ESE 3400: Medical Devices Lab

Lec 19: December 12, 2022

Course Review

Medical Devices

- An apparatus used in the diagnosis, mitigation, therapy, or prevention of a disease not through a chemical action (i.e is not a drug)
- Eg.
  - Blood pressure monitor *diagnoses* hypertension
  - Ablation catheter destroys Barret's esophagus precancerous cells *mitigates* the spread of cancer
  - Cochlear implant is *therapy* for hearing ability
  - A condom *prevents* STI infection

Motivating Questions

- What is the clinical need?
- What biometric signals are needed if any?
  - What sensors can acquire this?
  - Is diagnosis needed?
- What medical intervention/stimulation is needed?
  - Electrical stimulation for mitigation or therapy?

Motivating Questions (con't)

- What is the use model of the device?
  - Long term/short term use?
  - Does it need to be mobile?
  - Power source/management?
  - Is it wearable or implantable?
  - Data management/transmission?
- Patient and operator safety concerns?

Learning Objectives

- Utilize sensors to monitor biometric signals
- Design differential analog circuitry to acquire and condition biometric signal
- Employ circuitry to digitize and transmit data wirelessly via Bluetooth
- Build and populate a PCB given circuit schematic
- Extract biometrics (eg. Heart rate, respiration, etc.) from discrete-time signal
- Relate time-domain behaviour to frequency domain content of discrete time signals
- Implement simple digital filters

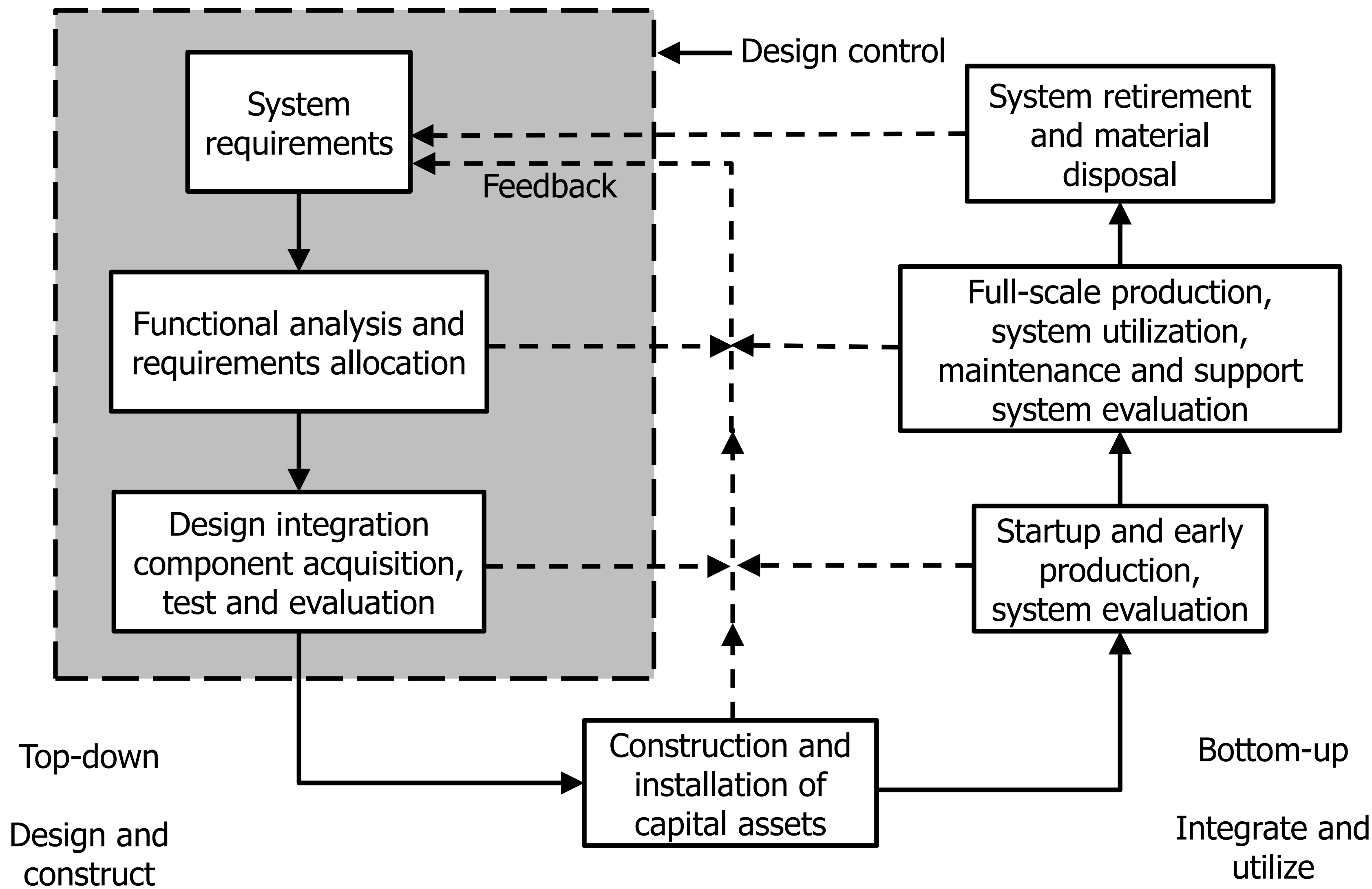
Learning Objectives

- In other words…
  - Hands on lab experience

Systems and Platforms

Signal Conditioning and Acquisition

Systems Development Process



Medical Instrument Systems

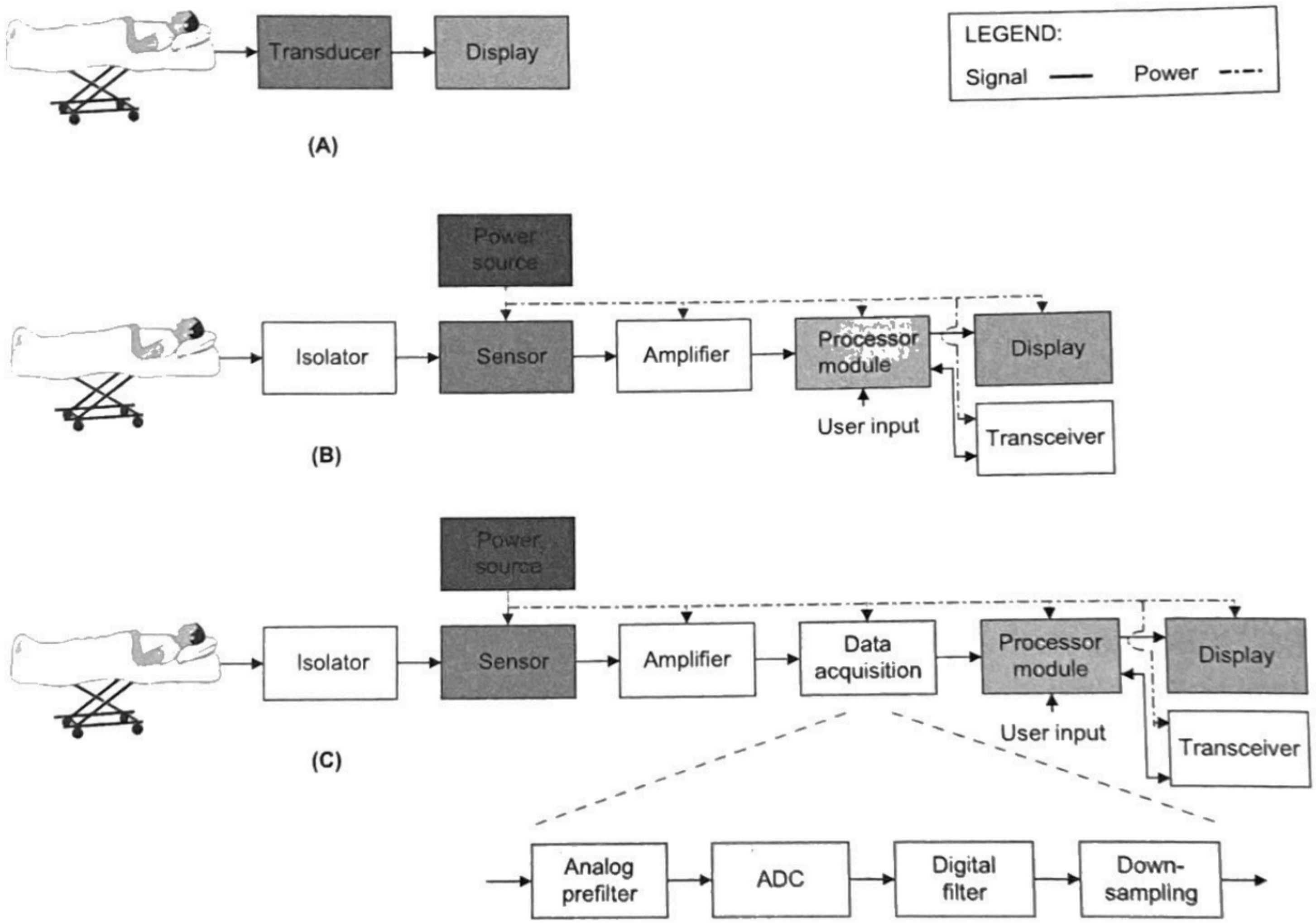


FIGURE 1.1

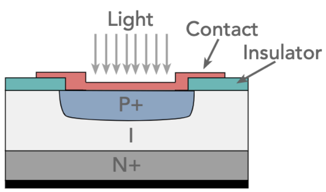
Three types of medical instruments. (A) Simple. (B) Analog. (C) Digital.

Monitoring Vital Signs

- Body Temperature
  - Thermistors

- Heart Rate and Heart Rate Variability
  - Surface electrodes

- Respiration Rate
  - Photodiodes



PIN photodiode structure

- Blood Pressure
  - Pressure sensors
- Height/Weight
  - Scale and ruler

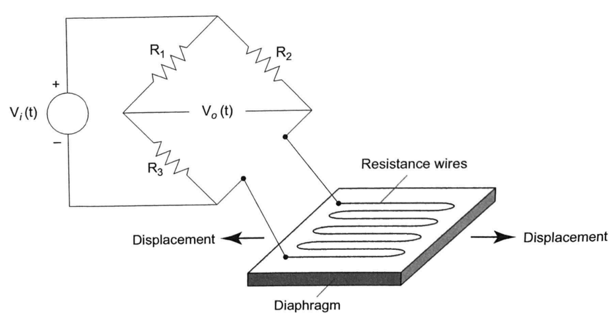
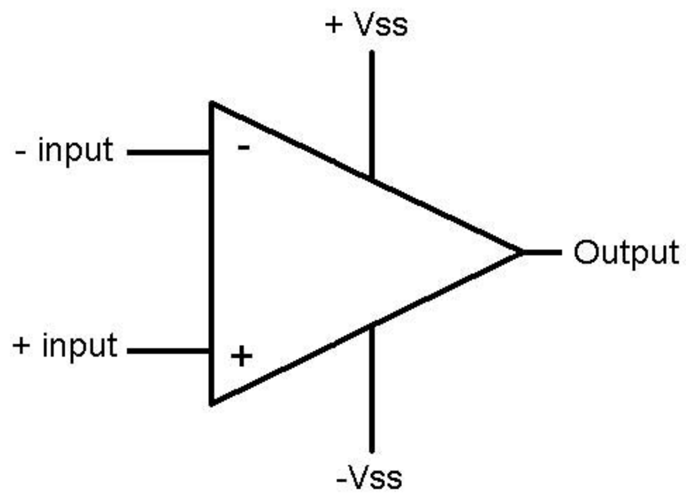


FIGURE 1.11
Pressure sensor components: a diaphragm, strain gauge, and Wheatstone bridge.

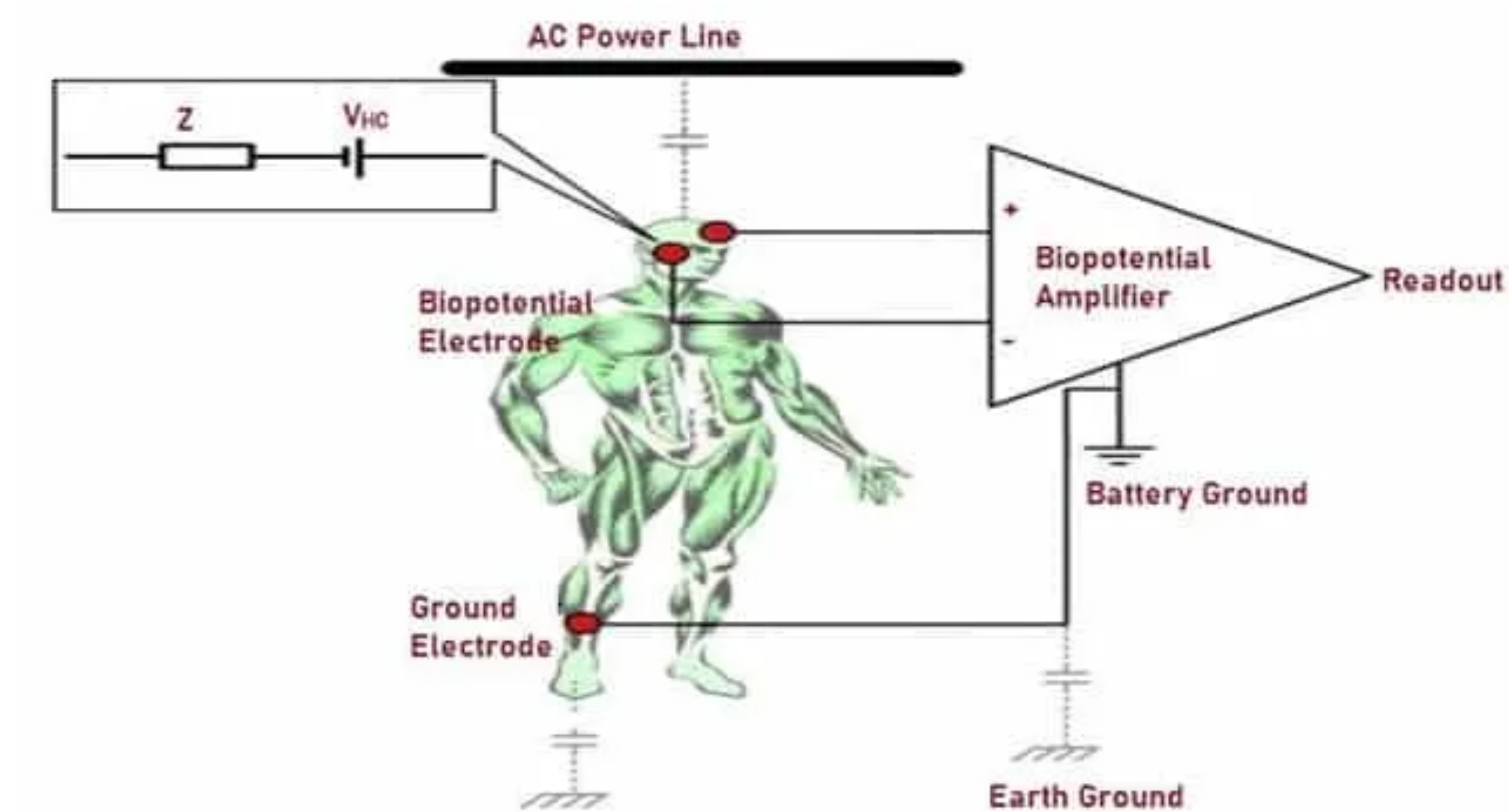
Amplification

- Sensor outputs may (read: amost always) need amplification for any sort of acquisition and data analysis
- Use operational amplifier to do this
  - Amplifies differential input: Out = $A(V_{in+}-V_{in-})$, where A is large

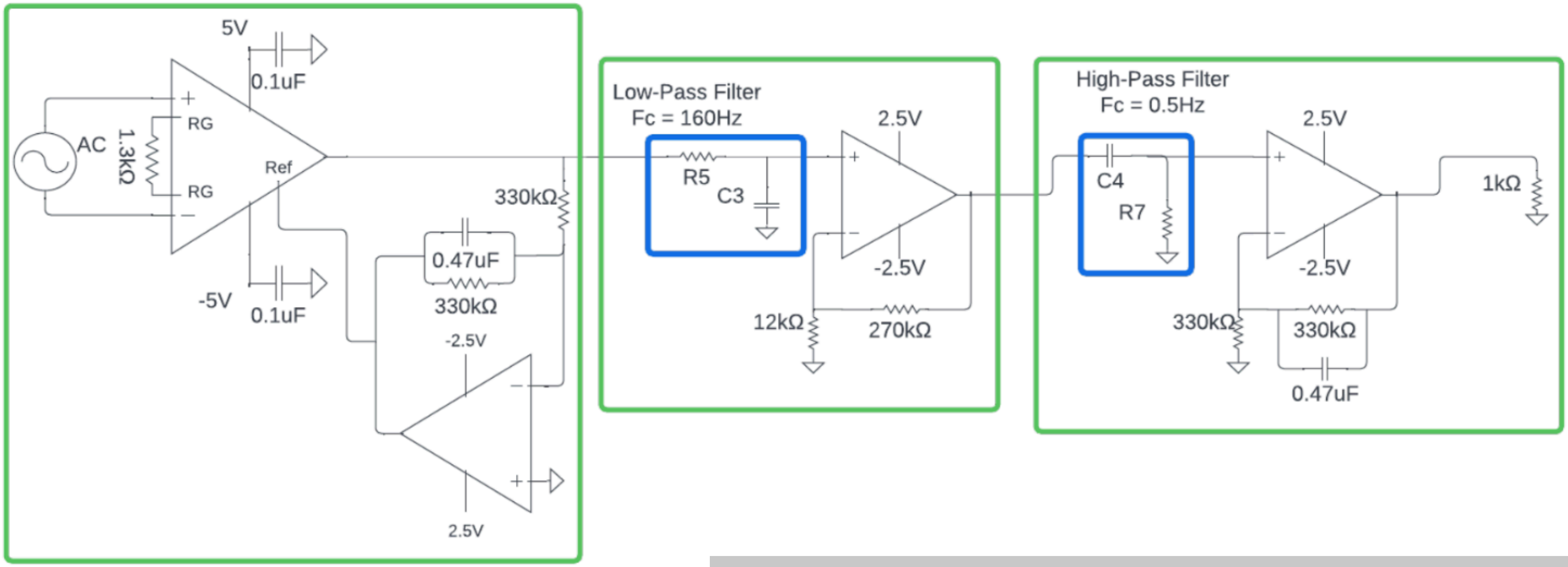


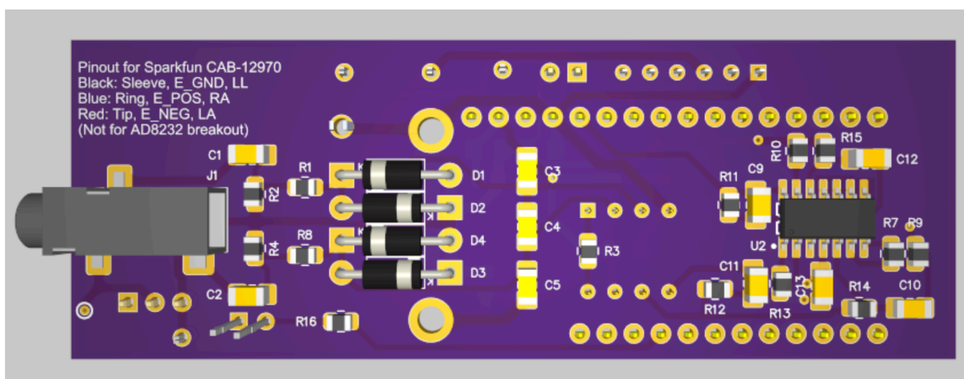
Biopotential Amplifier

- Differential amplifier

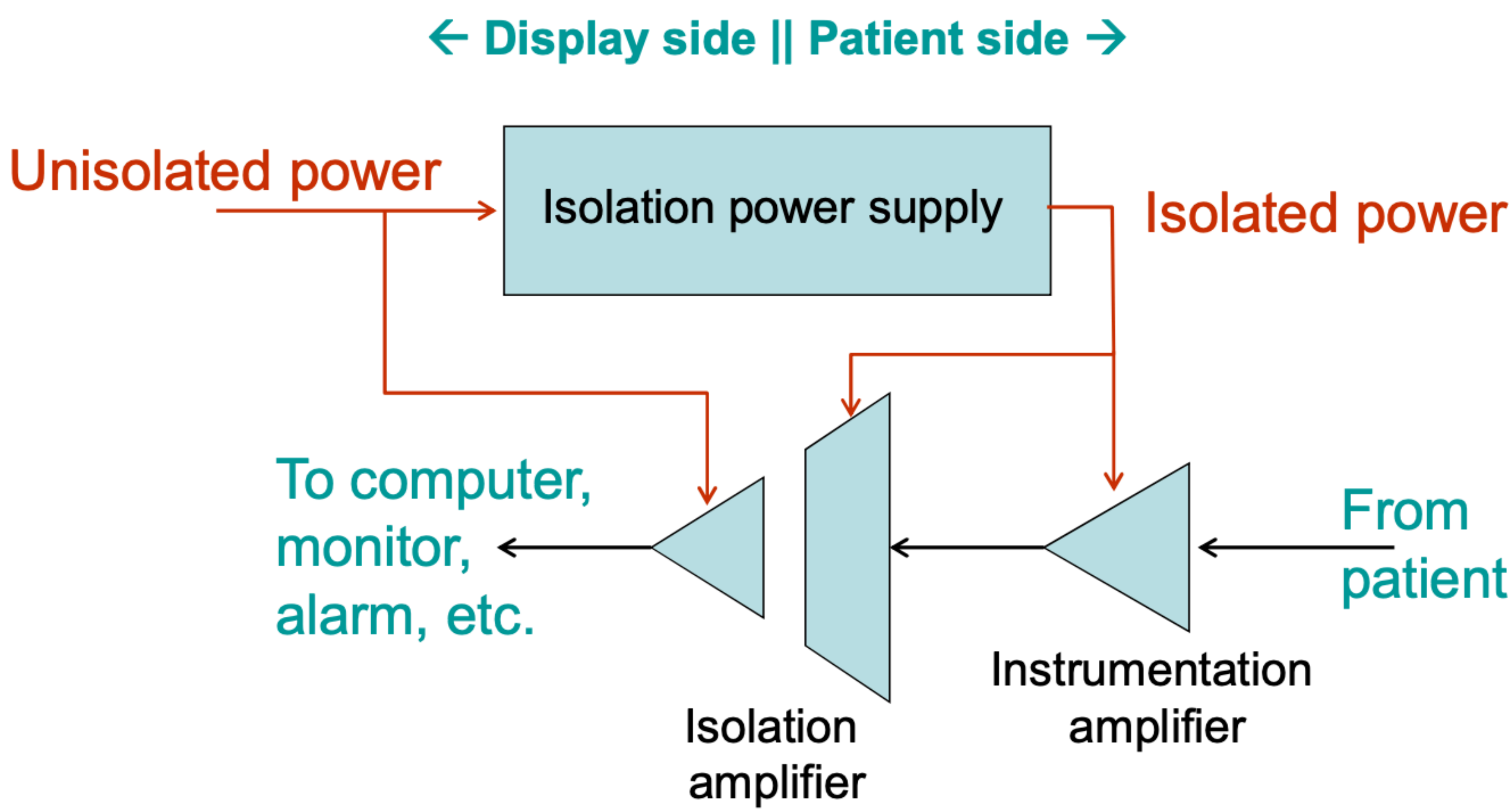


Signal Conditioning

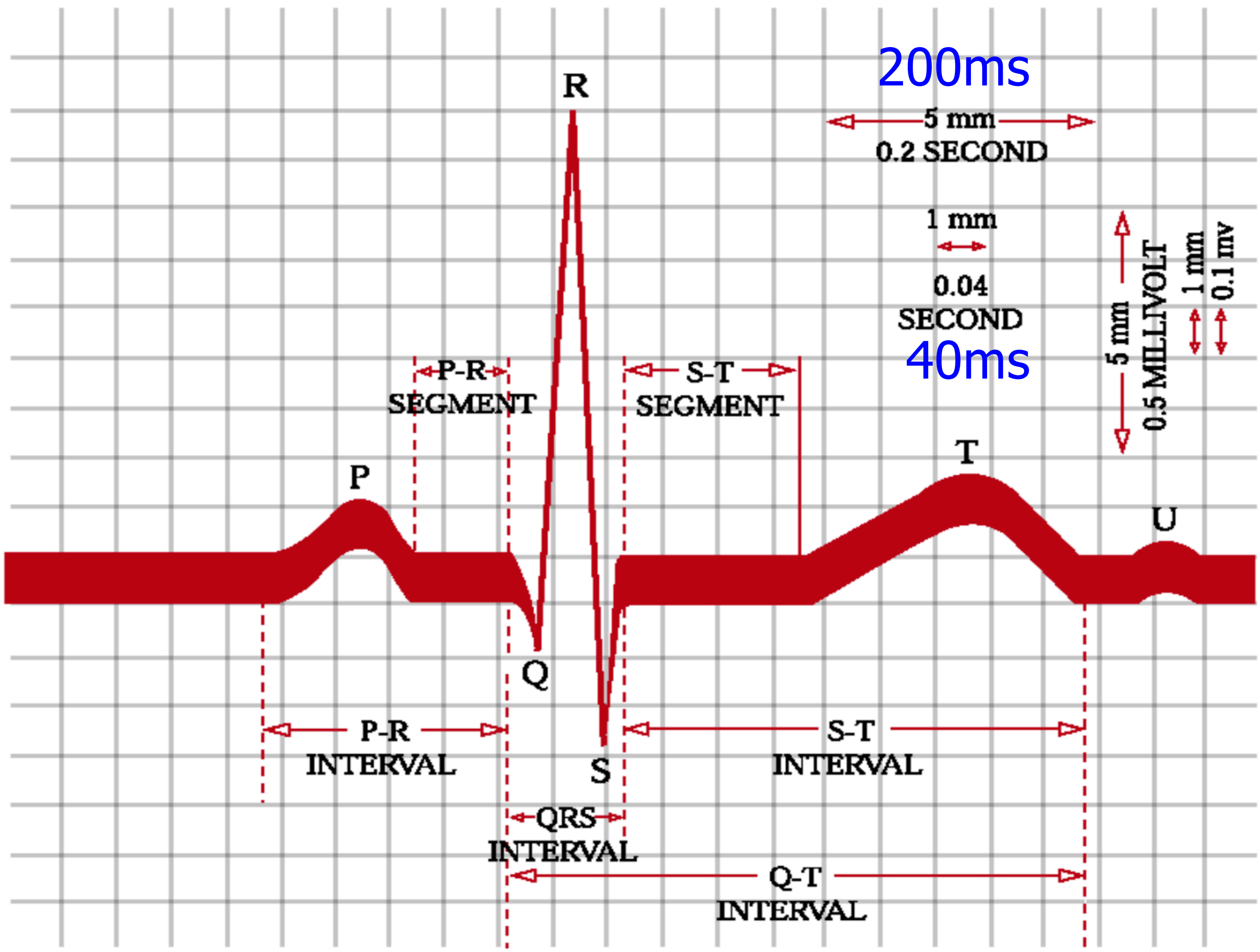




Basic Isolation System



Typical ECG Signal



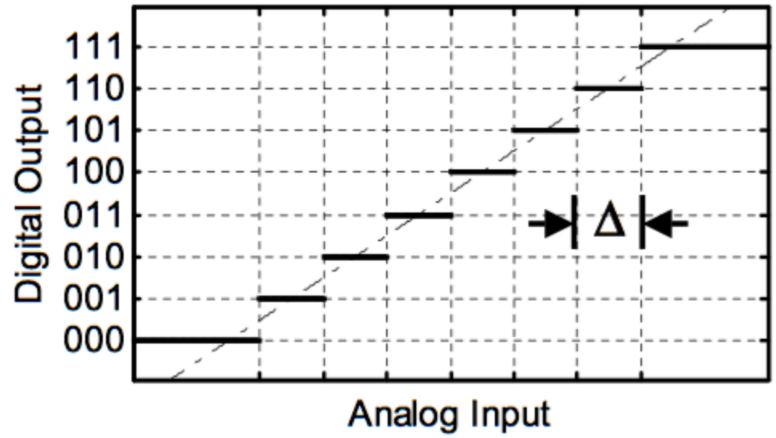
Recording Conventions, Waveform Nomenclature, and Normal Values for the Electrocardiogram.

ADC

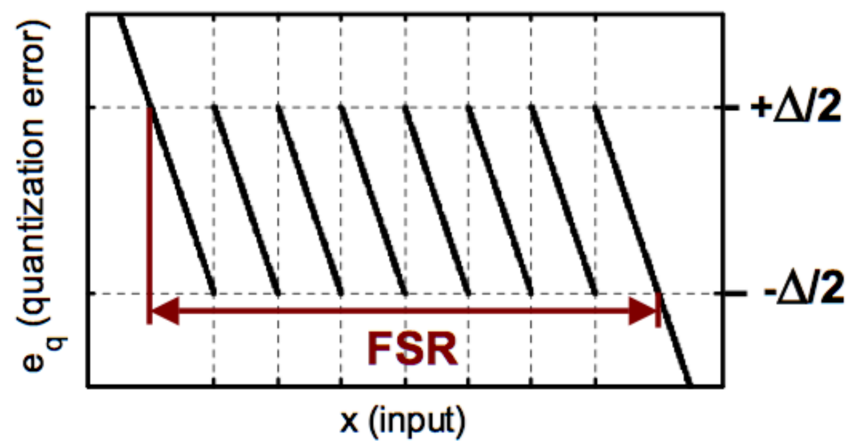
Analog to Digital Converter

Ideal B-bit Quantizer

- Practical quantizers have a limited input range and a finite set of output codes
- E.g. a 3-bit quantizer can map onto $2^3=8$ distinct output codes



- Quantization error grows out of bounds beyond code boundaries
- We define the full scale range (FSR) as the maximum input range that satisfies $|e_q| \leq \Delta/2$
  - Implies that $FSR = 2^B \cdot \Delta$



Signal-to-Quantization-Noise Ratio

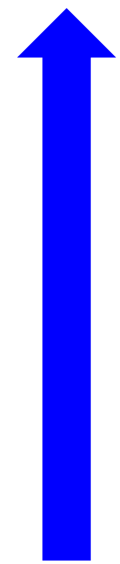
- Assuming full-scale sinusoidal input, we have

$$SNR_Q = 6.02B + 1.76 \text{ dB}$$

B (Number of Bits)	SQNR
8	50dB
12	74dB
16	98dB
20	122dB

Nyquist ADC Architectures

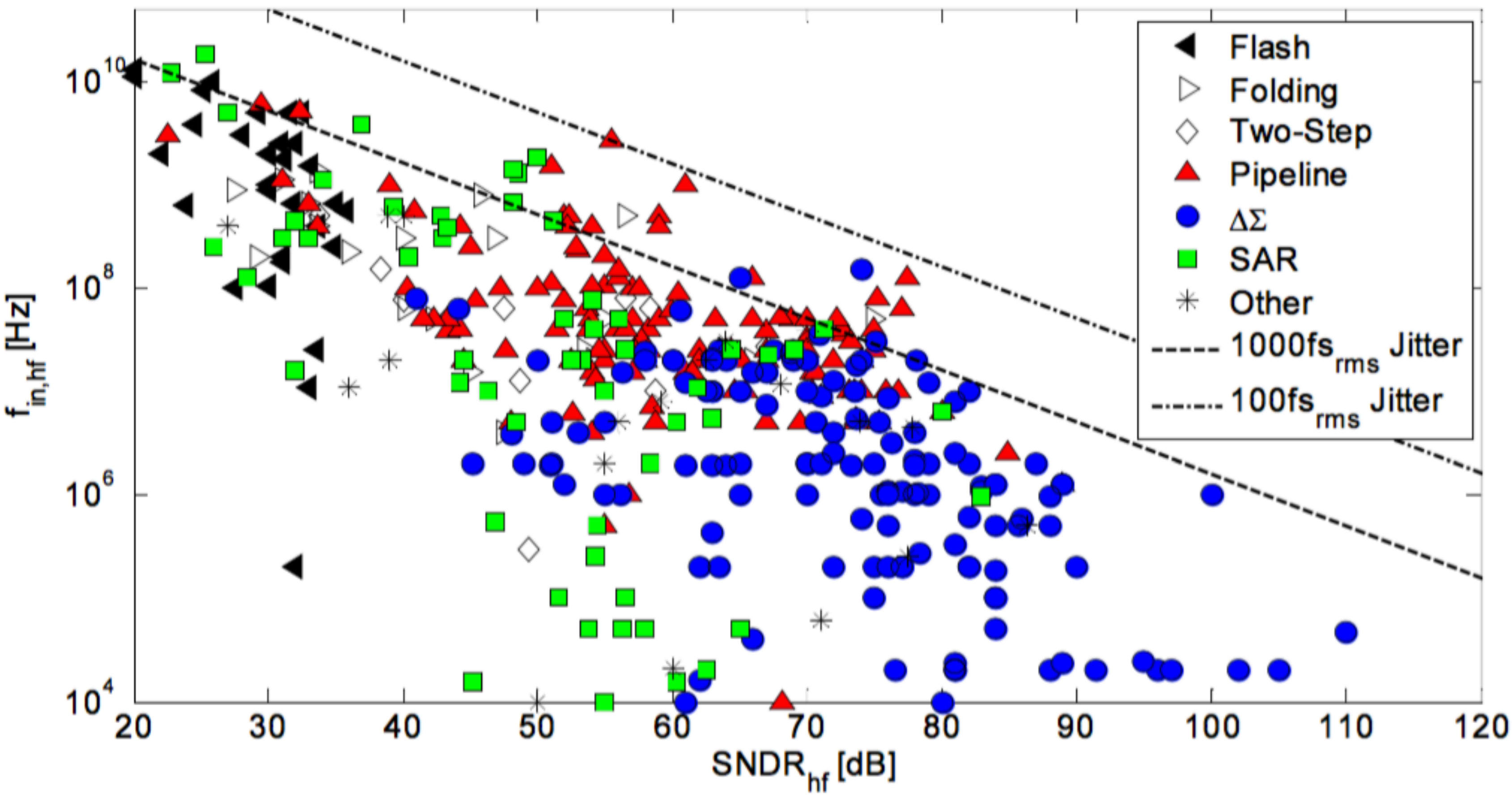
- Word-at-a-time
  - E.g. flash ADC
  - Instantaneous comparison with 2^B-1 reference levels
- Multi-step
  - E.g. pipeline ADCs
  - Coarse conversion, followed by fine conversion of residuals
- Bit-at-a-time
  - E.g. successive approximation ADCs
  - Conversion via a binary search algorithm



speed

ADC Survey (ISSCC & VLSI 1997-2013)

Data: http://www.stanford.edu/~murmann/adcsurvey.html



ADC Big Ideas

- SQNR
  - SQNR determined by bit resolution, B
- Nyquist ADCs
  - Flash ADCs
    - Word-at-a-time for high speed, low resolution applications
  - SAR ADCs
    - Bit-at-a-time for low speed, low power applications
    - Highly suited for medical devices
- Oversampling
  - Enables reduction in quantization noise with digital filter
  - Sigma-Delta ADCs
    - Use integrator in feedback to shape noise and achieve high resolution
    - Usually for low speed, low power applications

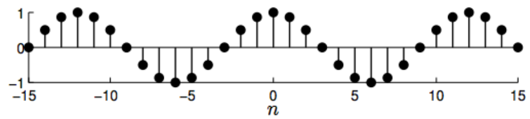
Signals and Systems

Discrete-Time Sinusoids

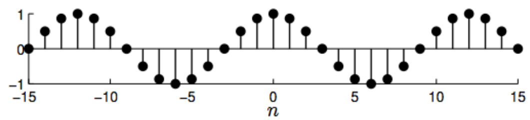
- Discrete-time sinusoids $e^{j(\omega n+\phi)}$ have two counterintuitive properties

- Both involve the frequency ω

$x_1[n] = \cos\left(\frac{\pi}{6}n\right)$



$x_2[n] = \cos\left(\frac{13\pi}{6}n\right) = \cos\left(\left(\frac{\pi}{6}+2\pi\right)n\right)$



- **Property #1**: Aliasing

- **Property #2**: Aperiodicity

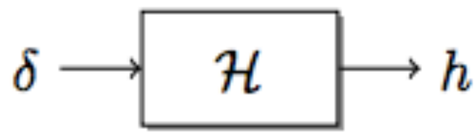
$$\omega = \frac{2\pi k}{N}, \quad k, N \in \mathbb{Z}$$

LTI Systems

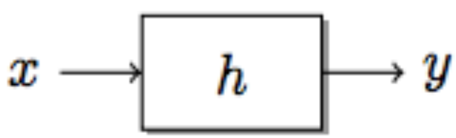
DEFINITION

A system $\mathcal{H}$ is **linear time-invariant** (LTI) if it is both linear and time-invariant

- LTI system can be completely characterized by its impulse response



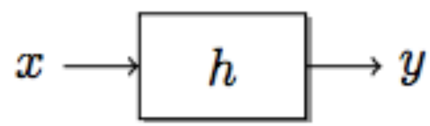
- Then the output for an arbitrary input is a sum of weighted, delay impulse responses



$$y[n] = \sum_{m=-\infty}^{\infty} h[n-m]\, x[m]$$

$$y[n] = x[n] * h[n]$$

Convolution



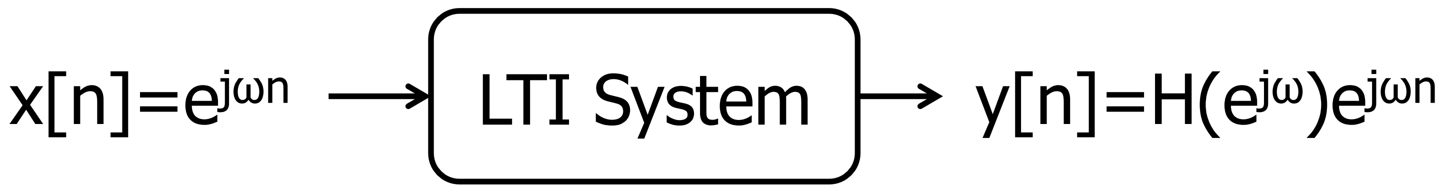
- Convolution formula:

$$y[n] = x[n] * h[n] = \sum_{m=-\infty}^{\infty} h[n-m]\, x[m]$$

- Convolution method:
  - 1) Time reverse the impulse response and shift it *n* time steps to the right
  - 2) Compute the inner product between the shifted impulse response and the input vector
  - Repeat for evey *n*

LTI System Frequency Response

- (DT)Fourier Transform of impulse response



$$H(e^{j\omega}) = \sum_{k=-\infty}^{\infty} h[k] e^{-j\omega k}$$

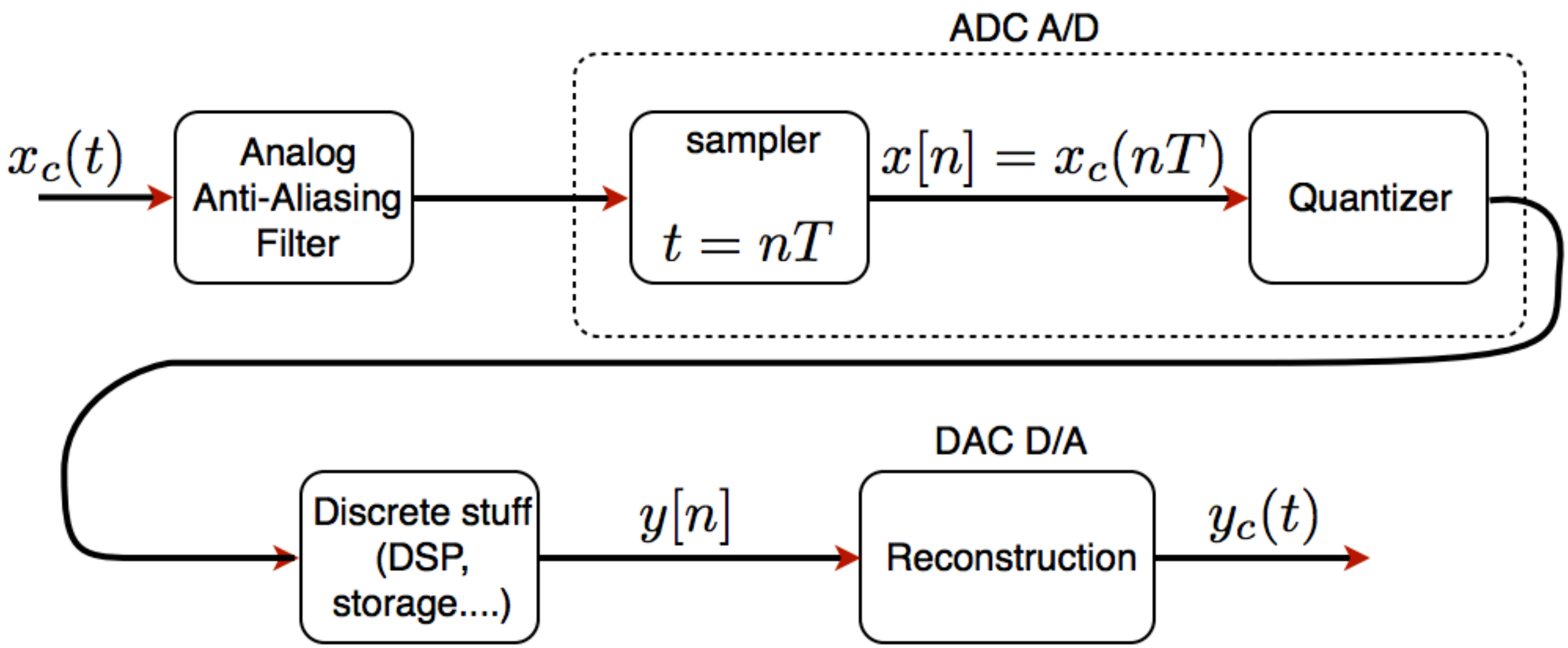
DTFT and Sampling

DTFT Definition

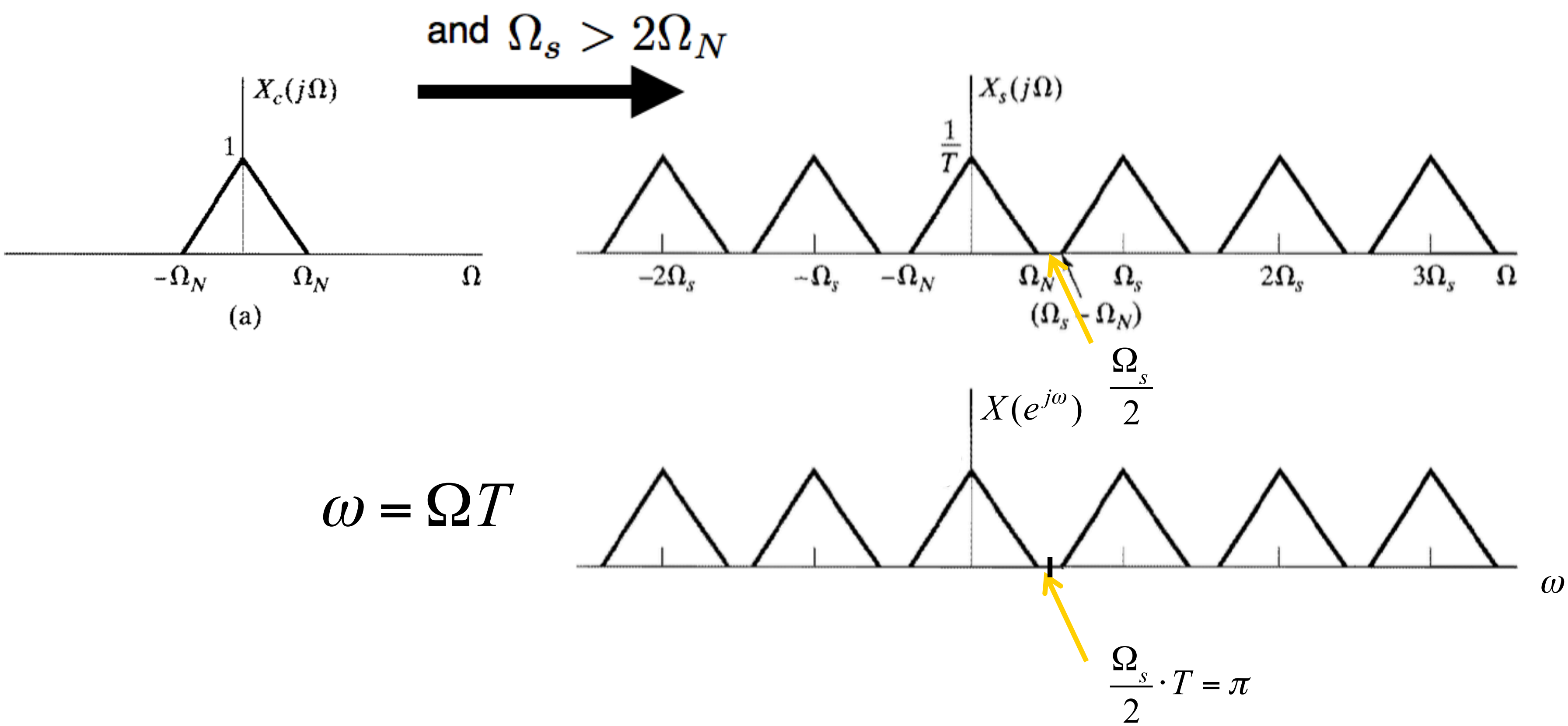
$$X(e^{j\omega}) = \sum_{k=-\infty}^{\infty} x[k] e^{-j\omega k}$$

$$x[n] = \frac{1}{2\pi} \int_{-\pi}^{\pi} X(e^{j\omega}) e^{j\omega n} d\omega$$

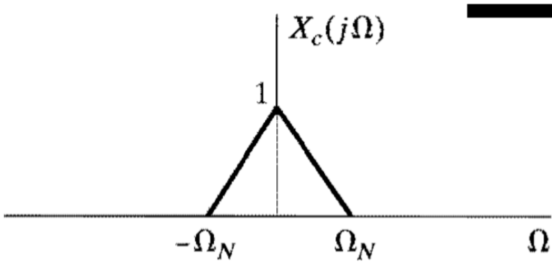
DSP System


ADC A/D
$x_c(t)$
Analog Anti-Aliasing Filter
sampler
$t = nT$
$x[n] = x_c(nT)$
Quantizer
DAC D/A
Discrete stuff (DSP, storage....)
$y[n]$
Reconstruction
$y_c(t)$

Frequency Domain Analysis

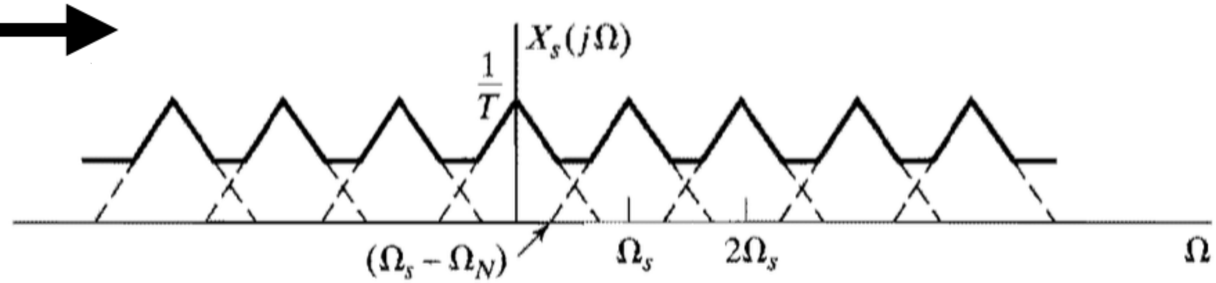


Frequency Domain Analysis w/Aliasing

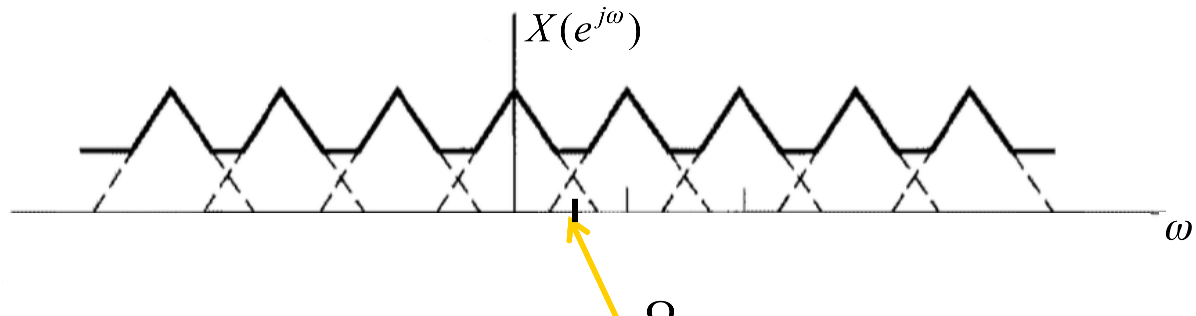


(a)

and $\Omega_s < 2\Omega_N$

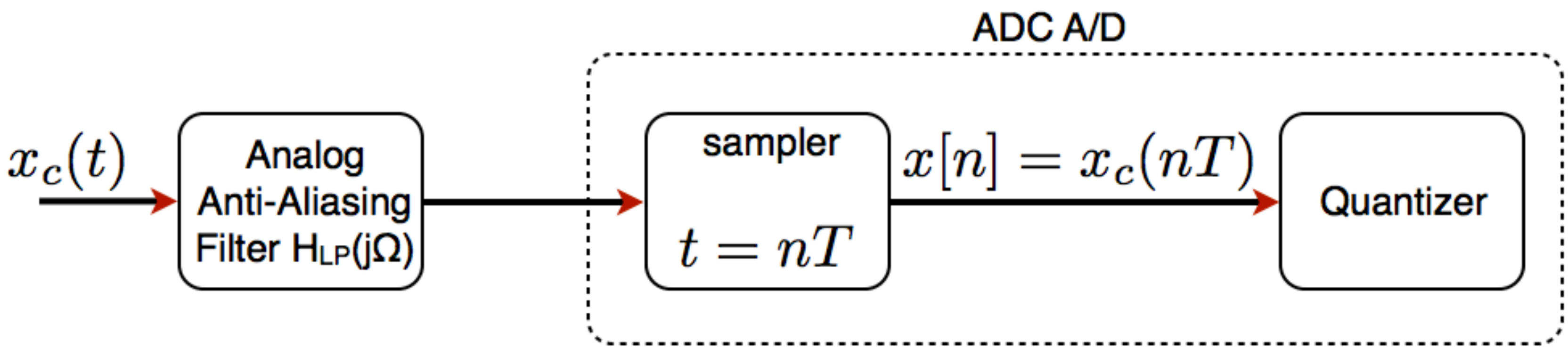


$$\omega = \Omega T$$

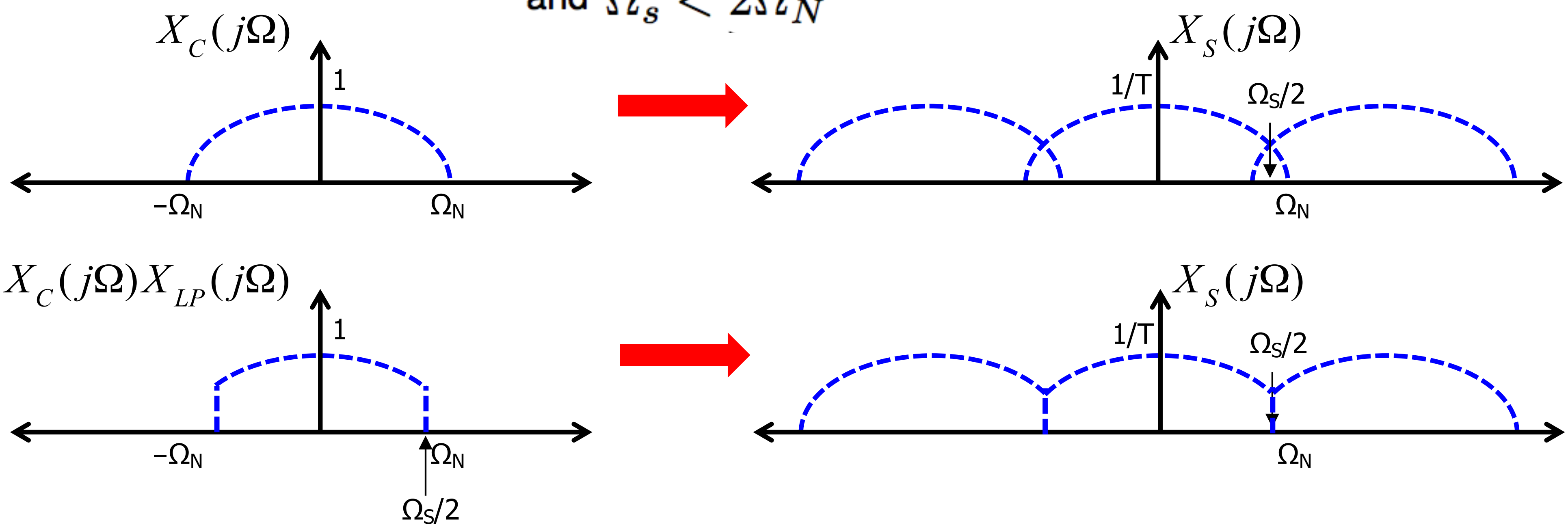


$$\frac{\Omega_s}{2} \cdot T = \pi$$

Anti-Aliasing Filter

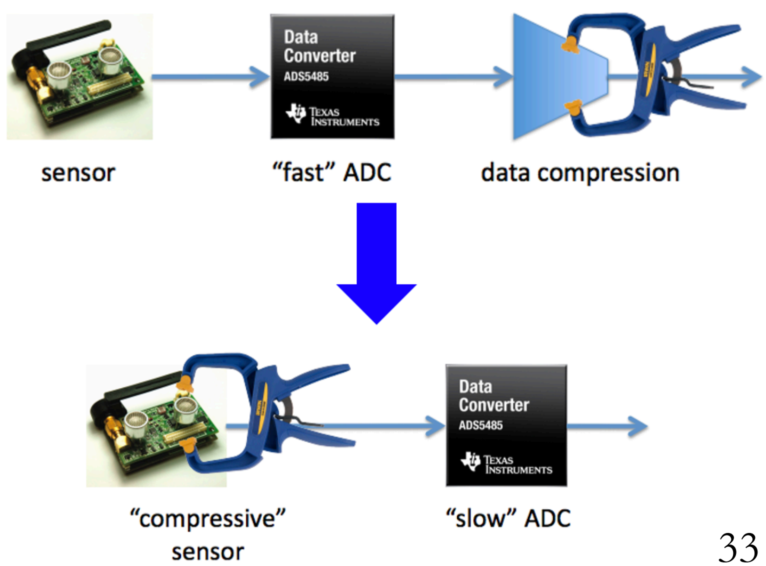


and $\Omega_s < 2\Omega_N$



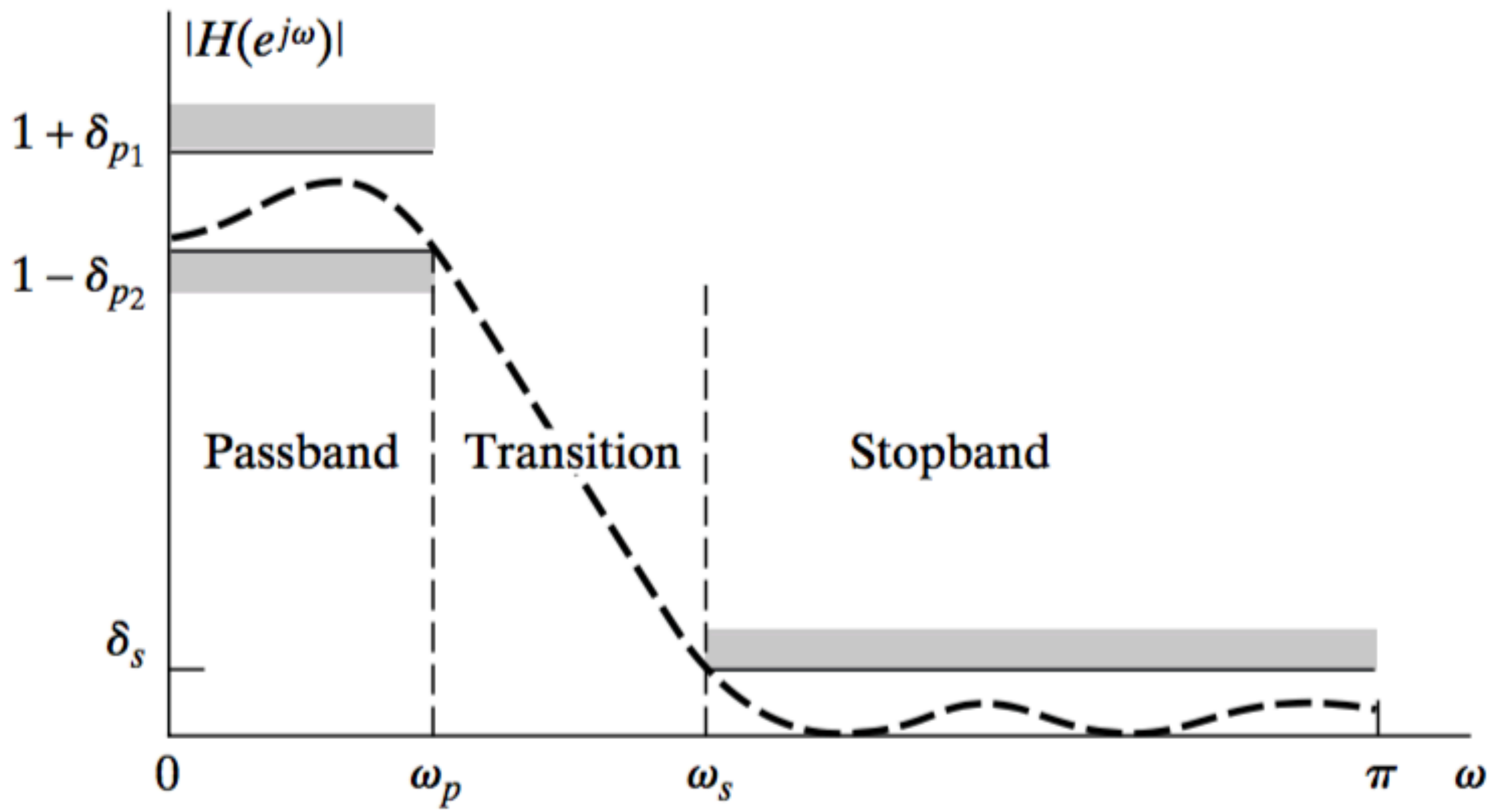
Compressive Sensing

- Shannon/Nyquist theorem is pessimistic
  - 2 × bandwidth is the worst-case sampling rate — holds uniformly for any bandlimited data
  - Sparsity/compressibility is irrelevant
  - Shannon sampling based on a linear model, compression based on a nonlinear model
- Compressive sensing
  - New sampling theory that leverages compressibility
  - Two conditions needed:
    - Sparsity in some domain
    - Transformation to incoherent domain

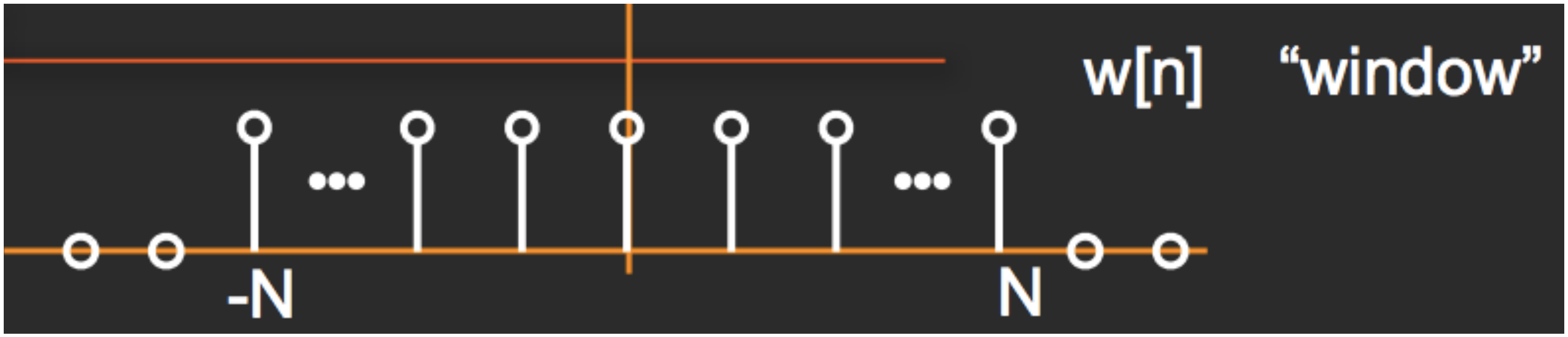


Digital Filters

Filter Specifications



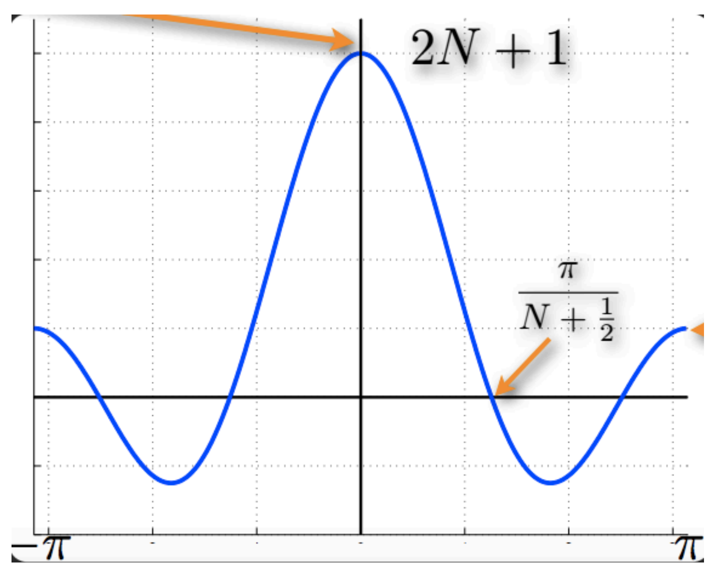
Example: Window DTFT



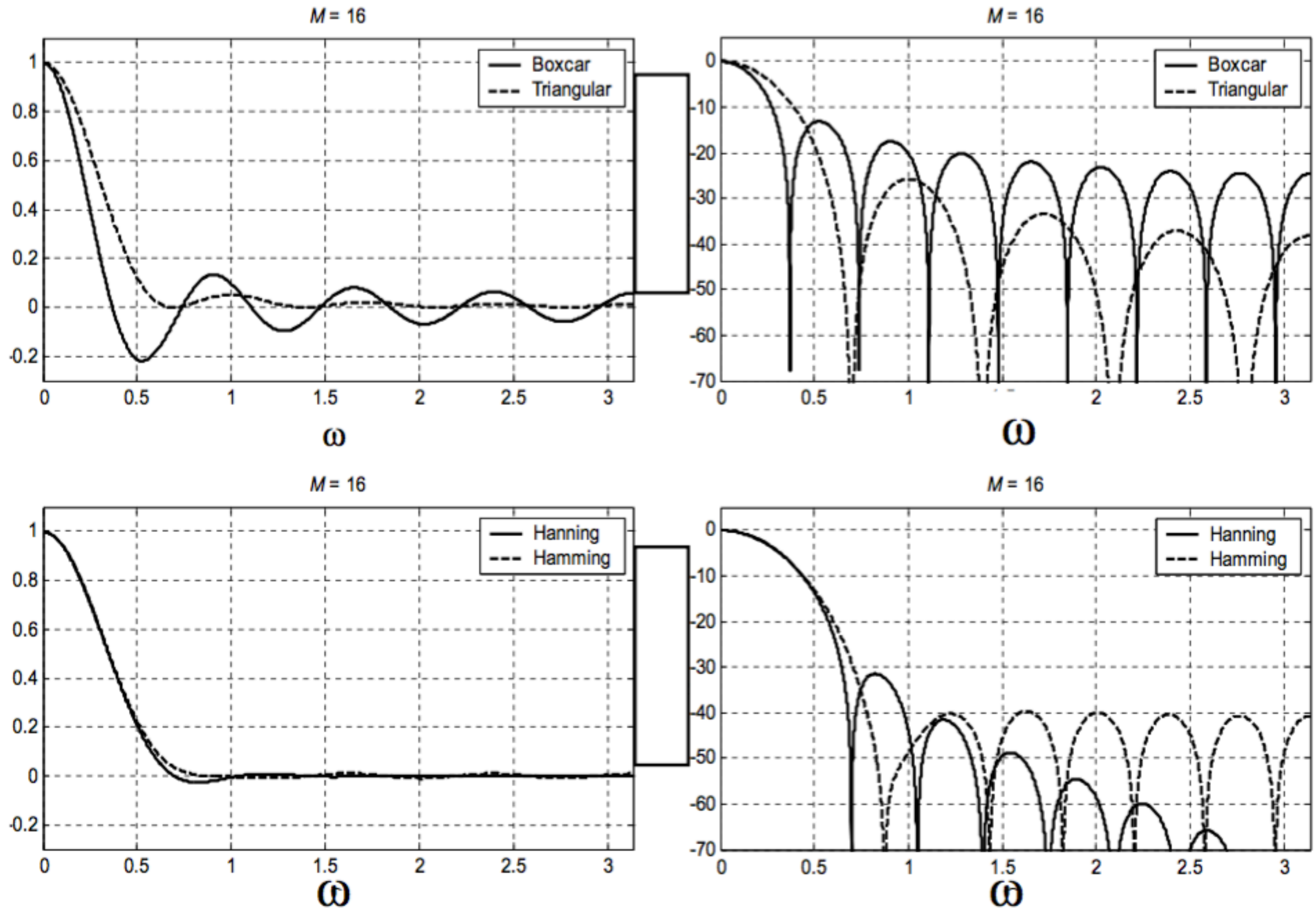
$$W(e^{j\omega}) = \sum_{k=-\infty}^{\infty} w[k] e^{-j\omega k}$$

$$= \sum_{k=-N}^{N} e^{-j\omega k}$$

$$W(e^{j\omega}) = \frac{\sin\left((N+1/2)\omega\right)}{\sin\left(\omega/2\right)}$$



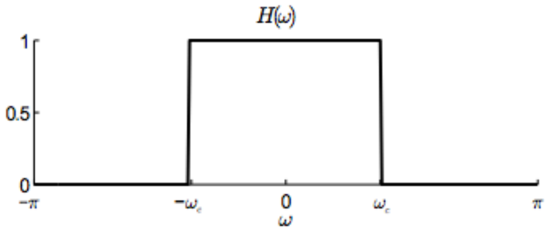
Tradeoff – Ripple vs. Transition Width



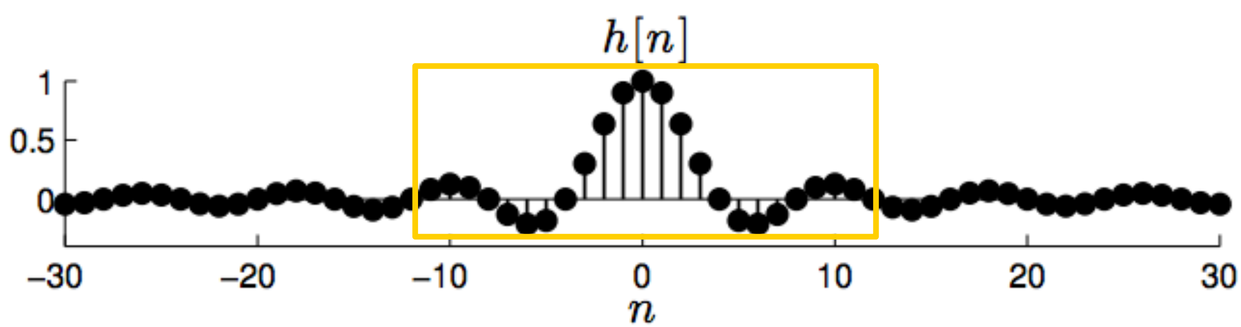
Example: Ideal Low-Pass Filter

- The frequency response $H(\omega)$ of the ideal low-pass filter passes low frequencies (near $\omega = 0$) but blocks high frequencies (near $\omega = \pm\pi$)

$$H(\omega) = \begin{cases} 1 & -\omega_c \leq |\omega| \leq \omega_c \\ 0 & \text{otherwise} \end{cases}$$



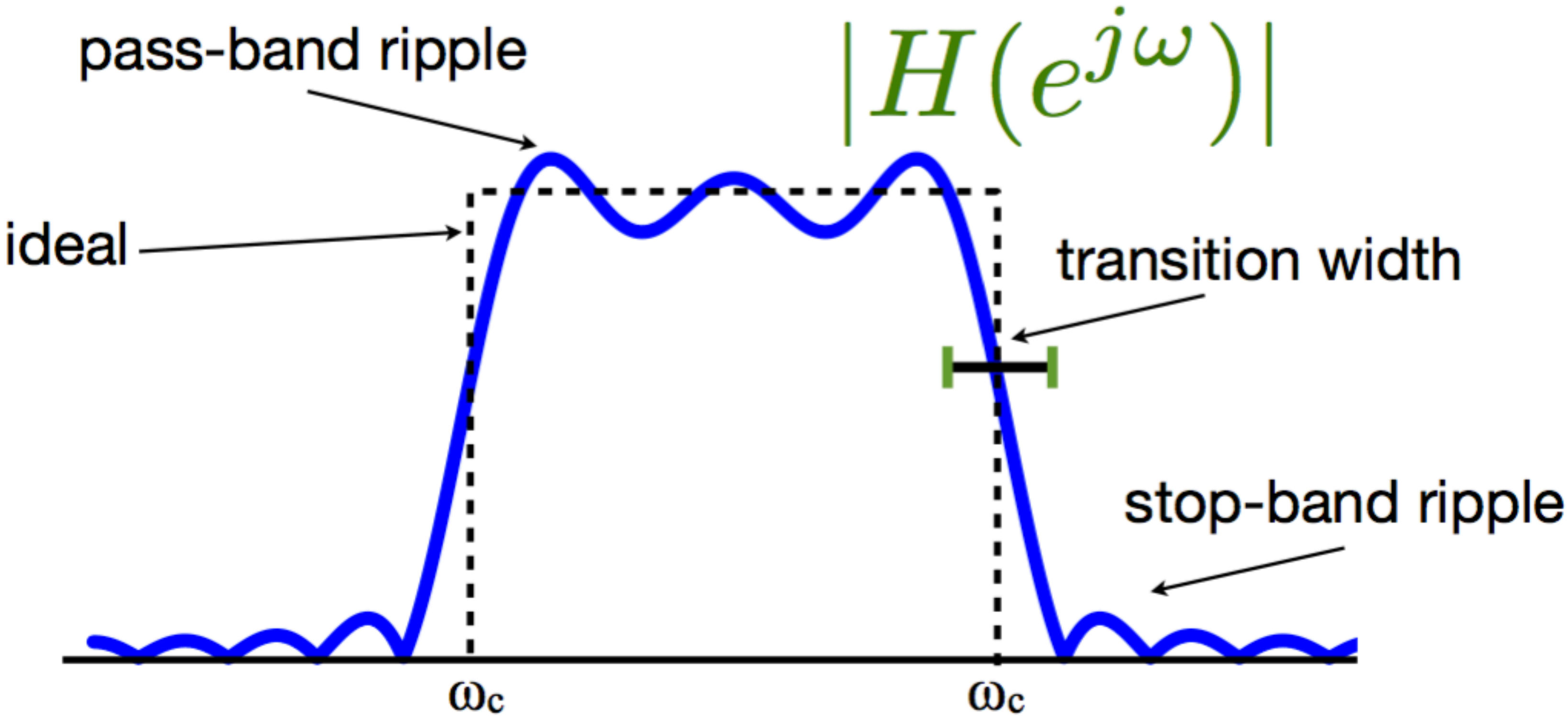
$$h[n] = 2\omega_c \frac{\sin(\omega_c n)}{\omega_c n}$$



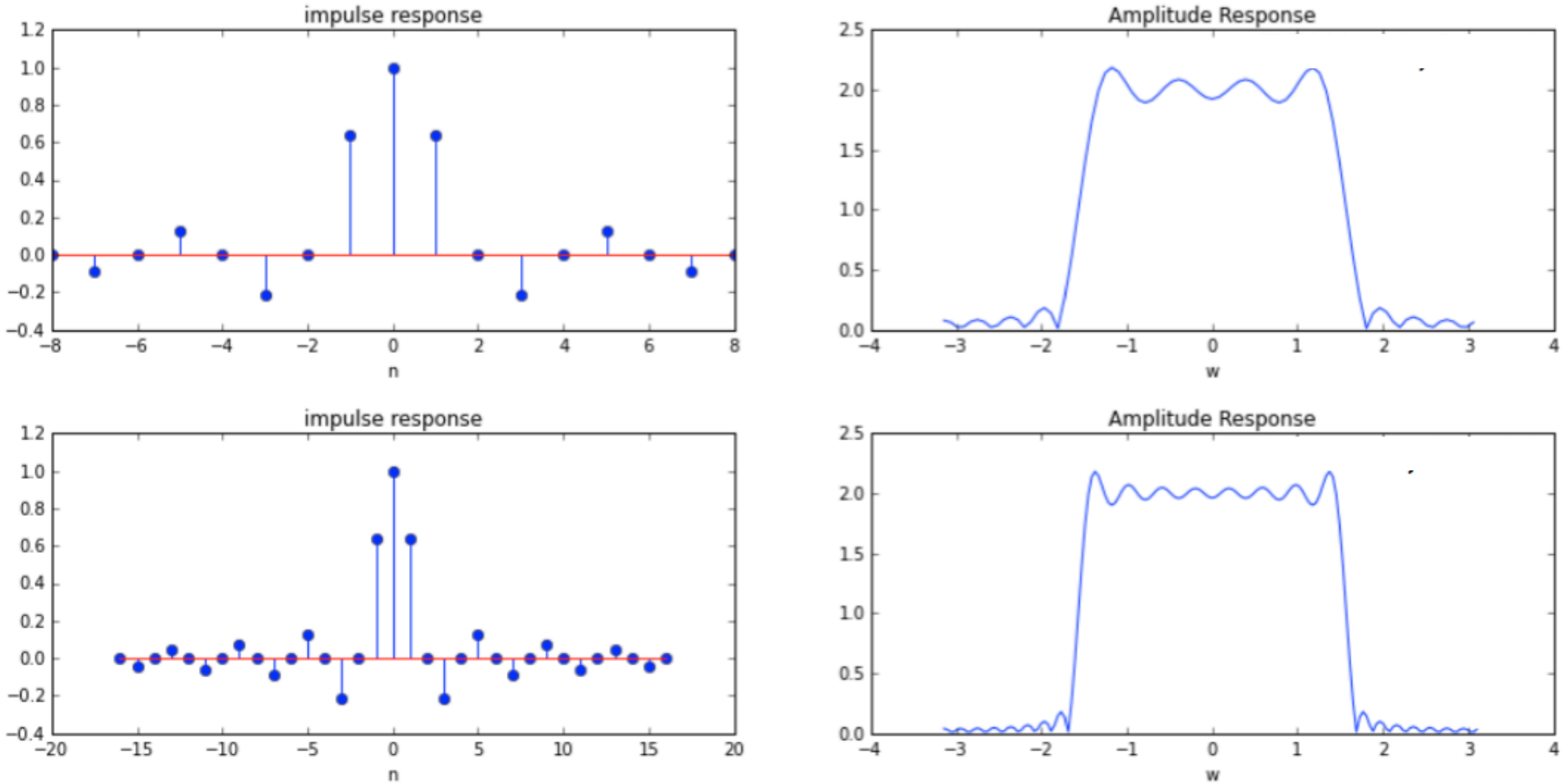
Truncate and shift

$$h_{LP}[n] = w_N[n-N] \cdot h[n-N]$$

FIR Design by Windowing

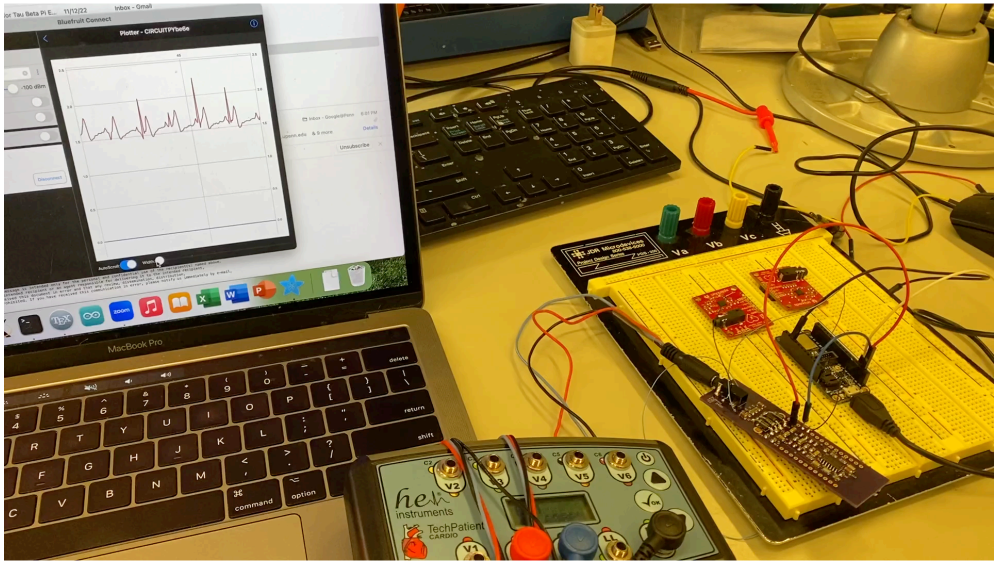


Time Bandwidth Product



Final Project

- Hands-on Skills learned:
  - Sensor Characterization
  - Filter Characterization
  - Circuit Simulation in SPICE
  - Board level implementation
  - PCB design and layout in Altium
  - Arduino Microcontroller and BLE experience
  - Python coding
    - And CircuitPython!



Feedback?

- What was your experience?
- What would you covered that wasn't?
  - What did you want more detail on?
- What was covered that you don't care about?
- What did you need more/less time for?
- What did you need more guidance/references on?

- Send me an email
- Slip a note under my office door
- Write in course review
- Send by carrier pigeon

Admin

- Make sure you turn in all Labs, Presentations, and Report by tonight at Midnight
  - Anything submitted after is subject to late penalty

- Thank you for all your hard work and participation this semester!