Analog I/O

ECE 476 Advanced Embedded Systems

Jake Glower - Lecture #9

Please visit Bison Academy for corresponding
lecture notes, homework sets, and solutions

Introduction:

Up to now, we have been dealing with binary inputs and outputs (I/O).

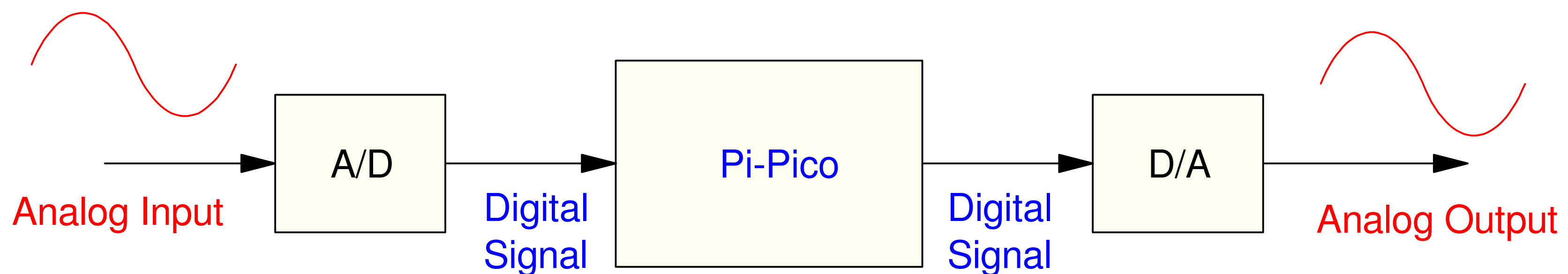
The real world is typically analog, however.

- Voltages can take on any value - not just 0V and 3.3V
- Resistance's can take on any positive value
- Temperatures can be any value

Microcontrollers like the Pi-Pico usually allow analog I/O

- A/D: Read an analog input
- D/A: Drive an analog outputo can read

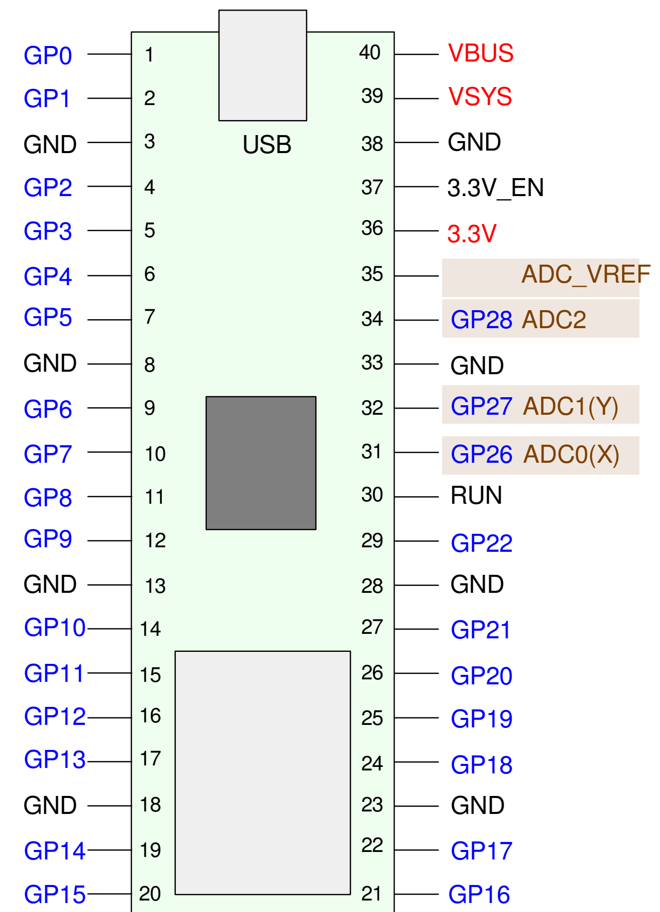
This lecture looks at how to input and output analog signals from a Pi-Pico.



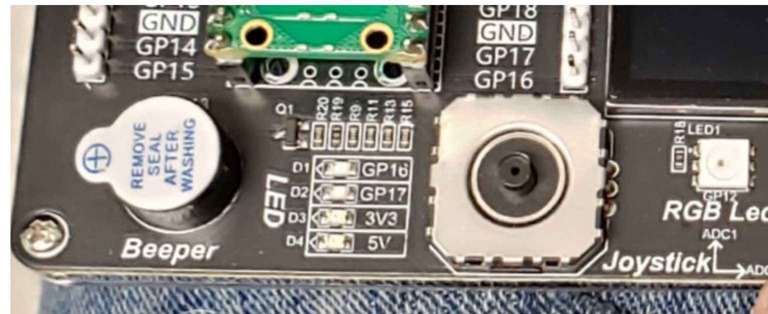
Analog Inputs: A/D

The Pi-Pico has five 12-bit A/D ports built in - with three connected to I/O pins.

- ADC0: joystick x position
- ADC1: joystick y position
- ADC2: voltage on GP28
- ADC3: is not connected, and
- ADC4: the temperature of the Pi-Pico



Reading the Joystick Position



x = ADC0 (pin 26)

y = ADC1 (pin 27)

- 0V = 0
- 3.3V = 65,535

```
from machine import ADC
from time import sleep_ms

a2d0 = ADC(0)
a2d1 = ADC(1)

while(1):
    x = a2d0.read_u16()
    y = a2d1.read_u16()

    print(x, y)
    sleep_ms(200)
```

Left vs. Right Justified

The Pico has a 12-bit A/D

- 0 to 4095 if right justified
- 0 to 65,535 if left justified

Left justified allows the code to be independent of the A/D resolution

- Max reading is 65,536 regardless of the number of bits
- Makes the code more transportable
- Kind of becoming the standard

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
12-bit A/D reading (0x000 to 0xFFF)												0	0	0	0

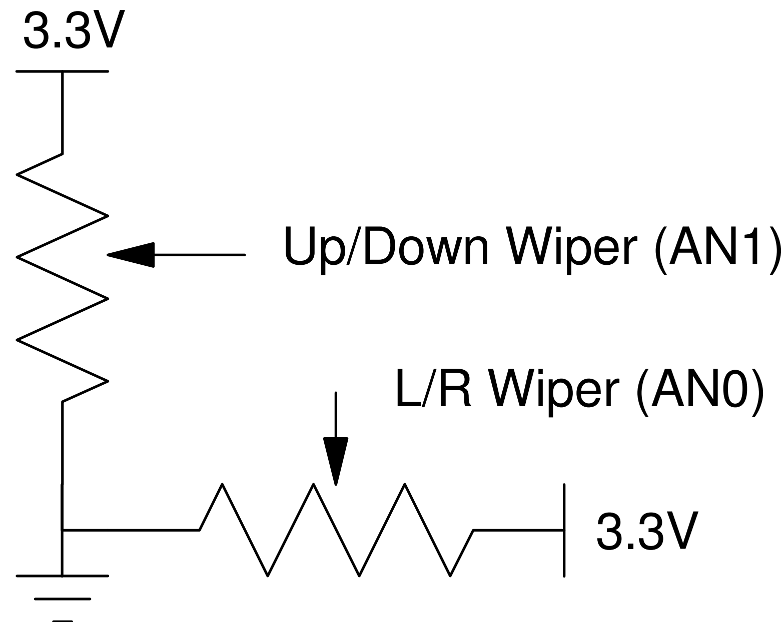
Reading 0V to 3.3V (Joystick Input)

The joystick consists of two potentiometers

- Endpoint = 0V and 3.3V
- Wiper = A/D input

As you move the joystick, the voltage goes from 0V to 3.3V

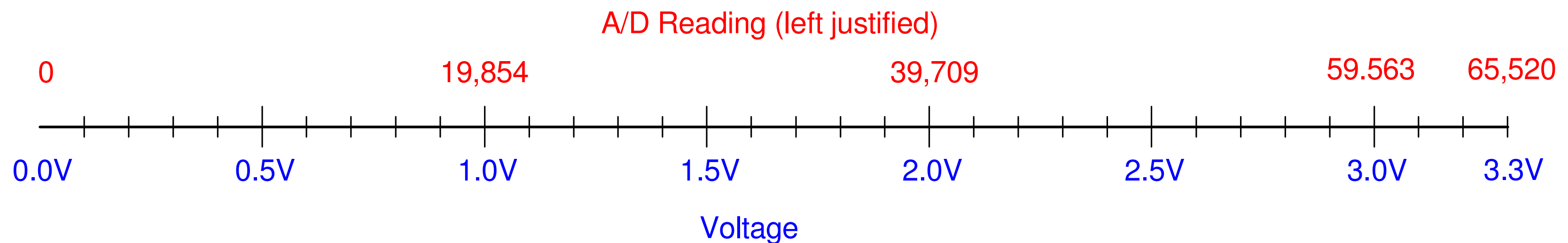
- A/D reading is 0 to 65,535



Converting A/D Reading to Voltage

The A/D reading is proportional to volage

- 0V = 0
- 3.3V = 65,535



Analog Inputs: A/D reading is proportional to voltage

Reading Voltage (cont'd)

Voltage is proportional to the A/D reading

$$V_i = \left(\frac{3.30V}{65{,}520}\right) \cdot A2D_i$$

Sensitivity is one count (12-bits = 4095)

$$dV = \left(\frac{3.3V}{4095}\right) = 806.86\mu V$$

A/D channels 0-2 read voltage

- Connected to GPIO pins

A/D channel 4 measures the temepratureof the Pi-Pico

$$^{0}C = 0.02927 * (14940 - A2D_4)$$

resolution = 0.468 deggrees C

Code

Read the voltage on

- Joystick X (ADC0)
- Joystick Y (ADC1)

Read the temperature of the Pi-Pico

- ADC4

Results:

- Vx = 1.447679V
- Vy = 1.499254V
- temp = 23.21111C

```
from machine import ADC
from time import sleep_ms

a2d0 = ADC(0)
a2d1 = ADC(1)
a2d4 = ADC(4)

k = 3.3 / 65535

while(1):
    a0 = a2d0.read_u16()
    a1 = a2d1.read_u16()
    a4 = a2d4.read_u16()

    V0 = a0 * k
    V1 = a1 * k
    Temp = 0.02927*(14940 - a4)

    print(V0, V1, Temp)
    sleep_ms(200)
```

shell

```
    Vx        Vy      degrees C
1.447679  1.499254  23.21111
1.435554  1.501671  23.21111
```

Reading 0-10V:

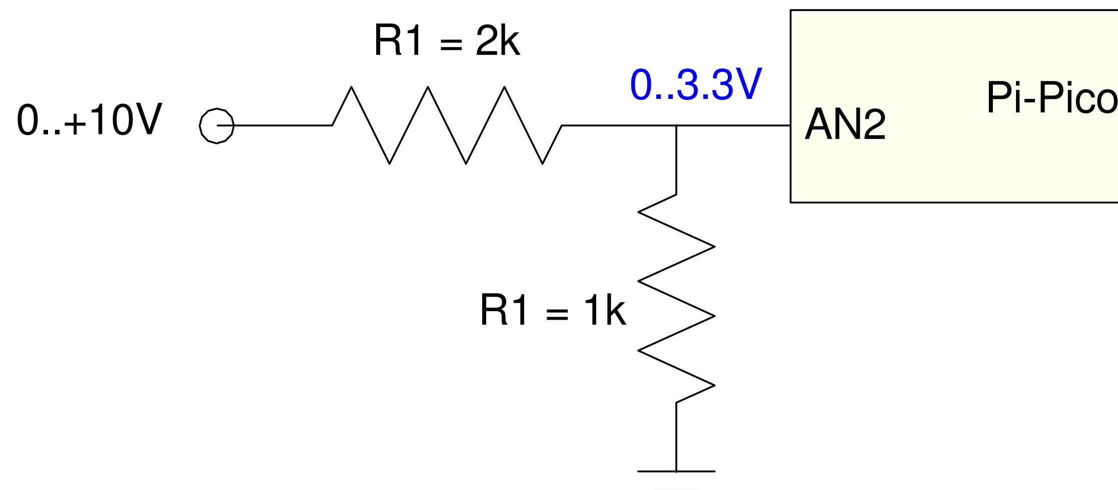
The Pi-Pico always reads 0V to 3.3V

To read 0..10V

- Convert 0-10V to 0-3.3V
- Voltage divider with a gain of 0.33

If R1 = 1k, then

$$R_2 = \left(\frac{1-0.33}{0.33}\right) R_1 = 2.03k \approx 2k$$



Code for Reading 0..10V

- Scale the computed voltage accordingly:

```
from machine import ADC
from time import sleep_ms

a2d2 = ADC(2)

k = 10.0 / 65535

while(1):
    a2 = a2d2.read_u16()
    V2 = a2 * k

    print(V2, ' Volts')
    sleep_ms(200)
```

shell

```
4.9932 Volts
5.0221 Volts
```

Reading -10V to +10V:

To convert -10V to +10V to 0 to 3.3V, use three resistors

- Other solutions exist

If

- x: -10V to +10V
- B: +3.3V
- C: 0V

the output should be

$$y = (x + 10)\left(\frac{3.3V}{20V}\right) = 0.1650x + 1.650$$

You can set this up as a weighted average of {A, B, C}

$$y = (0.1650x + 0.500B)$$

Add a term so the coefficients add to 1.000

$$y = 0.1650x + 0.500B + 0.335C$$

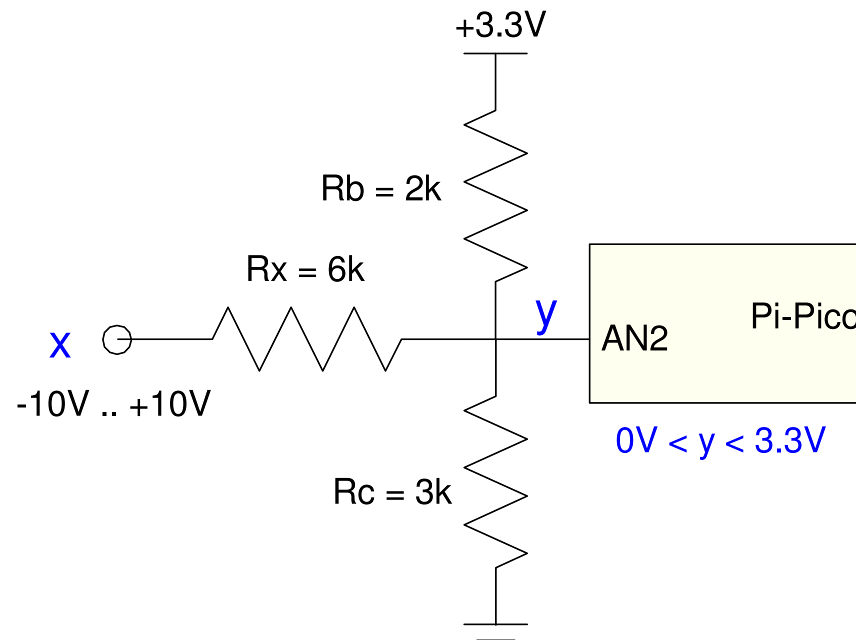
Pick your favorite resistor value, such as 1k.

The weightings tell you how the resistors are scaled:

$$R_x = \frac{1k}{0.1650} = 6.06k$$

$$R_b = \frac{1k}{0.500} = 2k$$

$$R_c = \frac{1k}{0.335} = 2.98k$$



The corresponding Python code would be:

- -10V reads as 0
- +10V reads as 65,535

```
from machine import ADC
from time import sleep_ms

a2d2 = ADC(2)

k = 20.0 / 65535

while(1):
    a2 = a2d2.read_u16()
    V2 = k * a2 - 10

    print(V2, ' Volts')
    sleep_ms(200)
```

shell

```
0.12131 Volts
0.01231 Volts
```

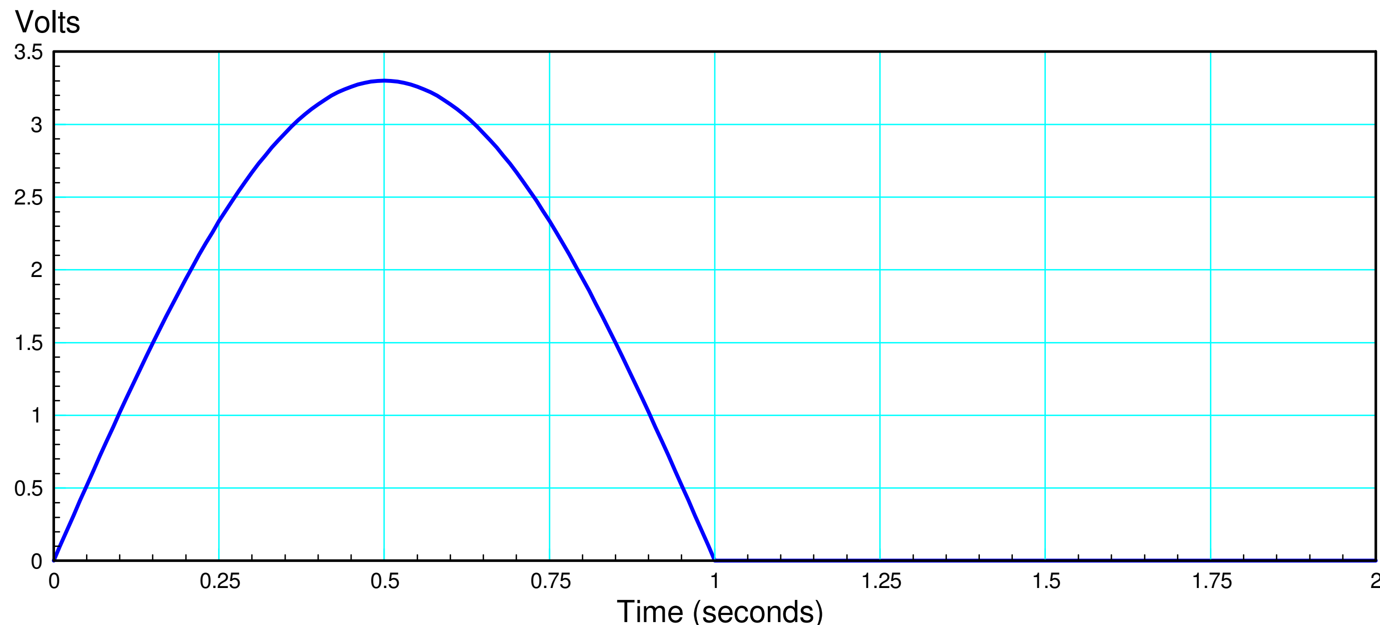
Analog Outputs:

Analog outputs can assume multiple values between 0V and 3.3V

- In theory, infinite values
- In practice, a finite but large number of values

Example: output a half-rectified since wave with a period of 2 seconds:

- Using PWM, PWM + Filter, D/A



PWM (pulse width modulation)

From before, the *machine* library has a PWM function

This allows you to output

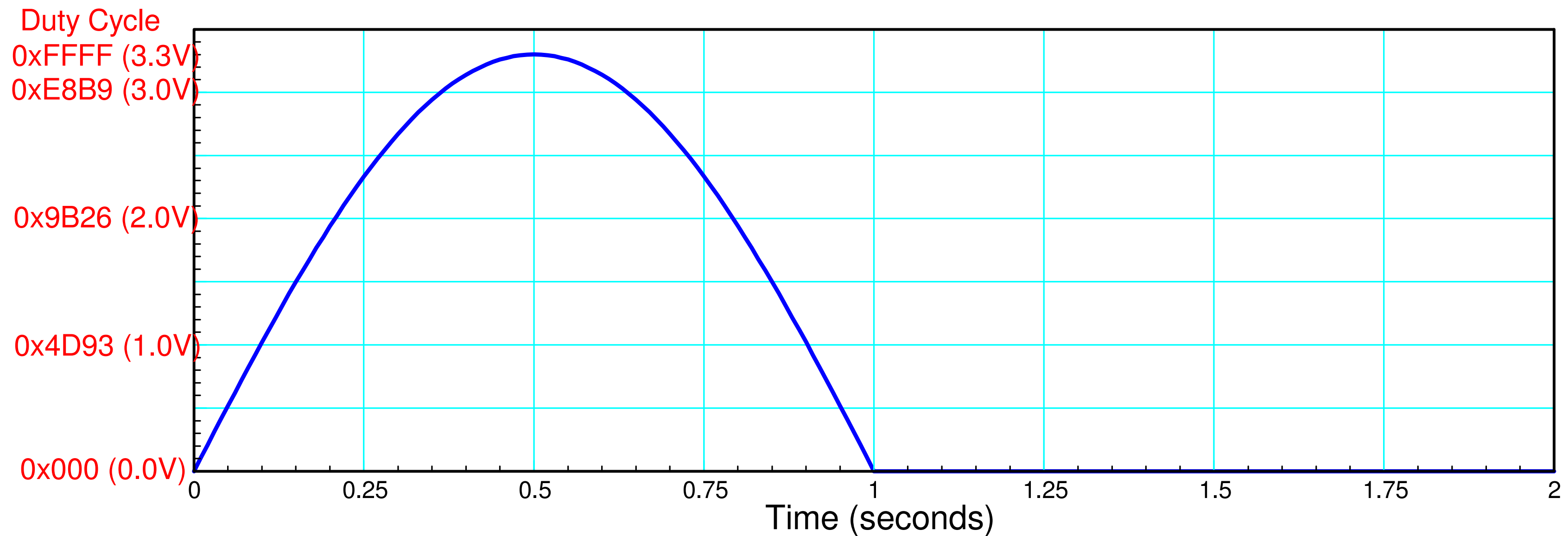
- A square wave,
- At a given frequency,
- With a given duty cycle.

For example, the following code outputs a

- 1kHz square wave (line 5)
- with a frequency of 1kHz (line 6: 10% of 65,535 = 6553)

```
1  from machine import Pin, PWM
2
3  Aout = Pin(16, Pin.OUT)
4  Aout = PWM(Pin(16))
5  Aout.freq(1000)
6  Aout.duty_u16(6553)
7  while(1):
8      pass
```

If you adjust the duty cycle, you can vary the average from 0V (0%) to 3.3V (100%). To output a half-rectified sine wave, vary the duty cycle according to the figure below:



By varying the duty cycle, you can output any voltage from 0.0V to 3.3V

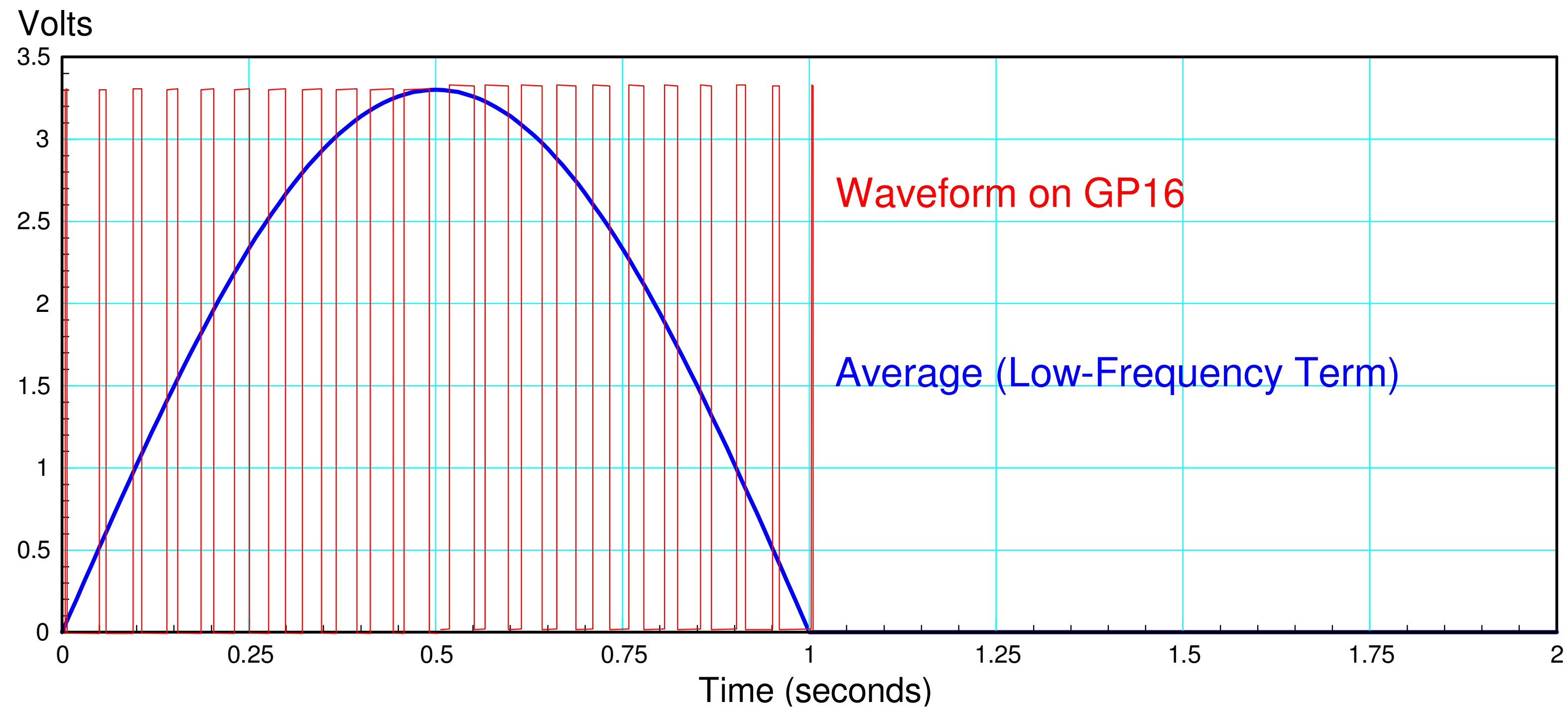
Code:

To speed up execution

- A look-up table is used
- sin() is computed prior to the main loop

```
from machine import Pin, PWM
from time import sleep_ms
from math import sin, pi

Aout = Pin(16, Pin.OUT)
Aout = PWM(Pin(16))
Aout.freq (1000)

Table = []
for i in range(0,100):
    Table.append(int(65535*sin(i*pi/100)))
for i in range(0,100):
    Table.append(0)

i = 0
while(1):
    i = (i + 1) % 200
    Aout.duty_u16(Table[i])
    sleep_ms(10)
```

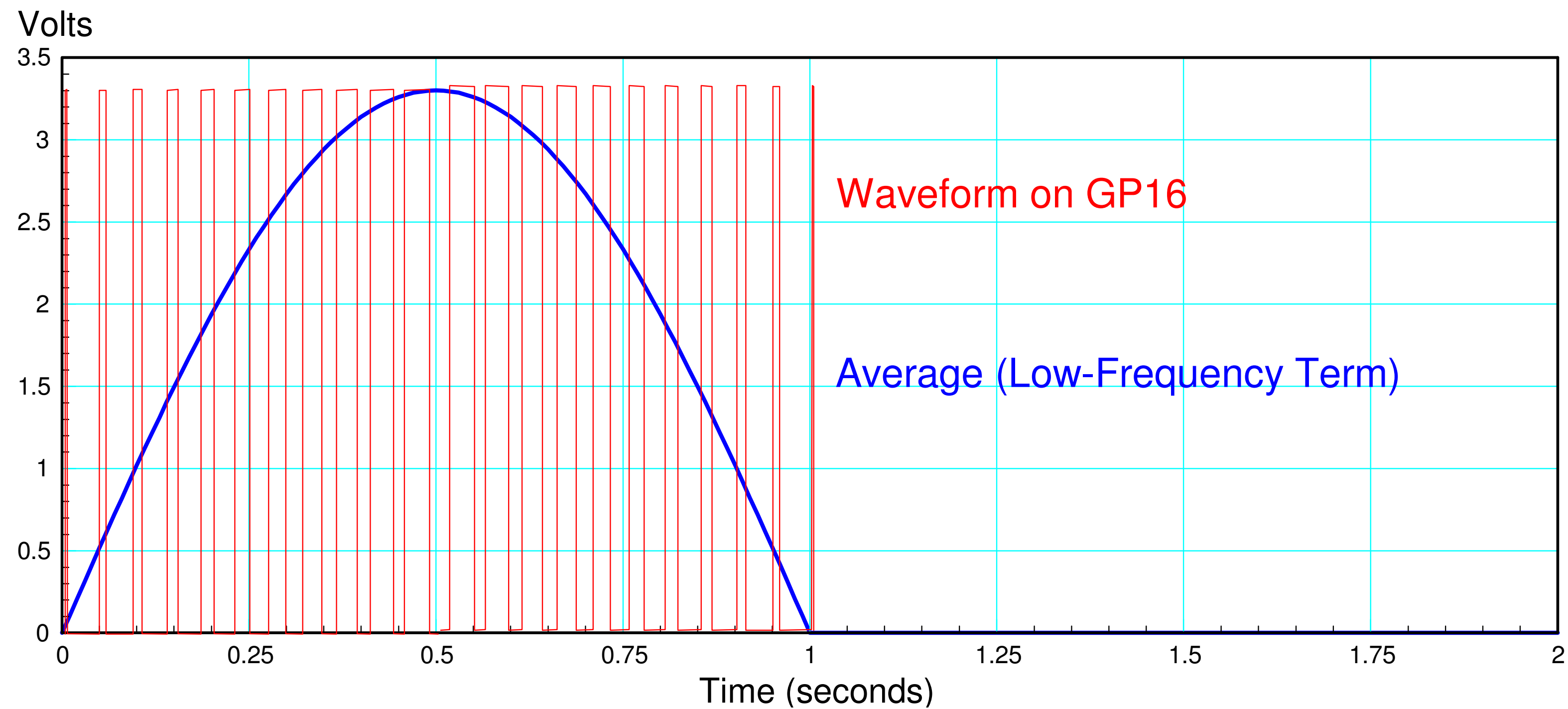
If you look at an LED attached to GP16, the LED will be fading in and out as desired. If you look on an oscilloscope, however, you'll see noise:



PWM & Frequency Content

The PWM signal contains

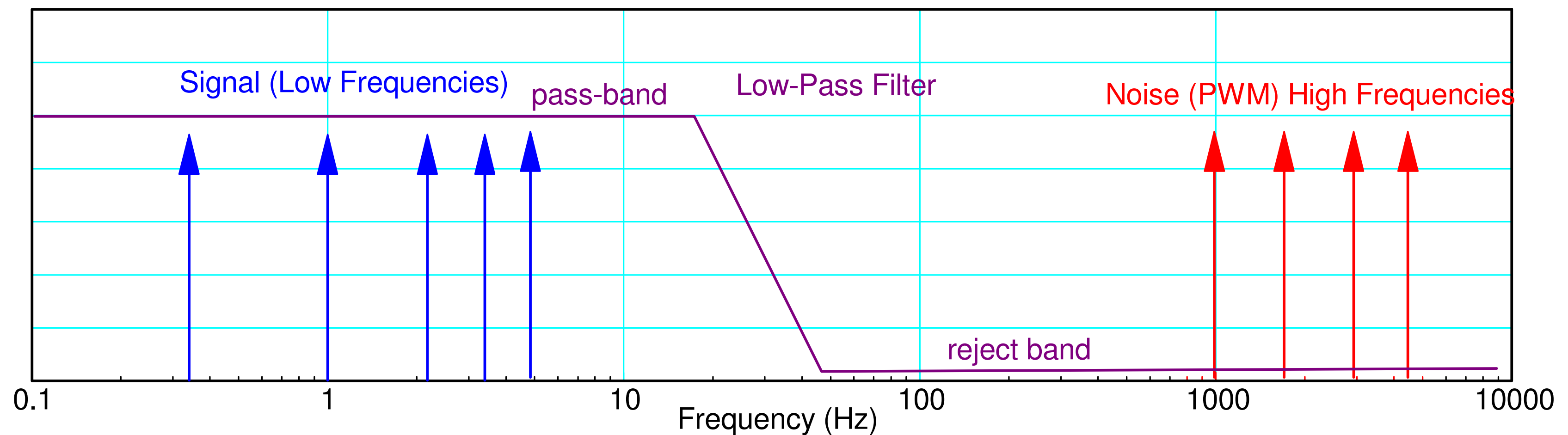
- The signal (blue line) at 1Hz, and
- Harmonics of the 1kHz PWM waveform (red line)



To output a clean signal, you want to

- Pass the low frequency terms (frequencies below something like 10Hz), and
- Reject frequencies above 1kHz.

In short, you need to add a low-pass filter.

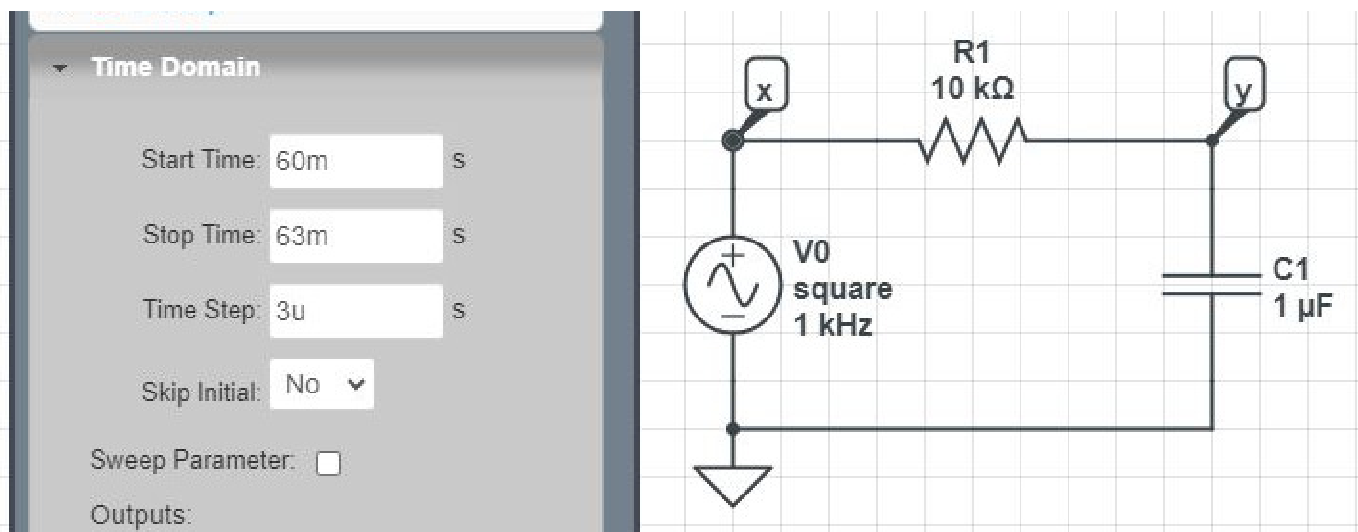


Add a low-pass filter to pass the signal (frequencies below 10Hz) and reject noise (frequencies above 1kHz)

There are many types of low-pass filters. Two of these are

- A single-stage RC low-pass filter, and
- An active 2nd-order low-pass filter

RC Low-Pass Filter: RC filters are simple and not very good. It works OK in this application since there is a large separation between the signal (<10Hz) and the noise (PWM at 1kHz).



Typically, you place the corner frequency (1/RC) in-between the pass-band (10Hz) and the reject band (1kHz). Assume for convenience you pick 100 rad/sec or 15.9Hz:

$$\frac{1}{RC} = 100\frac{rad}{\sec} = 15.9Hz$$

The gain of the filter is then

$$y = \left(\frac{\frac{1}{RC}}{s+\frac{1}{RC}}\right)x = \left(\frac{100}{s+100}\right)x$$

What this filter does is

- For frequencies below 100 rad/sec (15.9Hz), the gain is approximately one.
- For frequencies above 100 rad/sec, the gain drops off as 1/s.
- At 1kHz (6280 rad/sec), the gain is 0.016: noise at 1kHz is attenuated by a factor of 0.016

Going back to the 1/2-wave rectified since wave. What you expect the output of the filter to be is:

- A DC term (unchanged - the DC gain is one), and
- An AC term which has been attenuated.

You can approximate the amplitude of the AC term (i.e. the noise on the signal) as

$$Output = Gain \cdot Input$$

At 1kHz, the PWM signal is a 3.3Vpp square wave.

At 1kHz (6280 rad/sec), the gain of the filter is

$$gain = \left(\frac{100}{s+100}\right)_{s=j6280}$$

Putting it together, the AC (noise) component of the filter's output should be:

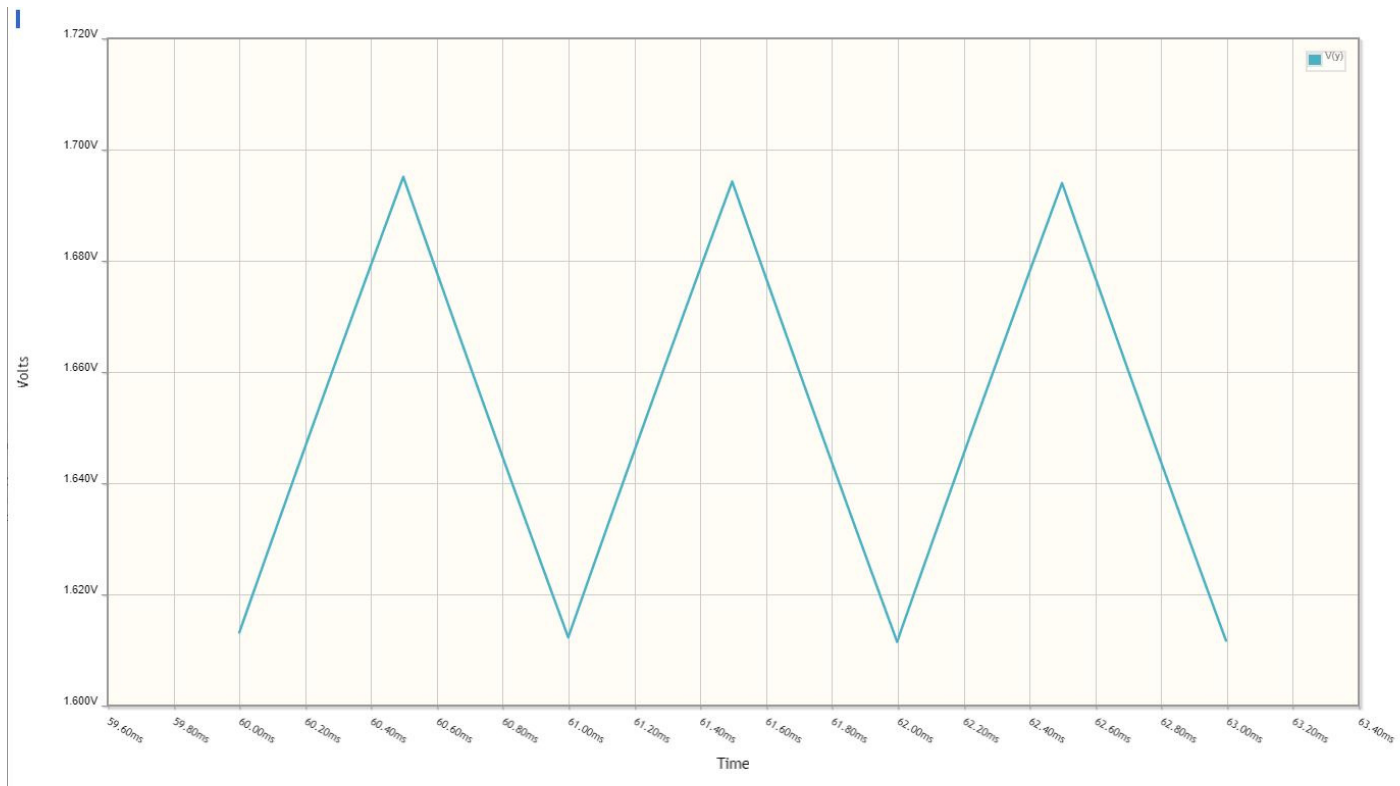
$$y = \left(\frac{100}{s+100}\right) x$$

$$|y| \approx \left(\frac{100}{s+1000}\right)_{s=j6280} \cdot 3.3V_{pp}$$

$$|y| \approx 0.0525V_{pp}$$

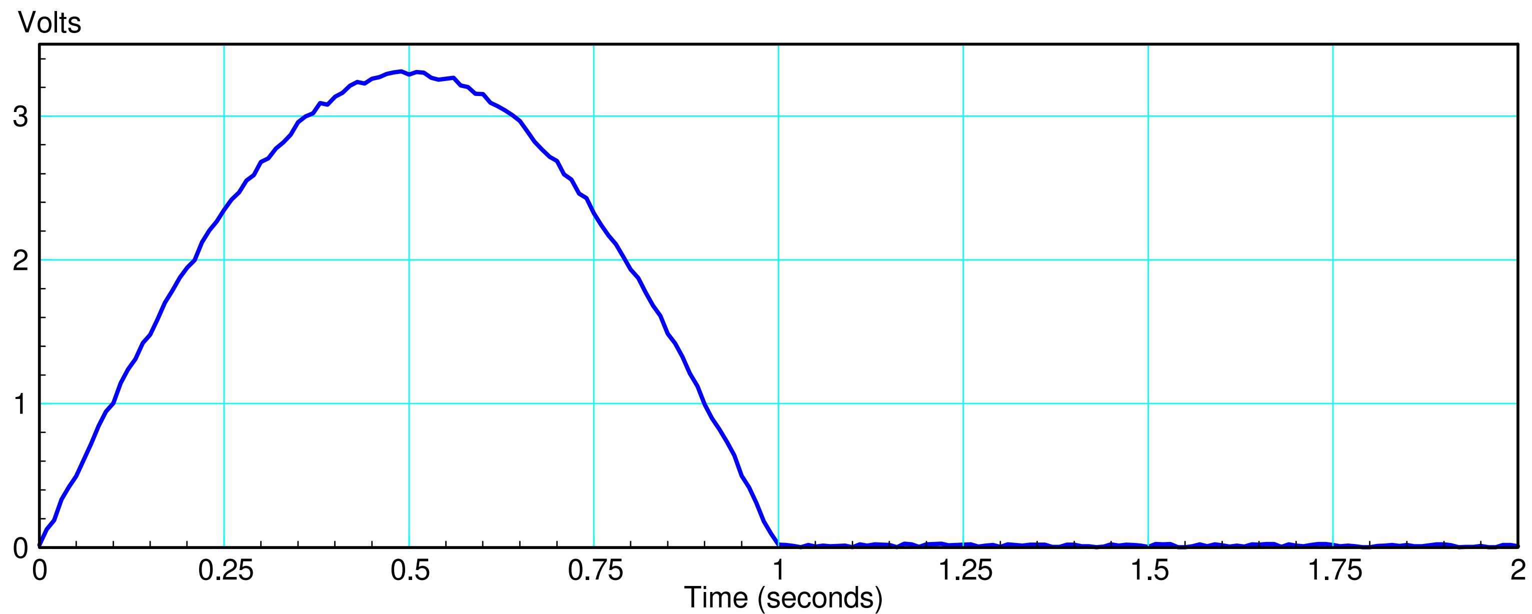
The signal at y should have the DC term plus a 52.5mVpp ripple.

You can check this in CircuitLab. Running a time-domain simulation results in the ripple actually being 80mVpp



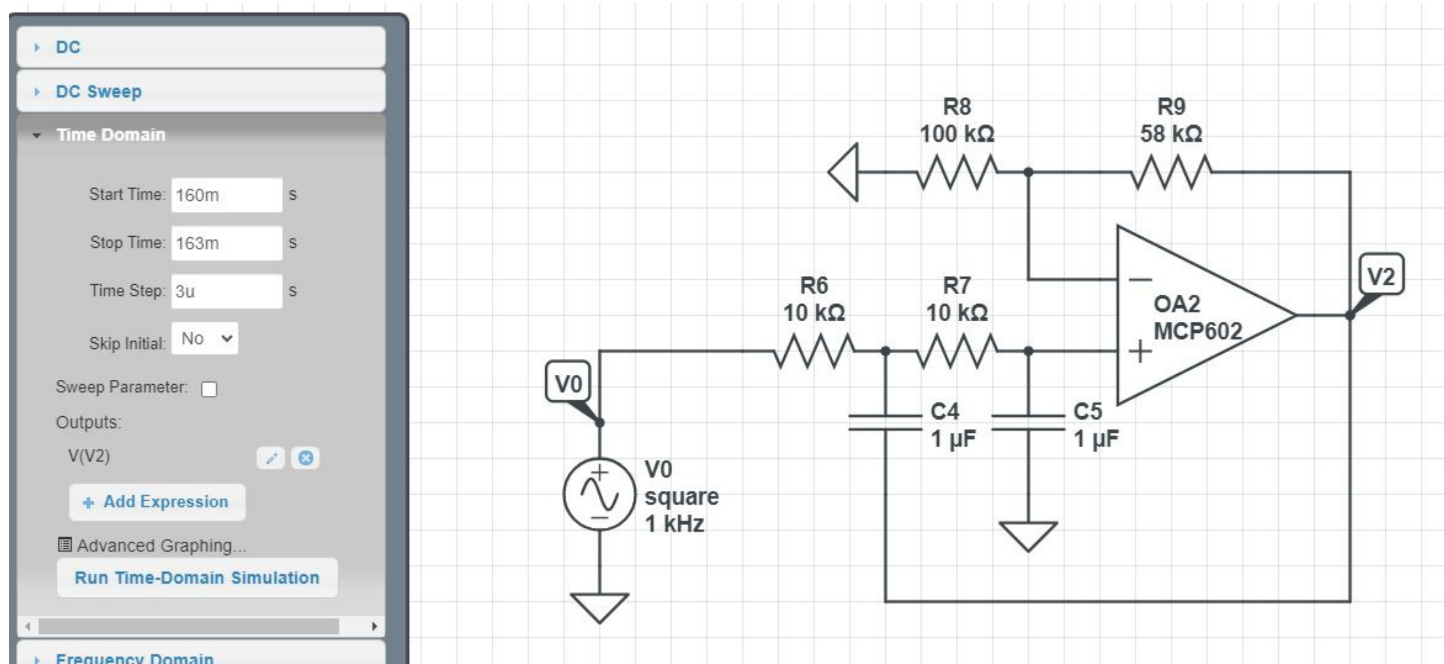
Time-Domain Simulation: The RC filter passes the DC term (average voltage is 1.65V)
The ripple has been reduced from 3.3Vpp to 80mVpp

If you apply the RC filter to the output of the PWM signal, the output should look like this:



Output of the PWM & RC Low-Pass Filter.
The noise on the signal is due the PWM signals at 1kHz getting through the filter.

Active 2nd-Order Low-Pass Filter: A better filter would be a 2nd-order Butterworth low-pass filter:



2nd-order Butterworth low-pass filter with corner at 100 rad/sec V0 represents the PWM output of a Pi-Pico

The magnitude of the poles (aka the corner frequency) is set by R5*C4

$$\frac{1}{R_5 C_4} = 100$$

The angle of the poles is set by R8 and R9

$$k = 1 + \frac{R_9}{R_8}$$

$$3 - k = 2\cos\theta$$

The above circuit gives poles at 100 with an angle of 45 degrees (a 2nd-order Butterworth low-pass filter).

The gain of this filter is

$$y = \left(\frac{100^2 \cdot k}{\left(s+100\angle 45^0\right)\left(s+100\angle -45^0\right)} \right) x$$

or

$$y = k\left(\frac{100^2}{s^2+141s+100^2} \right) x$$

The DC gain is 1.58 (k), meaning the DC term at x (0..3.3V) will be (0..5.21V) at y.

The ripple at x is 3.3Vpp

The ripple at y will be approximately

$$y \approx k\left(\frac{100^2}{s^2+141s+100^2}\right)_{s=j6280} \cdot 3.3V_{pp}$$

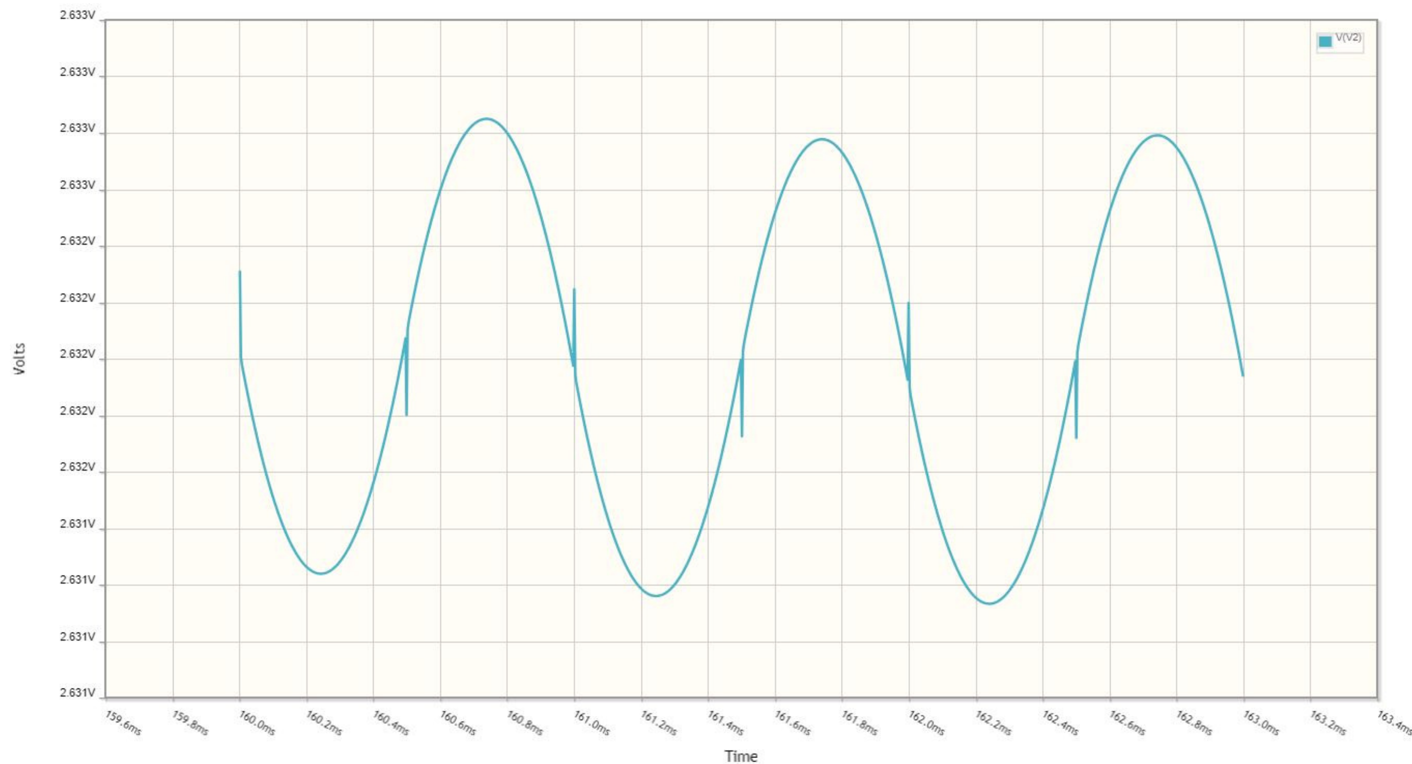
$$|y| \approx 0.0013$$

Meaning y(t) should have

- A DC term of 2.61V (1.58 * 50% of 3.3V)
- An AC term of 1.3mVpp

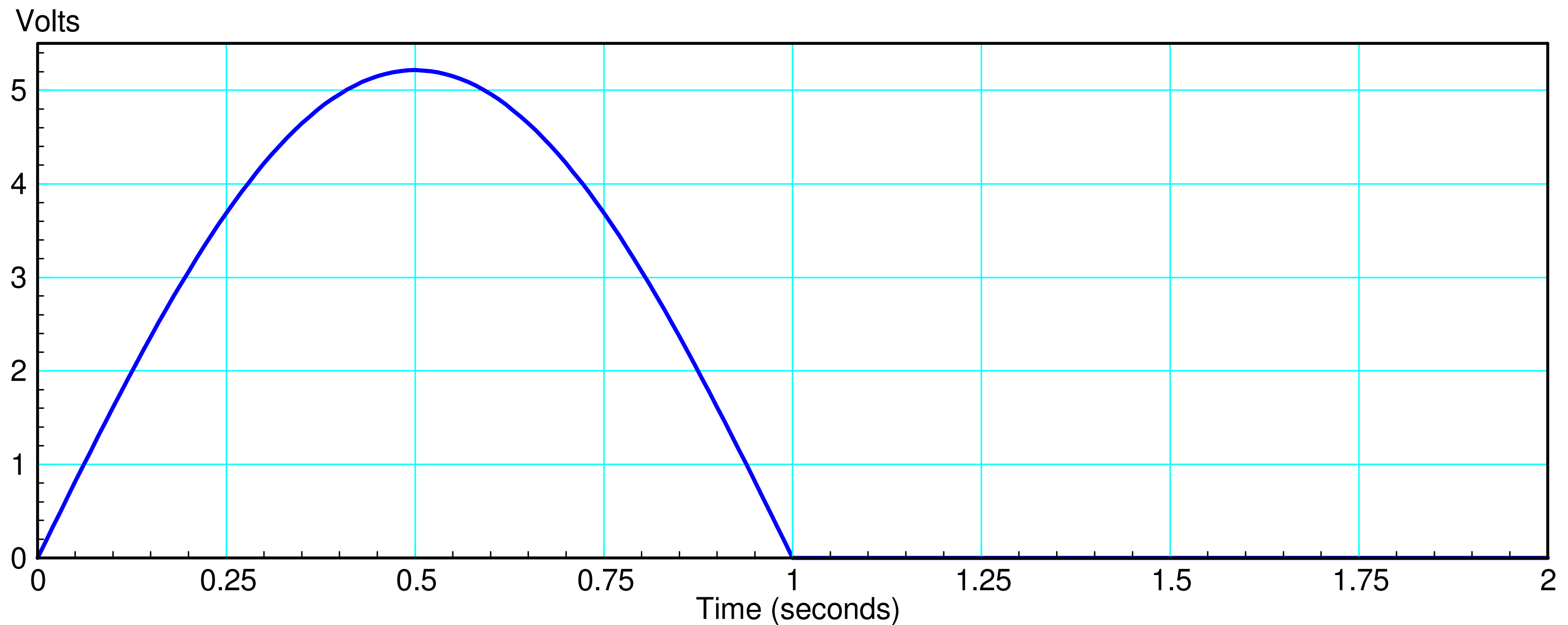
In CircuitLab, you can check the actual result is

- DC term = 2.632V (as expected)
- AC term = 1.6mVpp (slightly larger than calculated)



Output of the Butterworth Low-Pass Filter: A DC term with 1.6mVpp ripple

The output of the PWM signal plus filter looks much smoother than the RC filter.



Output of PWM signal & a 2nd-order Active Low-Pass Filter
Less noise at 1kHz gets through the filter, producing a smoother output

D/A Converter: MCP4921

D/A: Digital to Analog converter

- Outputs 0V to Vdd analog
  - 2.7V < Vdd < 5.5V
- 12-bit D/A (meaning 4096 steps)
- SPI data interface
- $2.81 each (Digikey as of June 7, 2024)

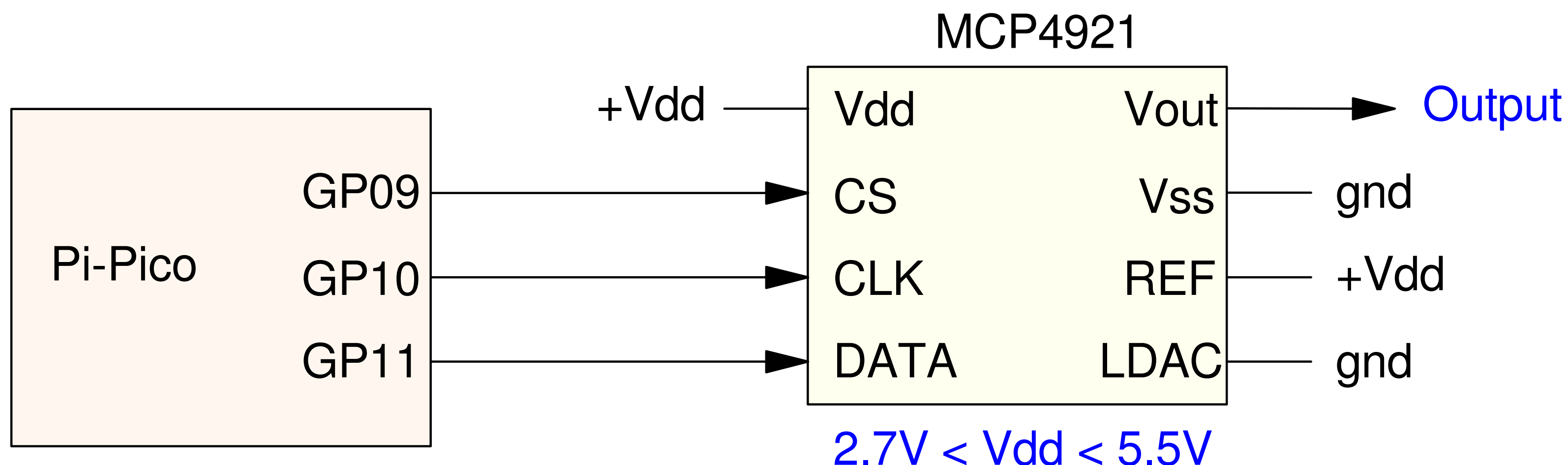
Like the A/D, the D/A's voltage is proportional to the number written to it:

$$D/A_Out = \left(\frac{\#}{4095}\right) \cdot V_{dd}$$

Vdd can be anything from 2.7V to 5.5V

- 5.5V doesn't hurt a Pi-Pico
- No data is sent back to the Pi-Pico

The connections for a MCP4921 to a Pi-Pico are:

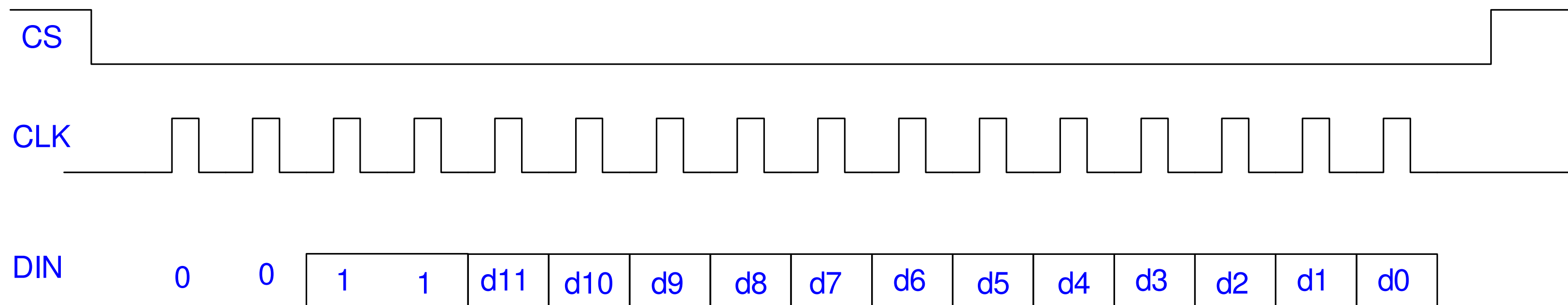


Three output pins are needed to drive the MCP4921.
Any pins can be used for bit-banging, the SPI port is needed if using the SPI module in machine

To send a 12-bit number,

- Pad the first four bits of the message with binary 0011
- Then, pull chip-select low (CS = 0)
- Clock in each bit, starting with the most significant bit.
- Once all 16 bits have been sent, pull CS high.

At that point, a voltage should appear on Vout



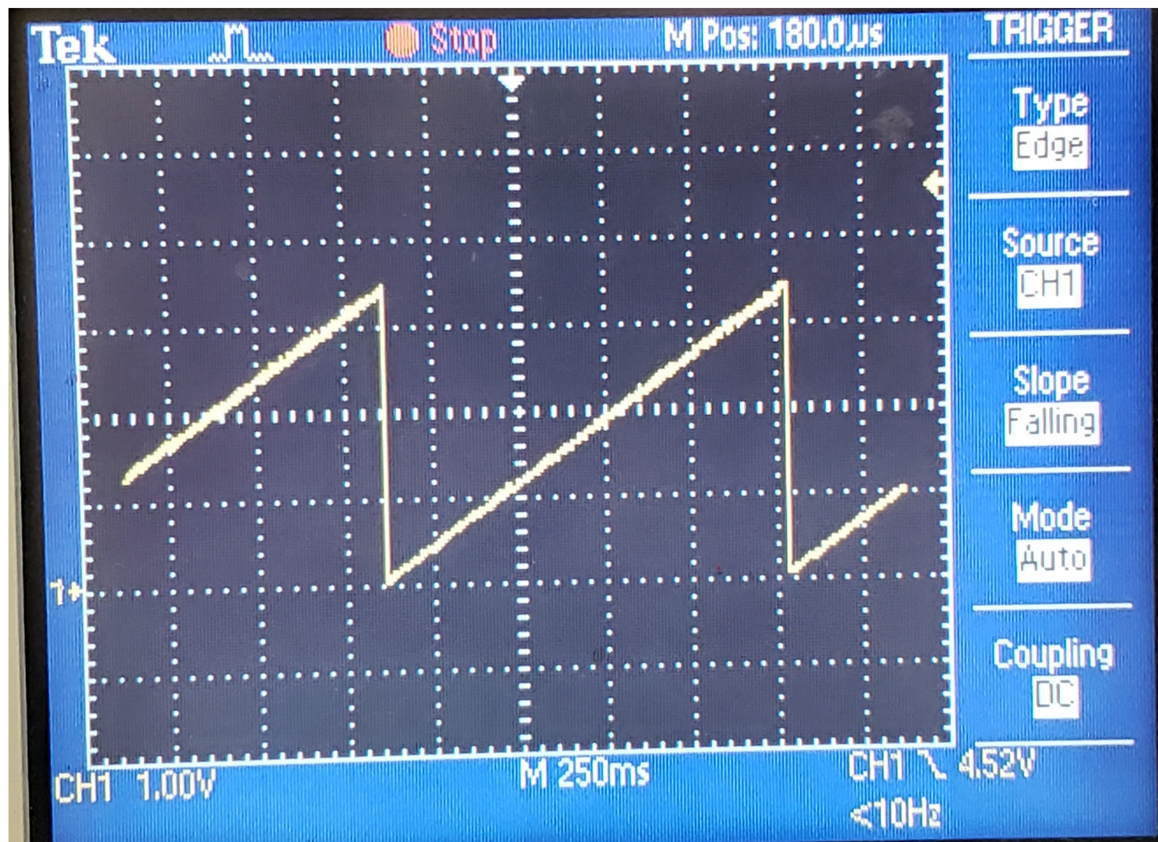
Timing diagram for a MCP4921

You can implement this in software with a bit-banging routine:

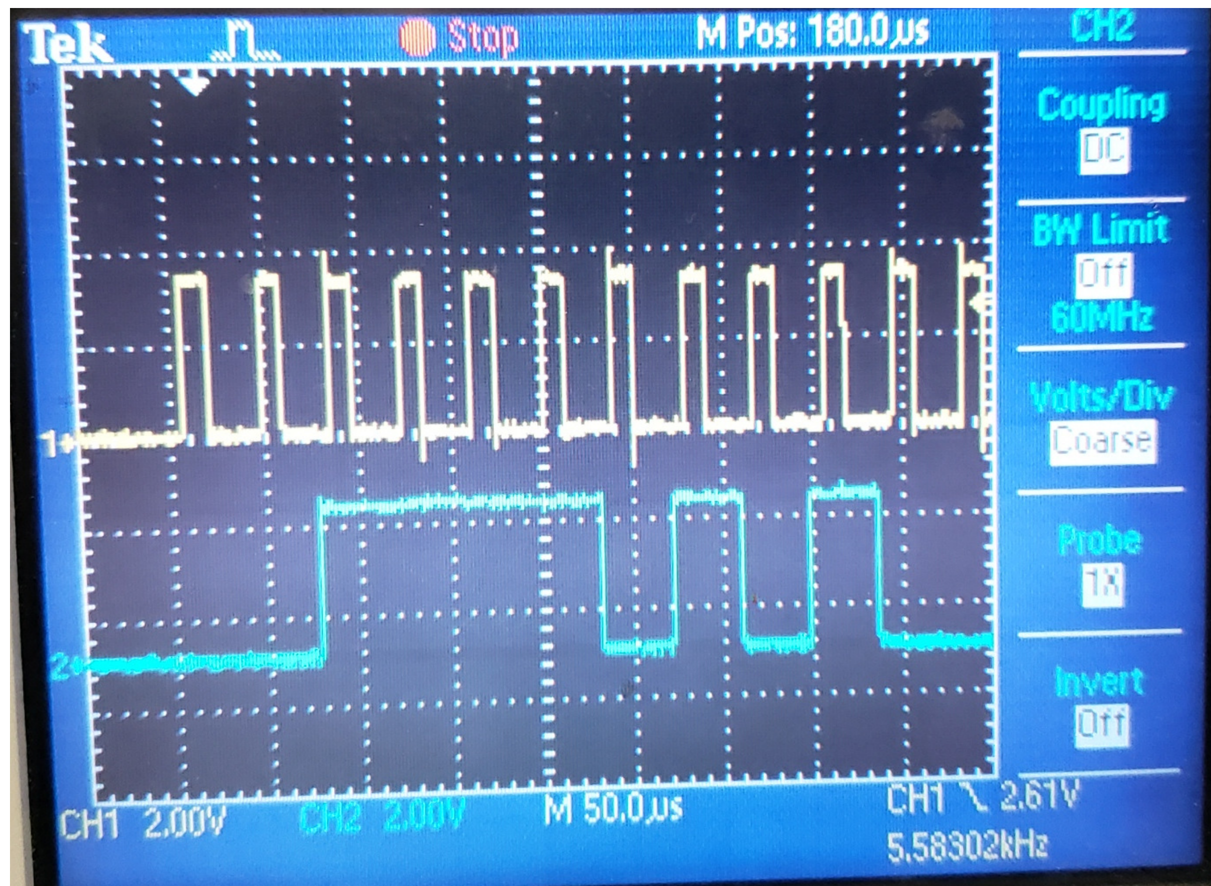
```
from machine import Pin
from time import sleep_ms, sleep_us, ticks_us

CLK  = Pin(10, Pin.OUT)
DATA = Pin(11, Pin.OUT)
CS   = Pin(9, Pin.OUT)

def MCP4921(X):
    X = X & 0x0FFF
    X = X | 0x3000

    CS.value(0)
    CLK.value(0)
    sleep_us(1)
    for i in range(0,16):
        if(X & (0x8000 >> i)):
            DATA.value(1)
        else:
            DATA.value(0)
        CLK.value(1)
        sleep_us(1)
        CLK.value(0)
        sleep_us(1)
    CS.value(1)
    DATA.value(0)
    sleep_ms(1)

x = 0
while(1):
    x = (x + 10) & 0x0FFF
    MCP4921(x)
    sleep_ms(1)
```

Counting results in a sawtooth wave

- Count goes from 0 to 4095
- Voltage goes from 0V to 3.3V (Vdd)



If you look at the CLK and DATA lines on an oscilloscope, you can see the data being clocked out as well:



CLK (yellow) and DATA (blue) lines going to the MCP4921 D/A chip

Using the SPI function is better

- 1700us with bit-banging
- 120us with SPI

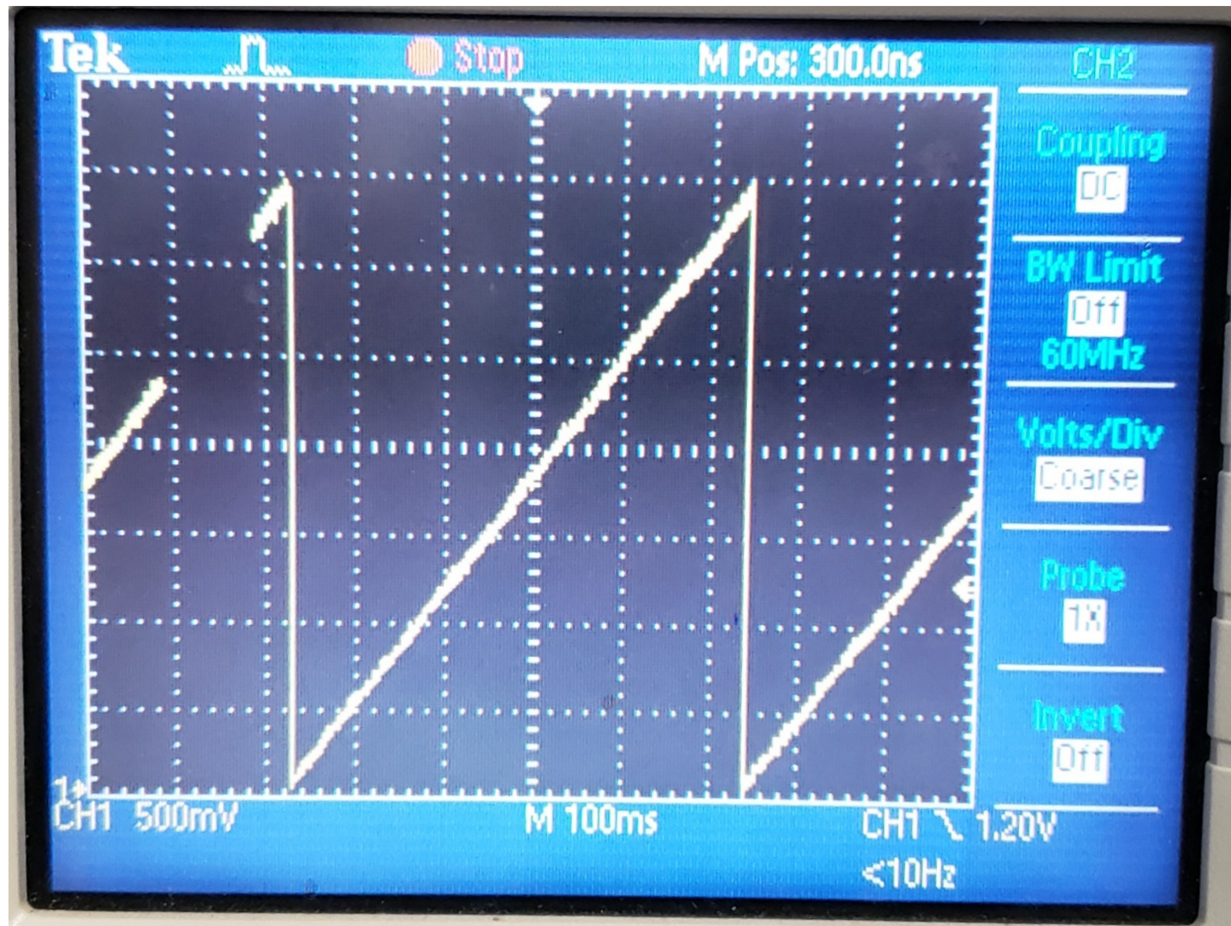
Also simplifies the code

```
from machine import Pin, SPI
from time import sleep_ms, sleep_us,
ticks_us

CS   = Pin(9, Pin.OUT)

spi = SPI(1, baudrate=10_000_000,
polarity=0, phase=1, bits=8, sck=10,
mosi=11, miso=12)


def MCP4921(X):
    X = X & 0x0FFF
    X = X | 0x3000
    Y = bytearray()
    Y.append(X >> 8)
    Y.append(X & 0xFF)
    CS.value(0)
    spi.write(Y)
    CS.value(1)

x = 0
while(1):
    x = (x + 10) & 0x0FFF
    MCP4921(x)
    sleep_ms(1)
```

By using the SPI funciton, data is sent at 10MHz

- 14x faster than bit-banging
- Oscilloscope traces show limitations of a 60MHz scope.

CLK and DATA lines as seen on a 60MHz oscilloscope

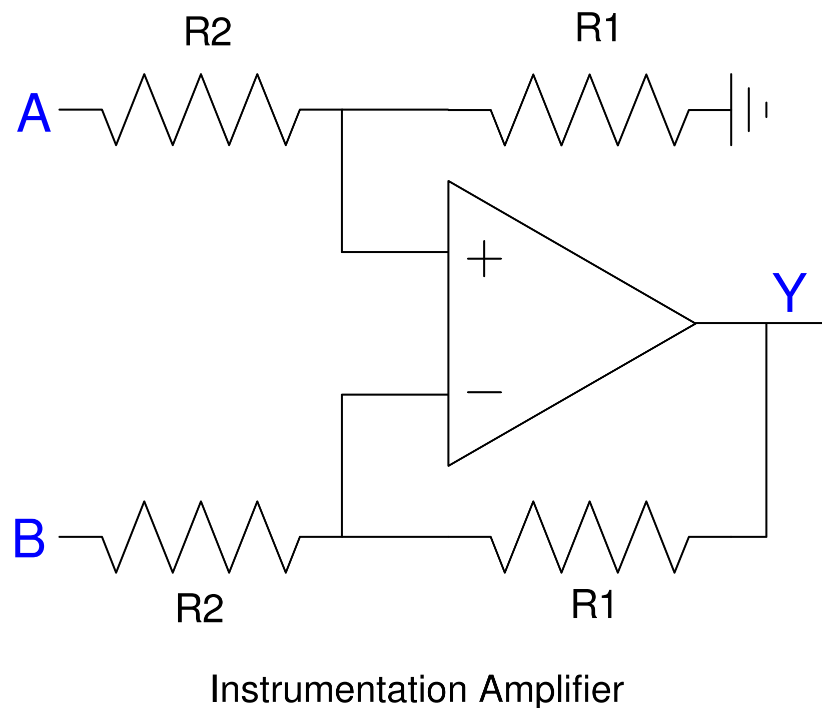


Output when the SPI bus is clocked at 10MHz.
The D/A is working at this speed: the output is a sawtooth wave when counting

Output -10V to +10V

Finally, if you want to output something other than 0V to 3.3V, an instrumentation amplifier can be added to the output. The gain of the following circuit is

$$Y = \left(\frac{R_1}{R_2}\right)(A - B)$$



Instrumentation Amplifier

If you want the output to go from -10V to +10V and x represents the D/A output

$$x = 0V..3.3V \qquad \text{D/A output}$$

then

$$y = 6.06x - 10$$

Rewriting this in the form of the previous equation

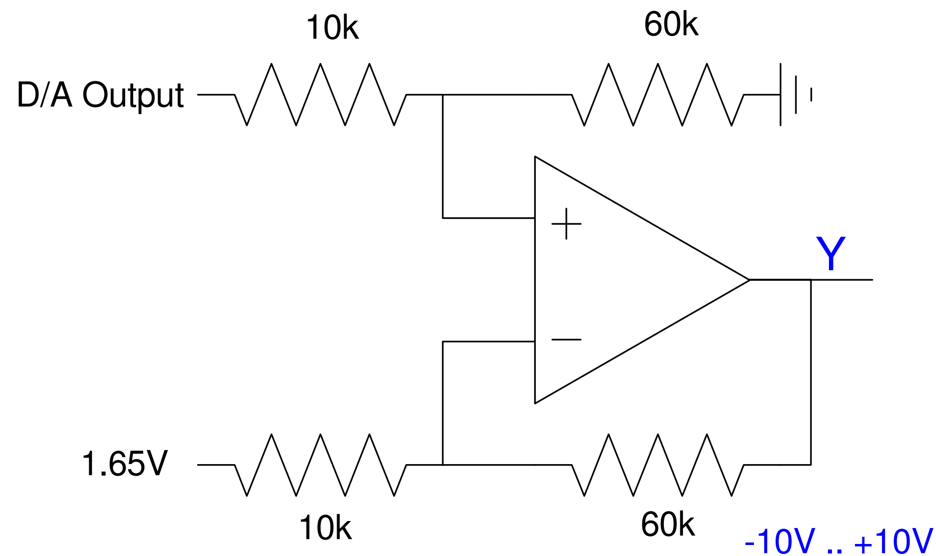
$$y = 6.06(x - 1.65)$$

Let

- A = x
- B = 1.65V
- (R1/R2) = 6.06

then adding an instrumentation amplifier to the output of the D/A will produce

- -10V when you write 0x000 to the D/A
- +10V when you write 0xFFF to the D/A



Summary:

With a little code and some hardware, it isn't hard to

- Read analog voltages or
- Output analog voltages

When using a chip with an SPI input, you can use bit-banging to drive this device. Bit-banging has the advantage that you have complete control over how data is sent - but it tends to be slow. Using the built-in SPI port allows 10MHz or more data transfers, speeding up the process considerable (it also simplifies the code.)