Building the Infinite Brain

COMP 590/790

Raghavendra Pradyumna Pothukuchi
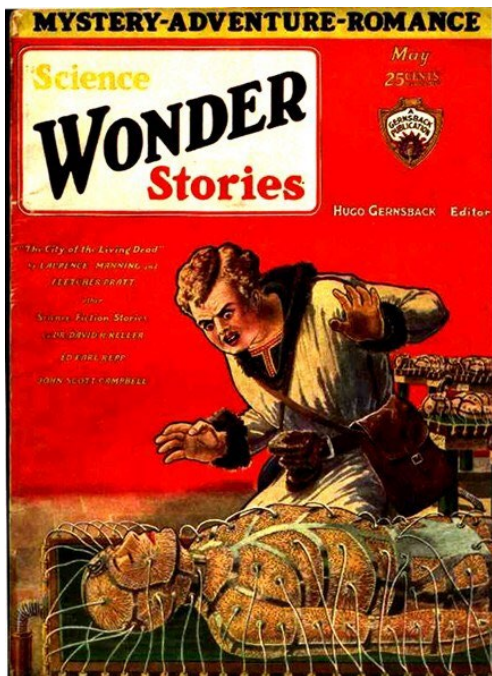
THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

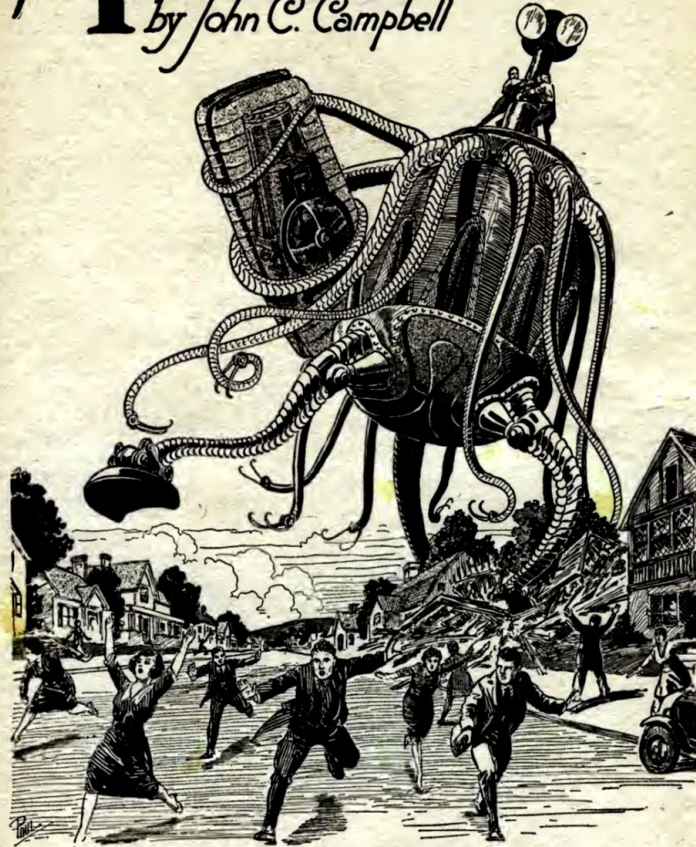✉ raghav@cs.unc.edu

The Infinite Brain

JOHN C. CAMPBELL

MYSTERY-ADVENTURE-ROMANCE
Science WONDER Stories
May 25 CENTS
Hugo Gernsback Editor

The INFINITE BRAIN
by John C. Campbell

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

(Illustration by Paul)

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
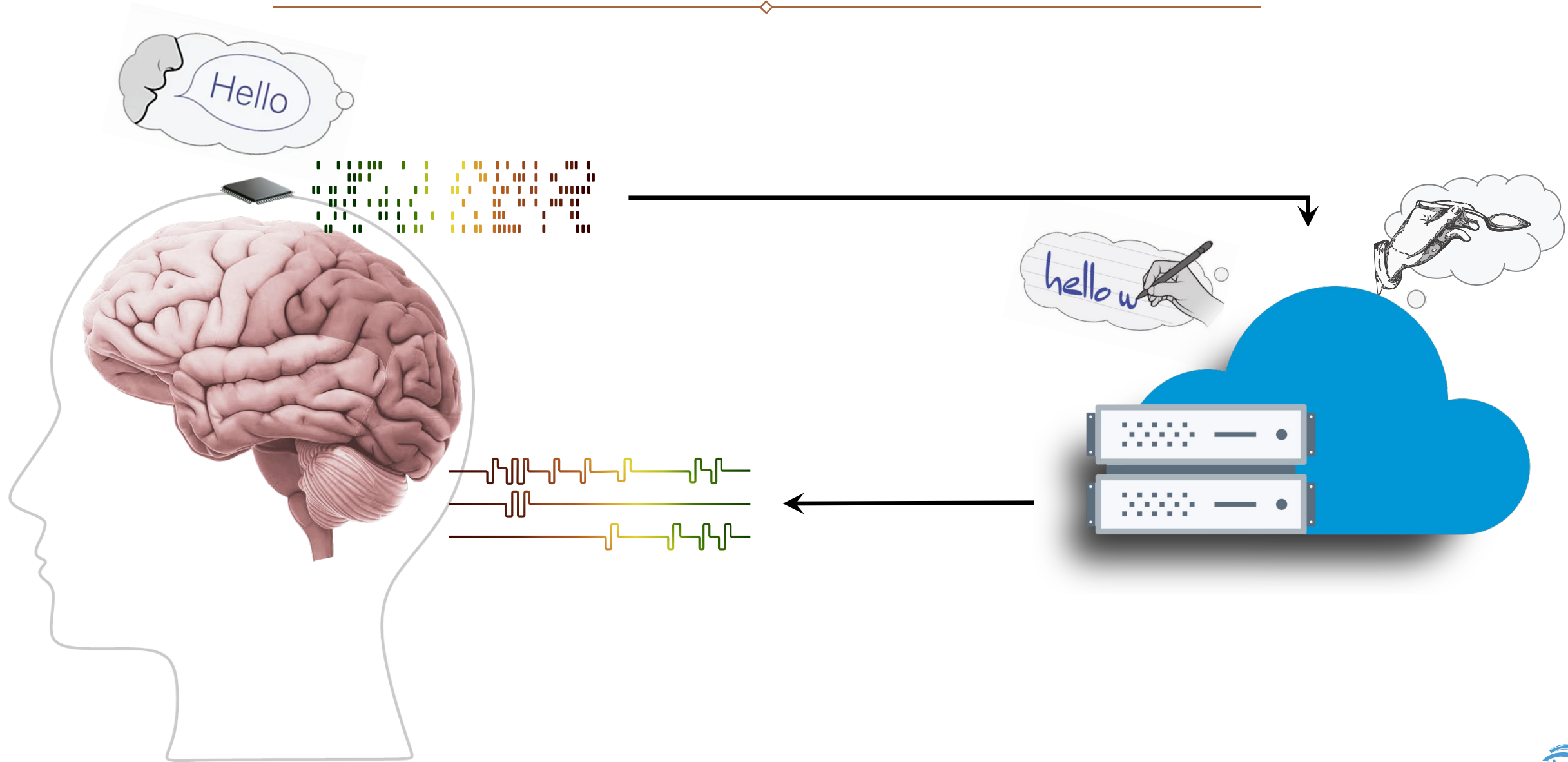
Talk To The Brain and Think Like The Mind

Health Conditions ∨   Health Products ∨   Discover ∨   Tools ∨   Connect ∨   SUBSCRIBE   🔍

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

FEATURE | BIOMEDICAL

OLYMPIC ATHLETES ARE ELECTRIFYING THEIR BRAINS, AND YOU CAN TOO

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*
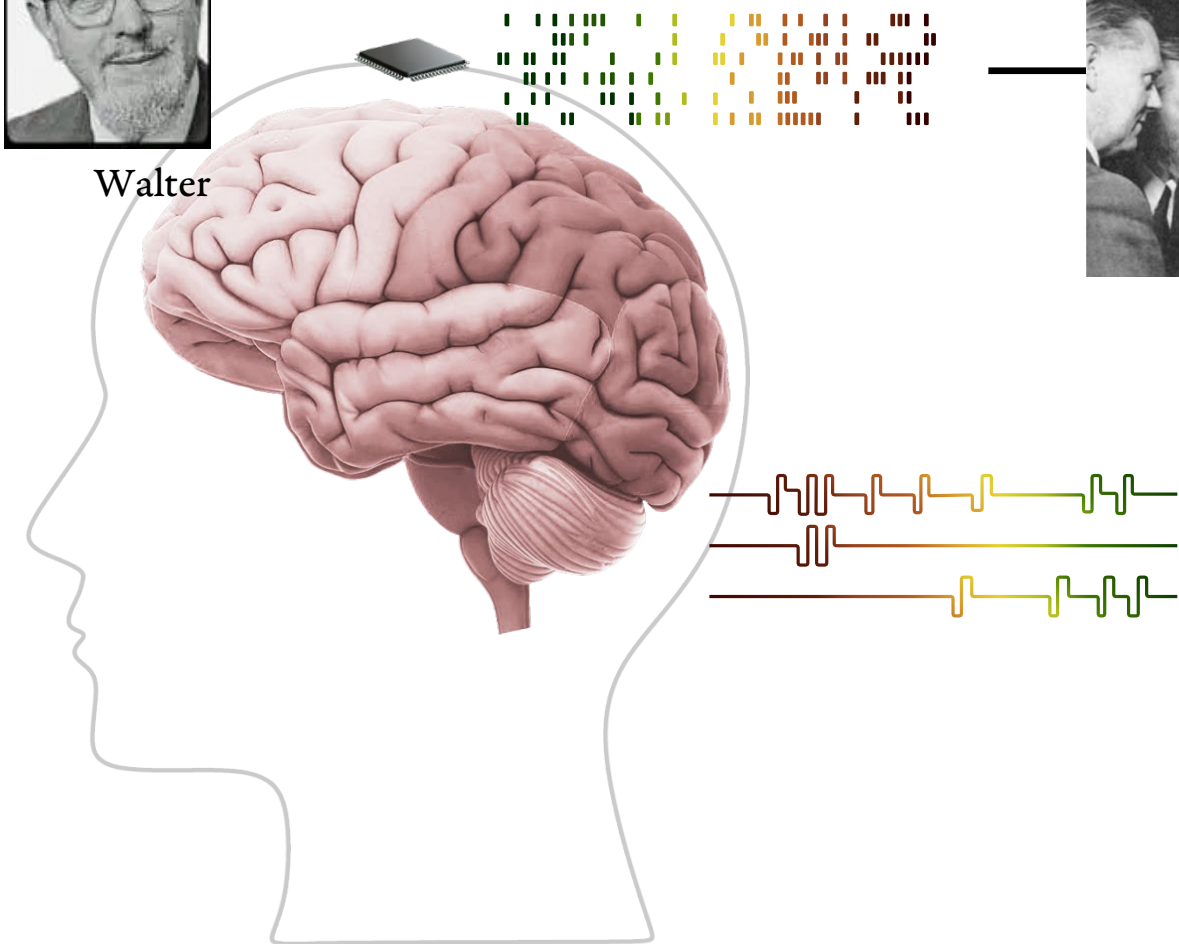
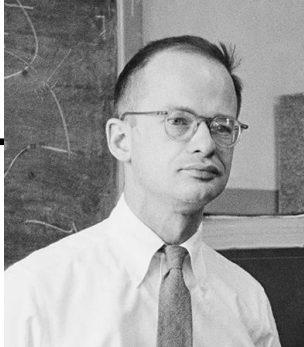# Brain Inspiration Helped Advance Computing

Brain implant

Walter

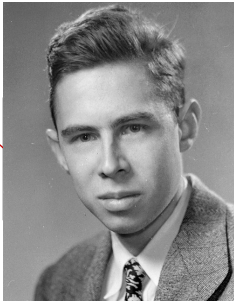**Cybernetics, Computational neuroscience**

Ashby, McCulloch, Walter, Wiener

Pitts

Machine Learning
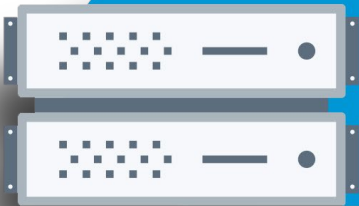
Hebb

Rosenblatt

Memex

Bush

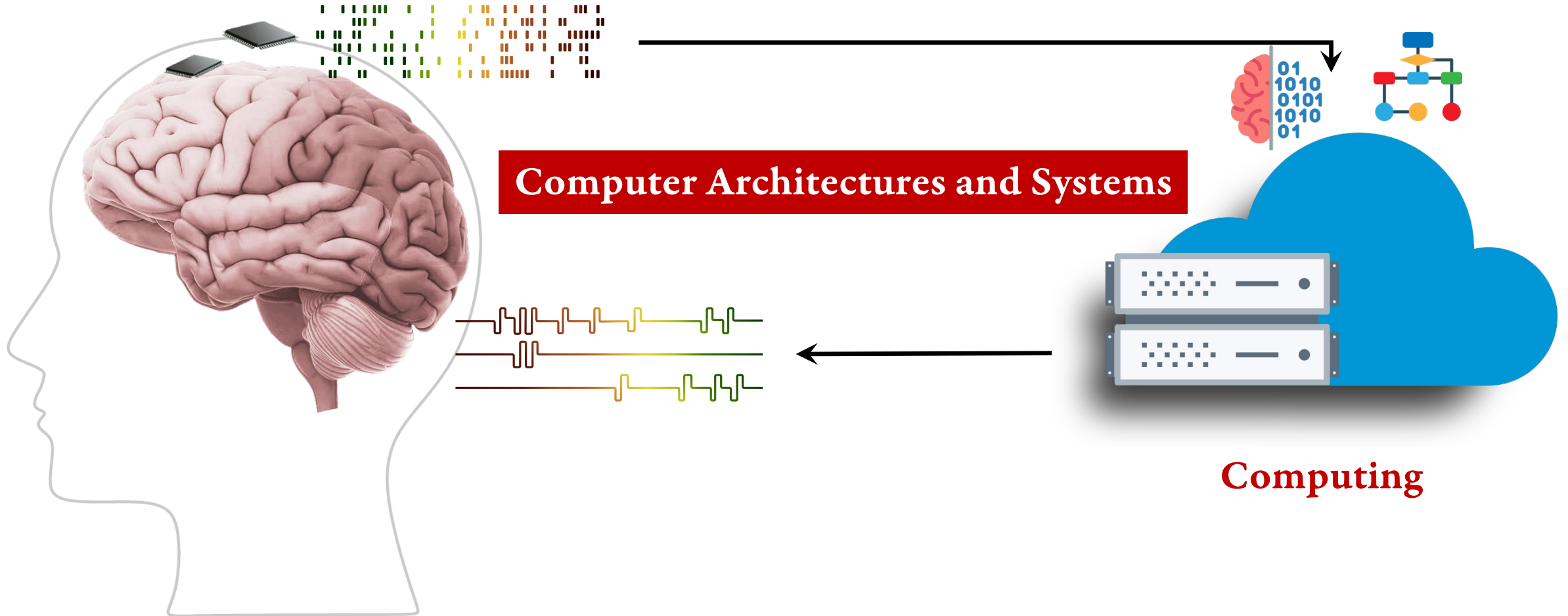**Computing, Computer architecture**

Turing

von Neumann

Opportunity Today: Spur a New Virtuous Cycle

Brain-computer interfaces (BCIs)

Cognitive frameworks
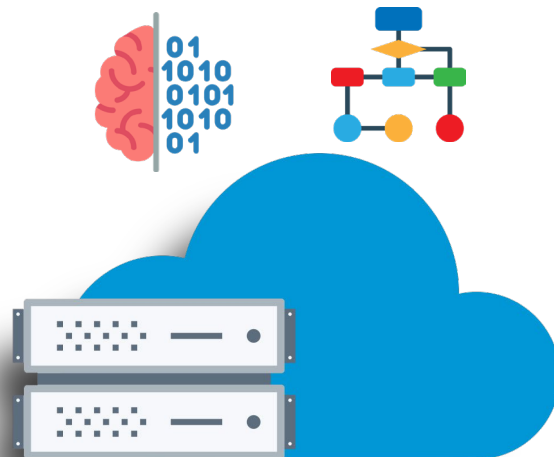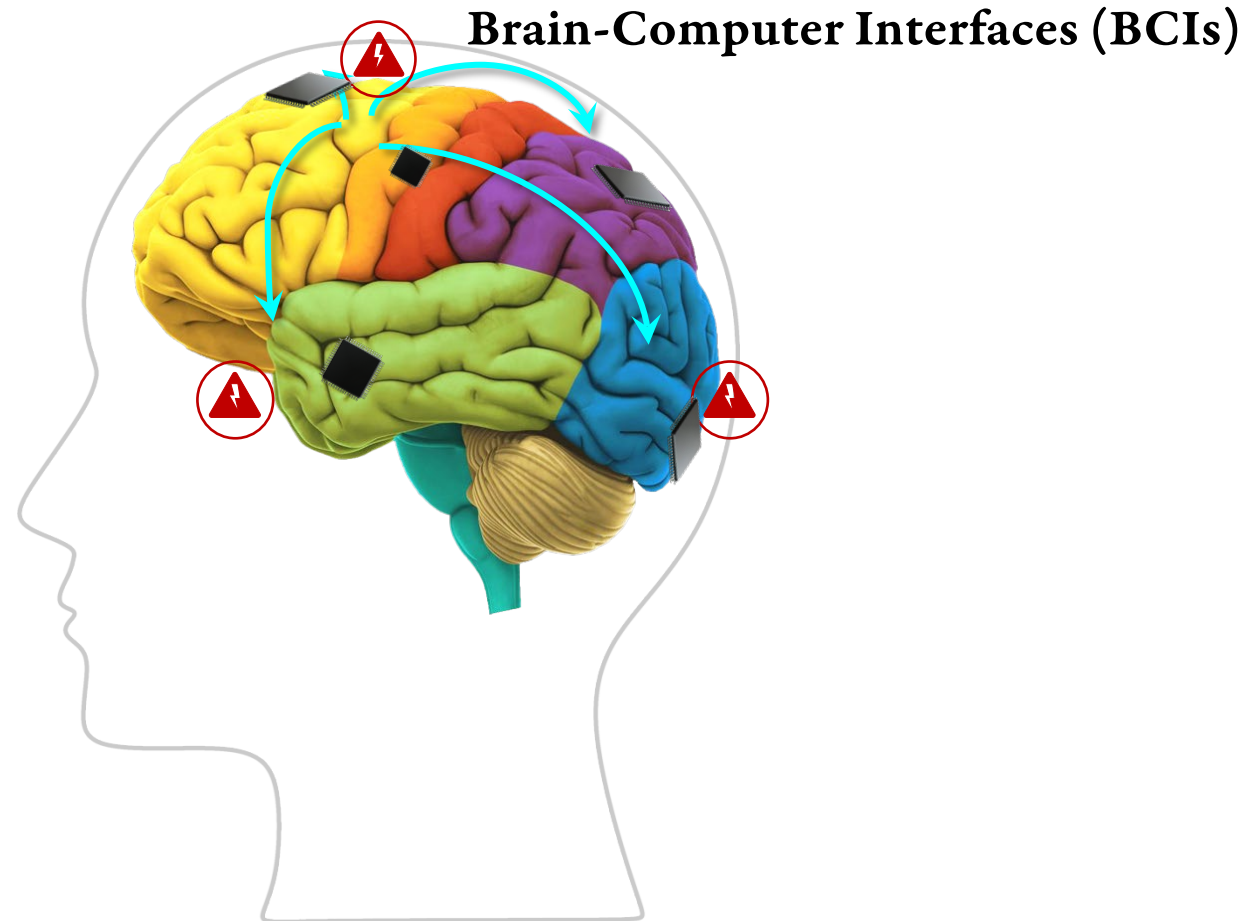
Computer Architectures and Systems

Computing

Example Application

Restoring function

**Computational cognitive
frameworks**

Mitigating seizures

Brain-Computer Interfaces (BCIs)

My Research

IEEE Micro (HotChips)'23
HALO: Single-site BCI
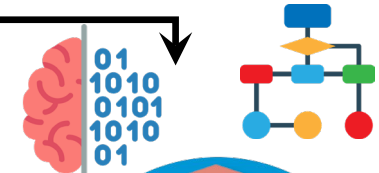
ISCA'23 (Best paper), Top Picks'24
SCALO: Multi-site BCI

arXiv'25
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
Adaptive systems for efficiency and security

My Research

IEEE Micro (HotChips)'23
HALO: Single-site BCI

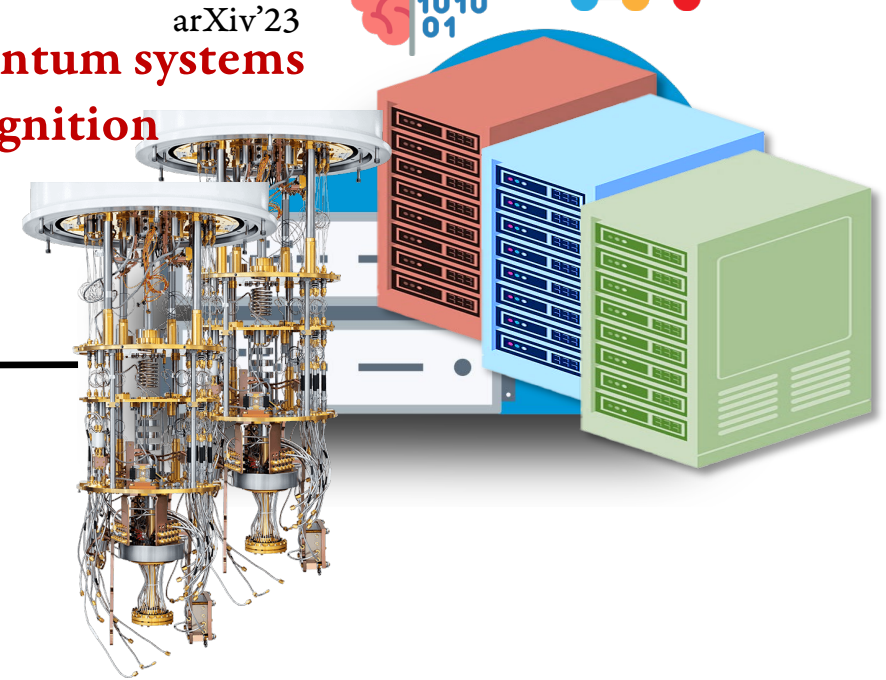ISCA'23 (Best paper), Top Picks'24
SCALO: Multi-site BCI

EMBC'25, SPAA'25
Systematic co-design

ISCA'16, PA...
Ada...
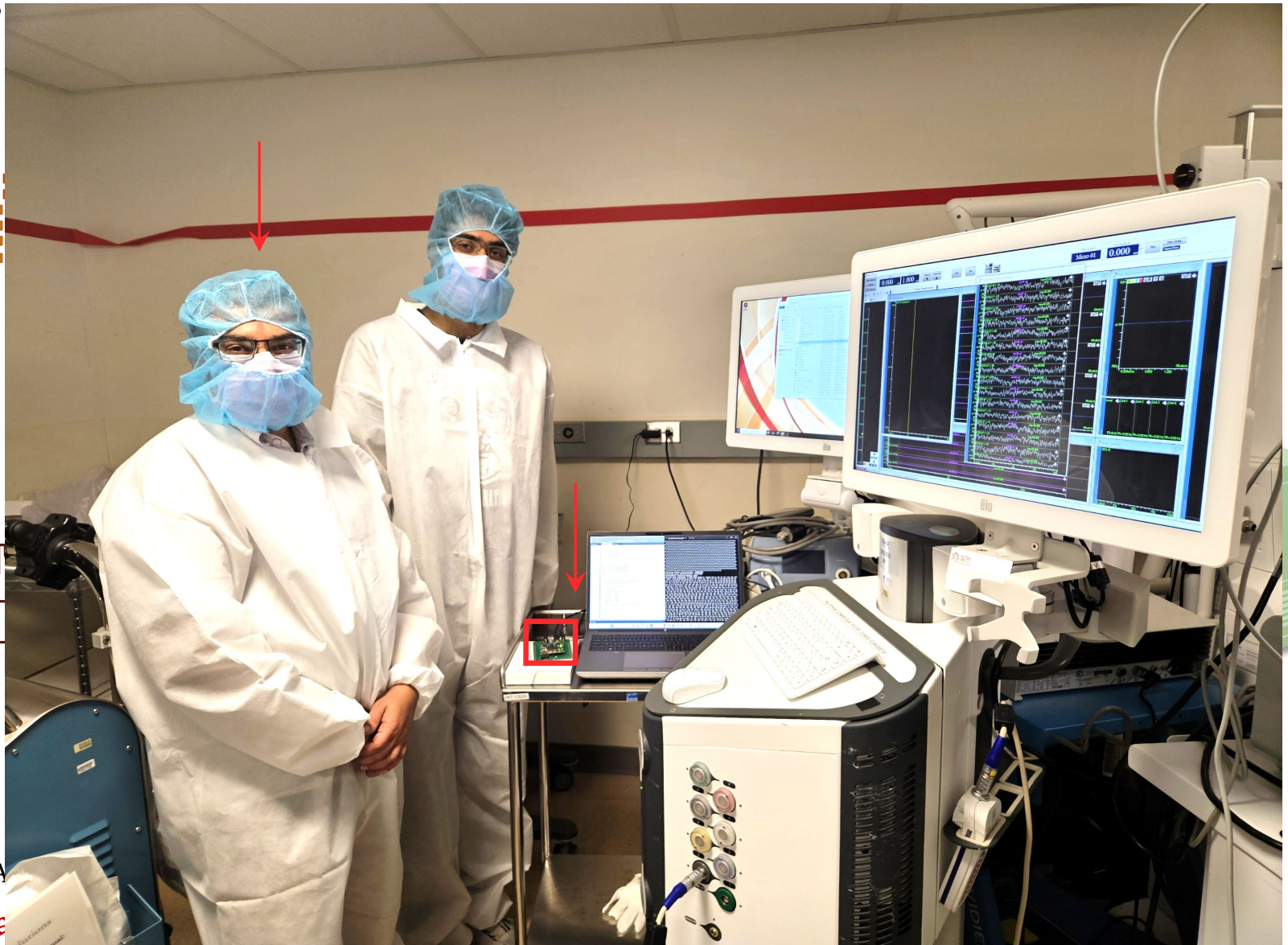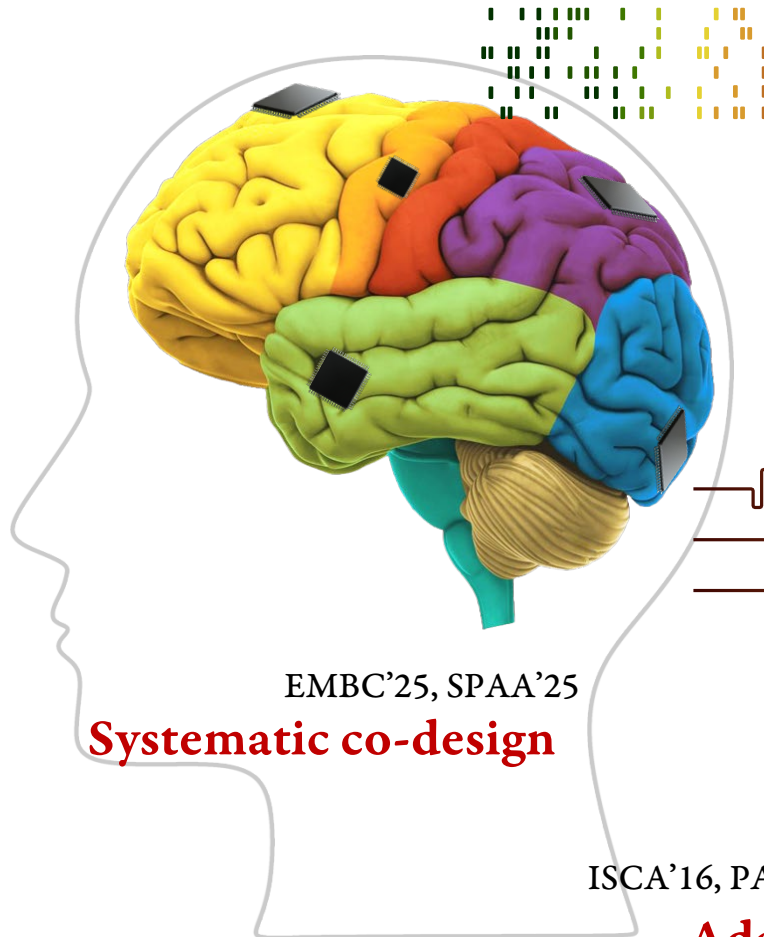
My Vision: Building the Infinite Brain

Real-time cognitive frameworks

Tbps, in vivo

Wearables

Edge servers

High performance cloud
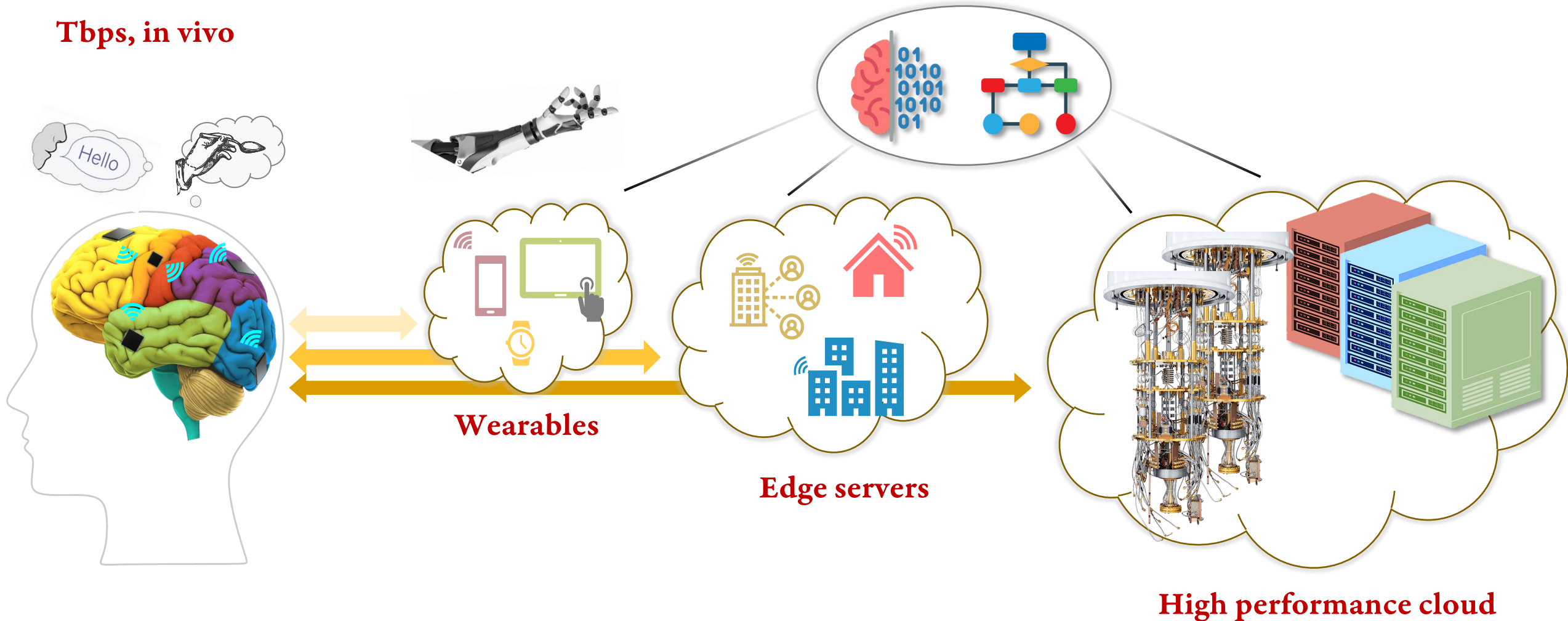
Central Theme: A Virtuous Cycle of Innovation

Architectures and systems for the brain sciences
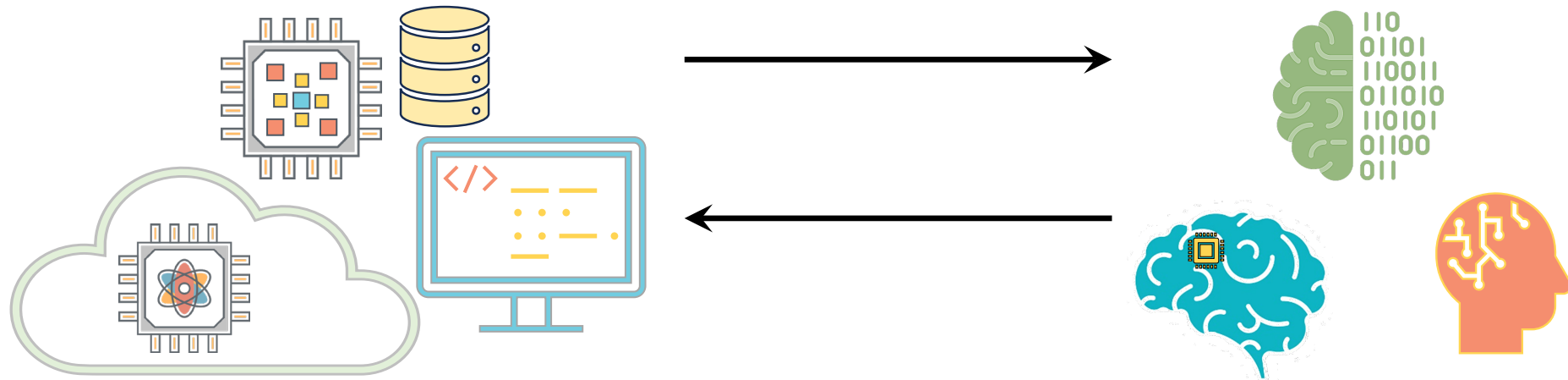
Constraints and inspiration from the brain sciences for architectures

Course Logistics

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

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

Date	Topic	Notes
Mon 8/18	Introduction	Homework 1 assigned
Wed 8/20	Computer architecture overview	
Mon 8/25	Pipelining	
Wed 8/27	Out of Order	Homework 1 due
Mon 9/1	Labor Day	
Wed 9/3	Caches	
Mon 9/8	Memory	
Wed 9/10	Multicore and multithreaded systems	
Mon 9/15	Well-being Day	
Wed 9/17	Parallel architectures	
Mon 9/22	Memories in parallel architectures	
Wed 9/24	Representative BCI Algorithms 1	
Mon 9/29	Representative BCI Algorithms 2	

Date	Topic
Wed 10/1	BCI arch paper 1 and arch paper 1
Mon 10/6	BCI arch paper 2 and arch paper 2
Wed 10/8	BCI arch paper 3 and arch paper 3
Mon 10/13	BCI arch paper 4 and arch paper 4
Wed 10/15	BCI arch paper 5 and arch paper 5
Mon 10/20	BCI arch paper 6 and arch paper 6
Wed 10/22	BCI system papers 1 and 2
Mon 10/27	BCI system papers 3 and 4
Wed 10/29	BCI system papers 5 and 6
Mon 11/3	Systems papers 7 and 8
Wed 11/5	
Mon 11/10	
Wed 11/12	
Mon 11/17	Invited lecture
Wed 11/19	Invited lecture
Mon 11/24	Putting it all together
Wed 11/26	Thanksgiving Recess
Mon 12/1	Project presentations
Wed 12/3	Project presentations

And, More

Assessment: Homeworks and a final working project related to the themes of the course
Extra targets for graduate students

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

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

Grading: Project (40%), presentation and Report (10%), homeworks (20%), paper reviews (10%), lead presentation (10%), discussion (10%)—*instruction discretion and subjective*

Course website: https://www.cs.unc.edu/~raghav/Courses/comp590790/fa25.php

Office hours: 30 minutes after class

Prerequisites: Familiarity with at least one instruction set, addressing modes, procedures etc.
Concept of processor pipelining, hazards, caches, memory and storage

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

For Today

- Course overview

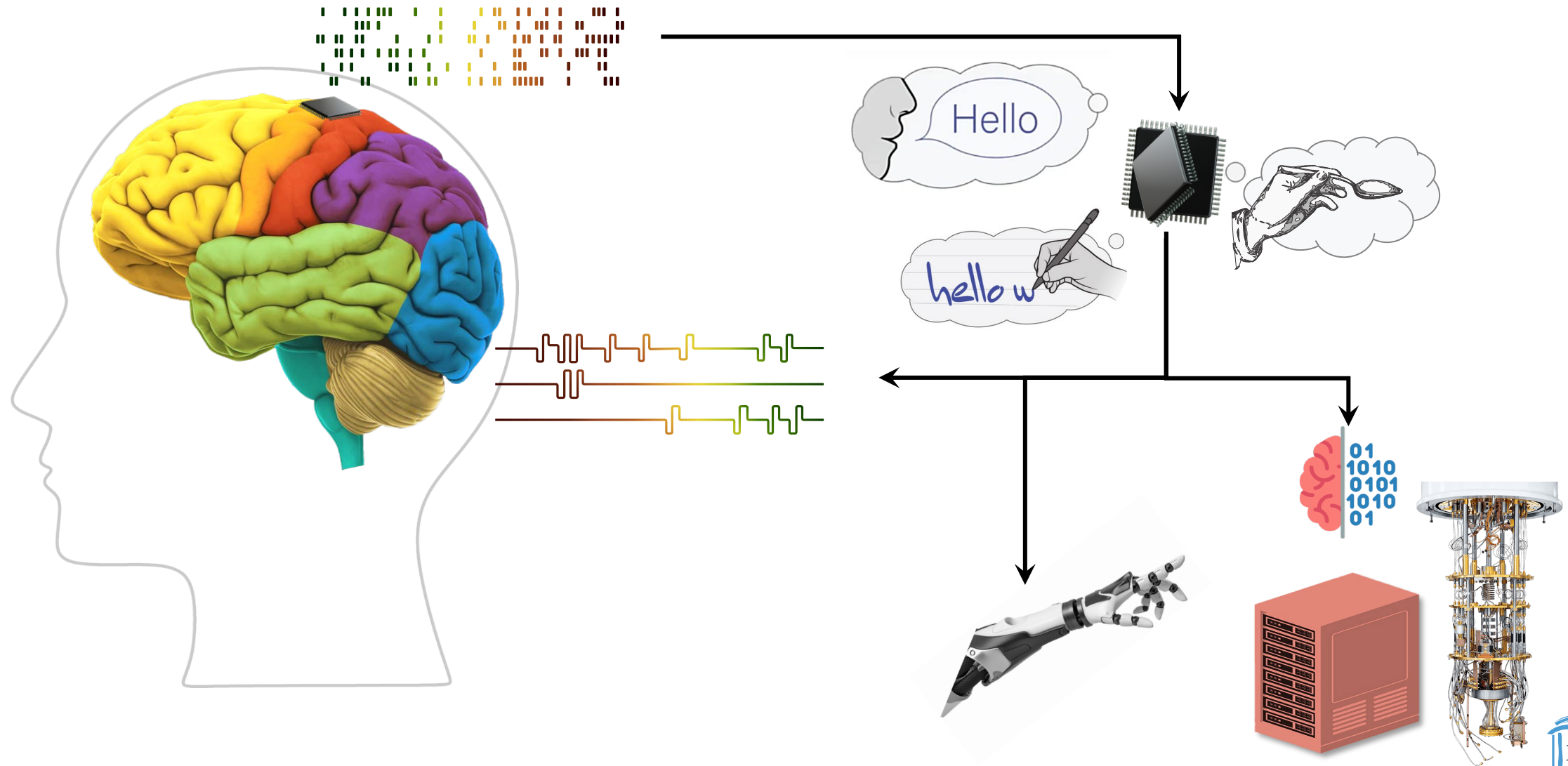- **What are BCIs?**

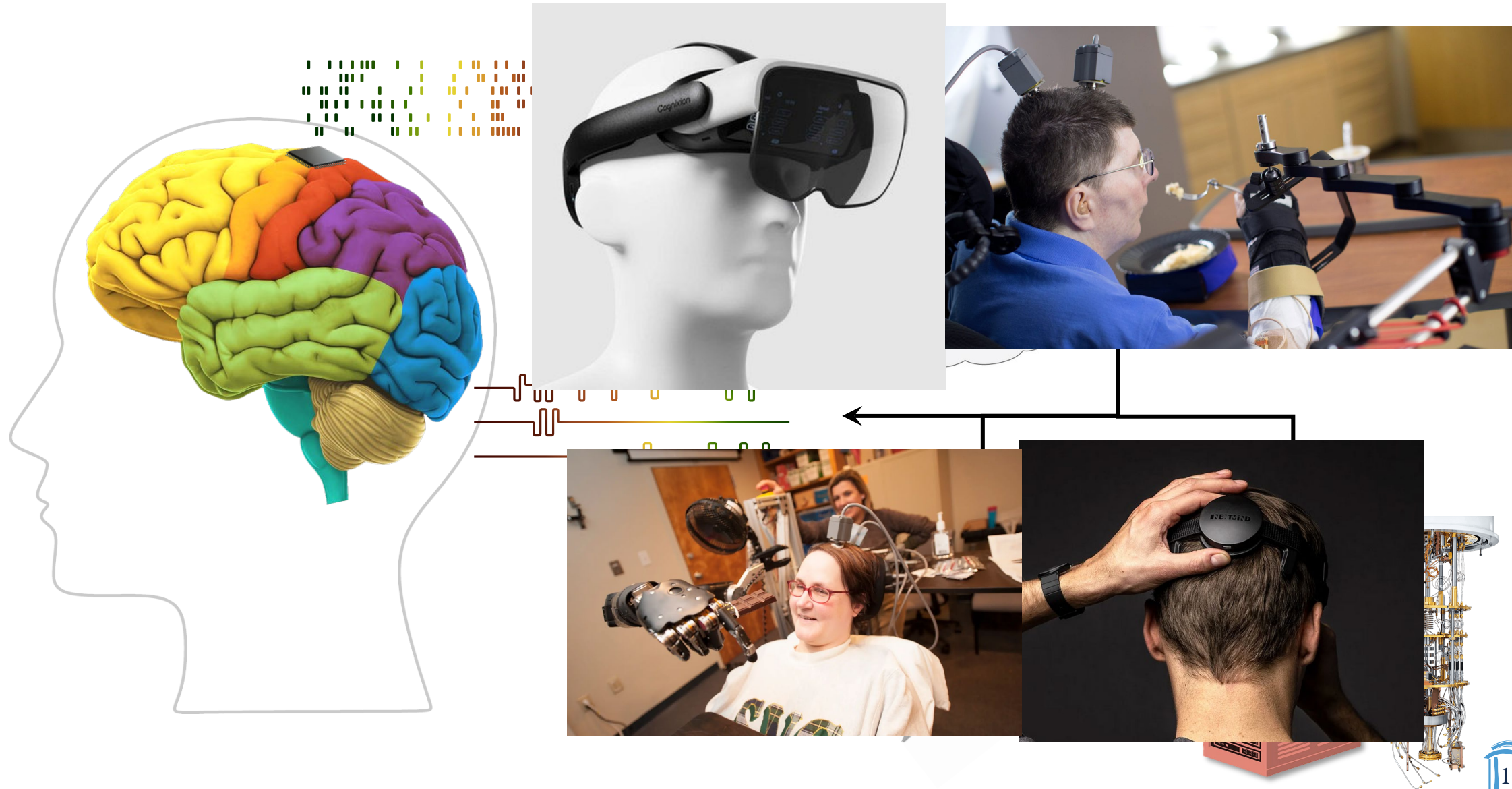- **What are the computational challenges?**

What Are BCIs?

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

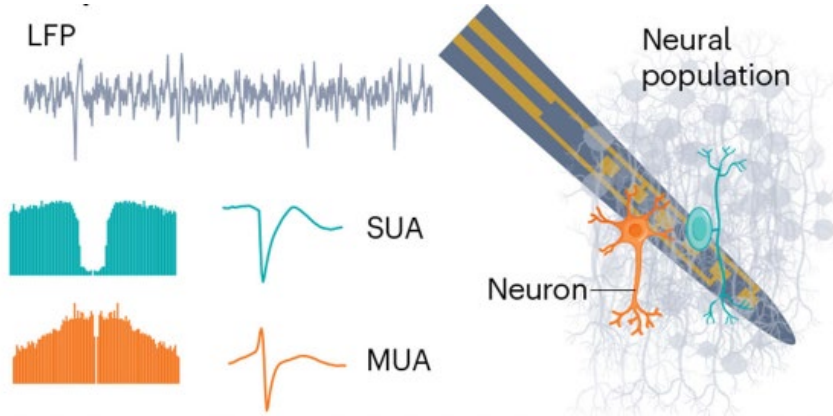Doesn't seem so with BCIs!

Brain Computer Interfaces (BCIs)
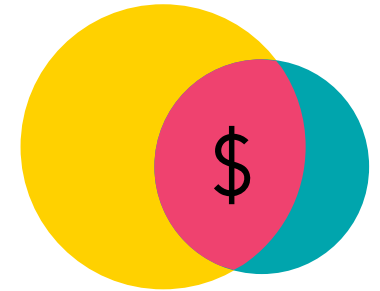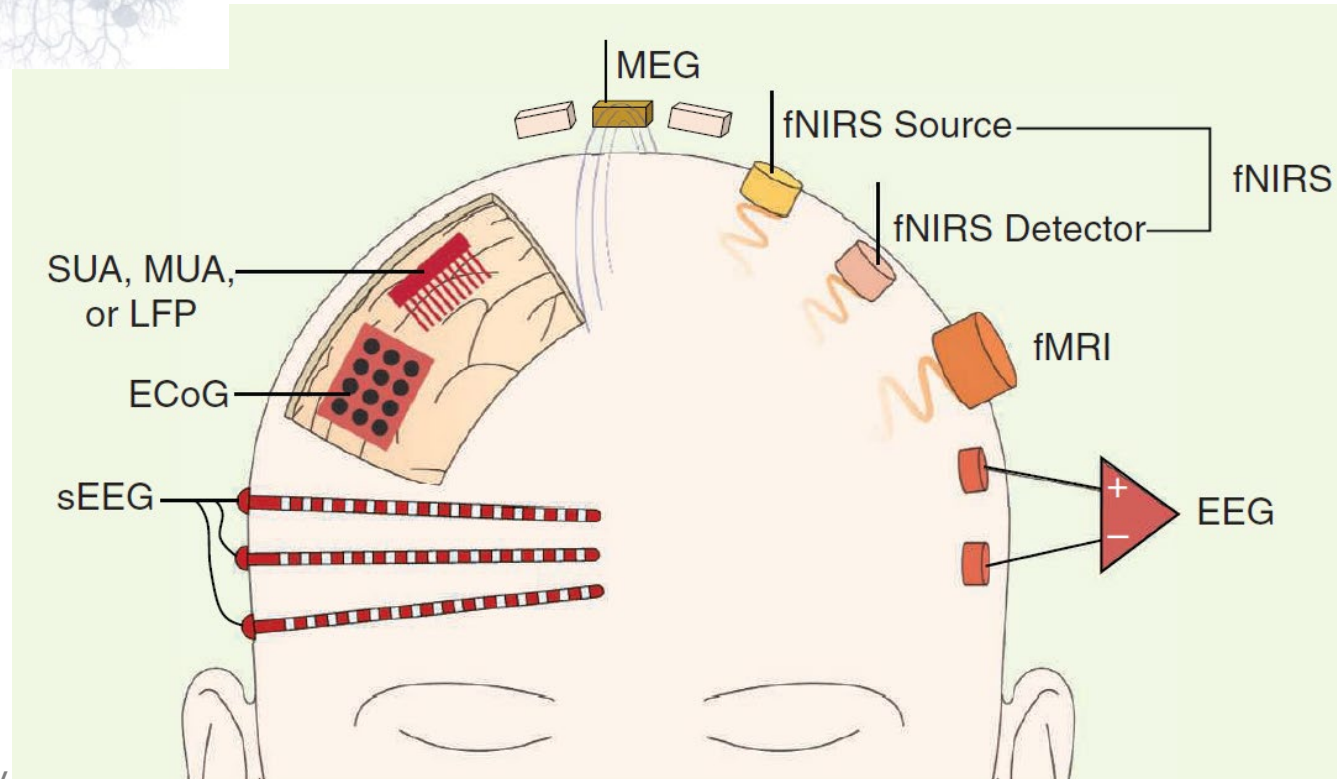
Brain Computer Interfaces (BCIs)
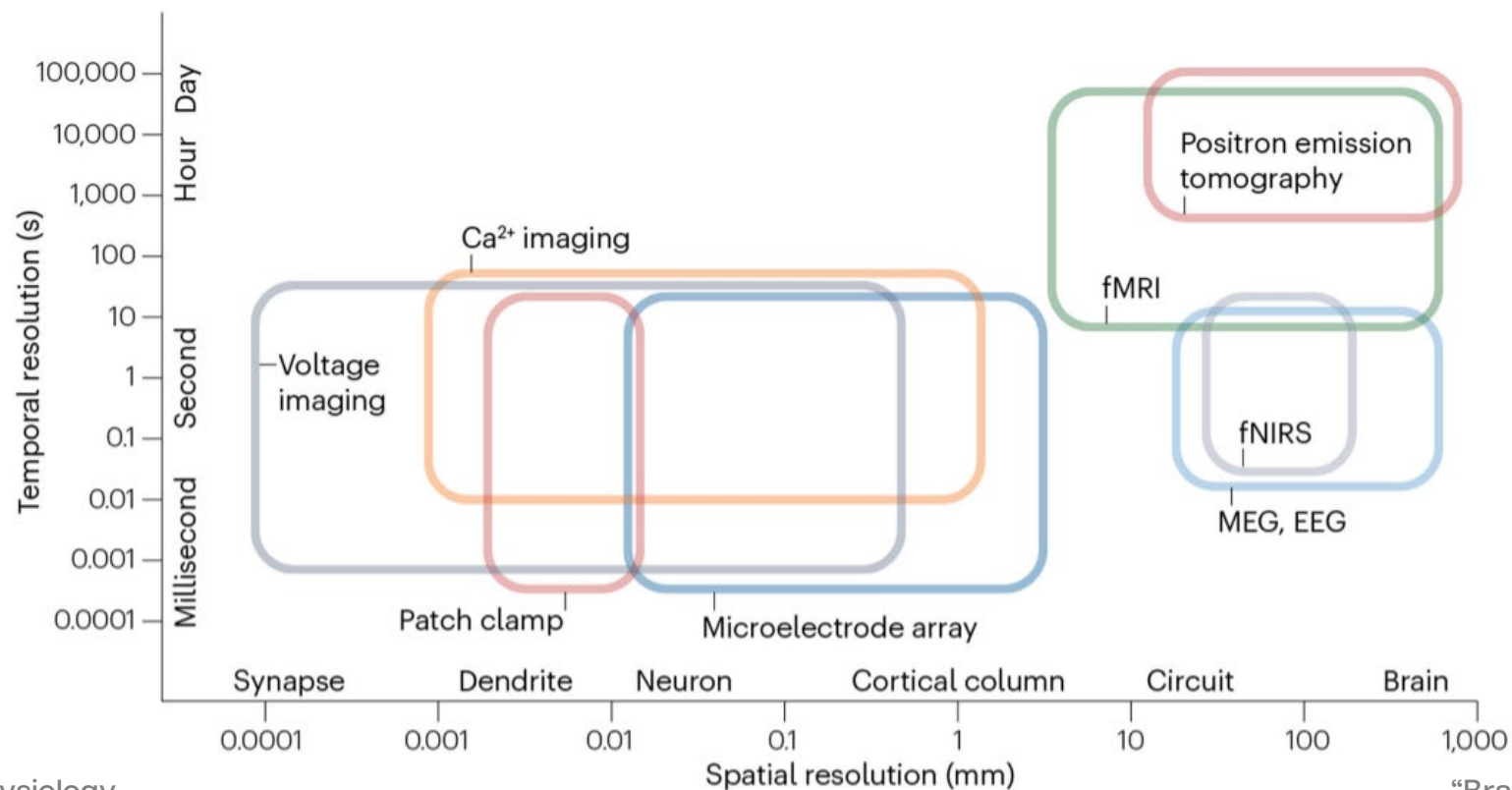
What's In a Name?

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

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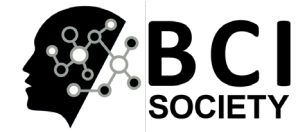MUA: Multi unit activity
LFP: Local field potential

TAMs and scope

What's In a Name?

What's In a Name?

"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

MEG

fNIRS Source

fNIRS

fNIRS Detector

SUA, MUA, or LFP

fMRI

ECoG

sEEG

EEG

$
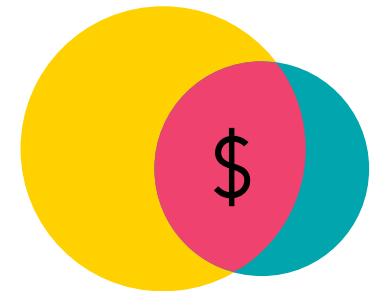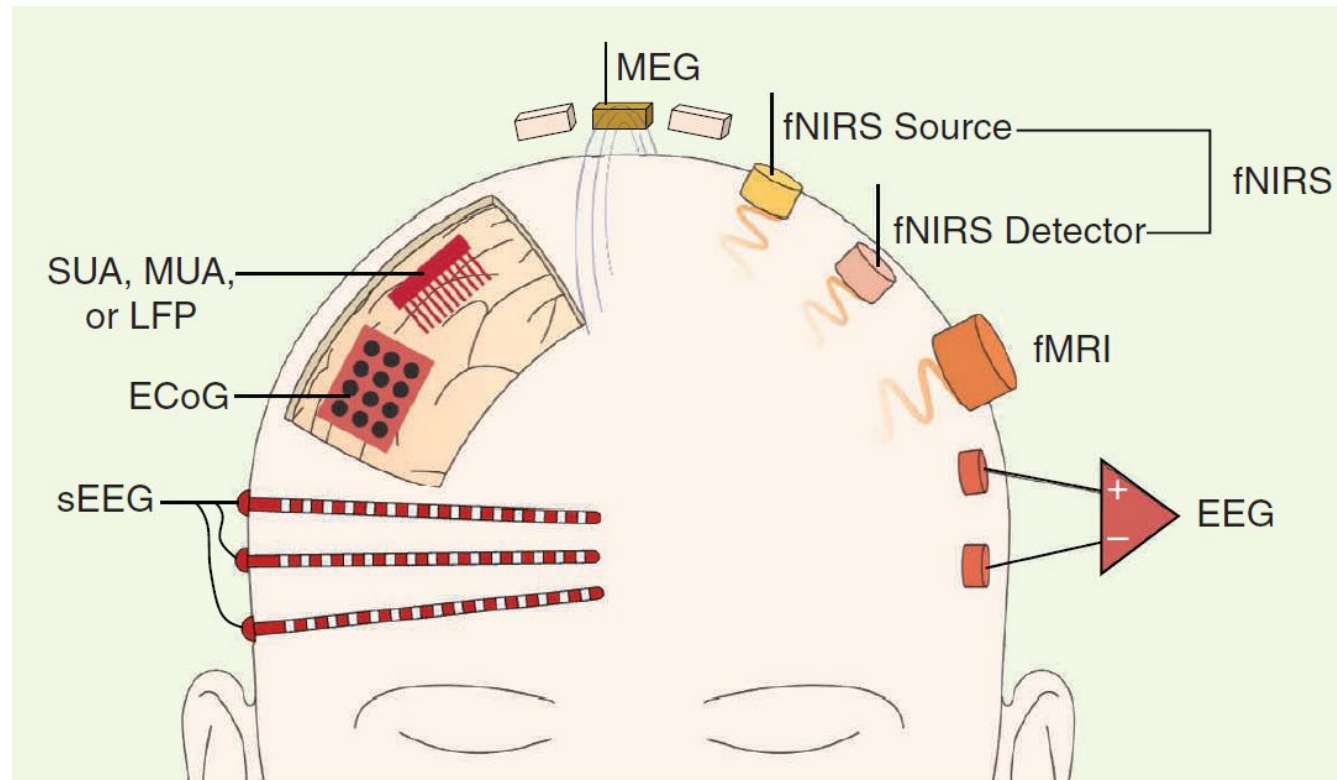
TAMs and scope

BCI Hardware

$$\Delta T \leq 1\,°C$$

$$< 50\ mW$$

Surface Penetrating Electrode
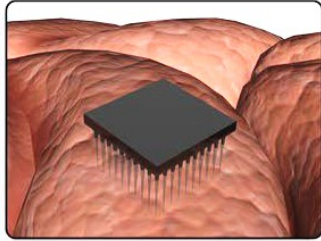
Depth Electrode

Surface ECoG Electrode
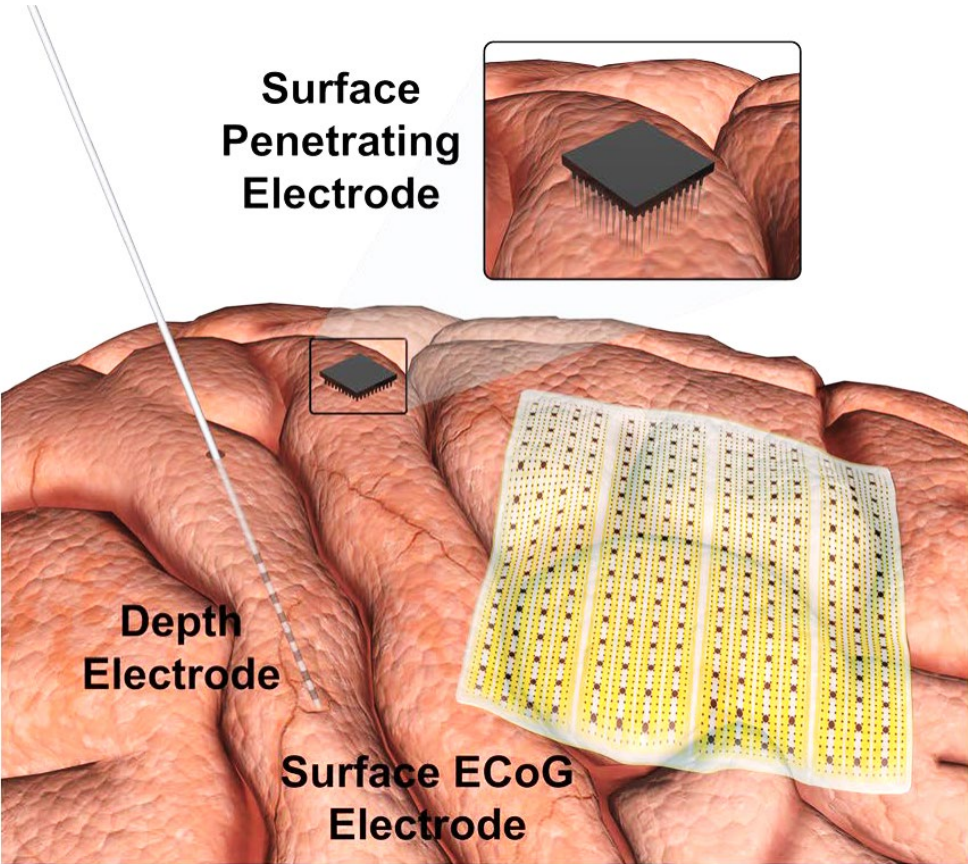
Battery, Wireless

Processing

Digitization

Electrodes

Illustrative BCI system

BCI Hardware

$\Delta T \leq 1\,°C$

< 50 mW

5-10 mm

10-20 mm
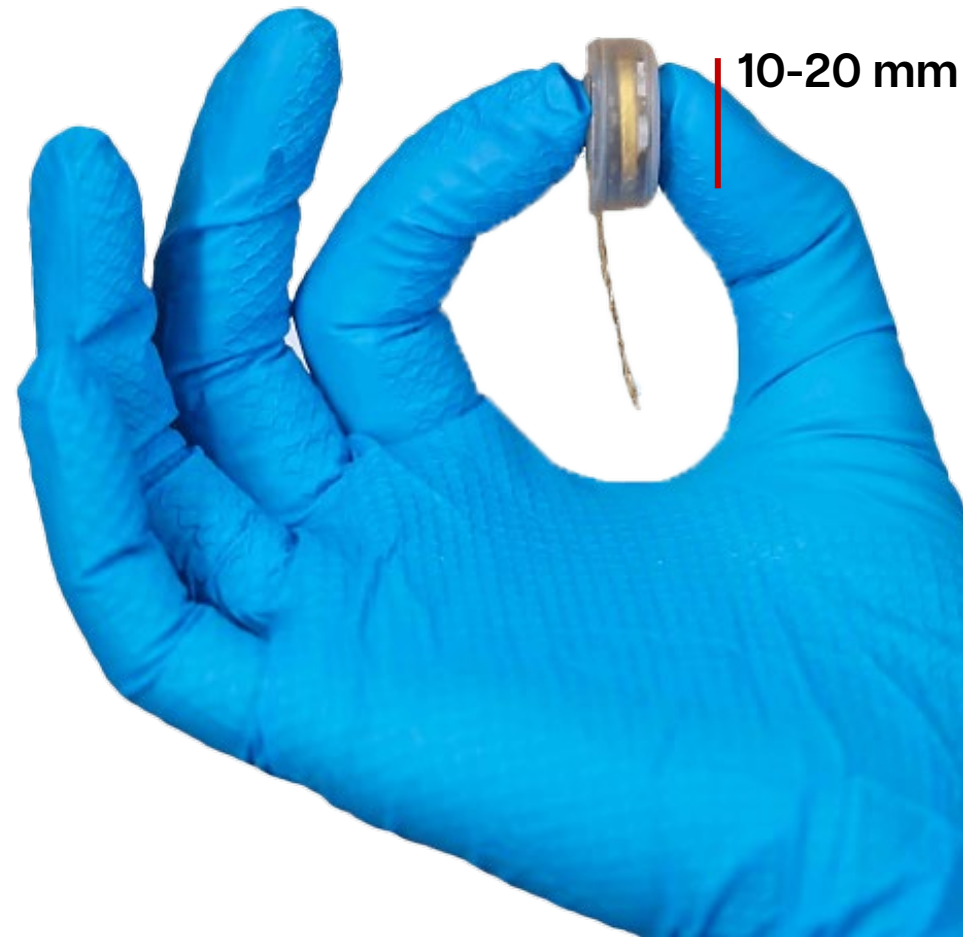
Implanted BCI Form Factors
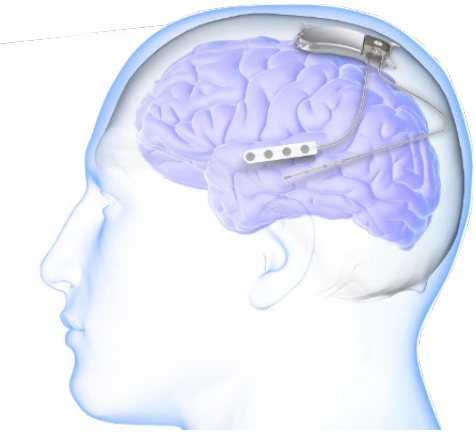
Design constraints vary in each scenario

Real-world BCI Demonstration

The BrainGate Collaboration, Brown University, Mass General

Another Real-world BCI Demonstration

José Delgado's stimoceiver, Yale University (1964)

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

Share full article

By Maggie Scarf
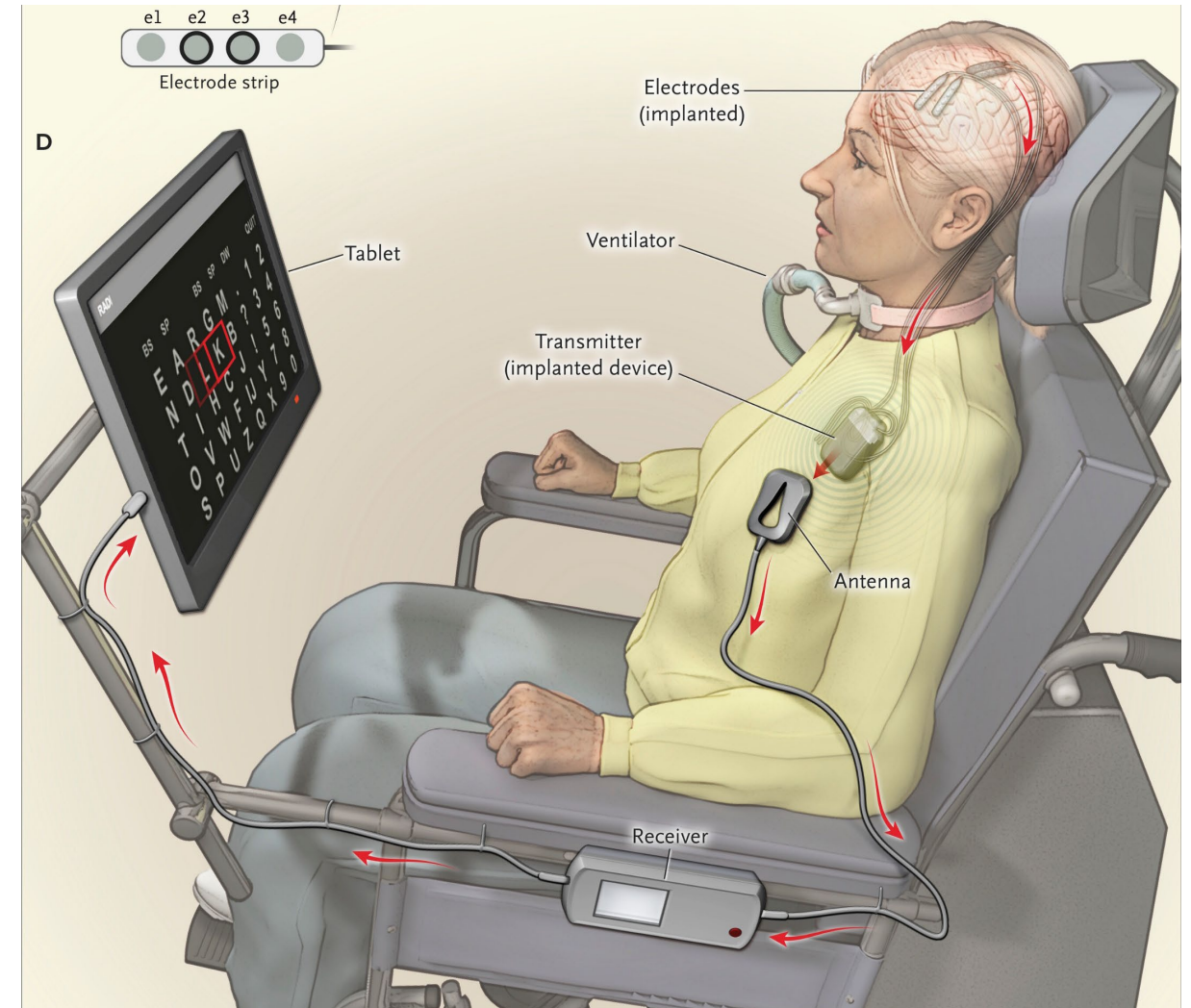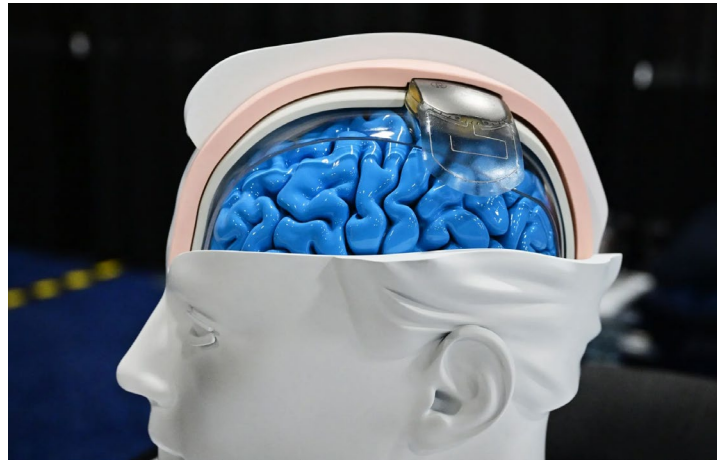Nov. 15, 1970

"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*
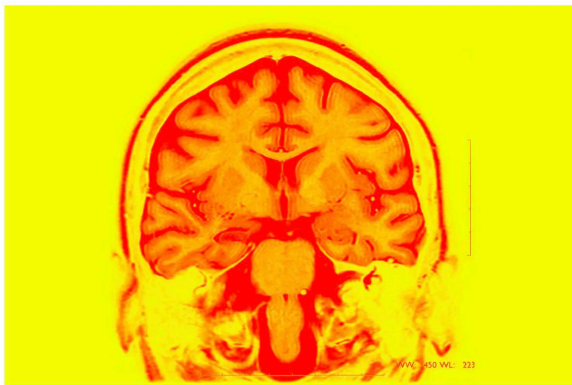
More Recent Examples

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

How are you today?

I am very good
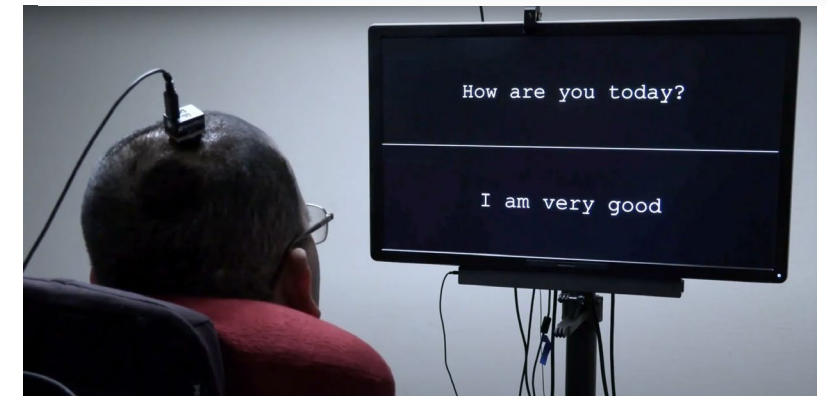
Growing Commercial Interest

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

Sensor → Seizure Detection → Signal Similarity

10 ms

2D surface projection

evidence of epileptogencity

x y

Revell et al., bioRxiv 2022

BCI Applications

Movement intent decoding

Distributed, on-device

Seizure network detection

Sensor → Feature Extraction → Decode Intent

50 ms

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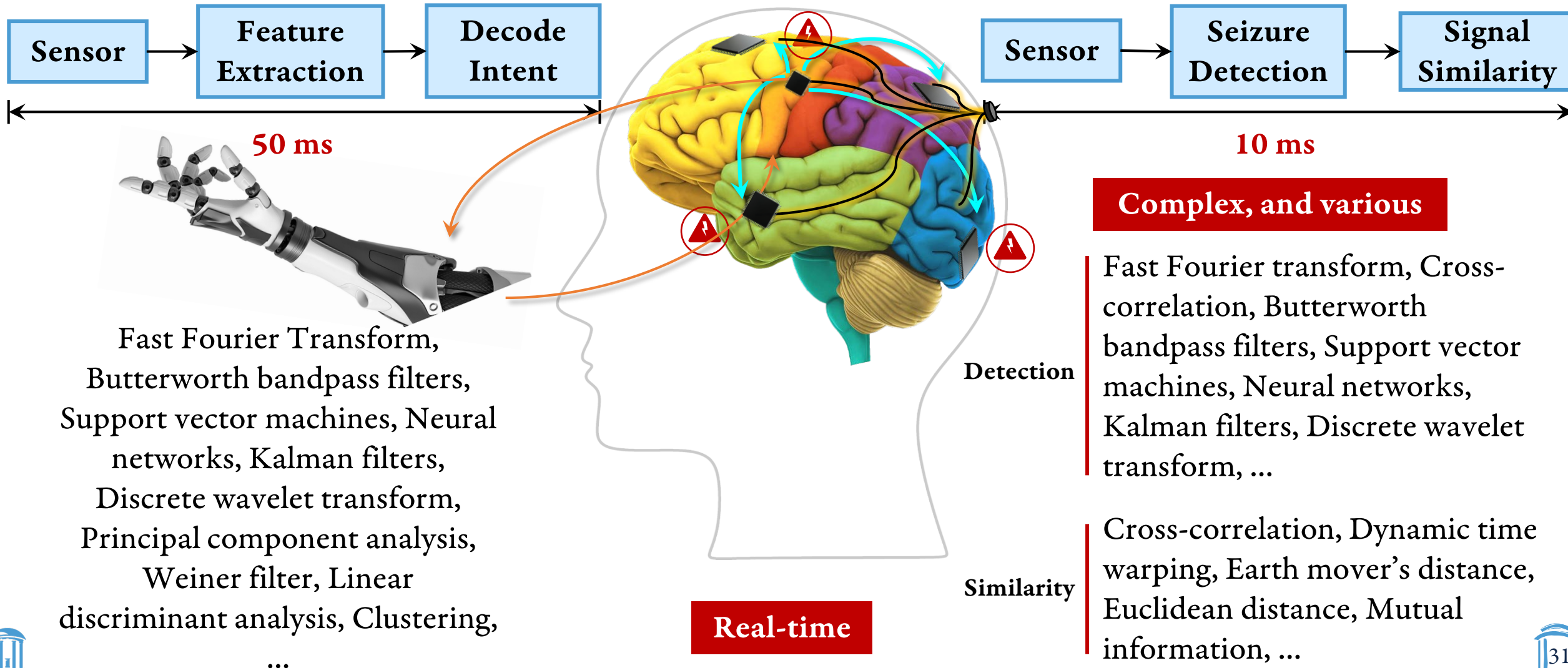
Fast Fourier Transform, Butterworth bandpass filters, Support vector machines, Neural networks, Kalman filters, Discrete wavelet transform, Principal component analysis, Weiner filter, Linear discriminant analysis, Clustering, ...

Similarity

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

Real-time

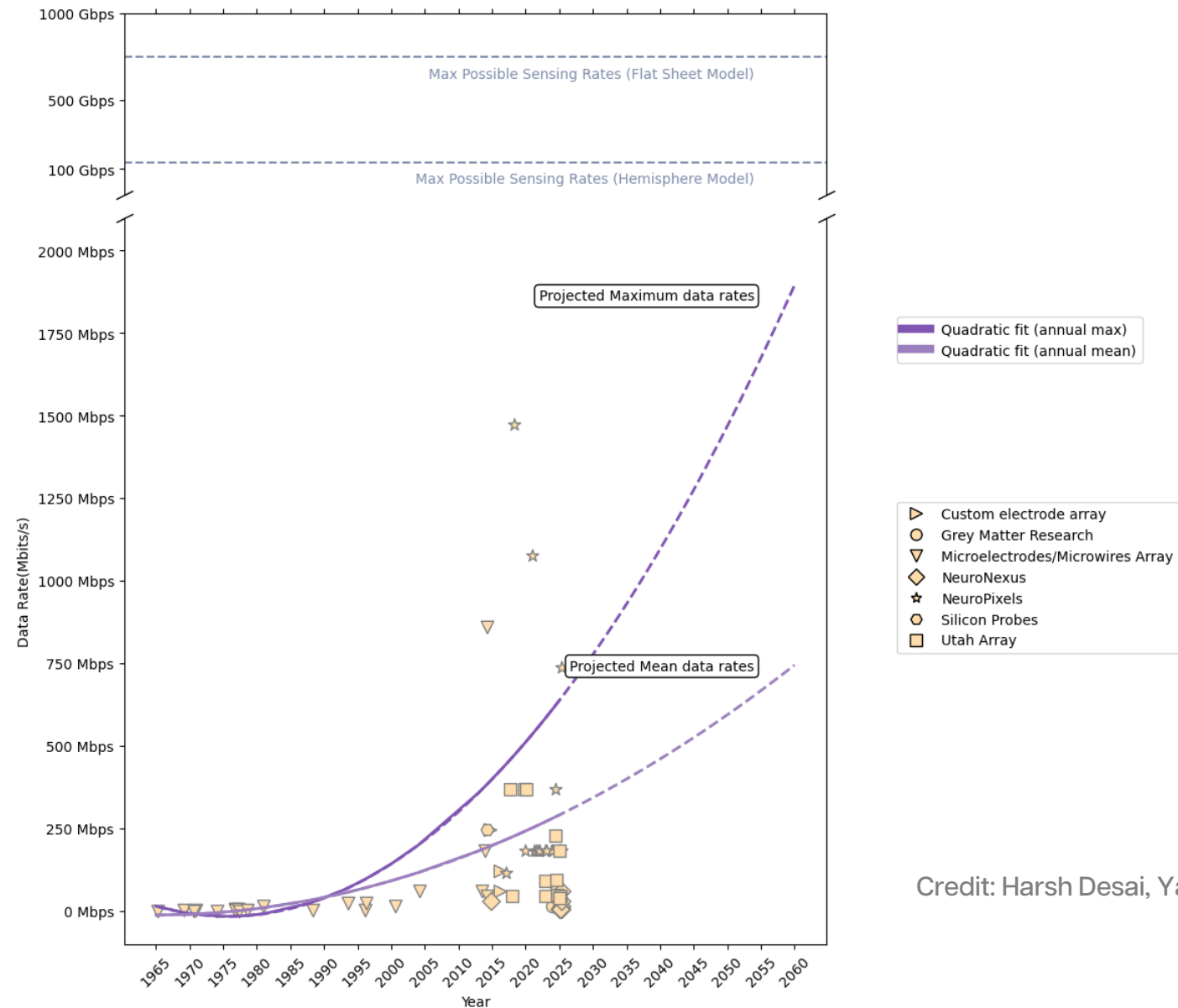# Summary of Design Challenges

High Throughput

100-1000 Mbps

"Innovating beyond electrophysiology through multimodal neural interfaces"

Summary of Design Challenges

High Throughput

100-1000 Mbps

Credit: Harsh Desai, Yale

Summary of Design Challenges

High Throughput

100-1000 Mbps

Complex Processing

Signal processing, Machine learning

Customization

Personalized treatment

Safety

$\leq$ 1 °C

$\leq$ few mW

Real-Time Performance
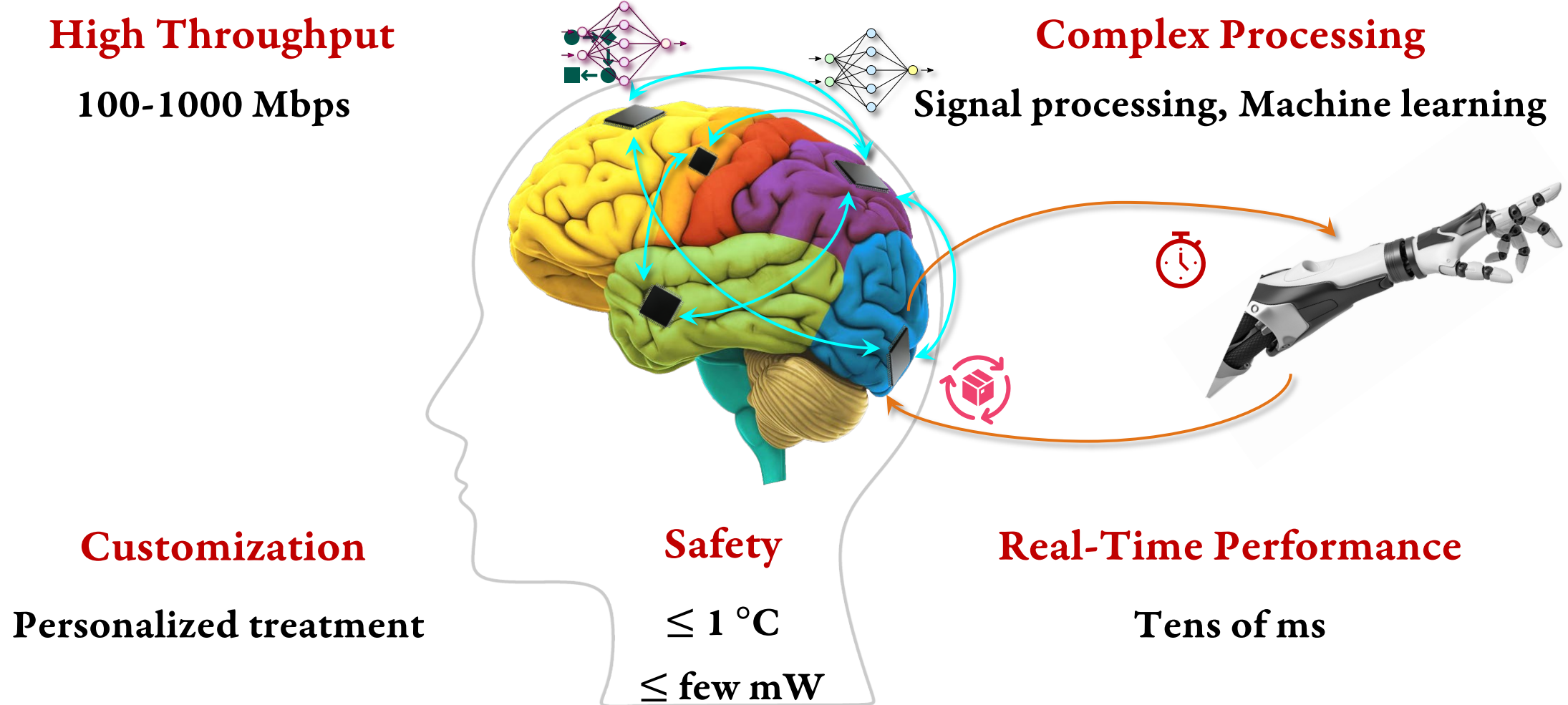
Tens of ms

BCI Processing Challenge: Efficiency vs Flexibility

Efficiency

High throughput

100-1000 Mbps

Real-time performance

Tens of ms

Safety

$\leq 1\,°C$

$\leq$ few mW

Flexibility

Complex processing

Signal processing, Machine learning

Customization

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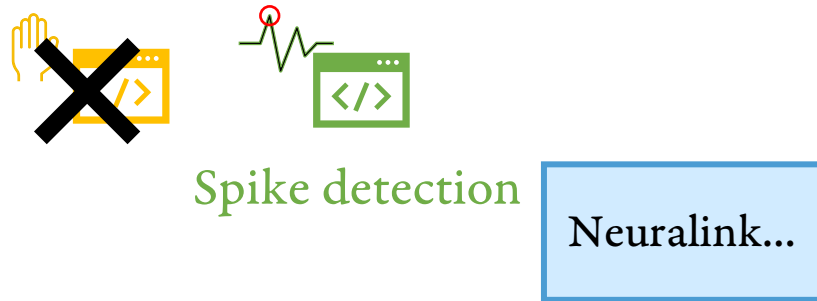adaptation to the brain, support
evolving methods

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, …
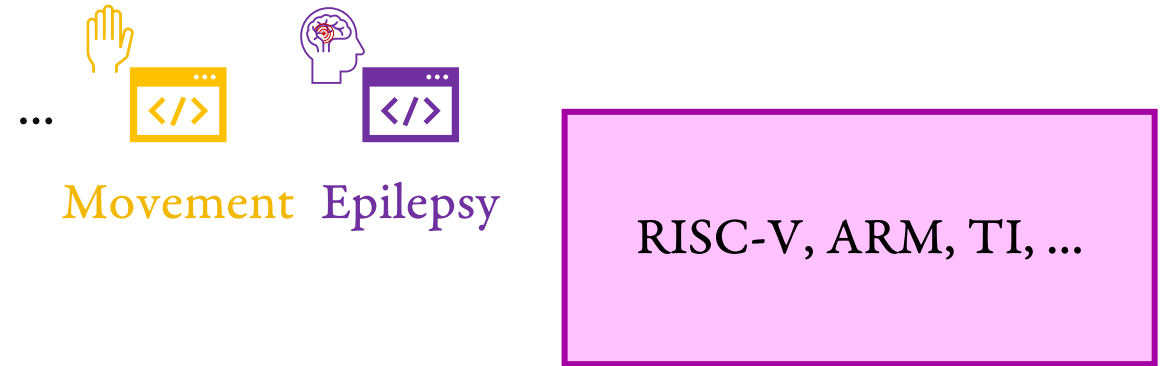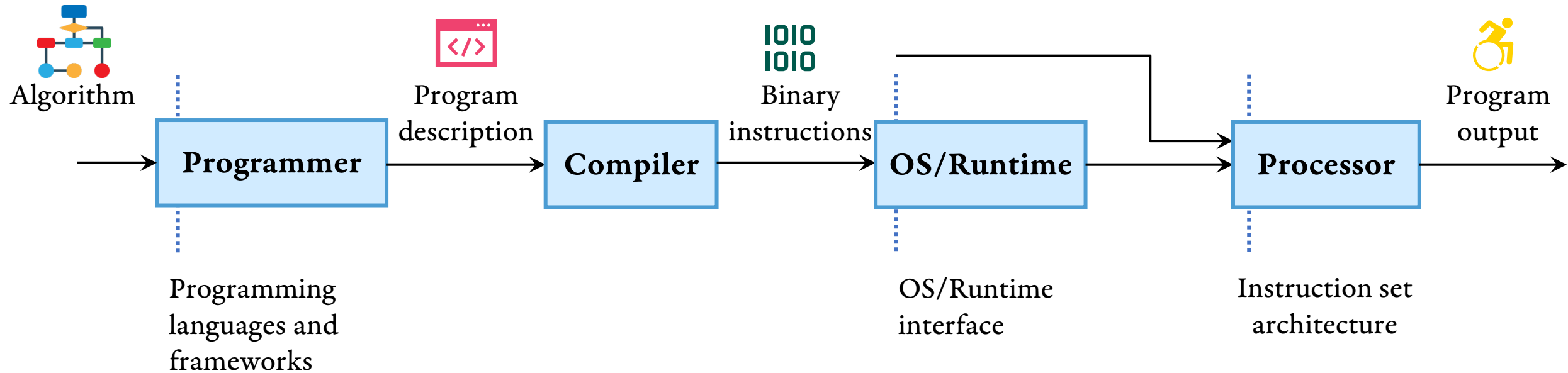
Flexible but not efficient

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

BCI Computing is a Full Stack Problem

Algorithm

Program description

Binary instructions

Program output

```
Programmer → Compiler → OS/Runtime → Processor
```

Programming languages and frameworks

OS/Runtime interface
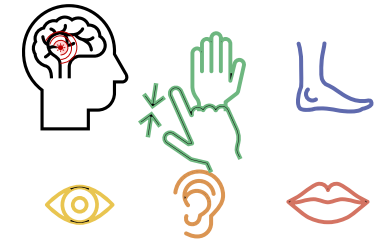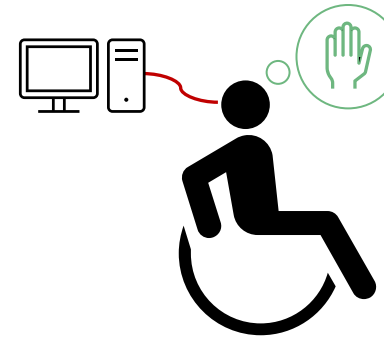
Instruction set architecture

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?

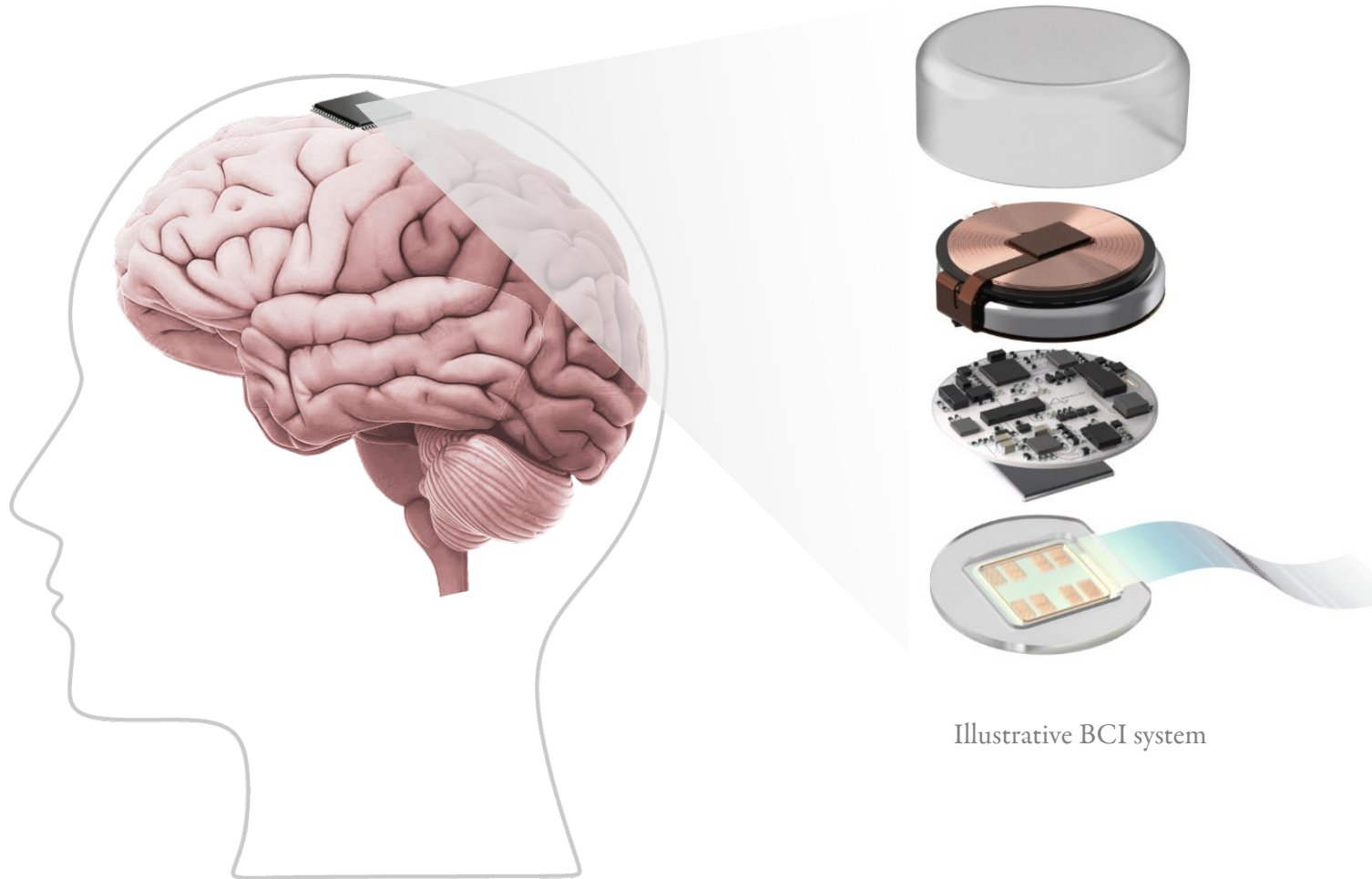**Lose autonomy**   **Lose functionality**

Battery, Wireless
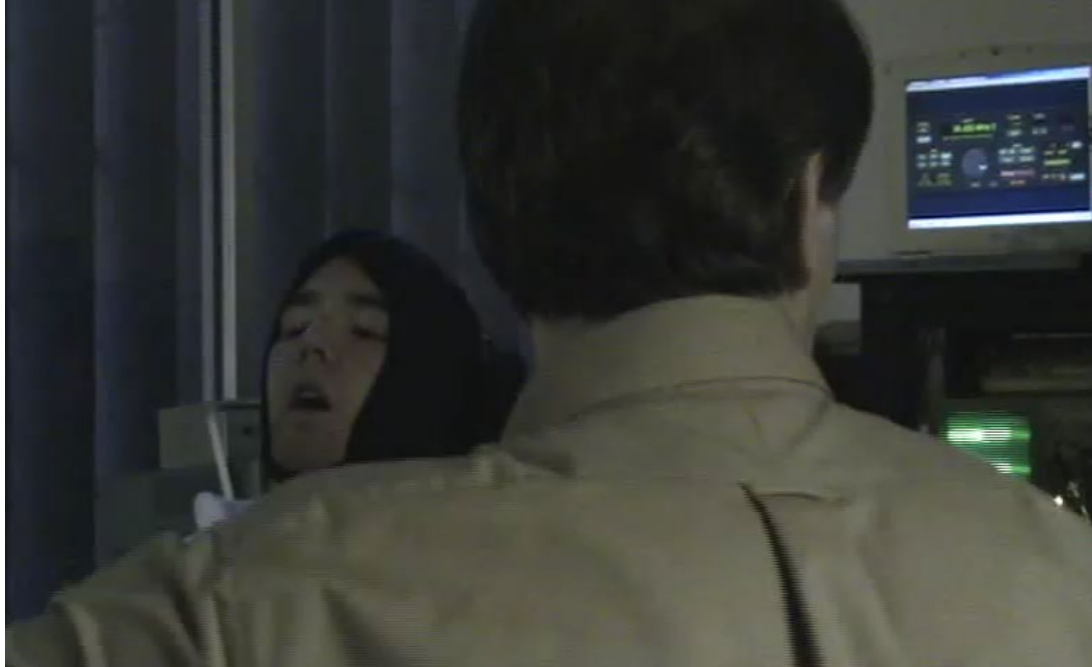
Processing   Inadequate

Digitization

Electrodes

Illustrative BCI system

The Need for Computing in Perspective
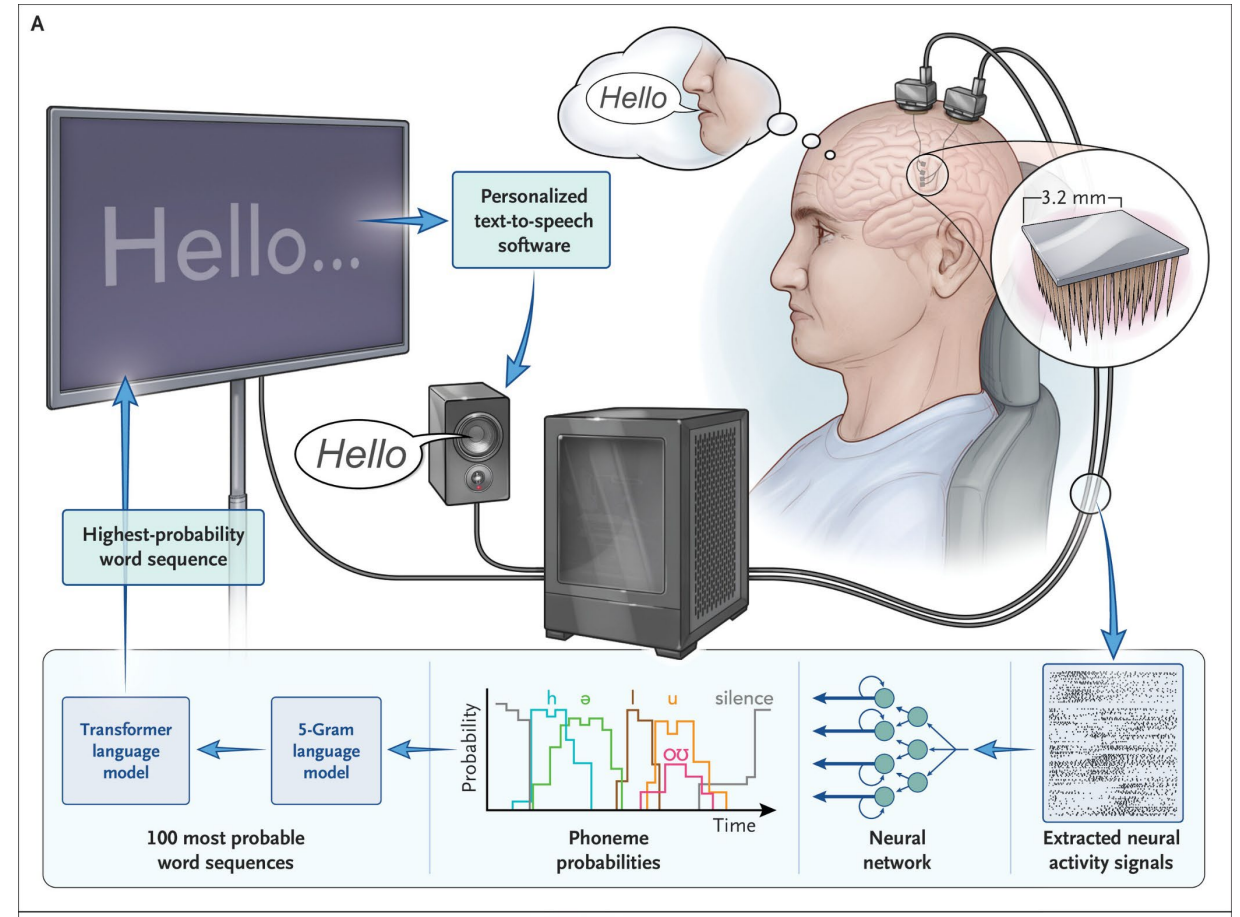
Phil Kennedy with patient Erik Ramsey, around 2004

"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

Phil Kennedy with patient Erik Ramsey, around 2004

Running on "BRAND: a platform for closed-loop experiments with deep network models"
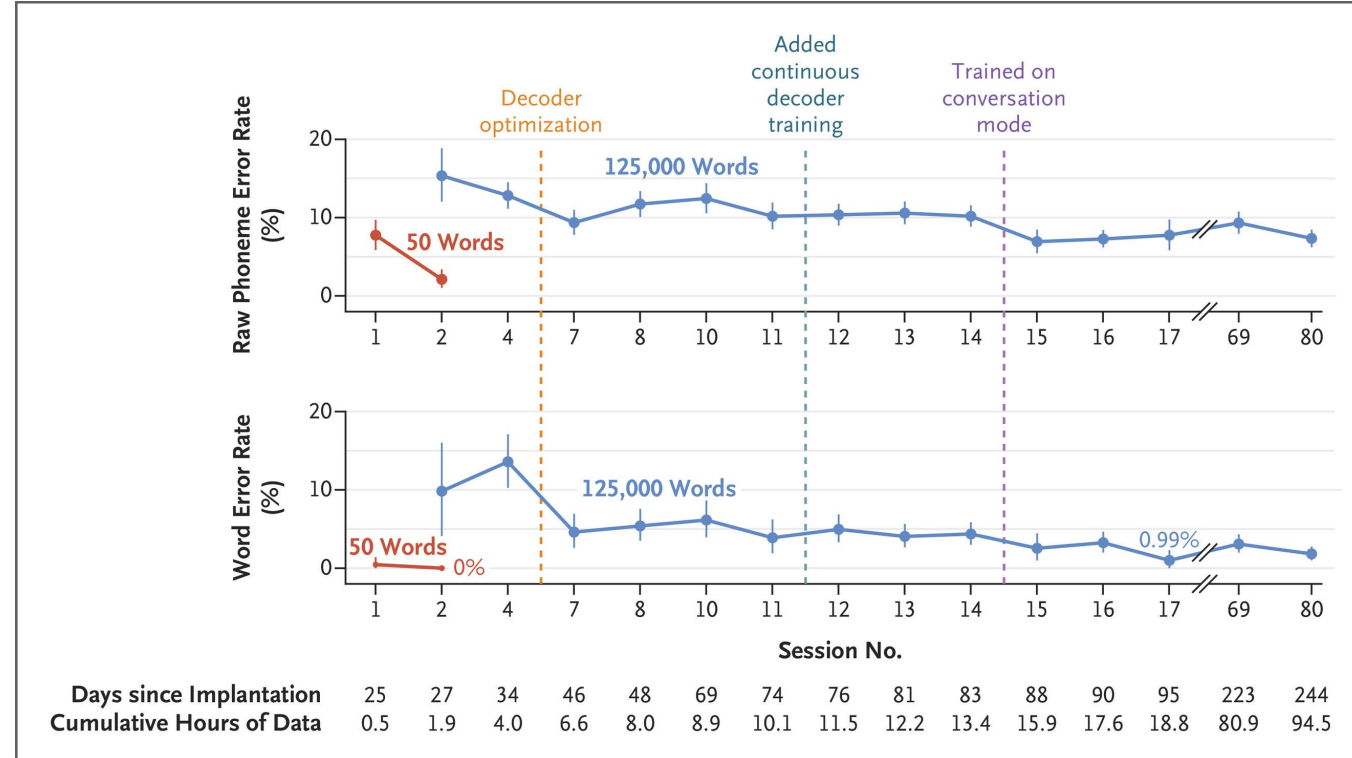
"An Accurate and Rapidly Calibrating Speech Neuroprosthesis", NEJM 2024

The Need for Computing in Perspective

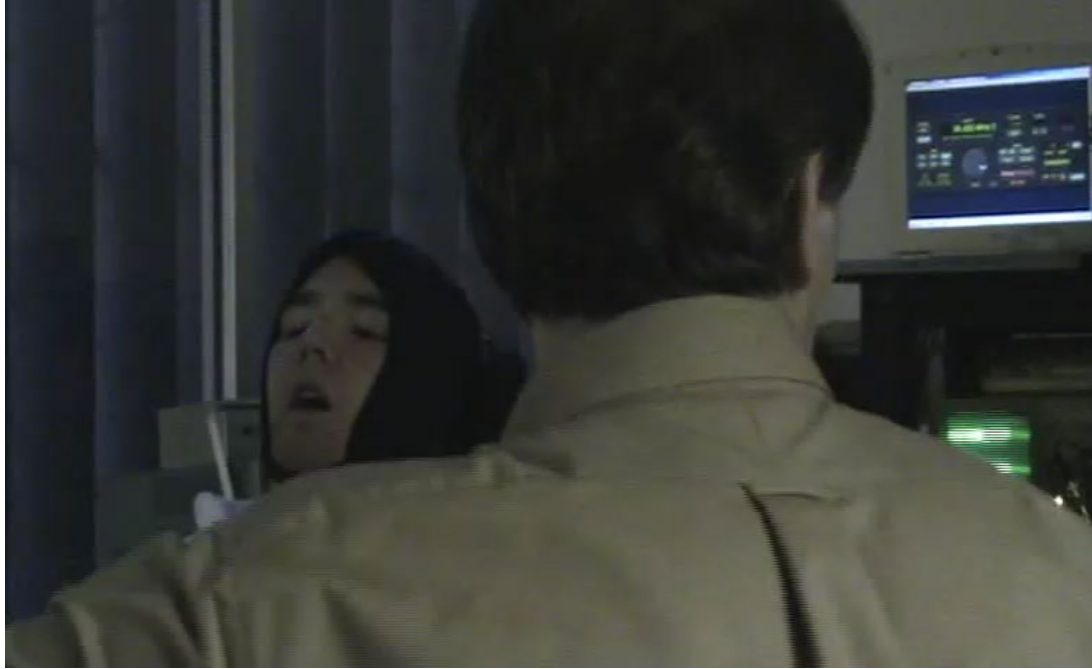LOCAL NEWS
IBM's Smallest PC Designed In Triangle
Posted 5:06 p.m. Aug 3, 2006 - Updated 5:16 a.m. Jun 11, 2004
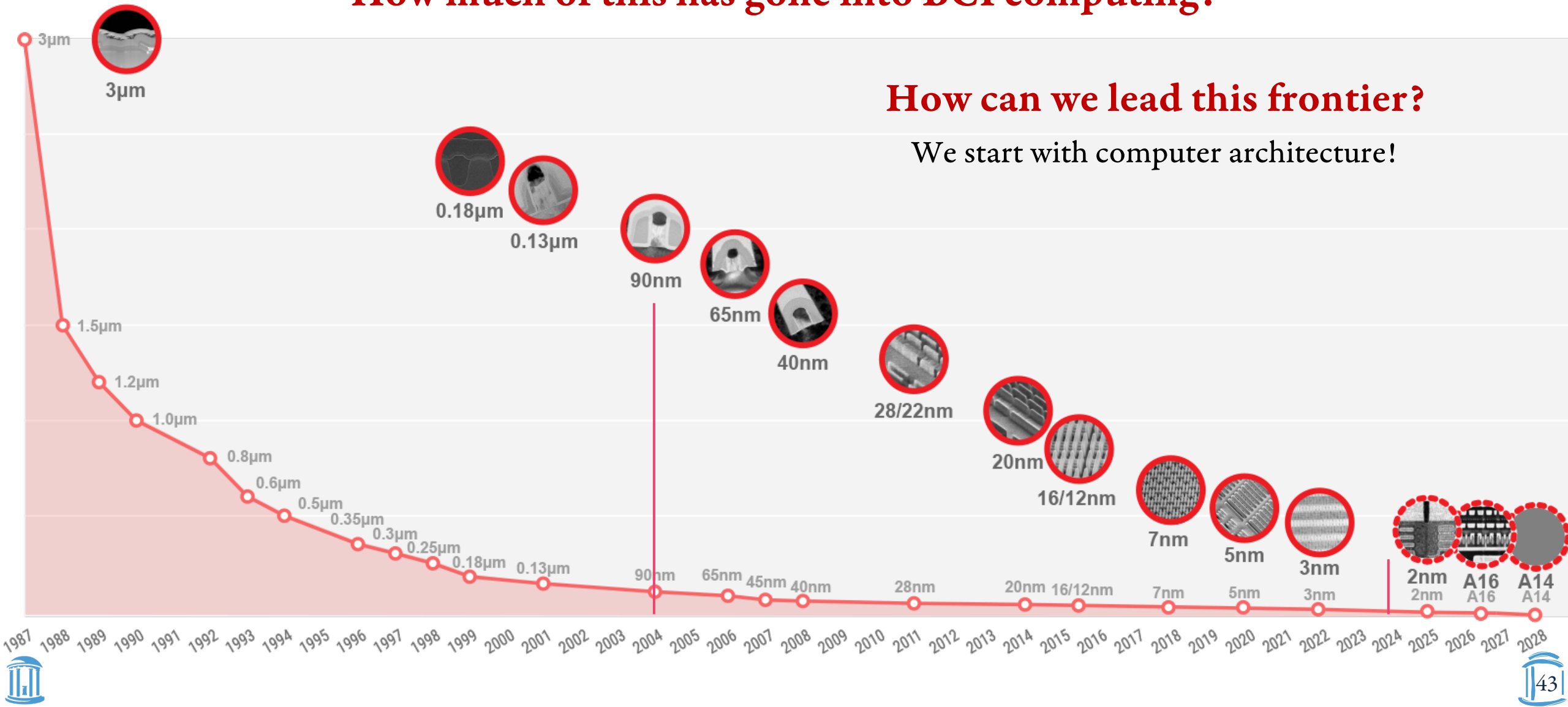
"weighs just 13 pounds"

"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

Start thinking about projects (pairs)

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

Introctions!

Name

Grad/undergrad

Focus area

Why are you taking the course?

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

2-page write-up due in class on 8/27

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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
- Picture of scientists: https://www.cs.auckland.ac.nz/~brian/rutherford8.html (original: Pierre de Latil), Bush (Carnegie Science), Others (Wikipedia)
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- 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)