



# 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
<b>Total</b>	<i>You will need at least 4.5 points to pass the subject.</i>	<b>11p</b>



# 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

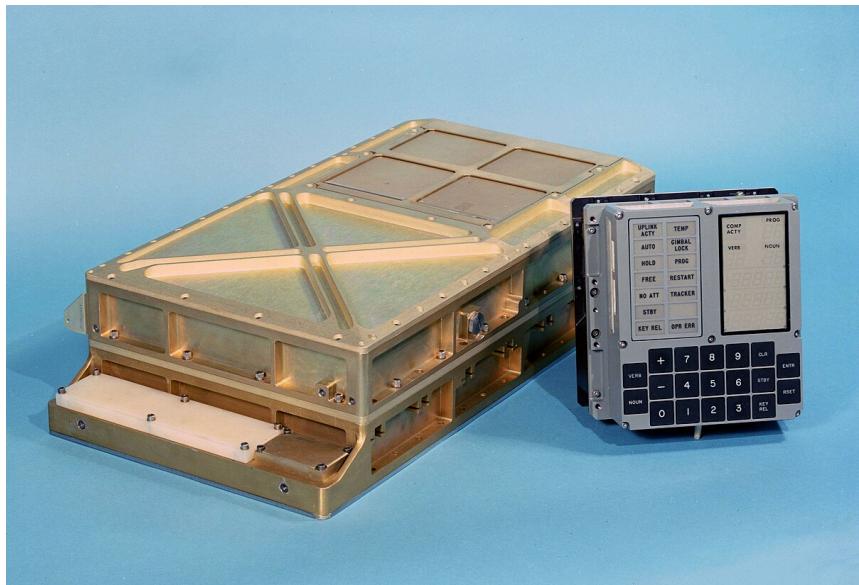
Frequency      2.048 MHz

Word Length    15 + 1 bit

RAM            4096 B

Storage        72 KB

Software API   AGC Assembly Language

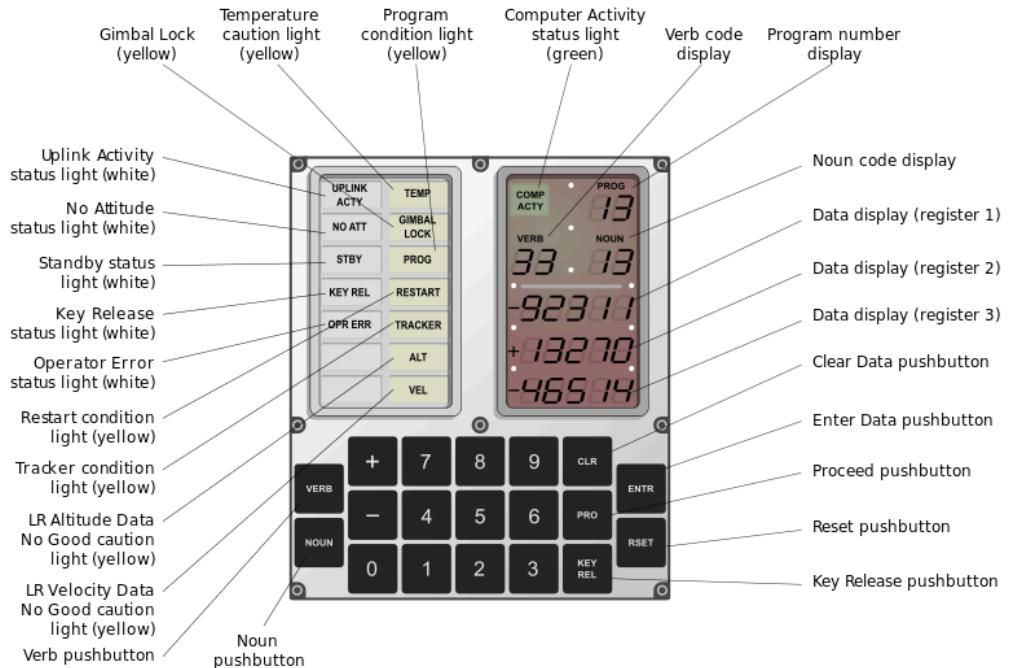


This landed the *moon eagle*.



# 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

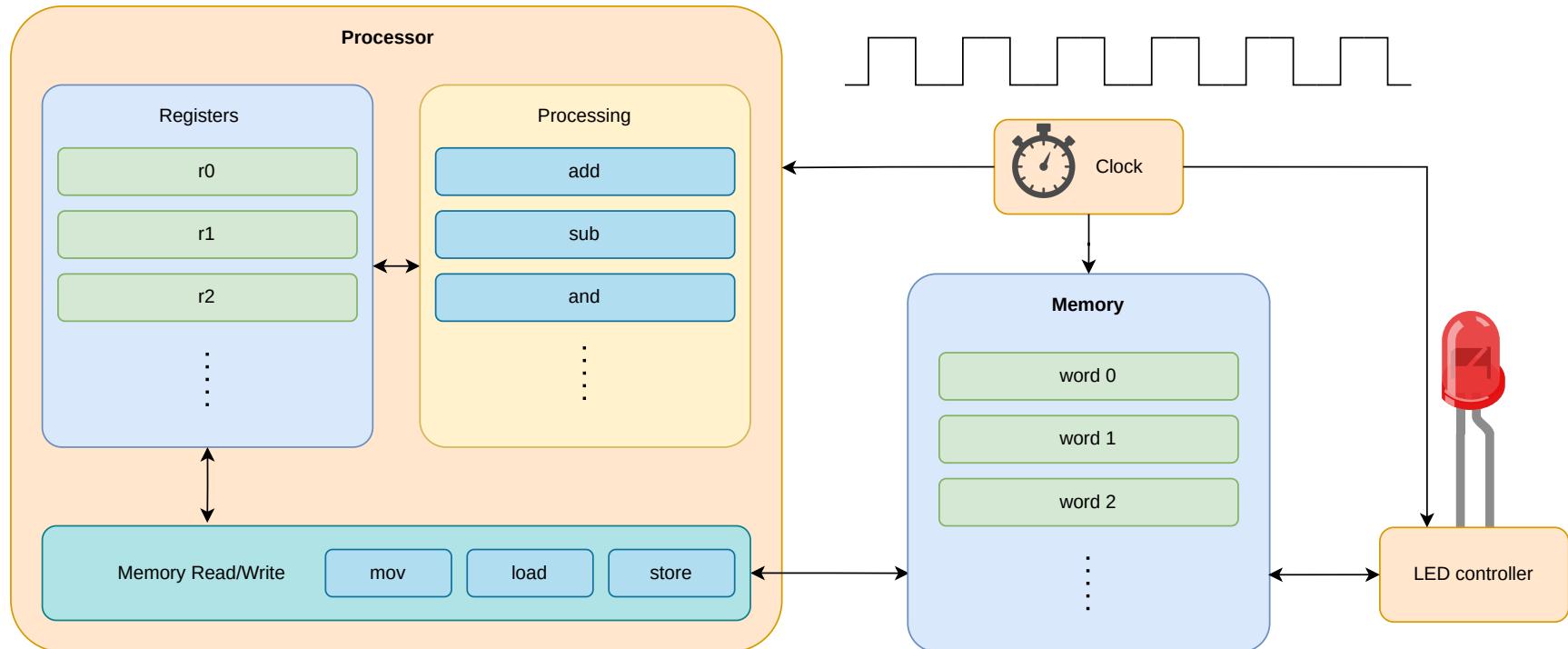
- high operating frequency (GHz)
- limited number of I/O ports
- usually requires an Operating System
- costs \$75 - \$500
- annual demand is tens of millions





# How a microprocessor works

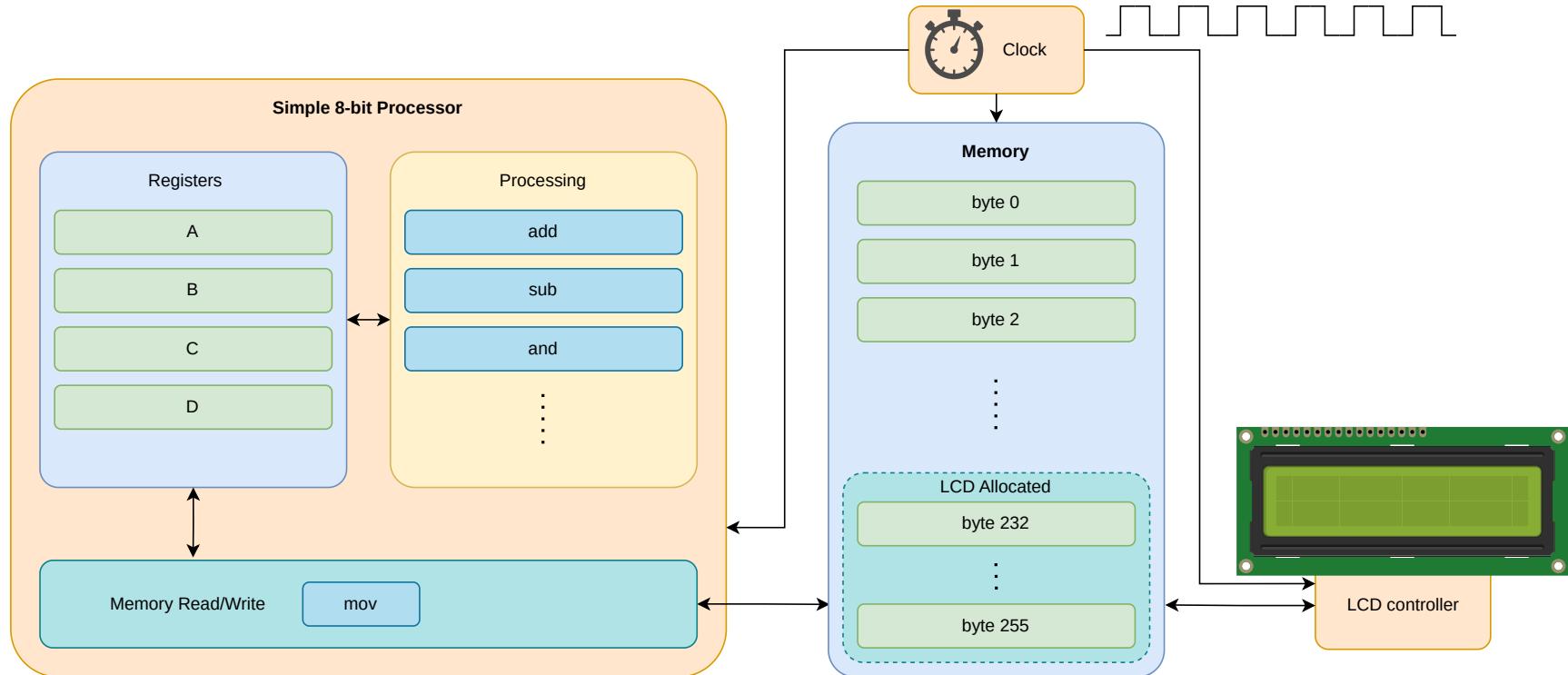
This is a simple processor





# 8 bit processor

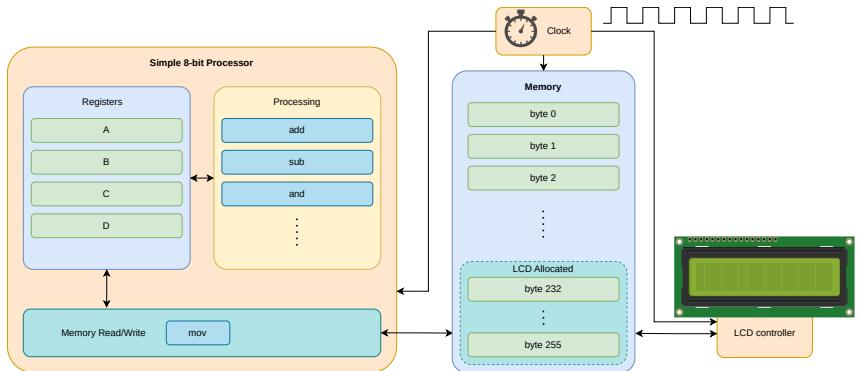
a simple 8 bit processor with a text display





# 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*

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Authors      Alf-Egil Bogen and Vegard Wollan

---

Vendor      Microchip (*Atmel*)

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ISA            AVR

---

Word          8 bit

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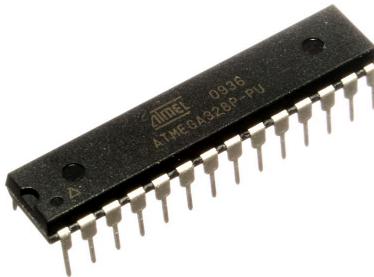
Frequency    1 - 20 MHz

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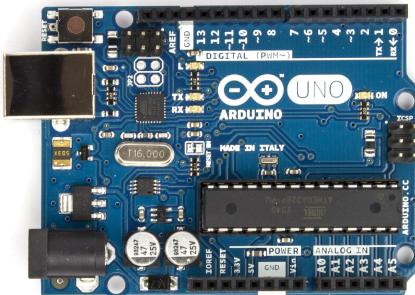
Storage       4 - 256 KB

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Variants      *ATmega, ATTiny*



Board





# PIC

Peripheral Interface Controller / Programmable Intelligent Computer

Vendor Microchip

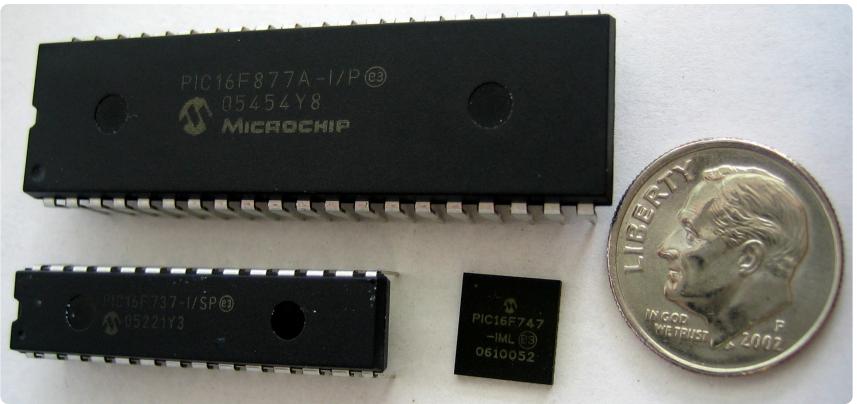
ISA PIC

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

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

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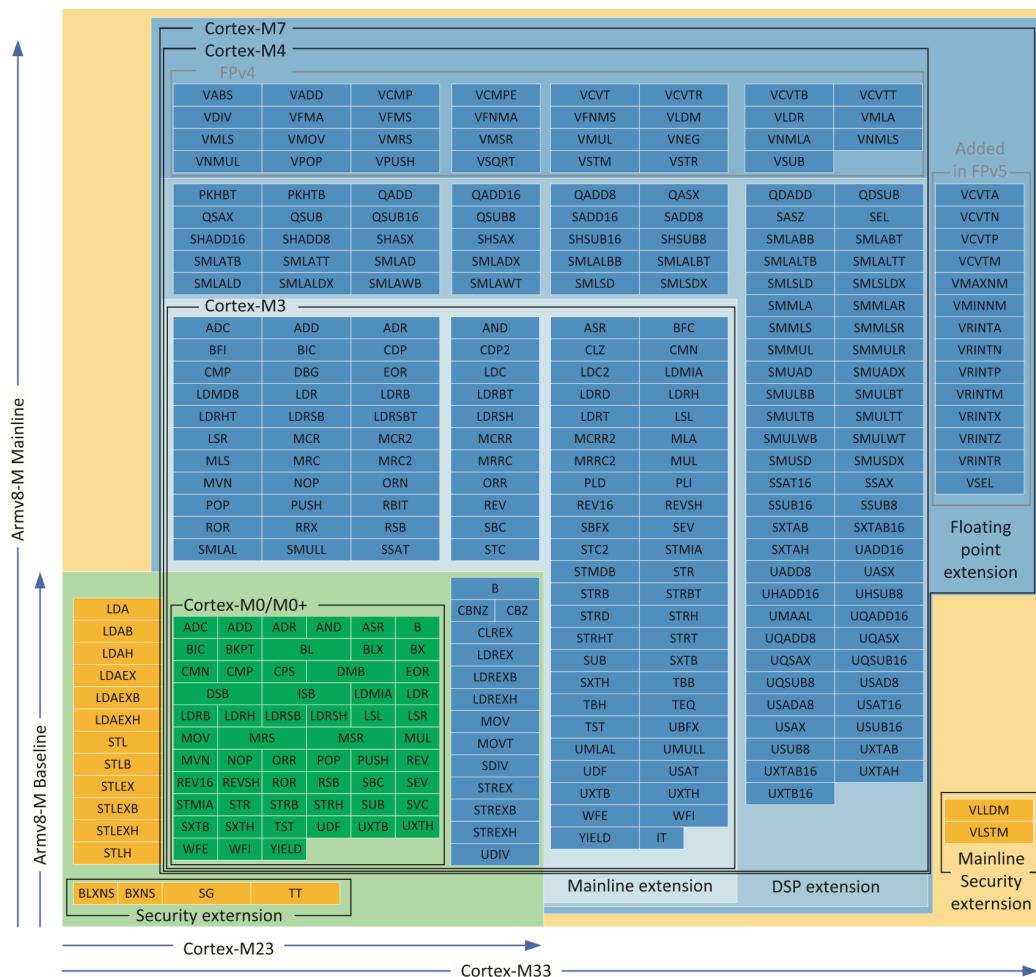


# ARM Cortex-M Instruction Set

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

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Authors      University of California, Berkeley

---

Vendor      Espressif System

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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

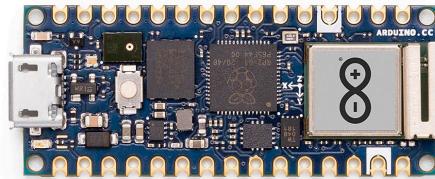
# Boards

that use RP2040

## Raspberry Pi Pico (W)

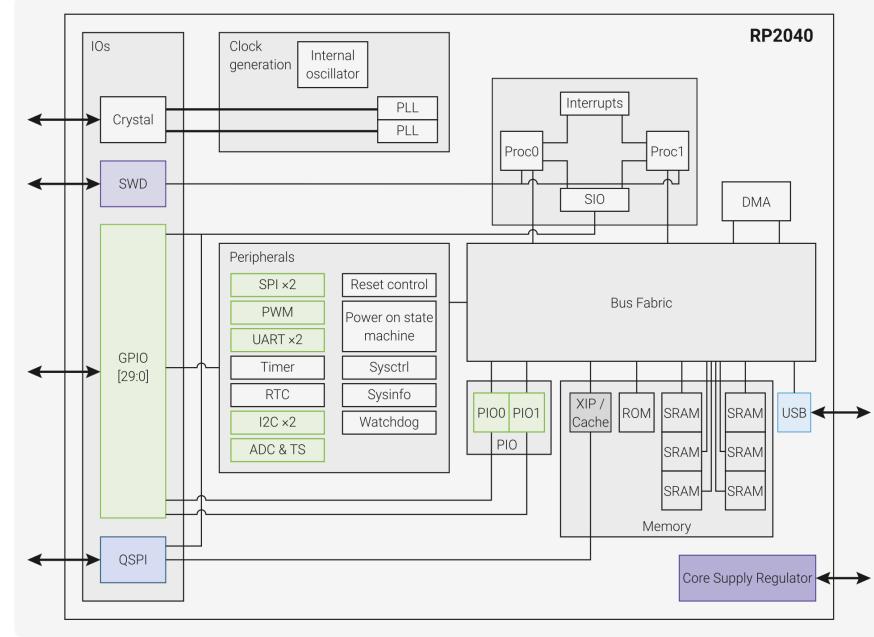


## Arduino Nano RP2040 Connect





# 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

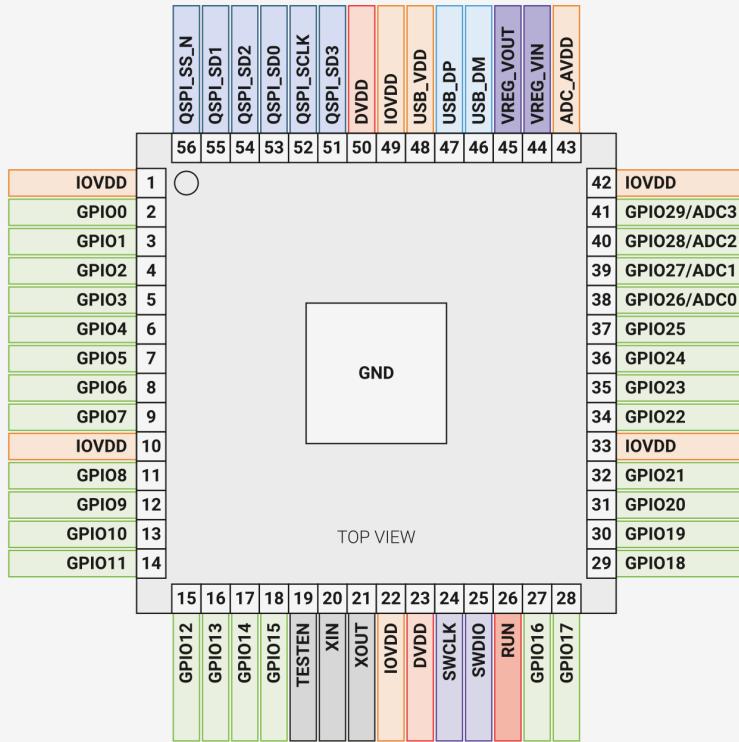
**I2C** Inter-Integrated Circuit

**PIO** Programmable Input/Output



# Pins

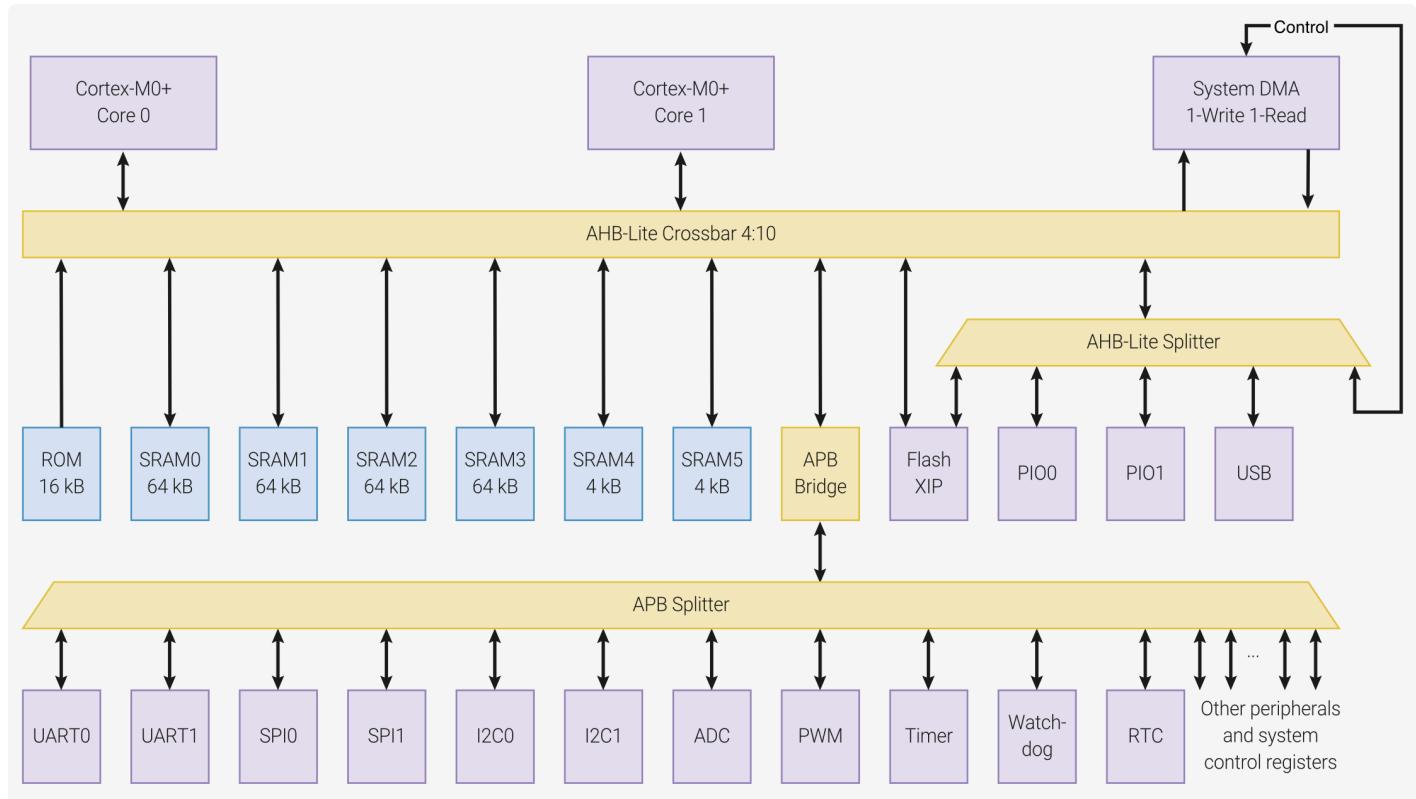
have multiple functions





# 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

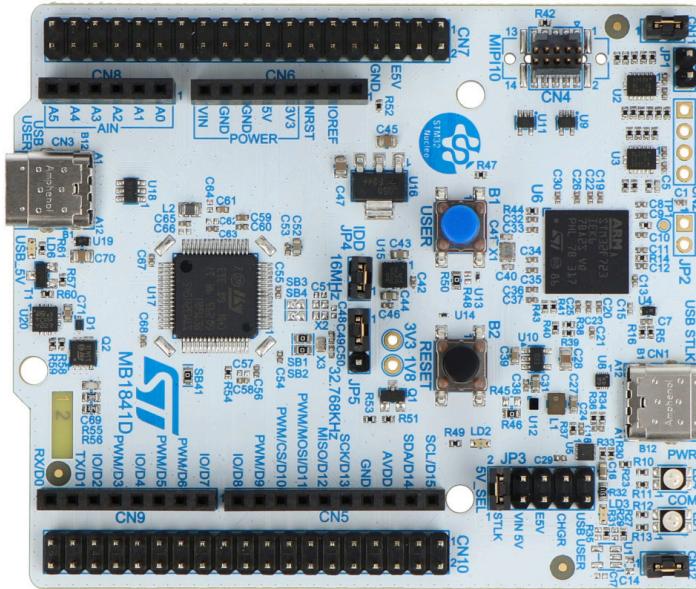
the MCU

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

# Board

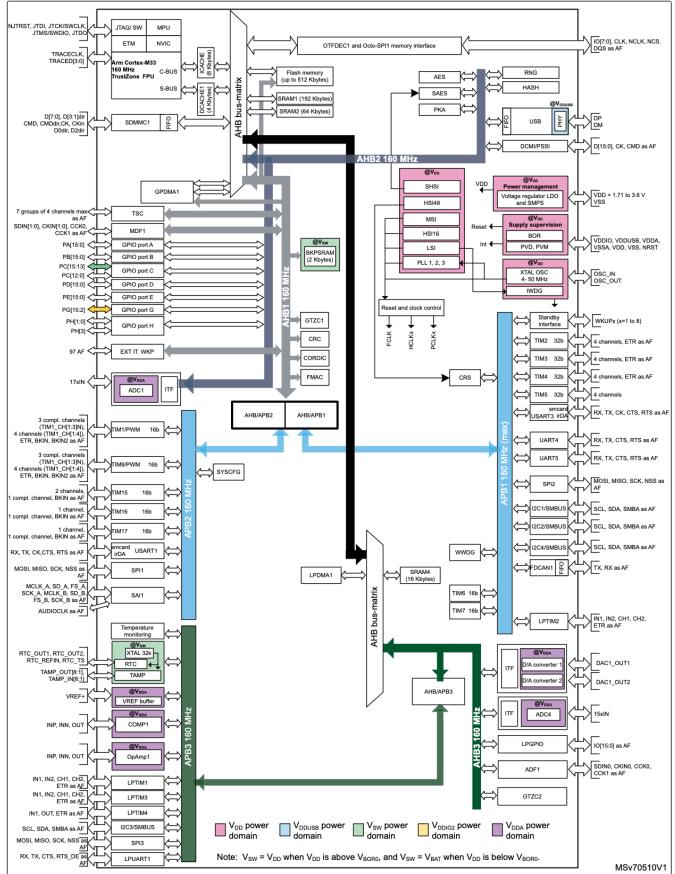
that use STM32U545RE

## 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 I<sup>2</sup>C, 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

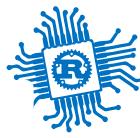
## Analog

**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

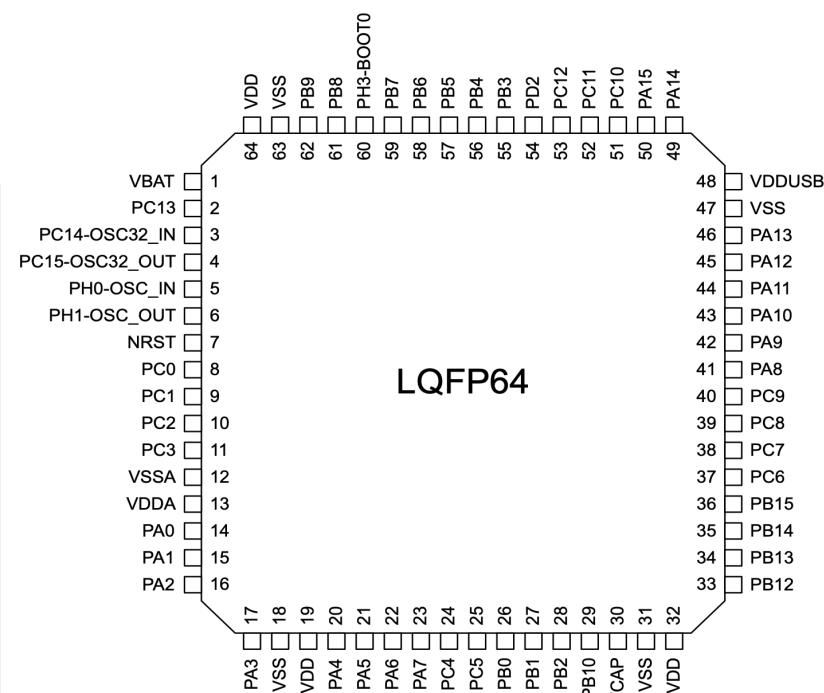


# Pins

have multiple functions

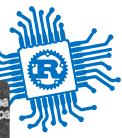
GPIO	F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
0		SPI0 RX	UART0 TX	I2C0 SDA	PWM0 A	SIO	PIO0	PIO1	PIO2	QMI CS1n	USB OVCUR DET	
1		SPI0 CSn	UART0 RX	I2C0 SCL	PWM0 B	SIO	PIO0	PIO1	PIO2	TRACECLK	USB VBUS DET	
2		SPI0 SCK	UART0 CTS	I2C1 SDA	PWM1 A	SIO	PIO0	PIO1	PIO2	TRACEDATA0	USB VBUS EN	UART0 TX
3		SPI0 TX	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

...



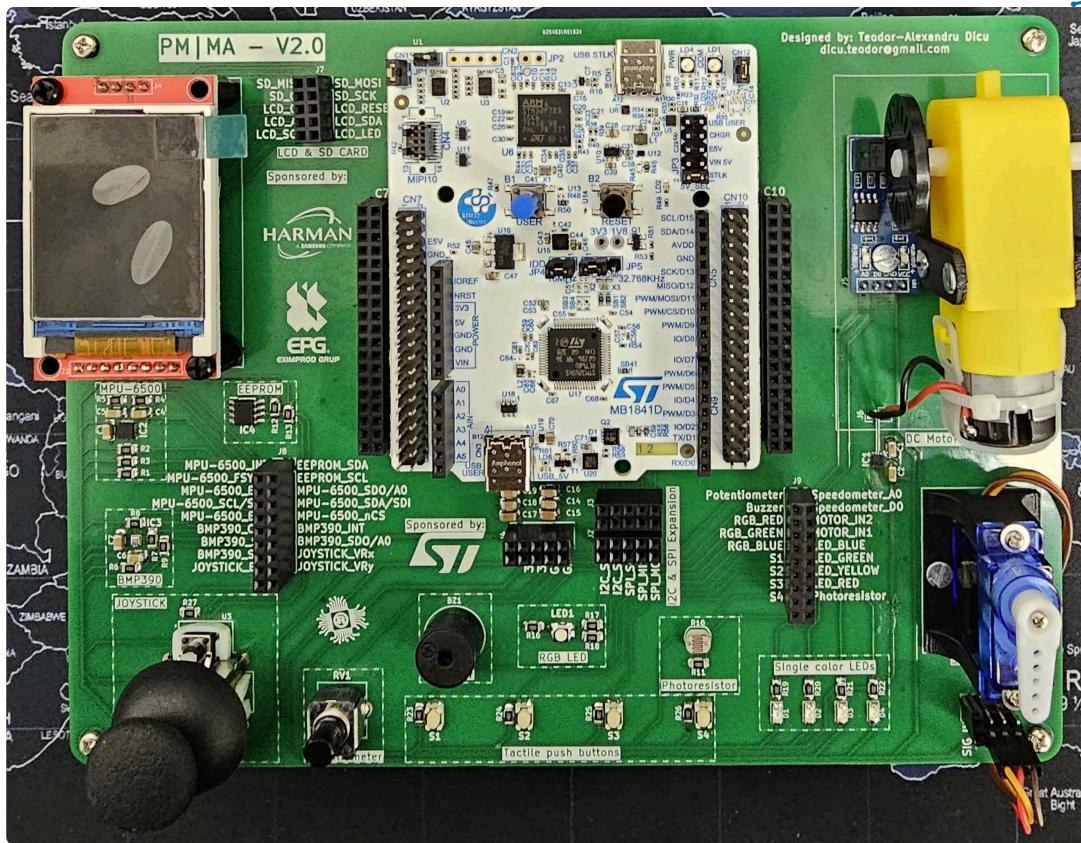
## The Bus

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





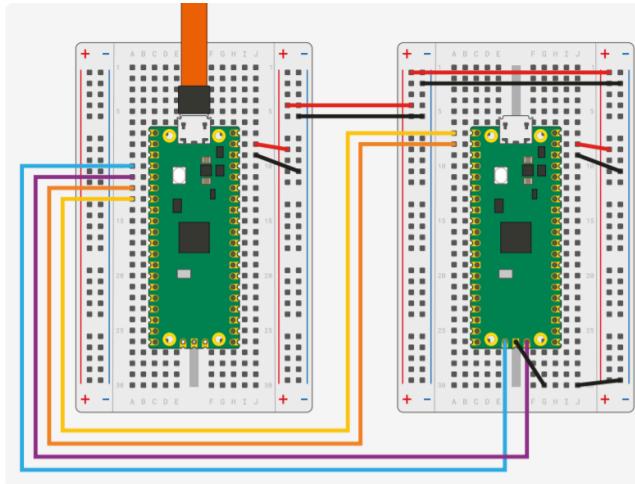
# Project

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