx.  */
}
```

Defines

UART init

GPIO init

Linker script

```
MEMORY
{
  SRAM (rwx) : ORIGIN = 0, LENGTH = 32M
}

SECTIONS
{
  .text :
  {
    KEEP (*(.traps))
    . = 0x1000;   /* Space for command line.  */
    *(.text .text.* .gnu.linkonce.t*)
  }

  .rodata : { *(.rodata .rodata.* .gnu.linkonce.r*) }

  .ARM.extab   : { *(.ARM.extab* .gnu.linkonce.armextab.*) }
  PROVIDE_HIDDEN (__exidx_start = .);
  .ARM.exidx   : { *(.ARM.exidx* .gnu.linkonce.armexidx.*) }
  PROVIDE_HIDDEN (__exidx_end = .);

  .data : { *(.data .data.* .gnu.linkonce.d*) }

  .bss (NOLOAD): {
   __bss_start = ALIGN(0x10);
   *(.bss .bss.*)
   *(COMMON)

   __bss_end = ALIGN(0x10);

   . = ALIGN(0x10);
   . += 0x1000;
   __cpu0_stack_end = .;

   _end = .;
  }

   __bss_dwords = (__bss_end - __bss_start) >> 3;
```

What next ?

- Make your own program
- Write drivers
  - GPIO are very easy
  - I2C, SPI, MMC aren’t difficult
  - Video is easy too (mainly handled by the Firmware)
  - USB, Bluetooth, Wifi, Ethernet need doc
- At this point it’s like an Arduino…

Performance

- You must enable cache
  - Performances are abysmal without cache
- But IO regions must not be cacheable
  - As IO regions have side effects
- So you need to setup MMU
  - To mark IO regions as uncacheable
  - Static 1-1 tables are enough (and easy to generate)

SMP

- RPI-3 has 4 cortex-A53 cores
- Use multi-processors
  - All processors start
  - Use mpidr to get core number
  - Assign different stack to each processor
  - Initialise hardware only once!

Processor mode

- Cores start at EL3 (Exception Level) Secure Monitor
  - Usually boot is handled by some firmware
- Need to switch to lower EL: EL1 is OS, EL2 is hypervisor
  - EL0 is not recommended (user applications)
- Per EL exceptions handlers
  - Could be used for debug (dump registers in case of crash)
- See smp/ directory in the github repo for the code

Demo: ray casting

- Written in Ada 2012
  - (Could have been guessed from the company name)
- Realtime kernel (Ada ravenscar tasking profile)
- Use 4 cores
- DMA-2D, Vsync interrupt
- No GPU uses
- ~60 fps

Demo (photo of the display)

Demo: ray casting