DIGITAL TO ANALOG CONVERTERS (DACS)

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Digital to Analog Converter (DAC)

- In general, a DAC will map a (binary) number *D* to an output analog signal *A*

$$A = F(D)$$

- Depending on our application, there are many possible mappings, but for now we'll focus on "linear" conversion, in which an *n*-bit integer *D* produces a range of voltages between A_{min} and A_{max}, given by

$$A = A_{min} + \left(A_{max} - A_{min}\right)\frac{D}{2^n}$$

Bipolar DACs

- In all of our previous examples, if we replace *GND* with V_{min} and V_{ref} with V_{max}, then

$$V_{out} = V_{ref}\frac{D}{2^n} \rightarrow V_{min} + \left(V_{max} - V_{min}\right)\frac{D}{2^n}$$

- If V_{min}=-V_0 and V_{max} = +V_0

$$V_{out} = -V_0 + 2V_0\frac{D}{2^n}; \quad \mathrm{D}=2^{n-1} \rightarrow V_{out} = 0$$

- The natural encoding is "offset binary"
  - Some chips accept different encodings and convert them internally

(go to demo)

Commercial DACs range from...

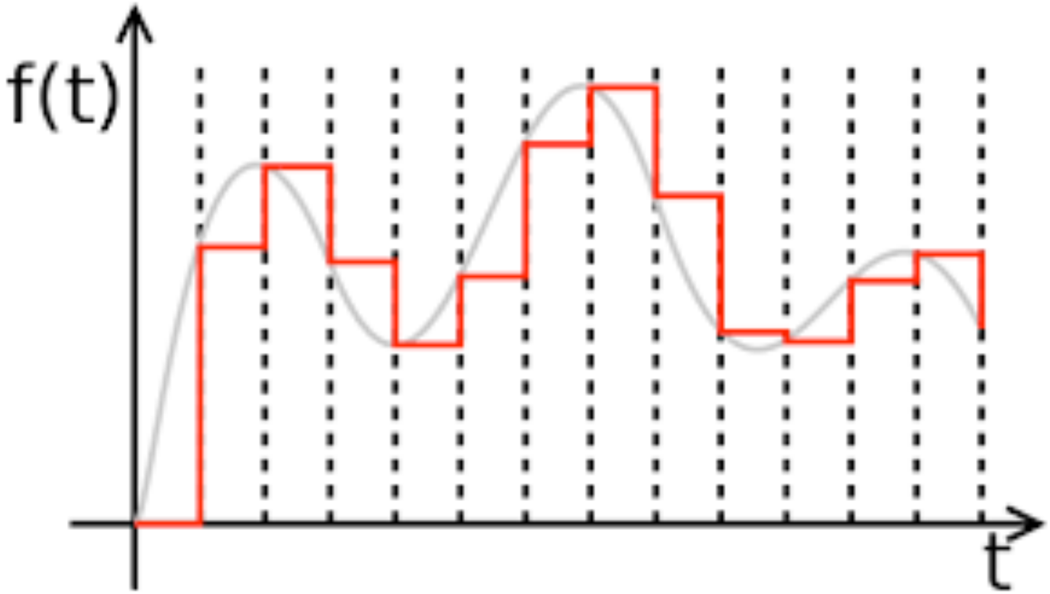
- Microchip MCP4921-E/P
  - Resolution: 12 bit
  - Data Input: serial
  - Settling time: 4.5 μs
  - Max rate: ~100 KHz
  - Price: 1@$2.08/each, 100@$1.49/each

to...

- TI DAC39J82
  - Channels: 2
  - Input: parallel
  - Resolution: 16-bit
  - Rate: 2 Gs/second
  - Price: 1000@$87.50/each

Finite Sampling

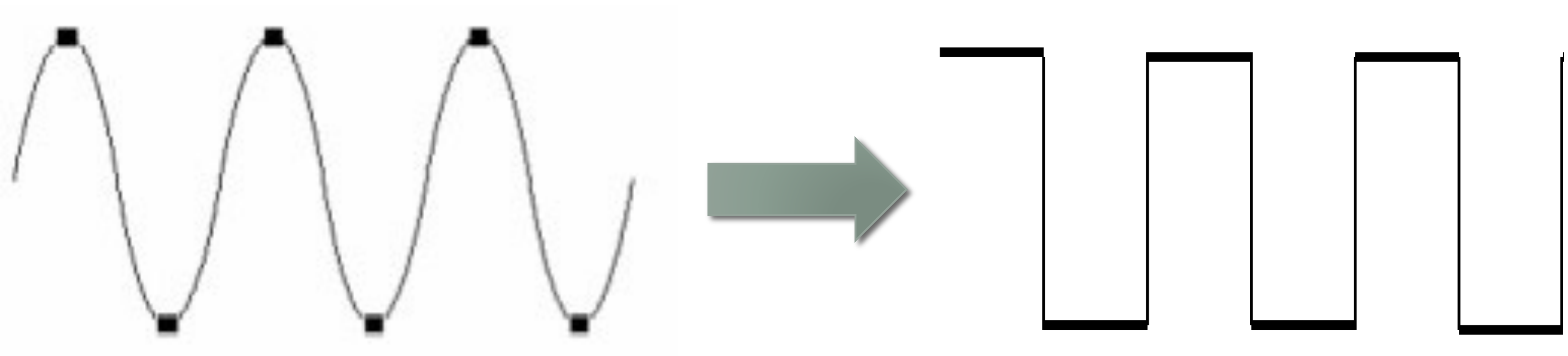
- A DAC produces an approximation of a waveform by outputing samples at discreet intervals



- There are limits to this approximation

Nyquist's Theorem

- We need a sampling frequency of *2f* to reproduce a frequency of *f*

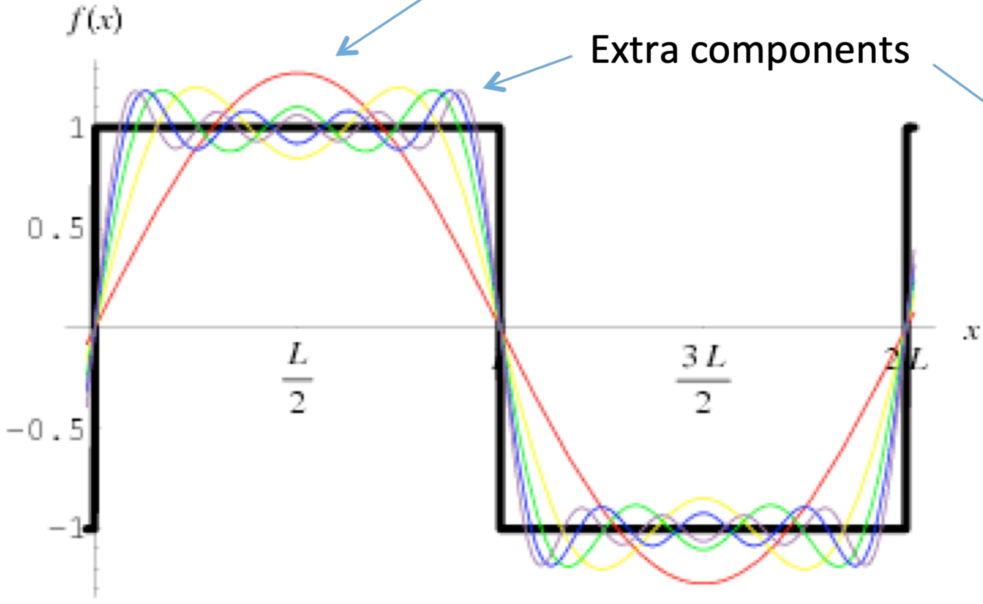


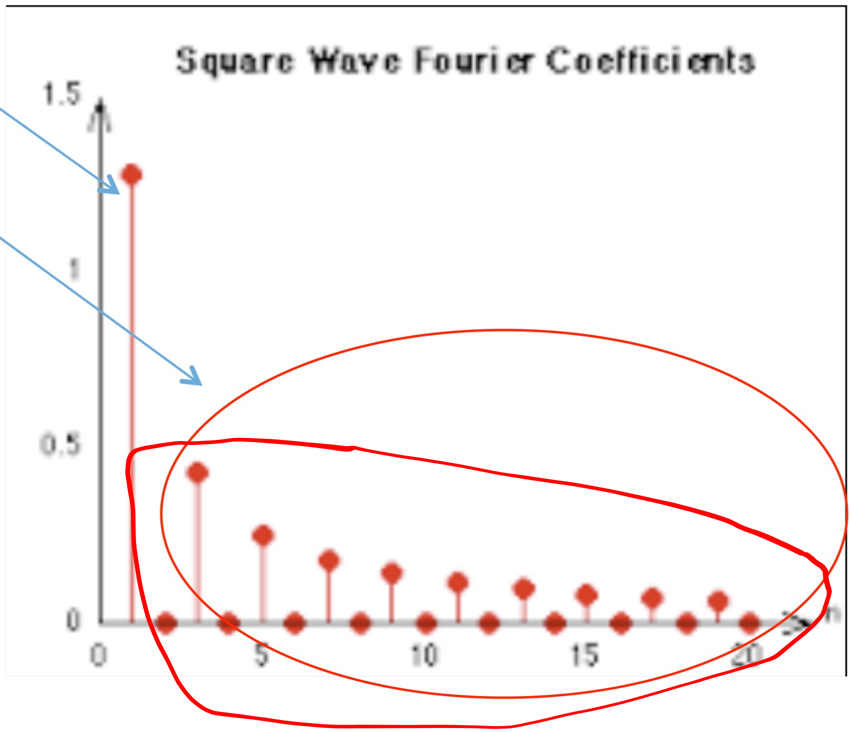
- If this the digital output is rendered perfectly, lots of high frequency harmonics are introduced.

Spurious Frequency Components

What we started with

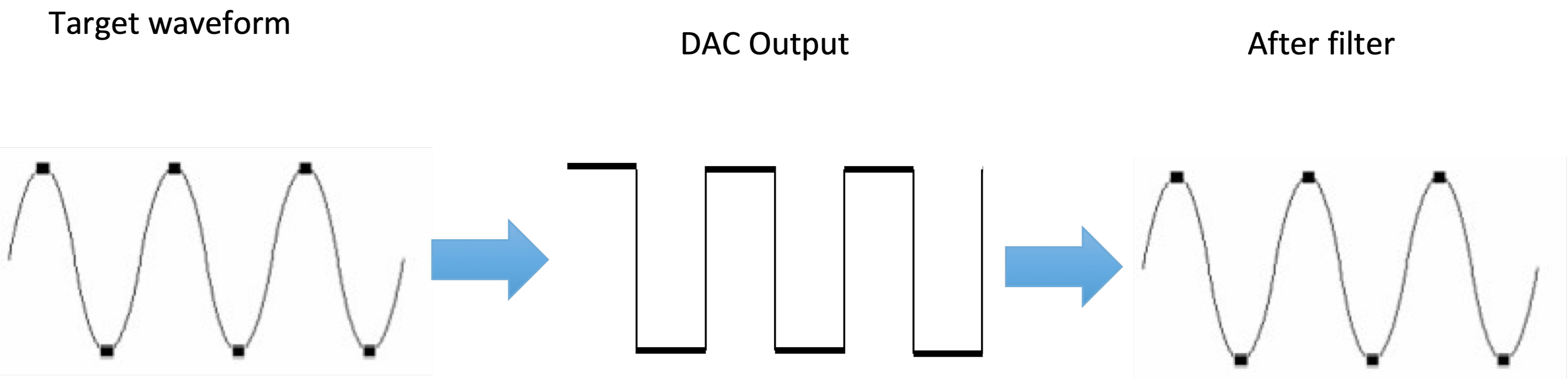
Extra components





Solution: Filtering

- In general, the output of a DAC should be filtered with a cutoff frequency of half the sampling frequency



Dynamic Range

- The dynamic range of the encoding is the largest value over the the least value. If we assume that noise is less than the LSB
  - For unipolar signals *n*-bits has a DR of

$$DR = 2^n$$

  - For bi-polar signals, we lose one bit for sign, so

$$DR = 2^{n-1}$$

- This is often expressed in decibels

$$dB = 10\log_{10}\left(\frac{P_{max}}{P_{min}}\right) = 10\log_{10}\left(\frac{A^2_{max}}{A^2_{min}}\right) = 20\log_{10}\left(DR\right)$$

Example: Audio Encoding

- The human ear is an amazing device
  - Bandwidth 20Hz-20kHz = 3 orders of magnitude
    - Required at least 40 kHz sampling frequency
  - Dynamic Range: 0dB (threshold of hearing) to 120 dB (threshold of pain)
    - 12 orders of magnitude in power
    - 6 orders of magnitude in amplitude
      - 1,000,000 ~ 2^{20}
      - At least 21-bit encoding (20 bit bipolar)
- "CD Quality"
  - 44.1 kHz rate
    - 22.05 kHz bandwidth (> human ear)*
  - 16-bit linear encoding
  - No compression!

For sound:

Threshold of hearing

$$0 \text{ dB} = 10^{-12} \text{ W/m}^2$$

$$120 \text{ dB} = 1 \text{ W/m}^2$$

Threshold of pain

*There's a little more to the story

16-bit Dynamic Range

- 16 bits can encode -2^{15}->$2^{15}-1$ = -32768->32767
- dB range

$$dB = 20\log_{10}(32767)$$

$$= 90$$

- Examples of 90 dB
  - Motorcycle at 25 feet
  - Lawnmower up close
- If your music is that loud, the LSB is at the limit of human hearing
- 90 dB Signal-to-noise ratio (SNR) is about the limit of top end audio gear
  - i.e. if you buy a $3K power amp and turn it all the way up, you might hit the limit of 16-bit audio
- For comparison, the best vinyl DR is about 70 dB.
- We'll discuss audio recording more shortly

Conversion from Analog to Digital

- Analog to digital conversion is just Digital to analog conversion in reverse.
  - Map an analog input to a digital (binary) number

$$A = F(D) \rightarrow D = F'(A)$$

  - For a linear ADC

$$A = A_{min} + \left(A_{max} - A_{min}\right)\frac{D}{2^n} \rightarrow D = \frac{\left(A - A_{min}\right)}{\left(A_{max} - A_{min}\right)}2^n$$

  - And for a unipolar ADC

$$A = V_{ref}\frac{D}{2^n} \rightarrow D = \frac{A}{V_{ref}}2^n$$

Commercial ADCs

- Low price example: Texas Instruments PCM1808PWR

  - Designed for audio encoding
    - 2-channel (i.e. stereo)
    - 24-bit resolution
    - 96 kHz sample rate
    - Serial interface
- $1.47/ea

State of the Art ADC Example

- Analog Devices AD9217BBPZ-10G

  - Optimized for high speed data acquisition
    - Single channel
    - 12-bit
    - 10.25 GHz digitization rate

Commercial DAC/ADC Example

- LabJack T7-Pro

  - 2 12-bit ADC inputs (0-5V)
  - 2 12-bit DAC outputs (0-5V)
  - 23 digital I/O
  - Up to 10 internal counters/timers
  - Wi/fi capable
  - $850

(go to demo)

Accessing the ADC and DAC in the SoundCard

- You can access the soundcard on your device by using the Ipython.display.Audio method and the sounddevice package

(Go to Demo)