



Introduction

Lecture 1



Welcome

to the *Microprocessor Architecture* engineering class

You will learn

- how hardware works
- how to actually build your own hardware device
- the Rust programming Language

We expect

- to come to class
- ask a lot of questions



Team



Our team

Lectures

- Alexandru Radovici

Labs

- Alexandru Radovici
- Teodor Dicu (Hardware)
- Genan Omer (Software)



Outline

Lectures

- 12 lectures
- 1 Q&A lecture for the project

Labs

- 7 labs

Project

- Build a hardware device running software written in Rust
- Presented at PM Fair during the last week of the semester





Grading

Part	Description	Points
Lecture tests	You will have a test at every class with subjects from the previous class.	1p
Final Lecture test	You will have a test during one of the lectures in January.	4p
Lab	Your work at every lab will be graded.	1p
Project	You will have to design and implement a hardware device. Grading will be done for the documentation, hardware design and software development.	3p
Final Test	You will have to take an exam during the last week of the semester.	2p
Total	<i>You will need at least 4.5 points to pass the subject.</i>	11p



Subjects



Theory

- How a microprocessor works
- How the ARM Cortex-M processor works
- Using digital signals to control devices
- Using analog signals to read data from sensors
- How interrupts work
- How asynchronous programming works (async/await)
- How embedded operating systems work



Practical

- How to use the STM32 Nucleo-U545RE-Q
 - Affordable
 - Powerful processor
 - Good documentation
- How to program in Rust
 - Memory Safe
 - *Java-like features, without Java's penalties*
 - Defines an embedded standard interface *embedded-hal*



Apollo Guidance Computer



We choose to go to the moon

John F. Kennedy, Rice University, 1961

in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too.



AGC

August 1966

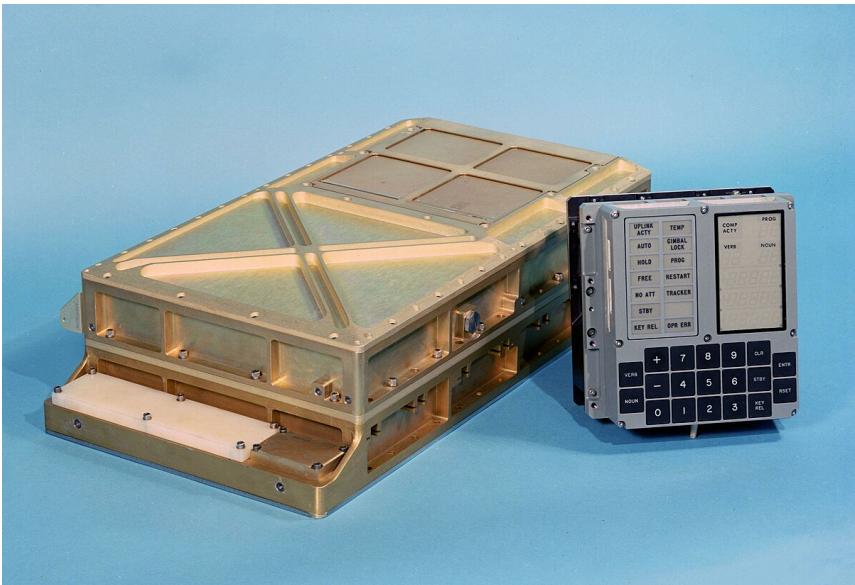
Frequency 2.048 MHz

Word Length 15 + 1 bit

RAM 4096 B

Storage 72 KB

Software API AGC Assembly Language

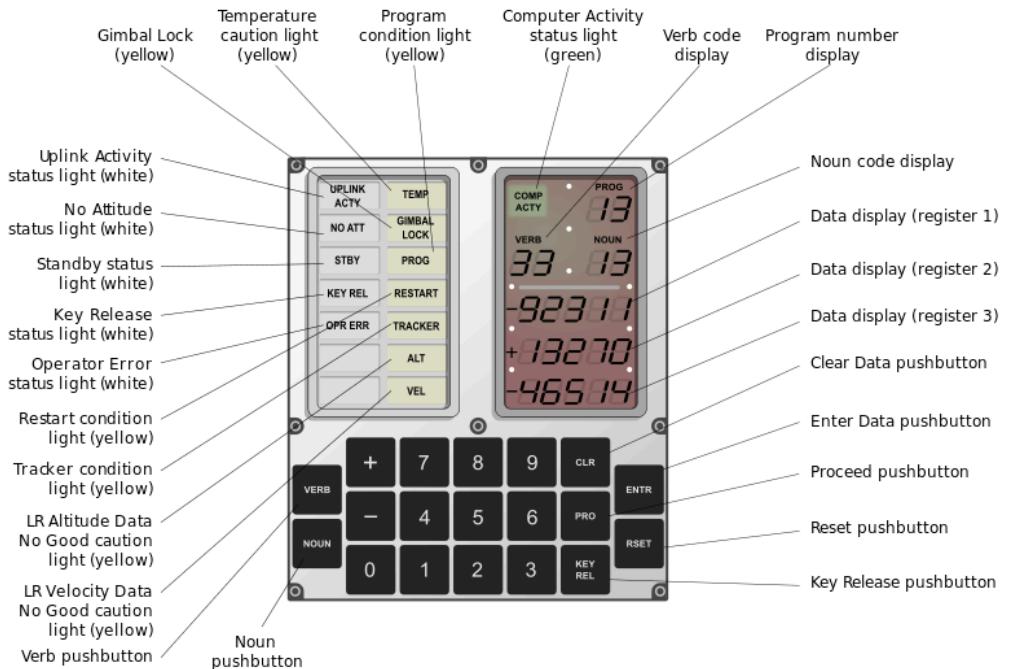


This landed the *moon eagle*.



DSKY

Display and keyboards





What is a microprocessor?



Microcontroller (MCU)

Integrated in embedded systems for certain tasks

- low operating frequency (MHz)
- a lot of I/O ports
- controls hardware
- does not require an Operating System
- costs \$0.1 - \$25
- annual demand is billions



Microprocessor (CPU)

General purpose, for PC & workstations

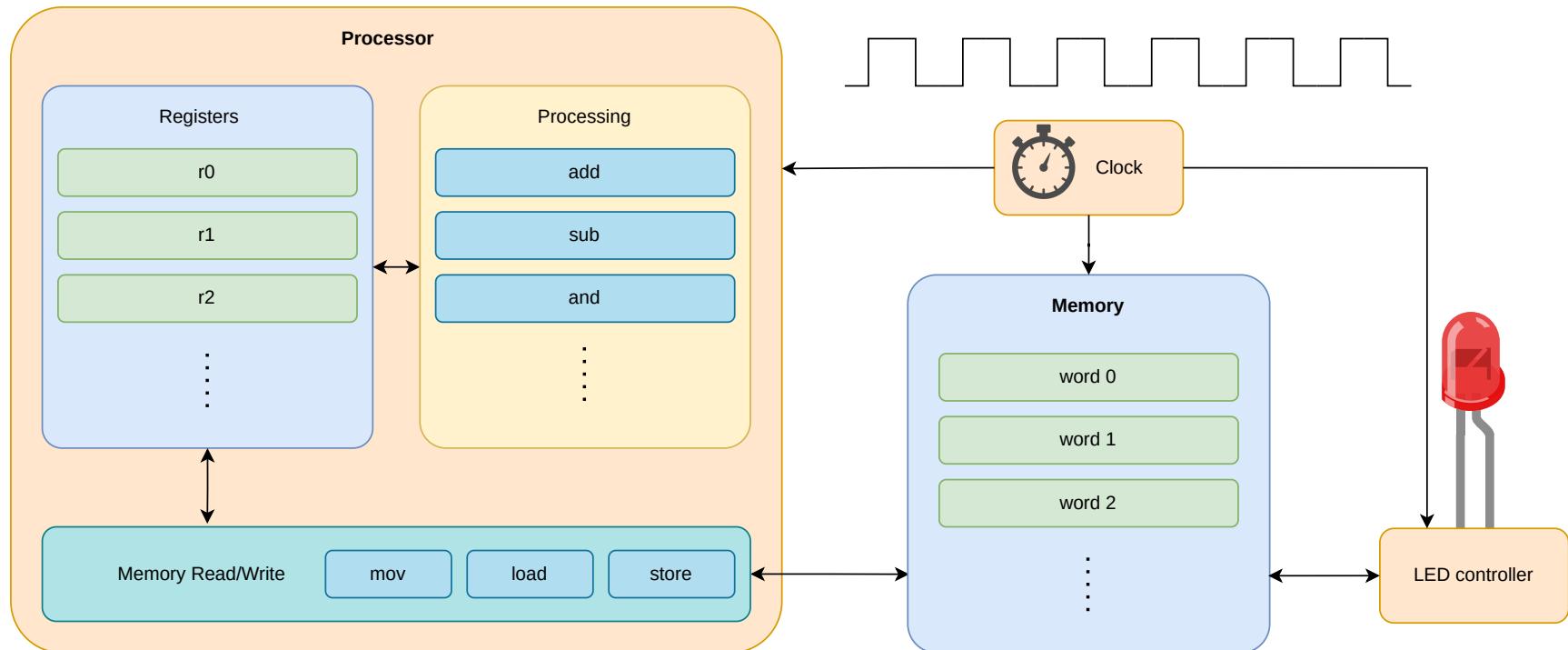
- high operating frequency (GHz)
- limited number of I/O ports
- usually requires an Operating System
- costs \$75 - \$500
- annual demand is tens of millions





How a microprocessor works

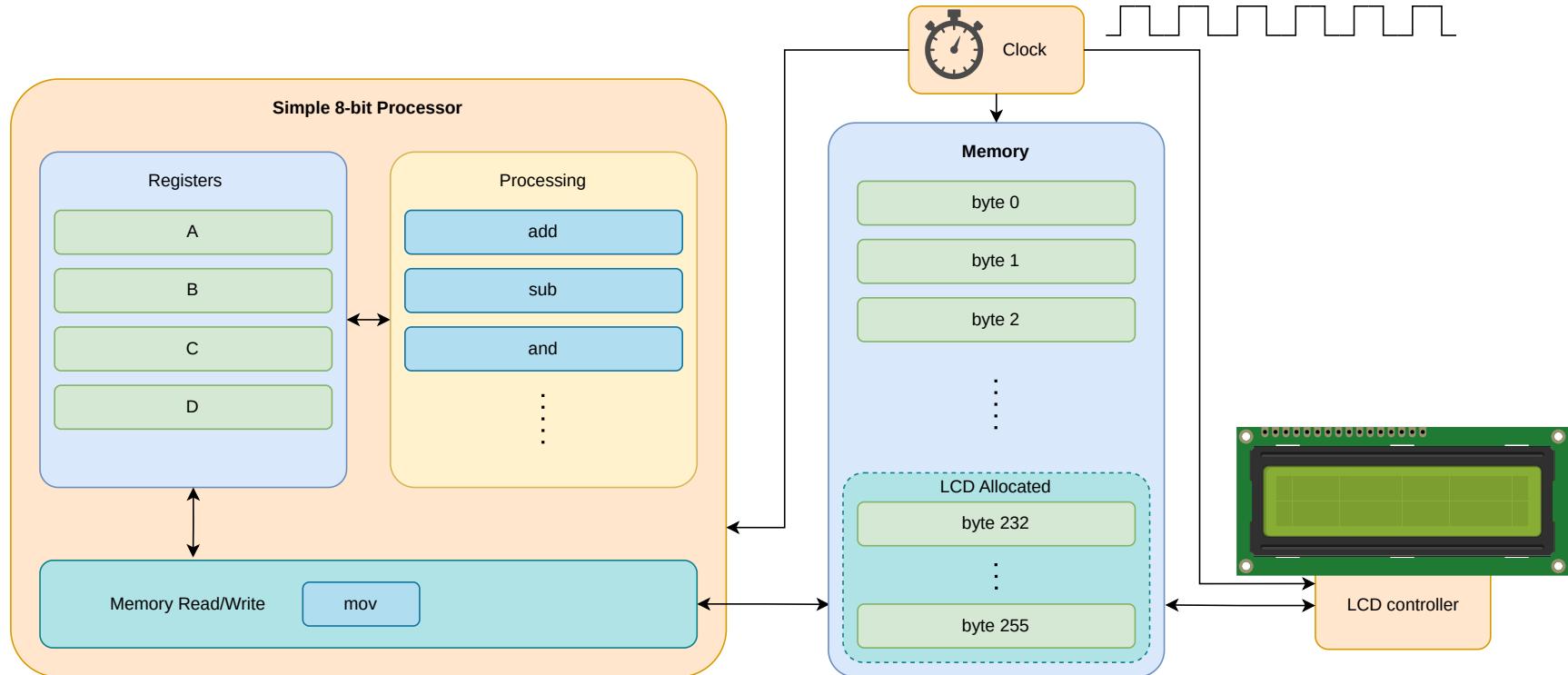
This is a simple processor





8 bit processor

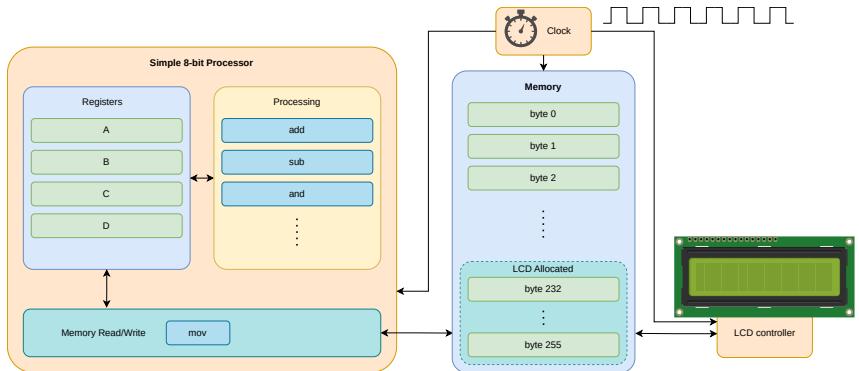
a simple 8 bit processor with a text display





Programming

in Rust



```
1 use eight_bit_processor::print;
2
3 static hello: &str = "Hello World!";
4
5 #[start]
6 fn start() {
7     print(hello);
8 }
```

Assembly

```
1      JMP start
2      hello: DB "Hello World!" ; Variable
3          DB 0 ; String terminator
4      start:
5          MOV C, hello    ; Point to var
6          MOV D, 232    ; Point to output
7          CALL print
8              HLT           ; Stop execution
9      print:      ; print(C:*from, D:*to)
10         PUSH A
11         PUSH B
12         MOV B, 0
13     .loop:
14         MOV A, [C]    ; Get char from var
15         MOV [D], A    ; Write to output
16         INC C
17         INC D
18         CMP B, [C]    ; Check if end
19         JNZ .loop ; jump if not
20
21         POP B
22         POP A
23         RET
```



Demo

a working example for the previous code

Start



Real World Microcontrollers

Intel / AVR / PIC / TriCore / ARM Cortex-M / RISC-V rv32i(a)mc



Bibliography

for this section

Joseph Yiu, *The Definitive Guide to ARM® Cortex®-M0 and Cortex-M0+ Processors, 2nd Edition*

- Chapter 1 - *Introduction*
- Chapter 2 - *Technical Overview*



Intel

Vendor	Intel
ISA	8051, 8051
Word	8 bit
Frequency	a few MHz
Storage	?
Variants	8048, 8051





AVR

probably *Alf and Vegard's RISC processor*

Authors Alf-Egil Bogen and Vegard Wollan

Vendor Microchip (*Atmel*)

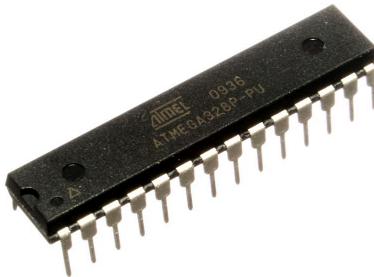
ISA AVR

Word 8 bit

Frequency 1 - 20 MHz

Storage 4 - 256 KB

Variants *ATmega, ATTiny*



Board





PIC

Peripheral Interface Controller / Programmable Intelligent Computer

Vendor Microchip

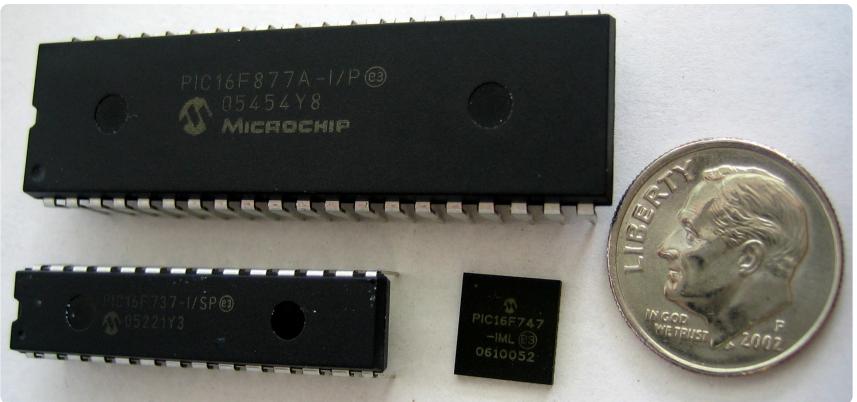
ISA PIC

Word 8 - 32

Frequency 1 - 20 MHz

Storage 256 B - 64 KB

Variants *PIC10, PIC12, PIC16, PIC18, PIC24, PIC32*





TriCore

Vendor	Infineon
ISA	AURIX32
Word	32 bit
Frequency	hundreds of MHz
Storage	a few MB
Variants	<i>TC2xx, TC3xx, TC4xx</i>





ARM Cortex-M

Advanced RISC Machine

arm

Vendor Qualcomm, NXP, Nordic Semiconductor,
 Broadcom, Raspberry Pi

ISA ARMv6-M (Thumb and some Thumb-2)
 ARMv7-M (Thumb and Thumb-2)
 ARMv8-M (Thumb and Thumb-2)

Word 32

Frequency 1 - 900 MHz

Storage up to a few MB

Variants *M0, M0+, M3, M4, M7, M23, M33*

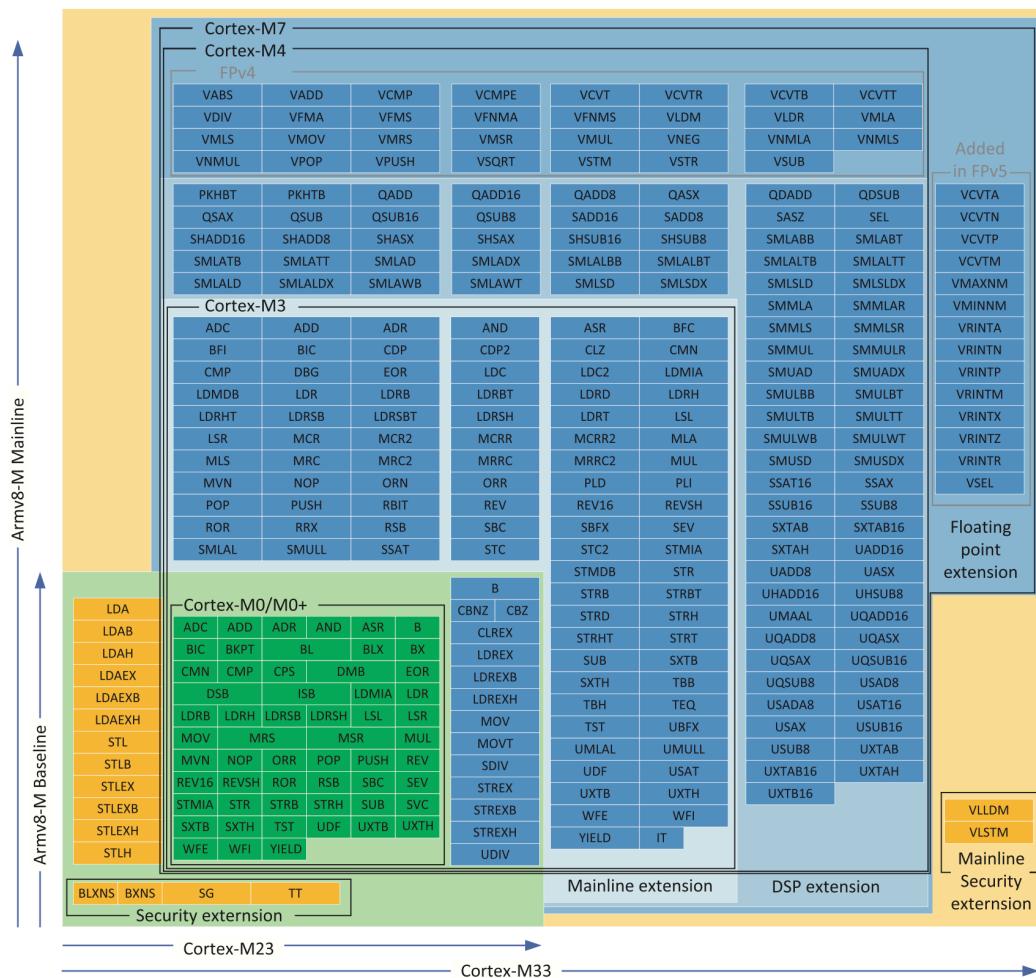


ARM Cortex-M Instruction Set

what the MCU can do

Fun Facts

- M0/M0+ has no `div`
- M0 - M3 have no floating point
- M23 and M33 have security extensions





RISC-V rv32i(a)mc

Fifth generation of RISC ISA

Authors University of California, Berkeley

Vendor Espressif System

ISA rv32i(a)mc

Word 32 bit

Frequency 1 - 200 MHz

Storage 4 - 256 KB

Variants *rv32imc, rv32iamc*





RP2040

ARM Cortex-M0+, built by Raspberry Pi



Bibliography

for this section

Raspberry Pi Ltd, RP2040 Datasheet

- Chapter 1 - *Introduction*
- Chapter 2 - *System Description*
 - Section 2.1 - *Bus Fabric*



RP2040

the MCU

Vendor Raspberry Pi

Variant ARM Cortex-M0+

ISA ARMv6-M (Thumb and some Thumb-2)

Cores 2

Word 32 bit

Frequency up to 133 MHz

RAM 264 KB

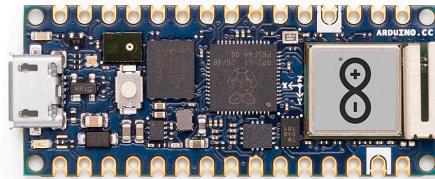
Boards

that use RP2040

Raspberry Pi Pico (W)

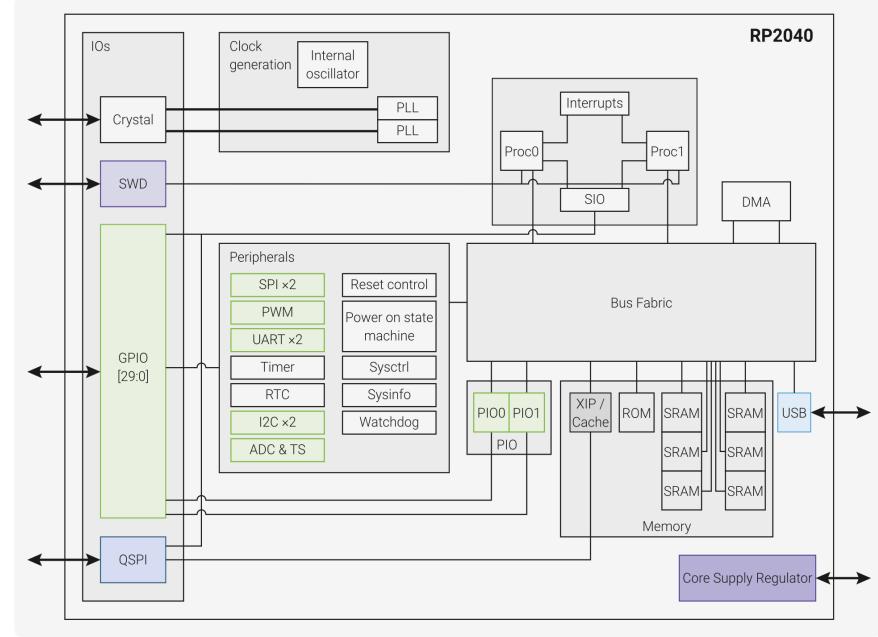


Arduino Nano RP2040 Connect





The Chip



GPIO: General Purpose Input/Output

SWD: Debug Protocol

DMA: Direct Memory Access

Peripherals

SIO Single Cycle I/O (implements GPIO)

PWM Pulse Width Modulation

ADC Analog to Digital Converter

(Q)SPI (Quad) Serial Peripheral Interface

UART Universal Async. Receiver/Transmitter

RTC Real Time Clock

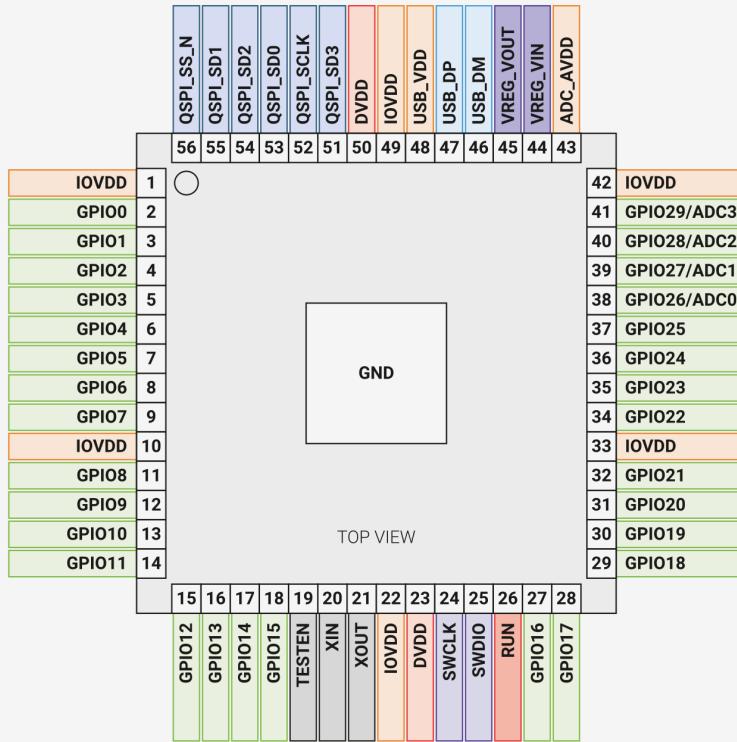
I2C Inter-Integrated Circuit

PIO Programmable Input/Output



Pins

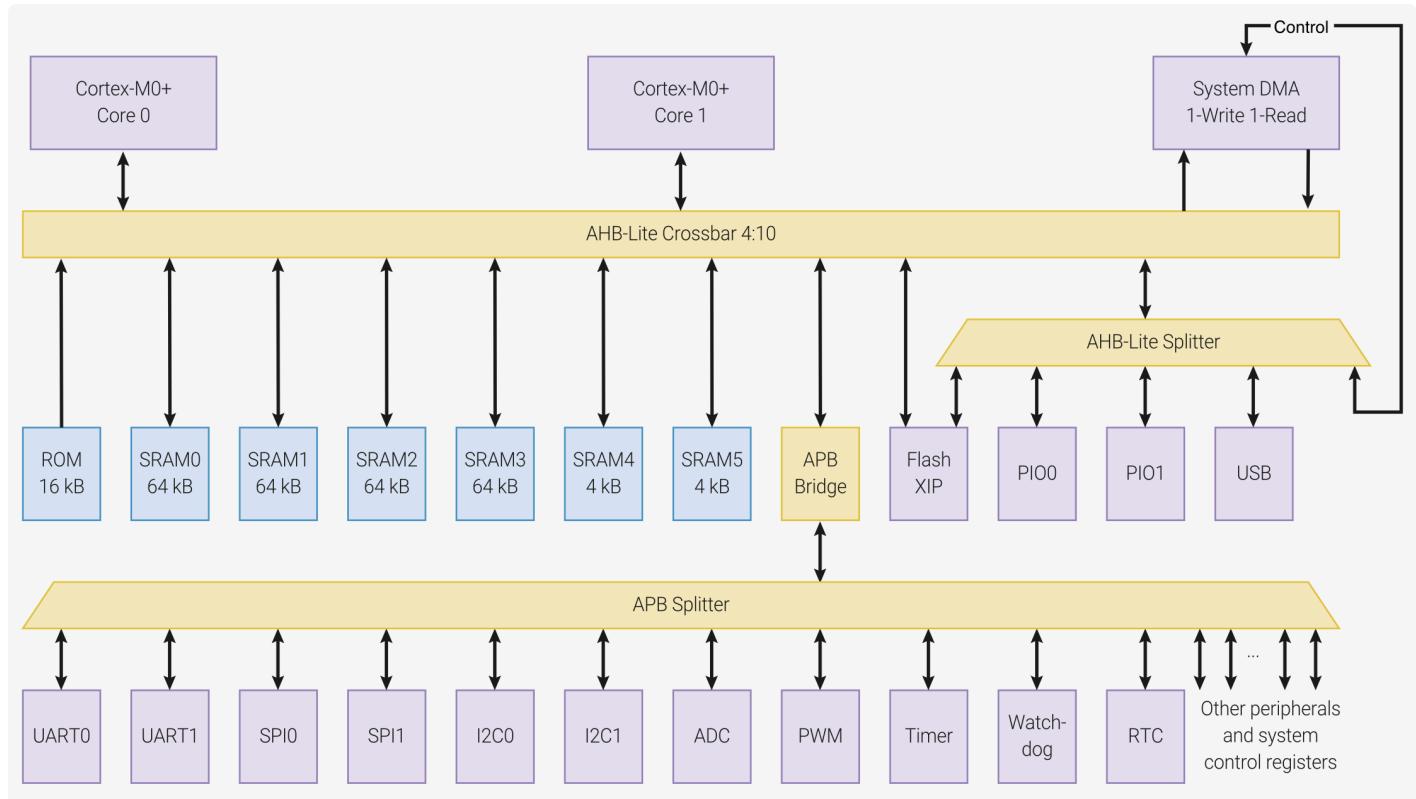
have multiple functions





The Bus

that interconnects the cores with the peripherals





STM32U545RE

ARM Cortex-M33, built by STMicroelectronics



Bibliography

for this section

STMicroelectronics, STM32U5 Reference Manual

- Chapter 2 - *Memory and bus architecture*
 - Section 2.1 - *System architecture*

STMicroelectronics, STM32U5 Datasheet

- Chapter 2 - *Description*"
- Chapter 4 - *"Pinout, pin description, and alternate function"*



STM32U545RE

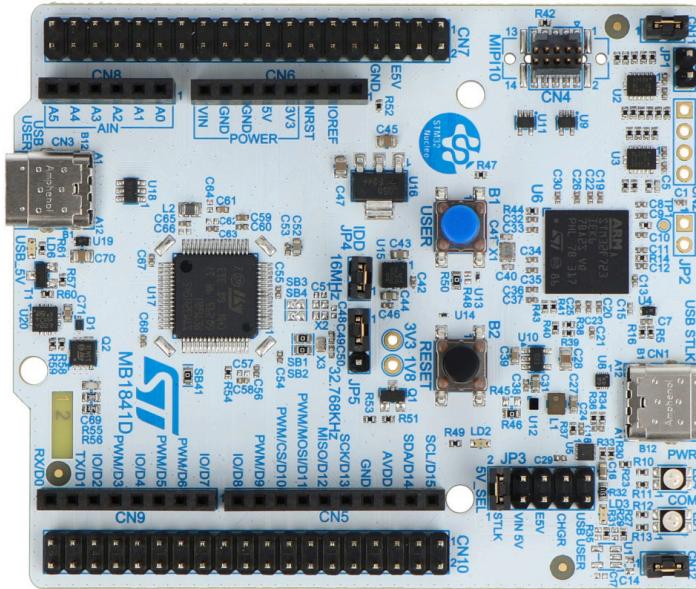
the MCU

Vendor	STMicroelectronics
Variant	ARM Cortex-M33
ISA	ARMv8-M
Cores	1
Word	32 bit
Frequency	up to 160 MHz
RAM	272 KB

Board

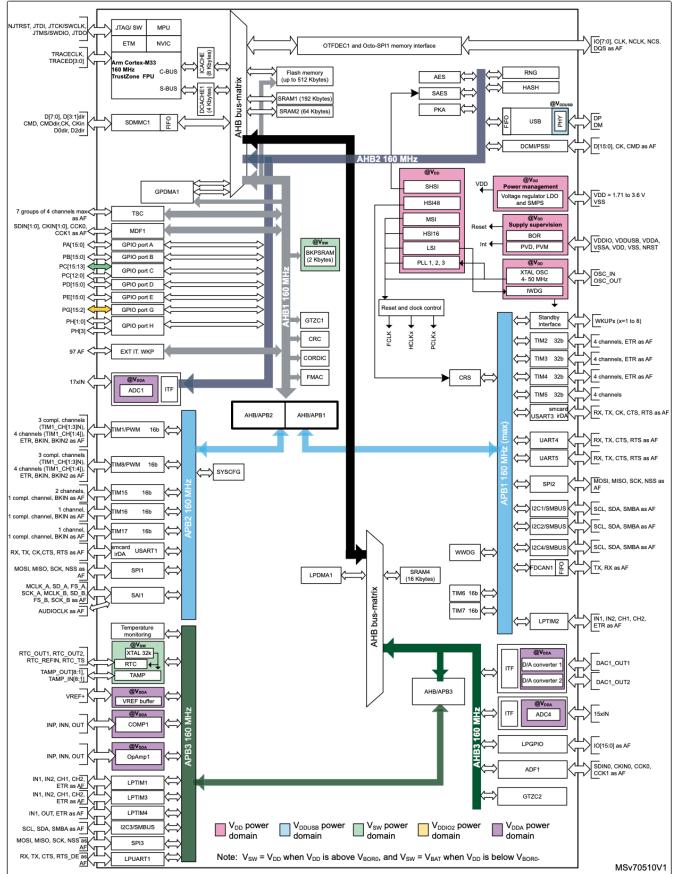
that use STM32U545RE

Nucleo U545RE-Q





The Chip



Peripherals

Parallel interface

FSMC 8-/16-bit
(TFT-LCD, SRAM,
NOR, NAND)

Arm® Cortex®-M33 CPU

160 MHz
TrustZone®
FPU
MPU
ETM

LPDMA

ART Accelerator™

19 timers including:
2 x 16-bit advanced
motor control timers
4 x ULP timers
5 x 16-bit timers
4 x 32-bit timers

connectivity

USB Host/Device
1 x SD/SDIO/MMC, 3 x SPI,
4 x I²C, CAN FD,
1 x Octo-SPI,
4 x USART + 1 x LPUART

Digital

AES (256-bit),
SHA-1, SHA-256,
TRNG, PKA, 1 x SAI,
1 x MDF, 2 x ADF

Analog

**1x 14-bit ADC 2 MSPS,
1x 12-bit ADC 2 MSPS,
2 x DAC, 2 x comparators,
1 x op amps
1 x temperature sensor**

VOS

Touch-sensing controller Camera Interface

Datasheet STM32U545RE

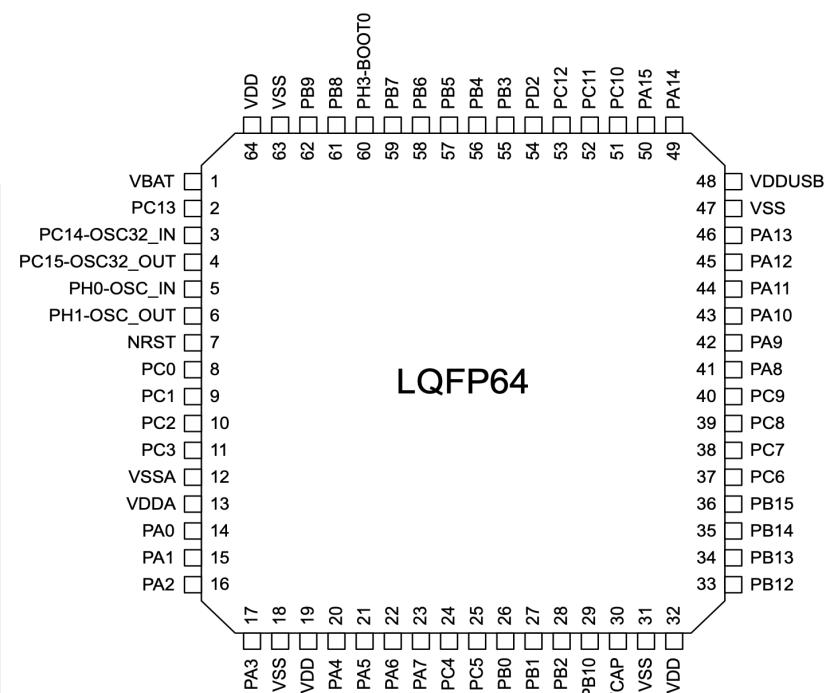


Pins

have multiple functions

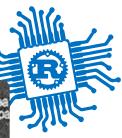
GPIO	F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
0		SPI0 RX	UART0 TX	I2C0 SDA	PWM0 A	SIO	PIO0	PIO1	PIO2	QMI CS1n	USB OVCUR DET	
1		SPI0 CSn	UART0 RX	I2C0 SCL	PWM0 B	SIO	PIO0	PIO1	PIO2	TRACECLK	USB VBUS DET	
2		SPI0 SCK	UART0 CTS	I2C1 SDA	PWM1 A	SIO	PIO0	PIO1	PIO2	TRACEDATA0	USB VBUS EN	UART0 TX
3		SPI0 TX	UART0 RTS	I2C1 SCL	PWM1 B	SIO	PIO0	PIO1	PIO2	TRACEDATA1	USB OVCUR DET	UART0 RX
4		SPI0 RX	UART1 TX	I2C0 SDA	PWM2 A	SIO	PIO0	PIO1	PIO2	TRACEDATA2	USB VBUS DET	
5		SPI0 CSn	UART1 RX	I2C0 SCL	PWM2 B	SIO	PIO0	PIO1	PIO2	TRACEDATA3	USB VBUS EN	
6		SPI0 SCK	UART1 CTS	I2C1 SDA	PWM3 A	SIO	PIO0	PIO1	PIO2	USB OVCUR DET	UART1 TX	
7		SPI0 TX	UART1 RTS	I2C1 SCL	PWM3 B	SIO	PIO0	PIO1	PIO2		USB VBUS DET	UART1 RX
8		SPI1 RX	UART1 TX	I2C0 SDA	PWM4 A	SIO	PIO0	PIO1	PIO2	QMI CS1n	USB VBUS EN	
9		SPI1 CSn	UART1 RX	I2C0 SCL	PWM4 B	SIO	PIO0	PIO1	PIO2		USB OVCUR DET	
10		SPI1 SCK	UART1 CTS	I2C1 SDA	PWM5 A	SIO	PIO0	PIO1	PIO2		USB VBUS DET	UART1 TX
11		SPI1 TX	UART1 RTS	I2C1 SCL	PWM5 B	SIO	PIO0	PIO1	PIO2		USB VBUS EN	UART1 RX
12	HSTX	SPI1 RX	UART0 TX	I2C0 SDA	PWM6 A	SIO	PIO0	PIO1	PIO2	CLOCK GPIN0	USB OVCUR DET	
13	HSTX	SPI1 CSn	UART0 RX	I2C0 SCL	PWM6 B	SIO	PIO0	PIO1	PIO2	CLOCK GPOUT0	USB VBUS DET	
14	HSTX	SPI1 SCK	UART0 CTS	I2C1 SDA	PWM7 A	SIO	PIO0	PIO1	PIO2	CLOCK GPIN1	USB VBUS EN	UART0 TX
15	HSTX	SPI1 TX	UART0 RTS	I2C1 SCL	PWM7 B	SIO	PIO0	PIO1	PIO2	CLOCK GPOUT1	USB OVCUR DET	UART0 RX
16	HSTX	SPI0 RX	UART0 TX	I2C0 SDA	PWM0 A	SIO	PIO0	PIO1	PIO2		USB VBUS DET	
17	HSTX	SPI0 CSn	UART0 RX	I2C0 SCL	PWM0 B	SIO	PIO0	PIO1	PIO2		USB VBUS EN	
18	HSTX	SPI0 SCK	UART0 CTS	I2C1 SDA	PWM1 A	SIO	PIO0	PIO1	PIO2		USB OVCUR DET	UART0 TX
19	HSTX	SPI0 TX	UART0 RTS	I2C1 SCL	PWM1 B	SIO	PIO0	PIO1	PIO2	QMI CS1n	USB VBUS DET	UART0 RX
20		SPI0 RX	UART1 TX	I2C0 SDA	PWM2 A	SIO	PIO0	PIO1	PIO2	CLOCK GPIN0	USB VBUS EN	
21		SPI0 CSn	UART1 RX	I2C0 SCL	PWM2 B	SIO	PIO0	PIO1	PIO2	CLOCK GPOUT0	USB OVCUR DET	
22		SPI0 SCK	UART1 CTS	I2C1 SDA	PWM3 A	SIO	PIO0	PIO1	PIO2	CLOCK GPIN1	USB VBUS DET	UART1 TX

...



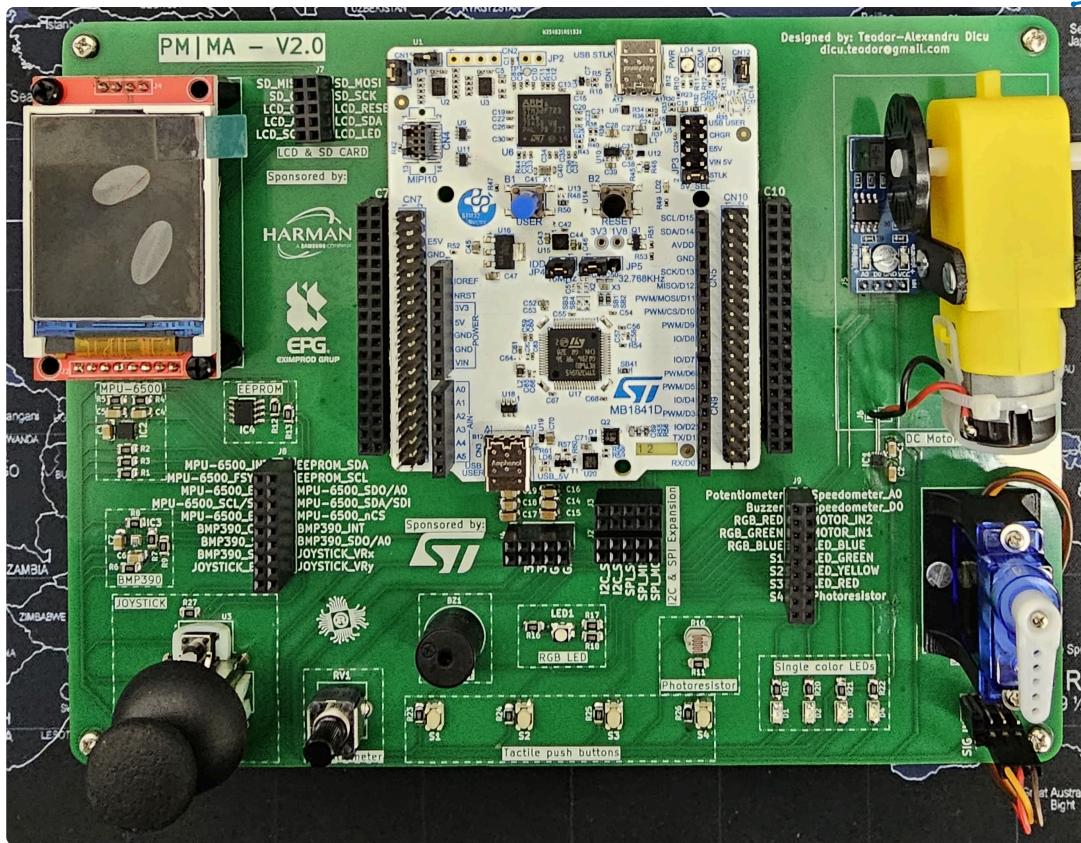
The Bus

that interconnects the core with the peripherals



Lab Board

- Nucleo U545RE-Q Slot / Board
- 4 buttons
- 5 LEDs
- potentiometer
- buzzer
- photoresistor
- I2C EEPROM
- MPU-6500 accelerometer & Gyro
- BMP 390 Pressure sensor
- SPI LCD Display
- SD Card Reader
- servo connectors
- stepper motor





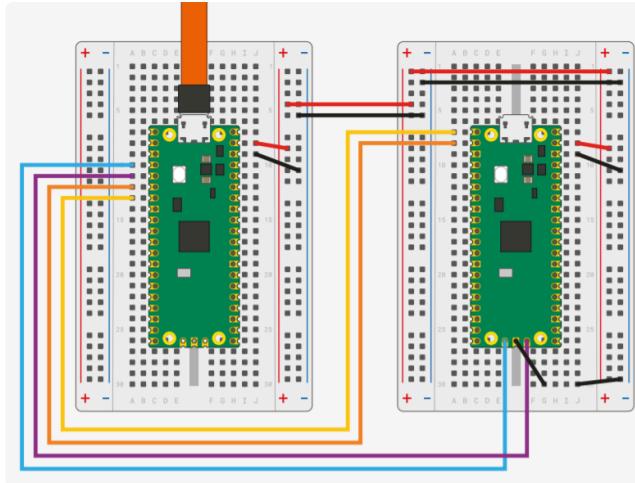
Project

suggested hardware

- the hardware should not cost more than 150 RON
- STM32 Nucleo F446RE or Nucleo U545RE-Q board (include debuggers)
- Raspberry Pi Pico with a debugger

Raspberry Pi Pico 2W + Debug Probe

Raspberry Pi Pico 2W + Raspberry Pi Pico 1





Bitwise Ops

How to set and clear bits



Set bit

set the `1` on position `bit` of register

```
1 fn set_bit(register: usize, bit: u8) -> usize {  
2     // assume register is 0b1000, bit is 2  
3     //   1 << 2 is 0b0100  
4     //   0b1000 | 0b0100 is 0b1100  
5     register | 1 << bit  
6 }
```

Set multiple bits

```
1 fn set_bits(register: usize, bits: usize) -> usize {  
2     // assume register is 0b1000, bits is 0b0111  
3     //   0b1000 | 0b0111 is 0b1111  
4     register | bits  
5 }
```



Clear bit

Set the `0` on position `bit` of register

```
1 fn clear_bit(register: usize, bit: u8) -> usize {  
2     // assume register is 0b1100, bit is 2  
3     //   1 << 2 is 0b0100  
4     //   !(1 << 2) is 0b1011  
5     //   0b1100 & 0b1011 is 0b1000  
6     register & !(1 << bit)  
7 }
```

Clear multiple bits

```
1 fn clear_bits(register: usize, bits: usize) -> usize {  
2     // assume register is 0b1111, bits is 0b0111  
3     //   !bits = 0b1000  
4     //   0b1111 & 0b1000 is 0b1000  
5     register & !bits  
6 }
```



Flip bit

Flip the bit on position `bit` of register

```
1 fn flip_bit(register: usize, bit: u8) -> usize {  
2     // assume register is 0b1100, bit is 2  
3     //   1 << 2 is 0b0100  
4     //   0b1100 ^ 0b0100 is 0b1000  
5     register ^ 1 << bit  
6 }
```

Flip multiple bits

```
1 fn flip_bits(register: usize, bits: usize) -> usize {  
2     // assume register is 0b1000, bits is 0b0111  
3     //   0b1000 ^ 0b0111 is 0b1111  
4     register ^ bits  
5 }
```



Let's see a combined operation for value extraction

- We presume an 32 bits ID = `0b1100_1010_1111_1100_0000_1111_0110_1101`
- And want to extract a portion `0b1100_1010_1111_1100_0000_1111_0110_1101`

```
1  const MASK: u32 = 0b0000_0000_0000_0000_1111_1111_1111;
2
3  fn print_binary(label: &str, num: u32) {
4      println!("{}: {:032b}", label, num);
5  }
6
7  fn main() {
8      let large_id: u32 = 0b1100_1010_1111_1100_0000_1111_0110_1101;
9      let extracted_bits = (large_id >> 20) & MASK;
10
11     // Print values in binary
12     print_binary("Original_", large_id);
13     print_binary("Mask_____", MASK);
14     print_binary("Extracted", extracted_bits);
15 }
16 /* RESULT
17 Original_: 110010101111100000111101101101
18 Mask_____: 0000000000000000000000111111111111
19 Extracted: 00000000000000000000110010101111 */
```



With nice formating

```
1 const MASK: u32 = 0b0000_0000_0000_0000_1111_1111_1111;
2 fn format_binary(num: u32) -> String {
3     (0..32).rev()
4         .map(|i| {
5             if i != 0 && i % 4 == 0 {
6                 format!("{}_", (num >> i) & 1)
7             } else {
8                 format!("{}", (num >> i) & 1)
9             }
10        })
11        .collect::<Vec<_>>()
12        .join("")
13    }
14 fn print_binary(label: &str, num: u32) { println!("{}: {}", label, format_binary(num));}
15 fn main() {
16     let large_id: u32 = 0b1100_1010_1111_1100_0000_1111_0110_1101;
17     let extracted_bits = (large_id >> 20) & MASK;
18     print_binary("Original_", large_id);
19     print_binary("Extracted", extracted_bits);
20 }
21 /* RESULTS:
22 Original_: 1100_1010_1111_1100_0000_1111_0110_1101
23 Extracted: 0000_0000_0000_0000_1100_1010_1111 */
```



Conclusion

we talked about

- How a processor functions
- Microcontrollers (MCU) / Microprocessors (CPU)
- Microcontroller architectures
- ARM Cortex-M
- RP2040 and STM32U545RE