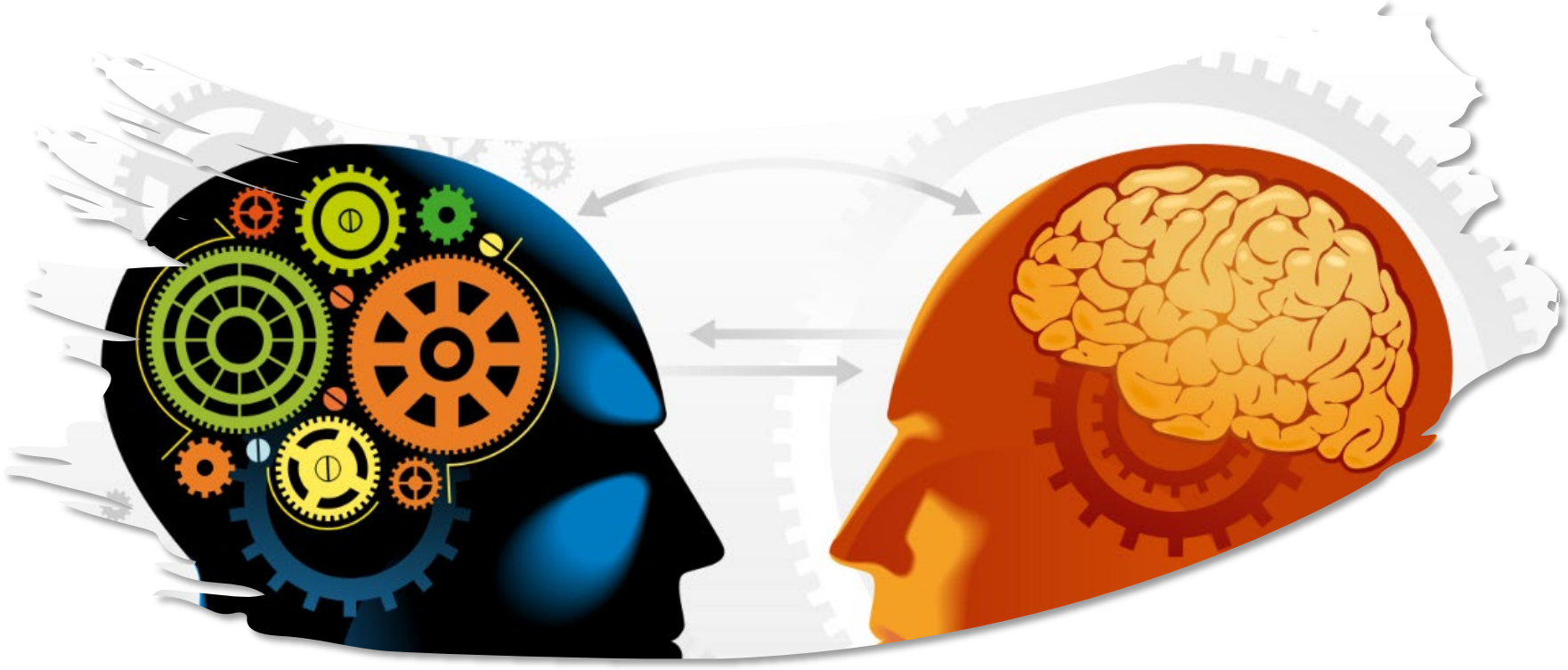


# Building the Infinite Brain

COMP 690 (193)

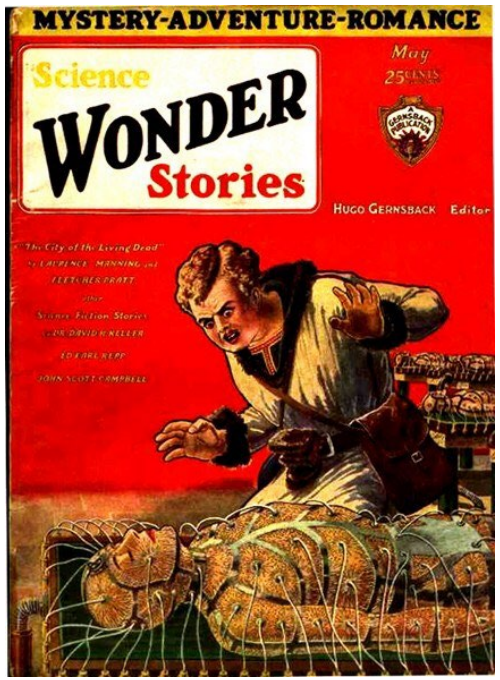
**Raghavendra Pradyumna Pothukuchi**

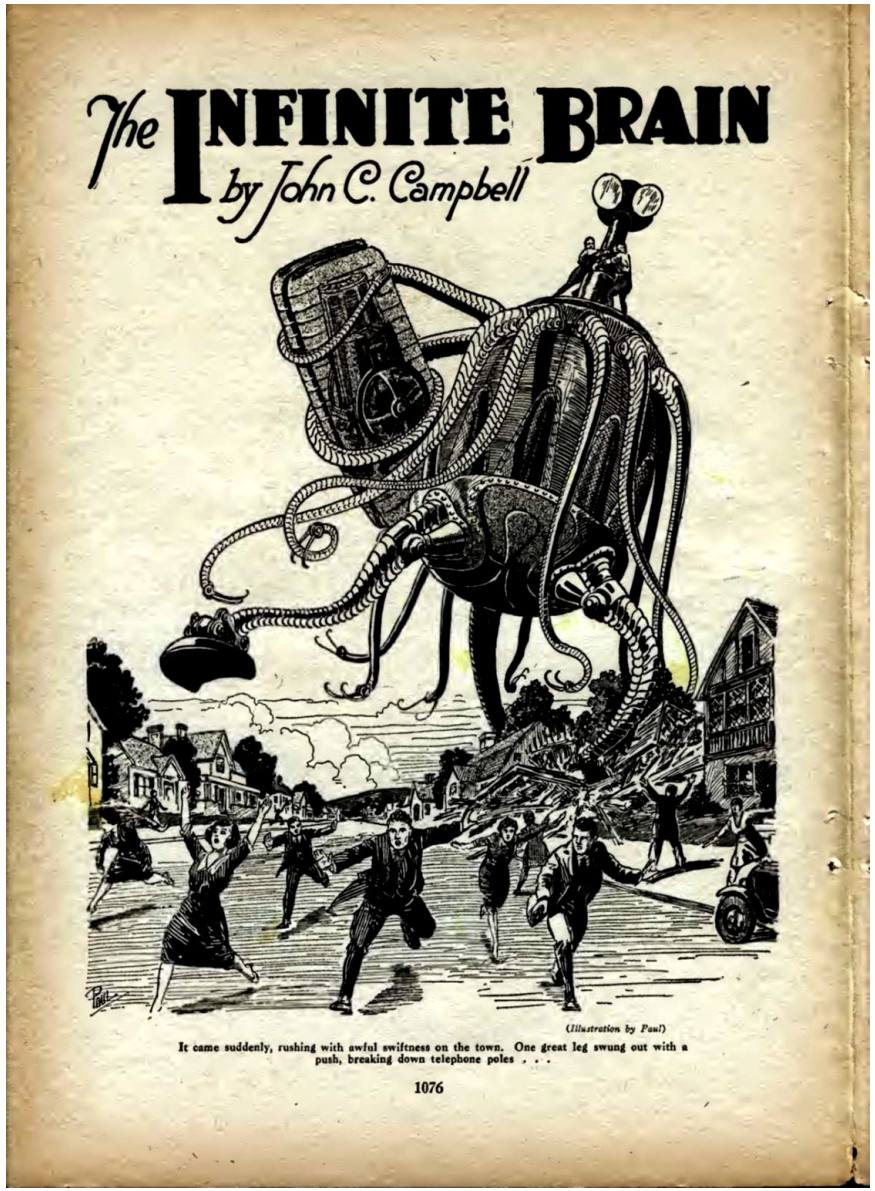
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

raghav@cs.unc.edu

# The Infinite Brain

JOHN C. CAMPBELL



The INFINITE BRAIN
by John C. Campbell

(Illustration by Paul)

It came suddenly, rushing with awful swiftness on the town. One great leg swung out with a push, breaking down telephone poles . . .

1076

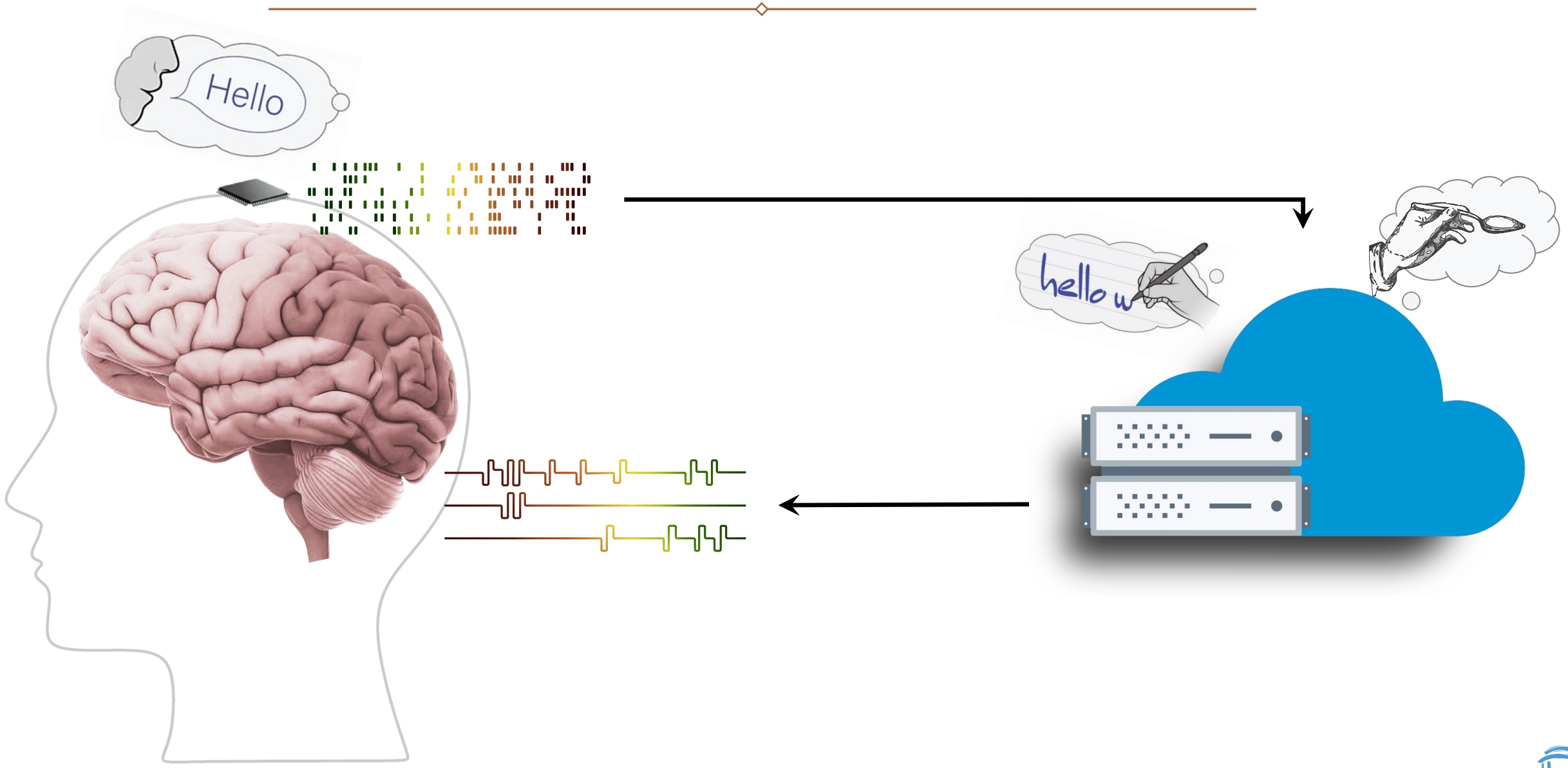
"I am attempting to construct a mechanism exactly duplicating the mechanical and electrical processes occurring in the human brain and constituting the phenomena known as *thought*."

"And if a man had an infinite mind—what then? He could understand the entire Universe at a glance."

"I, Anton Des Roubles, am dead—my body is dead—but I still live. I am this machine. These racks of apparatus are my brain, which is thinking even as yours is."

"I suppose I am the only person in the world spending money upon such a fool thing, but I feel that every day brings me nearer to my goal."

# Talk To The Brain and Think Like The Mind



# Talk To The Brain and Think Like The Mind

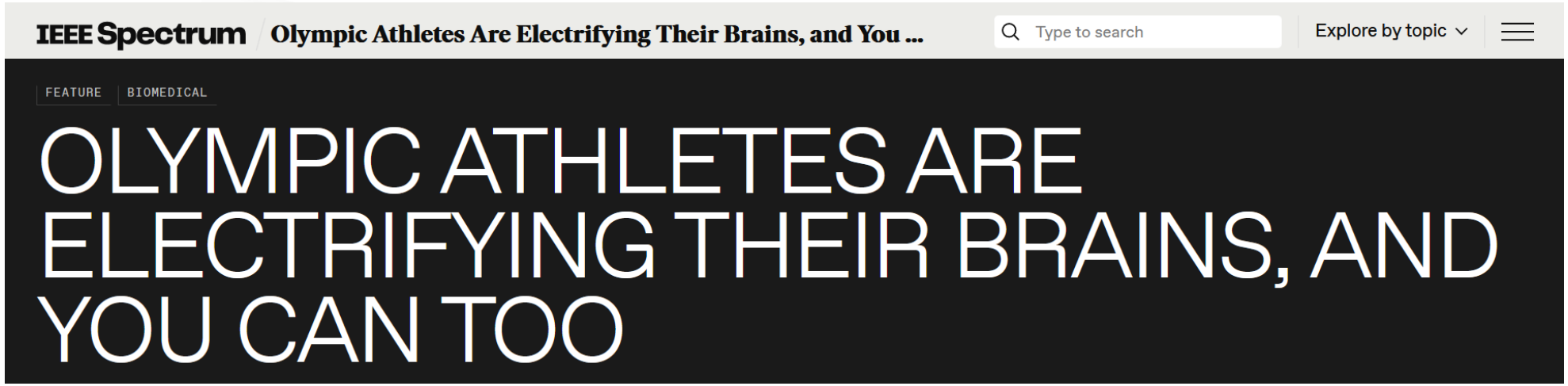


## Alzheimer's: Brain implant could improve cognitive function

By Maria Cohut, Ph.D. on January 31, 2018 — Fact checked by Jasmin Collier

Researchers report the success of a clinical trial that tested the effectiveness of deep brain stimulation for slowing function-related cognitive decline. This enables people affected by Alzheimer's to keep living independently for longer.

# Talk To The Brain and Think Like The Mind




MIND & MOOD

## Can electrical brain stimulation boost attention, memory, and more?

*Home devices marketed to enhance brain performance or treat brain disorders are not yet cleared by the FDA.*

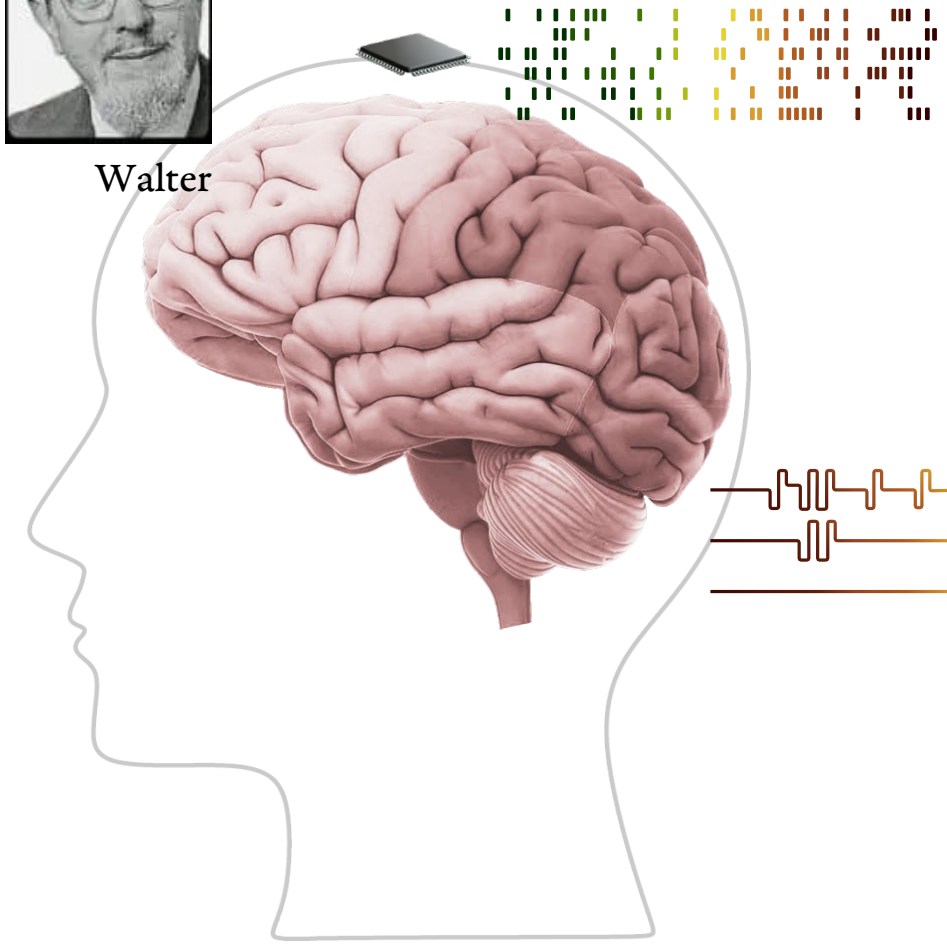
March 3, 2023

***By Robert H. Shmerling, MD**, Senior Faculty Editor, Harvard Health Publishing; Editorial Advisory Board Member, Harvard Health Publishing*

# Brain Inspiration Helped Advance Computing

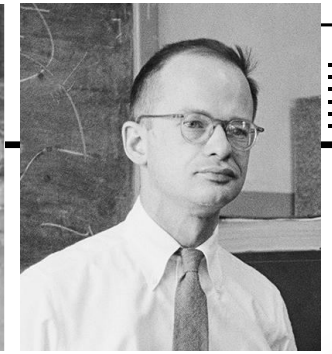
**Brain implant**

Walter



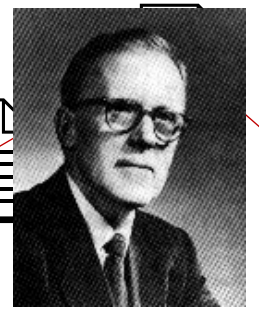
**Cybernetics, Computational neuroscience**

Ashby, McCulloch, Walter, Wiener

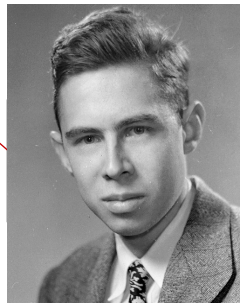


Pitts

**Machine Learning**

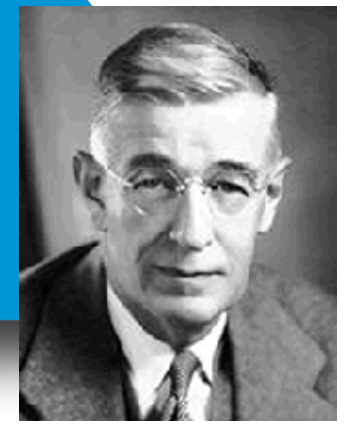


Hebb



Rosenblatt

**Memex**



Bush

**Computing, Computer architecture**

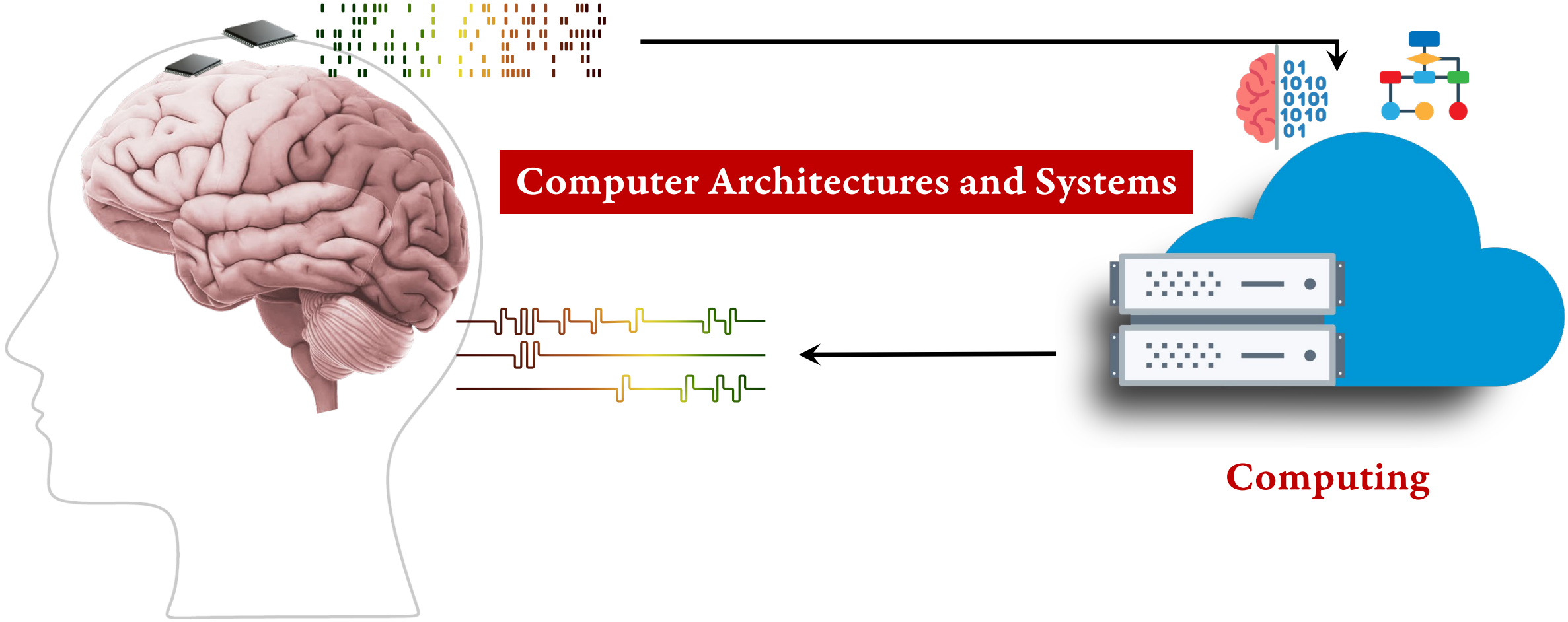
Turing

von Neumann

# Opportunity Today: Spur a New Virtuous Cycle

**Brain-computer interfaces (BCIs)**

**Cognitive frameworks**



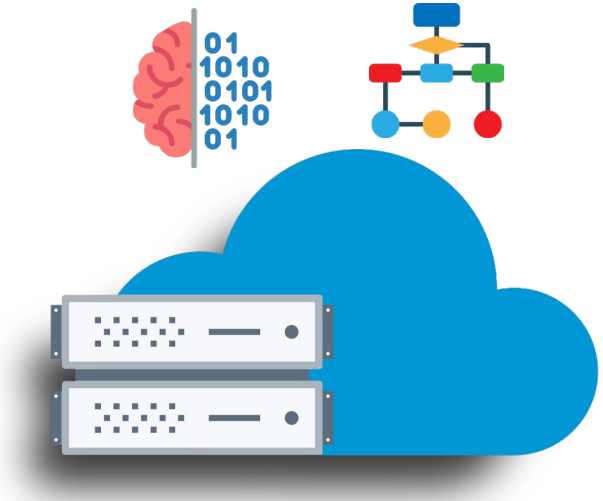

**Computer Architectures and Systems**

**Computing**

# Example Application

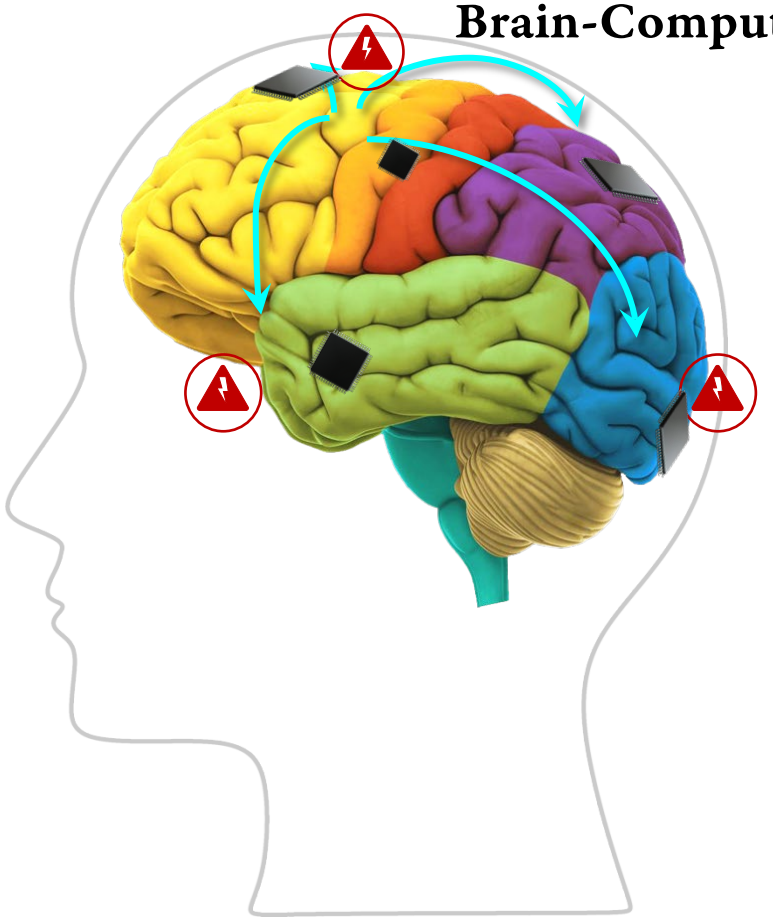
## Restoring function

Computational cognitive frameworks




## Mitigating seizures

Brain-Computer Interfaces (BCIs)



# My Research

IEEE Micro (HotChips)'23

**_HALO_: Single-site BCI**

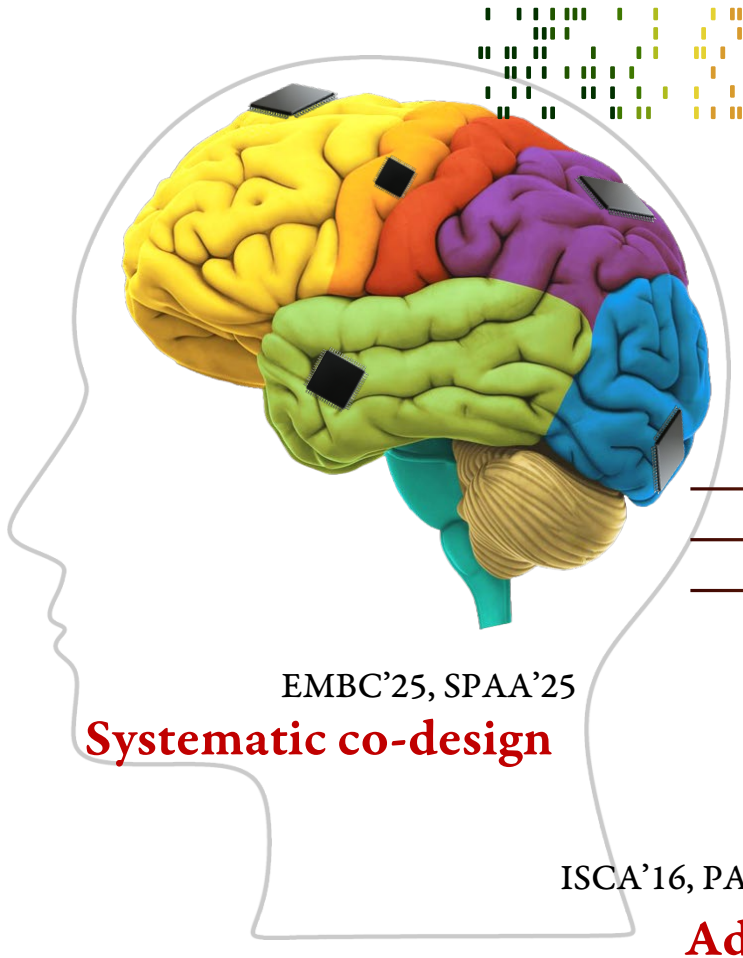
ISCA'23 (Best paper), Top Picks'24

**_SCALO_: Multi-site BCI**

Neuroethics'26

**Ethics and policy**

**_Distill_: Compiler for cognitive frameworks**




arXiv'23

**_Quatro_: Quantum systems for cognition**

EMBC'25, SPAA'25

**Systematic co-design**

HotOS'23

**Brain-inspired prefetching**

ISCA'16, PACT'17, ISCA'18, MICRO'19, ISCA'21, Top Picks'21, PACT'24, ISCA'26

**Adaptive systems for efficiency and security**

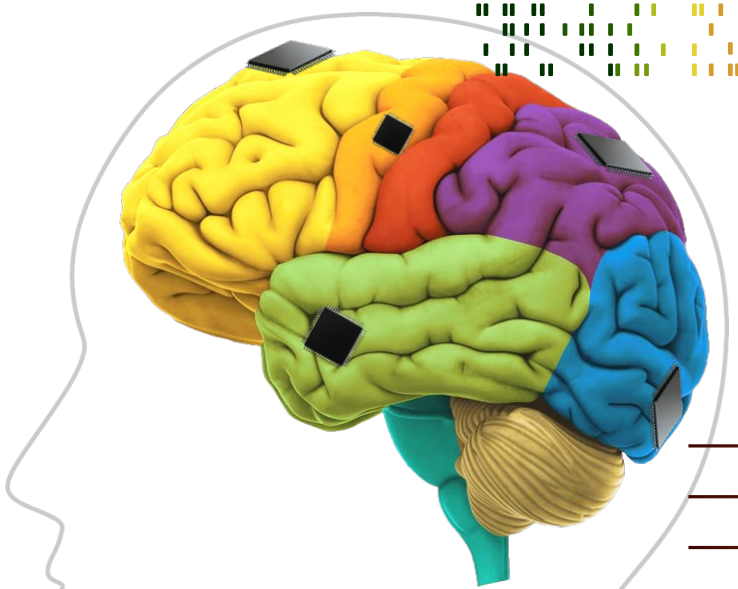
# My Research

IEEE Micro (HotChips)'23

**HALO: Single-site BCI**

ISCA'23 (Best paper), Top Picks'24

**SCALO: Multi-site BCI**

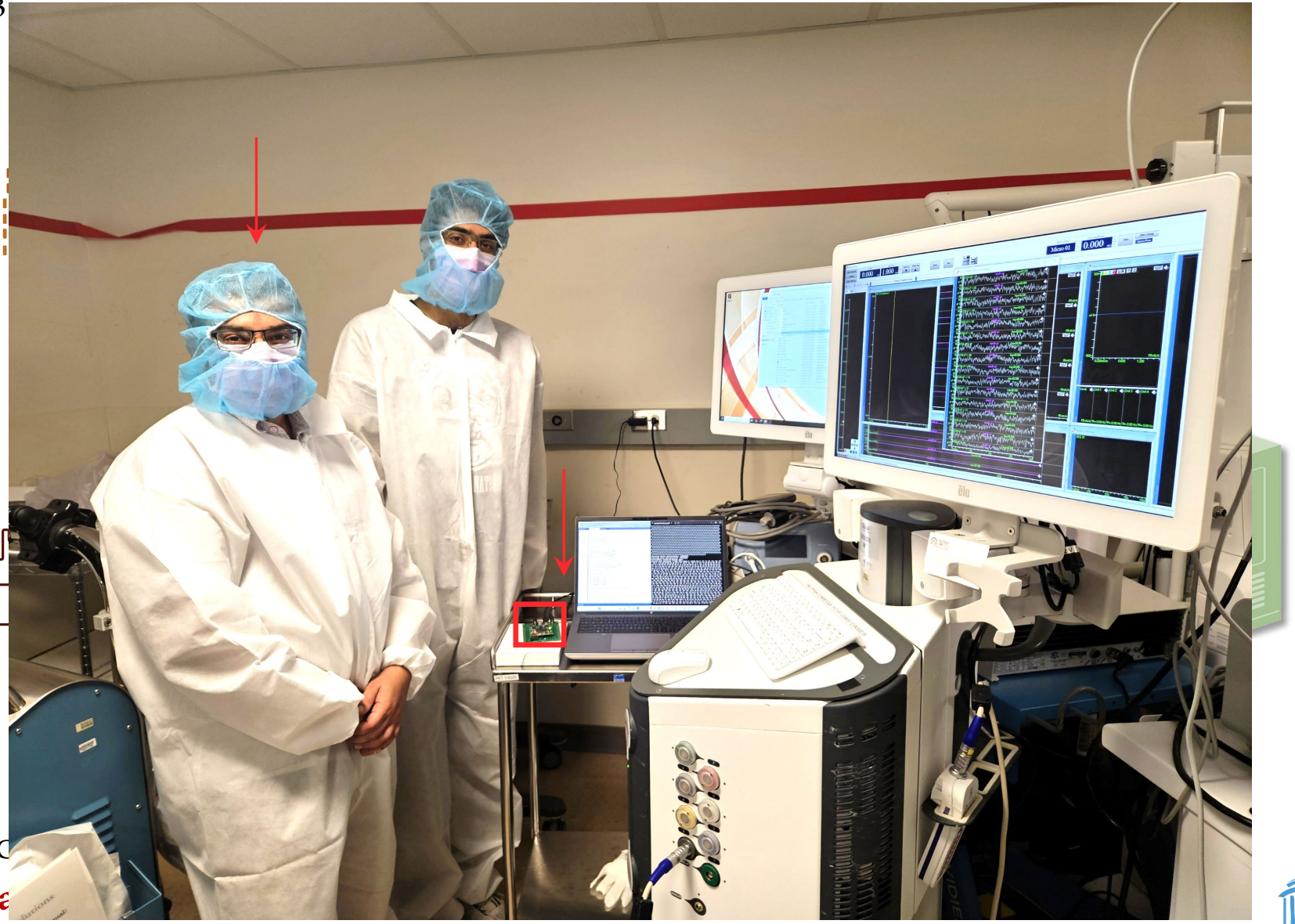


EMBC'25, SPAA'25

**Systematic co-design**

ISCA'16, PAC

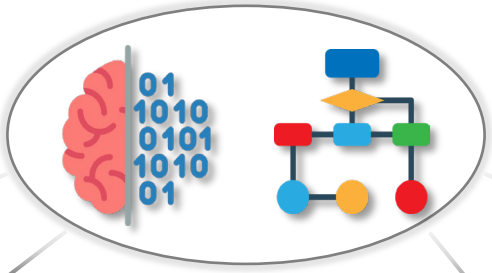
**Ada**



# My Vision: Building the Infinite Brain

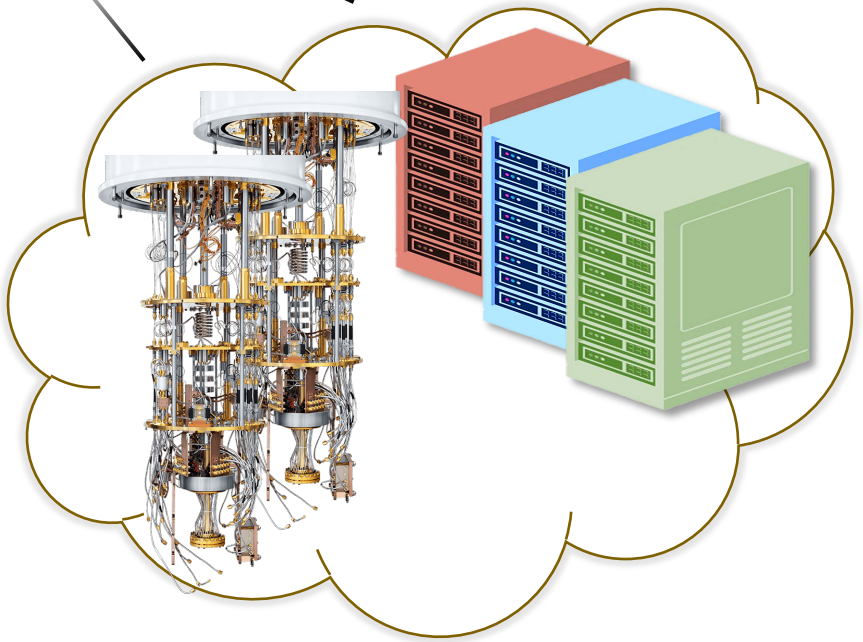
Real-time cognitive frameworks

Tbps, in vivo


Wearables

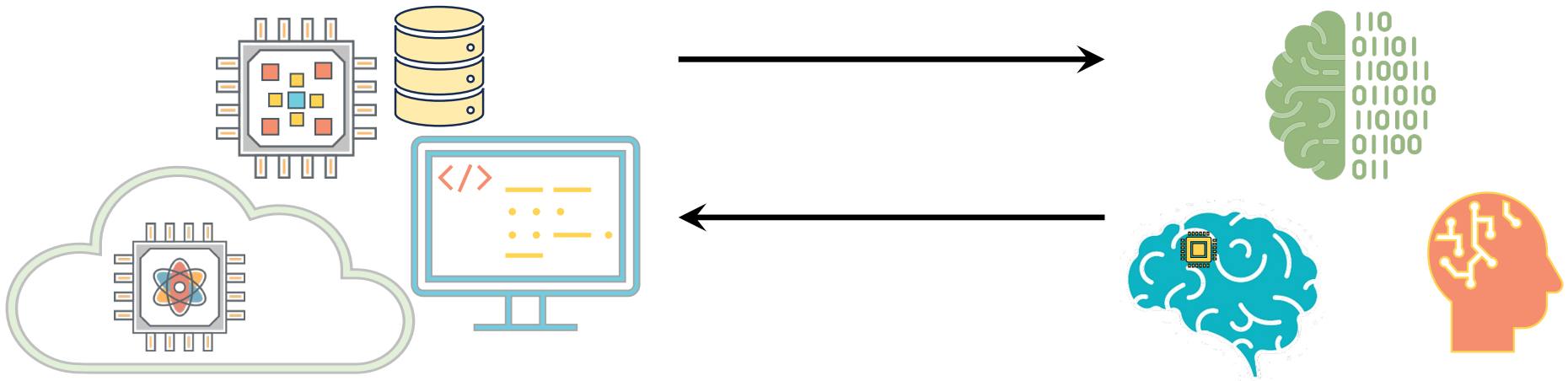
Edge servers



High performance cloud

# Central Theme: A Virtuous Cycle of Innovation

**Architectures and systems for the brain sciences**



**Constraints and inspiration from the brain sciences for architectures**

# Course Logistics

**Scope:** Computer architecture and systems (*not neuroscience, ML, AI, or robotics*)

**Mode:** Lectures, paper reviews, and student led paper discussion

Phase 1: The computational challenges in BCI Computing

Phase 2: Computer architecture and systems design

Phase 3: Designing and building processors

**Assessment:** Homeworks, paper reviews and presentations, a project, and lab exercises (new)

**Project:** "Working" (FPGA, compiler, simulator, algorithm), surveys (only if new insight)

**Time commitment:** Reading-heavy (papers and lighter reading), project-heavy

**Grading:** Project (30%), homeworks (20%), paper reviews (10%), lead presentation (10%), lab exercises (20%), discussion (10%)—*instruction discretion and subjective*

# And, More

**Course website:** https://www.cs.unc.edu/~raghav/Courses/comp690fa26/fa26.php

**Office hours:** 30 minutes after class

**Integrity:** No violations of the honor code

**Well-being, respect, and safety:** Know about UNC Care and UNC Safe

**Privacy:** Be sensitive to your classmates privacy, and refrain from recording

**Copyrights:** No sharing of course materials outside of the class

**AI tools:** Understand concepts or find related work, but no course materials (lecture slides, homeworks etc.) and works of other students (reviews etc.) can be shared

Sign up on Piazza!
https://piazza.com/unc/fall2026/comp690193

# For Today

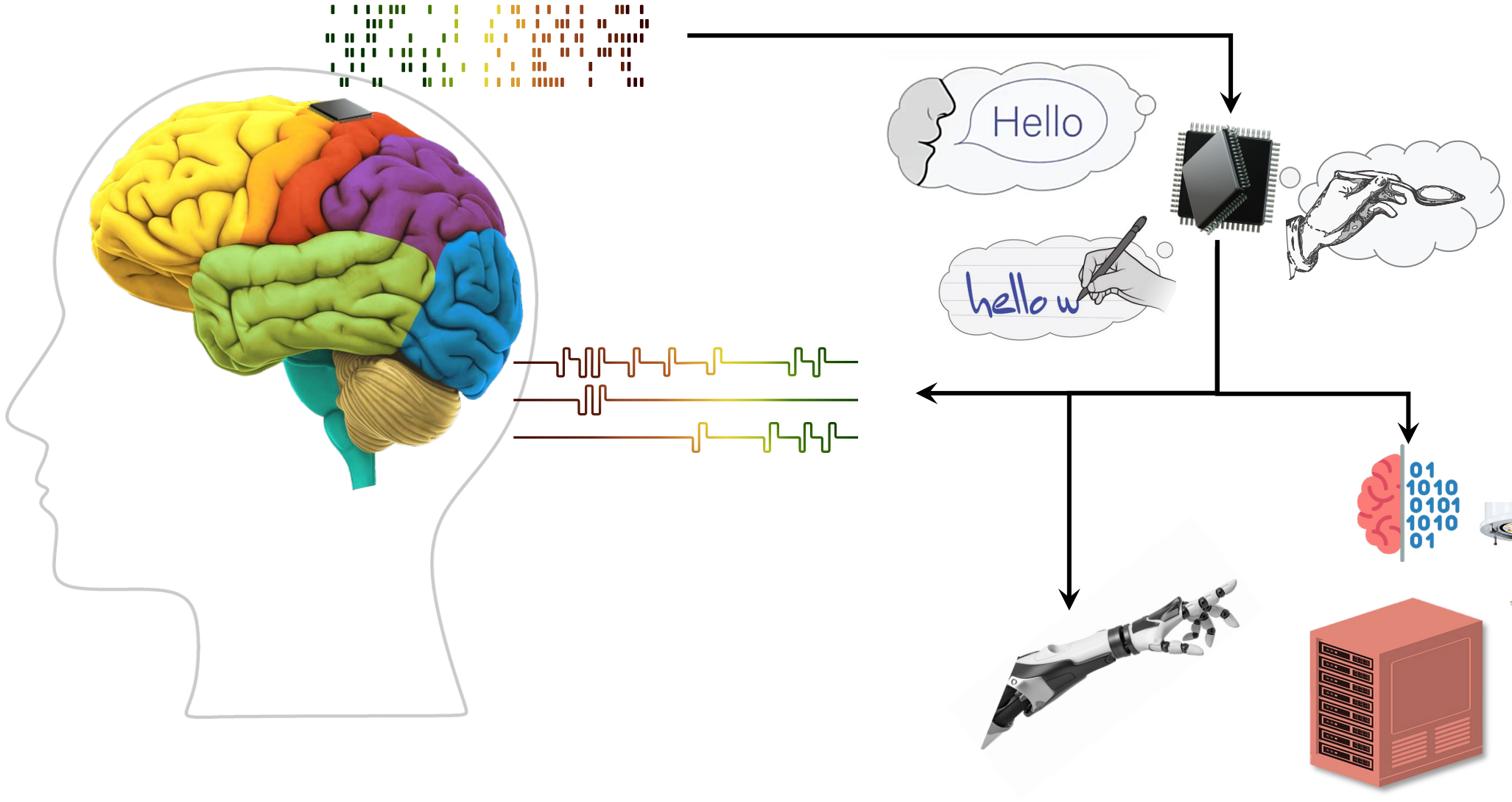
- Course overview
- **What are BCIs?**
- **What are the computational challenges?**

# What Are BCIs?

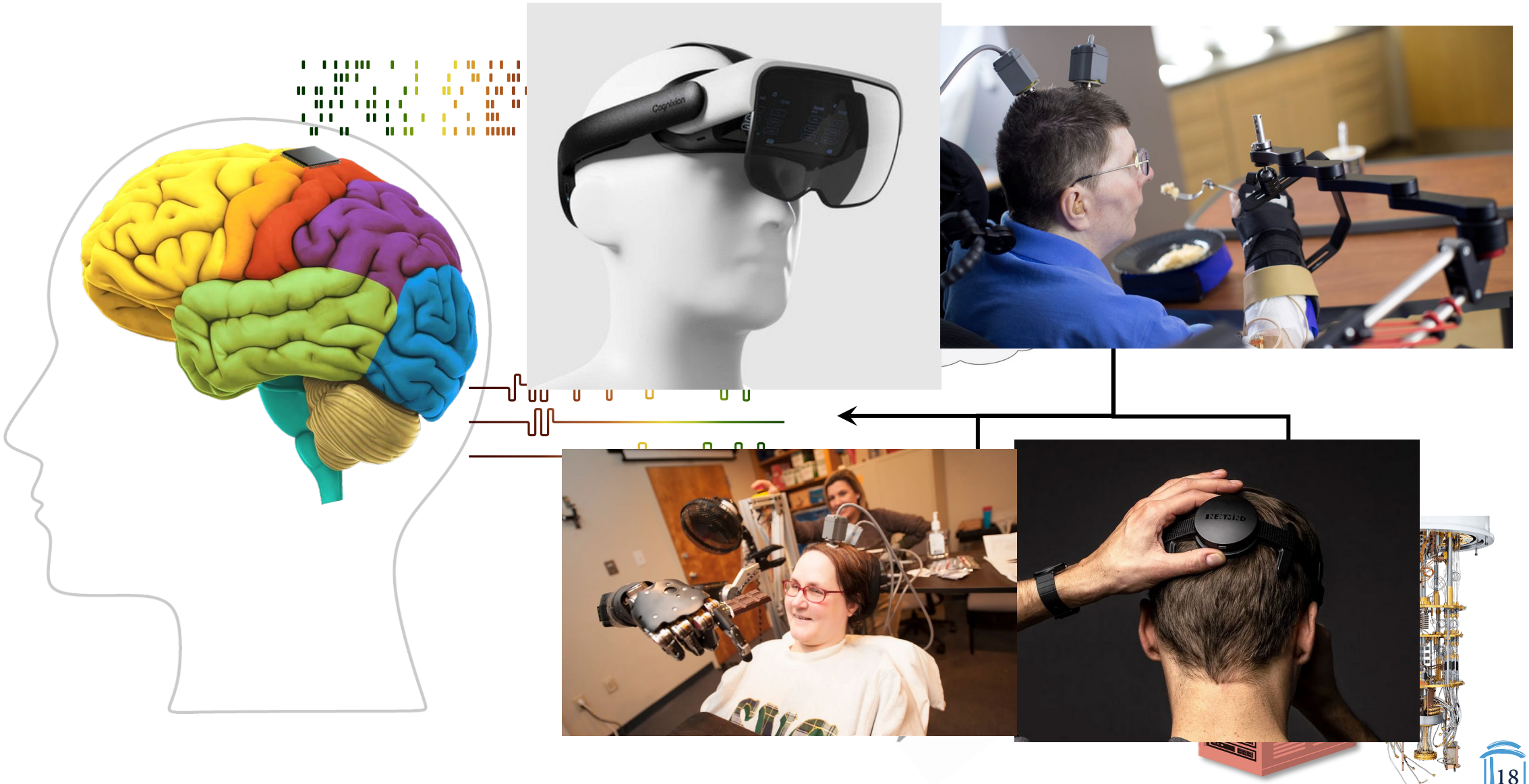
*"What's in a name? That which we call a rose by any other name would smell as sweet."*

Doesn't seem so with BCIs!

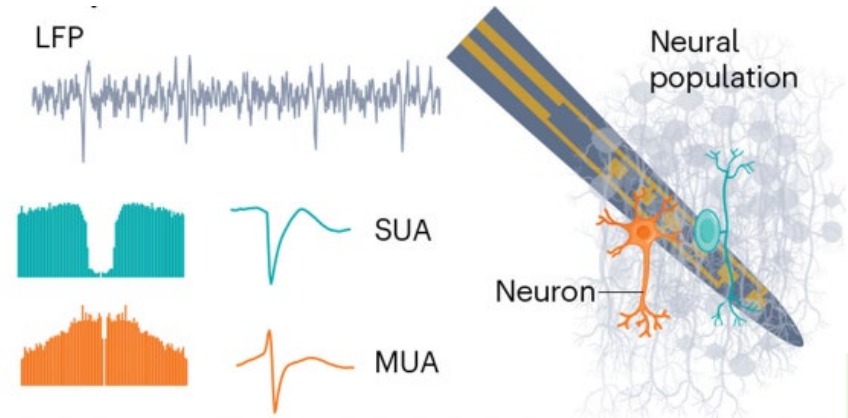
# Brain Computer Interfaces (BCIs)



# Brain Computer Interfaces (BCIs)

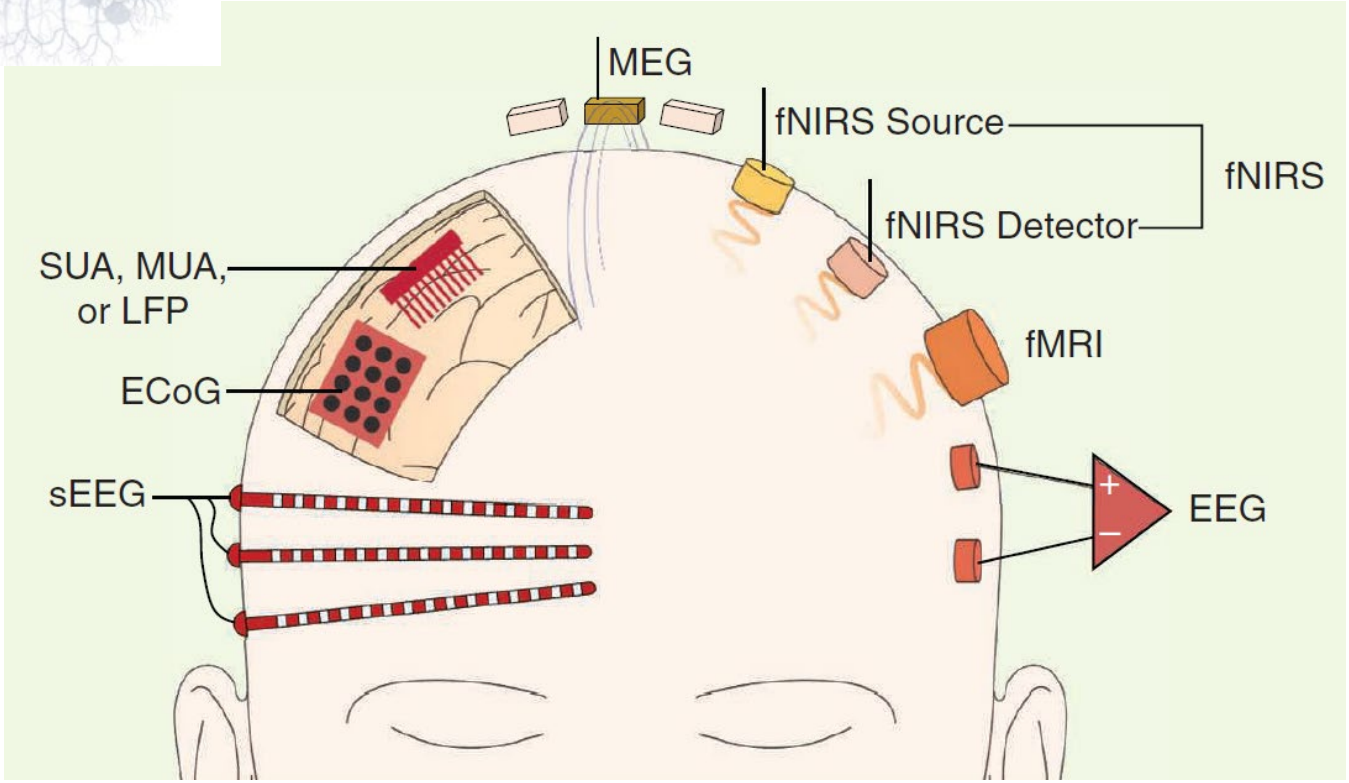


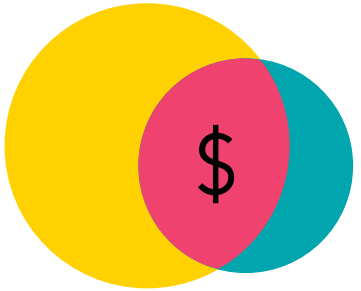
# What's In a Name?




SUA: Single unit activity
MUA: Multi unit activity
LFP: Local field potential

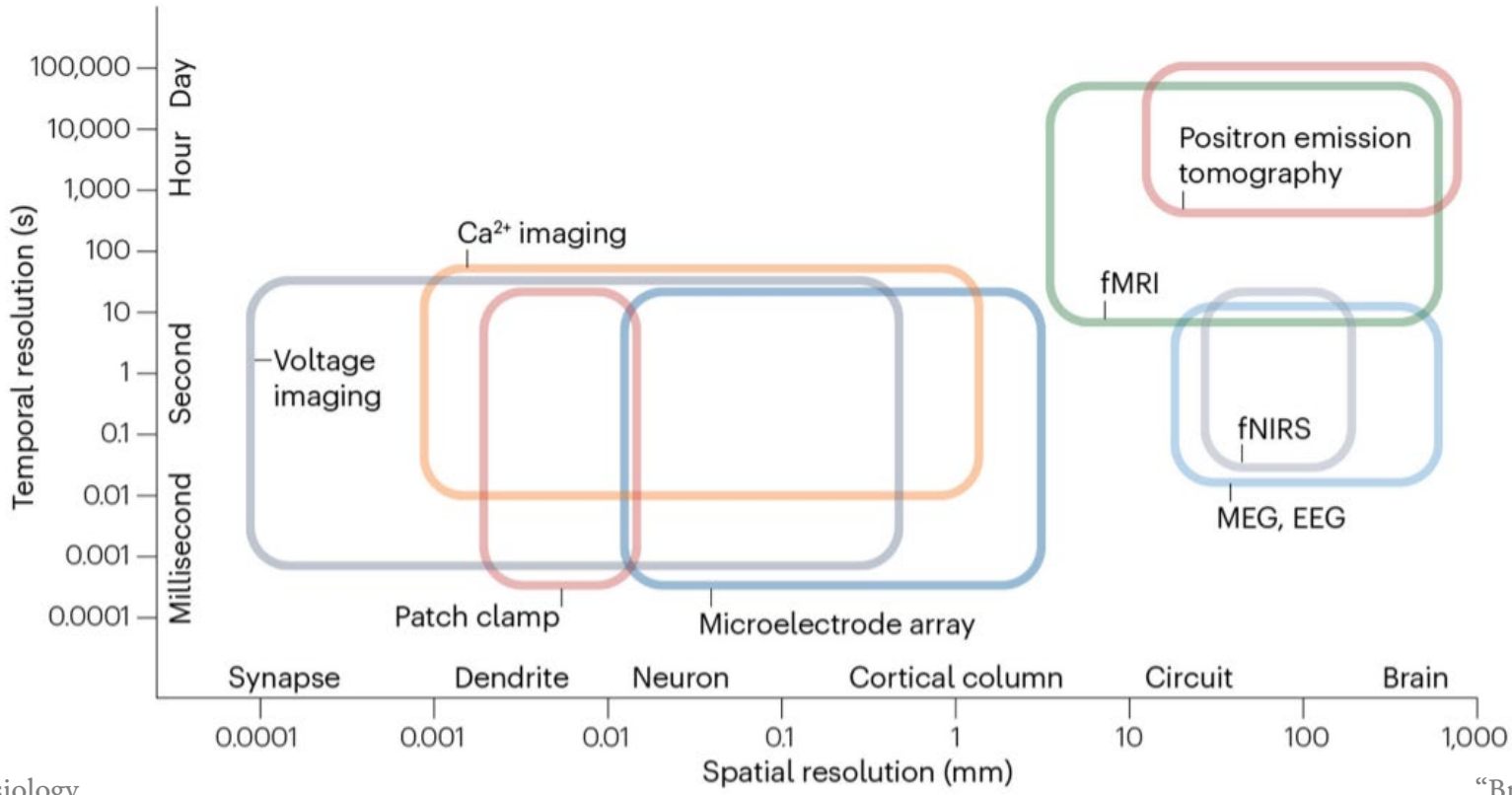
EEG: Electroencephalography
fMRI: functional magnetic resonance imaging
fNIRS: functional near-infrared spectroscopy
MEG: magnetoencephalography
ECoG: Electrocorticography
s/i EEG: stereotactic/intracortical EEG




**TAMs and scope**

# What's In a Name?




"Innovating beyond electrophysiology through multimodal neural interfaces"

"Brain–computer interfaces for communication and rehabilitation"

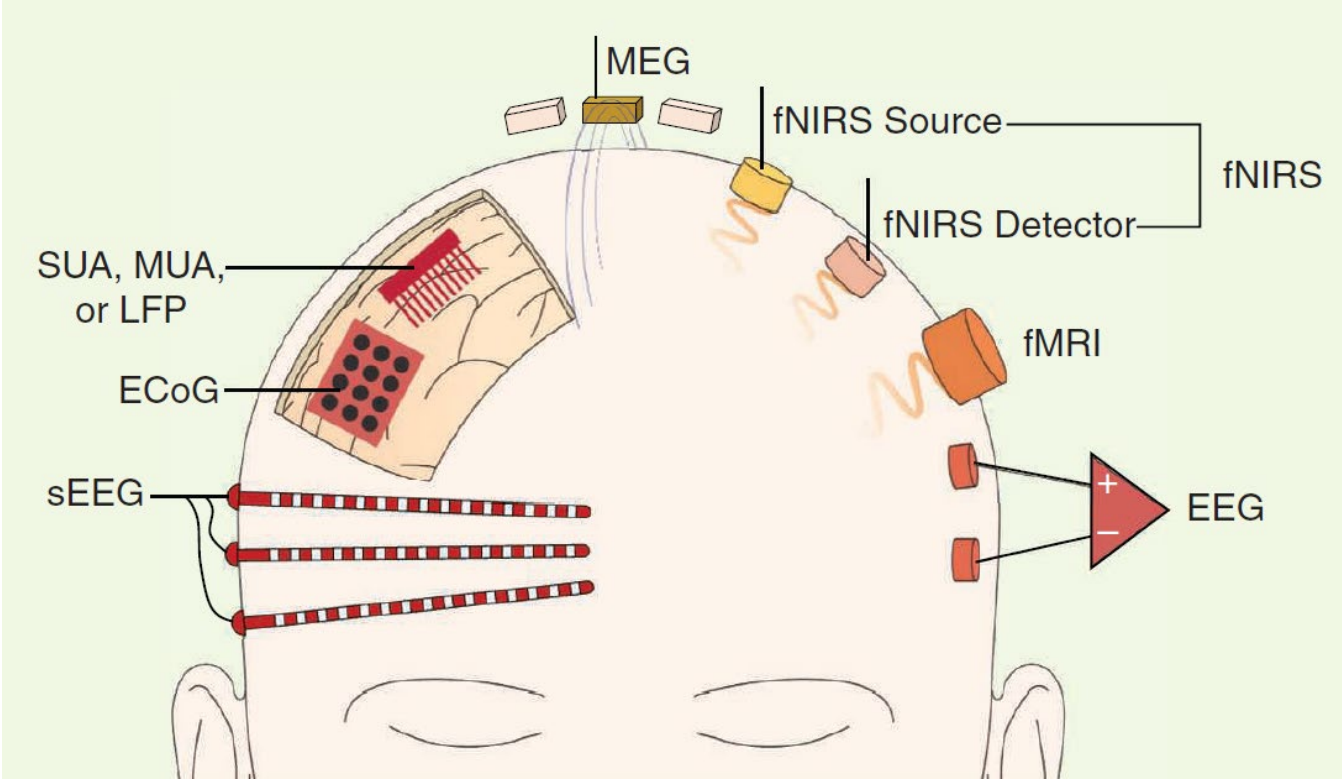
# What's In a Name?

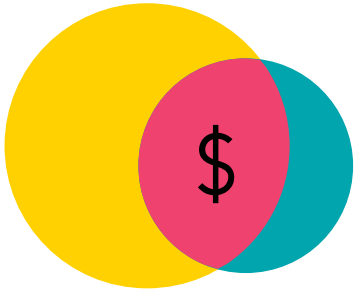
BCI SOCIETY

"A brain-computer interface is a system that measures brain activity and converts it in (nearly) real-time into functionally useful outputs to replace, restore, enhance, supplement, and/or improve the natural outputs of the brain, thereby changing the ongoing interactions between the brain and its external or internal environments. It may additionally modify brain activity using targeted delivery of stimuli to create functionally useful inputs to the brain."

FDA

**Designated pathways**



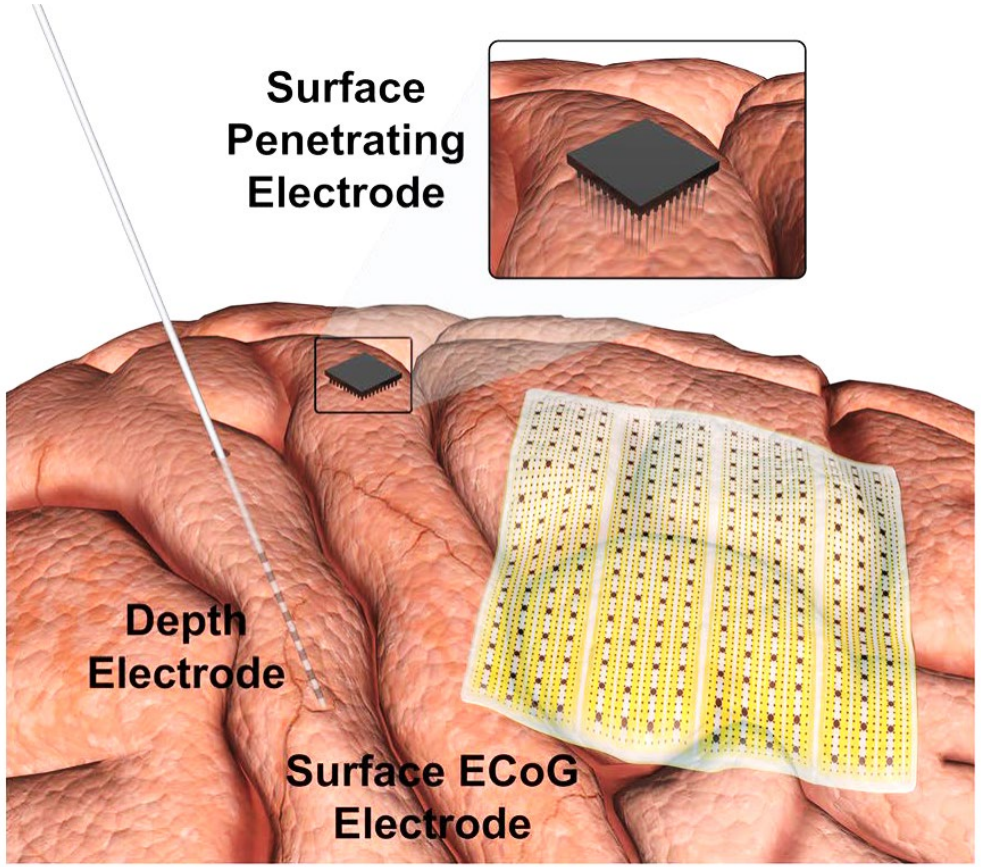

**TAMs and scope**

"Brain–computer interfaces for communication and rehabilitation"

# BCI Hardware

$\Delta T \leq 1\ °C$

$< 50\ mW$



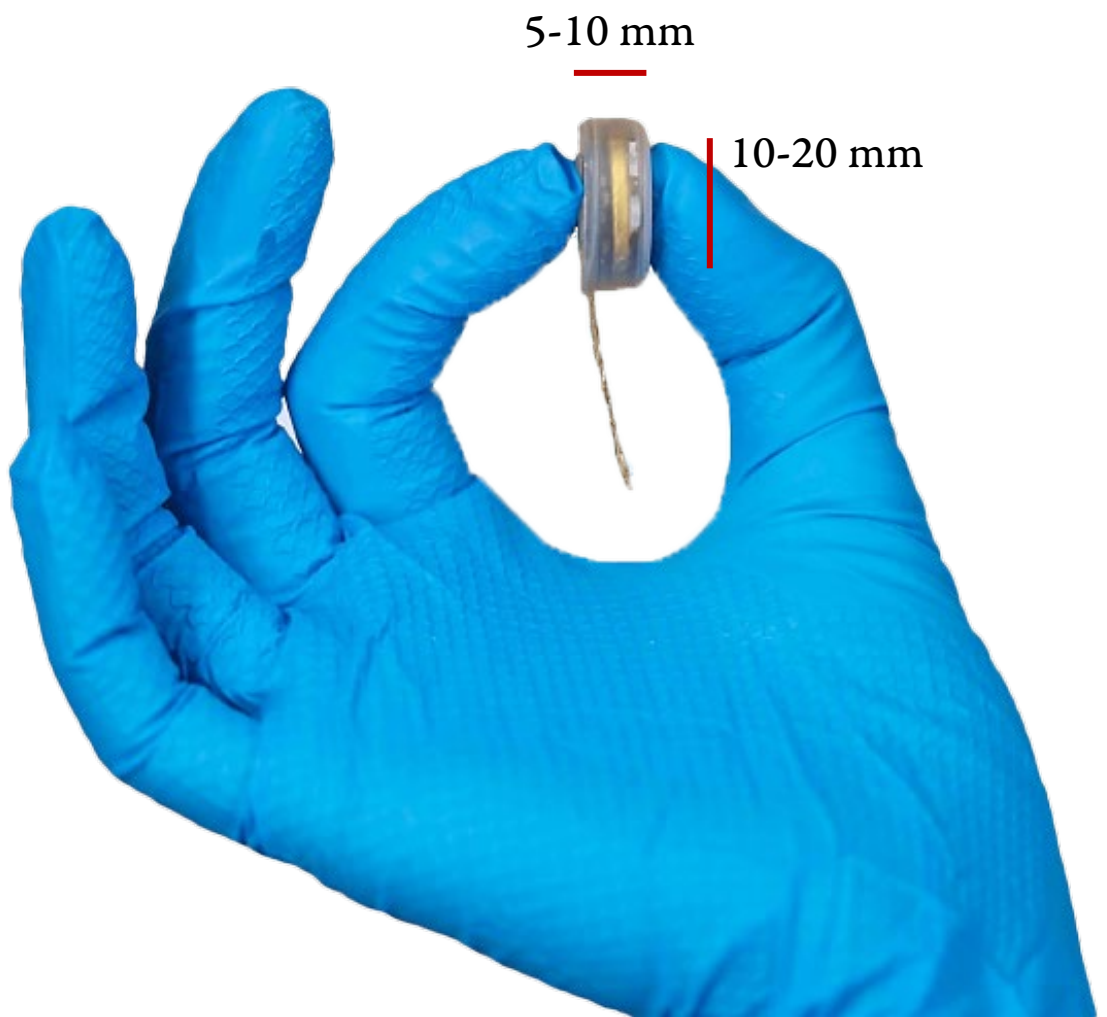

Illustrative BCI system

- Battery, Wireless
- Processing
- Digitization
- Electrodes

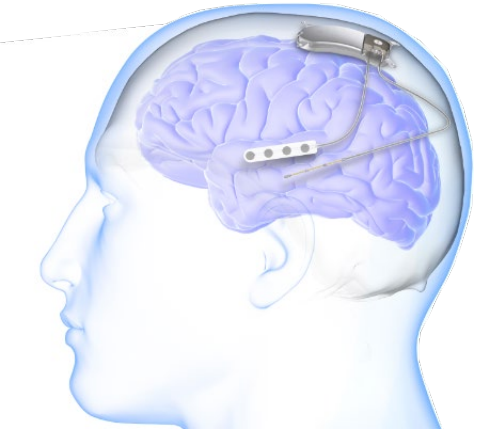
# BCI Hardware

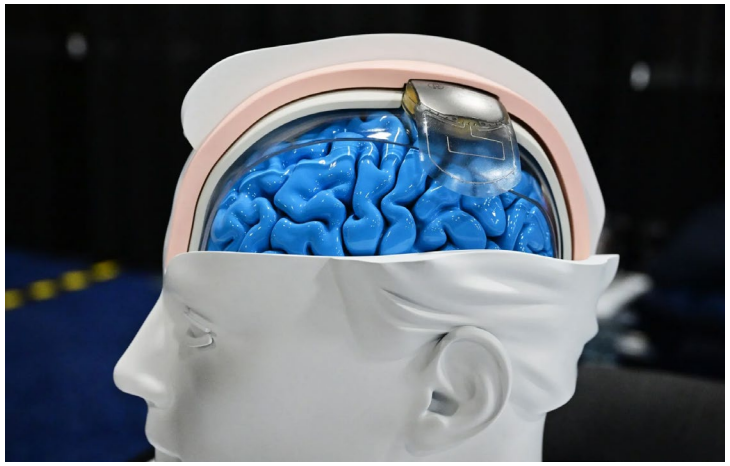
$\Delta T \leq 1\ °C$

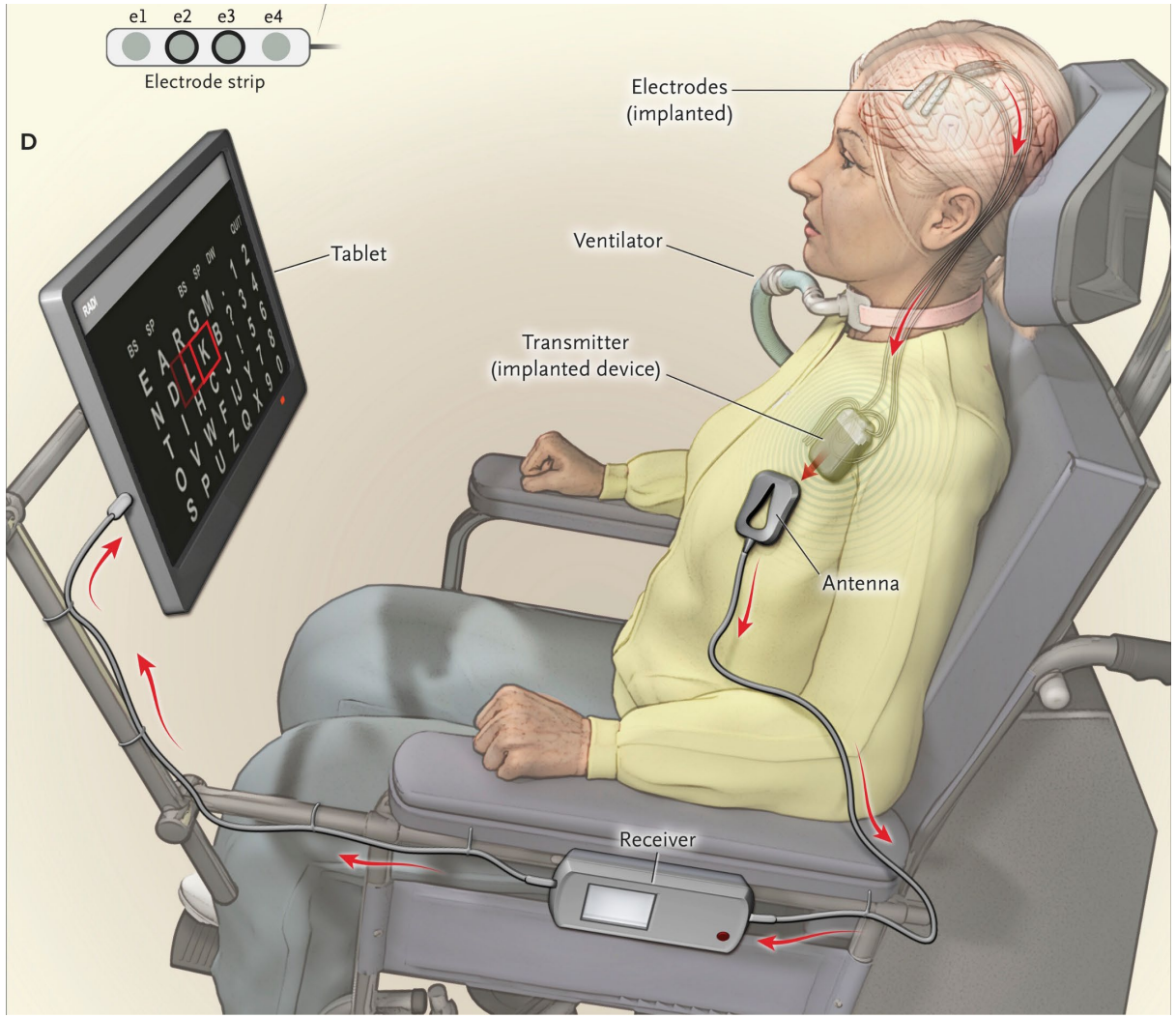
$< 50\ mW$



# Implanted BCI Form Factors






**Design constraints vary in each scenario**

# Real-world BCI Demonstration

The BrainGate Collaboration, Brown University, Mass General

# Another Real-world BCI Demonstration

José Delgado's stimoceiver, Yale University (1964)

The New York Times

*Brain Researcher José Delgado Asks — 'What Kind of Humans Would We Like to Construct?'*

Share full article

By Maggie Scarf

Nov. 15, 1970

"It distressed me greatly when I first came to this country in the early fifties to see so many patients without frontal lobes. Of course, much psychosurgery has now been re placed by drug treatment, but there are still people with dangerous seizures which simply do not respond to medication. In these cases, rather extensive portions of the temporal lobe may be removed —and since brain tissue doesn't regenerate, those functions which are lost are lost. Intracerebral electrodes offer a more conservative approach...For instance, there is one epileptic patient who uses a self-stimulator each time he feels a seizure coming on. By activating another part of the brain, he stops the discharge from spreading; the fit never develops."

**Computer architects in this space must consider ethics, rights, law, identity, the user, and— be sensitive to *public perception***

# More Recent Examples

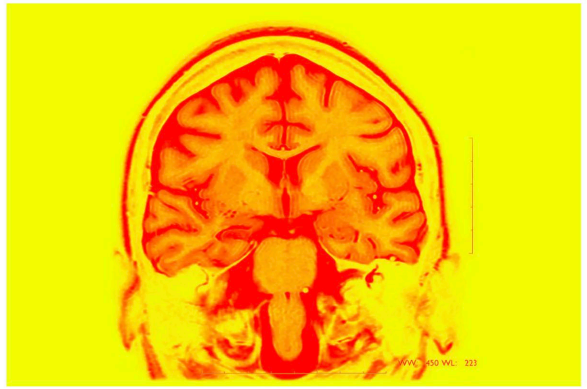
The New York Times

## *A 'Pacemaker for the Brain': No Treatment Helped Her Depression — Until This*

It's the first study of individualized brain stimulation to treat severe depression. Sarah's case raises the possibility the method may help people who don't respond to other therapies.

## *A Brain Implant Improved Memory, Scientists Report*

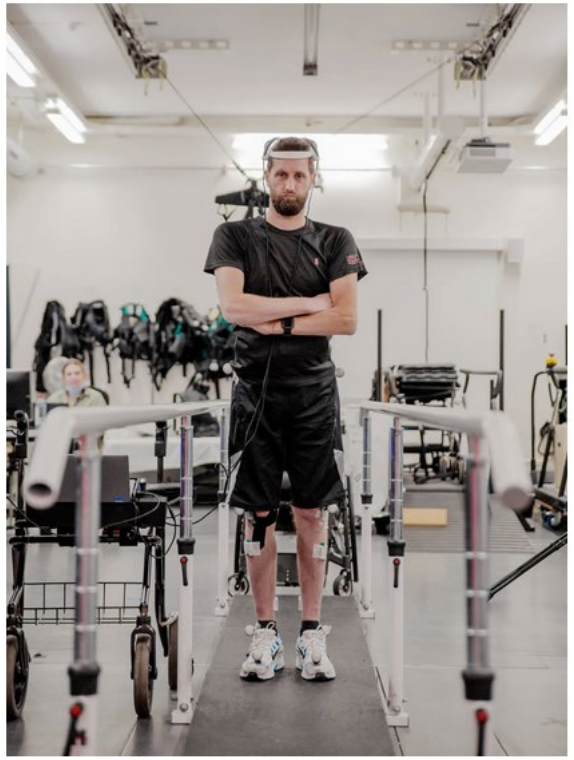
Give this article 12



A magnetic resonance image of an epileptic brain. Scientists have tested a brain implant on people with epilepsy that aided memory. Bsip/UIG, via Getty Images

## *Brain Implants Allow Paralyzed Man to Walk Using His Thoughts*

In a new study, researchers describe a device that connects the intentions of a paralyzed patient to his physical movements.



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MENTAL HEALTH

## Experimental Brain Implant Could Personalize Depression Therapy

Symptoms subsided for one woman after a carefully targeted neural circuit was stimulated

By Gary Stix on October 4, 2021

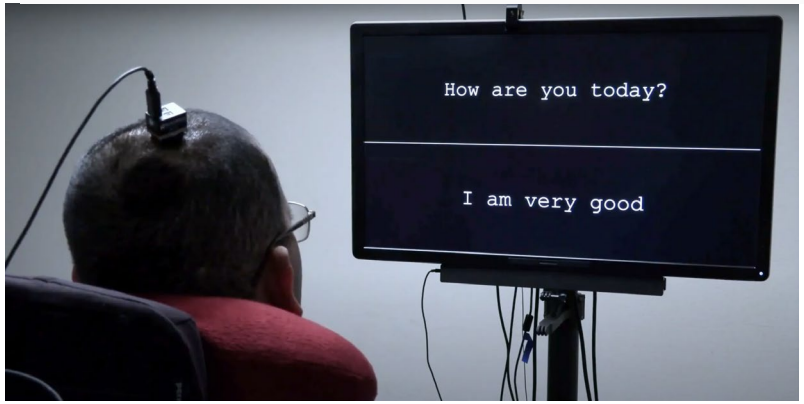
HEALTHCARE

## Brain Implants With The Potential To Restore Vision To The Blind

**William A. Haseltine** Contributor

Follow

Nov 5, 2021, 12:24pm EDT



# Growing Commercial Interest











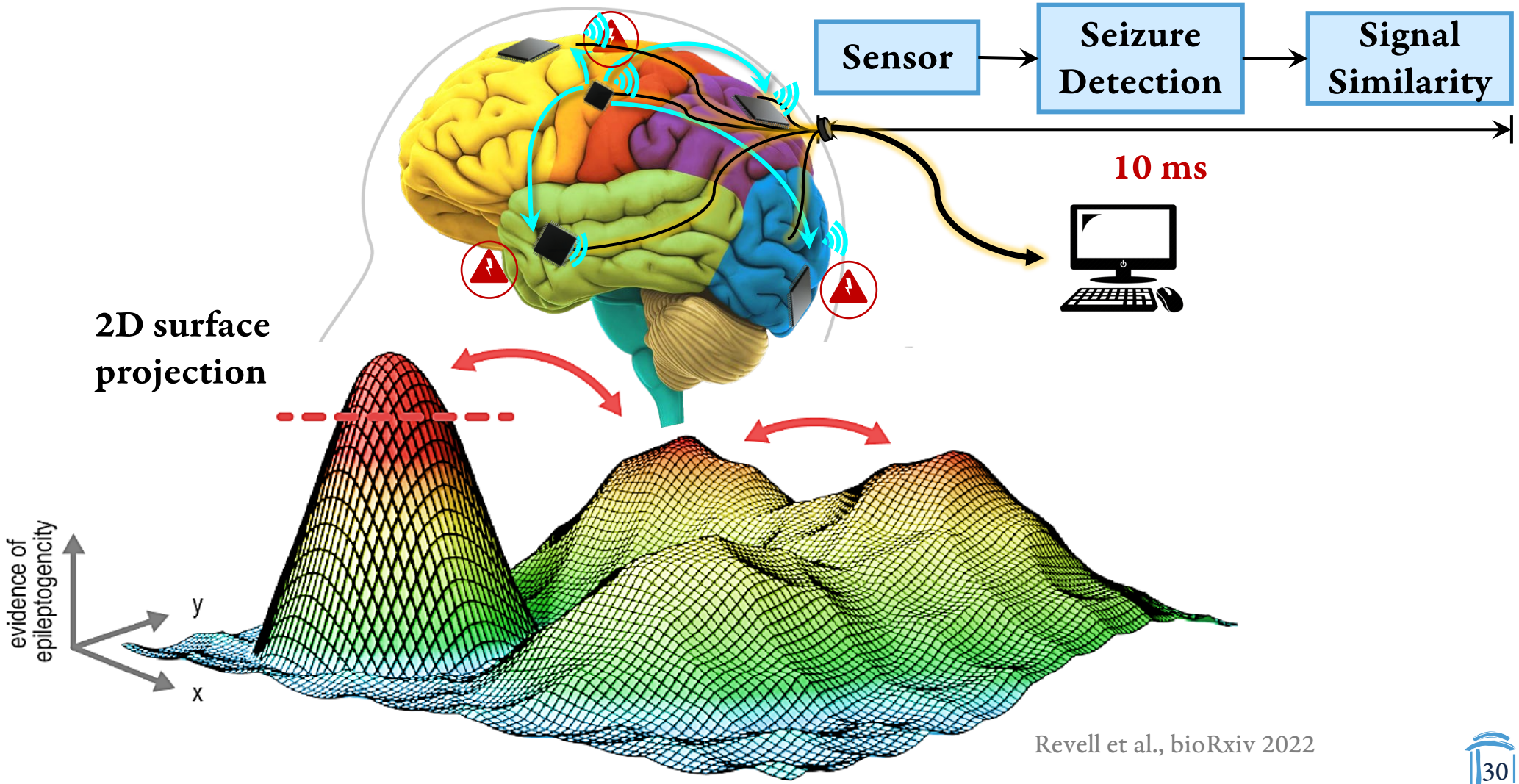

# What Are The Computational Challenges?

*Or, why must we learn computer architecture and systems for BCIs or the Infinite Brain?*

# BCI Applications

**Distributed, on-device**

**Seizure network detection**



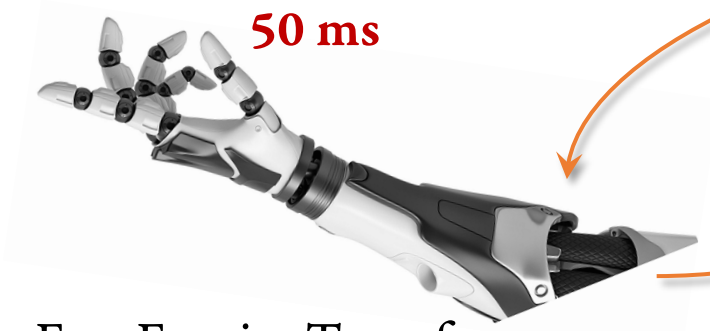

Revell et al., bioRxiv 2022

# BCI Applications

## Movement intent decoding

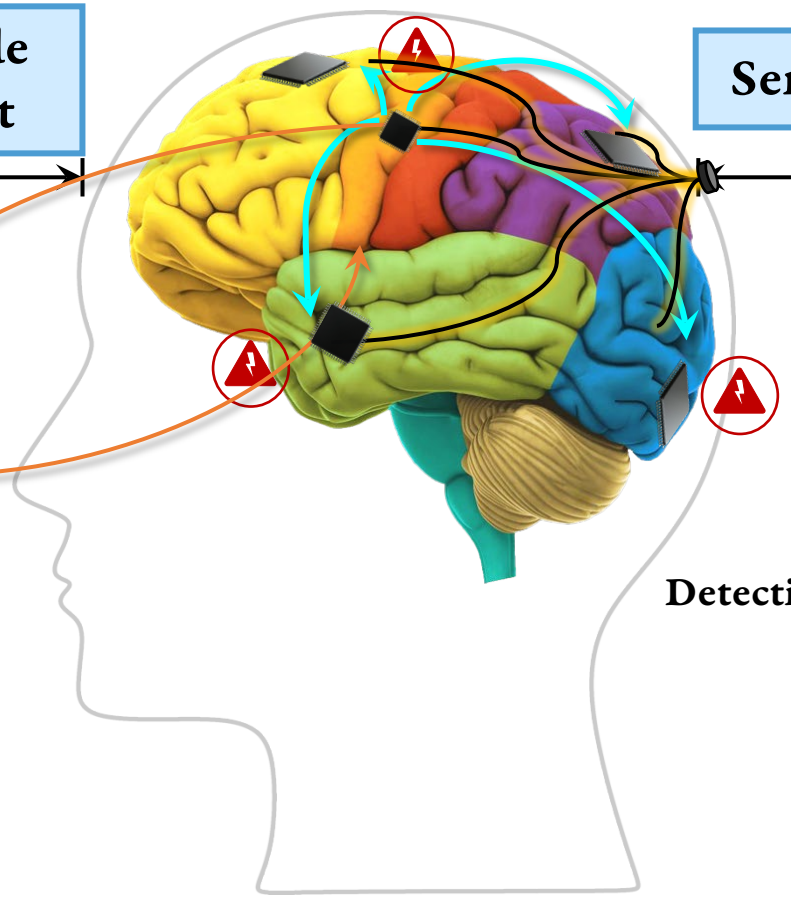
Sensor → Feature Extraction → Decode Intent

50 ms



Fast Fourier Transform, Butterworth bandpass filters, Support vector machines, Neural networks, Kalman filters, Discrete wavelet transform, Principal component analysis, Weiner filter, Linear discriminant analysis, Clustering, ...

**Distributed, on-device**



**Real-time**

## Seizure network detection

Sensor → Seizure Detection → Signal Similarity

10 ms

**Complex, and various**

**Detection**

Fast Fourier transform, Cross-correlation, Butterworth bandpass filters, Support vector machines, Neural networks, Kalman filters, Discrete wavelet transform, ...

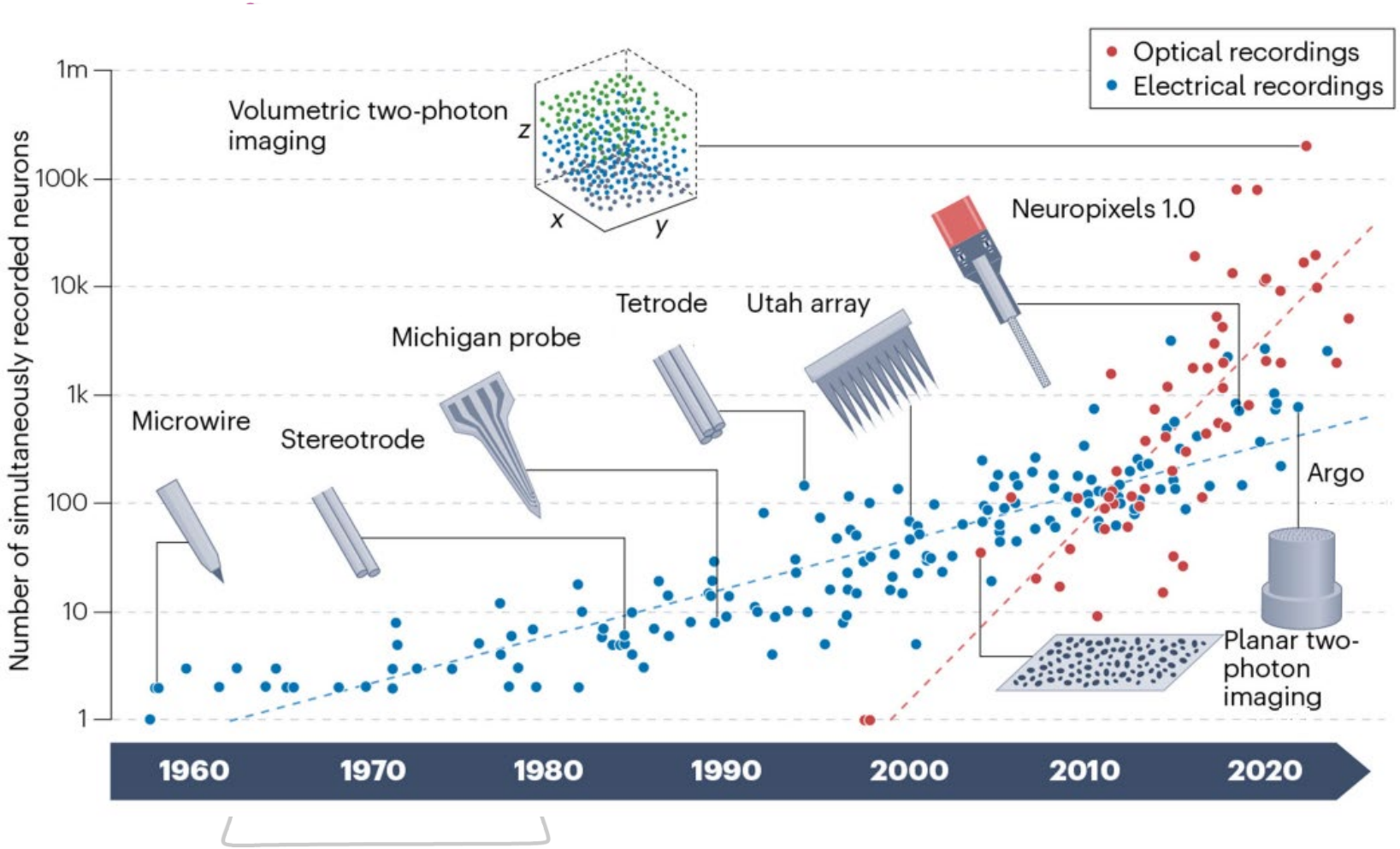
**Similarity**

Cross-correlation, Dynamic time warping, Earth mover's distance, Euclidean distance, Mutual information, ...

# Summary of Design Challenges

## High Throughput

**100-1000 Mbps**

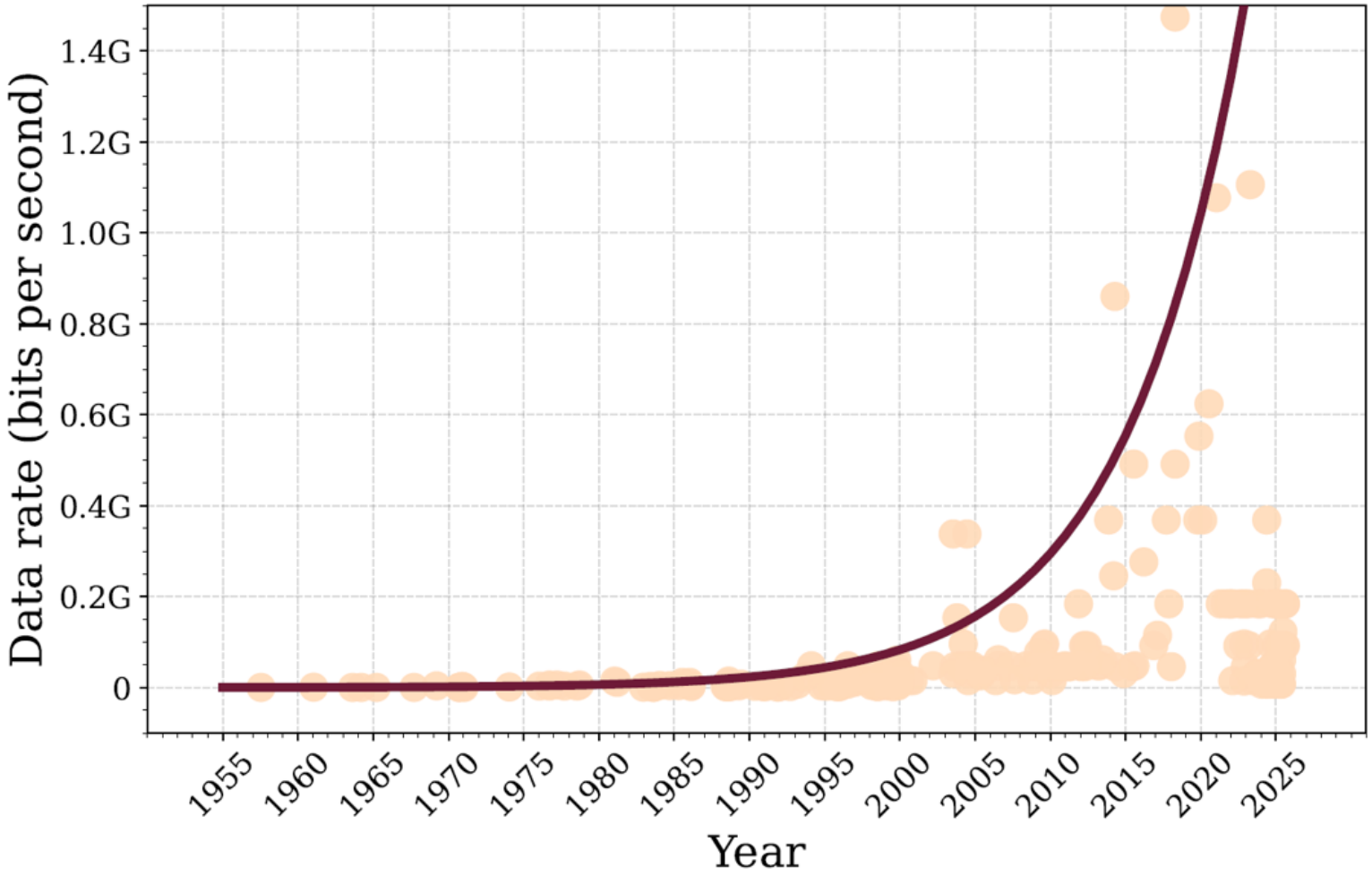



"Innovating beyond electrophysiology through multimodal neural interfaces"

# Summary of Design Challenges

**High Throughput**

**100-1000 Mbps**



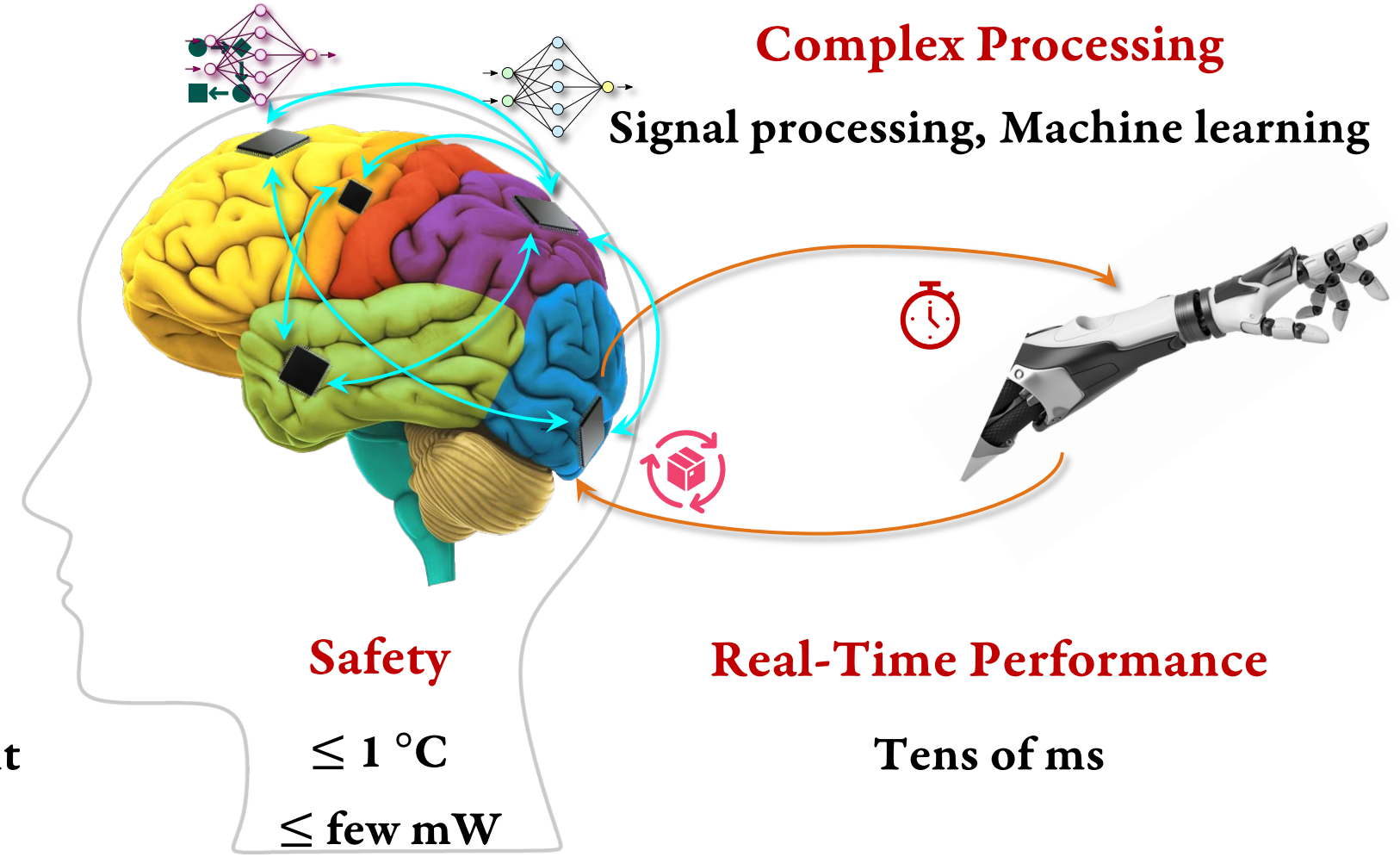
# Summary of Design Challenges

**High Throughput**

100-1000 Mbps

**Complex Processing**

Signal processing, Machine learning



**Customization**

Personalized treatment

**Safety**

≤ 1 °C

≤ few mW

**Real-Time Performance**

Tens of ms

# BCI Processing Challenge: Efficiency vs Flexibility

## Efficiency

**High throughput**

100-1000 Mbps

**Real-time performance**

Tens of ms

## Safety

≤ 1 °C

≤ few mW

## Flexibility

**Complex processing**

Signal processing, Machine learning

**Customization**

Personalized treatment, target multiple conditions, adaptation to the brain, support evolving methods

# Existing Approaches: Efficiency or Flexibility

## Specialized hardware?

Spike detection

Neuralink…

Efficient but not flexible

*Analogy: deliver a canned speech*

## Low power CPUs/GPUs/FPGAs?

…

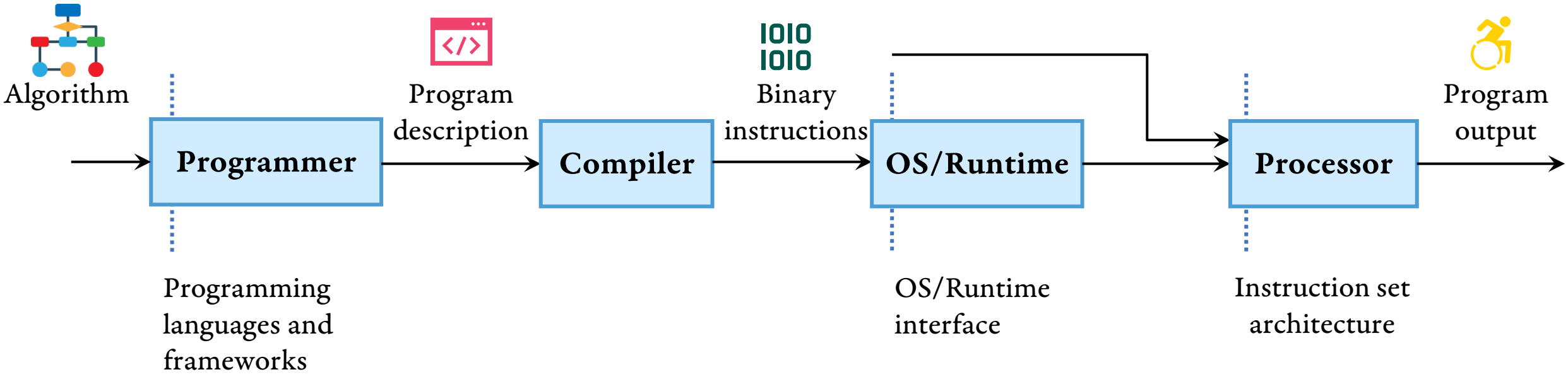
Movement Epilepsy

RISC-V, ARM, TI, …

Flexible but not efficient

*Analogy: compose a long speech by only speaking one letter at a time*

# BCI Computing is a Full Stack Problem

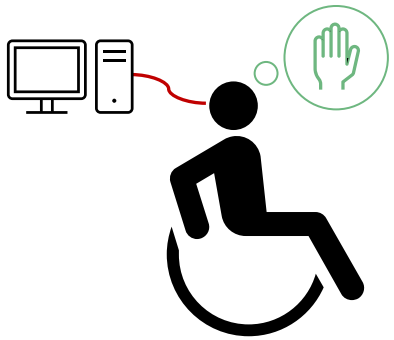


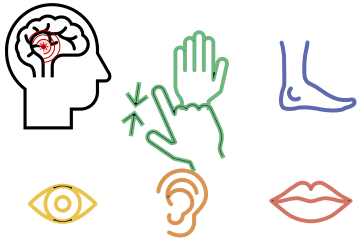

**Revisit what abstractions, design, methods and implementations are ideal, and create new as needed**

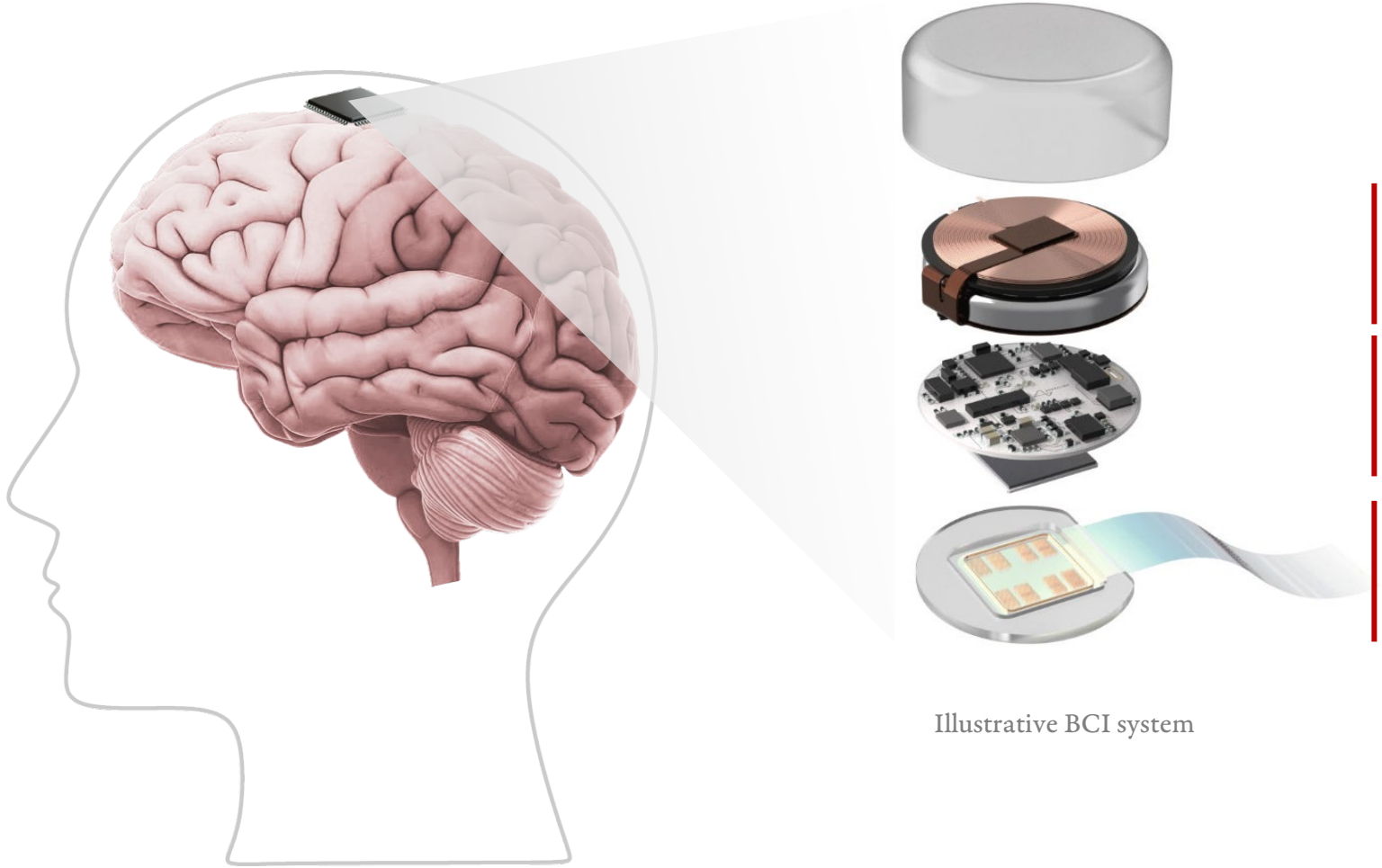
*Co-design*: Harmonious composition of the joint design of multiple components

# What Happens Without Capable BCI Processing?

**Lose autonomy** **Lose functionality**







Battery, Wireless

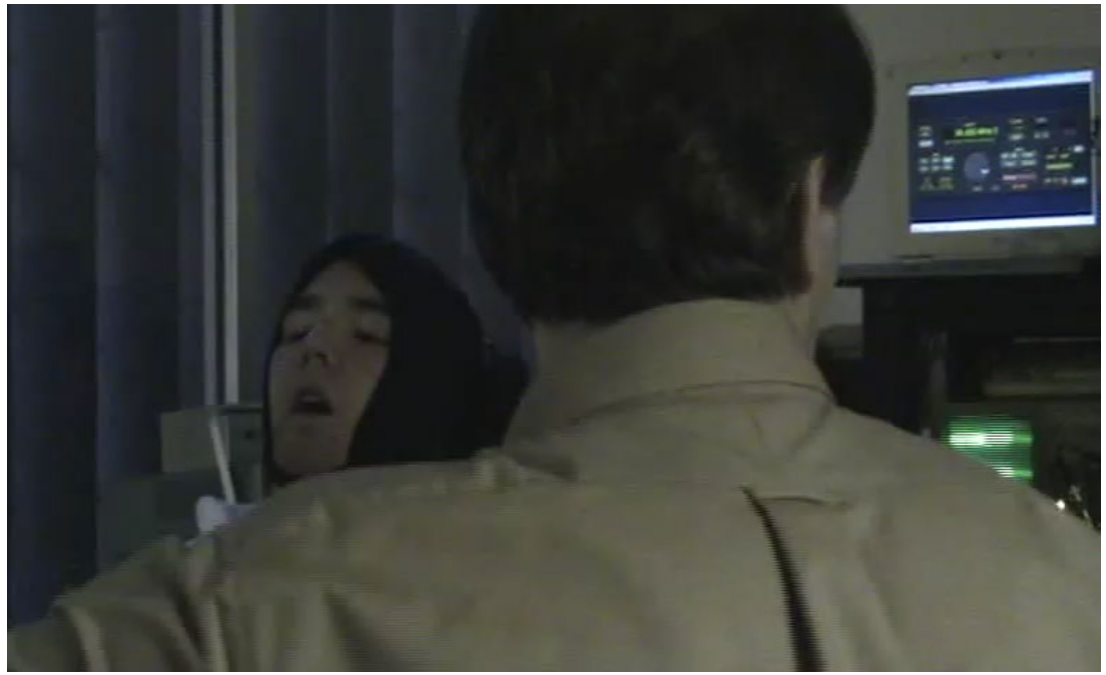
Processing **Inadequate**

Digitization

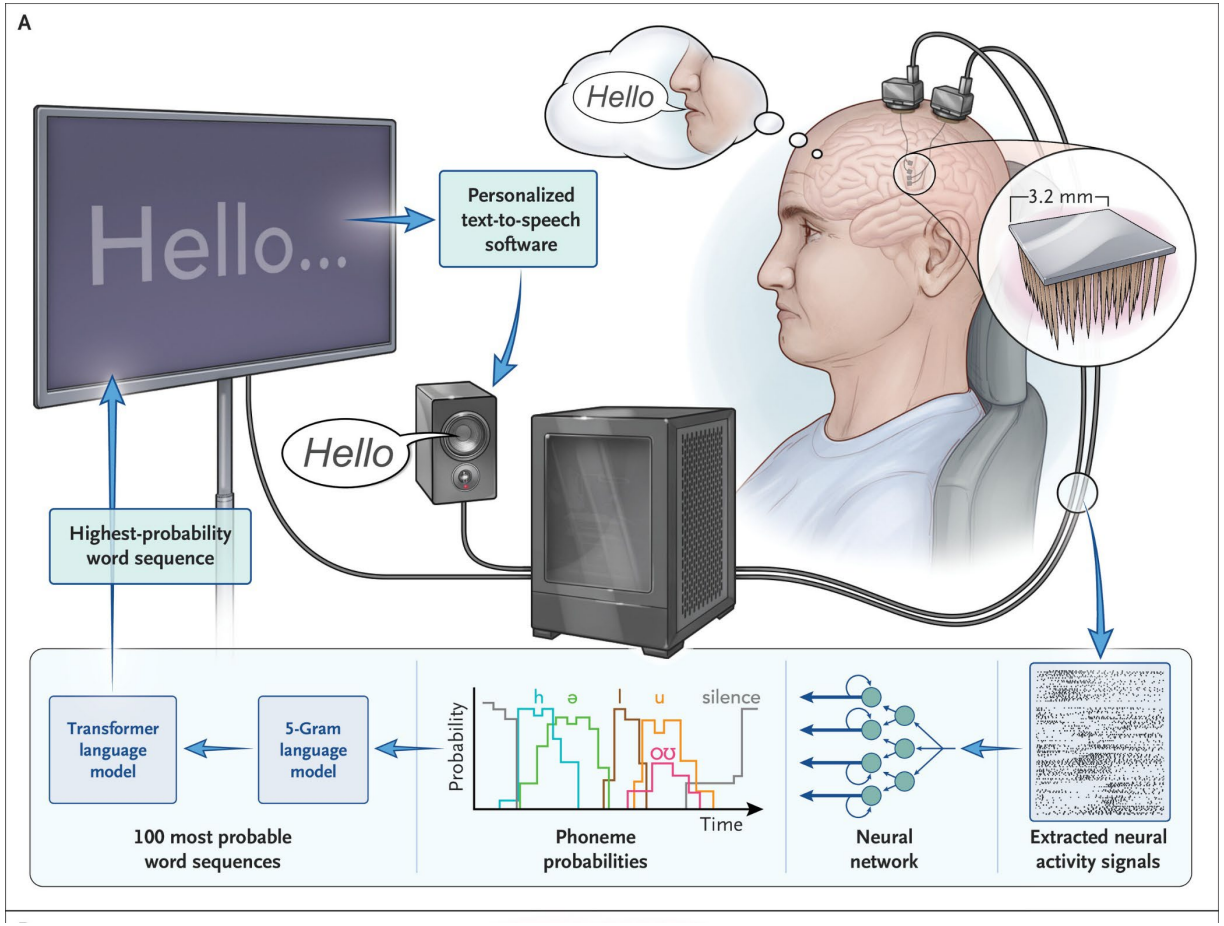
Electrodes

Illustrative BCI system

# The Need for Computing in Perspective

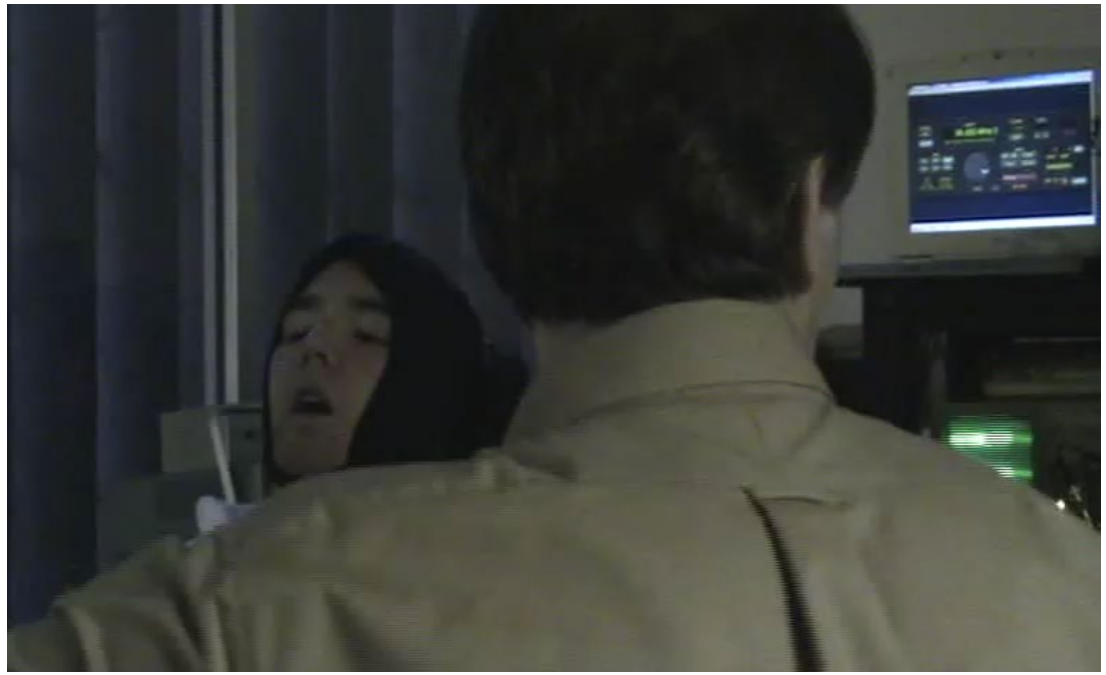


Phil Kennedy with patient Erik Ramsey, around 2004

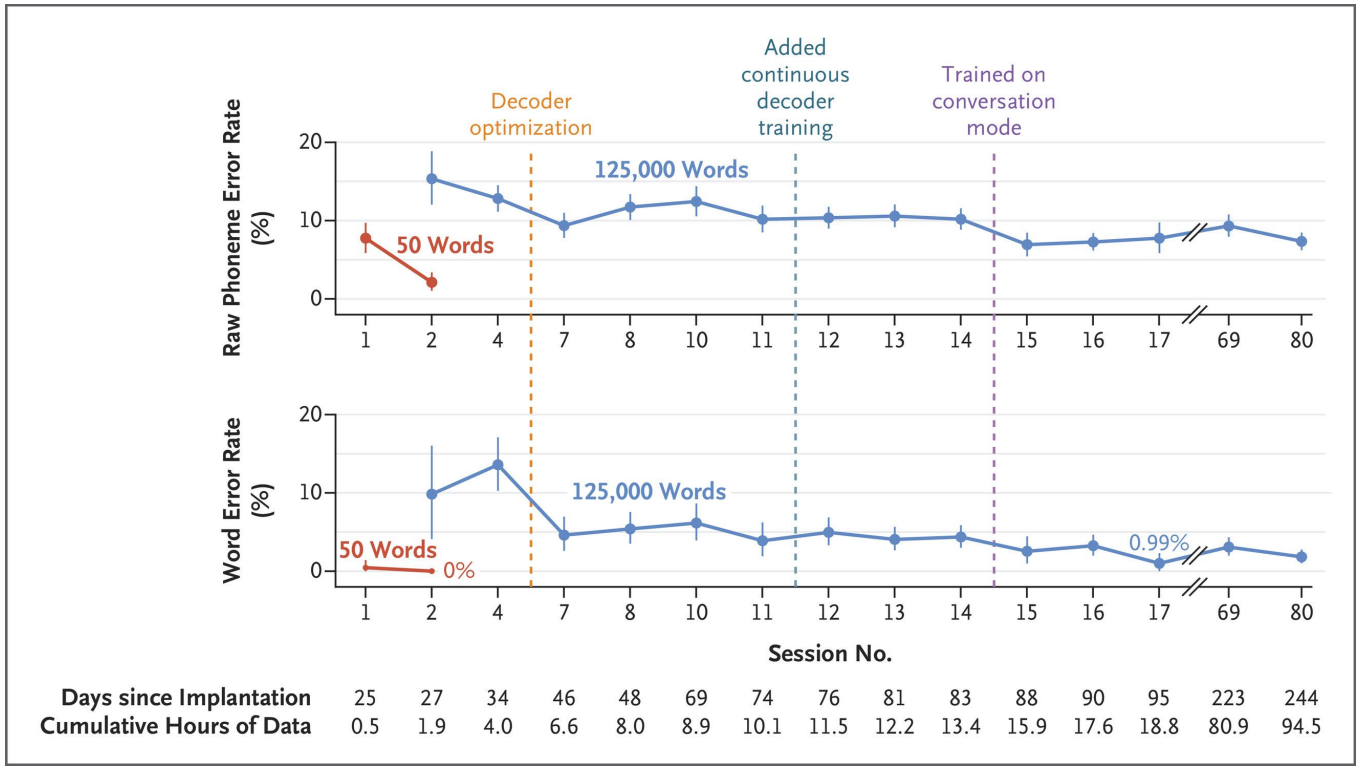



"An Accurate and Rapidly Calibrating Speech Neuroprosthesis", NEJM 2024

# The Need for Computing in Perspective



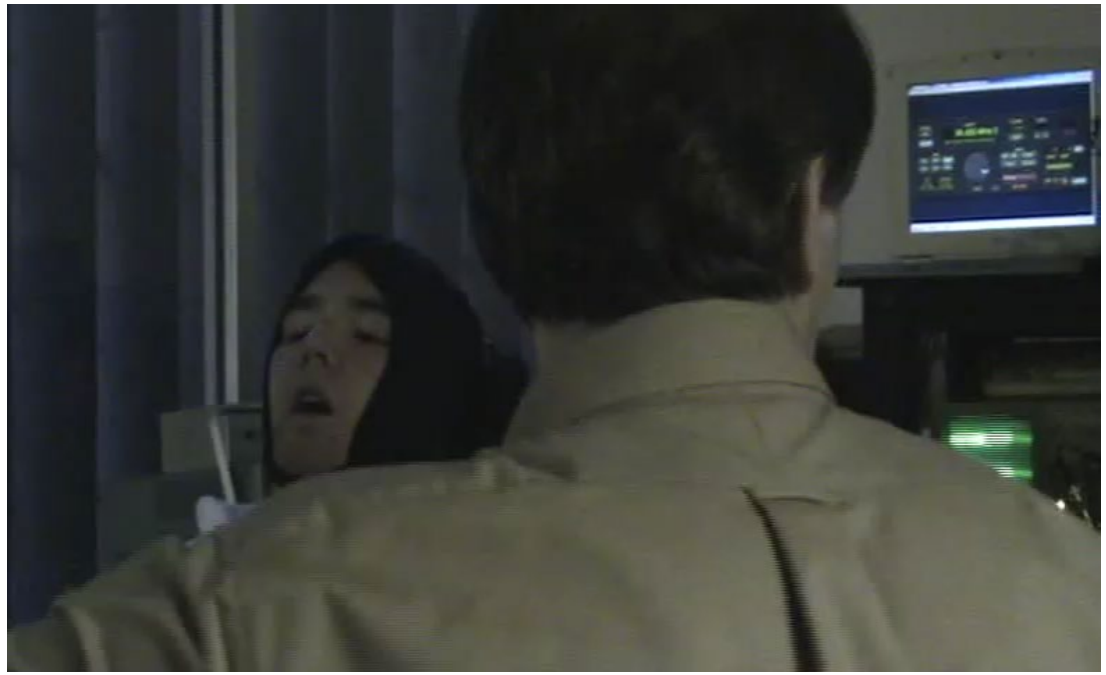
Phil Kennedy with patient Erik Ramsey, around 2004




Running on "BRAND: a platform for closed-loop experiments with deep network models"

"An Accurate and Rapidly Calibrating Speech Neuroprosthesis", NEJM 2024

# The Need for Computing in Perspective



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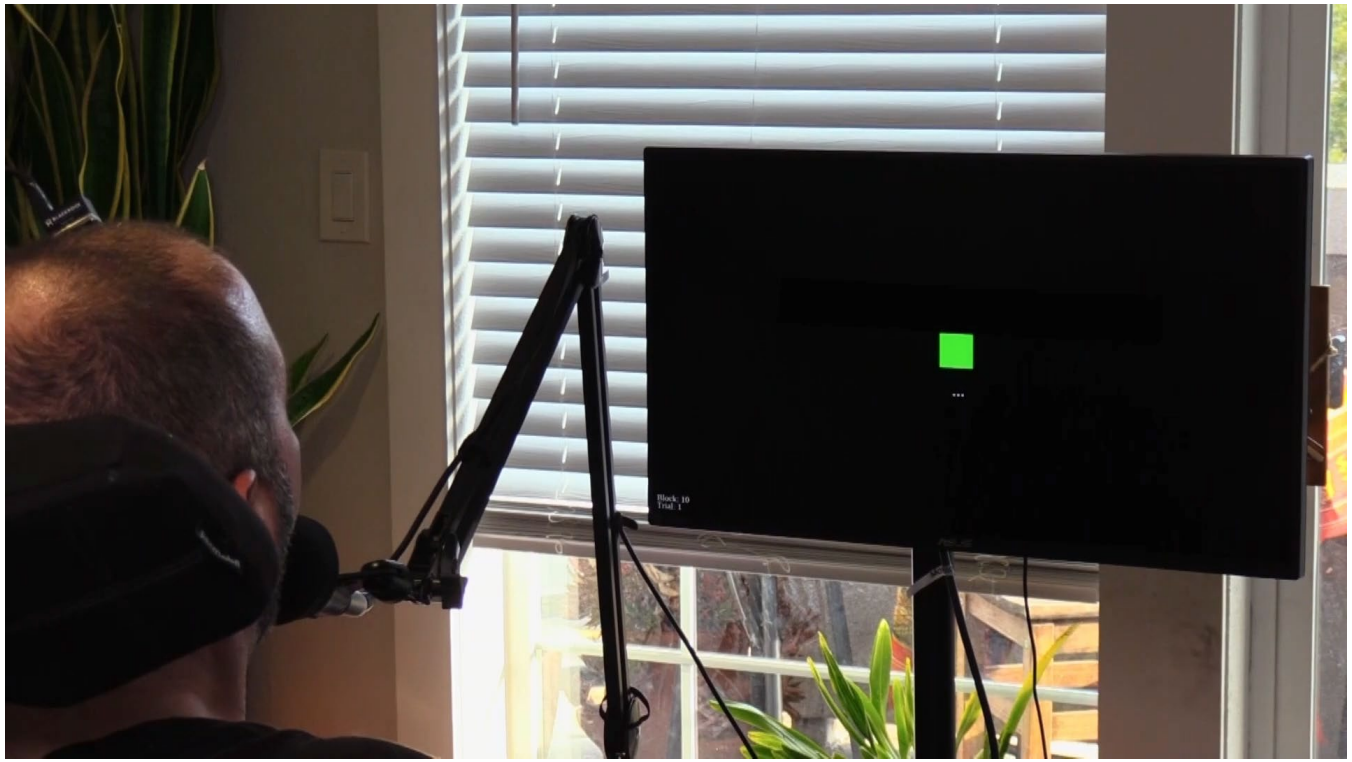

Running on “BRAND: a platform for closed-loop experiments with deep network models”

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# The Need for Computing in Perspective


LOCAL NEWS

**IBM's Smallest PC Designed In Triangle**

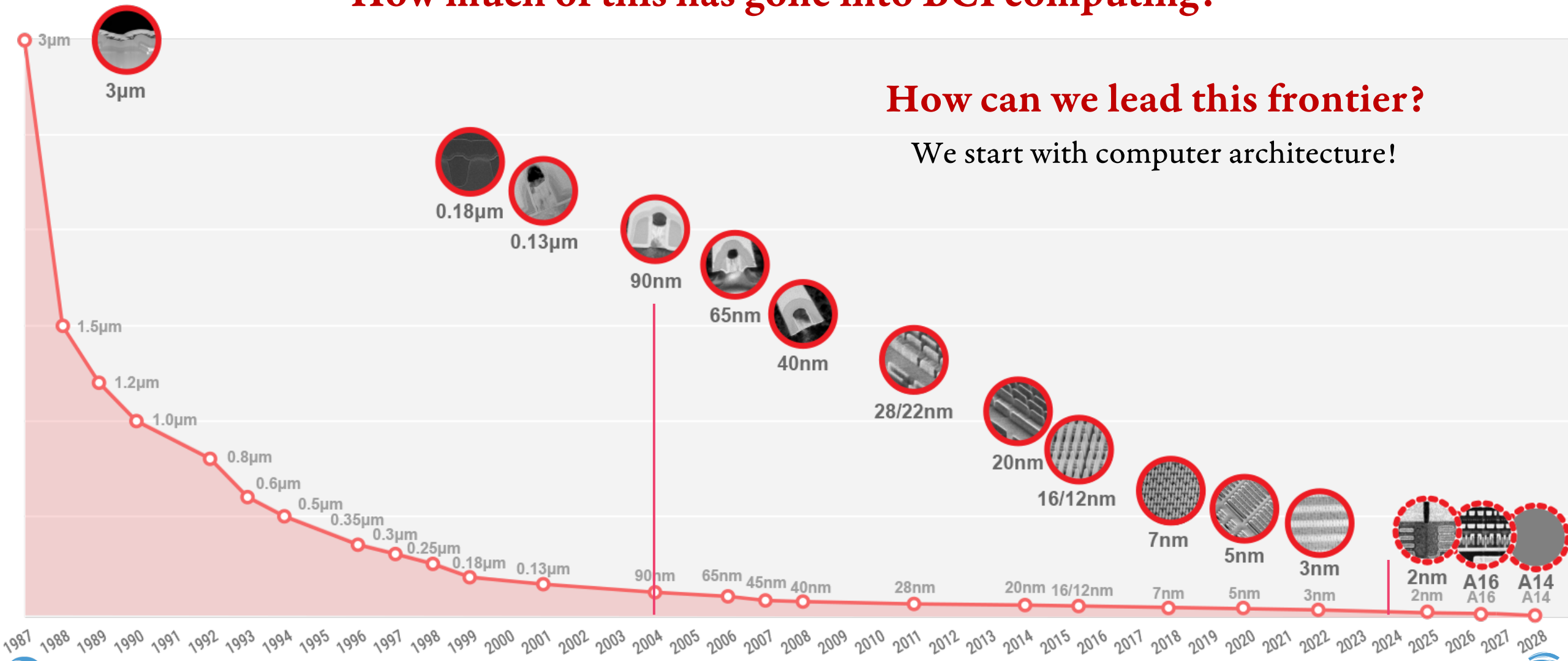
Posted 5:06 p.m. Aug 3, 2006 - Updated 5:16 a.m. Jun 11, 2004


"weighs just 13 pounds"

"It's designed to hold a 22-inch monitor and those things are about 100 to 125 pounds"

# The Need for Computing in Perspective

## How much of this has gone into BCI computing?




## How can we lead this frontier?

We start with computer architecture!

# Homework

*Yeah, I know.*

# Assignments

1-page write-up due in class on 8/24

Need 2 paper signups

**Reading:** **The Unspeakable Odyssey of the Motionless Boy**

https://www.esquire.com/news-politics/a4972/unspeakable-odyssey-motionless-boy-1008/

**Scientists seek to help 'locked-in' man speak**

https://www.cnn.com/2007/HEALTH/conditions/12/14/locked.in/index.html

**The Neurologist Who Hacked His Brain—And Almost Lost His Mind**

https://www.wired.com/2016/01/phil-kennedy-mind-control-computer/

**Brain-Computer Interfaces**

https://worksinprogress.co/issue/brain-computer-interfaces/

**How Did We Get to This Point?**

https://www.cruxucla.com/single-post/2019/01/20/how-did-we-get-to-this-point

***Signal Processing for Brain–Computer Interfaces: A Review and Current Perspectives***

https://ieeexplore.ieee.org/document/10188493

**Graduates (tech review, +1 pg):** **An Accurate and Rapidly Calibrating Speech Neuroprosthesis**

https://www.nejm.org/doi/full/10.1056/NEJMoa2314132

**Viewing:** **Father of the Cyborgs**

https://tubitv.com/movies/100021321/father-of-the-cyborgs

# Takeaways

## 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(2)-page write-up due in class on 8/24

# Introductions!

**Name**

**Grad/undergrad**

**Focus area**

**Why are you taking the course?**

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- Hand with spoon: public domain freepng
- 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)
- Flowchart: Pause08 – flaticon.com
- Digital brain: Smashicons – flaticon.com
- Server rack: upklyak – freepik.com
- Quantum processor icons created by Paul J. - Flaticon
- 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: "Signal Processing for Brain–Computer Interfaces: A review and current perspectives ", adapted from "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)