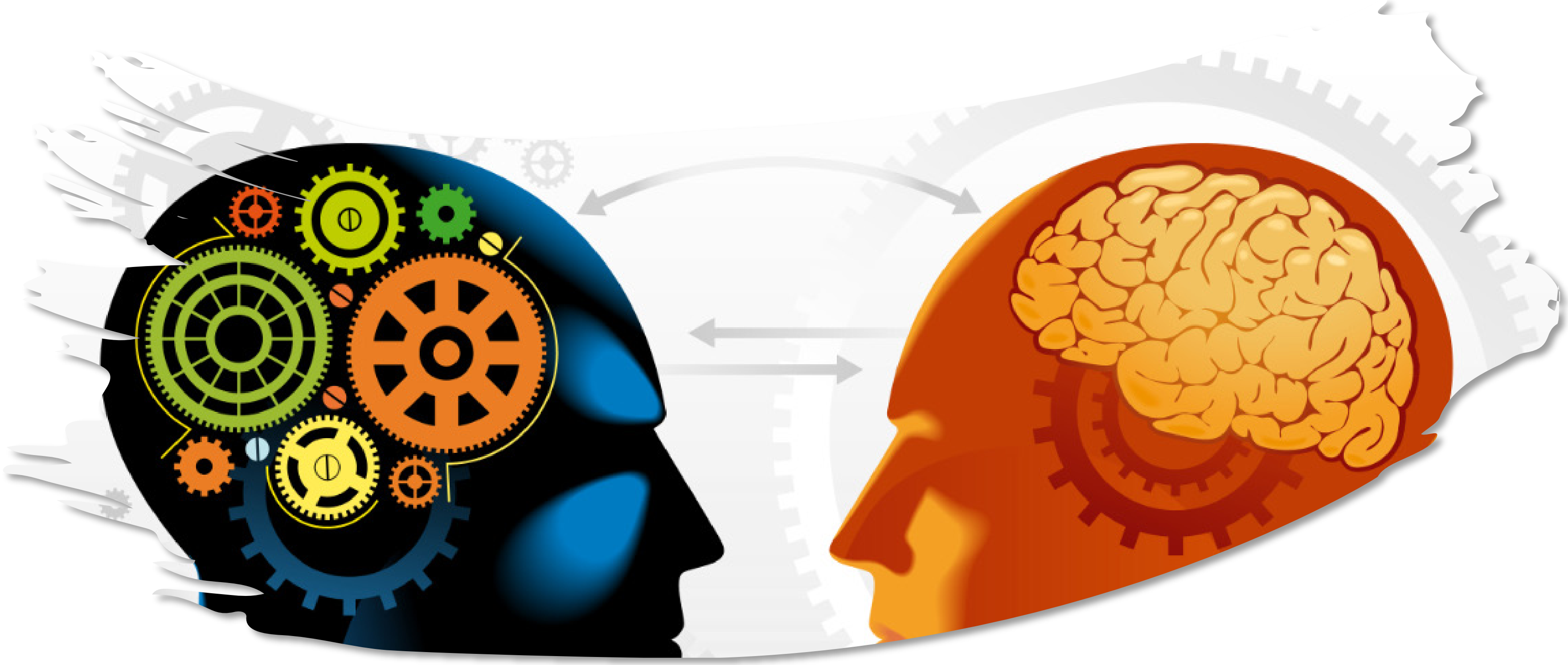

Building the Infinite Brain

COMP 690 (193)

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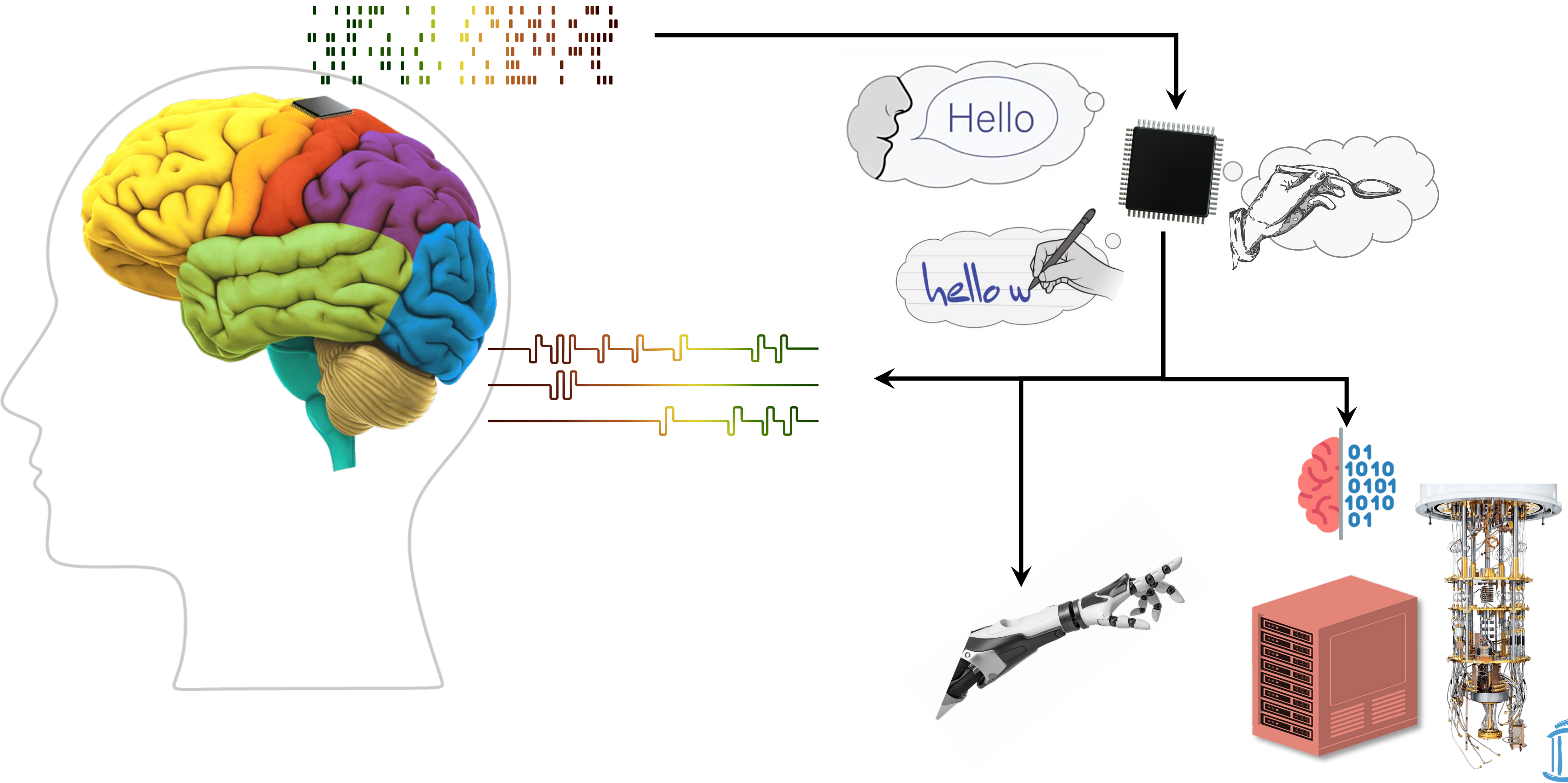
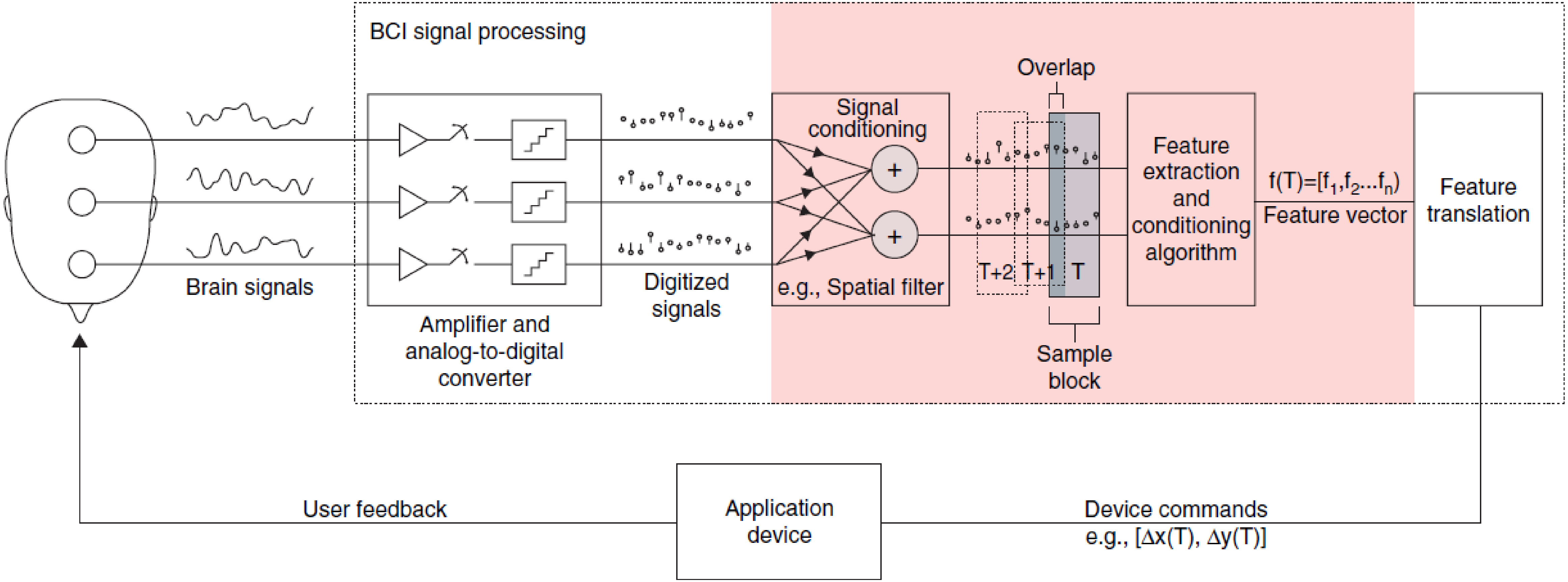
For Today

- **Overview of (digital) signal processing methods in brain-computer interfaces**

BCI Processing

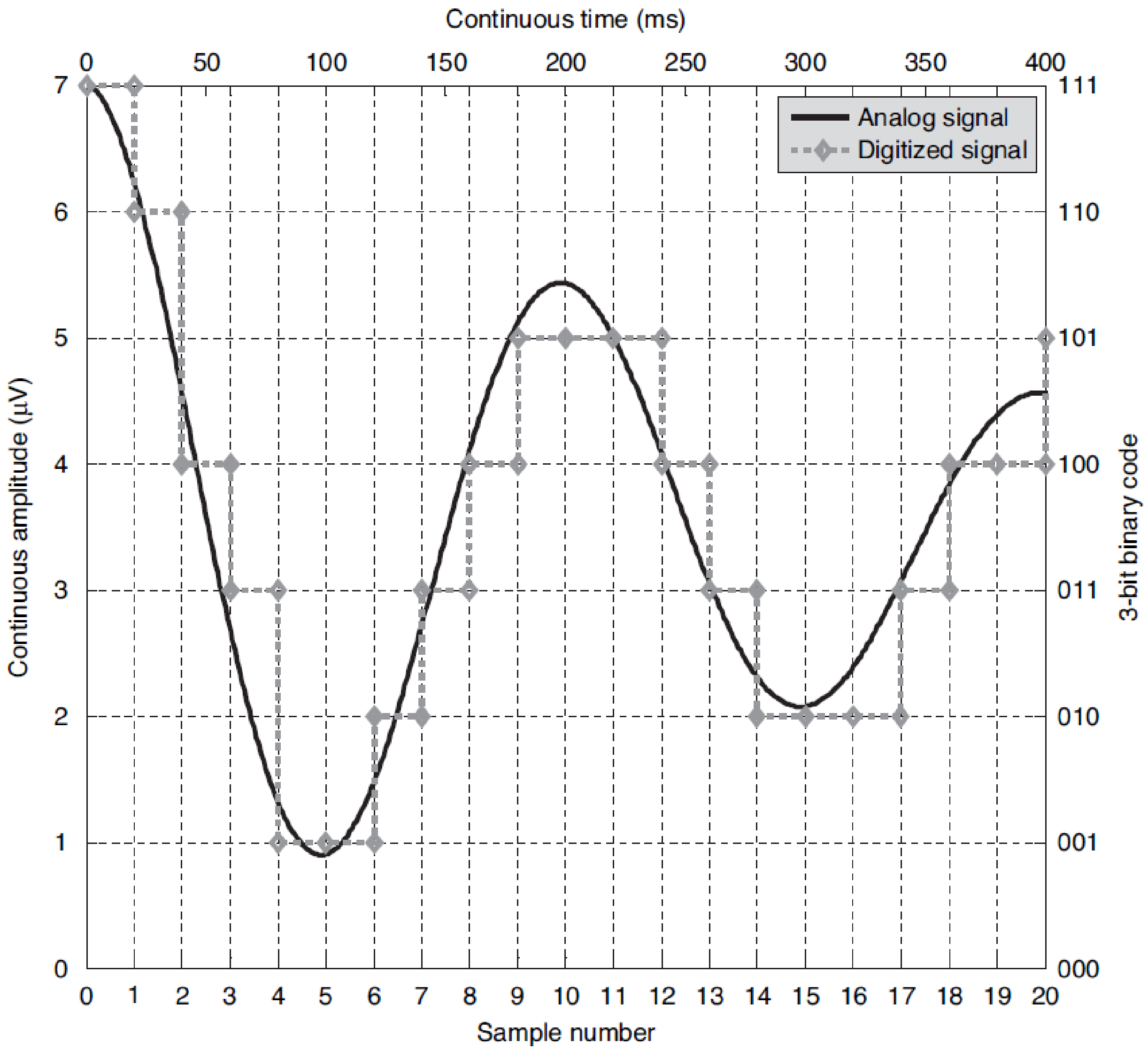


BCI Processing



Feature: property of a signal that is precisely characterized, modulated by users, and correlated with intent

Digitization



At most 16-bit samples at 30-45 kHz

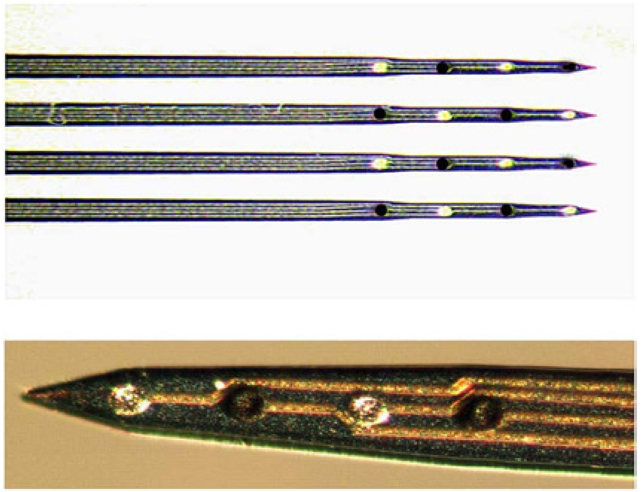
LFPs are lower resolution

Common Average Referencing

$$V_{clean} = V_{original} - \frac{1}{n}\sum_{i=1}^{n} V_i$$

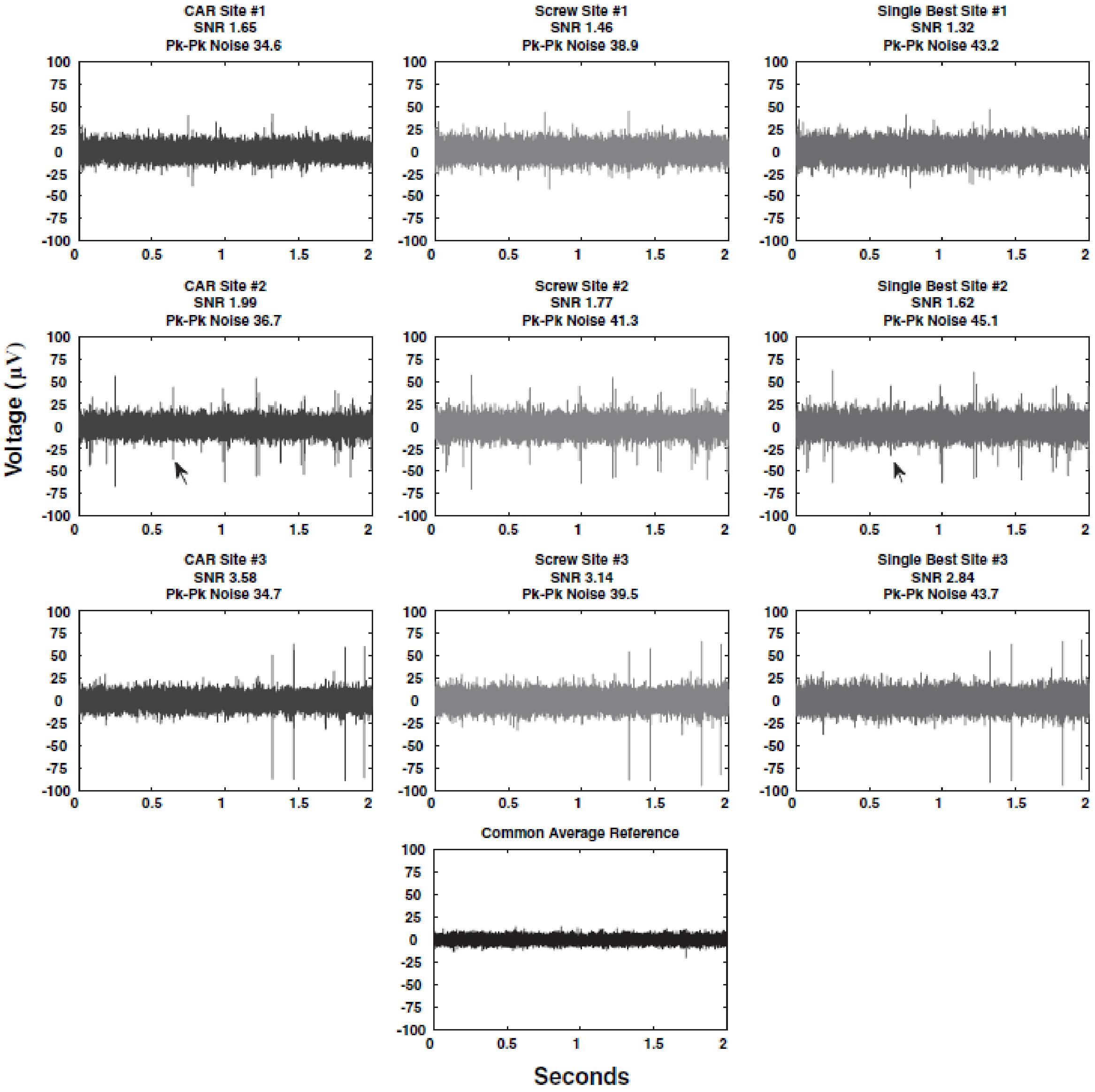
Average across all samples in a window

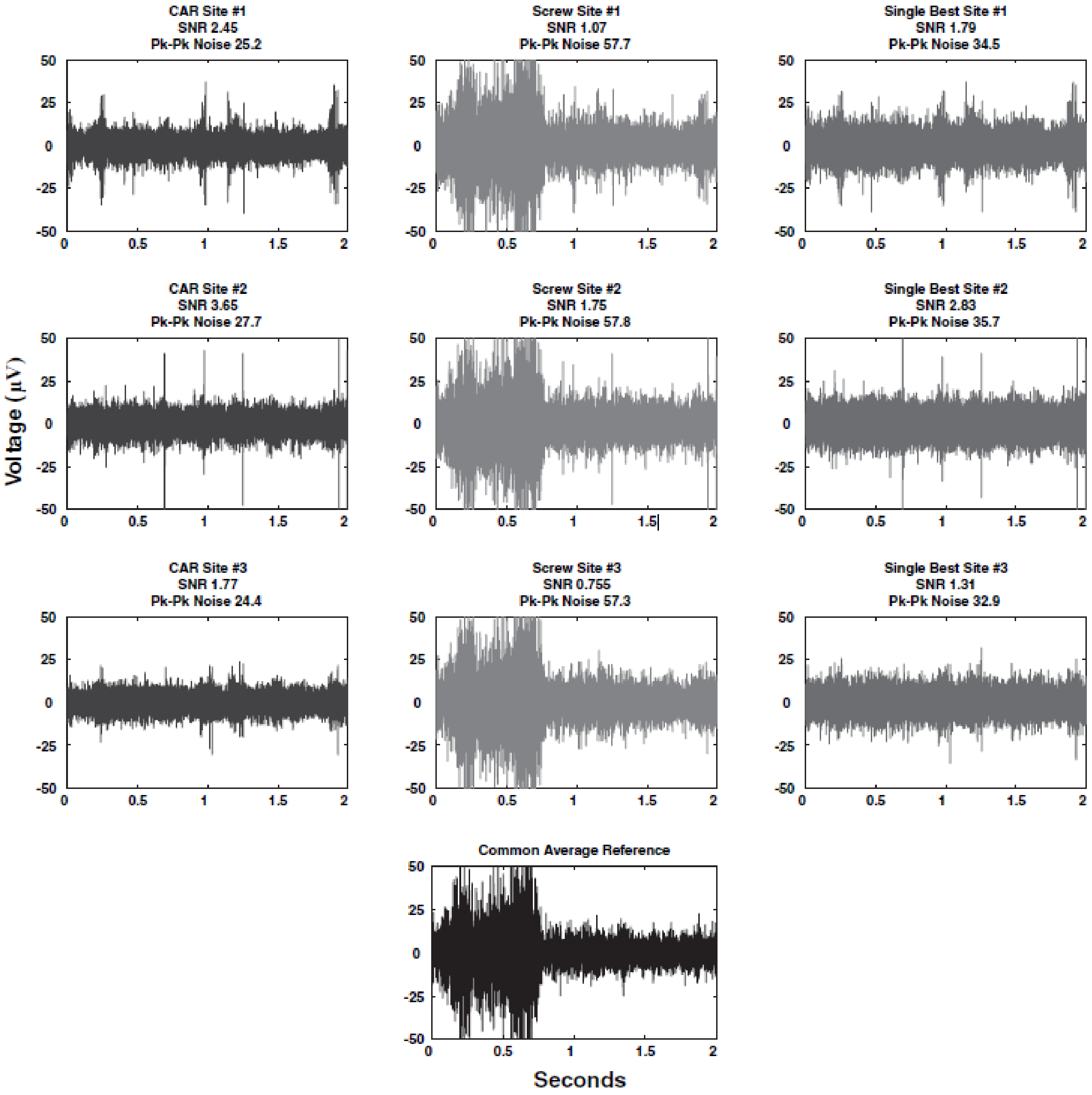
Common Average Referencing



Michigan array (16 channels)

Common Average Referencing





Filtering

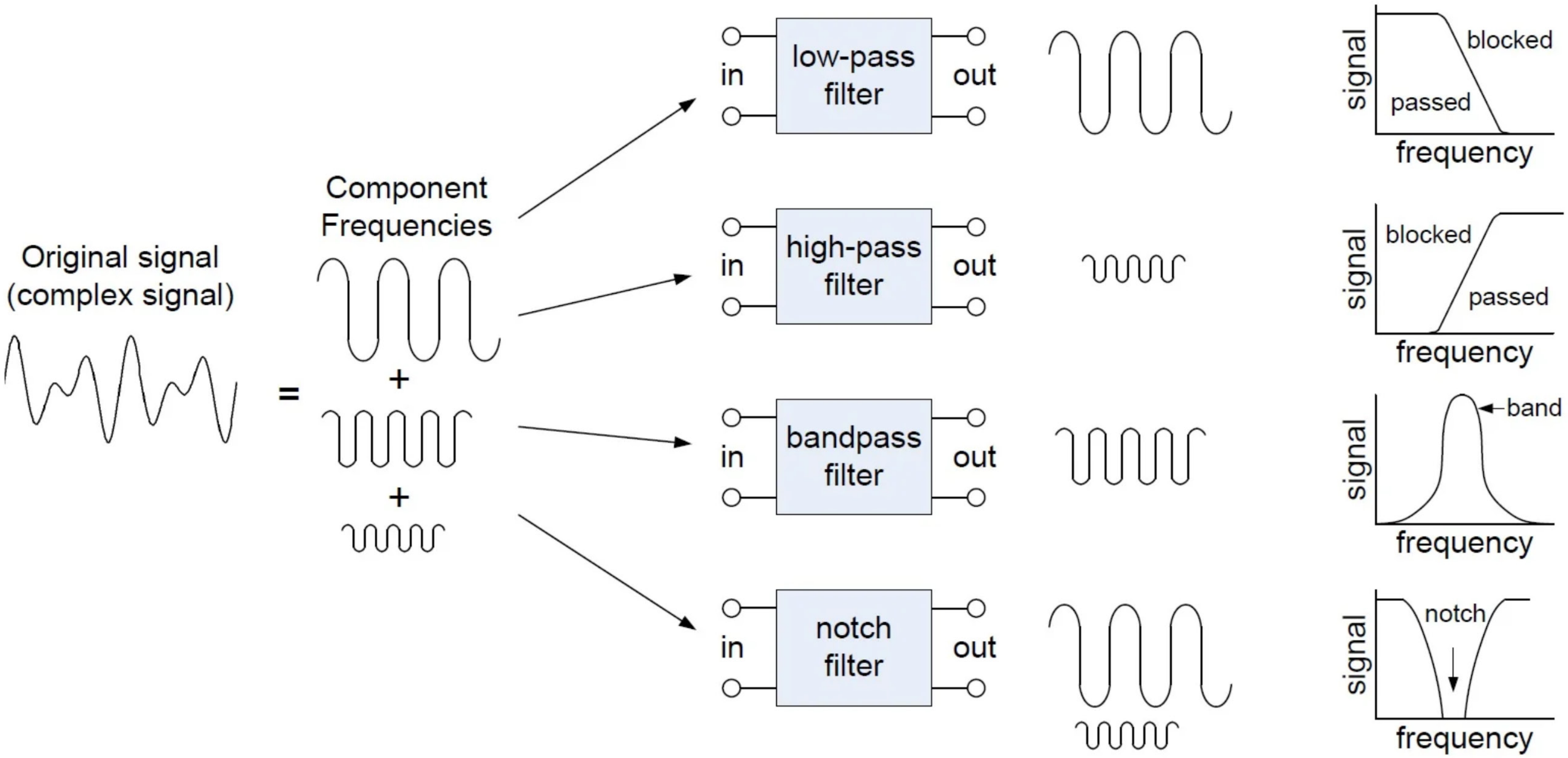
$$y[n] = \sum_{i=0}^{M} a_i \times x[n-i] \;\; - \sum_{j=1}^{L} b_i \times y[n-j]$$

Past inputs **Past outputs**

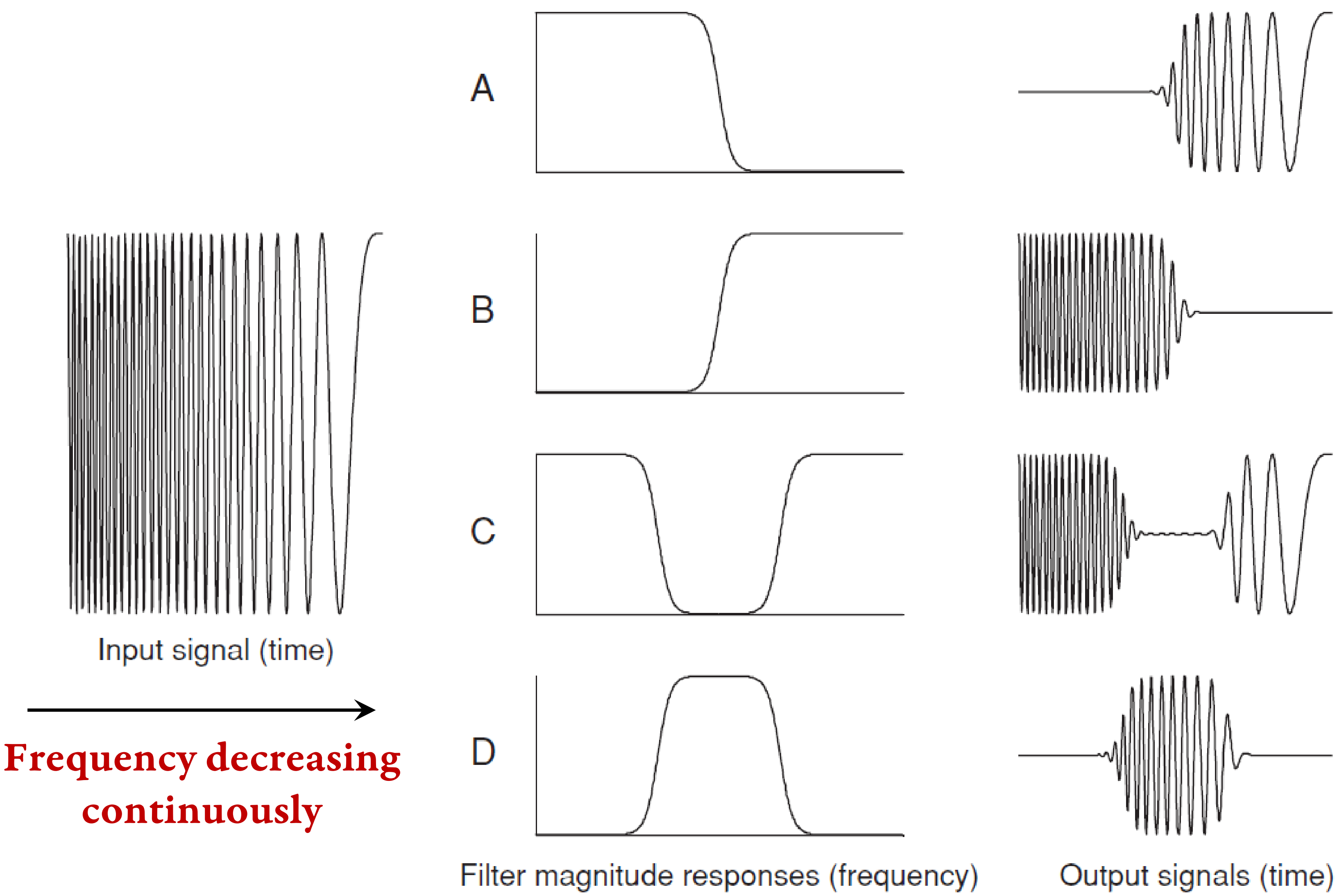
Finite impulse response: An input sample affects the output only for the duration (order) of the filter

Infinite impulse response: Long-term impact of inputs through output feedback

Filtering

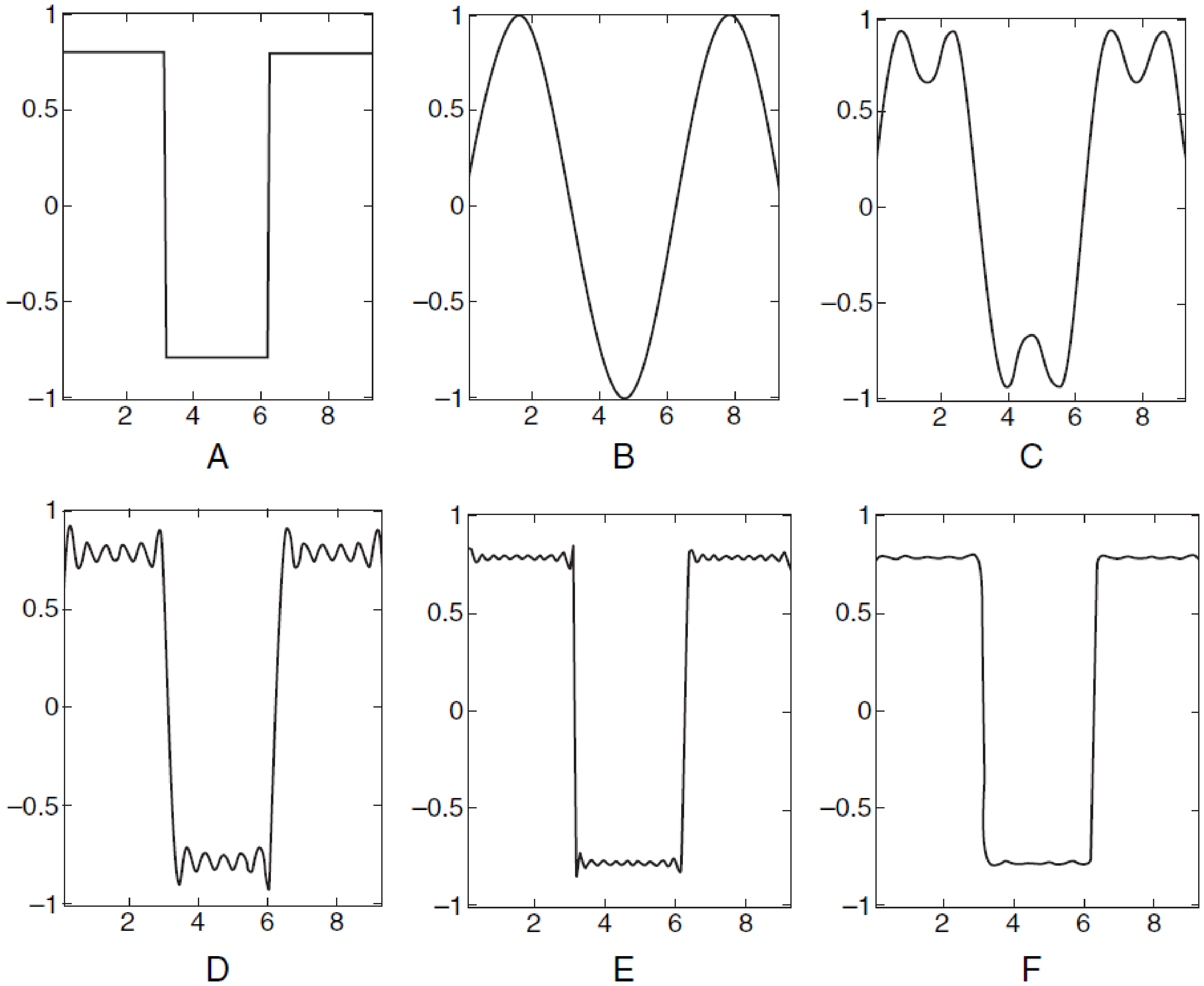

Original signal
(complex signal)
=
Component
Frequencies
+
+
in
low-pass
filter
out
in
high-pass
filter
out
in
bandpass
filter
out
in
notch
filter
out
signal
blocked
passed
frequency
signal
blocked
passed
frequency
signal
band
frequency
signal
notch
frequency

Filtering

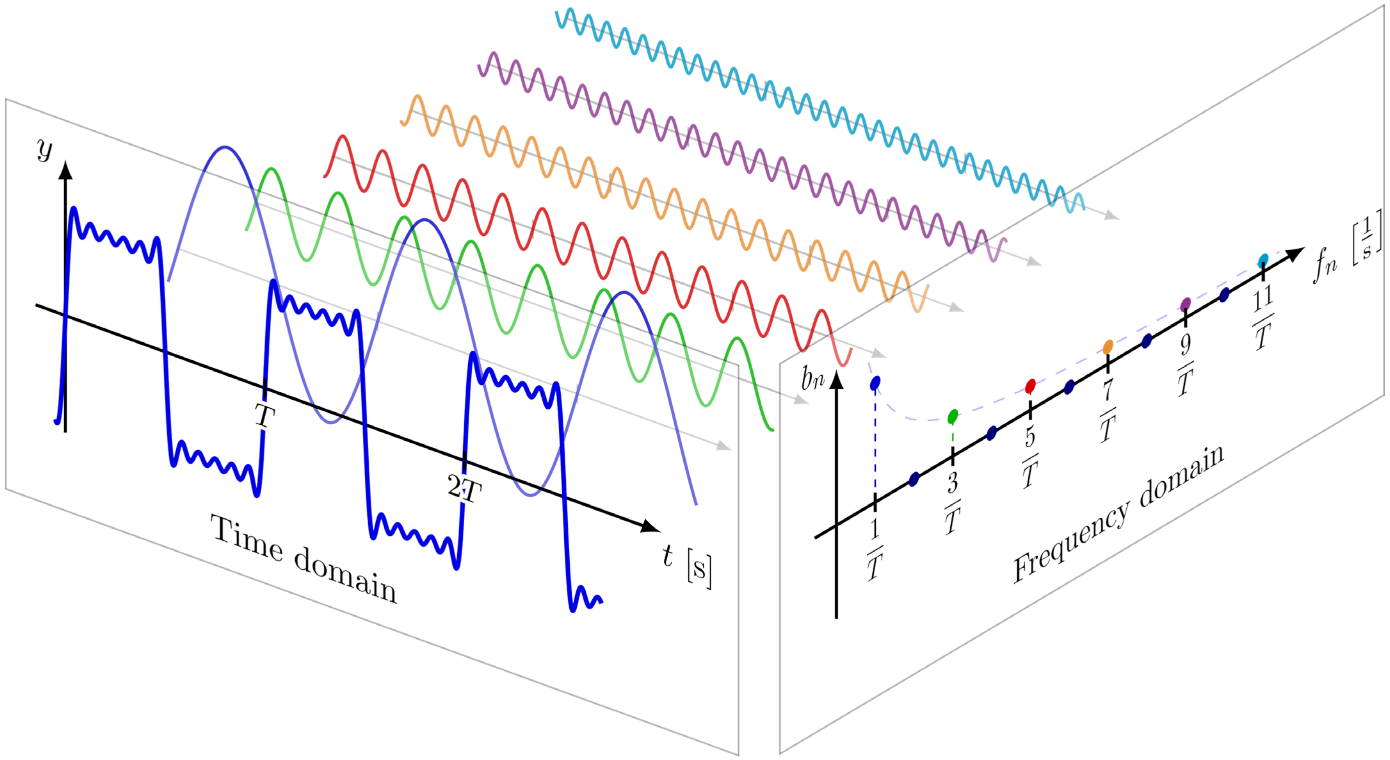


Frequency decreasing continuously

Fast Fourier Transform (FFT)



Fast Fourier Transform (FFT)



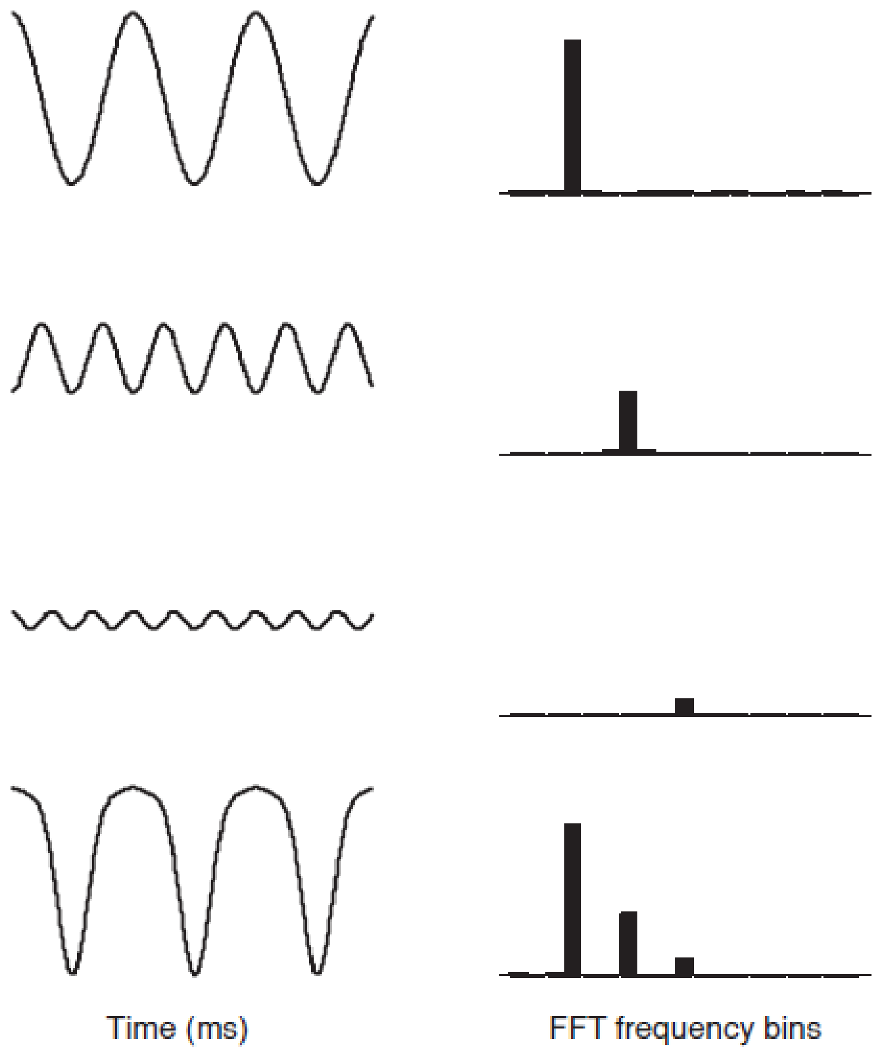
Fast Fourier Transform (FFT)

$$FFT[k] = \sum_{n=0}^{N-1} x[n] \cdot e^{-i\frac{2\pi}{N}kn}$$

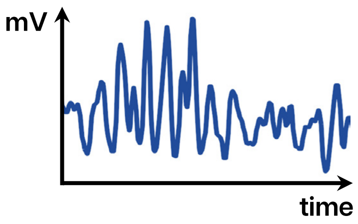
$$FFT[k] = \sum_{n=0}^{N-1} x[n] \cdot \omega_k^n$$

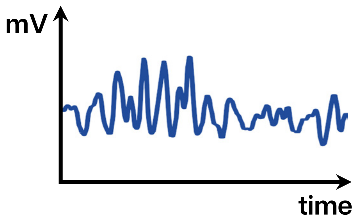
$$FFT[k] = \sum_{m=0}^{\frac{N}{2}-1} x[2m] \cdot \omega_k^{2m} + \omega_k \sum_{m=0}^{\frac{N}{2}-1} x[2m+1] \cdot \omega_k^{2m}$$

Fast Fourier Transform (FFT)



Cross-Correlation

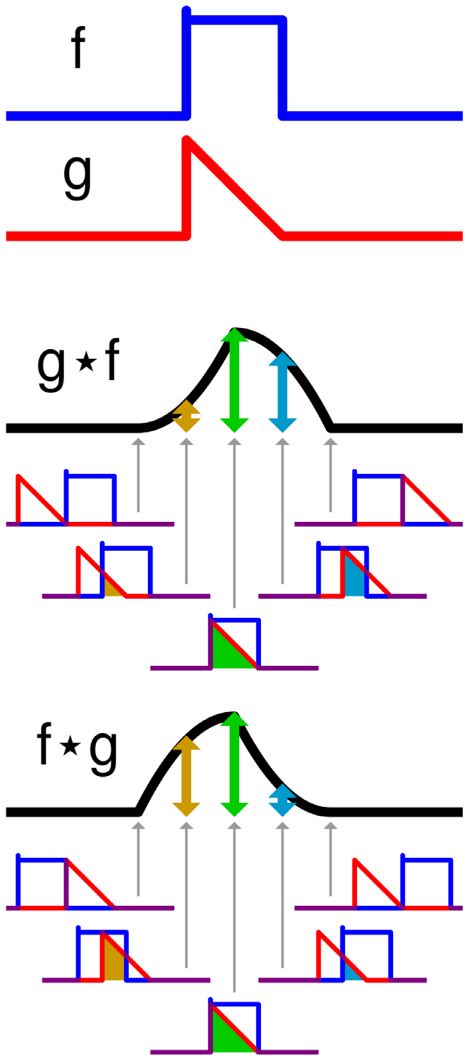




Same?

Similar?

Cross-Correlation



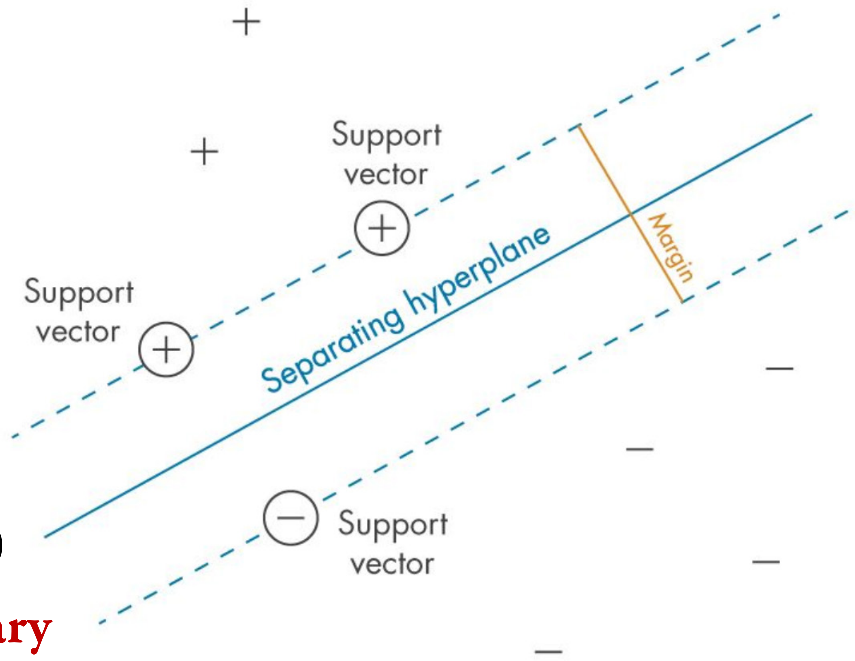
$$R_{xy} = \sum_t x(t) \cdot y(t)$$

$$R_{xy}(\tau) = \sum_t x(t) \cdot y(t+\tau)$$

Support Vector Machine (SVM)

Decision

$sign(y)$



$y = 0$

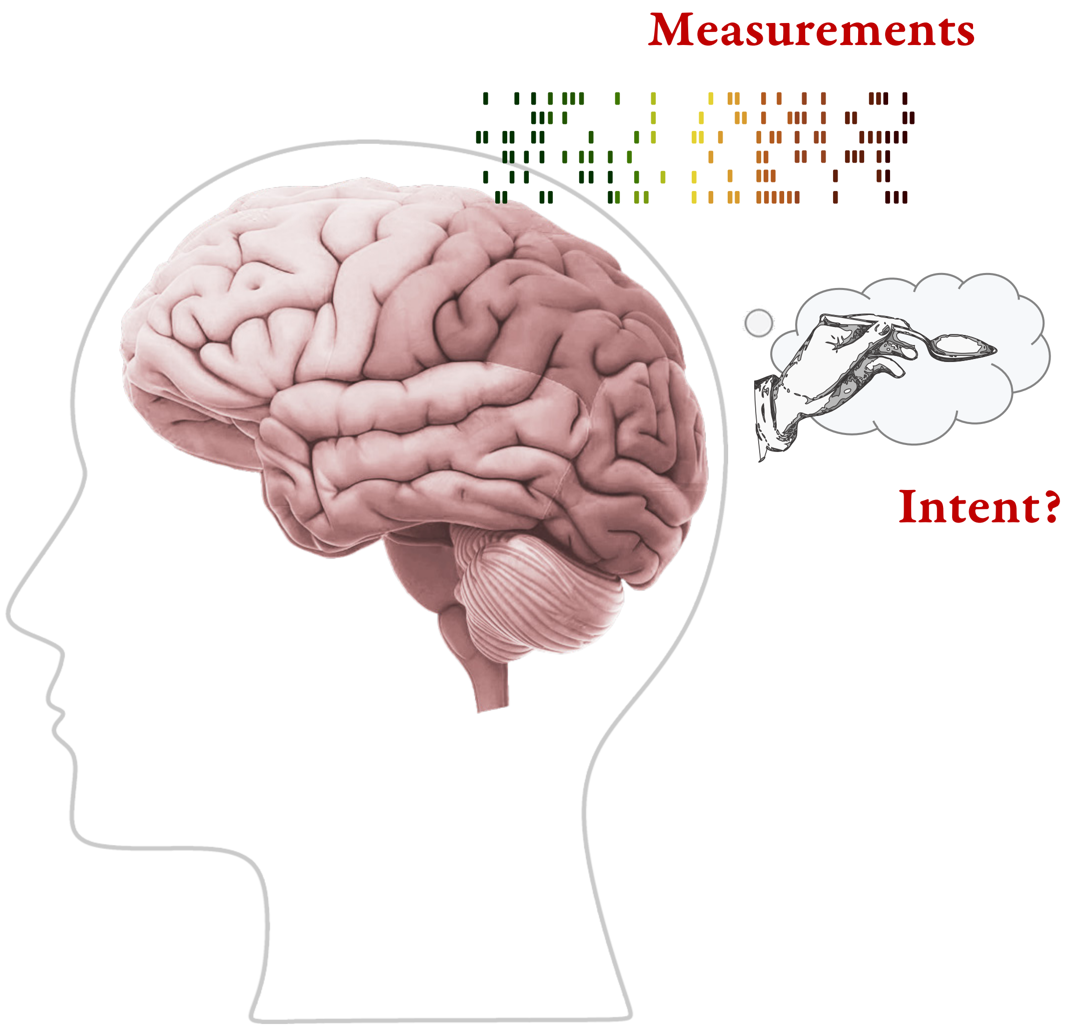
Boundary

$$y = w^T x + b$$

Design by optimization

$$\min \frac{1}{2} ||w||^2 \; subject\ to\ y_i(w^T x_i + b) \geq 1 \; \forall i$$

Kalman Filter



$$x_{t+1} = Ax_t + w_t$$
$$y_t = Cx_t + v_t$$

$\xrightarrow{y_t}$ **Kalman Filter** $\xrightarrow{\hat{x}_t}$

Brain

x_t: intent
w_t: process noise

y_t: measurement
v_t: measurement noise

$\hat{x}_t$: estimate of state
$P: Cov(\hat{x}_t)$

$$\hat{x}_t = (A + L_t C)\hat{x}_t - L_t y_t$$

$$L_t = -A\Sigma_t C^T (C\Sigma_t C^T + V)^{-1}$$

$$\Sigma_{t+1} = (A + L_t C)\Sigma_t A^T + W$$

Σ_t co-variance of x_t
V co-variance of v_t
W co-variance of w_t

A Few More

Other pre-processing methods

E.g., Principal Component Analysis

Some pre-processing steps are quite complex

E.g., Spike sorting

Other time-frequency feature extraction methods

E.g., Wavelets

Other similarity methods

E.g., Dynamic time warping

Other decision-making methods

E.g., Neural networks

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- Thought clouds: F. Willett et al./*Nature* 2021/Erika Woodrum, https://med.stanford.edu/neurosurgery/news/2022/bci-award. https://www.the-scientist.com/news-opinion/brain-computer-interface-user-types-90-characters-per-minute-with-mind-68762
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- Images of implanted users: Top: Case Western Reserve University (https://thedaily.case.edu/man-quadriplegia-employs-injury-bridging-technologies-move-just-thinking/), Bottom: Jan Scheuermann (University of Pittsburgh/UPMC; https://www.upmc.com/media/news/bci-press-release-chocolate)
- Images of wearable BCIs: Cognixion, NextMind
- Types of BCIs: "Brain–computer interfaces for communication and rehabilitation,
- Illustrative BCI: Neuralink
- Electrodes: "Electrochemical and electrophysiological considerations for clinical high channel count neural interfaces", Vatsyayan et al.
- Form factors: Neuropace, Medtronic, Bloomberg, "Fully Implanted Brain–Computer Interface in a Locked-In Patient with ALS" by Vansteensel et al., Blackrock Neurotech
- Jose Delgado's video: Online, various sources (CNN, Youtube)
- Video of Kennedy and Ramsey: Online, various sources (Youtube, Neural signals)
- Code snippet inspiration: ECE 252 slides at Duke (Dan Sorin et al.)
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- BCI Processing, Digitization, Filtering, FFT: *Brain–Computer Interfaces: Principles and Practice*, Ed: Jonathan Wolpaw and Elizabeth Winter Wolpaw
- Filtering: https://www.allaboutcircuits.com/technical-articles/an-introduction-to-filters/
- Common Average Referencing: "Using a Common Average Reference to Improve Cortical Neuron Recordings From Microelectrode Arrays", Ludwig et al., J Neurophysiol, 2008
- FFT: https://dibsmethodsmeetings.github.io/fourier-transforms/
- Cross-Correlation: https://commons.wikimedia.org/wiki/File:Comparison_convolution_correlation.svg CC-By-SA-3.0
- SVM: https://www.mathworks.com/discovery/support-vector-machine.html