

PWM and ADC

Lecture 4

PWM and ADC

- Counters
- Timers and Alarms
- About Analog and Digital Signals
- Pulse Width Modulation (PWM)
- Analog to Digital Converters (ADC)

Timers

Bibliography

for this section

Raspberry Pi Ltd, *RP2040 Datasheet*

- Chapter 2 - *System Description*
 - Chapter 2.15 - *Clocks*
 - Subchapter 2.15.1
 - Subchapter 2.15.2
- Chapter 4 - *Peripherals*
 - Chapter 4.6 - *Timer*

Clocks

all peripherals and the MCU use a clock to execute at certain intervals

| Source | Usage |
|--------------------------------|---|
| <i>external crystal (XOSC)</i> | a stable frequency is required, for instance when using USB |
| <i>internal ring (ROSC)</i> | low frequency, in between 1.8 - 12 MHz (varies) |

Embassy initializes the Raspberry Pi Pico with the clock source from the 12 MHz crystal.

```
1 let p = embassy_rp::init(Default::default());
```



Frequency divider

stabilizing the signal and adjusting it

1. divides down the clock signals used for the timer, giving reduced overflow rates
2. allows the timer to be clocked at a user desires the rate



Counter

increments a register at every clock cycle

| Registers | Description |
|-----------|--|
| value | the current value of the counter |
| direction | set to count UP or DOWN |
| reset | UP: the value at which the counter resets to 0 DOWN: the value to which the counter resets after getting to 0 |



SysTick

ARM Cortex-M time counter

The ARM Cortex-M0+ registers start at a base address of `0xe0000000` (defined as `PPB_BASE` in SDK).

| Offset | Name | Info |
|--------|-------------------------|-------------------------------------|
| 0xe010 | <code>SYST_CSR</code> | SysTick Control and Status Register |
| 0xe014 | <code>SYST_RVR</code> | SysTick Reload Value Register |
| 0xe018 | <code>SYST_CVR</code> | SysTick Current Value Register |
| 0xe01c | <code>SYST_CALIB</code> | SysTick Calibration Value Register |

- decrements the value of `SYST_CVR` every μs
- when `SYST_CVR` becomes 0 :
 - triggers the SysTick the exception
 - next clock cycle sets the value of `SYST_CVR` to `SYST_RVR`
- `SYST_CALIB` is the value of `SYST_RVR` for a 10ms interval (might not be available)

SYST_CSR register

| Bits | Name | Description | Type | Reset |
|-------|-----------|---|------|-------|
| 31:17 | Reserved. | - | - | - |
| 16 | COUNTFLAG | Returns 1 if timer counted to 0 since last time this was read. Clears on read by application or debugger. | RO | 0x0 |
| 15:3 | Reserved. | - | - | - |
| 2 | CLKSOURCE | SysTick clock source. Always reads as one if SYST_CALIB reports NOREF. Selects the SysTick timer clock source: 0 = External reference clock. 1 = Processor clock. | RW | 0x0 |
| 1 | TICKINT | Enables SysTick exception request: 0 = Counting down to zero does not assert the SysTick exception request. 1 = Counting down to zero to asserts the SysTick exception request. | RW | 0x0 |
| 0 | ENABLE | Enable SysTick counter: 0 = Counter disabled. 1 = Counter enabled. | RW | 0x0 |

$$f = \frac{1}{SYST_RVR} * 1,000,000 [Hz]_{SI}$$

SysTick

ARM Cortex-M peripheral

The ARM Cortex-M0+ registers start at a base address of `0xe0000000` (defined as `PPB_BASE` in SDK).

| Offset | Name | Info |
|--------|----------------------------|-------------------------------------|
| 0xe010 | SYST_CSR | SysTick Control and Status Register |
| 0xe014 | SYST_RVR | SysTick Reload Value Register |
| 0xe018 | SYST_CVR | SysTick Current Value Register |
| 0xe01c | SYST_CALIB | SysTick Calibration Value Register |

```
1  const SYST_RVR: *mut u32 = 0xe000_e014 as *mut u32;
2  const SYST_CVR: *mut u32 = 0xe000_e018 as *mut u32;
3  const SYST_CSR: *mut u32 = 0xe000_e010 as *mut u32;
4
5  // fire systick every 5 seconds
6  let interval: u32 = 5_000_000;
7  unsafe {
8      write_volatile(SYST_RVR, interval);
9      write_volatile(SYST_CVR, 0);
10     // set fields `ENABLE` and `TICKINT`
11     write_volatile(SYST_CSR, 0b11);
12 }
```

SYST_CSR register

| Bits | Name | Description | Type | Reset |
|-------|-----------|---|------|-------|
| 31:17 | Reserved. | - | - | - |
| 16 | COUNTFLAG | Returns 1 if timer counted to 0 since last time this was read. Clears on read by application or debugger. | RO | 0x0 |
| 15:3 | Reserved. | - | - | - |
| 2 | CLKSOURCE | SysTick clock source. Always reads as one if SYST_CALIB reports NOREF. Selects the SysTick timer clock source: 0 = External reference clock. 1 = Processor clock. | RW | 0x0 |
| 1 | TICKINT | Enables SysTick exception request: 0 = Counting down to zero does not assert the SysTick exception request. 1 = Counting down to zero to asserts the SysTick exception request. | RW | 0x0 |
| 0 | ENABLE | Enable SysTick counter: 0 = Counter disabled. 1 = Counter enabled. | RW | 0x0 |

Register SysTick handler

```
1  #[exception]
2  unsafe fn SysTick() {
3      /* systick fired */
4  }
```

Alarm

counter that triggers interrupts after a time interval

| Registers | Description |
|------------------------|---|
| <code>value</code> | the current value of the counter |
| <code>direction</code> | set to count UP or DOWN |
| <code>reset</code> | UP: max value before 0 DOWN: value after 0 |
| <code>alarm_x</code> | when <code>value == alarm_x</code> , triggers an interrupt, <code>x</code> in 1 ... n |



RP2040's Timer

- stores a 64 bit number (`reset` is $2^{64}-1$)
- starts with `0` at (the peripheral's) reset
- increments the number every μs
- in practice fully monotonic (cannot overflow)
- allows 4 alarms that trigger interrupts
 - `TIMER_IRQ_0`
 - `TIMER_IRQ_1`
 - `TIMER_IRQ_2`
 - `TIMER_IRQ_3`
- `alarm_0 ... alarm_3` registers are only 32 bits wide



RP2040's Timer

read the number of elapsed μ s since reset

The Timer registers start at a base address of `0x40054000` (defined as `TIMER_BASE` in SDK).

| Offset | Name | Info |
|--------|------------------------|--|
| 0x00 | TIMEHW | Write to bits 63:32 of time always write timelw before timehw |
| 0x04 | TIMELW | Write to bits 31:0 of time writes do not get copied to time until timehw is written |

Reading the time elapsed since restart

```
1  const TIMERLR: *const u32 = 0x4005_400c;  
2  const TIMERHR: *const u32 = 0x4005_4008;  
3  
4  let time: u64 = unsafe {  
5      let low = read_volatile(TIMERLR);  
6      let high = read_volatile(TIMERHR);  
7      high as u64 << 32 | low  
8  }
```

The **reading order matters** as reading `TIMERLR` latches the value in `TIMERHR` (stops being updated) until `TIMERHR` is read. Works only in **single core**.

| Offset | Name | Info |
|--------|--------------------------|---|
| 0x08 | TIMEHR | Read from bits 63:32 of time always read timelr before timehr |
| 0x0c | TIMELR | Read from bits 31:0 of time |
| 0x10 | ALARM0 | Arm alarm 0, and configure the time it will fire. Once armed, the alarm fires when <code>TIMER_ALARM0 == TIMELR</code> . The alarm will disarm itself once it fires, and can be disarmed early using the ARMED status register. |
| 0x14 | ALARM1 | Arm alarm 1, and configure the time it will fire. Once armed, the alarm fires when <code>TIMER_ALARM1 == TIMELR</code> . The alarm will disarm itself once it fires, and can be disarmed early using the ARMED status register. |
| 0x18 | ALARM2 | Arm alarm 2, and configure the time it will fire. Once armed, the alarm fires when <code>TIMER_ALARM2 == TIMELR</code> . The alarm will disarm itself once it fires, and can be disarmed early using the ARMED status register. |
| 0x1c | ALARM3 | Arm alarm 3, and configure the time it will fire. Once armed, the alarm fires when <code>TIMER_ALARM3 == TIMELR</code> . The alarm will disarm itself once it fires, and can be disarmed early using the ARMED status register. |
| 0x20 | ARMED | Indicates the armed/disarmed status of each alarm. A write to the corresponding ALARMx register arms the alarm. Alarms automatically disarm upon firing, but writing ones here will disarm immediately without waiting to fire. |
| 0x24 | TIMERAWH | Raw read from bits 63:32 of time (no side effects) |
| 0x28 | TIMERAWL | Raw read from bits 31:0 of time (no side effects) |
| 0x2c | DBGPAUSE | Set bits high to enable pause when the corresponding debug ports are active |
| 0x30 | PAUSE | Set high to pause the timer |
| 0x34 | INTR | Raw Interrupts |
| 0x38 | INTE | Interrupt Enable |
| 0x3c | INTF | Interrupt Force |
| 0x40 | INTS | Interrupt status after masking & forcing |

Alarm

triggering an interrupt at an interval

```
1  #[interrupt]
2  unsafe fn TIMER_IRQ_0() { /* alarm fired */ }

1  const TIMERLR: *const u32 = 0x4005_400c;
2  const ALARM0: *mut u32 = 0x4005_4010;
3  // + 0x2000 is bitwise set
4  const INTE_SET: *mut u32 = 0x4005_4038 + 0x2000;
5
6  // set an alarm after 3 seconds
7  let us = 3_0000_0000;
8
9  unsafe {
10     let time = read_volatile(TIMERLR);
11     // use `wrapping_add` as overflowing may panic
12     write_volatile(ALARM0, time.wrapping_add(us));
13     write_volatile(INTE_SET, 1 << 0);
14 };
```

- the alarm can be set only for the lower 32 bits
- maximum 72 minutes (use *RTC* for longer alarms)

| Offset | Name | Info |
|--------|--------------------------|---|
| 0x08 | TIMEHR | Read from bits 63:32 of time always read timelr before timehr |
| 0x0c | TIMELR | Read from bits 31:0 of time |
| 0x10 | ALARM0 | Arm alarm 0, and configure the time it will fire. Once armed, the alarm fires when <code>TIMER_ALARM0 == TIMELR</code> . The alarm will disarm itself once it fires, and can be disarmed early using the ARMED status register. |
| 0x14 | ALARM1 | Arm alarm 1, and configure the time it will fire. Once armed, the alarm fires when <code>TIMER_ALARM1 == TIMELR</code> . The alarm will disarm itself once it fires, and can be disarmed early using the ARMED status register. |
| 0x18 | ALARM2 | Arm alarm 2, and configure the time it will fire. Once armed, the alarm fires when <code>TIMER_ALARM2 == TIMELR</code> . The alarm will disarm itself once it fires, and can be disarmed early using the ARMED status register. |
| 0x1c | ALARM3 | Arm alarm 3, and configure the time it will fire. Once armed, the alarm fires when <code>TIMER_ALARM3 == TIMELR</code> . The alarm will disarm itself once it fires, and can be disarmed early using the ARMED status register. |
| 0x20 | ARMED | Indicates the armed/disarmed status of each alarm. A write to the corresponding ALARMx register arms the alarm. Alarms automatically disarm upon firing, but writing ones here will disarm immediately without waiting to fire. |
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| 0x40 | INTS | Interrupt status after masking & forcing |

Signals

Digital Signals - Recap

Signals

Analog vs Digital

- *analog signals* are *real* signals
- *digital signals* are a *numerical representation* of an analog signal (software level)
- hardware usually works with two-level digital signals (hardware level)

Exceptions

- in wireless and in high-speed cable communication things get more complicated

for PCB level / between integrated circuits on the same board / inside the same chip - things are a "a little simpler" - as detailed in the following



Why use digital in computing?

Signal that we *want* to generate with an output pin



Signal that what we actually generate



Why we still use it? Because after passing through an IC or a gate inside an IC - the signal is "rebuilt" and if the "digital discipline" described in the following is respected - we can preserve the information after numerous "passes". Thus, each element can behave with a large margin for error, yet the final result is correct.

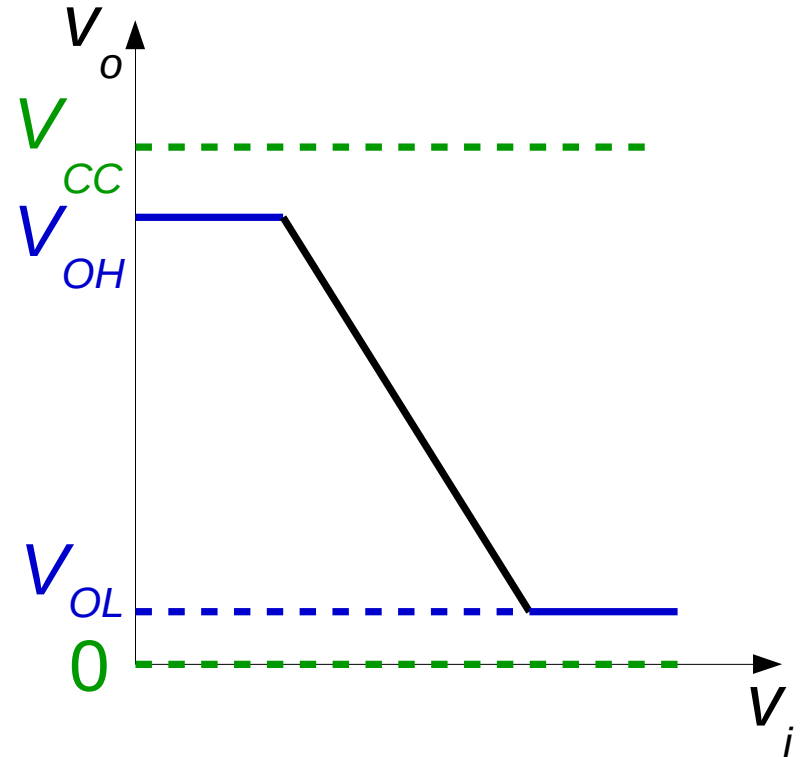
Noise Margin



Why is the output not ideal?

The two corresponding voltage output levels are affected by:

- power supply voltage
- output current
- temperature
- variations in the manufacturing process



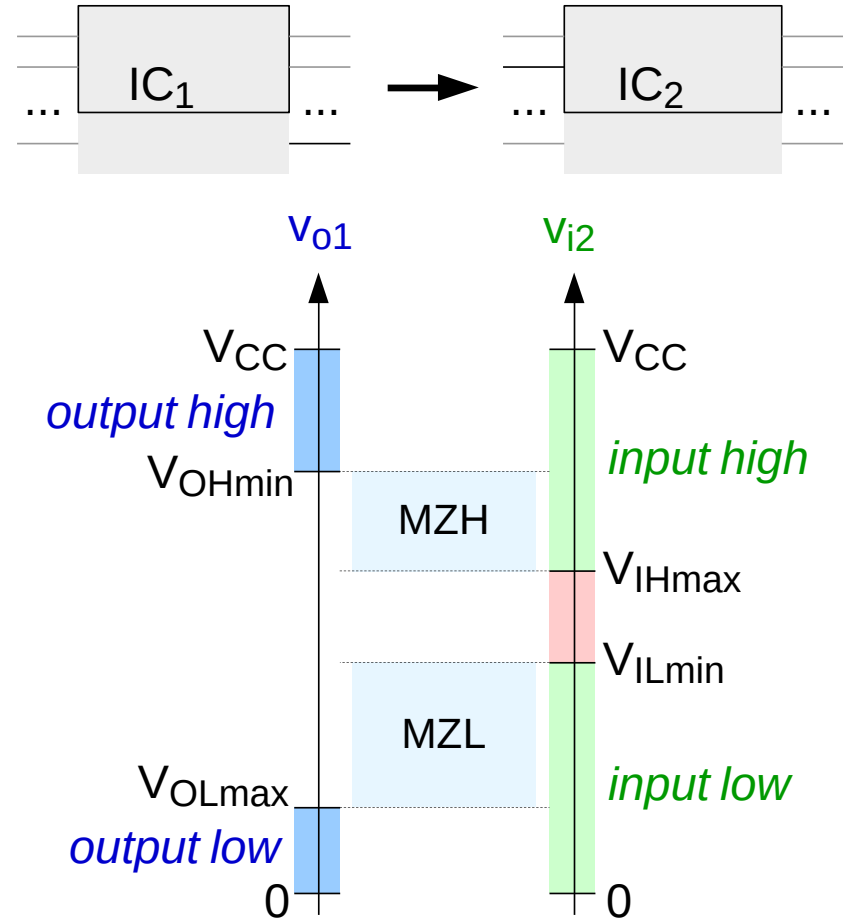
ICs same voltage

Usually will work as is

- usually, they will be compatible
- conditions:

$$V_{OH_transmitter} > V_{IH_receiver}$$

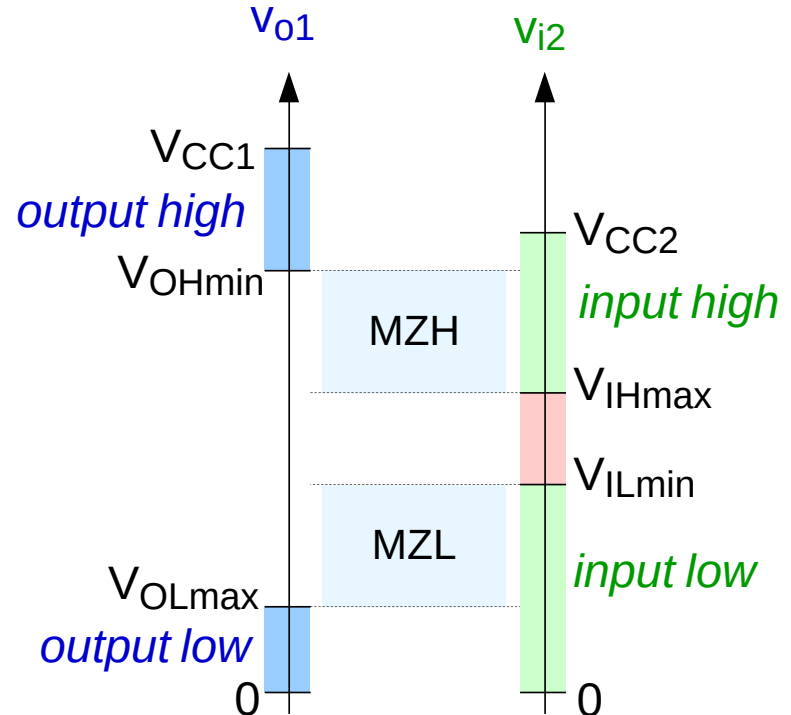
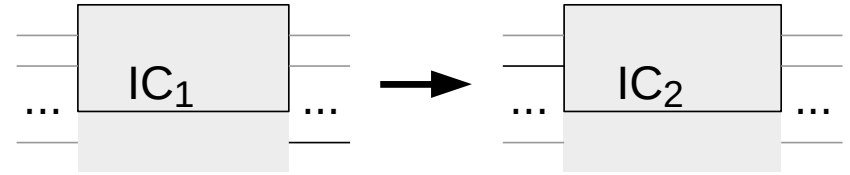
$$V_{OL_transmitter} < V_{IL_receiver}$$



$V_{CC1} > V_{CC2}$

Might work, might produce magic smock

$$V_{OH_transmitter} > V_{CC_receiver}$$



PROBLEM

Solutions:

- level shifter
- resistor divider / voltage limiter

Examples:

- Bi-Directional Level Shifter with 4 Channels
- Level Shifter Multi-Channel
- 8 Channels Level Shifter

$V_{CC1} < V_{CC2}$

Might work

$$V_{CC_transmitter} \lesssim V_{IH_receiver}$$

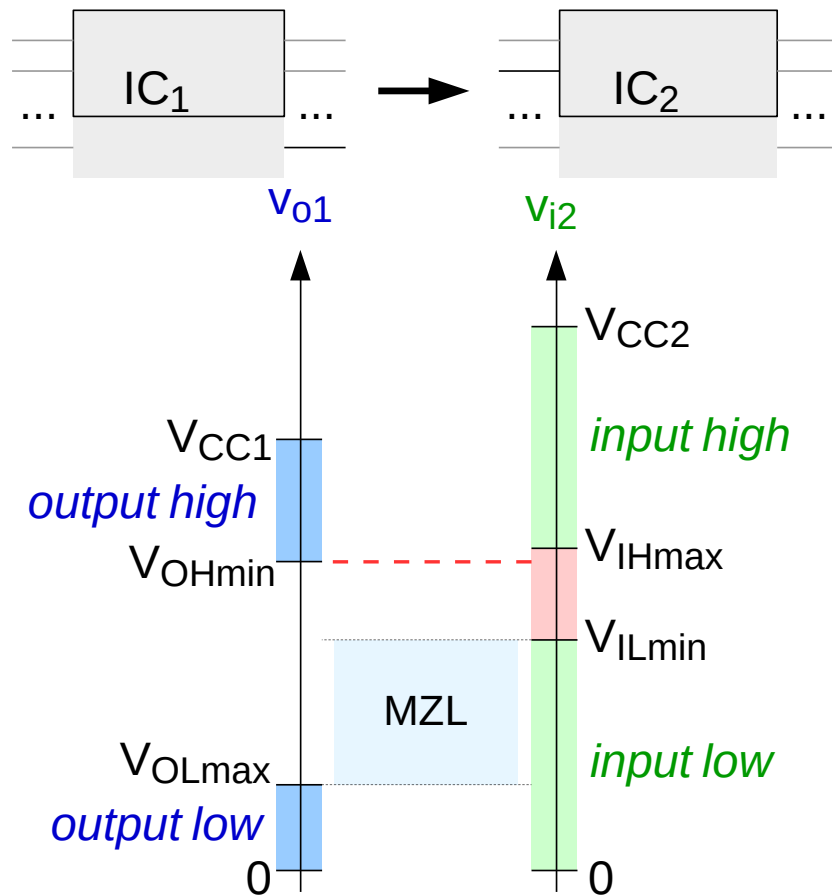
Might work in an intermittent mode - hard to debug!

Solutions:

- level shifter
- resistor divider / voltage limiter

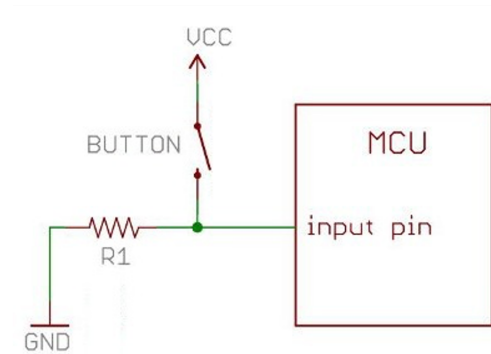
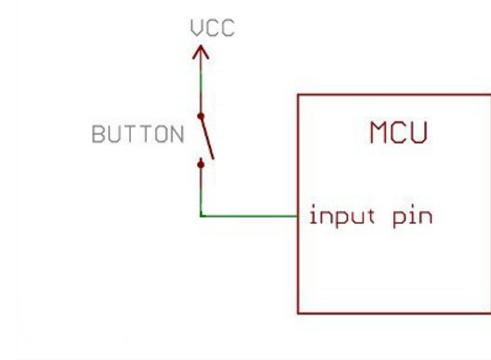
Examples:

- Bi-Directional Level Shifter with 4 Channels
- Level Shifter Multi-Channel
- 8 Channels Level Shifter



Why Pull-Down R

- Without pull-down – when the button is not pressed, it leaves the input pin floating.
- The second design ensures that the voltage level has a well-defined state, regardless of the button's state.
- R1 is called a "pull-down" resistor.

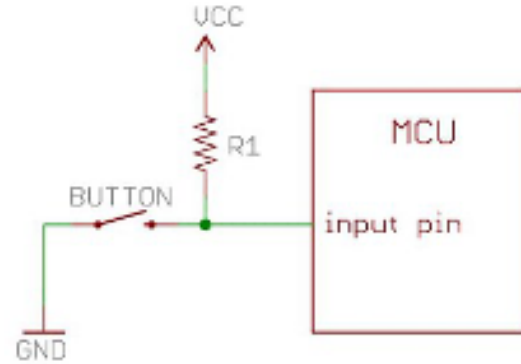


Why Pull-Up R

- Same reasoning
- R1 is called a "pull-up" resistor.

##Obs:

- most microcontrollers have at least a pull-up resistor incorporated on GPIOs - that can be activated in software
- some have both pull-up and pull-down
- typically, these are sized for a 50 - 10 nA current consumption



Notes on output pins

- most microcontrollers have a limit of around 10mA per output PIN
- ! do not connect an LED without a resistor in series (to limit the current)
- ! do not connect a motor / any type of inductive load

Solutions:

- use a transistor
- use an IC with incorporated Darlingtontons (eg: ULN2003)

PWM

Pulse Width Modulation

Bibliography

for this section

1. **Raspberry Pi Ltd**, *RP2040 Datasheet*

- Chapter 4 - *Peripherals*
 - Chapter 4.5 - *PWM*

2. **Paul Denisowski**, *Understanding PWM*

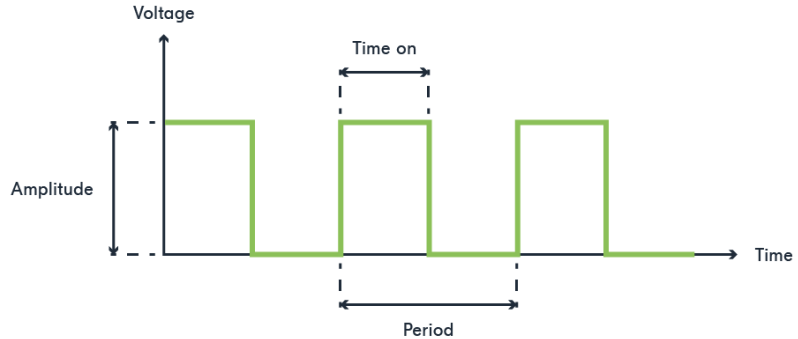
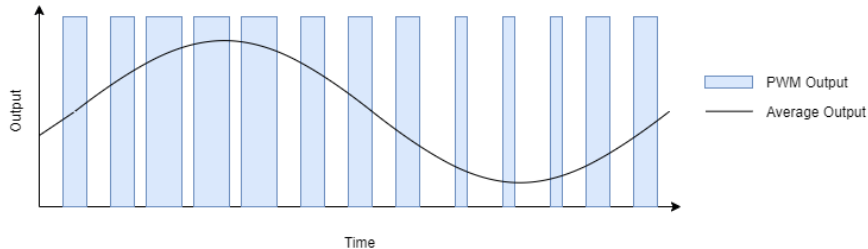
PWM

simulates an *analog* signal (using integration)

- generates a square signal
- if integrated (averaged), it looks like an analog signal

frequency Hz The number of repeats per s

duty_cycle % The percentage of the time when
the signal is High



$$f = \frac{1}{\text{period}} \left[\frac{1}{s} = 1\text{Hz} \right]_{SI}$$

$$\text{duty_cycle} = \frac{\text{time_on}}{\text{period}} \%$$

PWM

generic device

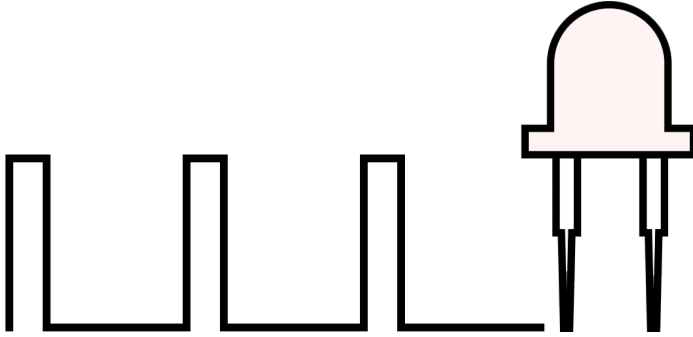
$$f = \begin{cases} \frac{f_{clock}}{divider \times (top+1)} & correction = 0 \\ \frac{f_{clock}}{divider \times 2 \times (top+1)} & correction = 1 \end{cases}$$

$$pin_{a,b} = \begin{cases} 0 & compare_{a,b} \geq value \\ 1 & compare_{a,b} < value \end{cases}$$

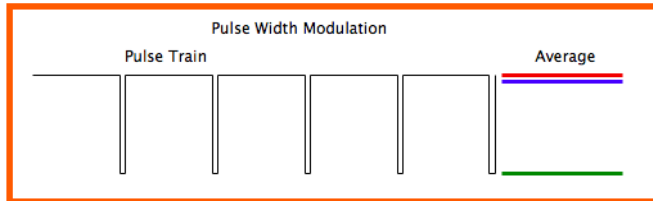


Usage examples

- dimming an LED

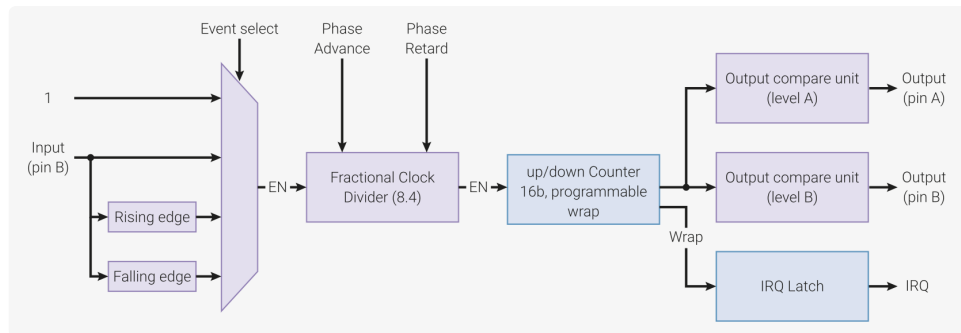


- controlling motors
 - controlling the angle of a stepper motor
 - controlling the RPM of a motor



RP2040's PWM

- generates square signals
- counts the pulse with of input signals
- 8 PWM units, each with 2 channels (A and B)
- each PWM channel is connected to a certain pin
- some channels are connected to two pins



All 30 GPIO pins on RP2040 can be used for PWM:

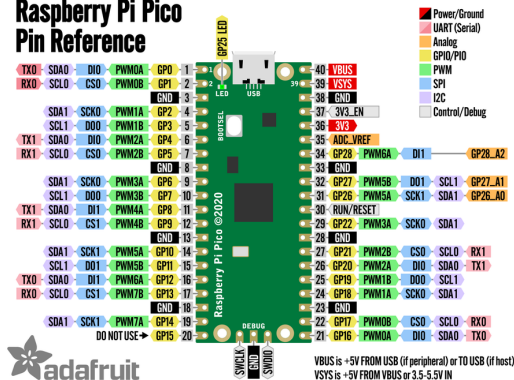
| | | | | | | | | | | | | | | | | |
|-------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| GPIO | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| PWM Channel | 0A | 0B | 1A | 1B | 2A | 2B | 3A | 3B | 4A | 4B | 5A | 5B | 6A | 6B | 7A | 7B |
| GPIO | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | | |
| PWM Channel | 0A | 0B | 1A | 1B | 2A | 2B | 3A | 3B | 4A | 4B | 5A | 5B | 6A | 6B | | |

Registers

The PWM registers start at a base address of `0x40050000` (defined as `PWM_BASE` in SDK).

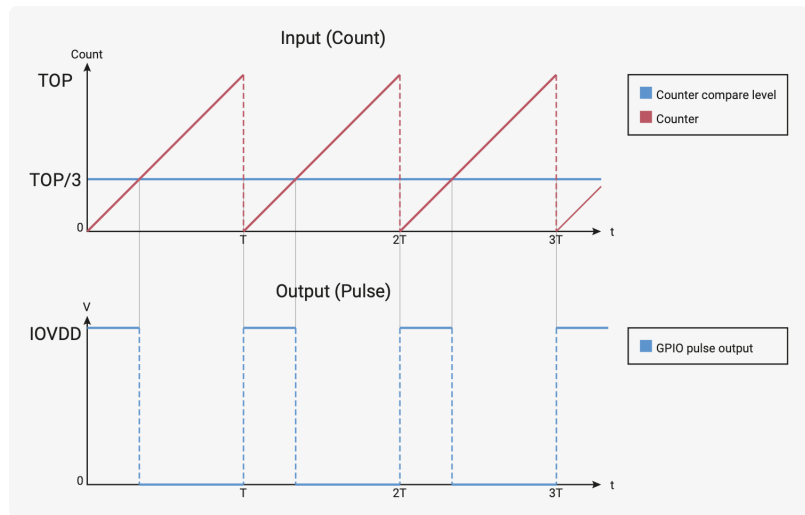
| Offset | Name | Info |
|--------|---------|---|
| 0x00 | CH0_CSR | Control and status register |
| 0x04 | CH0_DIV | INT and FRAC form a fixed-point fractional number. Counting rate is system clock frequency divided by this number. Fractional division uses simple 1st-order sigma-delta. |
| 0x08 | CH0_CTR | Direct access to the PWM counter |
| 0x0c | CH0_CC | Counter compare values |
| 0x10 | CH0_TOP | Counter wrap value |

Raspberry Pi Pico Pin Reference

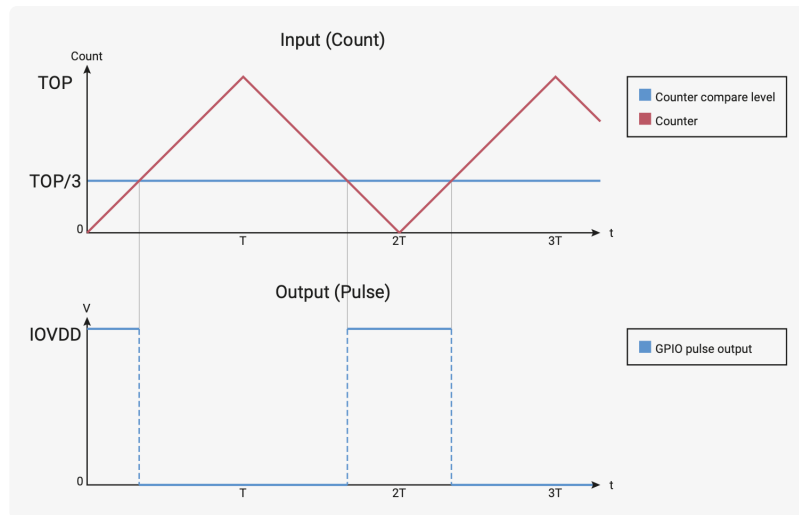


RP2040's PWM Modes

standard mode



phase-correct mode



$$period = (TOP + 1) \times (PH_CORRECT + 1) \times \left(DIV_INT + \frac{DIV_FRAC}{16} \right) [s]_{SI}$$

$$f = \frac{f_{sys}}{period} [Hz]_{SI}$$

Example

using Embassy

```
1 use embassy_rp::pwm::{Config, Pwm};
2
3 let p = embassy_rp::init(Default::default());
4
5 let mut c: Config = Default::default();
6 c.top = 0x8000;
7 c.compare_b = 8;
8
9 let mut pwm = Pwm::new_output_b(
10     p.PWM_CH4,
11     p.PIN_25,
12     c.clone()
13 );
14
15 loop {
16     info!("LED duty cycle: {}/32768", c.compare_b);
17     Timer::after_secs(1).await;
18     c.compare_b += 10;
19     pwm.set_config(&c);
20 }
```

```
pub struct Config {
    /// Inverts the PWM output signal on channel A.
    pub invert_a: bool,
    /// Inverts the PWM output signal on channel B.
    pub invert_b: bool,
    /// Enables phase-correct mode for PWM operation.
    pub phase_correct: bool,
    /// Enables the PWM slice, allowing it to generate an out
    pub enable: bool,
    /// A fractional clock divider, represented as a fixed-po
    /// 8 integer bits and 4 fractional bits. It allows preci
    /// the PWM output frequency by gating the PWM counter in
    /// A higher value will result in a slower output frequen
    pub divider: fixed::FixedU16<fixed::types::extra::U4>,
    /// The output on channel A goes high when `compare_a` is
    /// counter. A compare of 0 will produce an always low ou
    pub compare_a: u16,
    /// The output on channel B goes high when `compare_b` is
    /// counter.
    pub compare_b: u16,
    /// The point at which the counter wraps, representing th
    /// period. The counter will either wrap to 0 or reverse
    /// setting of `phase_correct`.
    pub top: u16,
}
```


ADC

Analog to Digital Converter

Bibliography

for this section

Raspberry Pi Ltd, *RP2040 Datasheet*

- Chapter 4 - *Peripherals*
 - Chapter 4.9 - *ADC and Temperature Sensor*
 - Subchapter 4.9.1
 - Subchapter 4.9.2
 - Subchapter 4.9.5

ADC

sampling an analog signal to an array of values

sampling rate

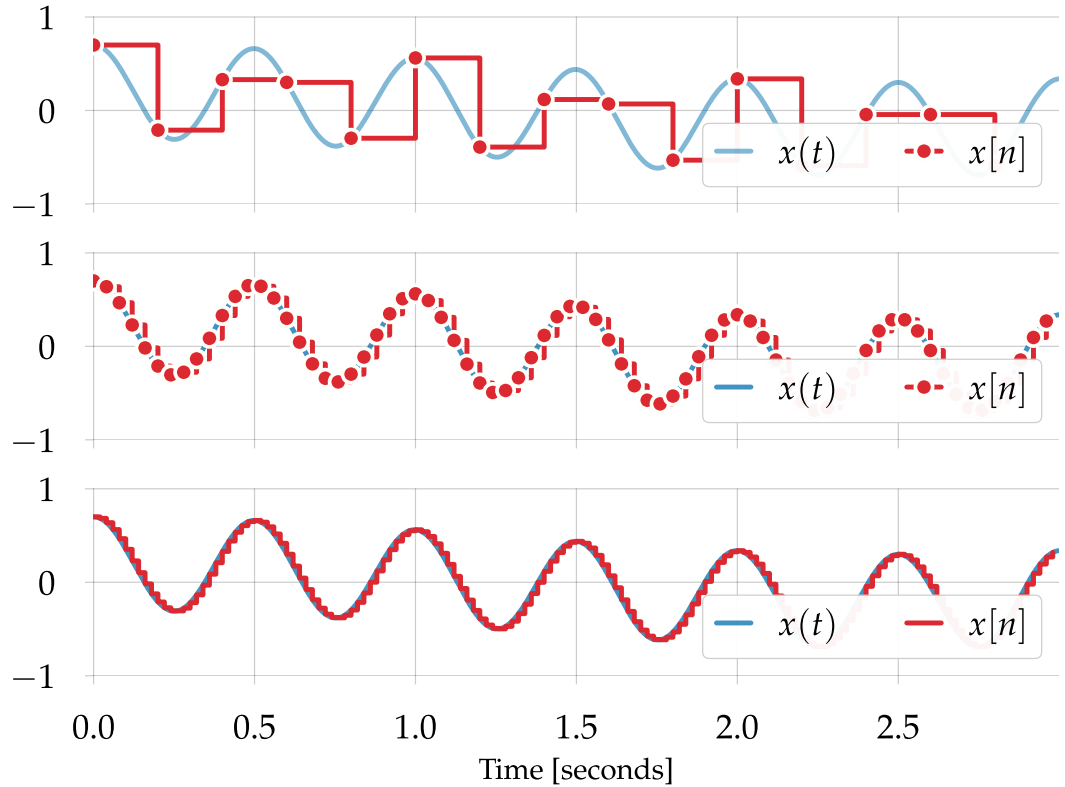
Hz

the frequency at which a new sample is read

resolution

bits

the number of bits used to store a sampled value

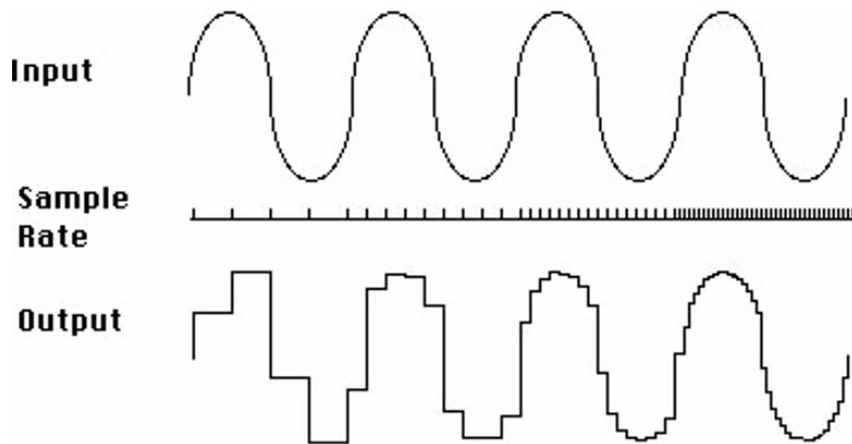


Lower sample rates yield the *aliasing effect*.

Nyquist–Shannon Sampling Theorem

$$sampling_f \geq 2 \times max_f$$

The **sampling frequency** has to be at least **two times higher** than the **maximum frequency** of the signal to avoid frequency aliasing^[1].

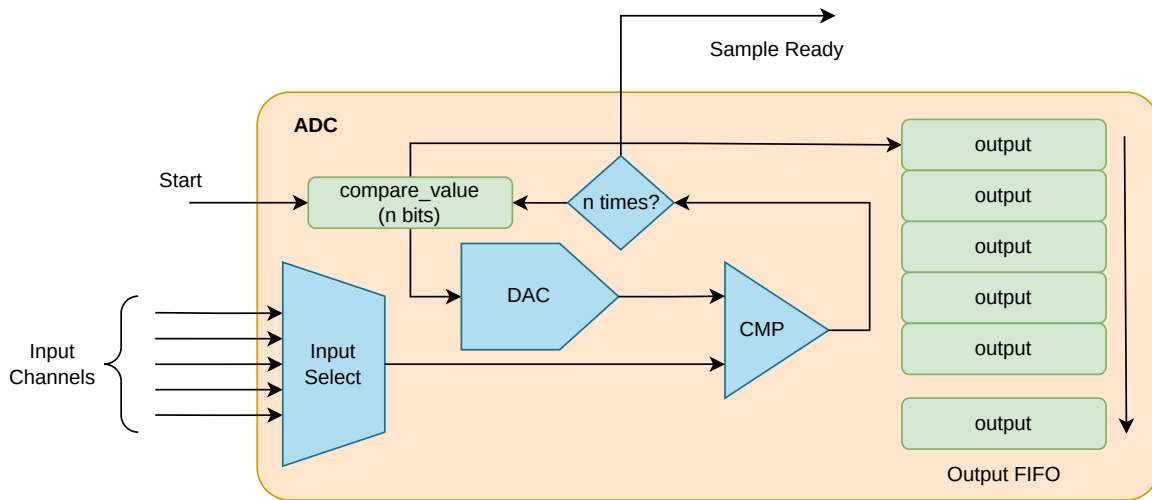


-
1. Aliasing is the overlapping of frequency components. This overlap results in distortion or artifacts when the signal is reconstructed from samples which causes the **reconstructed signal to differ from the original** continuous signal. ↩

Sampling

how the ADC works

- assumes bit_{n-1} of `compare_value` is 1
- compares the input signal with a generated analog signal from `compare_value`
 - if input is lower, bit_{n-1} is 0
 - if input is higher, bit_{n-1} is 1
- repeats for bit_{n-2} , $\text{bit}_{n-3} \dots \text{bit}_0$



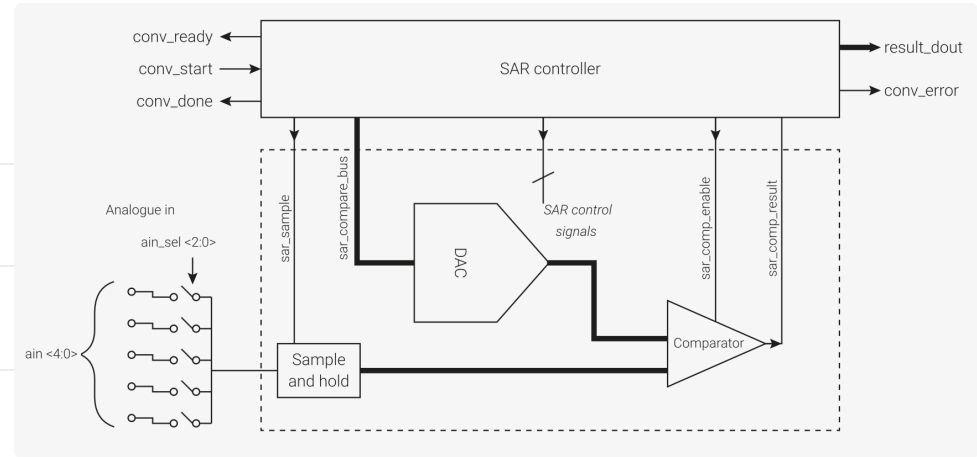
There are different types of ADCs depending on the architecture. The most common used is SAR (Successive Approximation Register) ADC, also integrated in RP2040.

RP2040's ADC

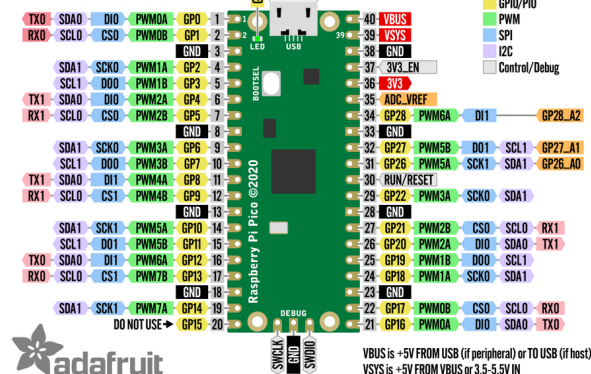
| | |
|------------------------|---------|
| <i>channels</i> | 5 |
| <i>sampling rate</i> | 500 kHz |
| <i>resolution</i> | 12 bits |
| <i>V_{max}</i> | 3.3 V |

- requires a 48 MHz clock signal
- channel 4 is connected to the internal temperature sensor

$$t = 27 - \frac{(V_{input_4} - 0.706)}{0.001721} [^{\circ}C]_{SI}$$



Raspberry Pi Pico Pin Reference



ADC

in Embassy

```
1  use embassy_rp::adc::{Adc, Channel, Config, InterruptHandler};
2
3  bind_interrupts!(struct Irqs {
4      ADC_IRQ_FIFO => InterruptHandler;
5  });
6
7  let p = embassy_rp::init(Default::default());
8  let mut adc = Adc::new(p.ADC, Irqs, Config::default());
9
10 let mut p26 = Channel::new_pin(p.PIN_26, Pull::None);
11
12 loop {
13     let level = adc.read(&mut p26).await.unwrap();
14     info!("Pin 26 ADC: {}", level);
15     let voltage = 3300 * level / 4095;
16     info!("Pin 26 voltage: {:.{}V", voltage / 1000, voltage % 1000);
17     Timer::after_secs(1).await;
18 }
```

Conclusion

we talked about

- Counters
- SysTick
- Timers and Alarms
- PWM
- Analog and Digital
- ADC