



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*

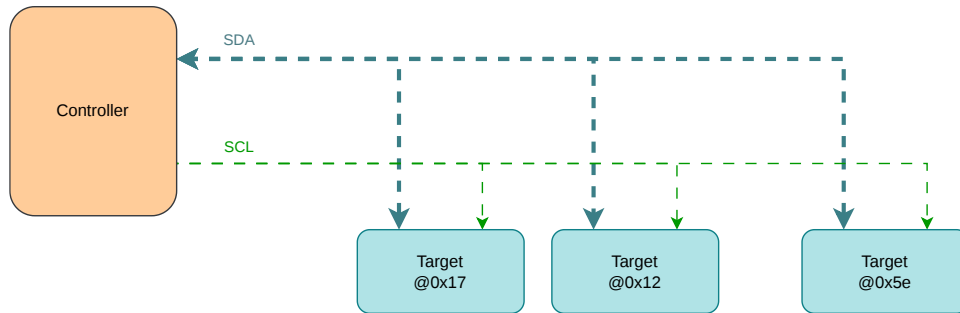
2. **Paul Denisowski**, *Understanding I2C*



I2C

a.k.a *I square C*

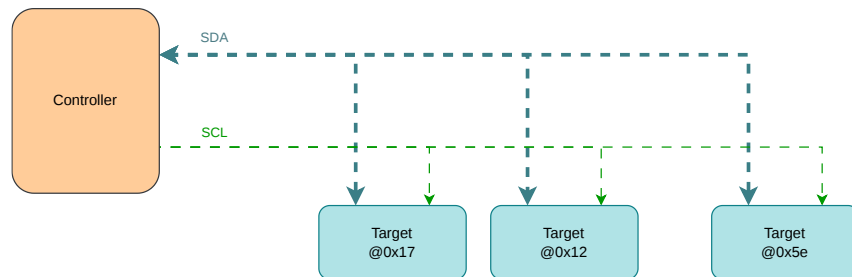
- Used for communication between integrated circuits
- Sensors usually expose an *SPI* and an *I2C* interface
- Two device types:
 - *controller* (master) - initiates the communication (usually MCU)
 - *target* (slave) - receive and transmit data when the *controller* requests (usually the sensor)





Wires & Addresses

- **SDA** - **S**erial **D**Ata line - carries data from the **controller** to the **target** or from the **target** to the **controller**
- **SCL** - **S**erial **C**Lock 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**





Transmission Example

7 bit address

1. **controller** issues a **START** condition
 - pulls the **SDA** line **LOW**
 - waits for $\sim 1/2$ 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**



I2C Modes

| 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 |



Facts

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



-
- Legend:**
- Power
 - Ground
 - UART / UART (default)
 - GPIO, PIQ, and PWM
 - ADC
 - SPI / SPI (default)
 - I2C / I2C (default)
 - System Control
 - Debugging
- Pin Functions:**
- | Pin | Function |
|-----|----------|
| 1 | UART0 TX |
| 2 | I2C0 SDA |
| 3 | SPI0 RX |
| 4 | GP0 |
| 5 | UART0 RX |
| 6 | I2C0 SCL |
| 7 | SPI0 CSn |
| 8 | GP1 |
| 9 | GND |
| 10 | I2C1 SDA |
| 11 | SPI0 SCK |
| 12 | GP2 |
| 13 | I2C1 SCL |
| 14 | SPI0 TX |
| 15 | GP3 |
| 16 | UART1 TX |
| 17 | I2C0 SDA |
| 18 | SPI0 RX |
| 19 | GP4 |
| 20 | UART1 RX |
| 21 | I2C0 SCL |
| 22 | SPI0 CSn |
| 23 | GP5 |
| 24 | GND |
| 25 | I2C1 SDA |
| 26 | SPI0 SCK |
| 27 | GP6 |
| 28 | I2C1 SCL |
| 29 | SPI0 TX |
| 30 | GP7 |
| 31 | UART1 TX |
| 32 | I2C0 SDA |
| 33 | SPI1 RX |
| 34 | GP8 |
| 35 | UART1 RX |
| 36 | I2C0 SCL |
| 37 | SPI1 CSn |
| 38 | GP9 |
| 39 | GND |
| 40 | I2C1 SDA |



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),  
}
```

```
1  use embassy_rp::i2c::Config as I2cConfig;  
2  
3  let sda = p.PIN_14;  
4  let scl = p.PIN_15;  
5  
6  let mut i2c = i2c::I2c::new_blocking(p.I2C1, scl, sda, I2cConfig::default());  
7  
8  let tx_buf = [0x90];  
9  i2c.write(0x5e, &tx_buf).unwrap();  
10  
11 let mut rx_buf = [0x00u8; 7];  
12 i2c.read(0x5e, &mut rx_buf).unwrap();
```



Embassy API

for RP2040, asynchronous

```
1  use embassy_rp::i2c::Config as I2cConfig;
2
3  bind_interrupts!(struct Irqs {
4      I2C1_IRQ => InterruptHandler<I2C1>;
5  });
6
7  let sda = p.PIN_14;
8  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 = [0x00u8; 7];
16 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)
 - *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

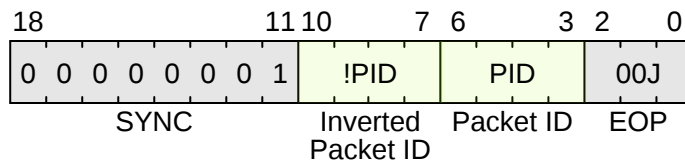
Token



Data



Handshake





Token Packet

usually asks for a data transmission

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

Address: ADDR : ENDP





Data Packet

transmits data

| Type | PID | Description |
|--------------|------|---|
| <i>DATA0</i> | 0011 | the data packet is the first one or follows after a <i>DATA1</i> packet |
| <i>DATA1</i> | 1011 | the data packet follows after a <i>DATA0</i> packet |

Data can be between 0 and 1024 bytes





Handshake Packet

acknowledges data

| Type | PID | Description |
|--------------|------|---|
| <i>ACK</i> | 0010 | data has been successfully received |
| <i>NACK</i> | 1010 | data has not been successfully received |
| <i>STALL</i> | 1110 | the device has an error |





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



Control

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





Control

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 losing a packet has a minimal impact

OUT - transfer data from the host to the device



IN - transfer data from the device to the host





Bulk

slow, but reliable transfer

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

OUT - transfer data from the host to the device



IN - transfer data from the device to the host





Interrupt

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 endpoints 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





USB 1.0 and 2.0 Modes

| 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 |



Facts

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



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 Irqs {
    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 = 0x02;
config.device_protocol = 0x01;
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 = [0; 64];

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.
let mut usb = builder.build();

// Run the USB device.
let usb_driver = usb.run();
```




Embassy API

for RP2040, use the USB device

```
1  let echo_loop = async {  
2    loop {  
3      class.wait_connection().await;  
4      info!("Connected");  
5      let _ = echo(&mut class).await;  
6      info!("Disconnected");  
7    }  
8  };  
9  
10 // Run everything concurrently.  
11 join(usb_driver, echo_loop).await;
```

```
1  async fn echo<'d, T: Instance + 'd>(class: &mut CdcAcmClass<'d, Driver<'d, T>>) -> Result<(), EndpointError> {  
2    let mut buf = [0; 64];  
3    loop {  
4      let n = class.read_packet(&mut buf).await?;  
5      let data = &buf[..n];  
6      info!("data: {:x}", data);  
7      class.write_packet(data).await?;  
8    }  
9  }
```



Sensors

Analog and Digital Sensors



Bibliography

for this section

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





BMP280 Digital Pressure Sensor

schematics



Datasheet



BMP280 Digital Pressure Sensor

registers map

| Register Name | Address | bit7 | bit6 | bit5 | bit4 | bit3 | bit2 | bit1 | bit0 | Reset state |
|-------------------|-------------|------------------|------|------|-------------|--------------|------|--------------|------|-------------|
| temp_xlsb | 0xFC | temp_xlsb<7:4> | | | | 0 | 0 | 0 | 0 | 0x00 |
| temp_lsb | 0xFB | temp_lsb<7:0> | | | | | | | | 0x00 |
| temp_msb | 0xFA | temp_msb<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] | | | osrs_p[2:0] | | | mode[1:0] | | 0x00 |
| status | 0xF3 | | | | | measuring[0] | | im_update[0] | | 0x00 |
| reset | 0xE0 | reset[7:0] | | | | | | | | 0x00 |
| id | 0xD0 | chip_id[7:0] | | | | | | | | 0x58 |
| calib25...calib00 | 0xA1...0x88 | calibration data | | | | | | | | individual |

| | | | | | | | |
|------------|--------------------|------------------|-------------------|----------------|------------------|-----------|------------|
| Registers: | Reserved registers | Calibration data | Control registers | Data registers | Status registers | Revision | Reset |
| | do not write | 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

```
1  const DEVICE_ADDR: u8 = 0x77;
2  const REG_ADDR: u8 = 0xf8;
3
4  i2c.write(DEVICE_ADDR, &[REG_ADDR]).unwrap();
5
6  let mut buf = [0x00u8];
7  i2c.read(DEVICE_ADDR, &mut buf).unwrap();
8
9  // use the value
10 let pressure_lsb = buf[1];
```

```
1  const DEVICE_ADDR: u8 = 0x77;
2  const REG_ADDR: u8 = 0xf8;
3
4  i2c.write(DEVICE_ADDR, &[REG_ADDR]).await.unwrap();
5
6  let mut buf = [0x00u8];
7  i2c.read(DEVICE_ADDR, &mut buf).await.unwrap();
8
9  // use the value
10 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

```
1  const DEVICE_ADDR: u8 = 0x77;
2  const REG_ADDR: u8 = 0xf4;
3
4  // see subchapters 3.3.2, 3.3.1 and 3.6
5  let value = 0b100_010_11;
6
7  i2c.write(DEVICE_ADDR, &[REG_ADDR]);
8
9  let buf = [REG_ADDR, value];
10 i2c.write(DEVICE_ADDR, &buf).unwrap();
```

```
1  const DEVICE_ADDR: u8 = 0x77;
2  const REG_ADDR: u8 = 0xf4;
3
4  // see subchapters 3.3.2, 3.3.1 and 3.6
5  let value = 0b100_010_11;
6
7  i2c.write(DEVICE_ADDR, &[REG_ADDR]);
8
9  let buf = [REG_ADDR, value];
10 i2c.write(DEVICE_ADDR, &buf).await.unwrap();
```




Conclusion

we discussed about

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