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

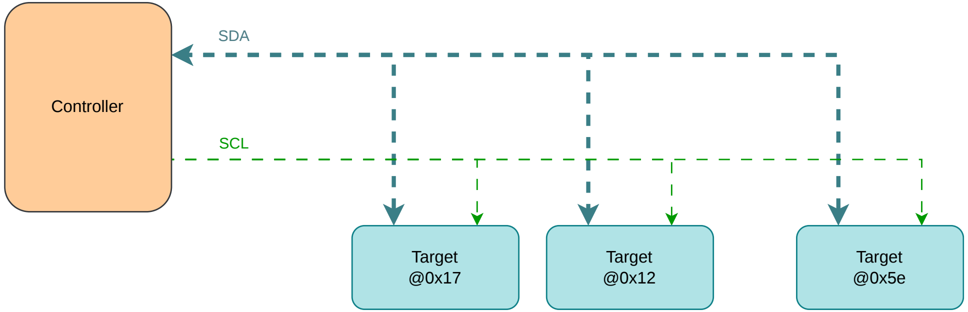
for this section

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

I2C

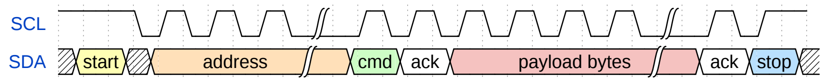
a.k.a *I square C*

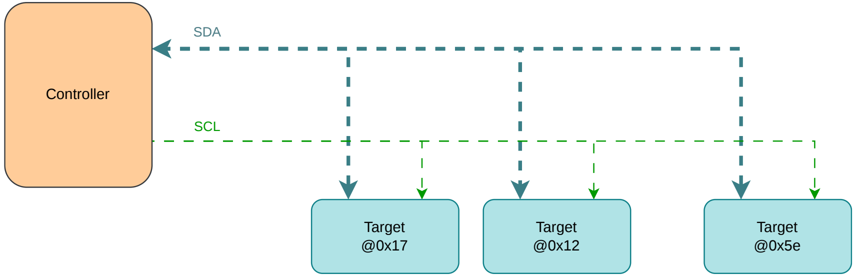
- Used for communication between integrated circuits
- Sensors usually expose an *SPI* and an *I2C* interface
- Two device types:
  - *controller* (master) - initiates the communication (usually MCU)
  - *target* (slave) - receive and transmit data when the *controller* requests (usually the sensor)



Wires & Addresses

- *SDA* - **S**erial **DA**ta line - carries data from the **controller** to the **target** or from the **target** to the **controller**
- *SCL* - **S**erial **CL**ock 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`



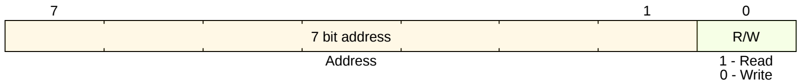


Transmission Example

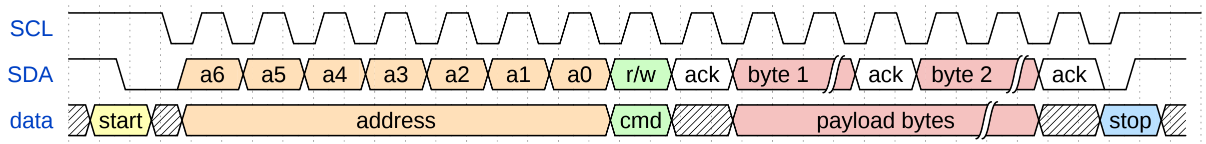
7 bit address

1. **controller** issues a `START` condition
   - pulls the `SDA` line `LOW`
   - waits for ~ 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

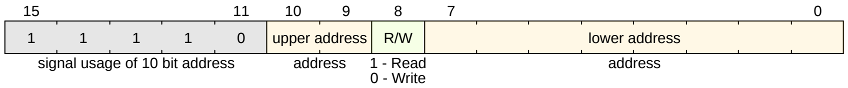


Transmission Example

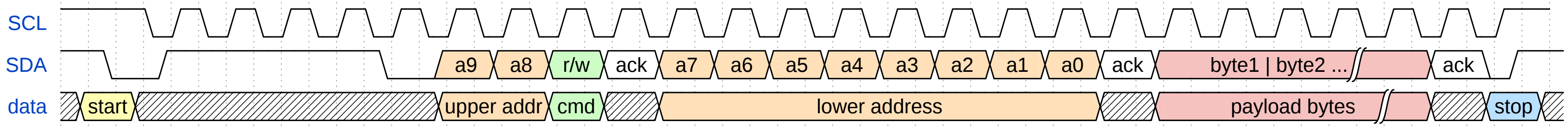
10 bit address

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

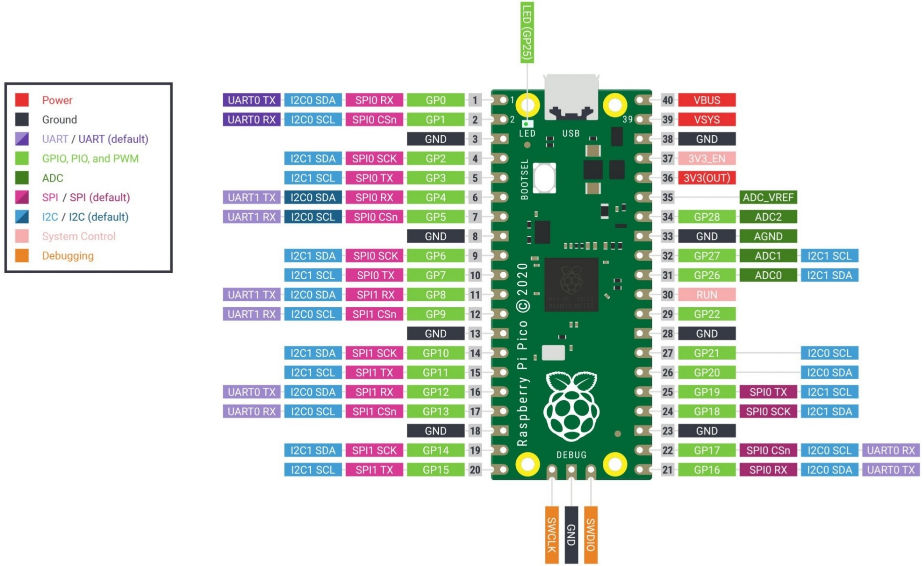
Mode	Speed	Capacity	Drive	Direction
Standard mode (Sm)	100 kbit/s	400 pF	Open drain	Bidirectional
Fast mode (Fm)	400 kbit/s	400 pF	Open drain	Bidirectional
Fast mode plus (Fm+)	1 Mbit/s	550 pF	Open drain	Bidirectional
High-speed mode (Hs)	1.7 Mbit/s	400 pF	Open drain	Bidirectional
High-speed mode (Hs)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

Facts

Transmission	*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

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

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

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

```rust
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

```rust
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;

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

let tx_buf = [0x90];
i2c.write(0x5e, &tx_buf).await.unwrap();

let mut rx_buf = [0x00u8; 7];
i2c.read(0x5e, &mut rx_buf).await.unwrap();
```

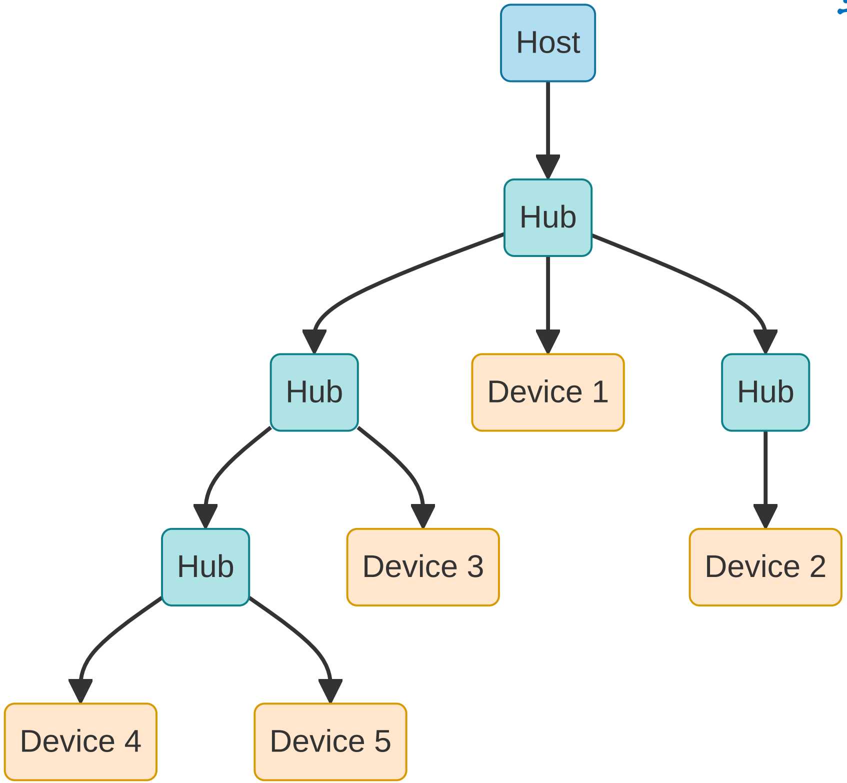
USB 2.0

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



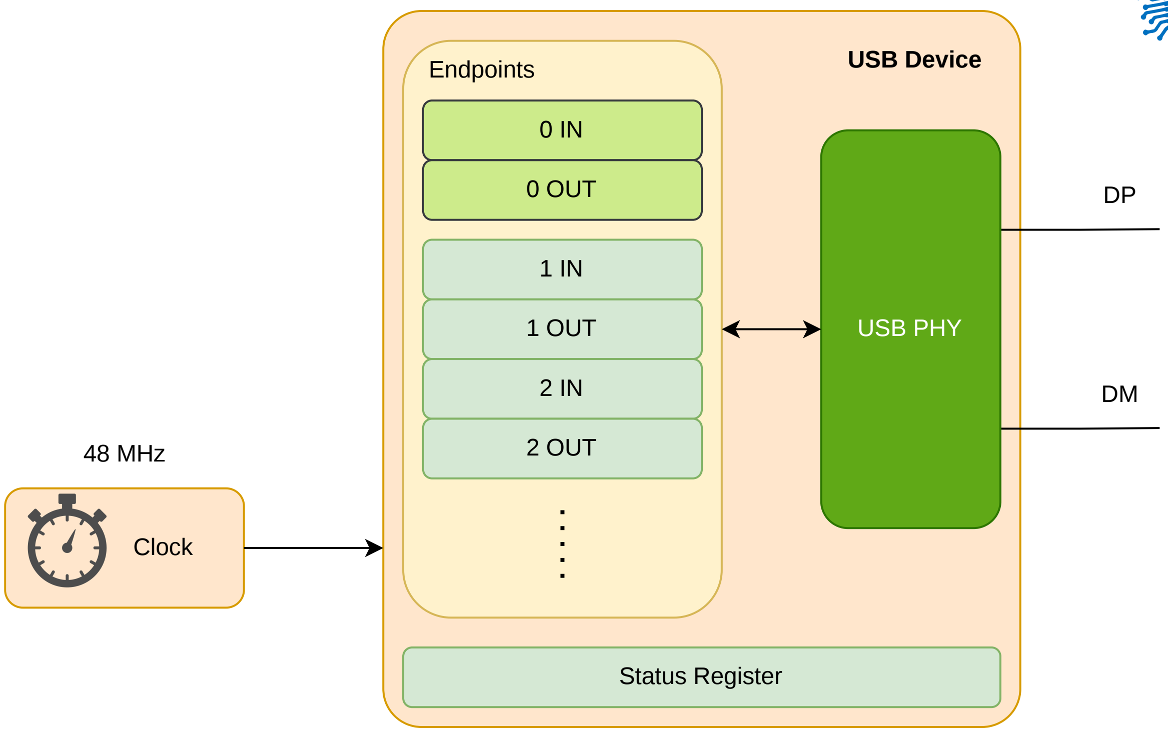
Bibliography

for this section

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

USB Device

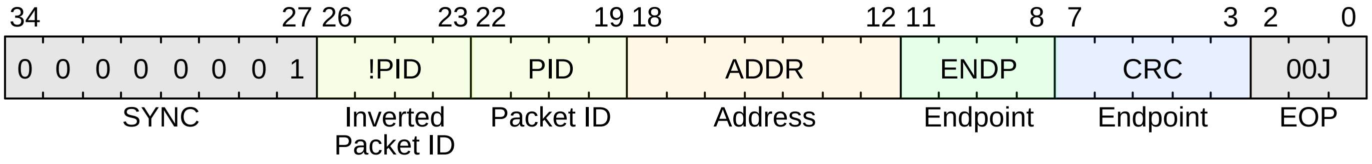
- can work as **host** or **device**, but not at the same time
- uses a differential line for transmission
- uses a 48 MHz clock
- maximum 16 endpoints (buffers)
  - *IN* - from **device** to **host**
  - *OUT* - from **host** to **device**
- endpoints 0 IN and OUT are used for control



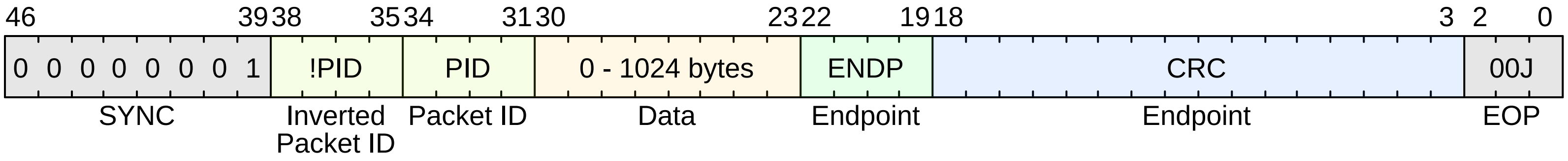
USB Packet

the smallest element of data transmission

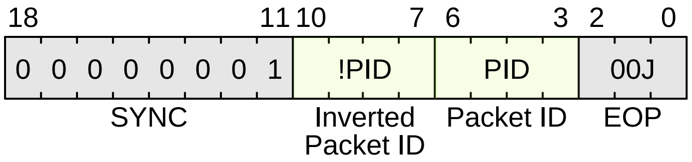
Token



Data



Handshake

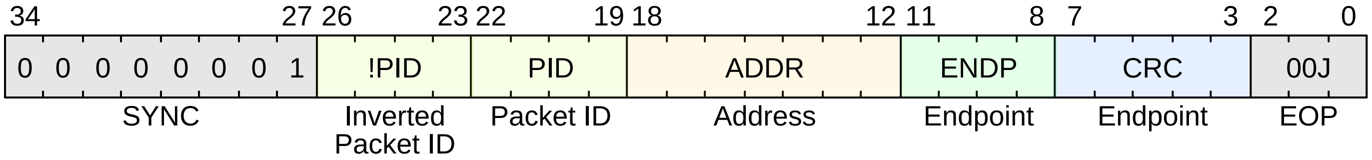


Token Packet

usually asks for a data transmission

Type	PID	Description
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`

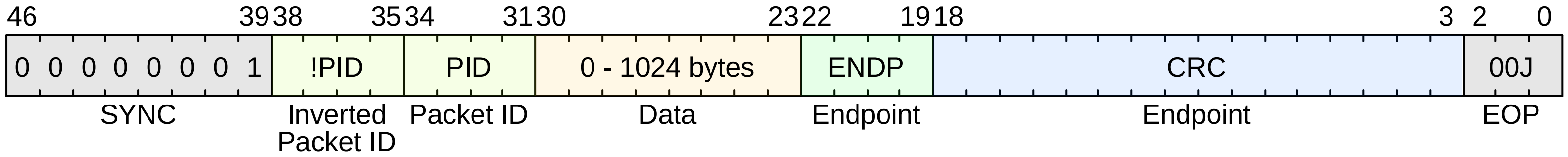


Data Packet

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 `DATA0` packet

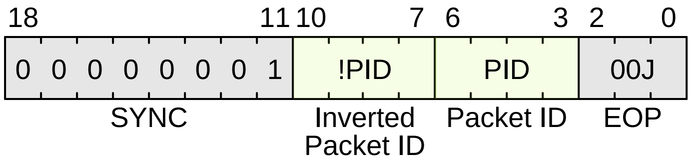
Data can be between 0 and 1024 bytes



Handshake Packet

acknowledges data

Type	PID	Description
ACK	`0010`	data has been **successfully received**
NACK	`1010`	data has **not** been **successfully received**
STALL	`1110`	the device has an **error**



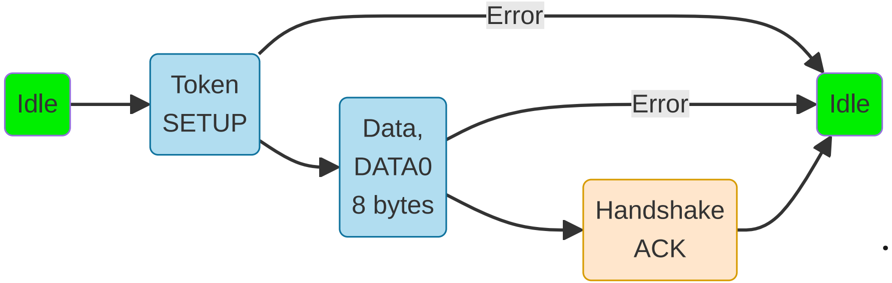
Transmission Modes

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

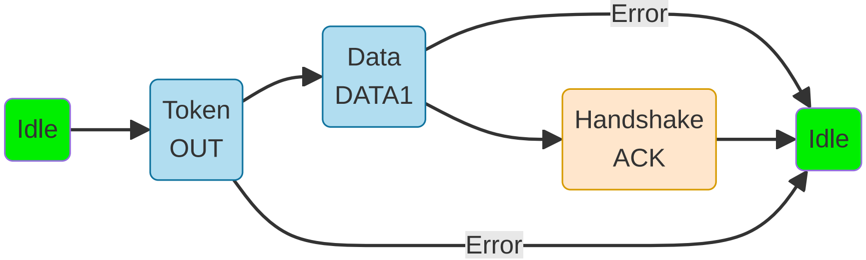
Control

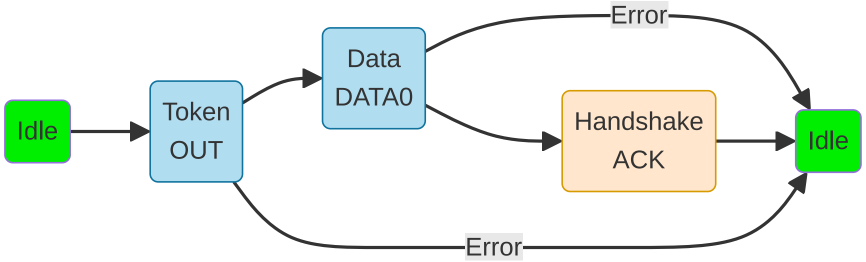
used to control a device - ask for data

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



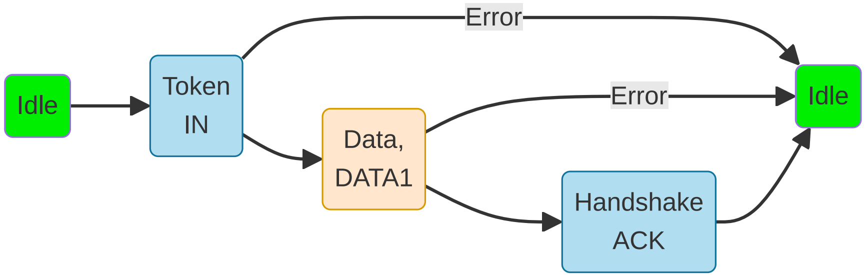
Data - *optional* several transfers, host transfers data





...

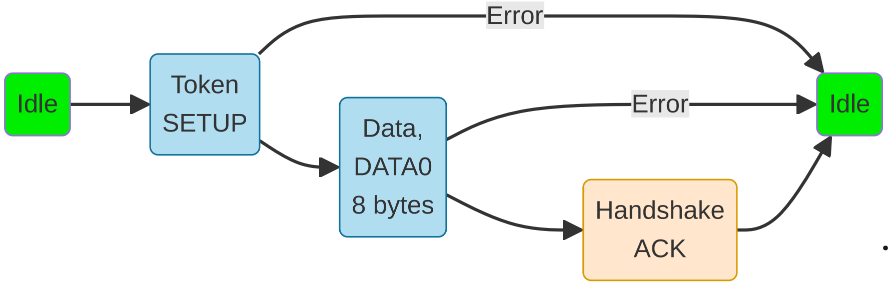
Status - report the status to the host



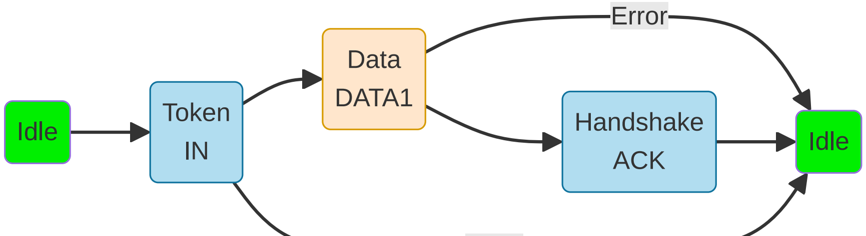
Control

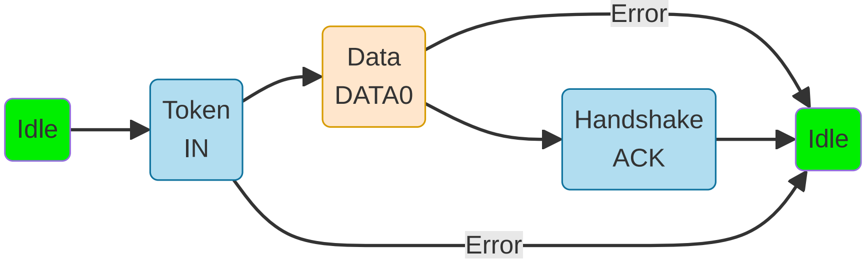
used to control a device - send data

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



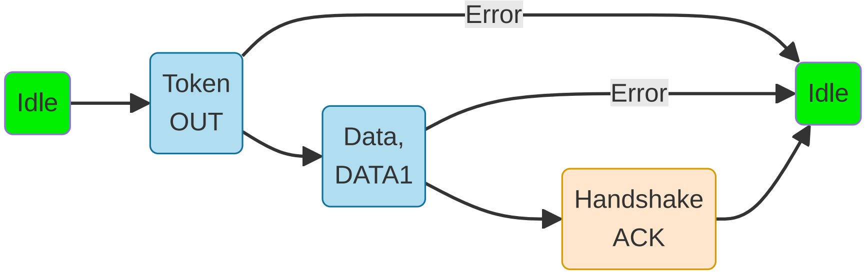
Data - *optional* several transfers, device transfers the requested data





...

Status - report the status to the device

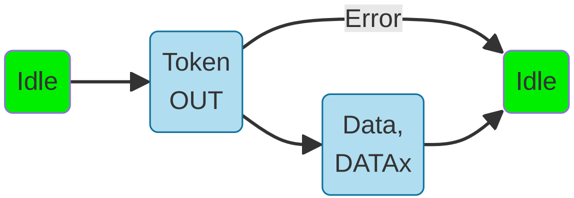


Isochronous

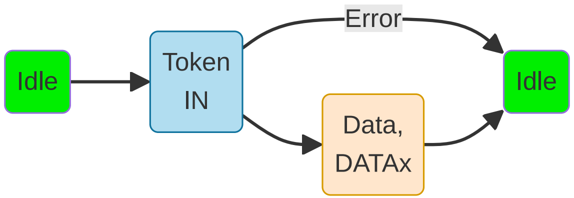
fast but not reliable transfer

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

OUT - transfer data from the host to the device



IN - transfer data from the device to the host

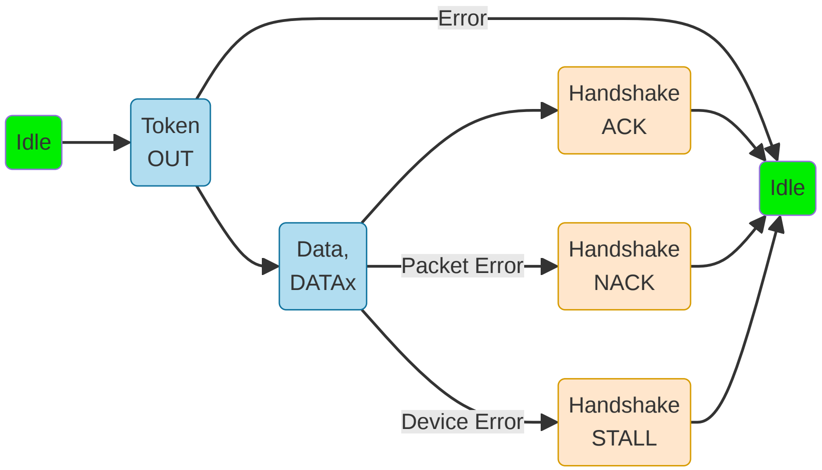


Bulk

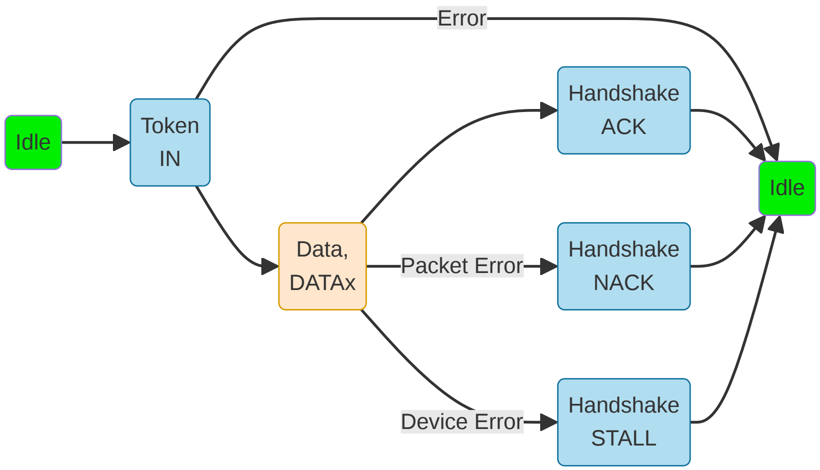
slow, but reliable transfer

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

OUT - transfer data from the host to the device



IN - transfer data from the device to the host

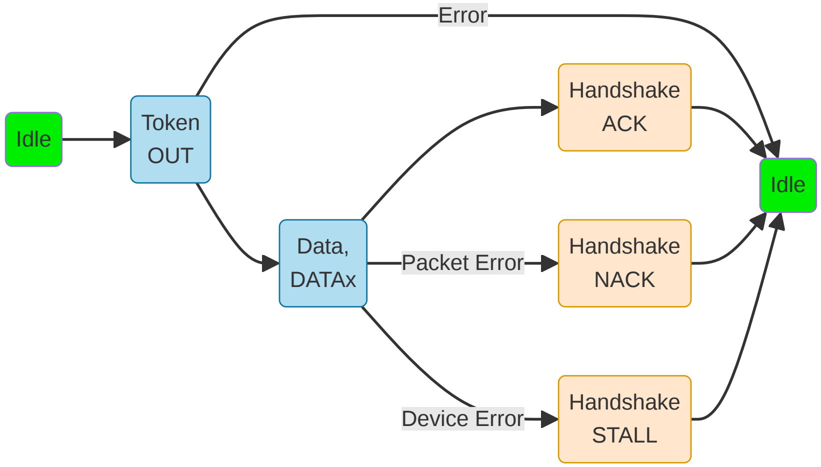


Interrupt

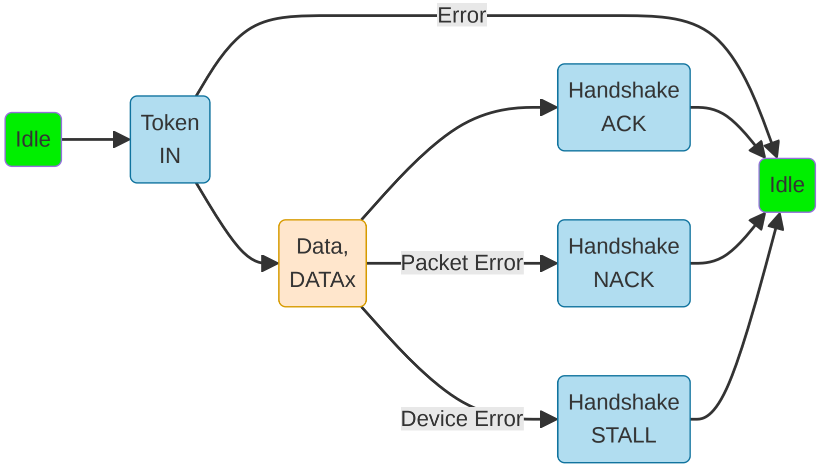
transfer data at a minimum time interval

- 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



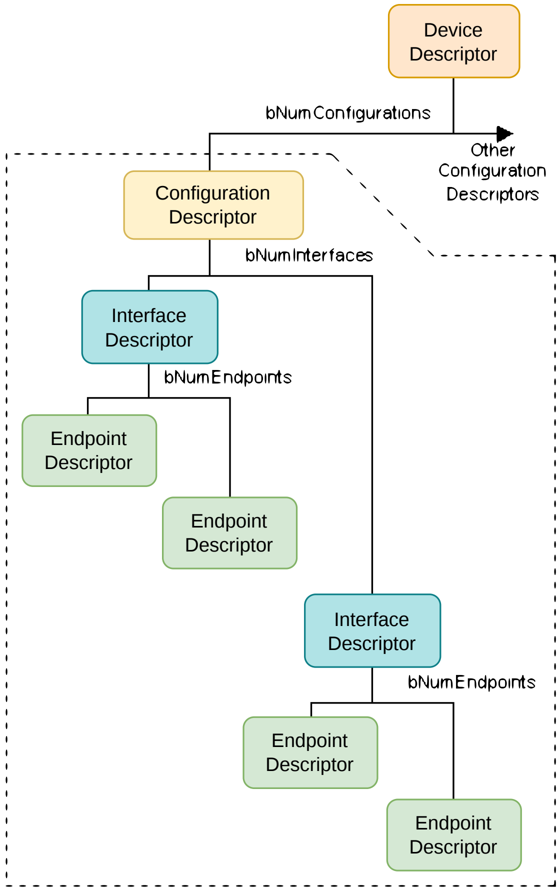
IN - transfer data from the device to the host



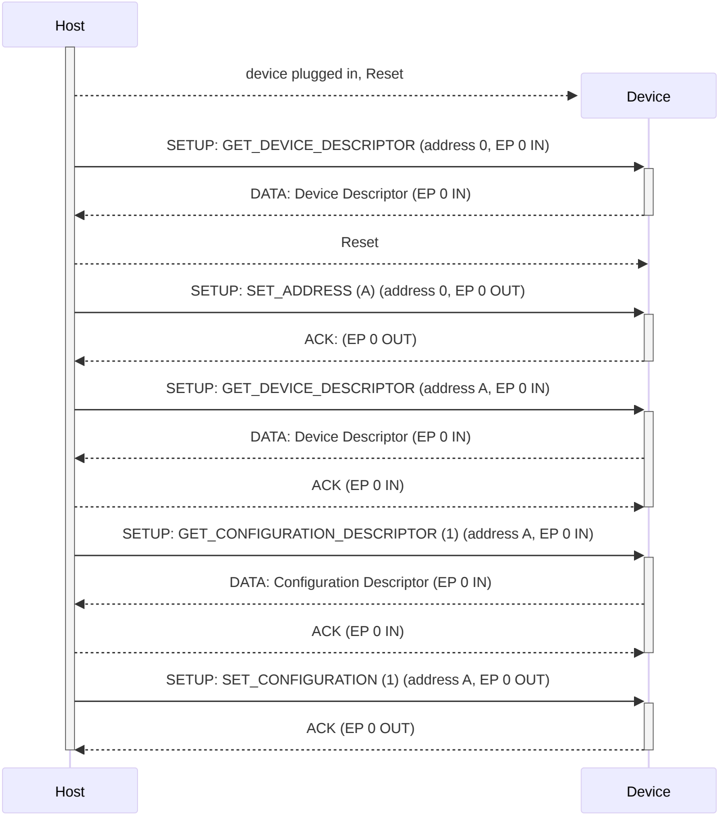
Device Organization

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 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

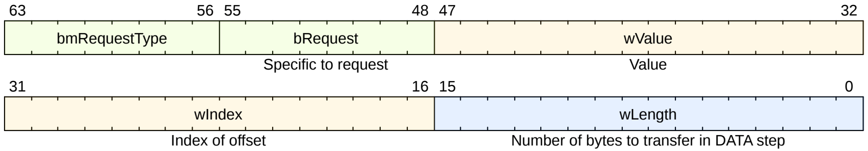


Connection

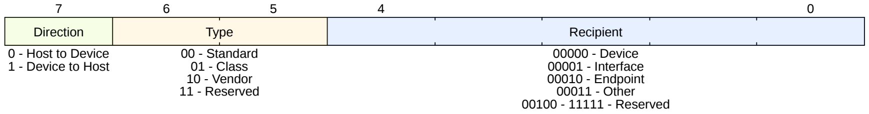


Token SETUP Packet

The DATA packet of the SETUP Control Transfer



bmRequestType field



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	*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

```rust
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;
```

```rust
// 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

```rust
let echo_loop = async {
  loop {
    class.wait_connection().await;
    info!("Connected");
    let _ = echo(&mut class).await;
    info!("Disconnected");
  }
};

// Run everything concurrently.
join(usb_driver, echo_loop).await;
```

```rust
async fn echo<'d, T: Instance + 'd>(class: &mut CdcAcmClass<'d, Driver<'d, T>>) -> Result<(), EndpointError> {
    let mut buf = [0; 64];
    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

for this section

BOSCH, *BMP280 Digital Pressure Sensor*

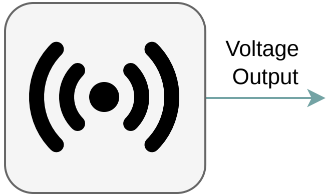
- Chapter 3 - *Functional Description*
- Chapter 4 - *Global memory map and register description*
- Chapter 5 - *Digital Interfaces*
  - Subchapter 5.2 - *I2C Interface*

Sensors

analog and digital

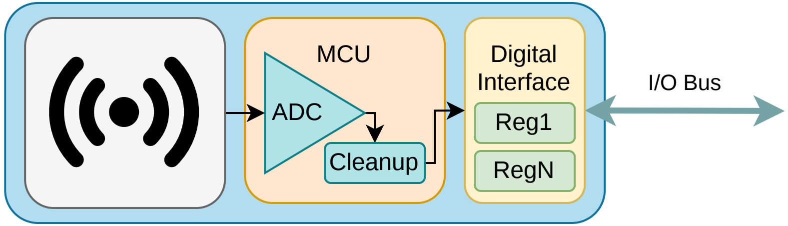
Analog

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



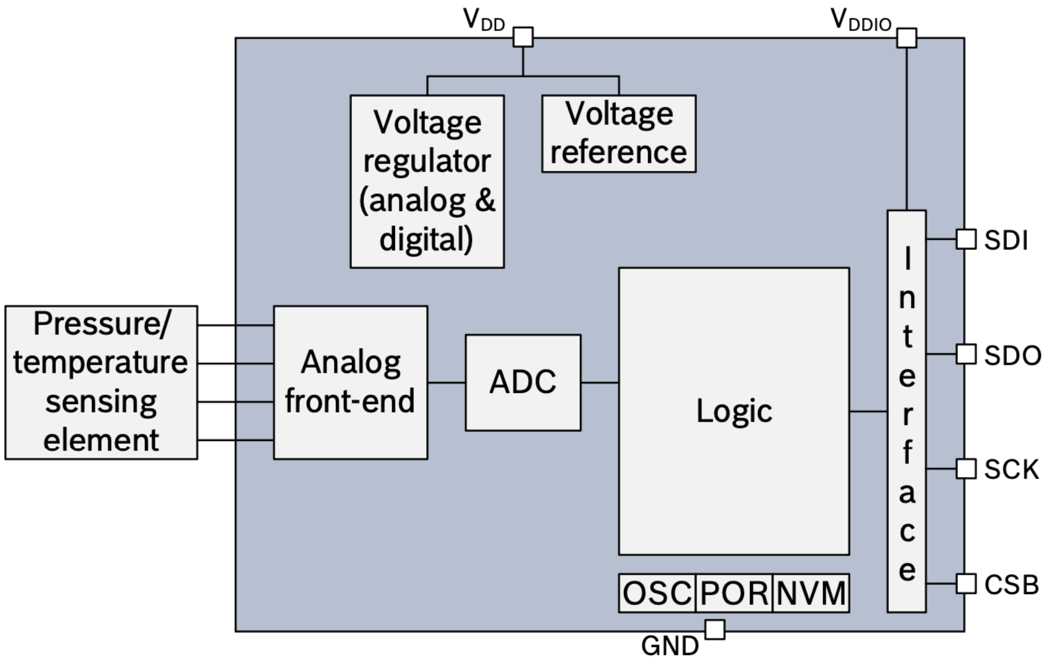
Digital

- 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**
Type:	**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

```rust
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];
```

```rust
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

```rust
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();
```

```rust
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