

I2C & USB 2.0

Lecture 7

I2C & USB 2.0

used by RP2040

- Buses
 - Inter-Integrated Circuit
 - Universal Serial Bus v2.0





I2C

Inter-Integrated Circuit

Bibliography

for this section

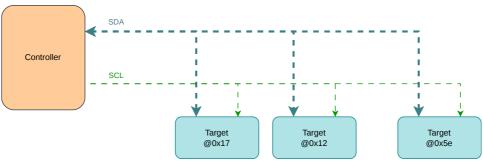
- 1. Raspberry Pi Ltd, RP2040 Datasheet
 - Chapter 4 Peripherals
 - Chapter 4.3 *I2C*
- 2. Paul Denisowski, *Understanding I2C*



I2C

a.k.a *I square C*

- Used for communication between integrated circuits
- Sensors usually expose an SPI and an I2C interface
- Two device types:
 - controller (master) initiates the communication (usually MCU)
 - target (slave) receive and transmit data when the controller requests (usually the sensor)



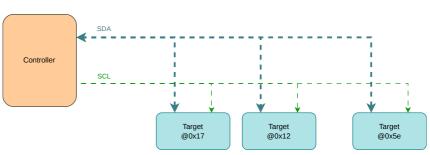






- SDA Serial DAta line carries data from the controller to the target or from the target to the controller
- SCL Serial CLock line the clock signal generated by the controller, targets
 - sample data when the clock is low
 - write data to the bus only when the clock is high
- each target has a unique address of 7 bits or 10 bits
- wires are never driven with LOW or HIGH
 - are always pull-up, which is HIGH
 - devices pull down the lines to write LOW







7 bit address

- 1. controller issues a START condition
 - pulls the SDA line LOW
 - waits for ~ 1/2 clock periods and starts the clock
- 2. **controller** sends the address of the **target**
- 3. **controller** sends the command bit (R/W)
- 4. target sends ACK / NACK to controller

5. **controller** or **target** sends data (depends on

R/W)

- receives ACK / NACK after every byte
- 6. **controller** issues a STOP condition
 - stops the clock
 - pulls the SDA line HIGH while CLK is HIGH

Address Format



Transmission





Transmission Example



10 bit address

- 1. controller issues a START condition
- 2. **controller** sends 11110 followed by the *upper address* of the **target**
- 3. **controller** sends the command bit (R/W)
- 4. target sends ACK / NACK to controller
- 5. **controller** sends the *lower address* of the **target**
- 6. target sends ACK / NACK to controller

- 7. **controller** or **target** sends data (depends on R/W)
 - receives ACK / NACK after every byte
- 8. controller issues a STOP condition

Address Format



Transmission



controller writes each bit when CLK is LOW, target samples every bit when CLK is HIGH





| Mode | Speed | Capacity | Drive | Direction |
|-----------------------|------------|----------|------------|----------------|
| Standard mode (Sm) | 100 kbit/s | 400 pF | Open drain | Bidirectional |
| Fast mode (Fm) | 400 kbit/s | 400 pF | Open drain | Bidirectional |
| Fast mode plus (Fm+) | 1 Mbit/s | 550 pF | Open drain | Bidirectional |
| High-speed mode (Hs) | 1.7 Mbit/s | 400 pF | Open drain | Bidirectional |
| High-speed mode (Hs) | 3.4 Mbit/s | 100 pF | Open drain | Bidirectional |
| Ultra-fast mode (UFm) | 5 Mbit/s | ? | Push-pull | Unidirectional |





| Transmission | half duplex | data must be sent in one direction at one time |
|--------------|------------------------------------|--|
| Clock | synchronized | the controller and target use the same clock, there is no need for clock synchronization |
| Wires | SDA / SCL | the same read and write wire and a clock wire |
| Devices | 1 controller several targets | a receiver and a transmitter |
| Speed | 5 Mbit/s | usually 100 Kbit/s, 400 Kbit/s and 1 Mbit/s |

Usage

- sensors
- small displays
- RP2040 has two I2C devices



Embassy API

for RP2040, synchronous

```
pub struct Config {
    /// Frequency.
    pub frequency: u32,
}
```

```
pub enum ConfigError {
    /// Max i2c speed is 1MHz
    FrequencyTooHigh,
    ClockTooSlow,
    ClockTooFast,
}
```

```
pub enum Error {
   Abort(AbortReason),
   InvalidReadBufferLength,
   InvalidWriteBufferLength,
   AddressOutOfRange(u16),
   AddressReserved(u16),
}
```

```
use embassy_rp::i2c::Config as I2cConfig;

let sda = p.PIN_14;

let scl = p.PIN_15;

let mut i2c = i2c::I2c::new_blocking(p.I2C1, scl, sda, I2cConfig::default());

let tx_buf = [0x90];

i2c.write(0x5e, &tx_buf).unwrap();

let mut rx_buf = [0x00u8; 7];

i2c.read(0x5e, &mut rx_buf).unwrap();
```

Embassy API



for RP2040, asynchronous

```
use embassy rp::i2c::Config as I2cConfig;
     bind_interrupts!(struct Irqs {
         I2C1 IRQ => InterruptHandler<I2C1>;
     });
     let sda = p.PIN 14;
     let scl = p.PIN_15;
 9
10
      let mut i2c = i2c::I2c::new async(p.I2C1, scl, sda, Irqs, I2cConfig::default());
11
12
     let tx_buf = [0x90];
13
     i2c.write(0x5e, &tx_buf).await.unwrap();
14
15
     let mut rx buf = \lceil 0 \times 000 u8; 7 \rceil;
     i2c.read(0x5e, &mut rx buf).await.unwrap();
```



USB 2.0

Universal Serial Bus

Universal Serial Bus

2.0

- Used for communication between a host and several devices that each provide functions
- Two modes:
 - host initiates the communication (usually a computer)
 - device receives and transmits data when the host requests it
- each device has a 7 bit address assigned upon connect
 - maximum 127 devices connected to a USB host
- devices are interconnected using hubs
- USB devices tree



Bibliography

for this section

- 1. Raspberry Pi Ltd, RP2040 Datasheet
 - Chapter 4 Peripherals
 - Chapter 4.1 *USB*
- 2. USB Made Simple



USB Device

- can work as **host** or **device**, but not at the same time
- uses a differential line for transmission
- uses a 48 MHz clock
- maximum 16 endpoints (buffers)

48 MHz

Clock

- *IN* from **device** to **host**
- *OUT* from **host** to **device**
- endpoints 0 IN and OUT are used for control



USB Packet



the smallest element of data transmission

Token



Data



Handshake







usually asks for a data transmission

| Type | PID | Description |
|-------|------|--|
| OUT | 0001 | host wants to transmit data to the device |
| IN | 1001 | host wants to receive data from the device |
| SETUP | 1101 | host wants to setup the device |

Address: ADDR: ENDP







transmits data

| Type | PID | Description |
|-------|------|--|
| DATA0 | 0011 | the data packet is the first one or follows after a DATA1 packet |
| DATA1 | 1011 | the data packet follows after a DATAO packet |

Data can be between 0 and 1024 bytes







acknowledges data

| Туре | PID | Description |
|-------|------|---|
| ACK | 0010 | data has been successfully received |
| NACK | 1010 | data has not been successfully received |
| STALL | 1110 | the device has an error |
| | | 18 |

Packet ID

Transmission Modes

- Control used for configuration
- Isochronous used for high bandwidth, best effort
- *Bulk* used for low bandwidth, stream
- Interrupt used for low bandwidth, guaranteed latency





Error-

used to control a device - ask for data

Setup - send a command (*GET_DESCRIPTOR*,...)



Status - report the status to the host

Data - optional several transfers, host transfers data







Error-

used to control a device - send data

Setup - send a command (*SET_ADDRESS*,...)



Data - *optional* several transfers, device transfers the requested data



Status - report the status to the device



Isochronous



fast but not reliable transfer

- has a guaranteed bandwidth
- allows data loss
- used for functions like streaming where loosing a packet has a minimal impact

OUT - transfer data from the host to the device

Token OUT Data, DATAx

IN - transfer data from the device to the host







slow, but reliable transfer

- does not have a guaranteed bandwidth
- secure transfer
- used for large data transfers where loosing packets is not permitted

OUT - transfer data from the host to the device

IN - transfer data from the device to the host







transfer data at a minimum time interval

- the endpoint descriptor asks the host start an interrupt transfer at a time interval
- used for sending and receiving data at certain intervals

OUT - transfer data from the host to the device

IN - transfer data from the device to the host



Device Organization

configuration, interfaces, endpoints

- a device can have multiple configurations
 - for instance different functionality based on power consumption
- a configuration has multiple interfaces
 - a device can perform multiple functions
 - Debugger
 - Serial Port
- each interface has multiple interfaces attached
 - endpoints are used for data transfer
 - maximum 16 endpoints, can be configured IN and OUT
- the device reports the descriptors in this order





Connection





Token SETUP Packet

The DATA packet of the SETUP Control Transfer



bmRequestType field







| Mode | Speed | Version |
|------------|------------|---------|
| Low Speed | 1.5 Mbit/s | 1.0 |
| Full Speed | 12 Mbit/s | 1.0 |
| High Speed | 480 Mbit/s | 2.0 |





| Transmission | half duplex | data must be sent in one direction at one time |
|--------------|---------------------------|---|
| Clock | independent | the host and the device must synchronize their clocks |
| Wires | DP/DM | data is sent in a differential way |
| Devices | 1 host several devices | a receiver and a transmitter |
| Speed | 480 MBbit/s | |

Embassy API

for RP2040, setup the device

```
use embassy rp::usb::{Driver, Instance, InterruptHandler};
use embassy usb::class::cdc acm::{CdcAcmClass, State};
bind interrupts!(struct Irgs {
    USBCTRL IRQ => InterruptHandler<USB>;
});
let driver = Driver::new(p.USB, Irqs);
let mut config = Config::new(0xc0de, 0xcafe);
config.manufacturer = Some("Embassy");
config.product = Some("USB-serial example");
config.serial number = Some("12345678");
config.max power = 100;
config.max packet size 0 = 64;
// Required for windows compatibility.
config.device class = 0xEF;
config.device sub class = 0 \times 02;
config.device protocol = 0 \times 01;
config.composite with iads = true;
```

```
// It needs some buffers for building the descriptors.
let mut config descriptor = [0; 256];
let mut bos descriptor = [0; 256];
let mut control buf = \lceil 0; 64 \rceil;
let mut state = State::new():
let mut builder = Builder::new(
  driver.
  config,
  &mut config descriptor,
  &mut bos descriptor,
 &mut [], // no msos descriptors
 &mut control buf,
);
// Create classes on the builder.
let mut class = CdcAcmClass::new(&mut builder, &mut state, 64
```

// Build the builder.

// Run the USB device.

let usb driver = usb.run();

let mut usb = builder.build();





for RP2040, use the USB device

Embassy API

```
let echo loop = async {
       loop {
          class.wait connection().await;
         info!("Connected");
         let _ = echo(&mut class).await;
         info!("Disconnected");
 6
     };
 9
10
     // Run everything concurrently.
     join(usb_driver, echo_loop).await;
     async fn echo<'d, T: Instance + 'd>(class: &mut CdcAcmClass<'d, Driver<'d, T>>) -> Result<(), EndpointError> {
         let mut buf = \lceil 0; 64 \rceil;
         loop {
             let n = class.read_packet(&mut buf).await?;
             let data = &buf[..n];
             info!("data: {:x}", data);
             class.write_packet(data).await?;
```



Sensors

Analog and Digital Sensors

Bibliography



BOSCH, BMP280 Digital Pressure Sensor

- Chapter 3 Functional Description
- Chapter 4 Global memory map and register description
- Chapter 5 *Digital Interfaces*
 - Subchapter 5.2 *I2C Interface*



Sensors

analog and digital

Analog

- only the transducer (the analog sensor)
- outputs (usually) voltage
- requires:
 - an ADC to be read
 - cleaning up the noise



Digital

- consists of:
 - a transducer (the analog sensor)
 - an ADC
 - an MCU for cleaning up the noise
- outputs data using a digital bus









schematics









registers map

| Register Name | Address | bit7 | bit6 | bit5 | bit4 | bit3 | bit2 | bit1 | bit0 | Reset state |
|----------------|----------|------|-----------------------------------|---------|----------|----------|------|------|------|----------------|
| temp_xlsb | 0xFC | | temp_x | sb<7:4> | | 0 | 0 | 0 | 0 | 0x00 |
| temp_lsb | 0xFB | | | | temp_l: | sb<7:0> | | | | 0x00 |
| temp_msb | 0xFA | | | | temp_m | isb<7:0> | | | | 0x80 |
| press_xlsb | 0xF9 | | press_xlsb<7:4> 0 0 0 0 | | | | | | 0x00 | |
| press_lsb | 0xF8 | | press_lsb<7:0> | | | | | | 0x00 | |
| press_msb | 0xF7 | | press_msb<7:0> | | | | | | 0x80 | |
| config | 0xF5 | | t sb[2:0] filter[2:0] spi3w en[0] | | | | | | 0x00 | |
| ctrl_meas | 0xF4 | | osrs_t[2:0] | | | | | | 0x00 | |
| status | 0xF3 | | measuring[0] im_update[0] | | | | | | 0x00 | |
| reset | 0xE0 | | reset[7:0] | | | | | | 0x00 | |
| id | 0xD0 | | chip_id[7:0] | | | | | 0x58 | | |
| calib25calib00 | 0xA10x88 | | | | calibrat | ion data | | | | individual |

Registers:

Type:

Reserved Calibration Data Control **Status** Revision Reset data registers registers registers registers do not read only read / write read only read only read only write only

Datasheet



Reading from a digital sensor

using synchronous/asynchronous I2C to read the press_lsb register of BMP280

```
const DEVICE_ADDR: u8 = 0x77;
const REG_ADDR: u8 = 0xf8;

i2c.write(DEVICE_ADDR, &[REG_ADDR]).unwrap();

let mut buf = [0x00u8];
i2c.read(DEVICE_ADDR, &mut buf).unwrap();

// use the value
let pressure_lsb = buf[1];
```

```
const DEVICE_ADDR: u8 = 0x77;
const REG_ADDR: u8 = 0xf8;

i2c.write(DEVICE_ADDR, &[REG_ADDR]).await.unwrap();

let mut buf = [0x00u8];
i2c.read(DEVICE_ADDR, &mut buf).await.unwrap();

// use the value
let pressure_lsb = buf[1];
```



Writing to a digital sensor

using synchronous/asynchronous I2C to set up the ctrl_meas register of the BMP280 sensor

```
const DEVICE_ADDR: u8 = 0x77;
const REG_ADDR: u8 = 0xf4;

// see subchapters 3.3.2, 3.3.1 and 3.6
let value = 0b100_010_11;

i2c.write(DEVICE_ADDR, &[REG_ADDR]);

let buf = [REG_ADDR, value];
i2c.write(DEVICE_ADDR, &buf).unwrap();
```

```
const DEVICE_ADDR: u8 = 0x77;
const REG_ADDR: u8 = 0xf4;

// see subchapters 3.3.2, 3.3.1 and 3.6
let value = 0b100_010_11;

i2c.write(DEVICE_ADDR, &[REG_ADDR]);

let buf = [REG_ADDR, value];
i2c.write(DEVICE_ADDR, &buf).await.unwrap();
```

Conclusion

we discussed about

- Buses
 - Inter-Integrated Circuit
 - Universal Serial Bus v2.0