Electronics & Signal Processing for Experimental Rigs

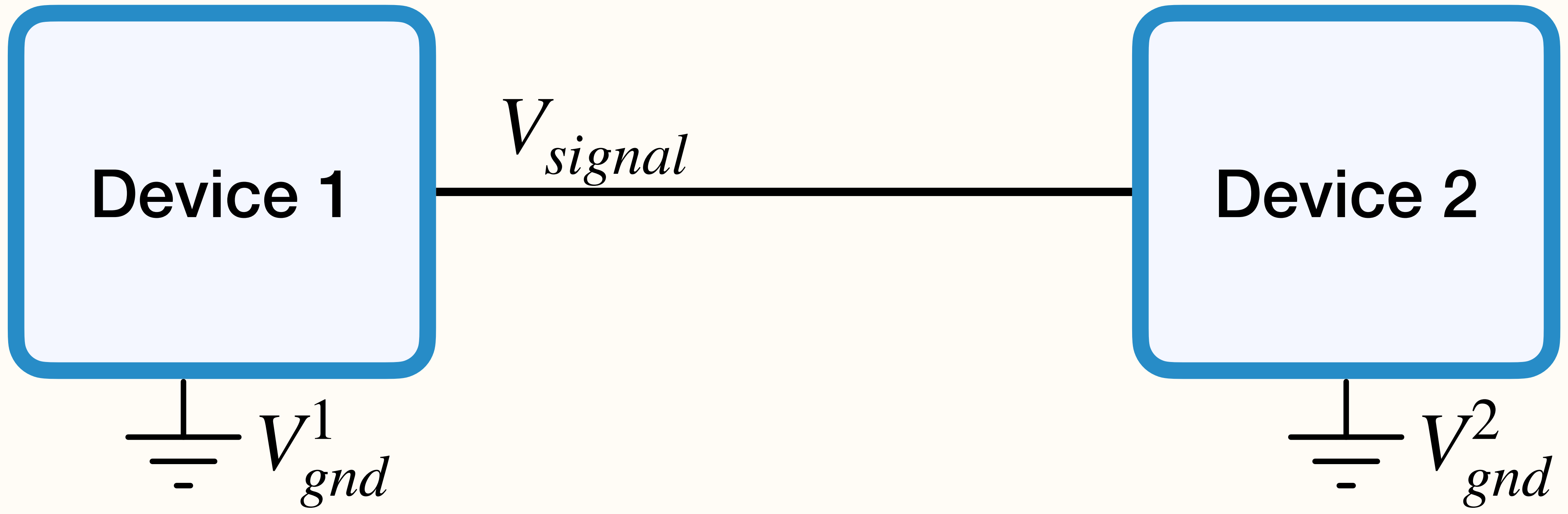
Day 3: Digitization & Signal Processing

Ofer Mazor and Pavel Gorelik

Lecture 3 Outline

- **Noise cont'd:**
  - Ground Noise
  - Differential Amplification
- **Frequency domain (Fourier transform, Power spectrum)**
- **Digitization**
  - Bit resolution/noise; dynamic range
  - Sampling rate / Nyquist
  - Aliasing
- **Filtering**
  - Types: H/W vs S/W; HP, LP, BP, Notch
  - Anti-alias LP filter
- **Timing** (clocks, drift, strategies for syncing)
  - Have a single master clock
  - Avoid software timing
- **O-Scope advanced features**
  - triggering
  - cursors, measuring?

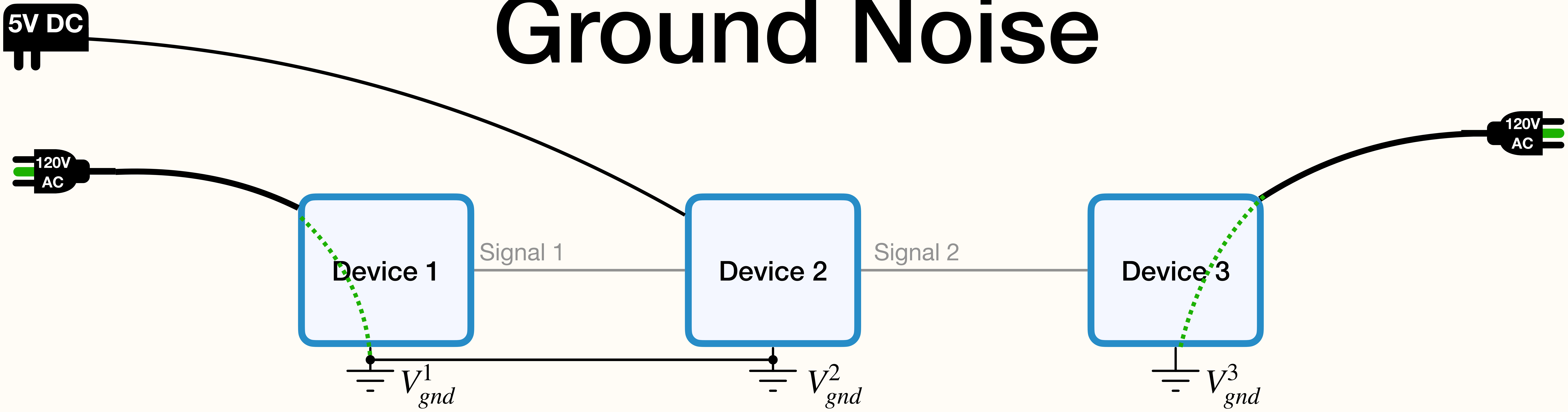
Ground Noise



Why is ground noise a problem?

- Voltage signals require a reference voltage (typically ground)
- So if $V^1_{gnd} \neq V^2_{gnd}$, signal corruption will result (even if V_{signal} is noise free)
- But isn't V_{gnd} *always* 0 V ?

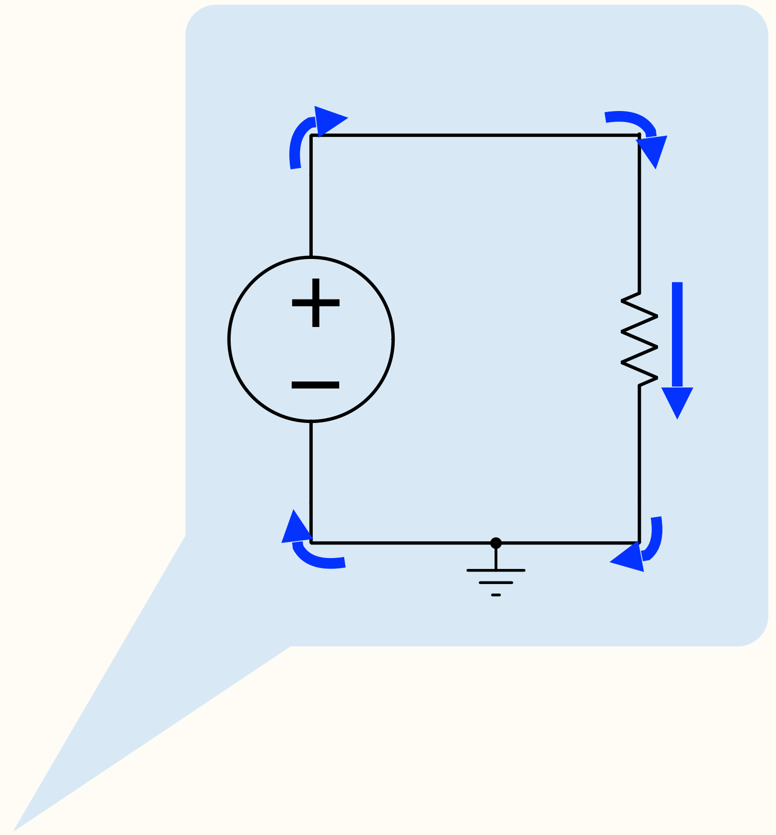
Ground Noise



What is “Ground” anyway?

Multiple purposes that sometimes conflict:

- Shared 0 V reference
- Low resistance path to the earth (i.e., “ground”)
- Sometimes the return path for current (intentionally or not)
  - E.g., a DC power supply outputs current on a “V+” power line, which returns on a “0 V” line



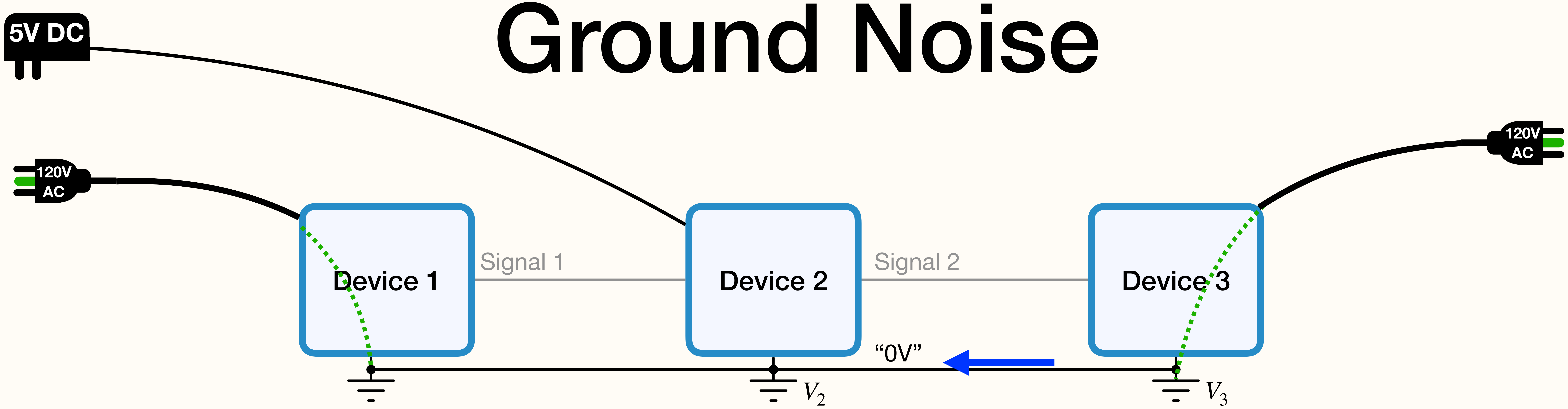
Ground Noise

Sources for ground noise (DC offsets & dynamics)

- Different sources of ground voltage
  - The ground pins of wall outlets can be at different potentials
  - We've seen static >300mV difference between different "grounds" on a rig
  - Digital devices often inject noise onto their ground lines

    (high frequency spikes and ripples from transistors switching)
- Current flowing through ground lines

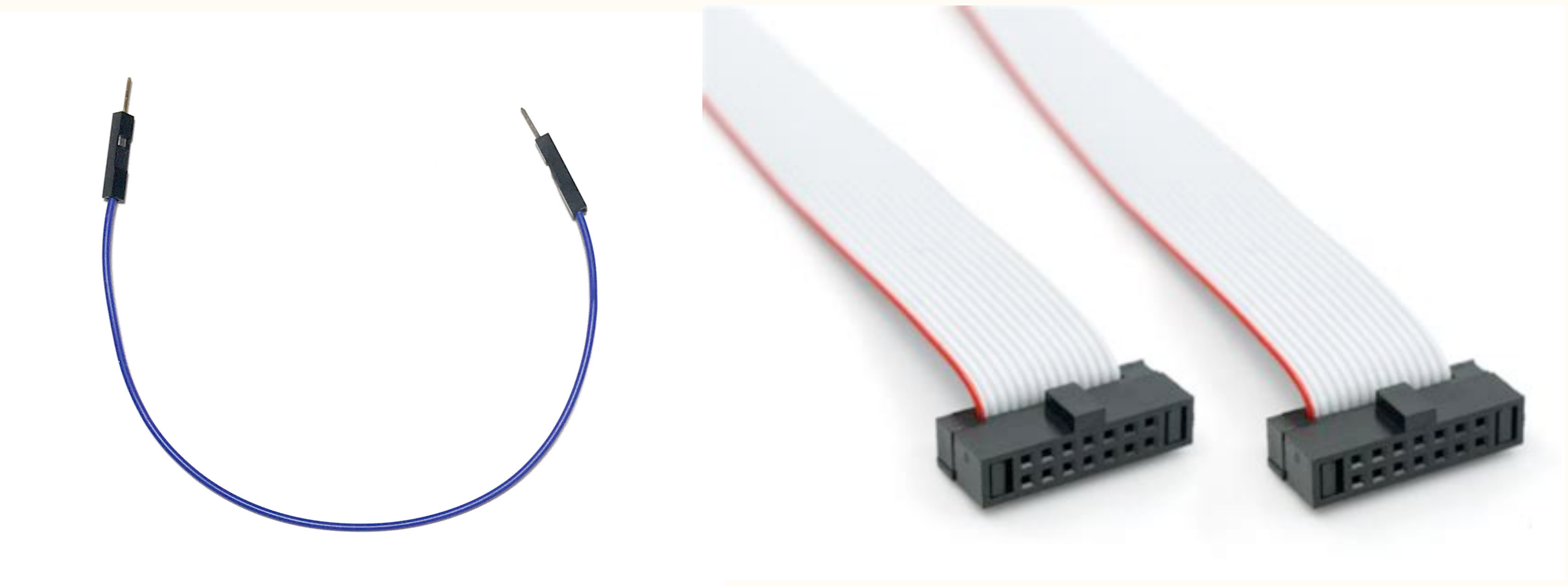
Ground Noise



Sources for ground noise (DC offsets & dynamics)

- Different sources of ground voltage
- Current flowing through ground lines
  - Small currents may flow between different ground points
  - Possible reasons: EM pickup; Magnetic field pickup; Power return path
  - Ohm's Law: $V_3 - V_2 = IR_{wire}$

Ground Noise



Jumper Wire, Ribbon Cable
~0.2 Ω/meter

14 Gauge Grounding Wire
~0.001 Ω/meter

Sources for ground noise (DC offsets & dynamics)

- Different sources of ground voltage
- Current flowing through ground lines
  - Small currents may flow between different ground points
  - Ohm's Law: $V_3 - V_2 = IR_{wire}$

Ground Noise

Grounding issues are hard:

- Interconnectivity: Many circuit elements need a ground connection
- Uncertainty: How is “ground” wired up within rig instruments?
- Conflicting demands:
  - **More ground wires:** to keep all grounds at the same potential
  - **Minimize ground wires:** to avoid (a) ground loops and (b) contamination by “noisy” grounds

Ground Noise

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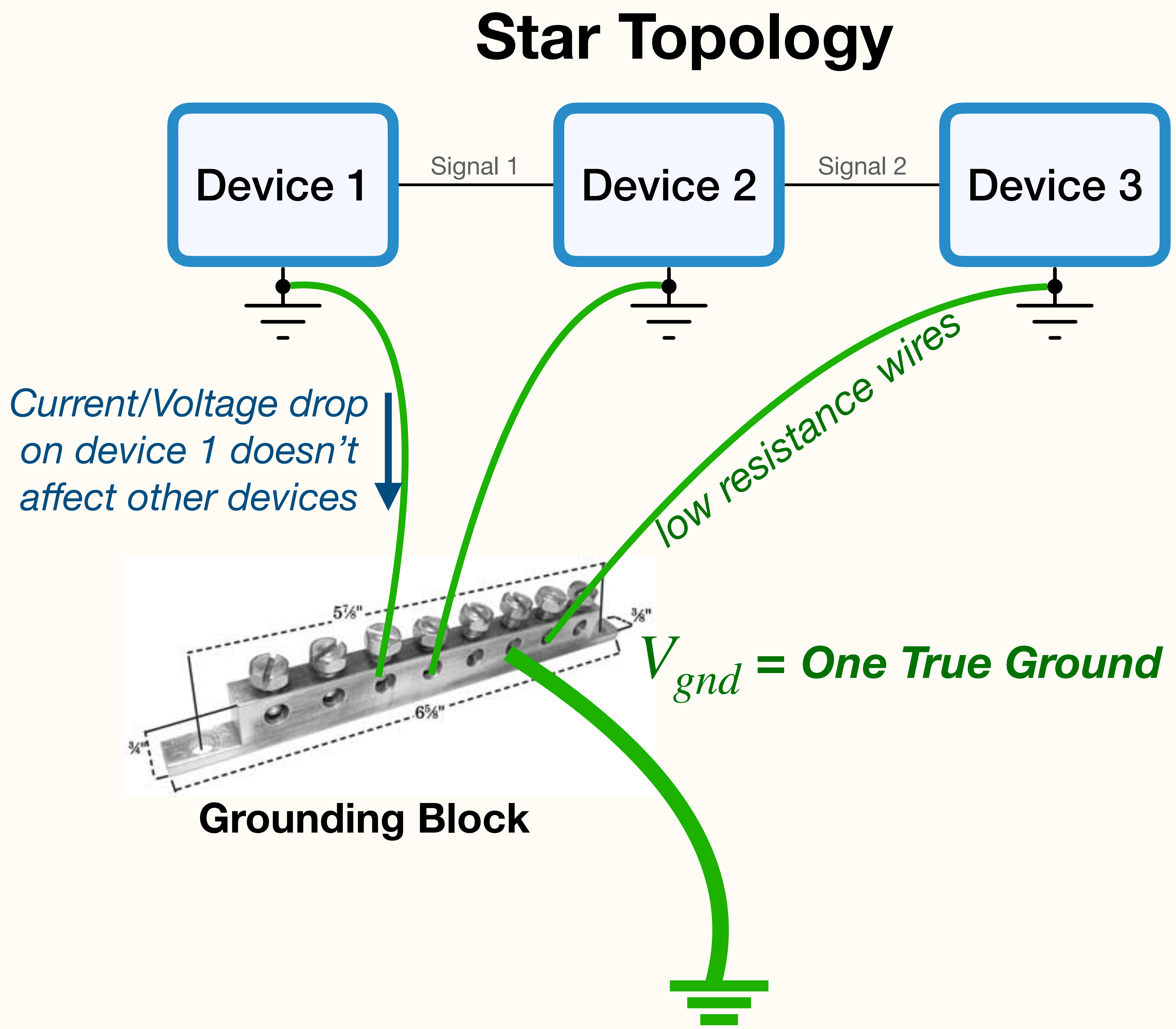
Grounding best practices:

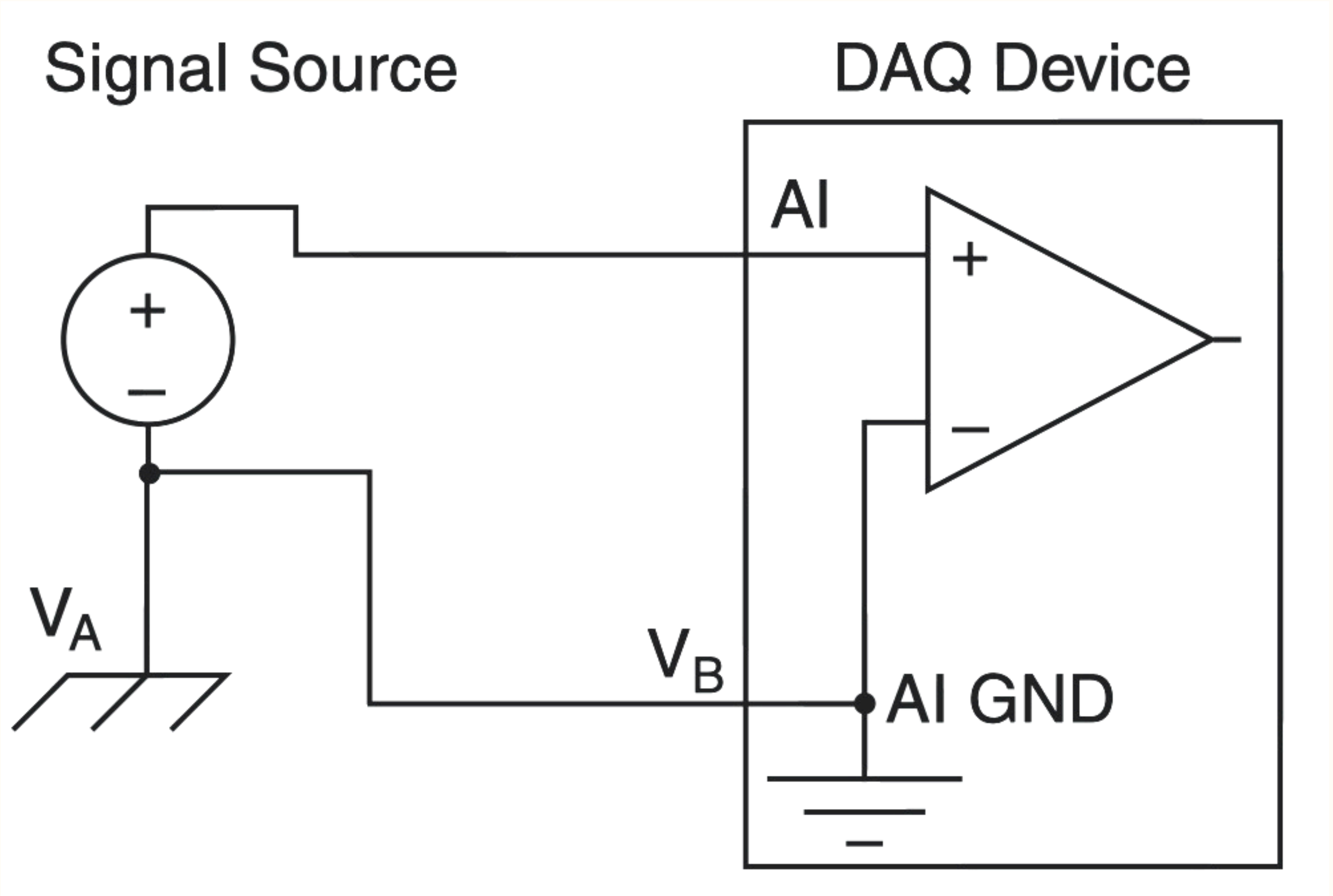
- Use low resistance ground wires & connections
  - don't use thin wires; don't "connect" them by twisting them together
- Grounding blocks / Star topology
  - All components connect directly to "one true ground"
  - Ground current from one device doesn't couple to others
  - Avoids ground loops



Single-Ended vs Differential Amplification

Single-Ended amplification

- Uses “ground” as reference voltage for input & output
- But signal corruption occurs when $V_A \neq V_B$



Single-Ended amplification

From National Instruments X Series User Manual
https://www.ni.com/pdf/manuals/370784k.pdf

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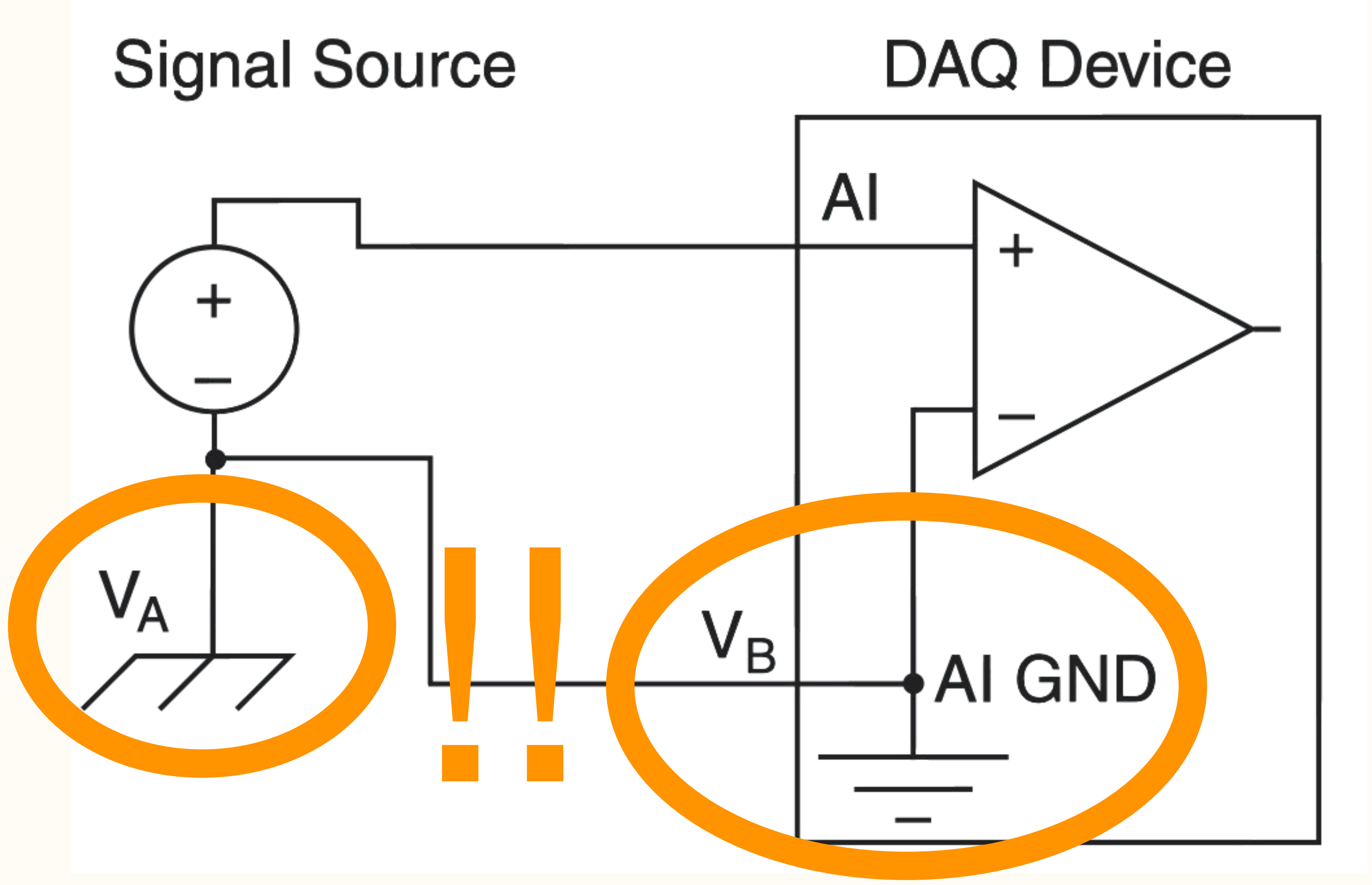

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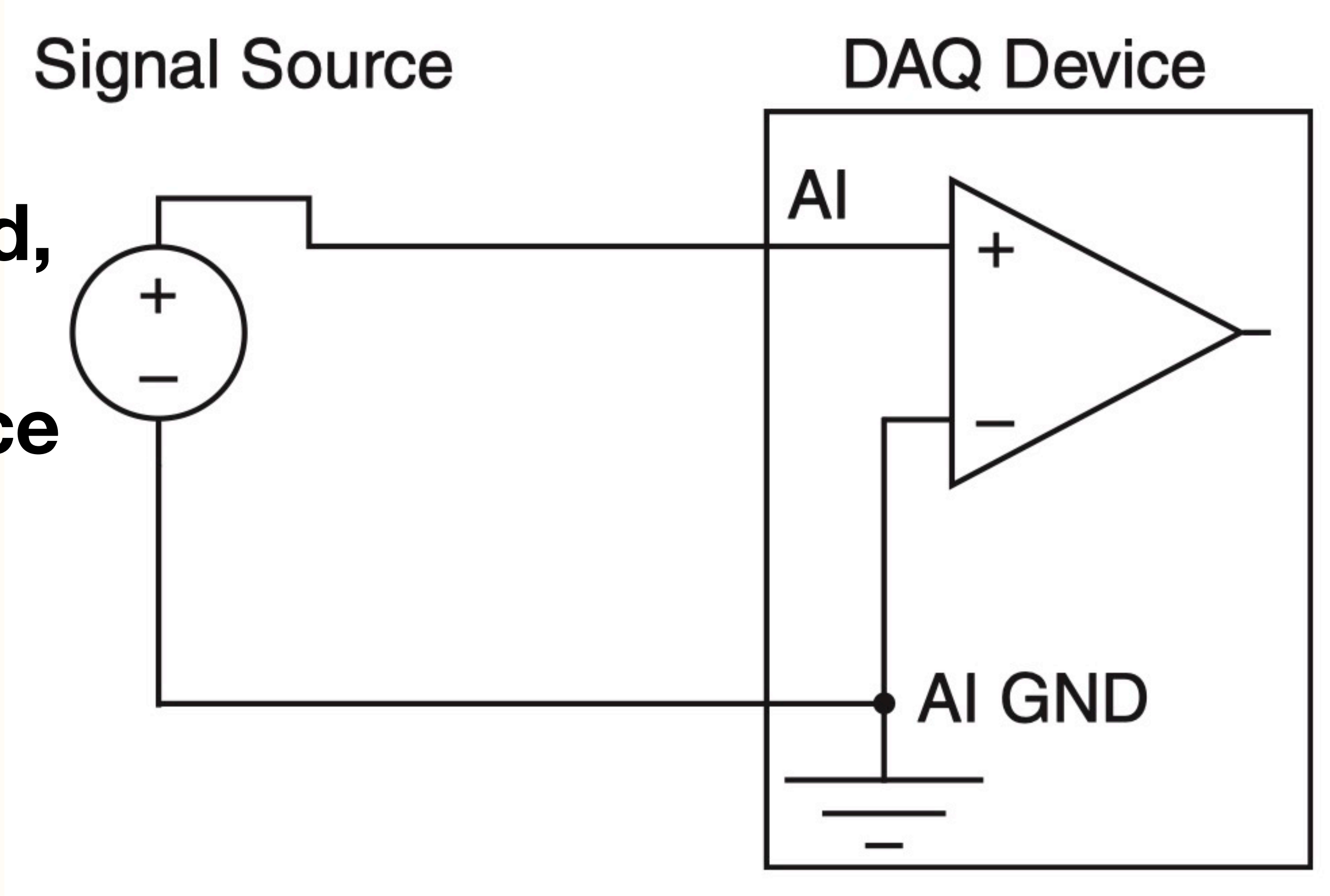
Single-Ended vs Differential Amplification

Single-Ended amplification

- Uses “ground” as reference voltage for input & output
- But signal corruption occurs when $V_A \neq V_B$
- OK to use with ungrounded (“isolated”) signal sources
  - E.g., battery-powered devices

Ungrounded, “isolated” signal source



Single-Ended amplification

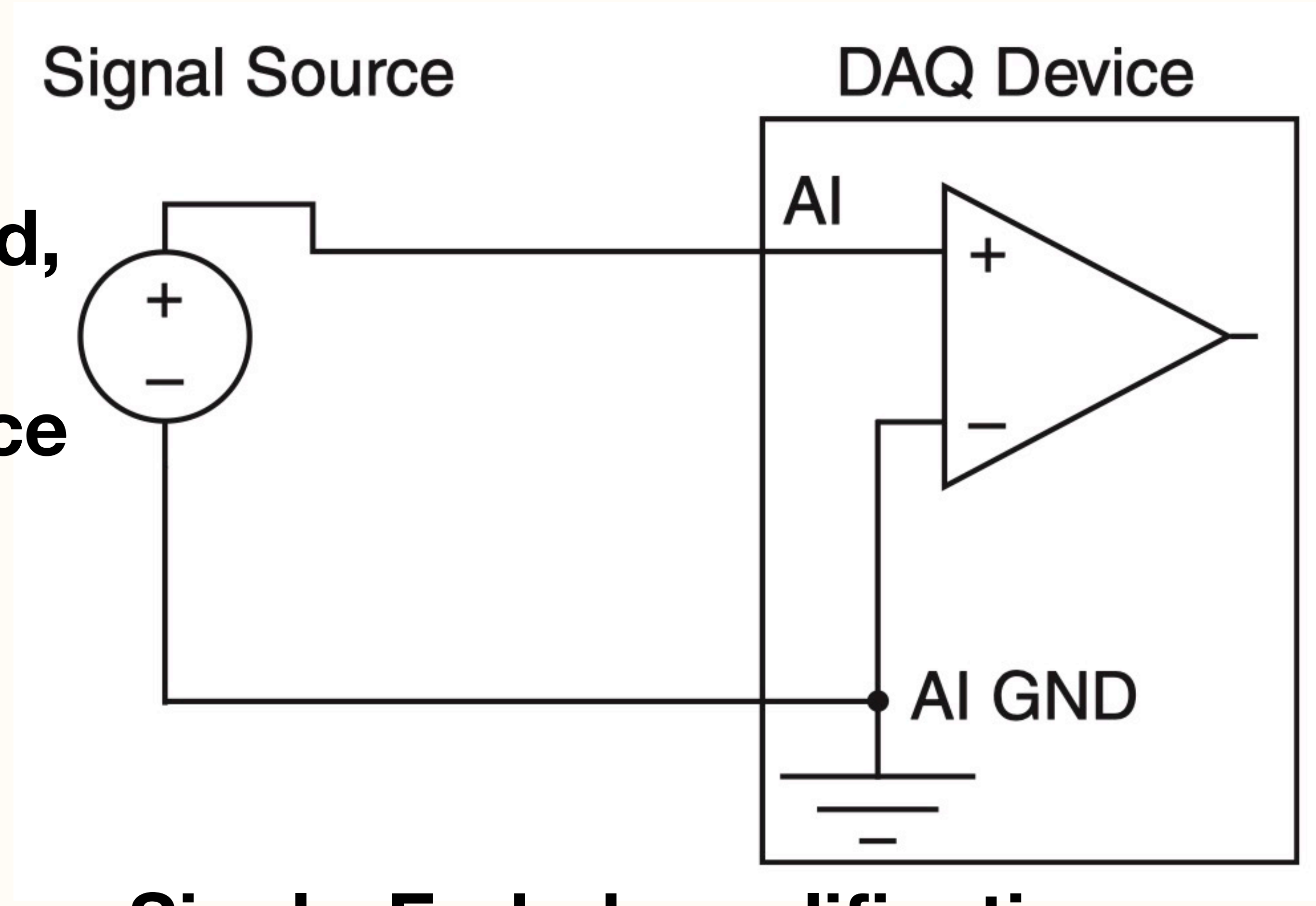
Single-Ended vs Differential Amplification

This may be a setting in your acquisition hardware and/or software

Single-Ended amplification

- Best to use with ungrounded (“isolated”) signal sources
  - E.g., battery-powered devices
- National Instruments call this *Referenced Single-Ended (RSE)*

Ungrounded, “isolated” signal source

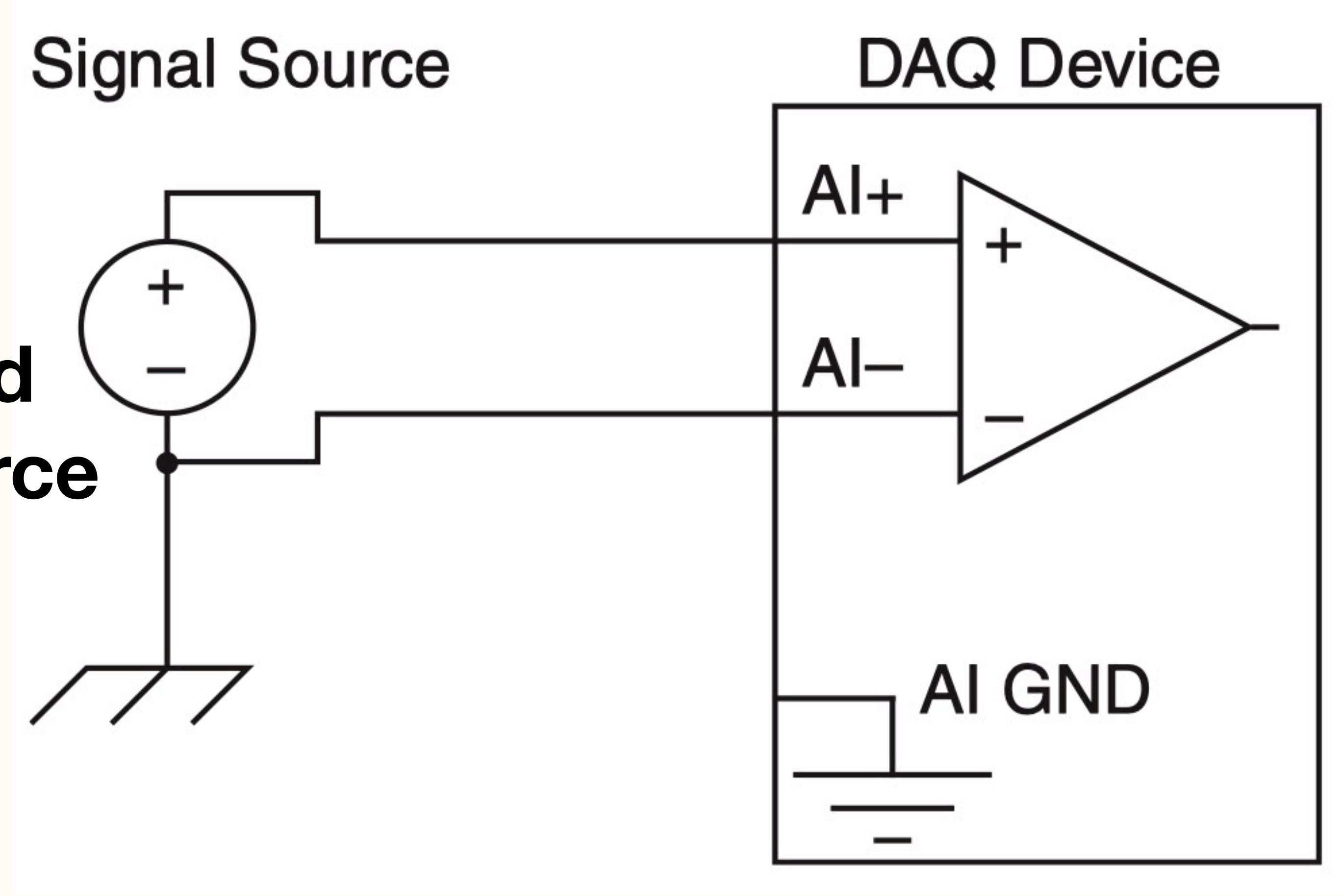


Single-Ended amplification

Differential amplification

- Use (if possible) when signal ground differs from amplifier ground
  - Not always available (or documented)
- Measures voltage between *Input+* and *Input-* pins
- Doesn’t tie *Input-* to Gnd
- Provides “Common mode noise” rejection:
  - Reduces noise picked up by both *Signal+* and *Signal-*
  - Useful for EEG, EMG

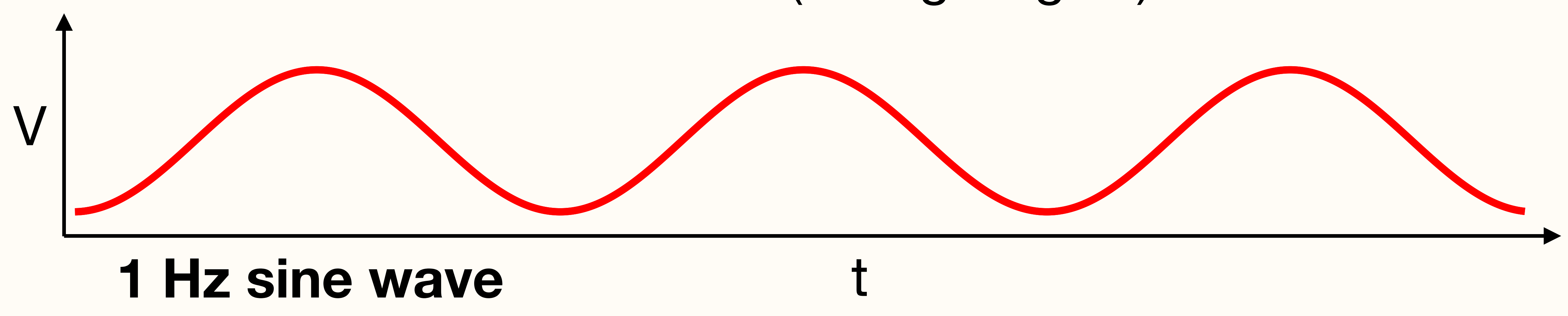
Grounded signal source



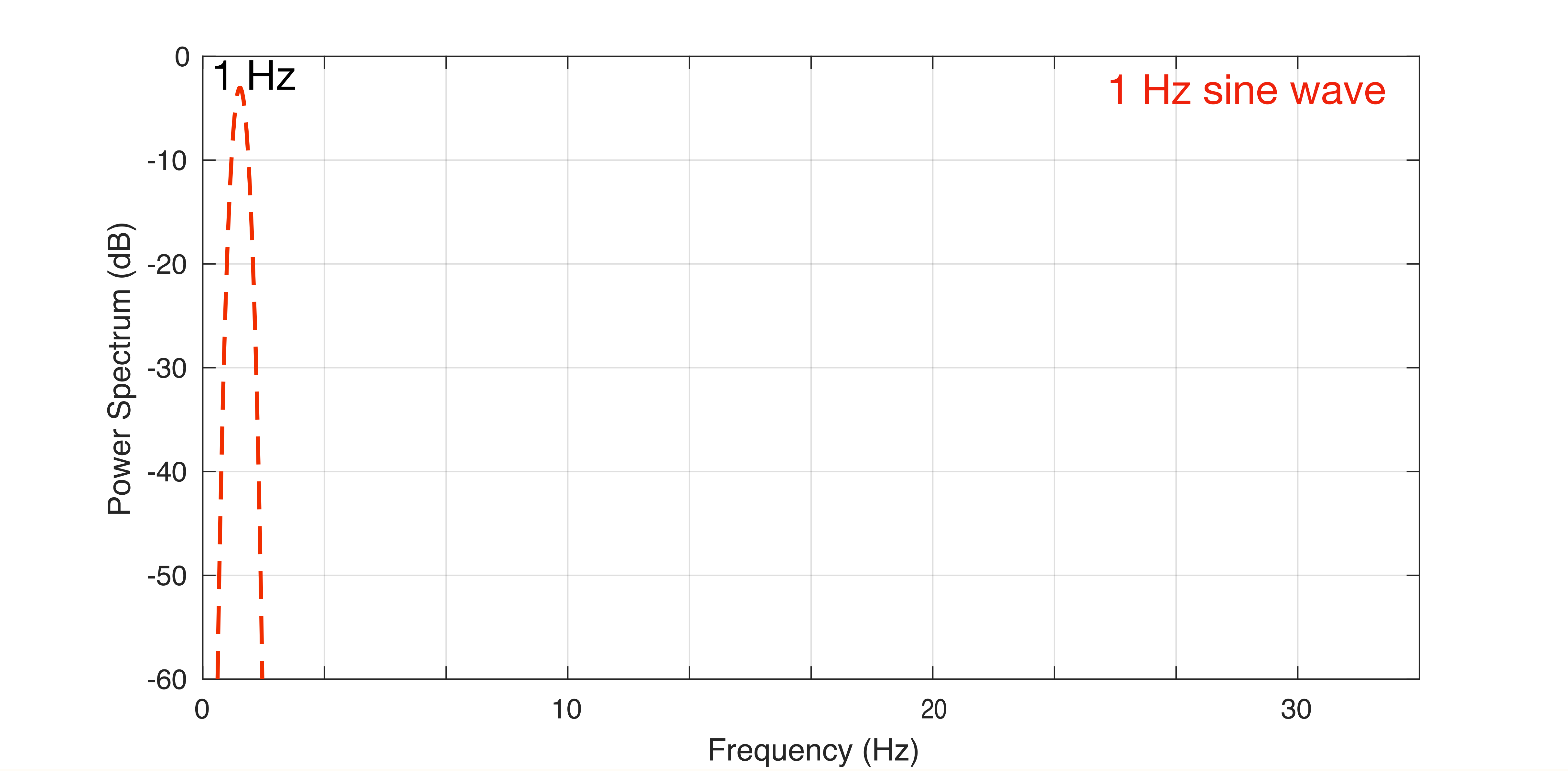
Differential amplification

Frequency Domain

Time Domain (voltage signal)

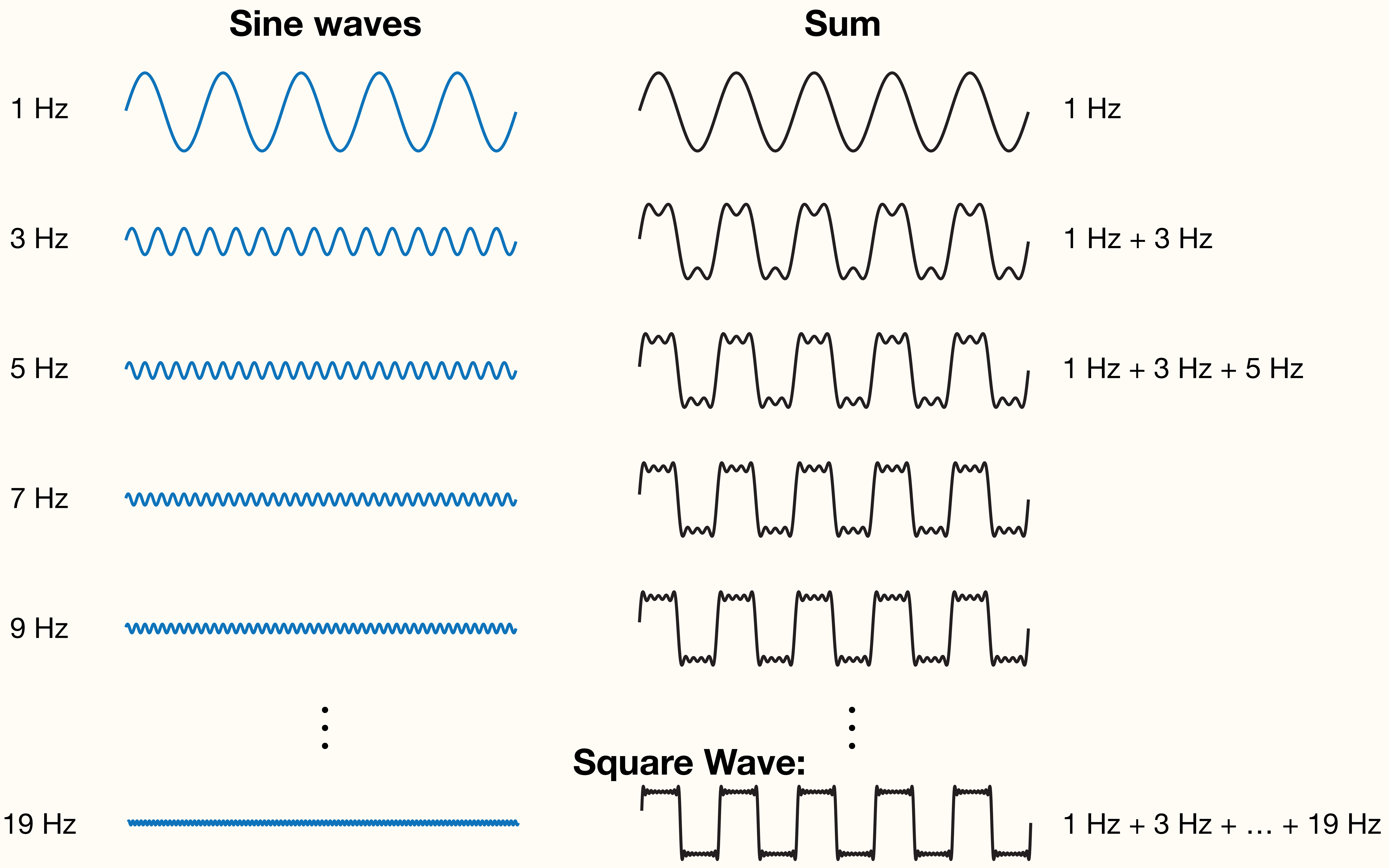


Frequency Domain (Power Spectrum)



It is often useful to think about signals (and signal processing) in the frequency domain.

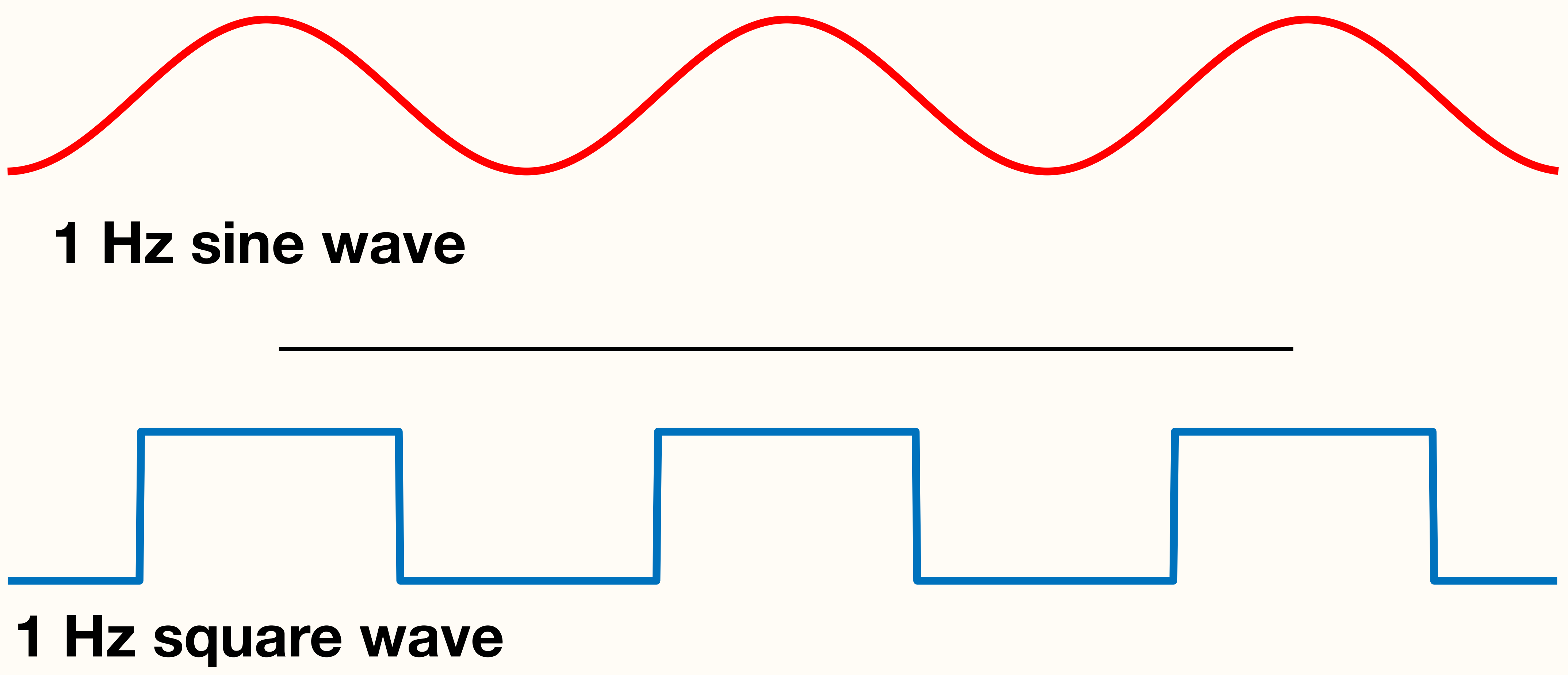
Fourier Series (Sine wave decomposition)



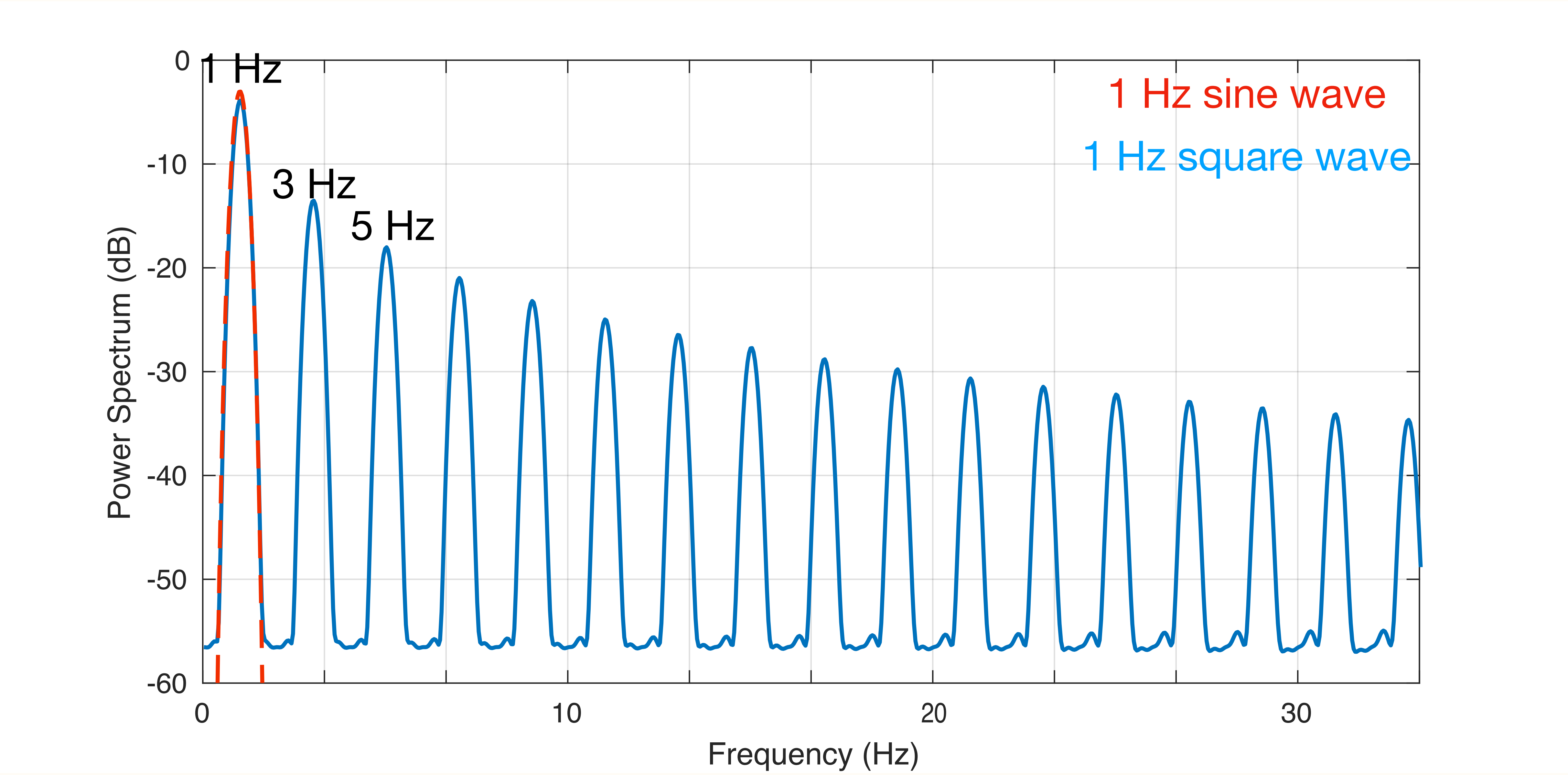
Arbitrary waveforms can be decomposed into a sum of sine waves

Frequency Domain

Time Domain (voltage signal)



Frequency Domain (Power Spectrum)

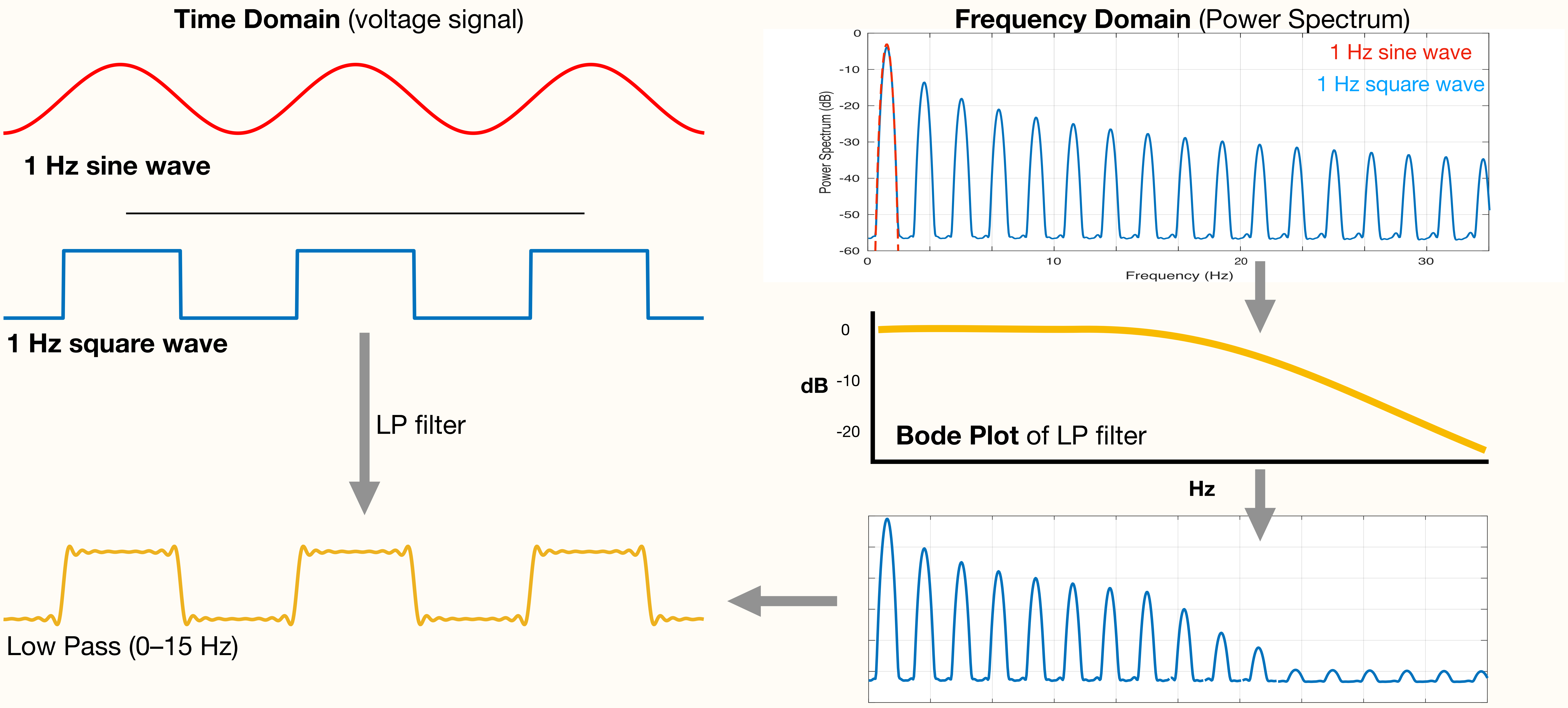


Arbitrary waveforms can be decomposed into a sum of sine waves

The power spectrum is one way of representing this decomposition

(Another representation is the Fourier Transform, which includes phase info)

Frequency Domain



Frequency Domain Examples

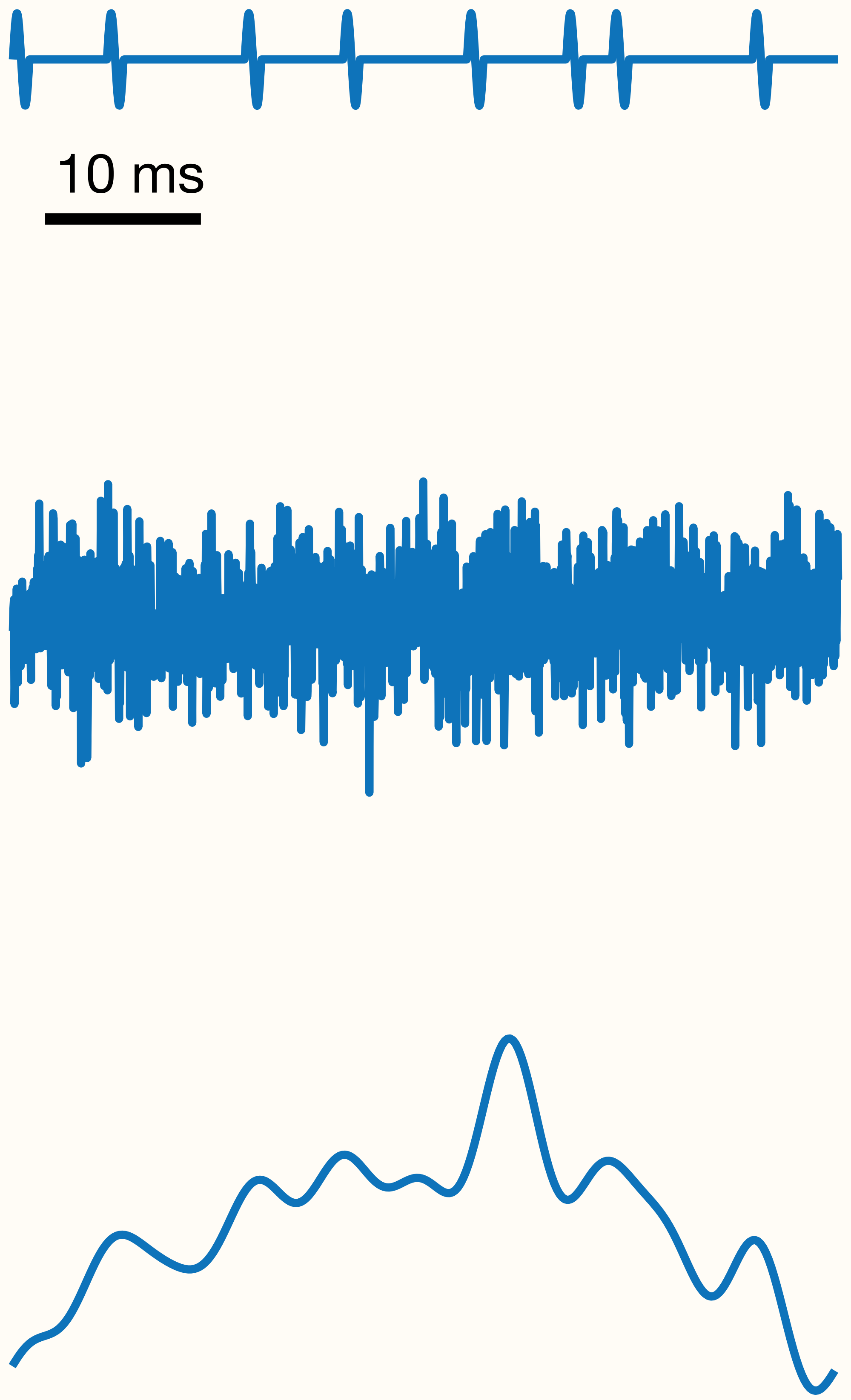
Time Domain (voltage signal)

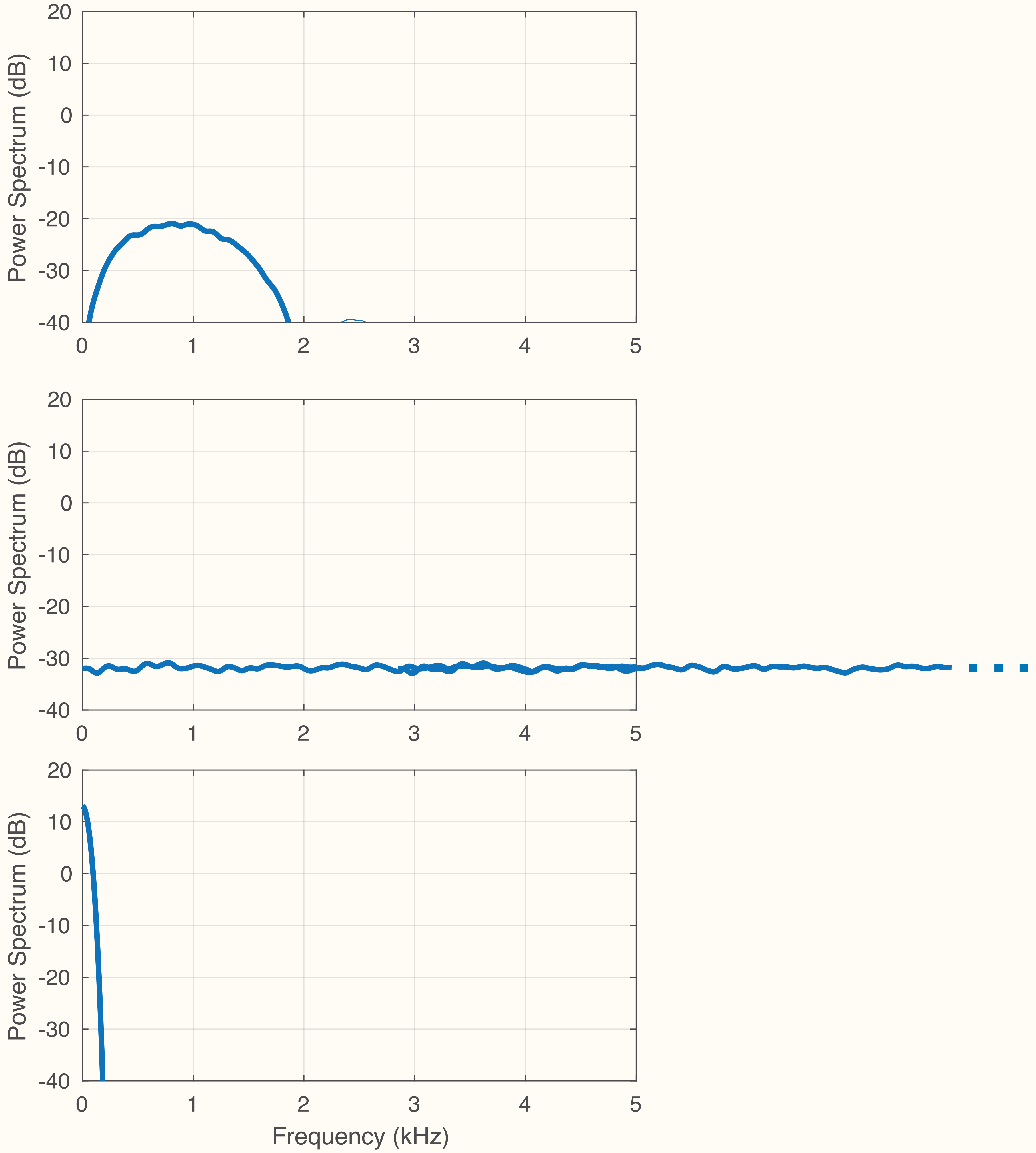
Frequency Domain (Power Spectrum)

Spikes

White noise

Drift



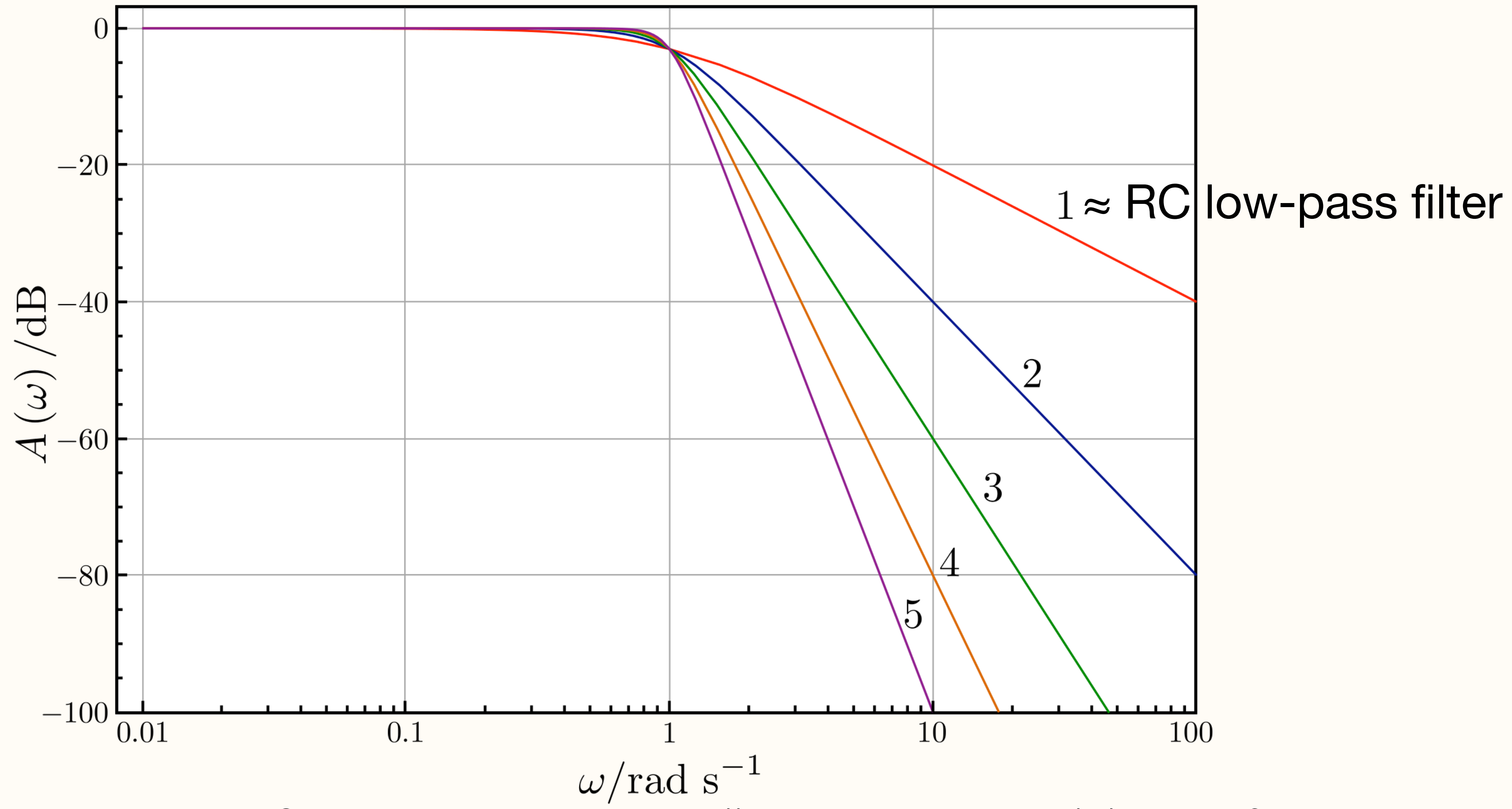


Filtering

Examples

- **High-pass, Low-pass**
  - First-order RC filters: already covered
    - shallow slope on Bode plot
  - Higher-order filters: sharper slopes
  - Different filter circuits (e.g., Butterworth, Bessel)

Butterworth LP filter: 1st – 5th Order



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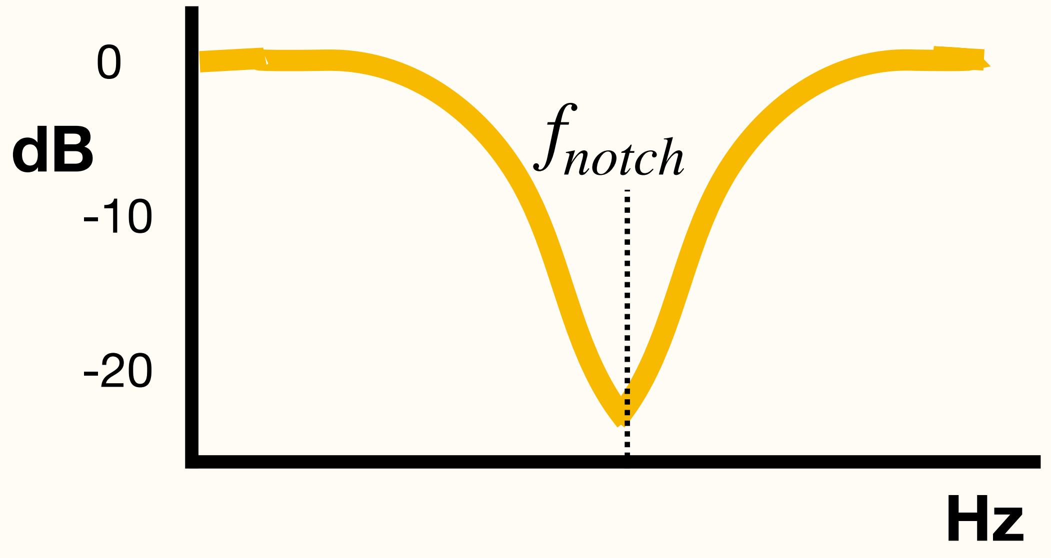
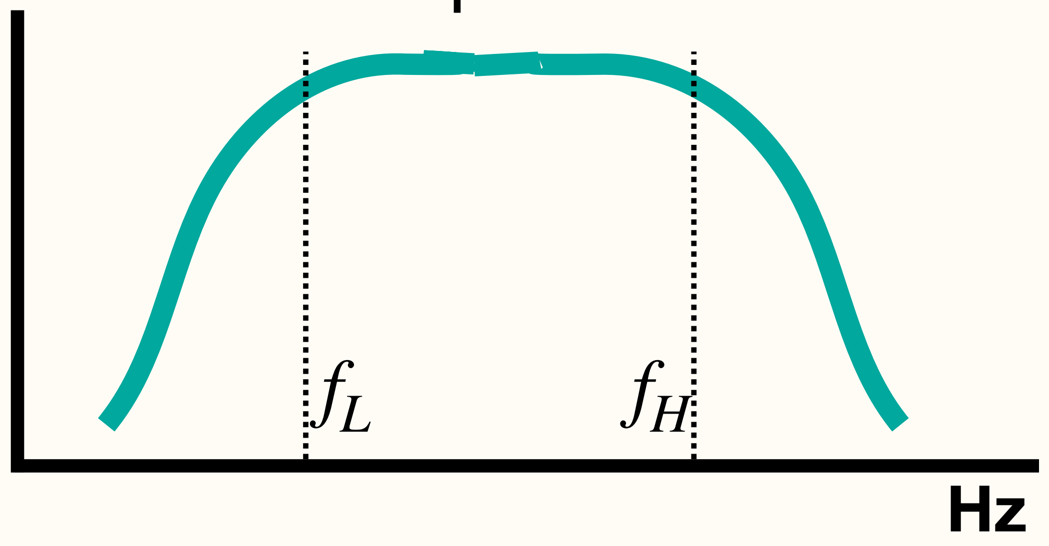
- **Also: Notch, Bandpass**
  - Notch: Removes a narrow frequency band, e.g., 60 Hz noise
  - Bandpass: Retain specific frequency band

Notch filter



Bandpass filter



Filtering

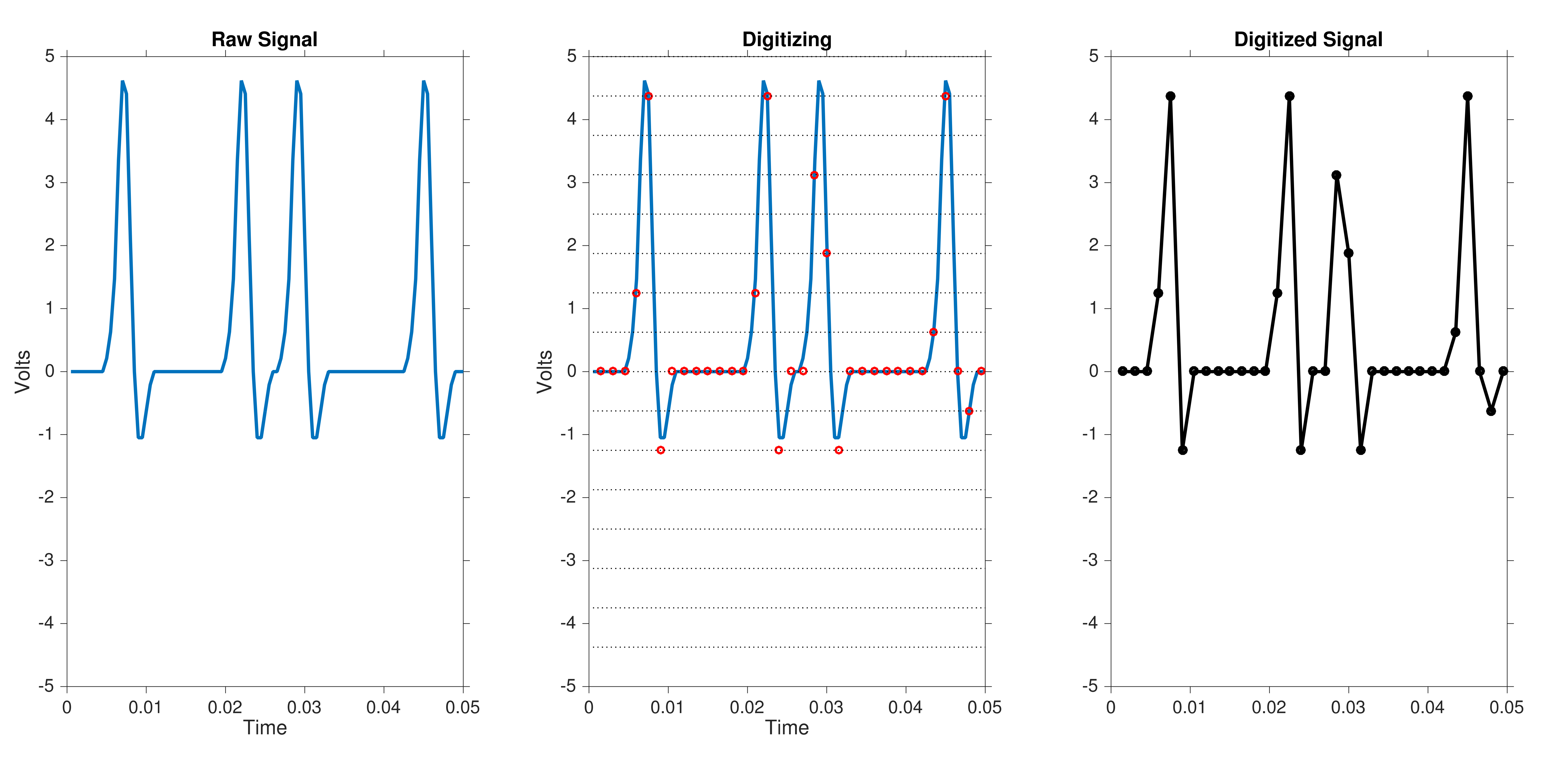
Hardware vs Software filtering

- Hardware filtering:
  - Useful for signal conditioning before digitization
    - AC-coupling; Anti-aliasing
  - Induces phase shifts
  - Fast
- Software filters:
  - May take time to compute
  - Can eliminate phase shift
  - More flexible (can be re-run with different settings)

Data Acquisition / Digitization

Digitizer / ADC (analog-to-digital converter)

- Takes continuous analog signal and discretizes it in time & voltage.
- Samples the voltage of the signal at a fixed rate in time
- Can only represent voltages within a fixed range (its dynamic range)
- Finite voltage resolution



Data Acquisition / Digitization

Dynamic Range & Bit Depth

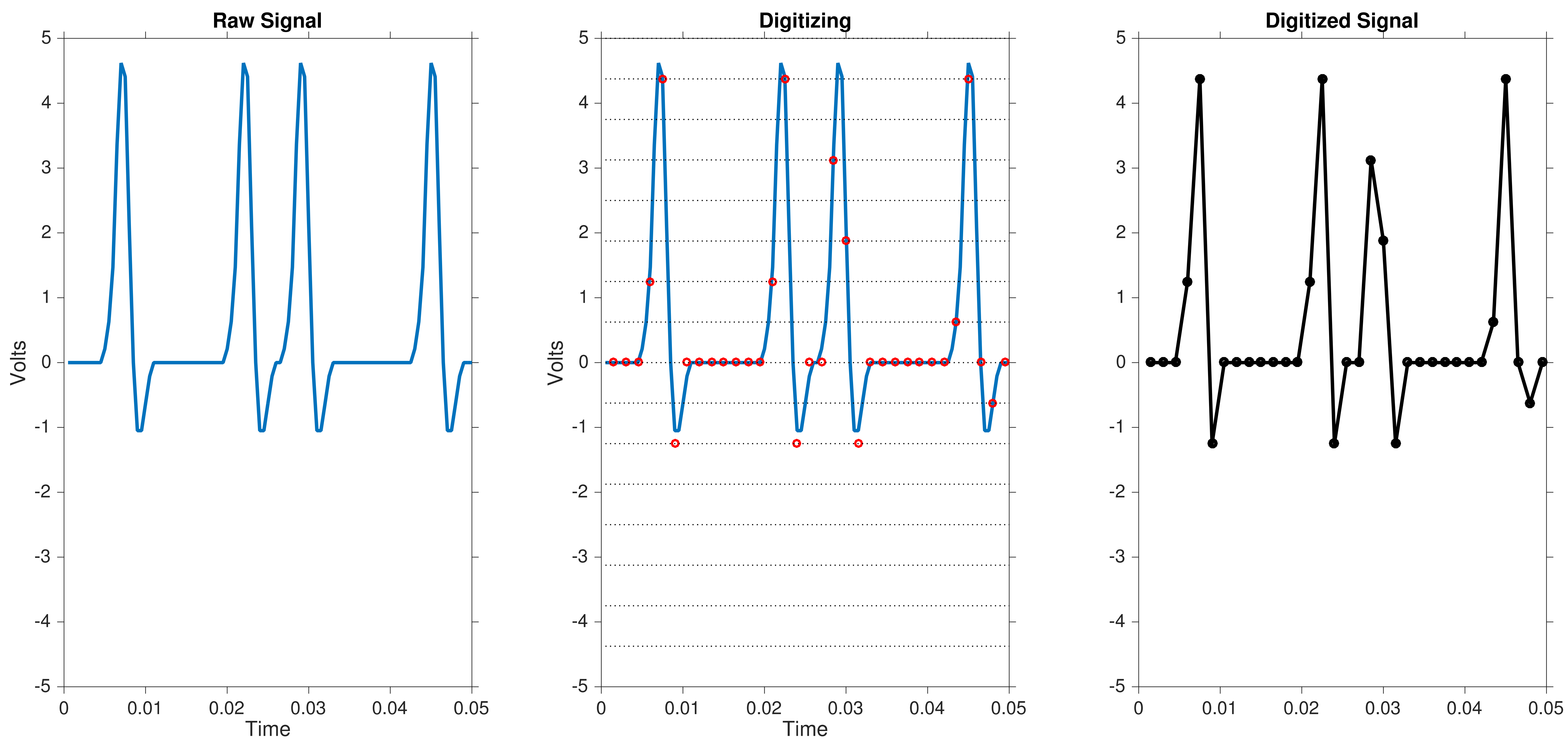
- Digitizers may have different dynamic ranges (+/-5 V, +/-10 V, 0-5 V, etc). Some are selectable (e.g., sone NI boards).

- Resolution specified by “bit depth”. Typically between 10–14 bits.

  E.g., “10 bit” = $2^{10} \approx 1000$ possible voltage values

- Figure:

  4-bit digitizer with +/-5 V range



2^4 = 16 possible voltage values

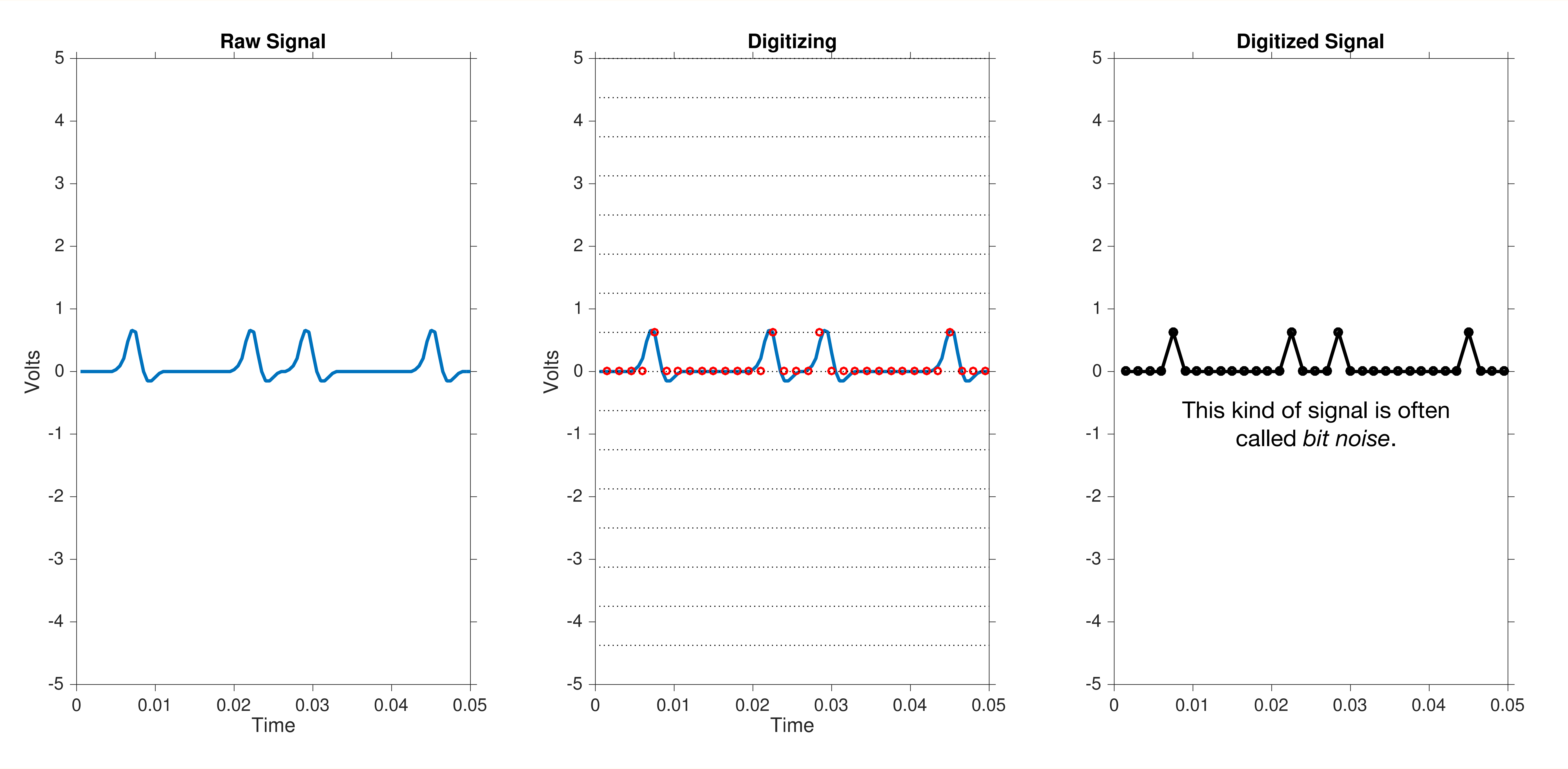
Data Acquisition / Digitization

Dynamic Range & Bit Depth

- Signal amplitude should be large compared to digitizer resolution.
- You should amplify small signals before digitization:

  Aim to fill the digitizer's dynamic range (with some breathing room).

- Typically digitizer resolution can be smaller than the existing (analog) noise sources



Data Acquisition / Digitization

Dynamic Range & Bit Depth

- Digitizer resolution should be *small* compared to signal amplitude.

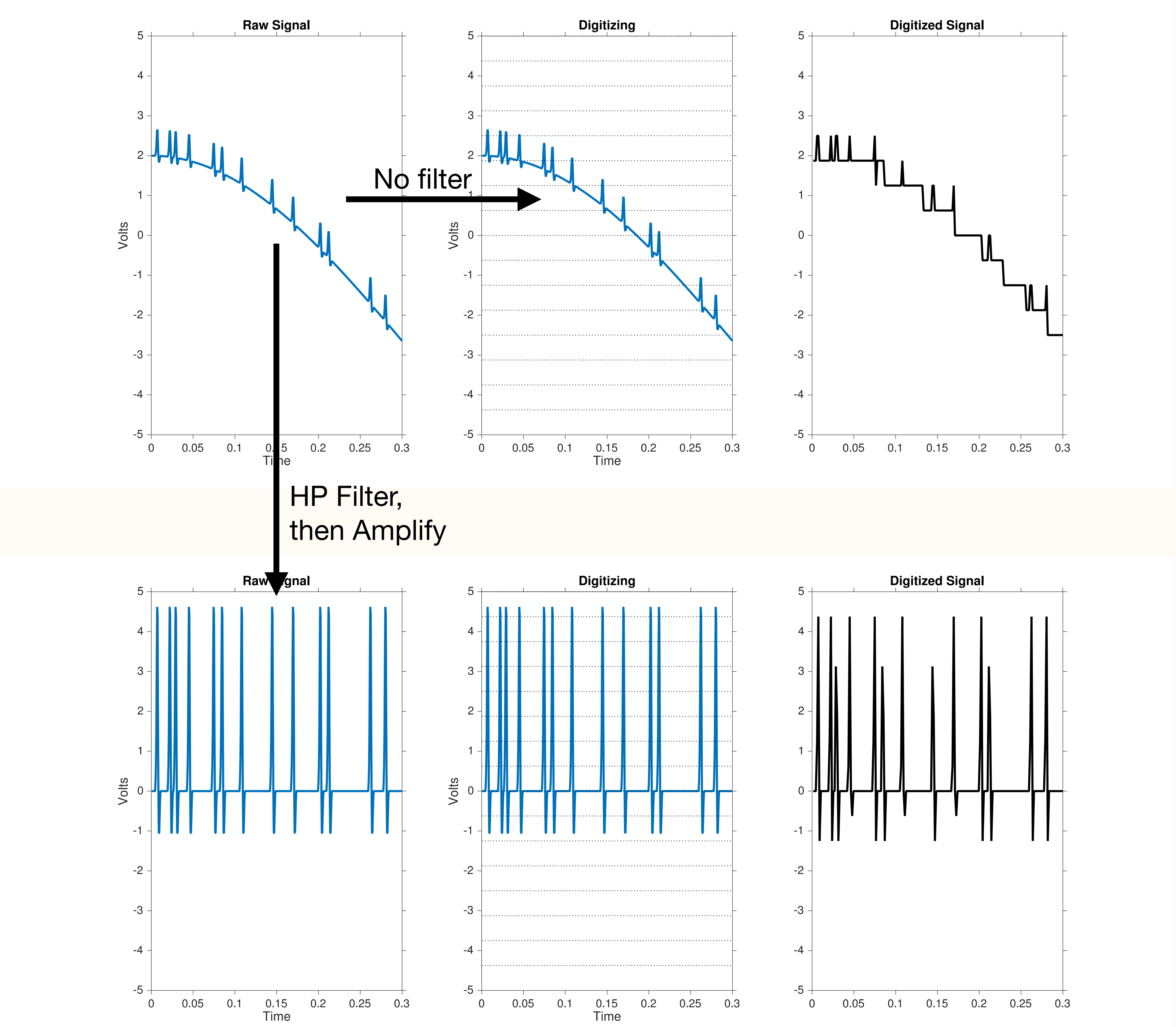
- You should amplify small signals before digitization:

  Aim to fill the digitizer's dynamic range (with some breathing room).

- Typically digitizer resolution can be smaller than the existing (analog) noise sources

- Signal drift: Use HP filter to remove drift before amplifying

  (Also known as AC-coupling)



Data Acquisition: Sampling Rate

How fast must we set our sampling rate to accurately capture our data?

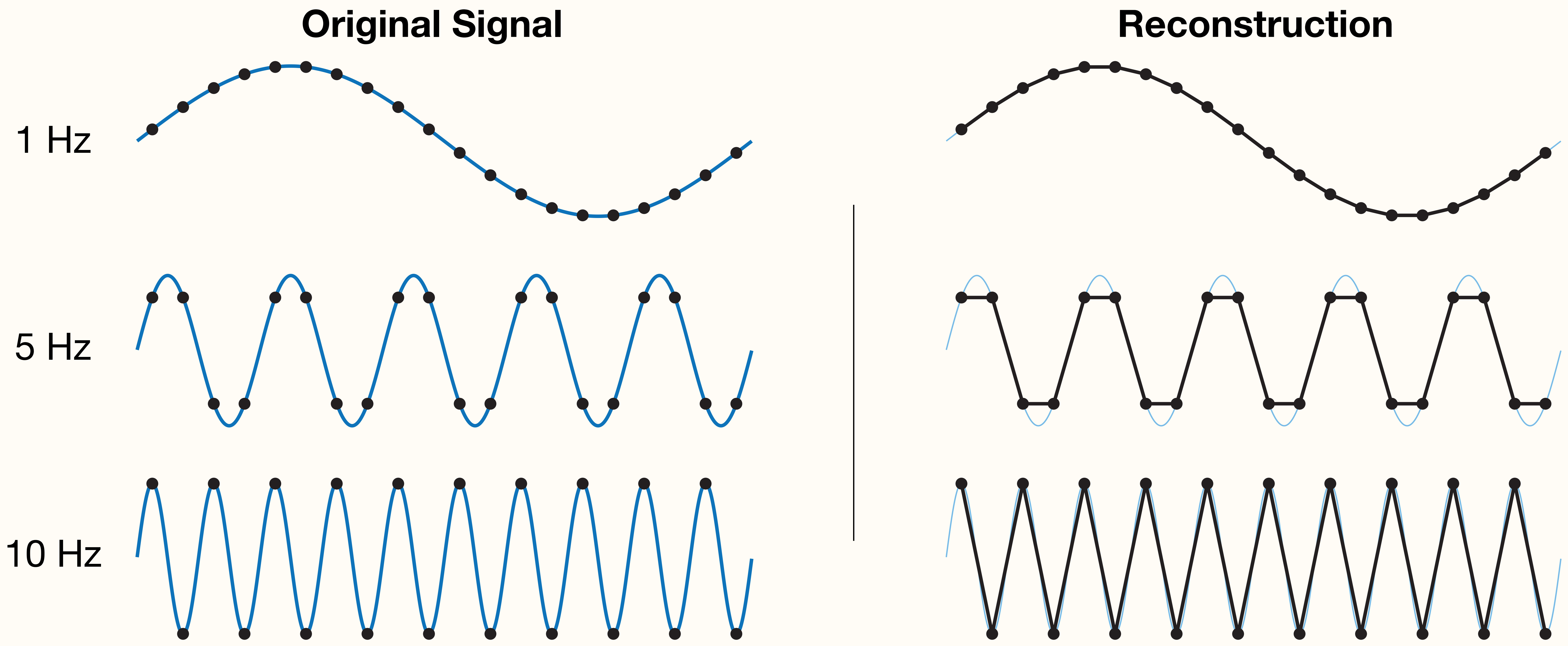
Nyquist Sampling Theorem (simplified)**:**

> If a signal contains no frequencies above frequency f, you must acquire it at a sampling rate of at least $2f$ to avoid losing information.

But in reality:

- You don't know the precise *highest frequency* in your signal
- You may have noise with higher frequencies than your signal
- Too low a sampling rate could lead to *aliasing*

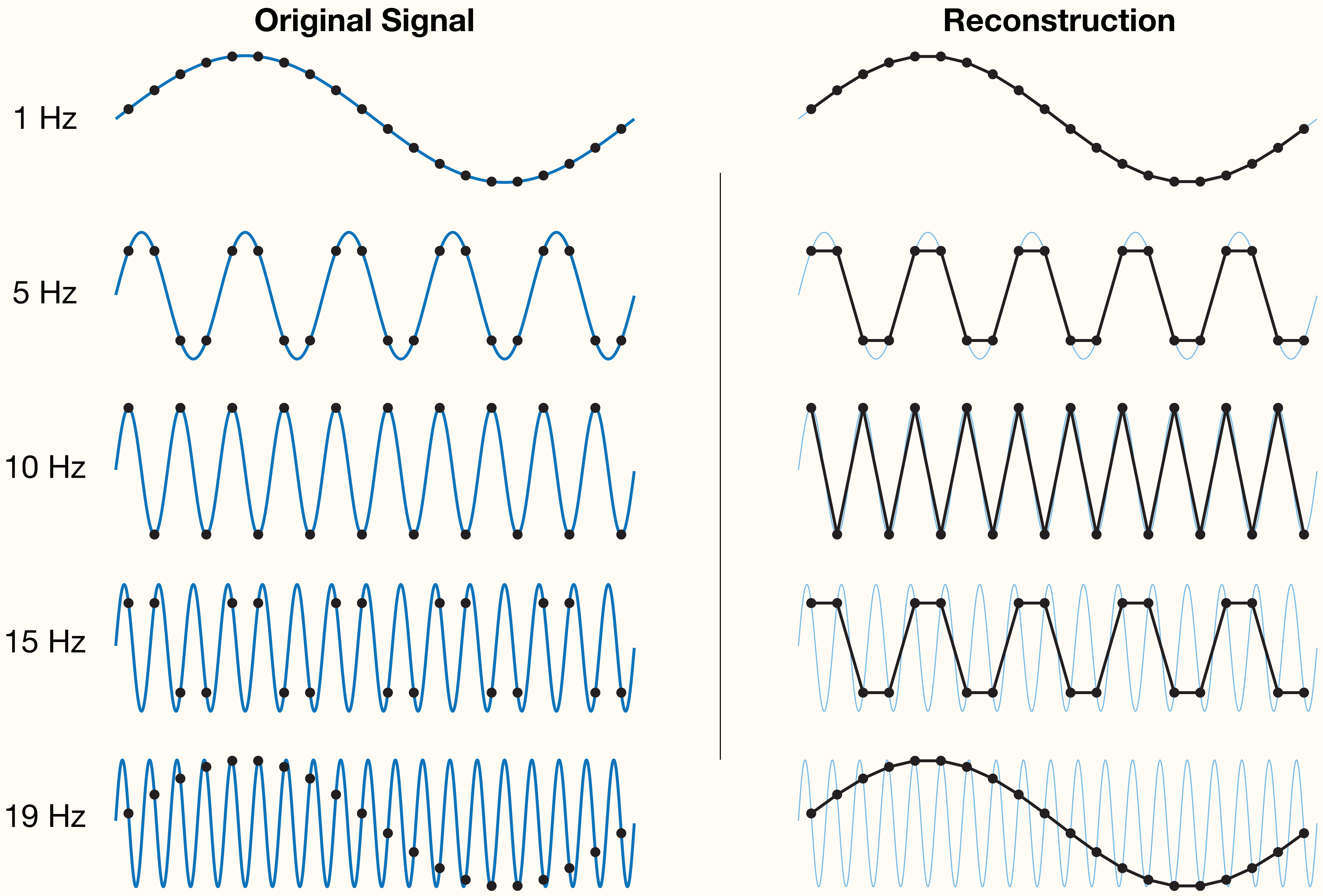
Data Acquisition: Aliasing



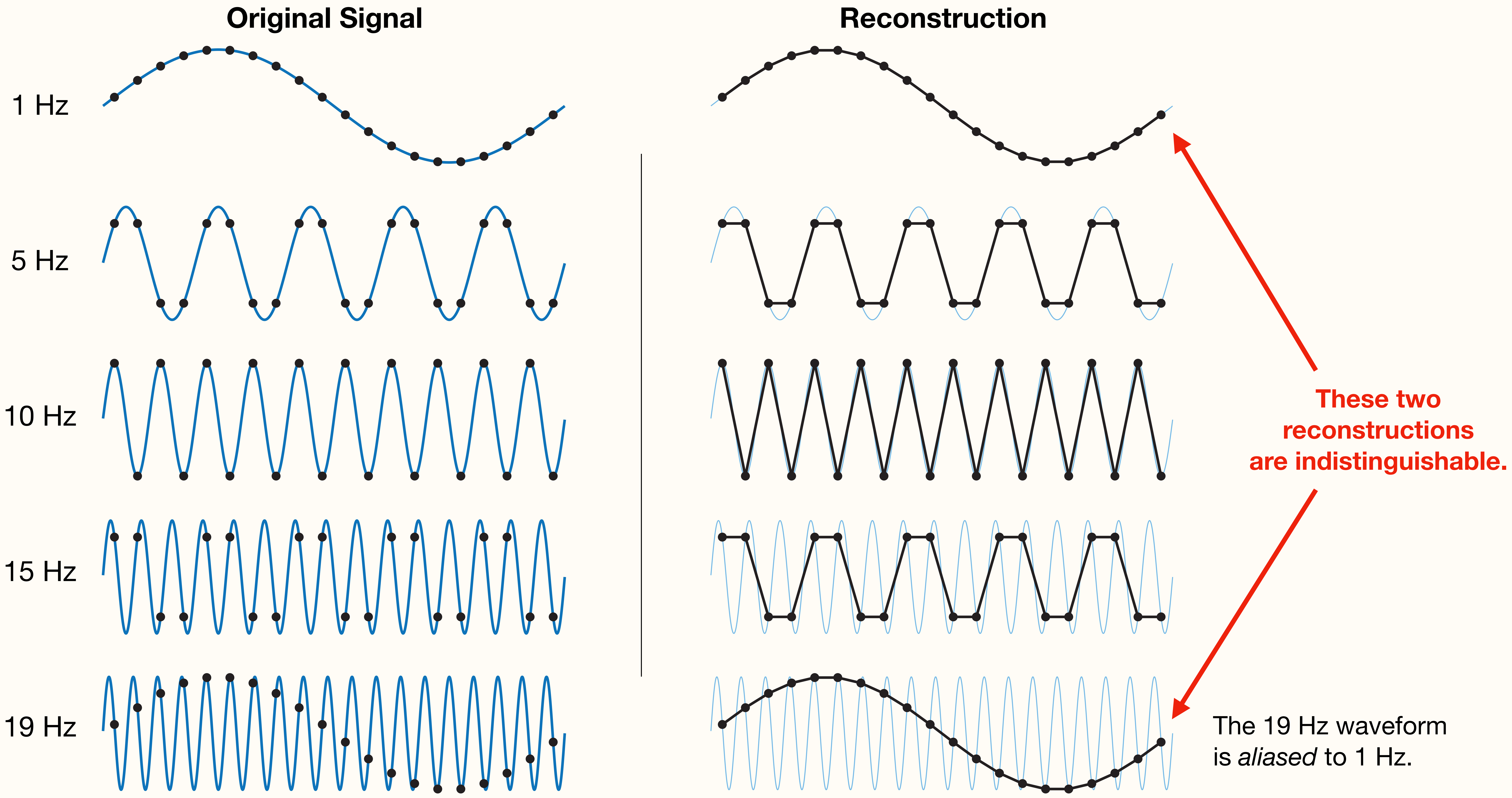
Example of 20 Hz sampling

- Nyquist frequency is 10 Hz — cannot reconstruct higher frequencies

Data Acquisition: Aliasing



Data Acquisition: Aliasing



Data Acquisition: Aliasing

Data Acquisition: Aliasing

How fast must we set our sampling rate to accurately capture our data?

Aliasing: Any frequency component greater than 1/2 of the sampling rate ***will still be acquired***, but will be *aliased* down to a lower frequency.

Proper procedure:

1) Determine the highest frequency (f) you care about and sample at »2f (often 5f or 10f).

2) Low-pass filter your data (at around 2f) before digitizing. (Anti-aliasing filter)

Aliasing: Simulation

Time Domain (voltage signal) **Frequency Domain** (Power Spectrum)

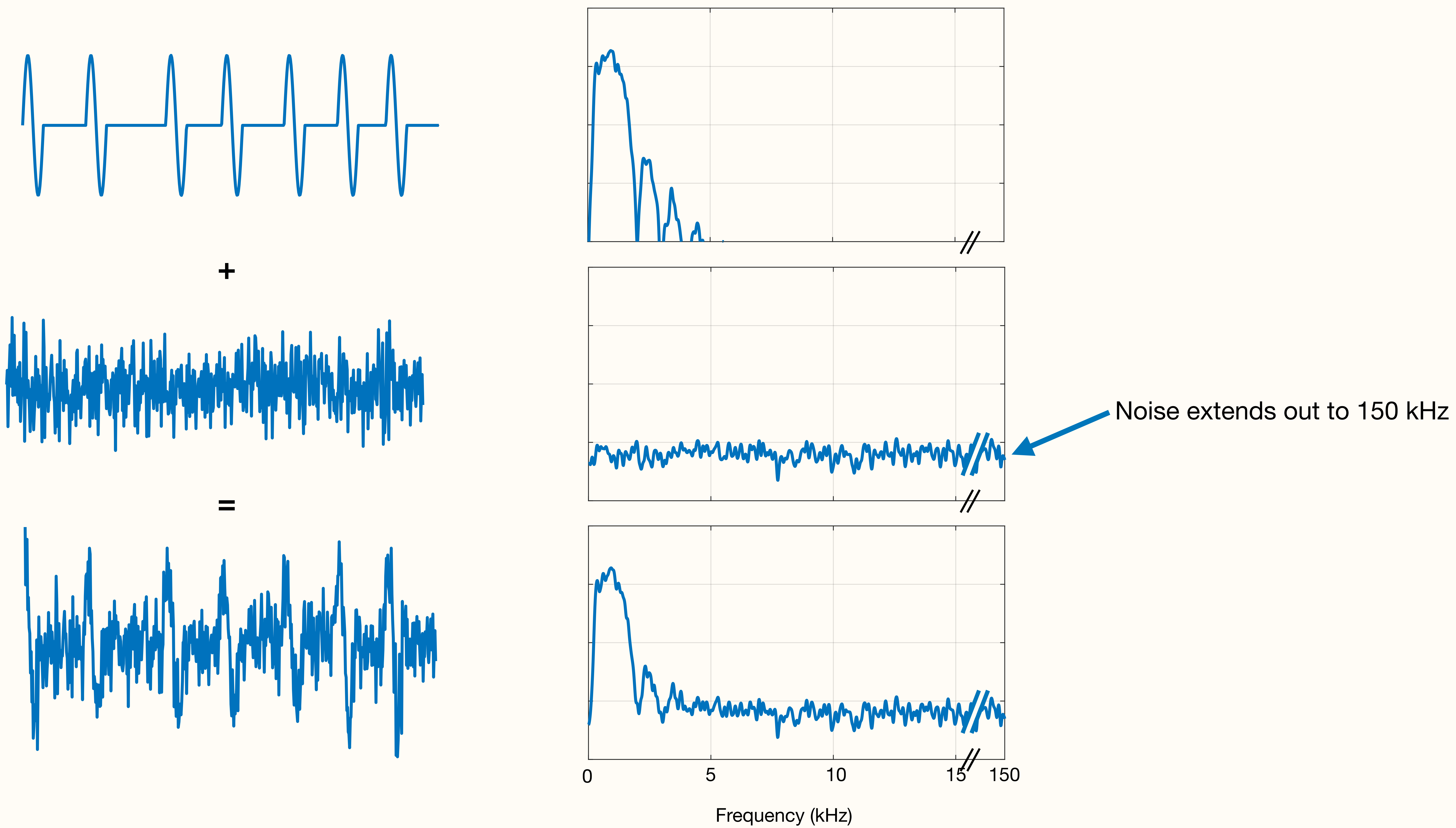
spikes

+

white noise
(constant power at all frequencies)

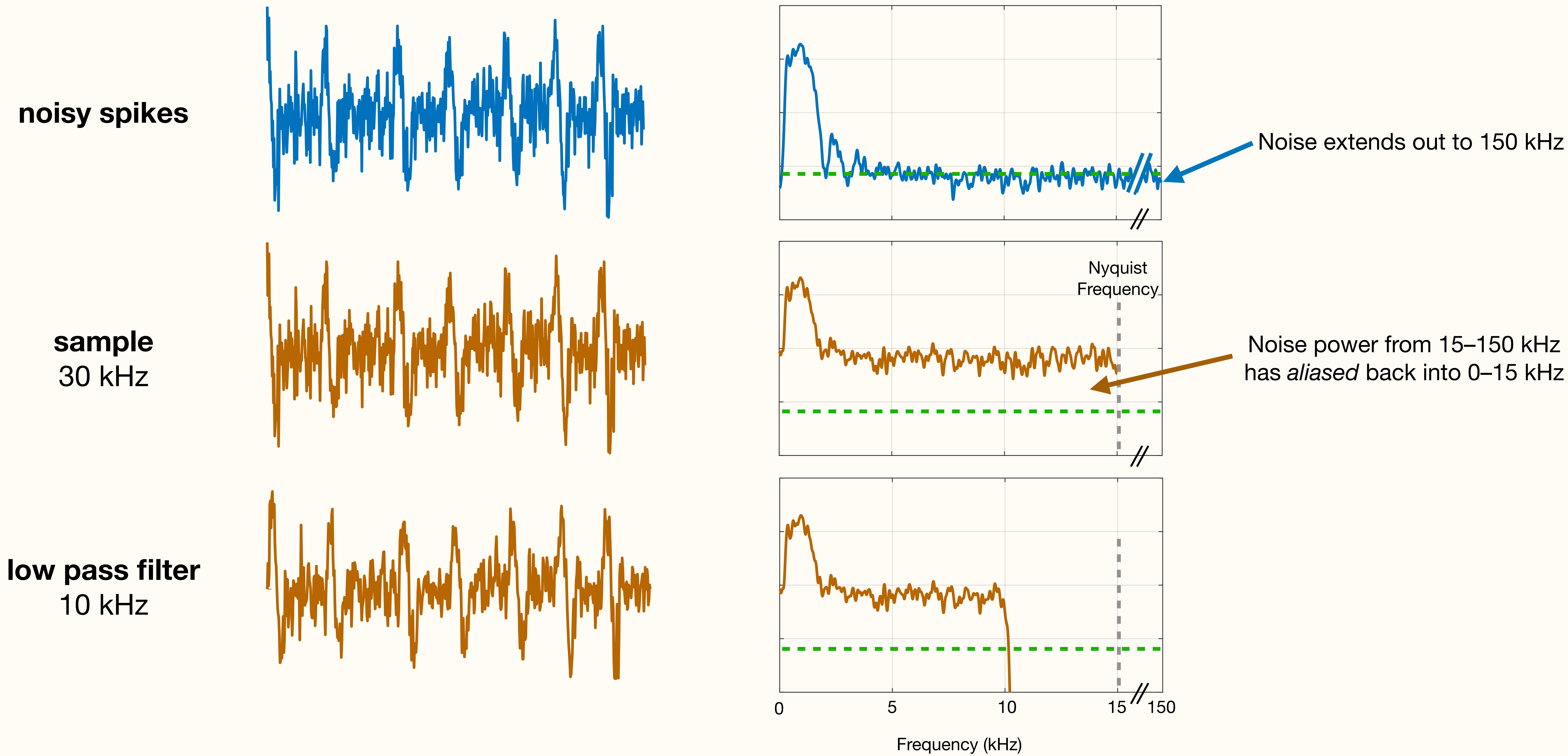
=

sum



Aliasing: Simulation

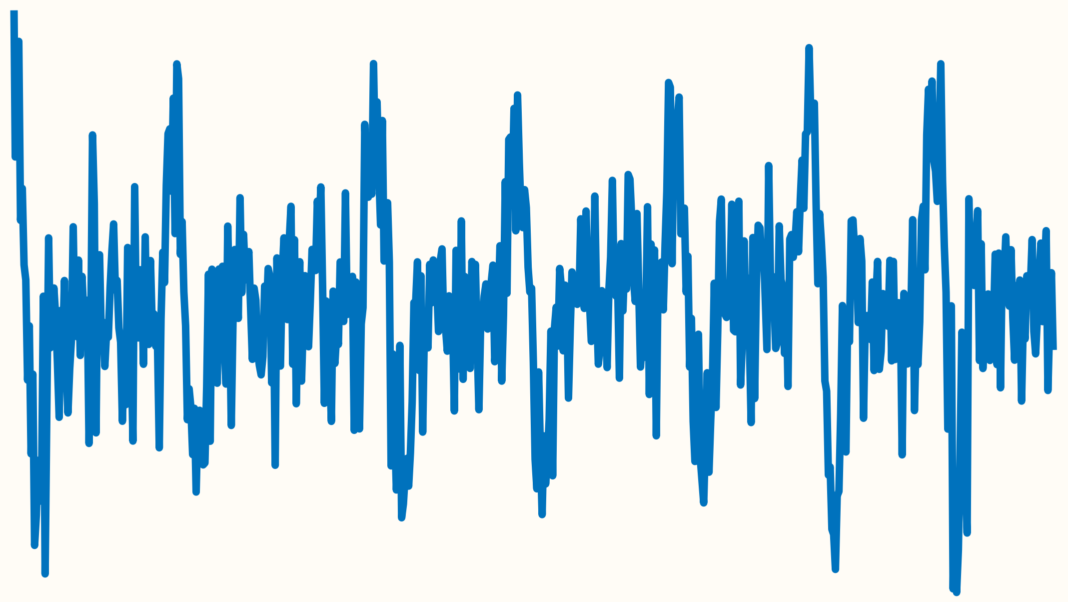
Time Domain (voltage signal) **Frequency Domain** (Power Spectrum)

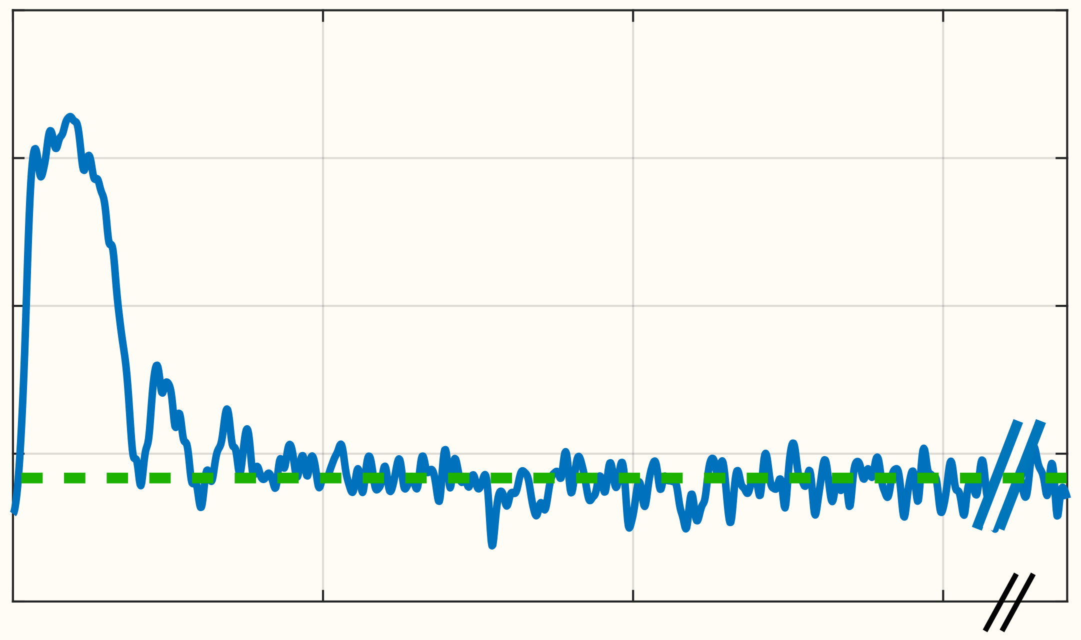


Aliasing: Simulation

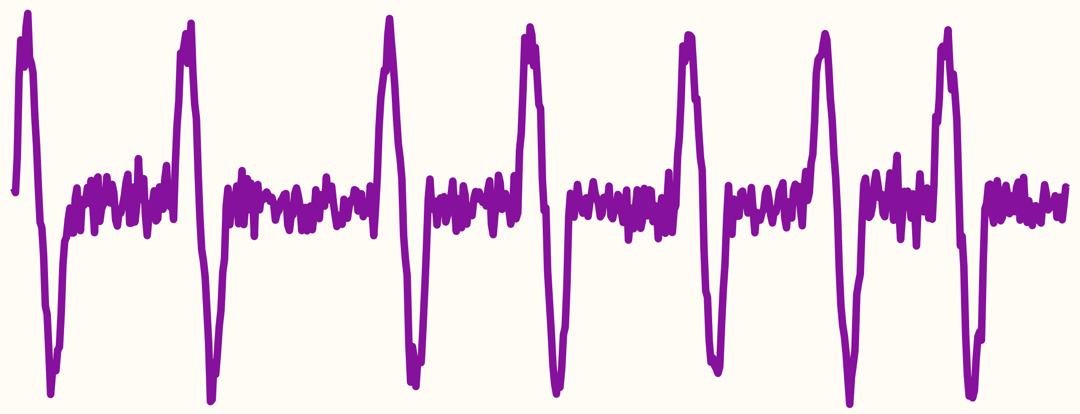
Time Domain (voltage signal) | **Frequency Domain** (Power Spectrum)

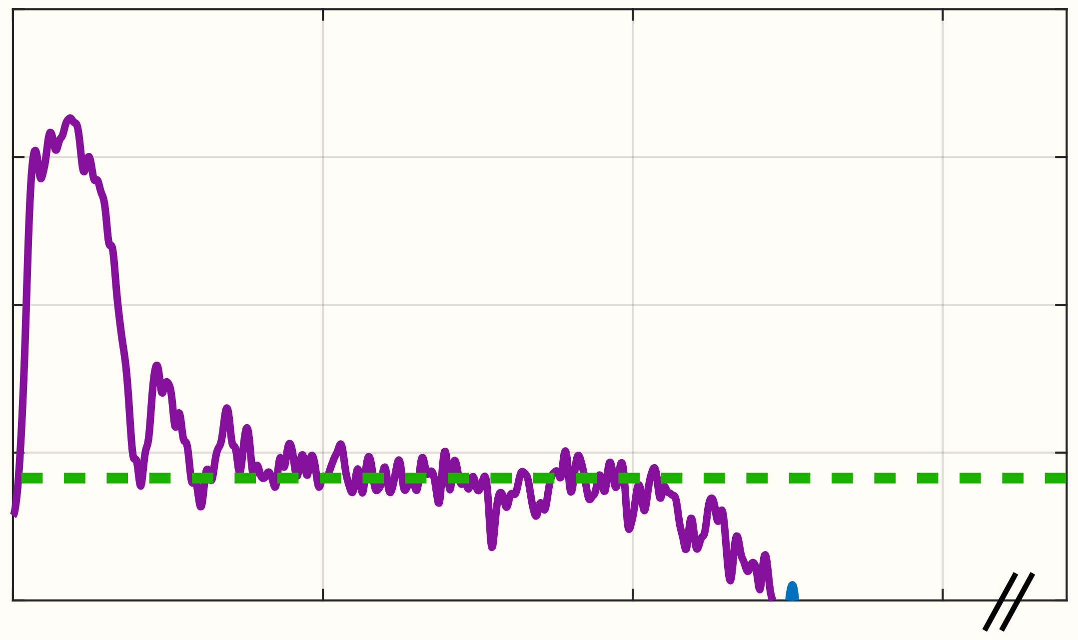
noisy spikes



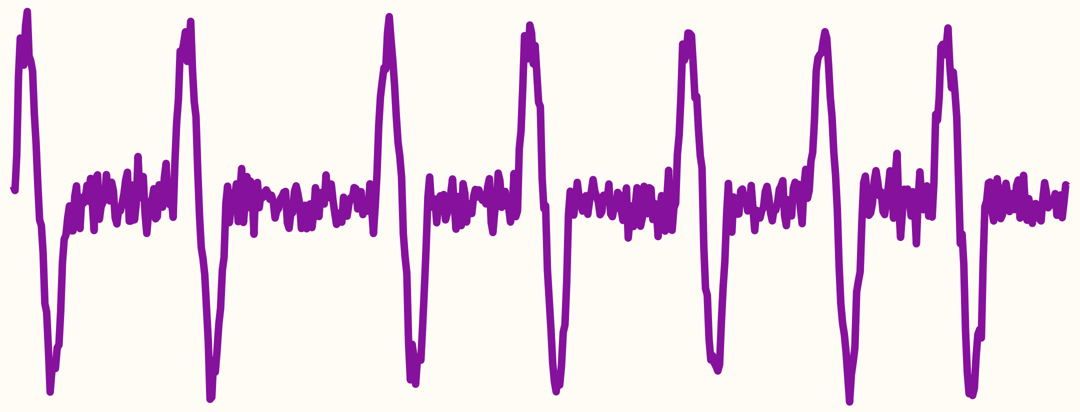


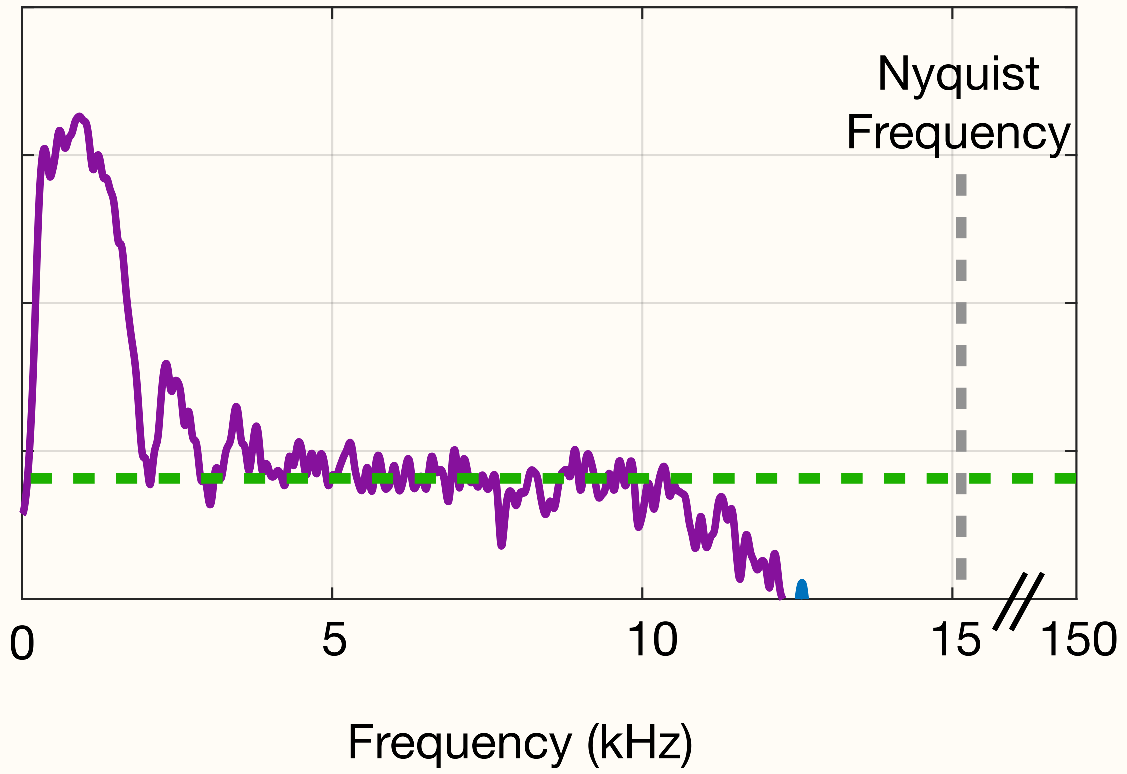
low pass filter
10 kHz





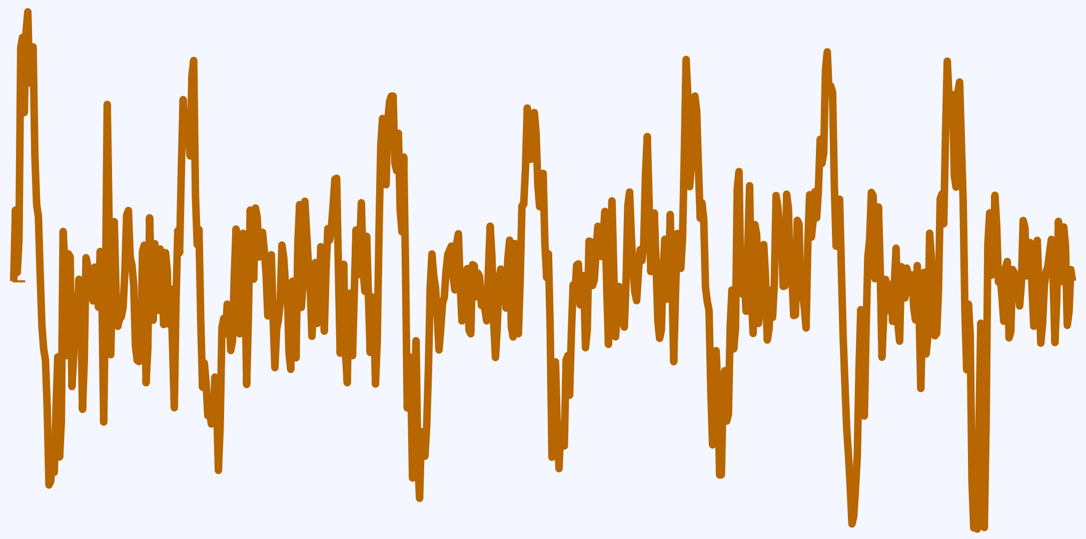
sample
30 kHz





filter then sample

Comparison:



sample then filter

Accurate Timing

- **Multiple clocks**
- **Precise Timing is hard to do with PCs/Software**

Accurate Timing

- **Multiple clocks**
  - Every device that generates or records a signal has its own clock
  - Clocks might drift (run at different speeds)
    - less of a problem for precision lab instruments
  - Clock synchronization is hard
    - E.g., How do you ensure that your video camera frames are aligned with your laser stimulation?
    - **Best solution:** Have one master clock (e.g., a DAQ board) generate & record all timing signals
    - **Alternate solution:** Use one master clock to record all signals
      - Use the AI channels on your DAQ board to acquire all relevant timing signals:
        - frame clock from your camera
        - trigger signal going to your laser
        - lick/reward/punishment control signals
      - You can now measure the relative timing of all the signals going in & out of your rig

- **Precise Timing is hard to do with PCs/Software**

Accurate Timing

- Multiple clocks

- **Precise Timing is hard to do with PCs/Software**
  - PCs are fast (GHz!) but with unreliable timing.
    - your operating system run many tasks in parallel: networking, disk writing, etc
  - Without a “real-time OS”, PC software can’t generate reliable (millisecond) time intervals or execute fast & repeatable closed loop control
  - Offload precise timing to dedicated hardware:
    - Play pre-computed waveforms on a sound card or DAQ board (e.g., NI card)
    - Closed-loop control: use triggers on DAQ board or Arduino
      - e.g., behaviorally triggered reward (juice valve) or punishment (shock)

Recap

- **Noise cont'd:**
  - Ground Noise; Differential Amplification
- **Frequency domain (Fourier transform, Power spectrum)**
- **Digitization**
  - Bit resolution/noise; dynamic range
  - Sampling rate / Aliasing
- **Filtering**
  - H/W vs S/W; HP, LP, BP, Notch
- **Timing**
  - Strategies for syncing
  - Avoid software timing
- **Conclusion**
- Oscilloscope demo / Work on assignments

Conclusion

Thanks for taking this nanocourse!

We'd be grateful for any feedback you may have.

Will be sending out an anonymous survey — Please respond!!

(Survey is required for course credit)

This week's assignment:

- Continue working on assignments 1, 2
- Start on Assignment 3
- Email us as much as you can get done in 60–90 minutes. No need to finish it all.

Return AnalogDiscovery kits

- Within the next week or so
- Leave a post-it note with your name inside, and return to the RIC Dropoff Locker

O-Scope Advanced Features

- **Multiple Channels**
  - Triggering ch2 on ch 1
  - change V scale separately; adjust V-offset for better viewing
  - can zoom in to non-0 V positions
- **Time base**
  - set trigger position
  - shift trigger offscreen to see end of pulse
- Other features
  - persistence, averaging
  - math (sum traces, FFT)