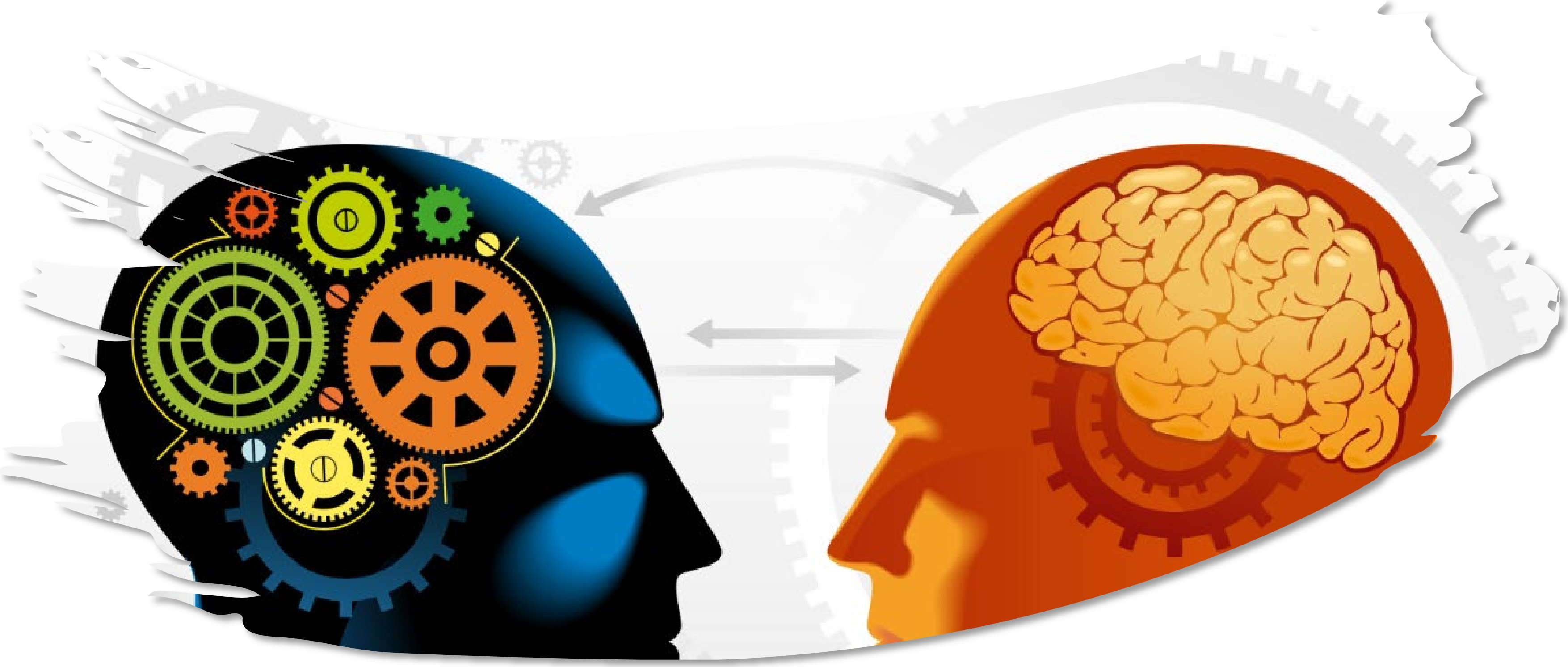

Building the Infinite Brain

COMP 690 (193)

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Quick Review

Signup on Piazza

What are BCIs?

Broadly, systems that read, process, and modulate neural activity in the brain

Types of BCIs

Many, both invasive/implanted and wearable

What are BCIs used for?

Understanding brain function, treat dysfunction, restore lost function, and augment cognition

Intimately tied to an individual's identity

What are the computational challenges in designing BCIs?

Growing sensor data needs to be processed on the device

Computers today are limited in achieving both efficiency and flexibility, under safety constraints

1-page write-up due on 8/24

General Suggestions

Take notes

No need to repeat what's in the slides, but note connections, insights

Write down ideas and follow-ups

Even if you don't plan to revisit them (for now)

When reading, go down (good) rabbit holes

Trails of papers—builds background knowledge, but don't lose sight of the overall goal: Tree traversal!

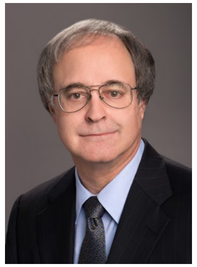
Learn to refine your thoughts into formal and precise summaries, ideas

Even if you don't plan to revisit them (for now)

"Writing is nature's way of letting you know how sloppy your thinking is. Math is nature's way of letting you know how sloppy your writing is." Leslie Lamport

Writing a Paper Review

Reviews due 8/24



The Task of the Referee
http://www2.eecs.berkeley.edu/Pubs/TechRpts/1989/CSD-89-511.pdf

Alan Smith, *Emeritus, UC Berkeley*

Summarize the paper

What did you learn?

What are the novel contributions of the paper?

Positives, strengths etc.

Negatives, limitations

Summary and review of assumptions, methods, results (check correctness too!)

Significance and Impact (past, present or future)

During paper presentations

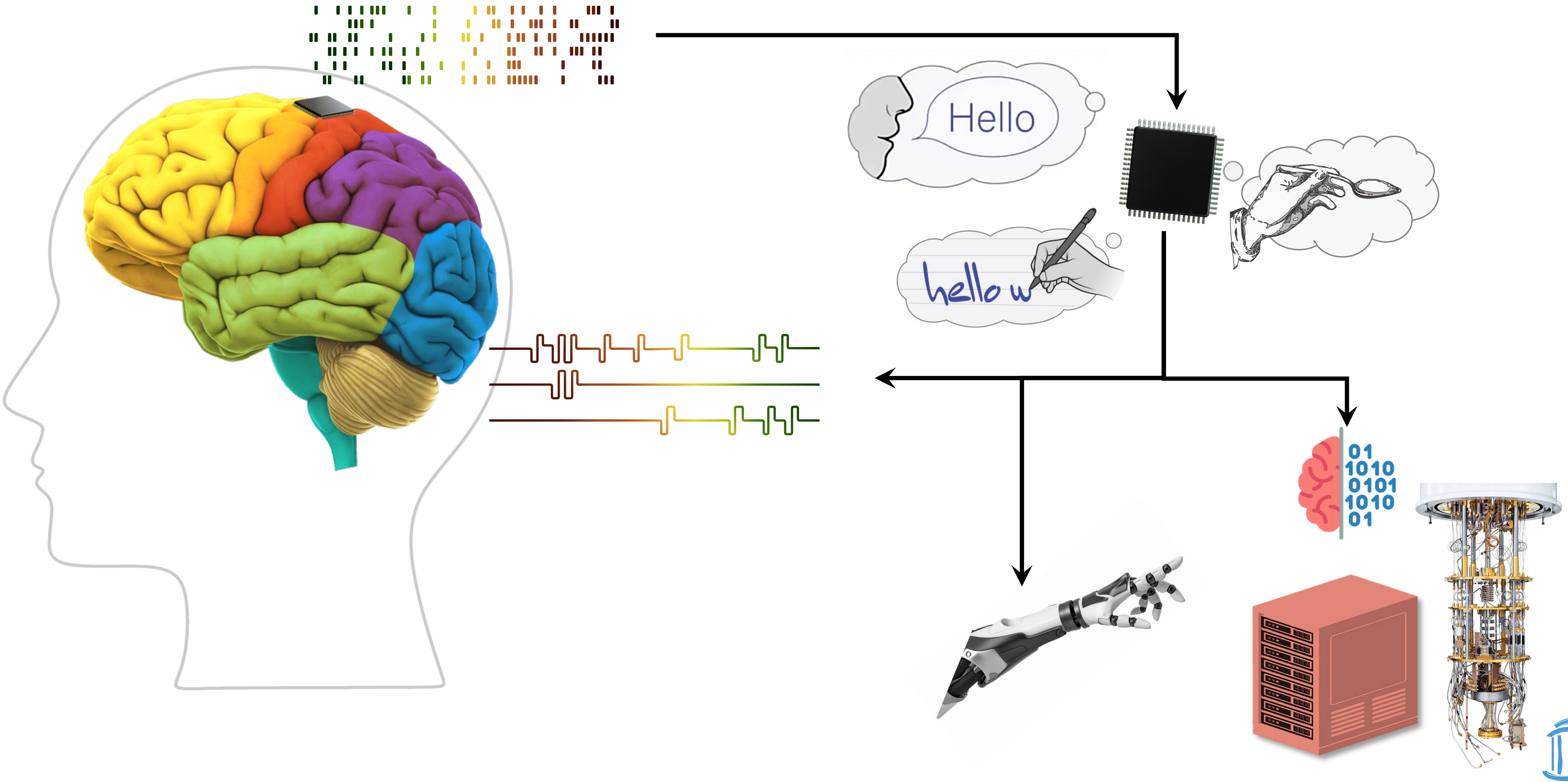
1-2 questions for discussion!

Connect the paper to the themes of the course and other papers

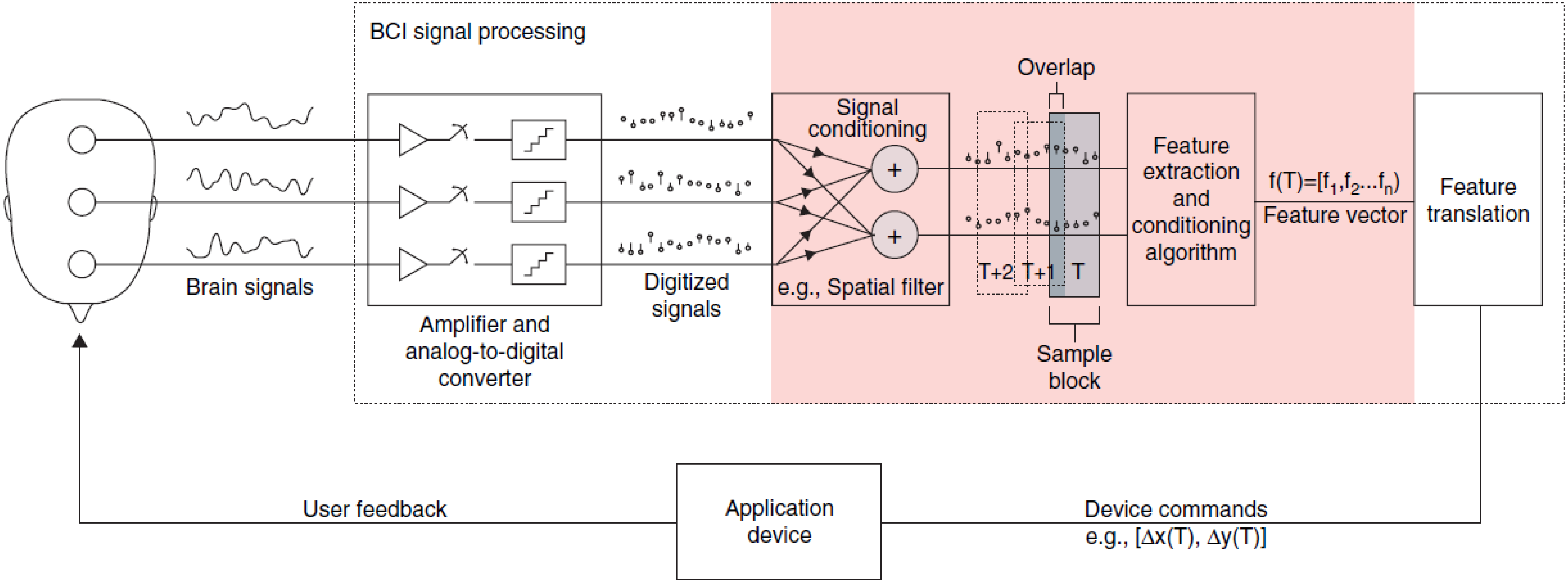
For Today

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

BCI Processing

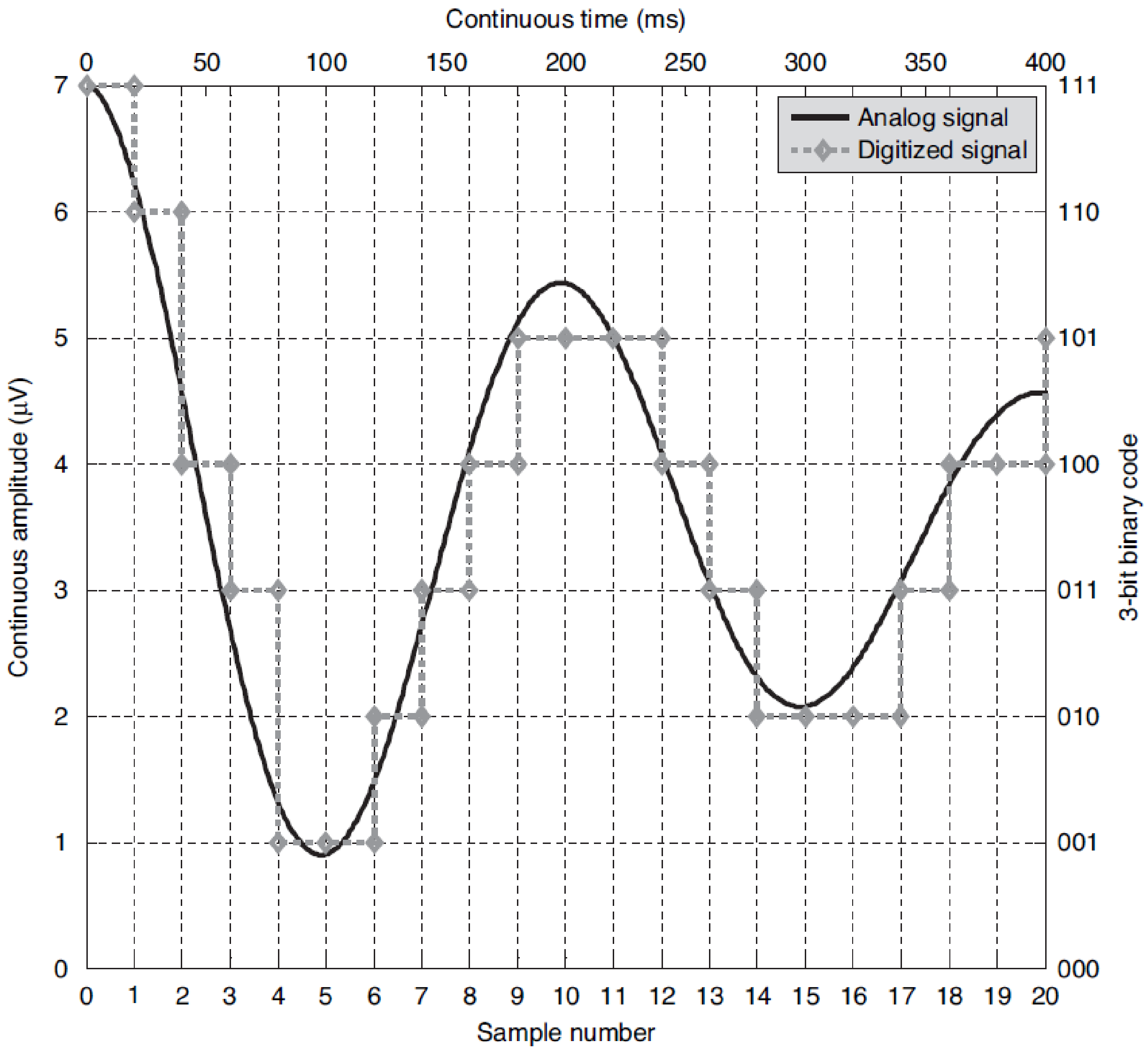


BCI Processing



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

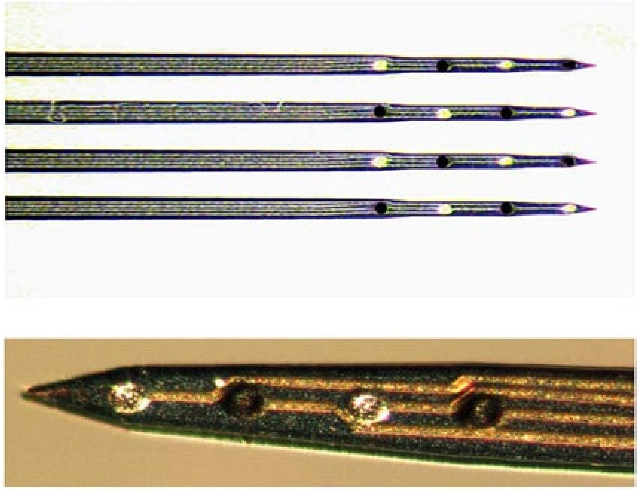
LFPs are lower resolution

Common Average Referencing

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

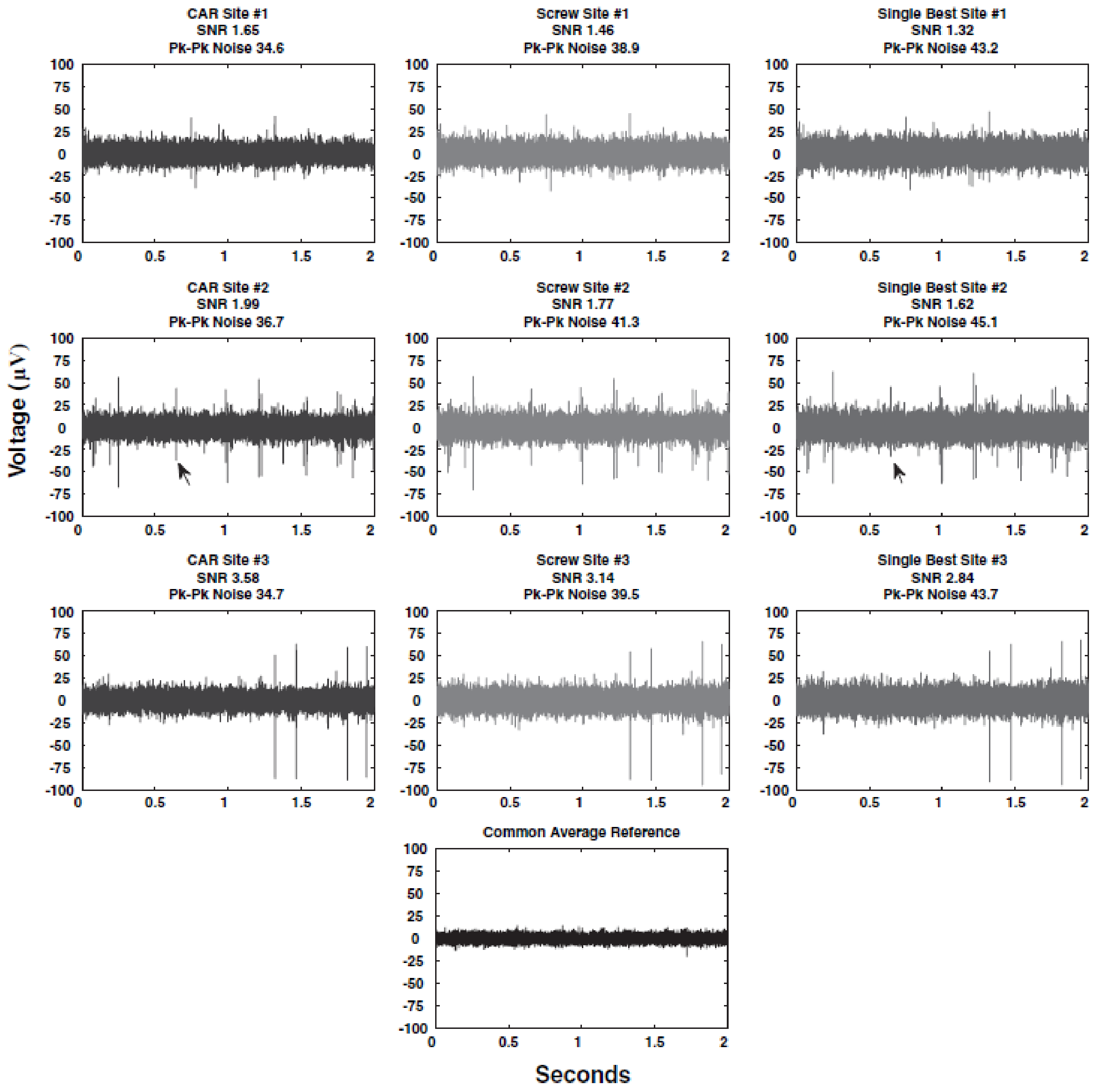
Average across all samples in a window

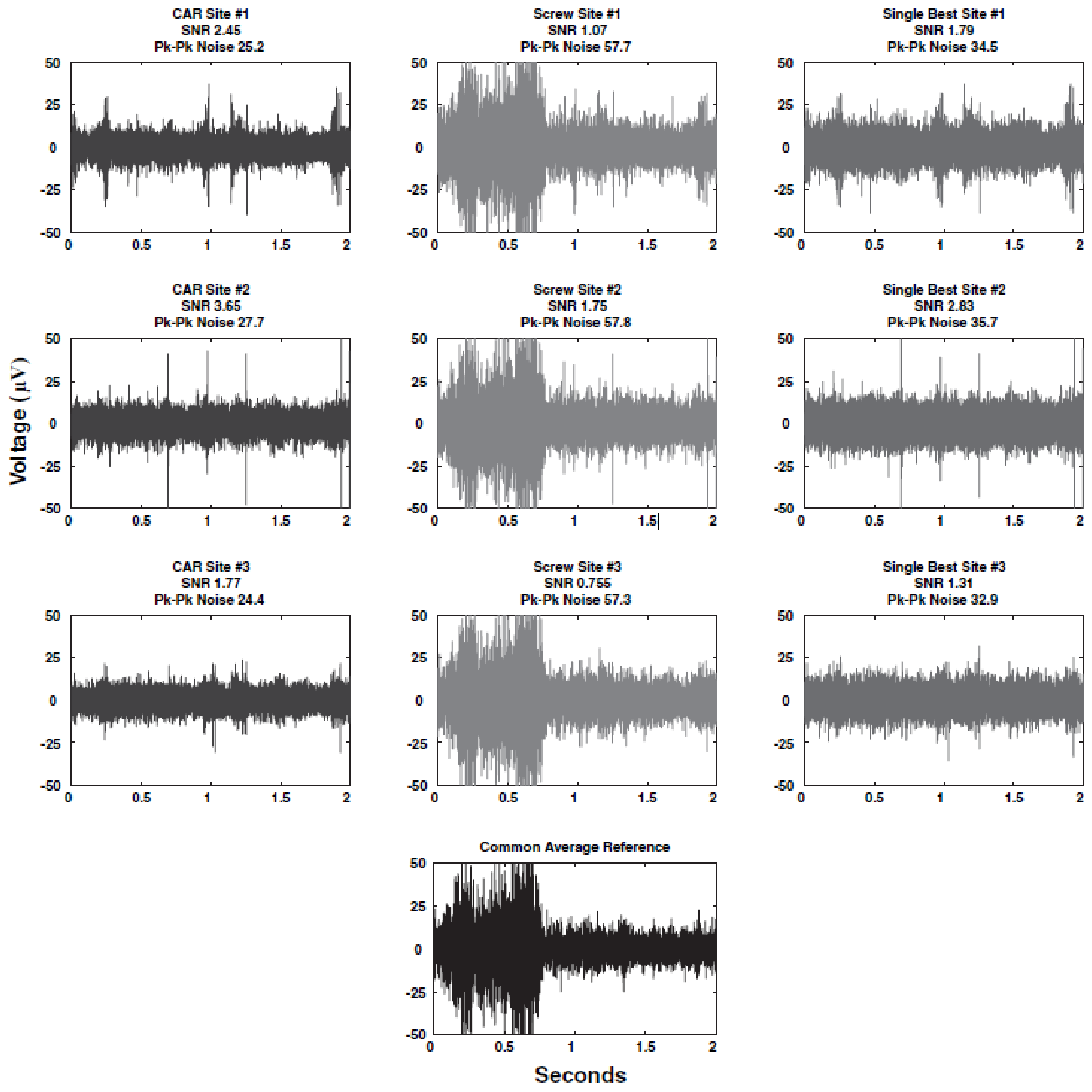
Common Average Referencing



Michigan array (16 channels)

Common Average Referencing





Filtering

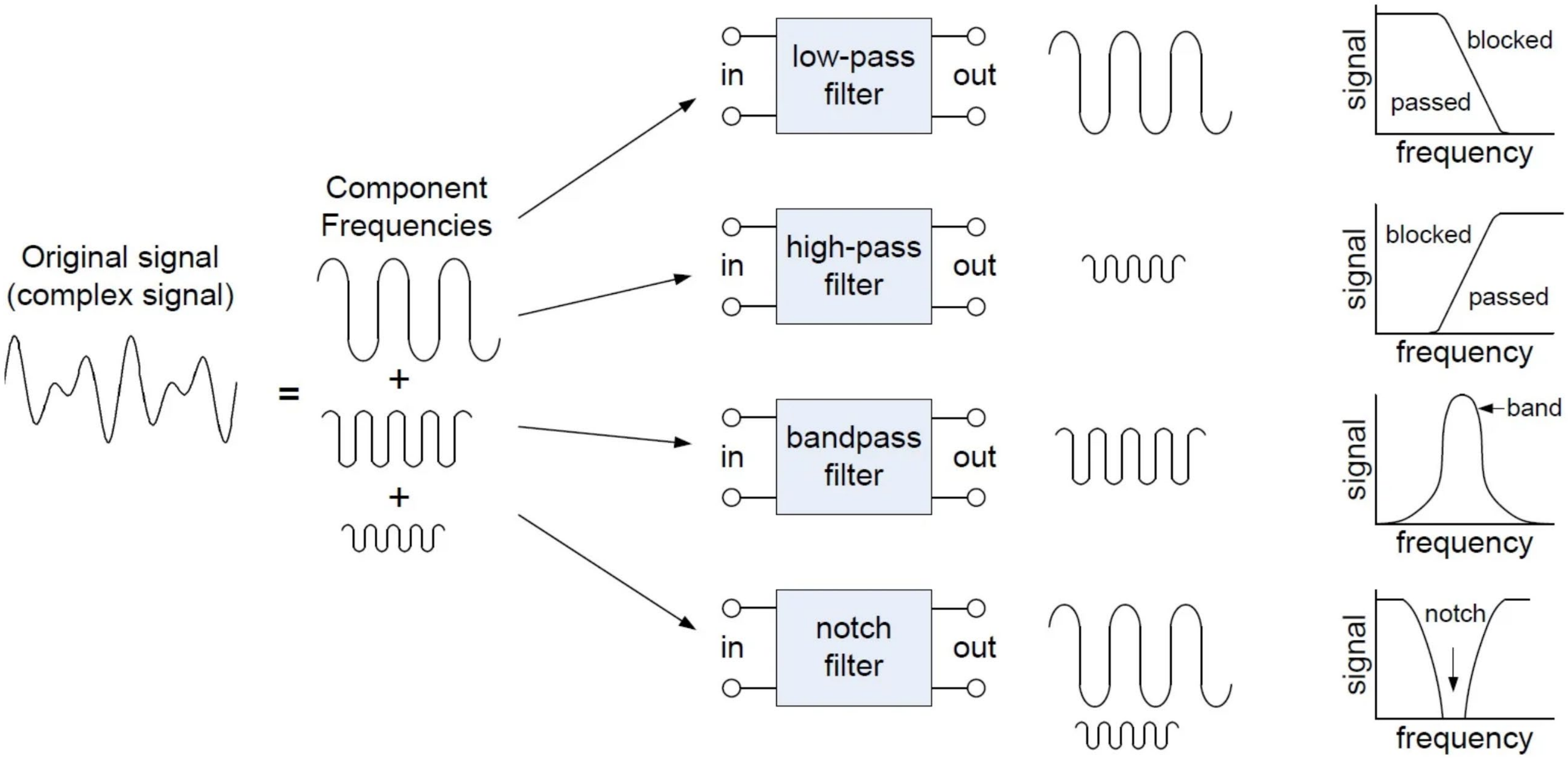
$$y[n] = \sum_{i=0}^{M} a_i \times x[n-i] \;\; - \sum_{j=1}^{L} b_i \times y[n-j]$$

Past inputs **Past outputs**

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

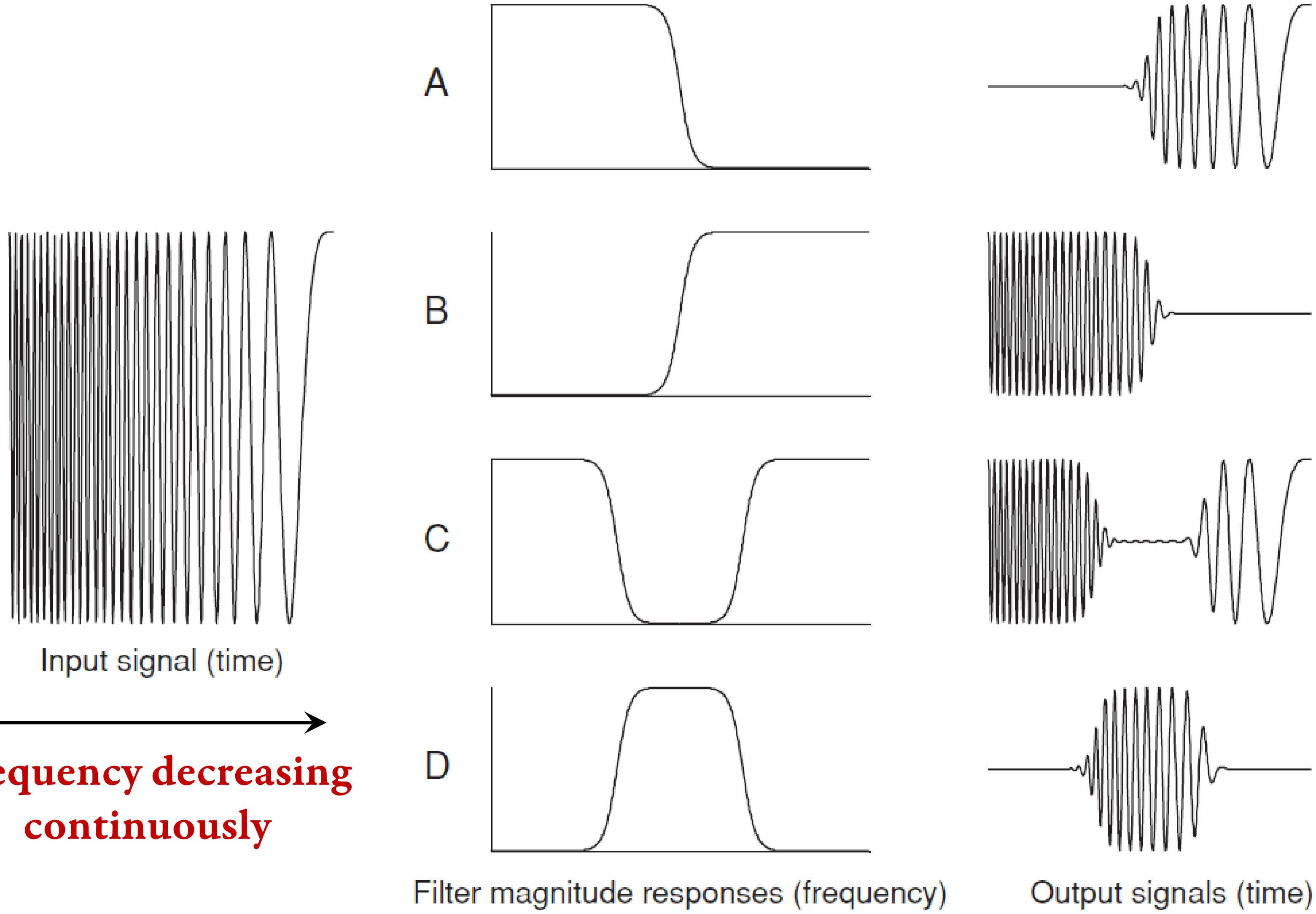
Infinite impulse response: Long-term impact of inputs through output feedback

Filtering



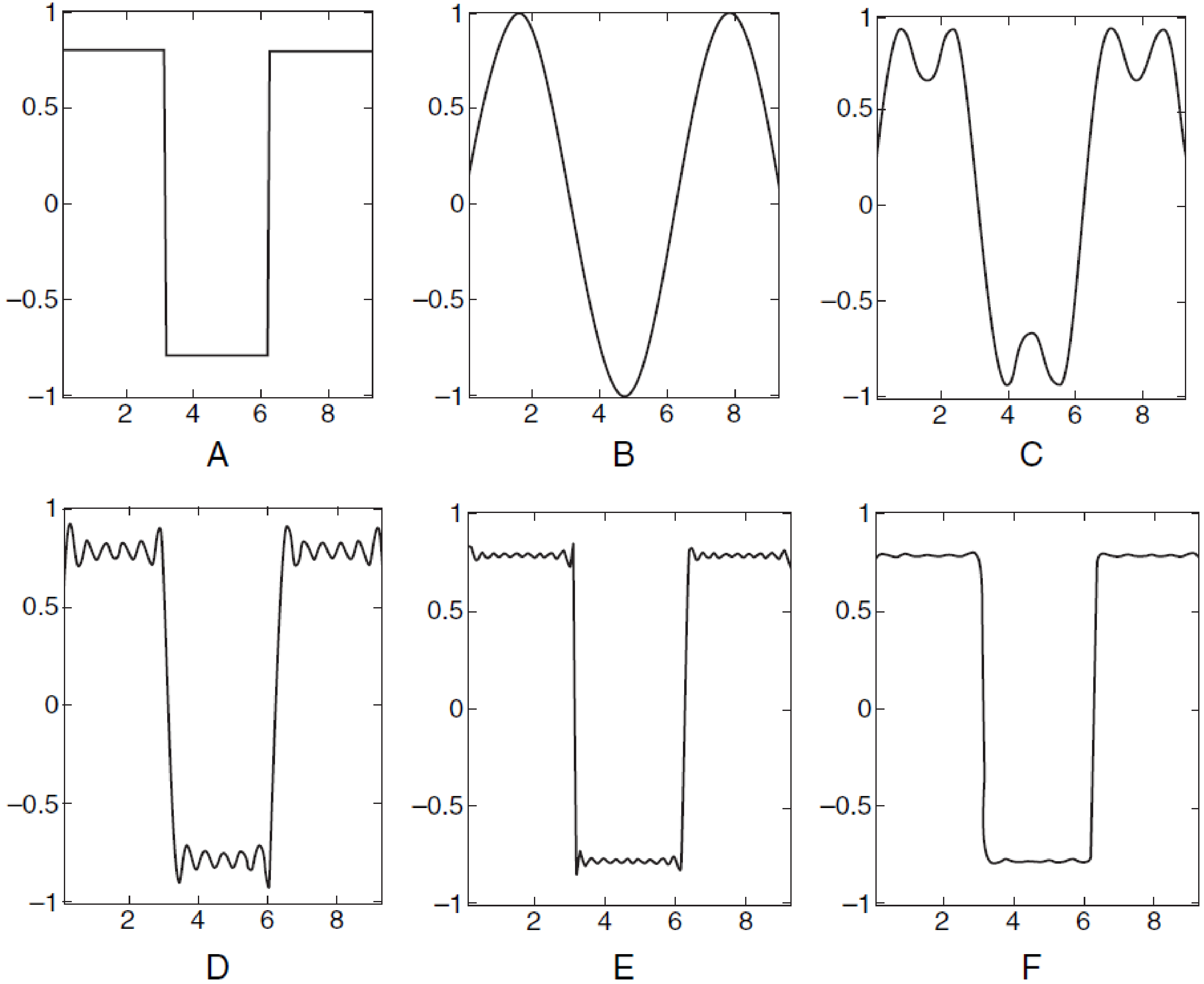
Original signal
(complex signal)
=
Component
Frequencies
+
+
in
low-pass
filter
out
in
high-pass
filter
out
in
bandpass
filter
out
in
notch
filter
out
signal
blocked
passed
frequency
signal
blocked
passed
frequency
signal
band
frequency
signal
notch
frequency

Filtering

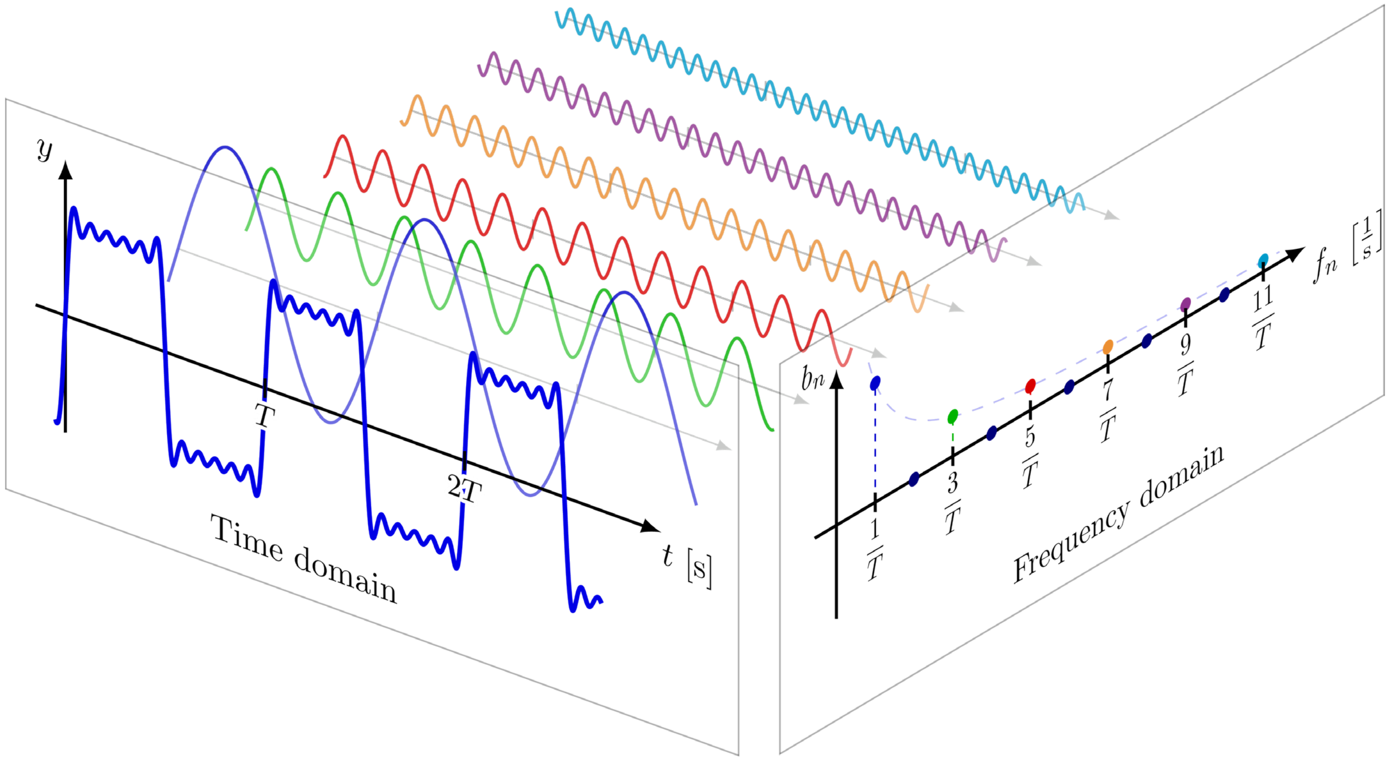


Frequency decreasing continuously

Fast Fourier Transform (FFT)



Fast Fourier Transform (FFT)



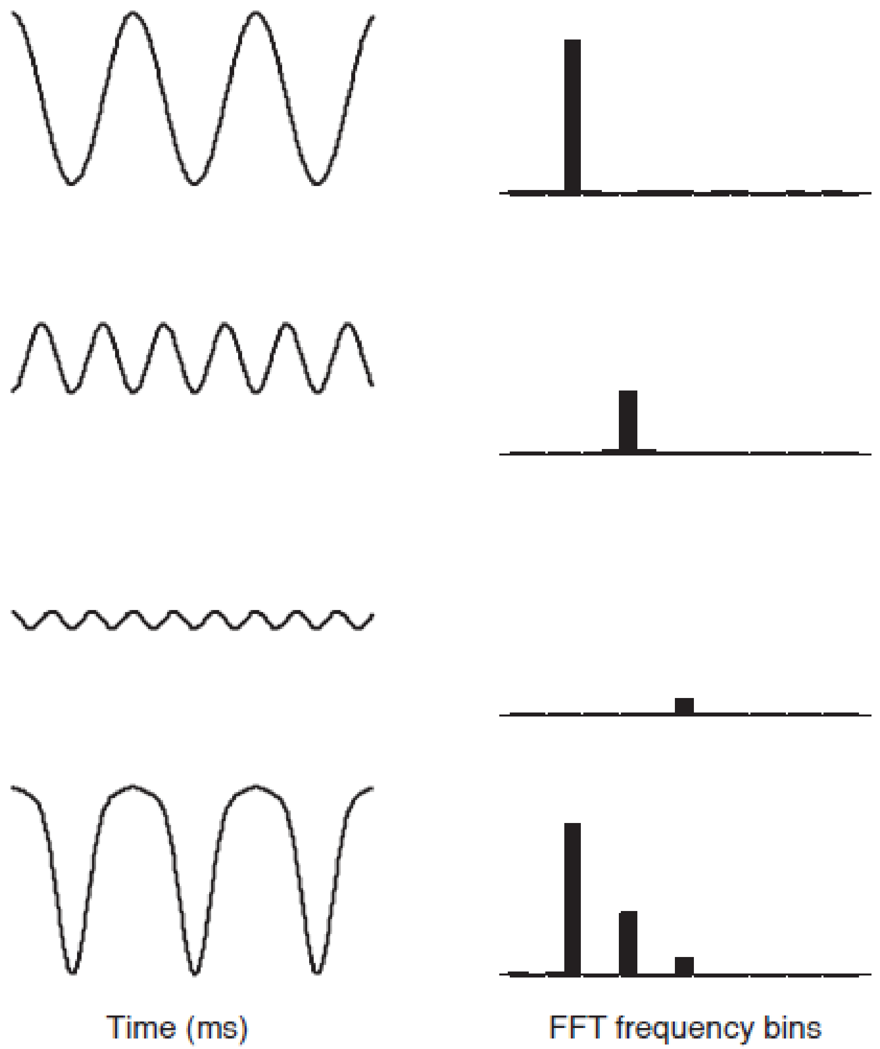
Fast Fourier Transform (FFT)

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

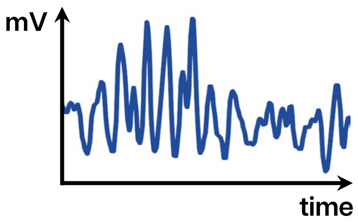
$$FFT[k] = \sum_{n=0}^{N-1} x[n] \cdot \omega_k^n$$

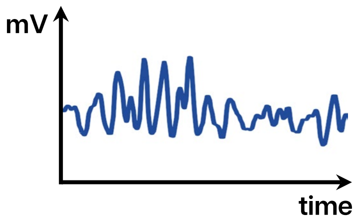
$$FFT[k] = \sum_{m=0}^{\frac{N}{2}-1} x[2m] \cdot \omega_k^{2m} + \omega_k \sum_{m=0}^{\frac{N}{2}-1} x[2m+1] \cdot \omega_k^{2m}$$

Fast Fourier Transform (FFT)



Cross-Correlation

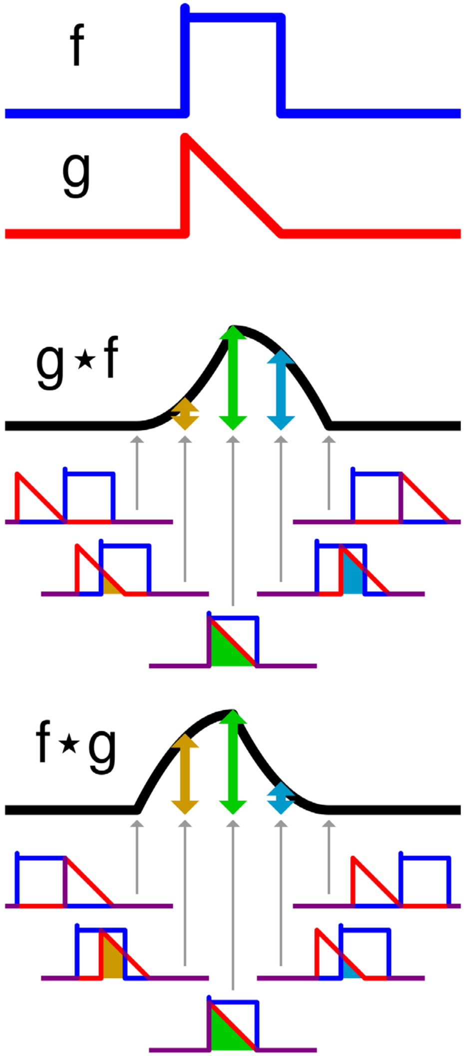




Same?

Similar?

Cross-Correlation



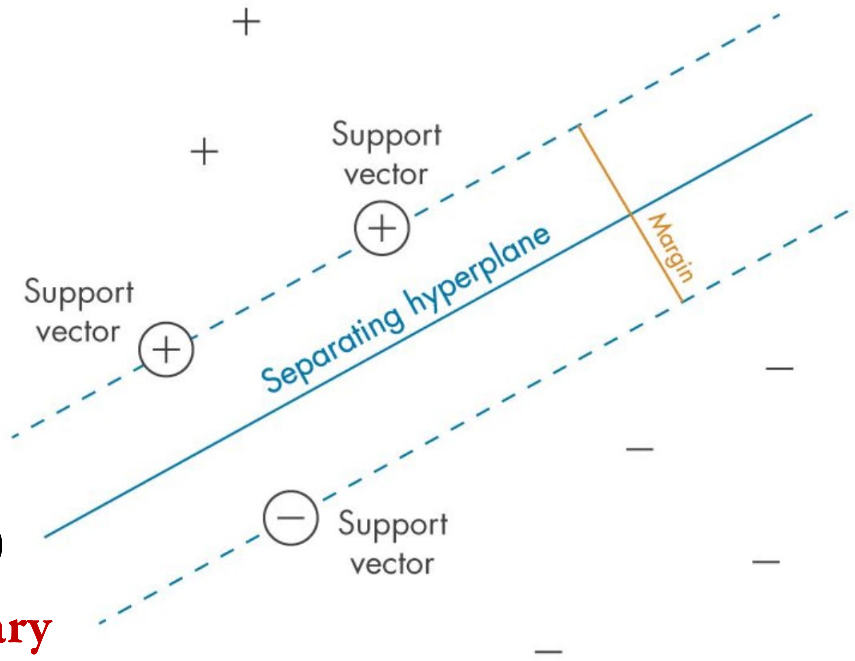
$$R_{xy} = \sum_t x(t) \cdot y(t)$$

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

Support Vector Machine (SVM)

Decision

$sign(y)$



$y = 0$

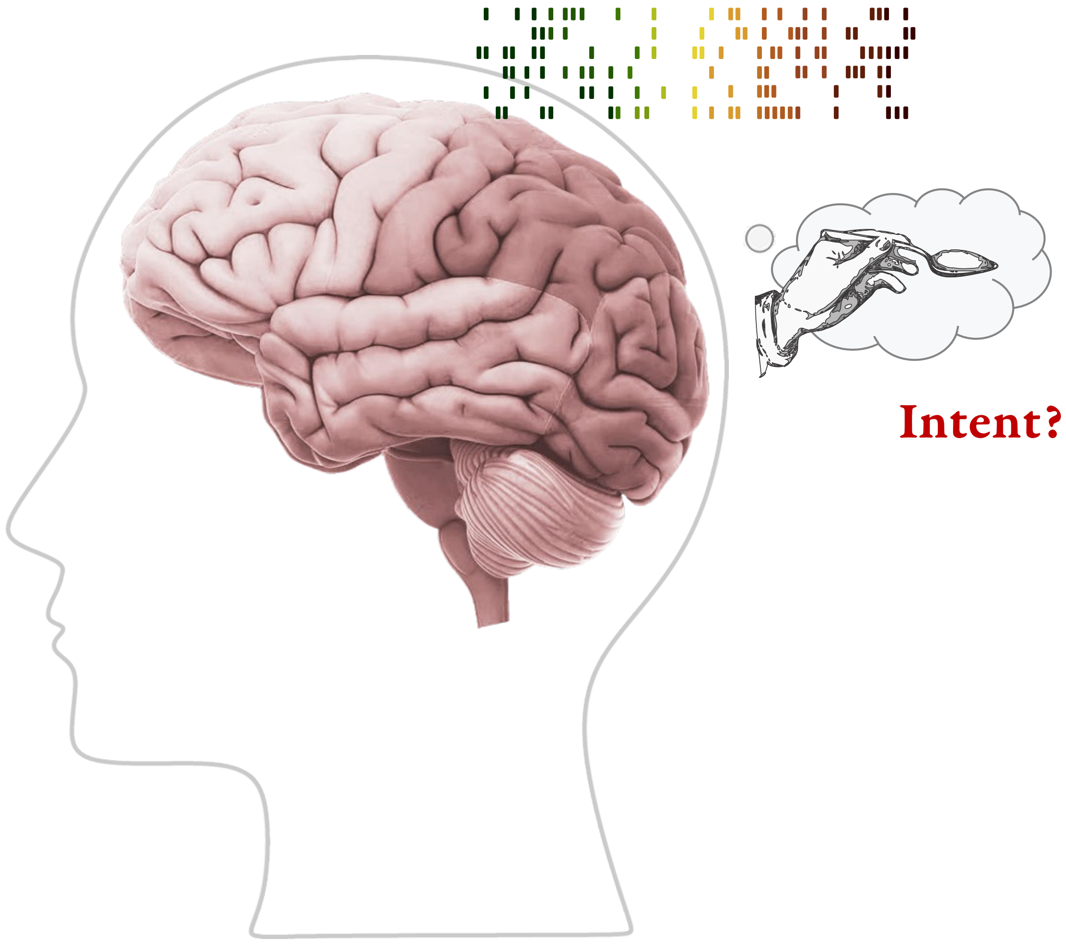
Boundary

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

Design by optimization

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

Kalman Filter



$$\boxed{\begin{aligned} x_{t+1} &= Ax_t + w_t \\ y_t &= Cx_t + v_t \end{aligned}} \xrightarrow{\;y_t\;} \boxed{\text{Kalman Filter}} \xrightarrow{\;\hat{x}_t\;}$$

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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- Signals: https://www.nature.com/articles/nrn3724
- 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
- Picture of scientists: https://www.cs.auckland.ac.nz/~brian/rutherford8.html (original: Pierre de Latil), Bush (Carnegie Science), Others (Wikipedia, National Academies, IEEE, and university profile images)
- Flowchart: Pause08 – flaticon.com; Digital brain: Smashicons – flaticon.com; Quantum processor icons created by Paul J. - Flaticon
- Server rack: upklyak – freepik.com
- Arm, Lotus: Adobe stock
- Quantum processor: Rigetti computing
- 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.)
- Apple processor pipeline: https://dougallj.github.io/applecpu/firestorm.html
- 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