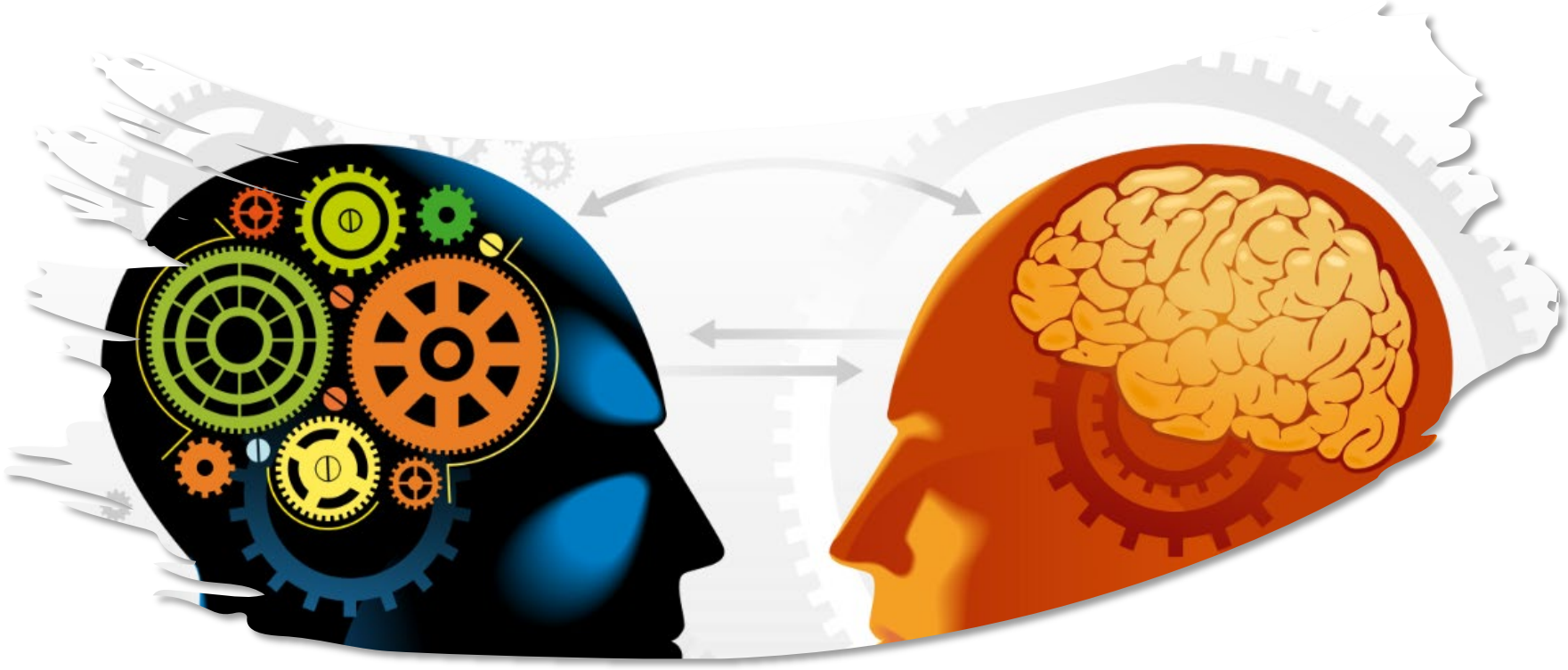


Building the Infinite Brain

COMP 690

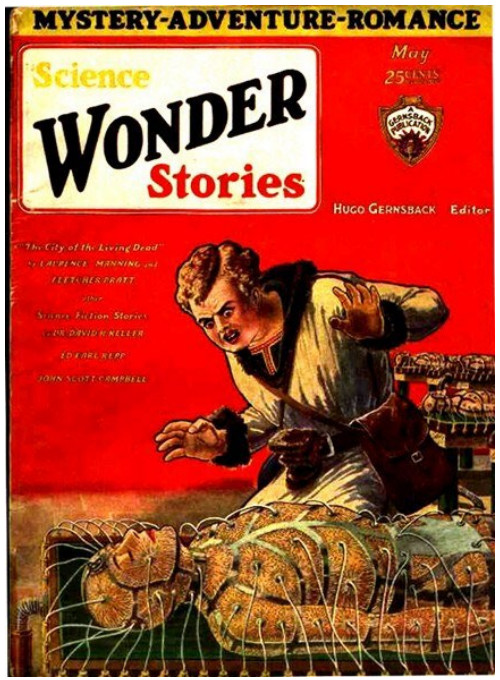
Raghavendra Pradyumna Pothukuchi

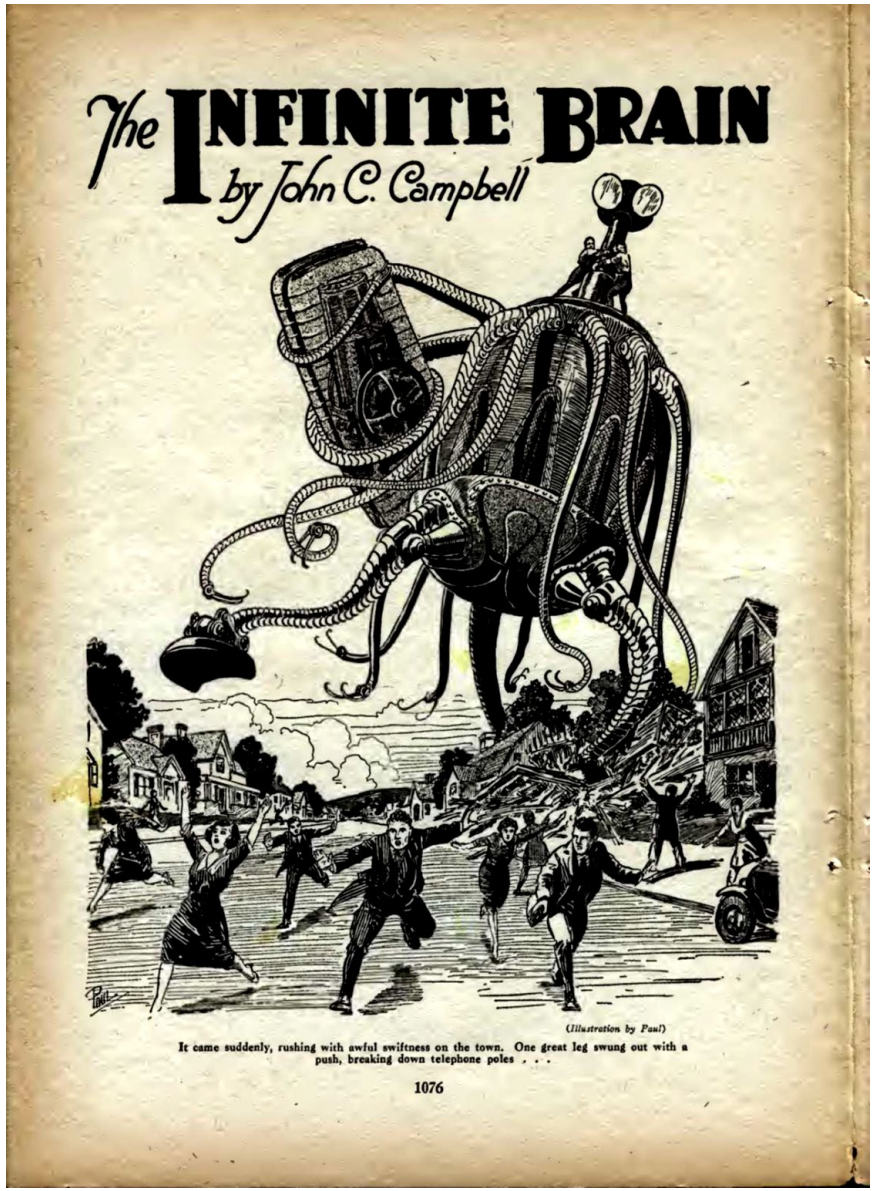
THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

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

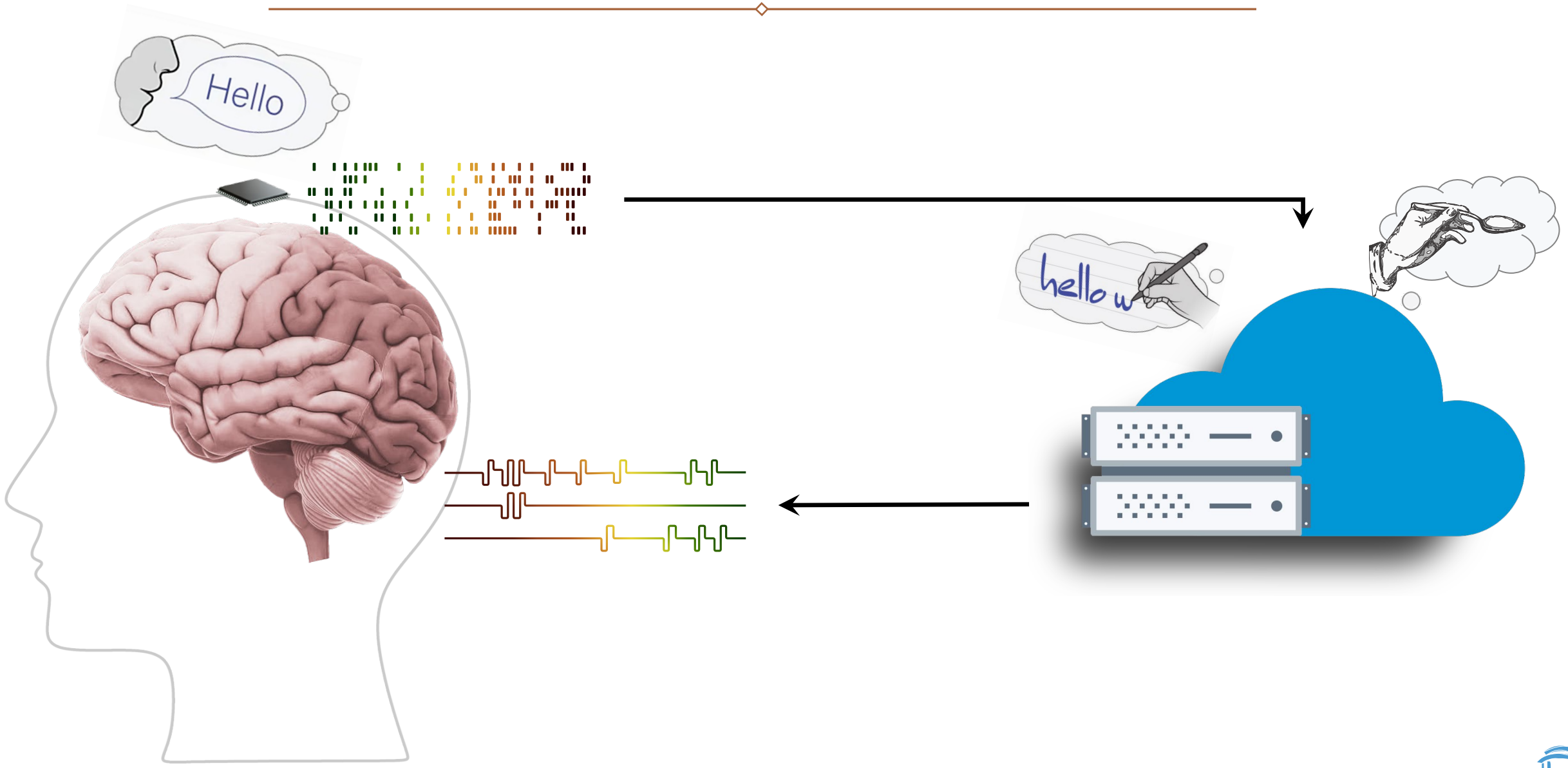
"I am attempting to construct a mechanism exactly duplicating the mechanical and electrical processes occurring in the human brain and constituting the phenomena known as *thought*."

"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



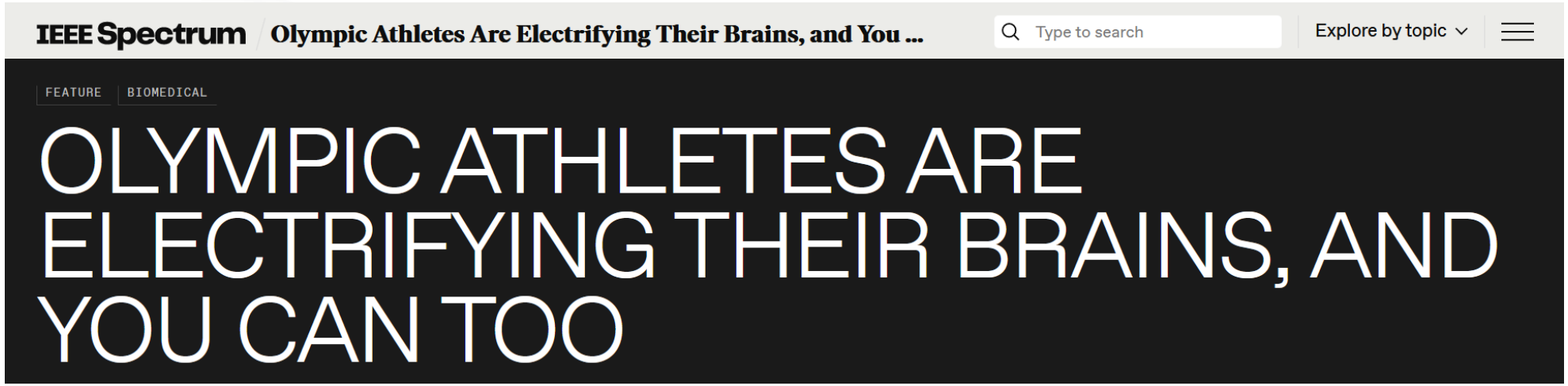
Talk To The Brain and Think Like The Mind

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.

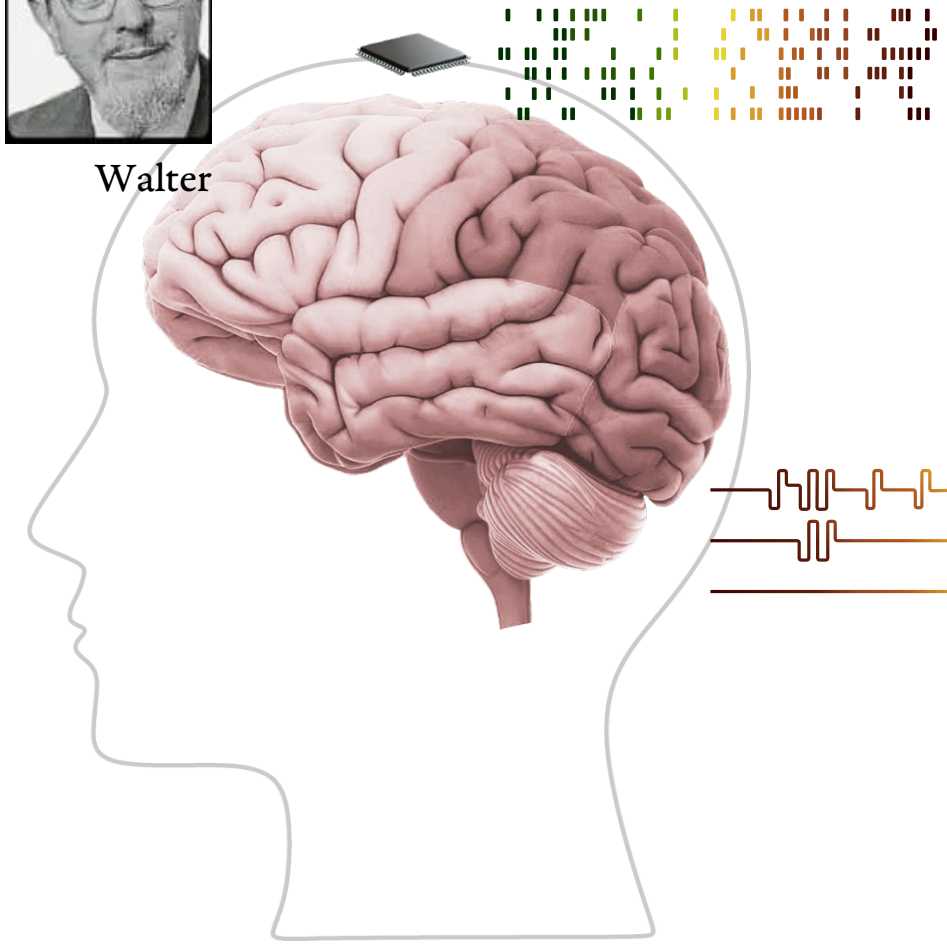
March 3, 2023

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

Brain Inspiration Helped Advance Computing

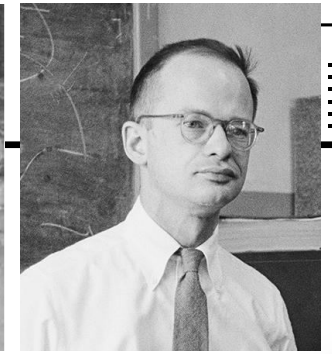
Brain implant

Walter



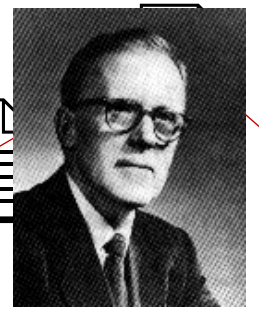
Cybernetics, Computational neuroscience

Ashby, McCulloch, Walter, Wiener

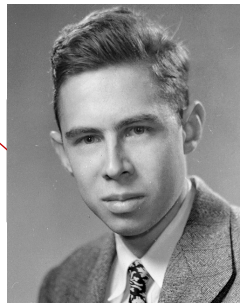


Pitts

Machine Learning

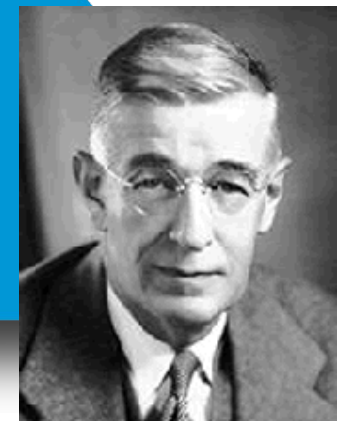


Hebb



Rosenblatt

Memex



Bush

Computing, Computer architecture

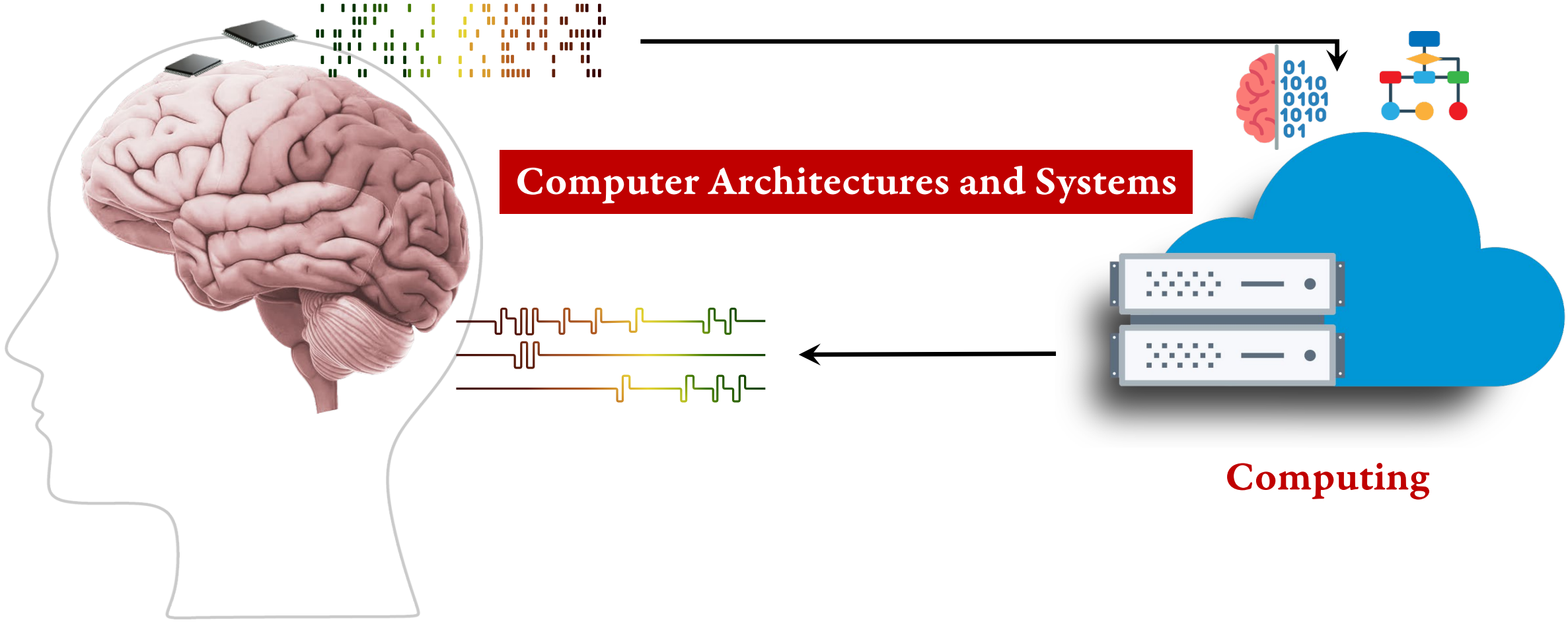
Turing

von Neumann

Opportunity Today: Spur a New Virtuous Cycle

Brain-computer interfaces (BCIs)

Cognitive frameworks



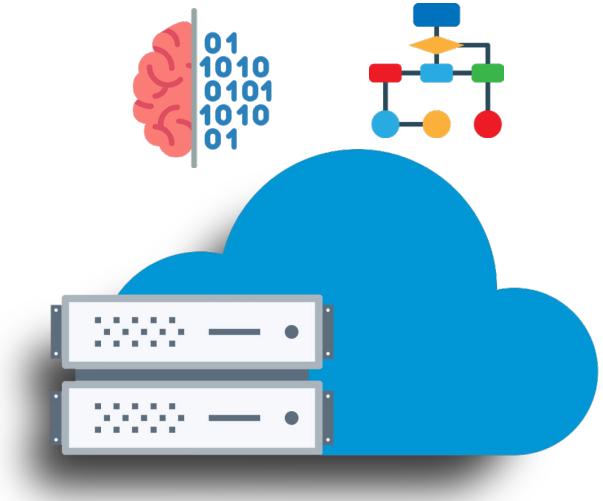
Computer Architectures and Systems

Computing

Example Application

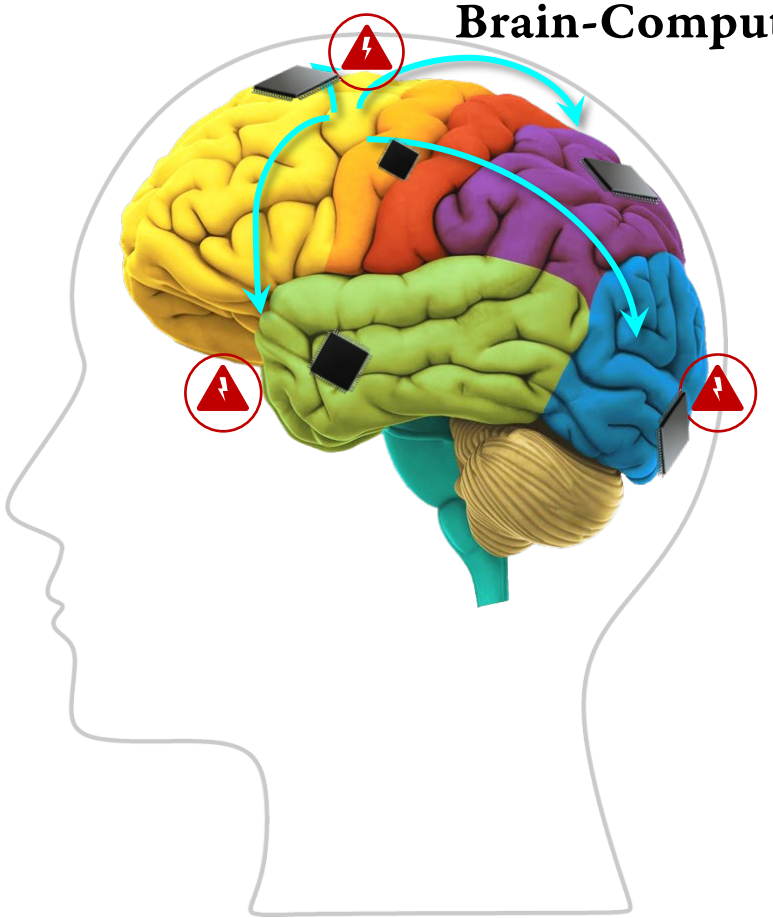
Restoring function

Computational cognitive frameworks



Mitigating seizures

Brain-Computer Interfaces (BCIs)



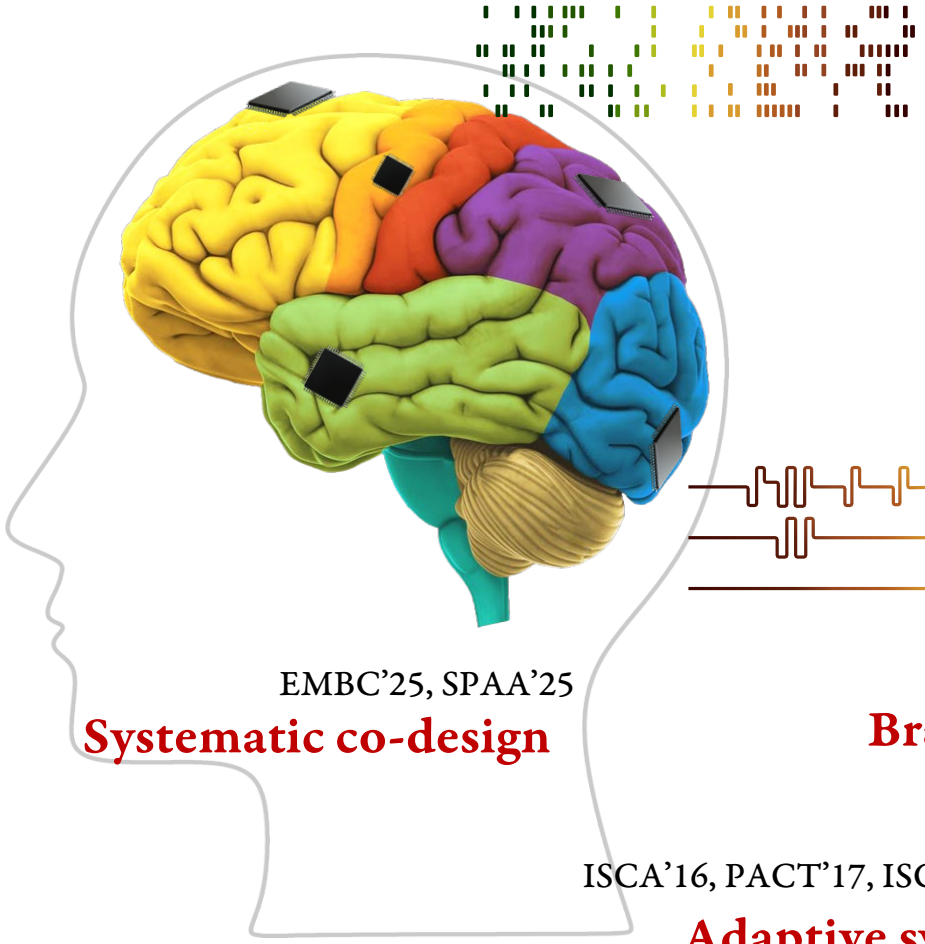
My Research

IEEE Micro (HotChips)'23

***HALO*: Single-site BCI**

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

***SCALO*: Multi-site BCI**



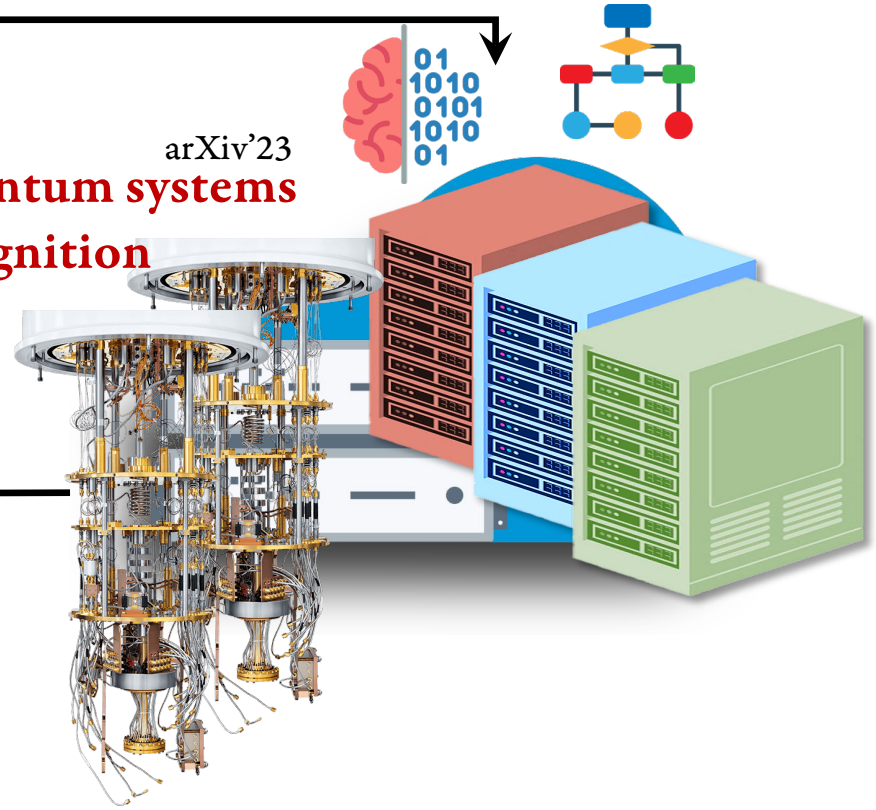
arXiv'25

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

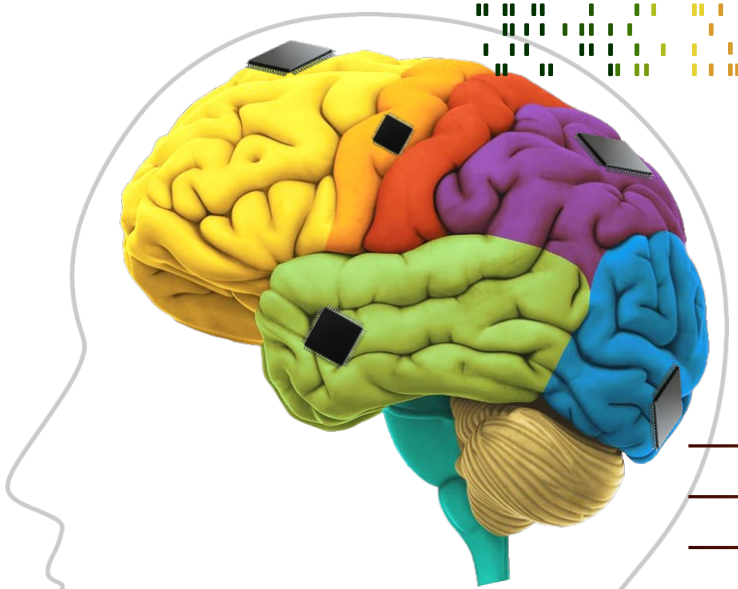
My Research

IEEE Micro (HotChips)'23

HALO: Single-site BCI

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

SCALO: Multi-site BCI

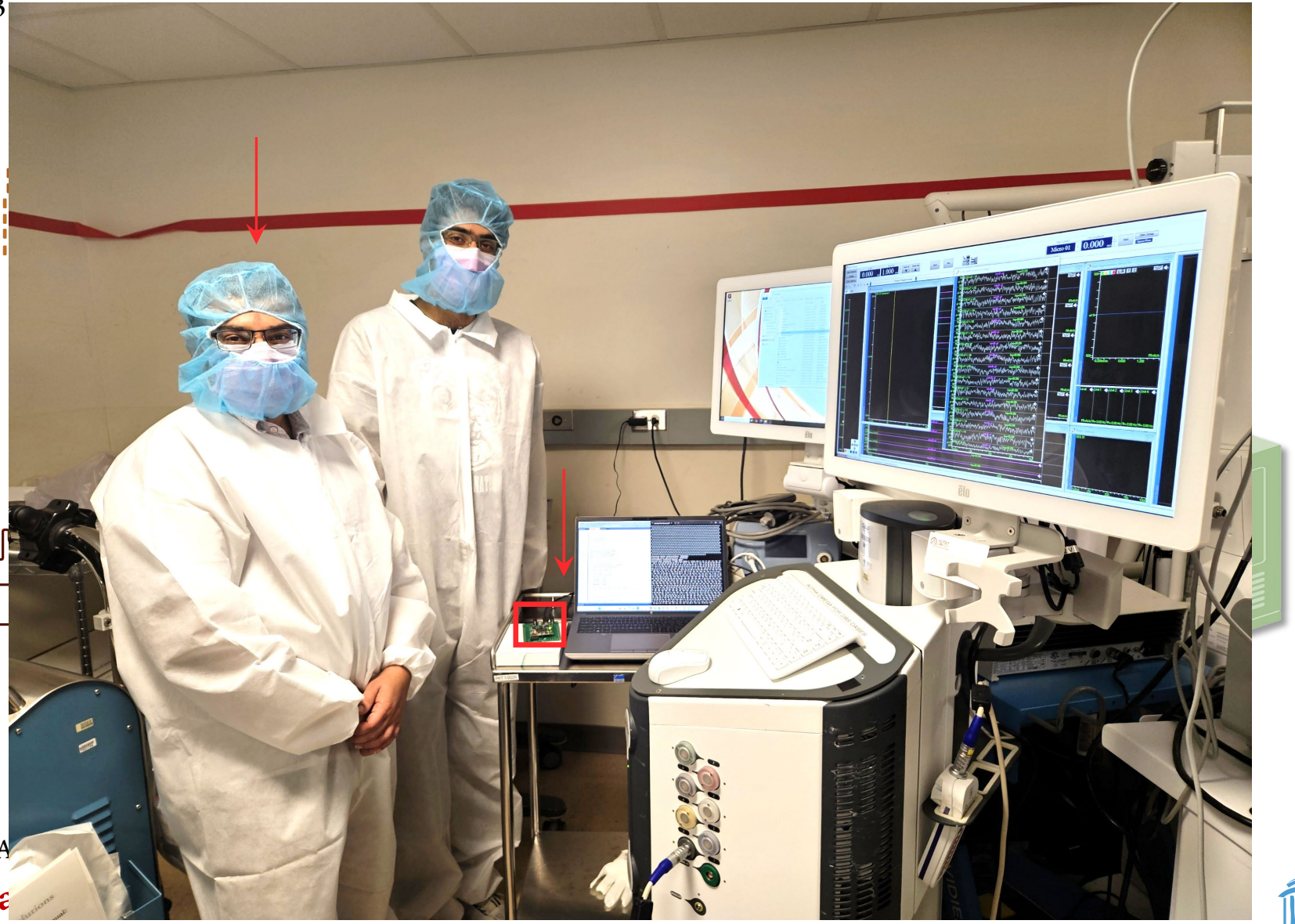


EMBC'25, SPAA'25

Systematic co-design

ISCA'16, PA

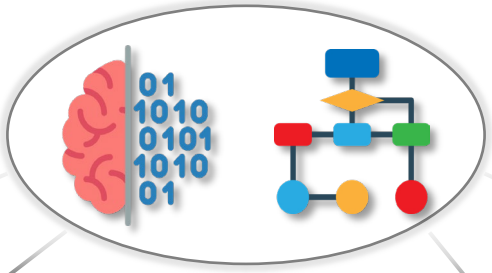
Ada



My Vision: Building the Infinite Brain

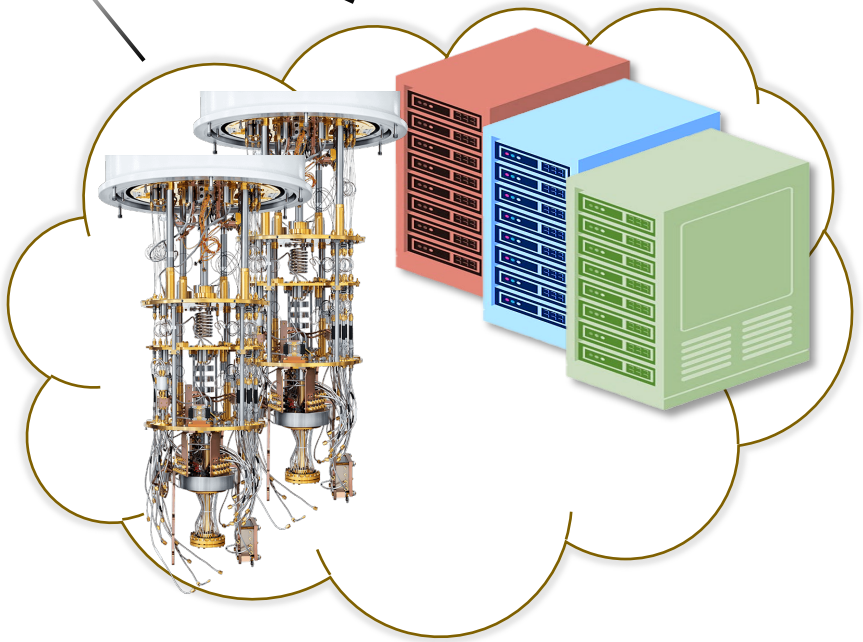
Real-time cognitive frameworks

Tbps, in vivo



Wearables

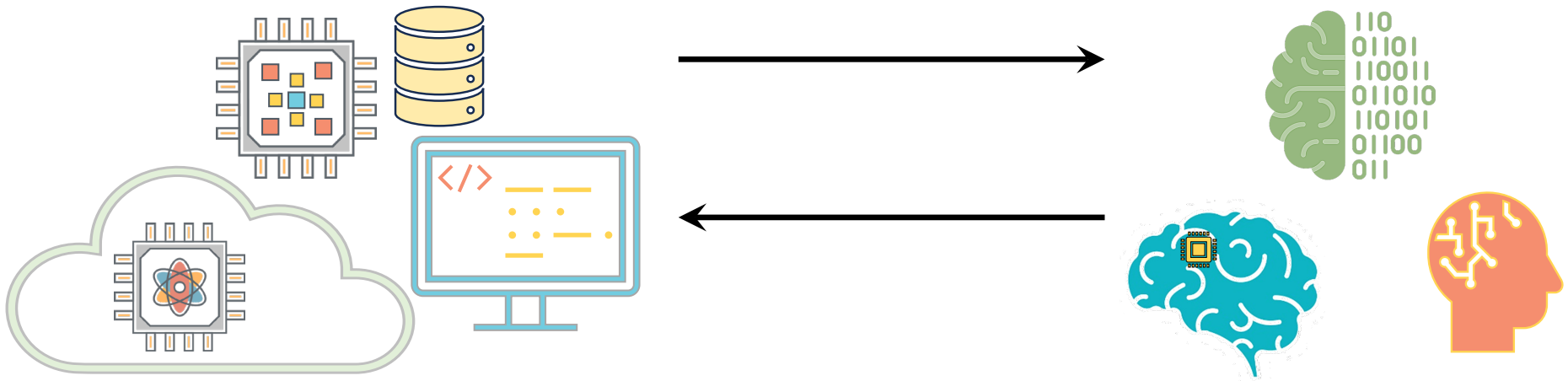
Edge servers



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	Readings
Wed 1/7	Introduction	HW 1 released	**B1**: Part 1, Part 2.Ch 1-3, 6 **B2**: Ch 1-5, 9-11, 19-23
Mon 1/12	Why computer architecture for BCIs?		**B3**: Ch 1 **Paper:** *Hints and Principles for Computer System Design* (Sections 1, 2, 3.1)
Wed 1/14	Goals of architecture design	HW 1 due	**Paper:** *Hints and Principles for Computer System Design* (Sections 3-6)
Mon 1/19	Martin Luther King, Jr. Day		
Wed 1/21	Pipelining	Project proposals due	**B3**: Appendix C
Mon 1/26	Out of Order		**B3**: Chapter 3, Review Appendix C **Paper:** *Complexity-effective Superscalar Processors* **Paper:** *Implementation of Precise Interrupts in Pipelined Processors*
Wed 1/28	Out of Order (contd.)	Proposals reviewed	
Mon 2/2	Out of Order (contd.)	Final proposals due. HW 2 released	
Wed 2/4	Overview of signal processing		**B1:** Chapters 4, 5. **B2:** Chapters 7, 8. **Paper:** *Signal Processing for Brain–Computer Interfaces: A review and current perspectives*
Mon 2/9	Well-Being Day		

Course Logistics

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

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

Wed 2/11	Caches		**B3:** Chapter 2, Appendix B **Paper:** *Cache Memories* **Paper:** *Measuring Cache and TLB Performance and Their Effect on Benchmark Runtimes* **Paper:** *Design of CPU Cache Memories*
Mon 2/16	Caches (contd.)	HW 2 due	
Wed 2/18	Memory		**B3:** Chapter 2 **Paper:** *Virtual Memory: Issues of Implementation* **Paper:** *Virtual Memory*
Mon 2/23	Memory (contd.)		
Wed 2/25	Multicore and multithreaded systems	HW 3 released	**B3:** Chapter 3.11, 5 **Paper:** *Multithreaded Processors*
Mon 3/2	Multicore and multithreaded systems (contd.)		
Wed 3/4	Memories in parallel architectures		**B3:** Chapter 5 **Paper:** *Shared memory consistency models: a tutorial* **Reference:** *A primer on memory consistency and cache coherence*
Mon 3/9	Memories in parallel architectures (contd.)		
Wed 3/11	Midterm project review	HW3 due	
Mon 2/9	Well-Being Day		

Course Logistics

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

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

Mon 3/16	Spring Break	
Wed 3/18	Spring Break	
Mon 3/23	Parallel architectures	**B3**: Chapter 5, Appendix C, G **Paper:** *A survey of parallel computer architectures*
Wed 3/25	BCI Papers 1 and 2	
Mon 3/30	BCI Papers 3 and 4	
Wed 4/1	BCI Papers 5 and 6	
Mon 4/6	BCI Papers 7 and 8	
Wed 4/8	BCI Papers 9 and 10	
Mon 4/13	BCI Papers 11 and 12	
Wed 4/15	BCI Papers 13 and 14	
Mon 4/20	Invited lecture (BCI applications in neuroscience)	
Wed 4/22	Invited lecture (Neurosurgery)	
Mon 4/25	Invited lecture (architecture and system design)	
Mon 4/27	Project presentations	
Wed 3/11	Midterm project review	HW3 due
Mon 2/9	Well-Being Day	

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 (50%), homeworks (20%), paper reviews (10%), lead presentation (10%), discussion (10%)—*instruction discretion and subjective*

Course website: https://www.cs.unc.edu/~raghav/Courses/comp690/sp26.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

For Today

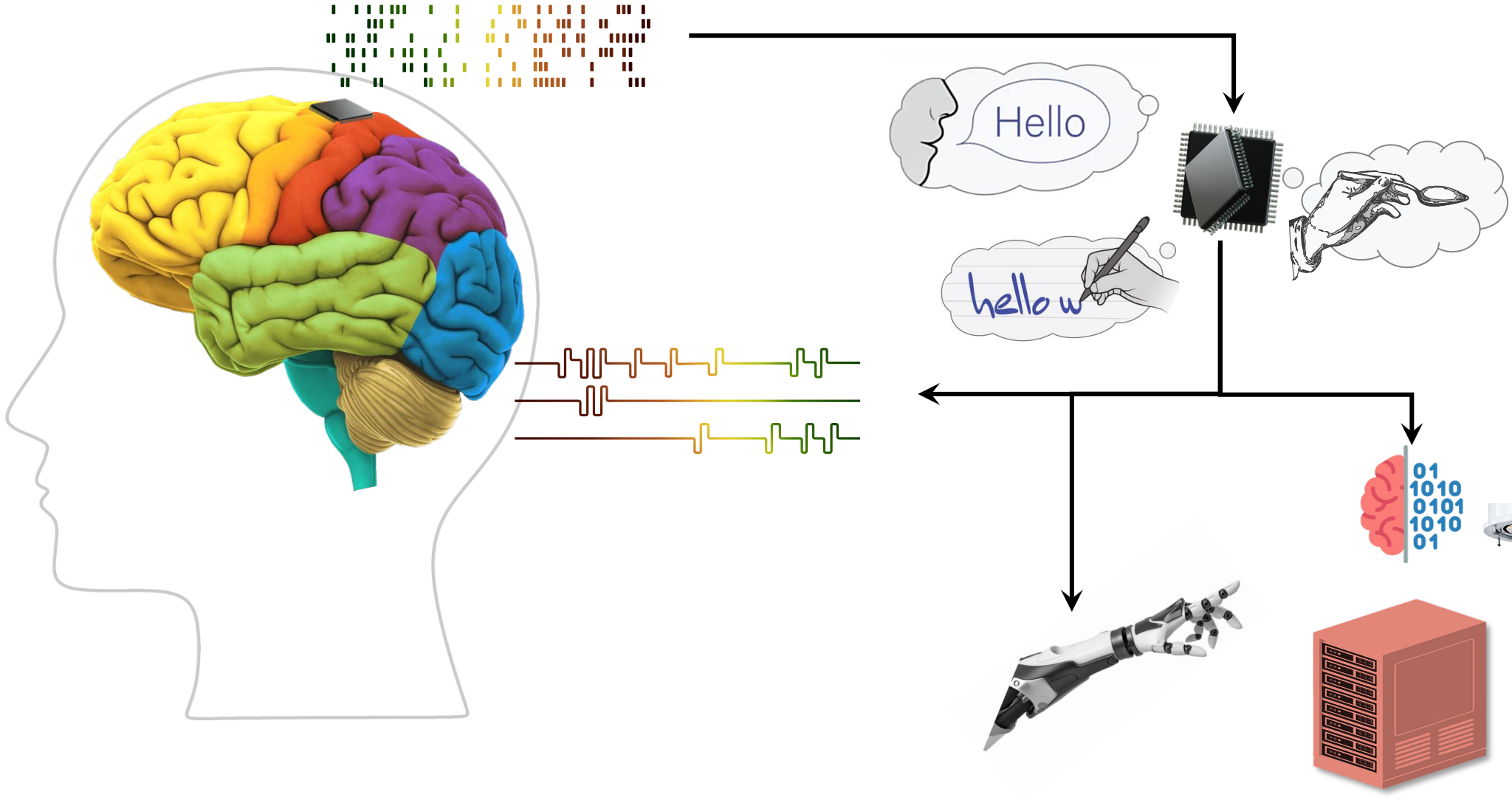
- Course overview
- **What are BCIs?**
- **What are the computational challenges?**

What Are BCIs?

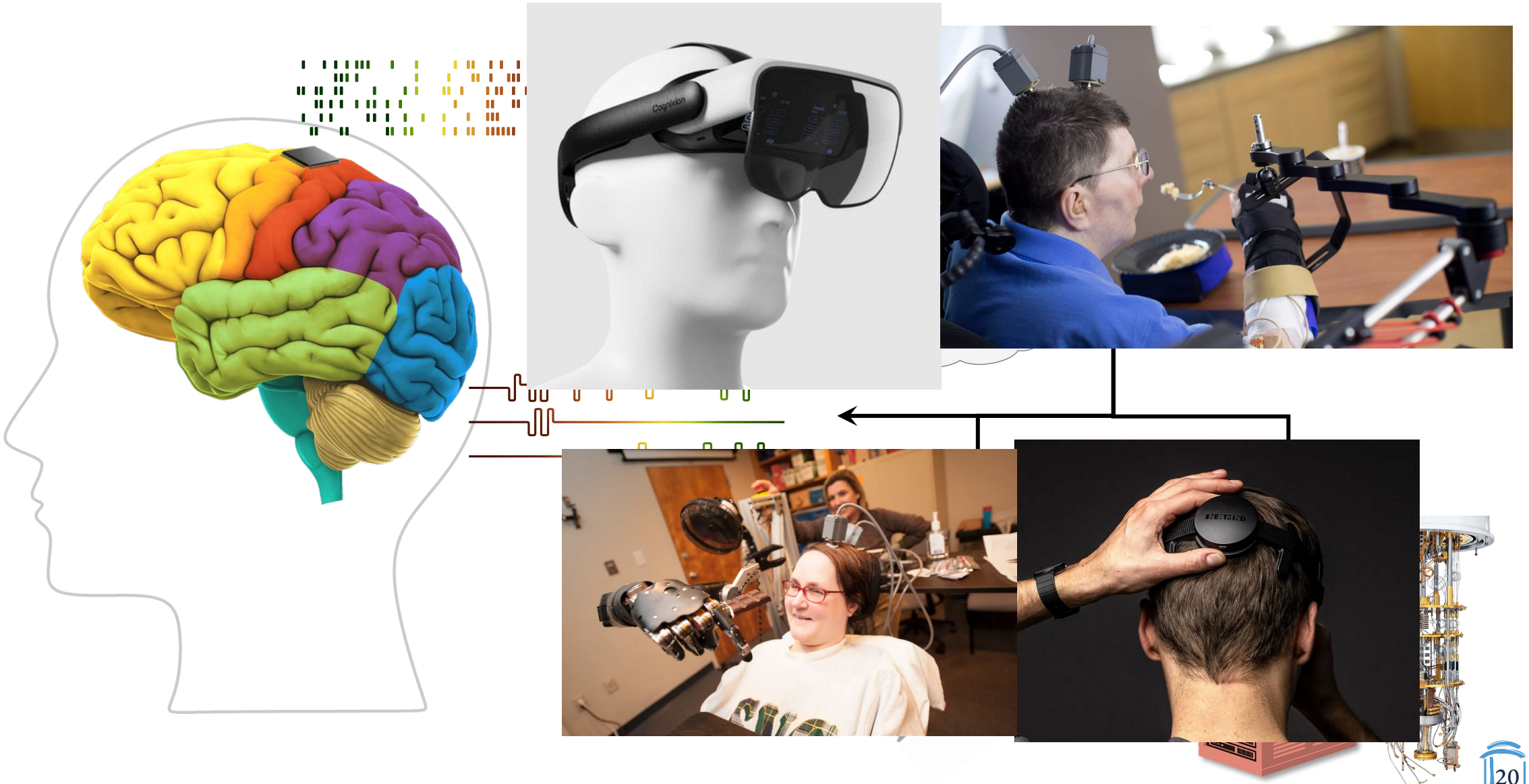
"What's in a name? That which we call a rose by any other name would smell as sweet."

Doesn't seem so with BCIs!

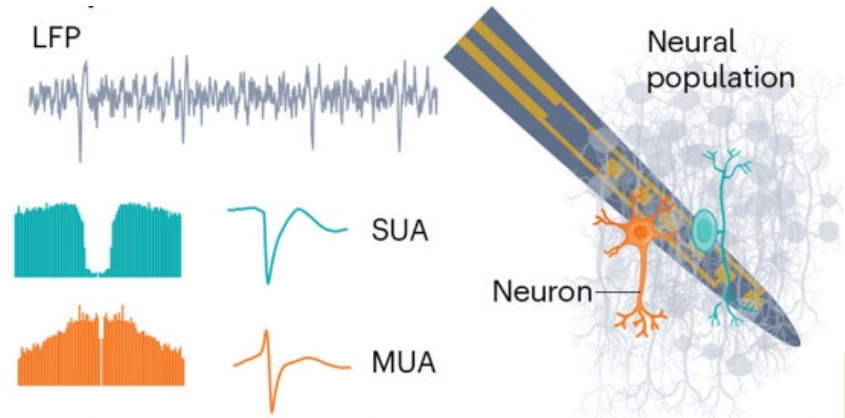
Brain Computer Interfaces (BCIs)



Brain Computer Interfaces (BCIs)

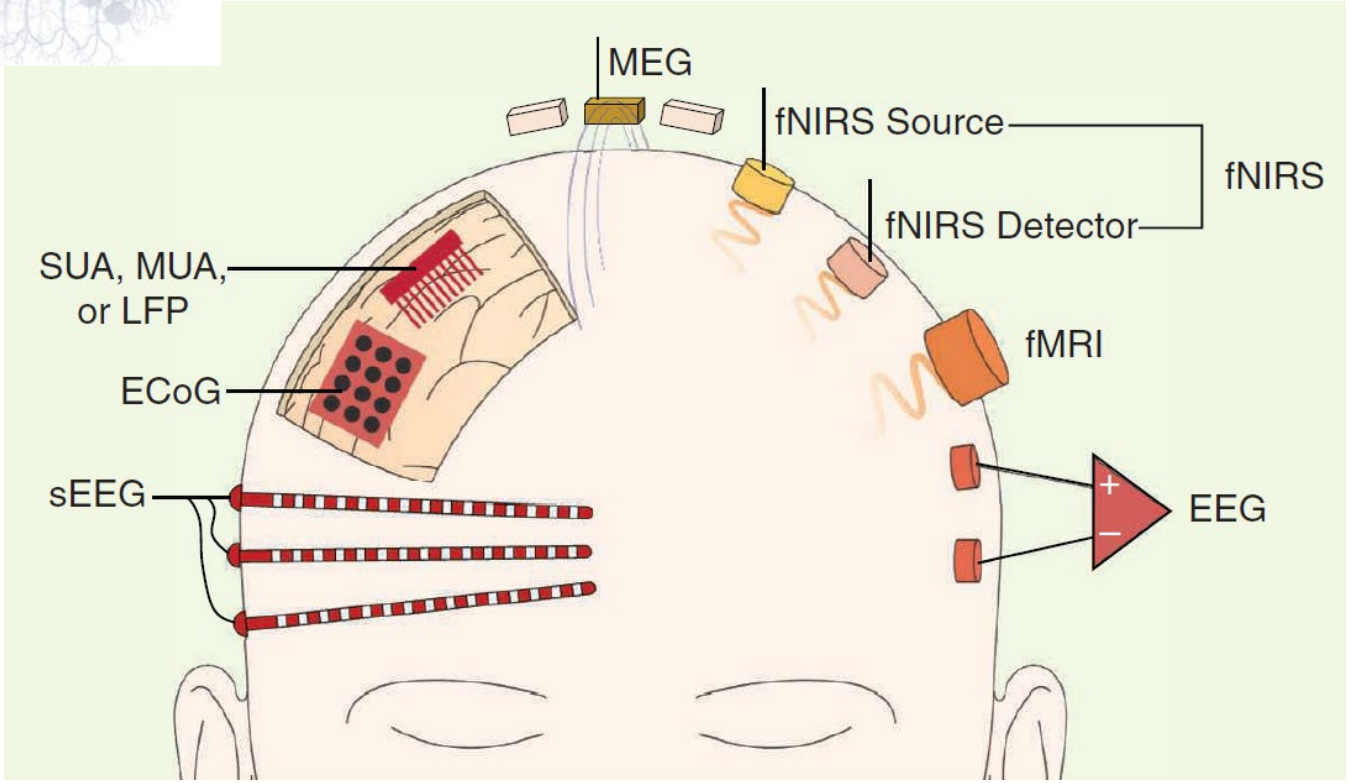


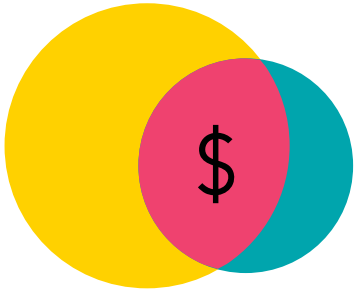
What's In a Name?



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

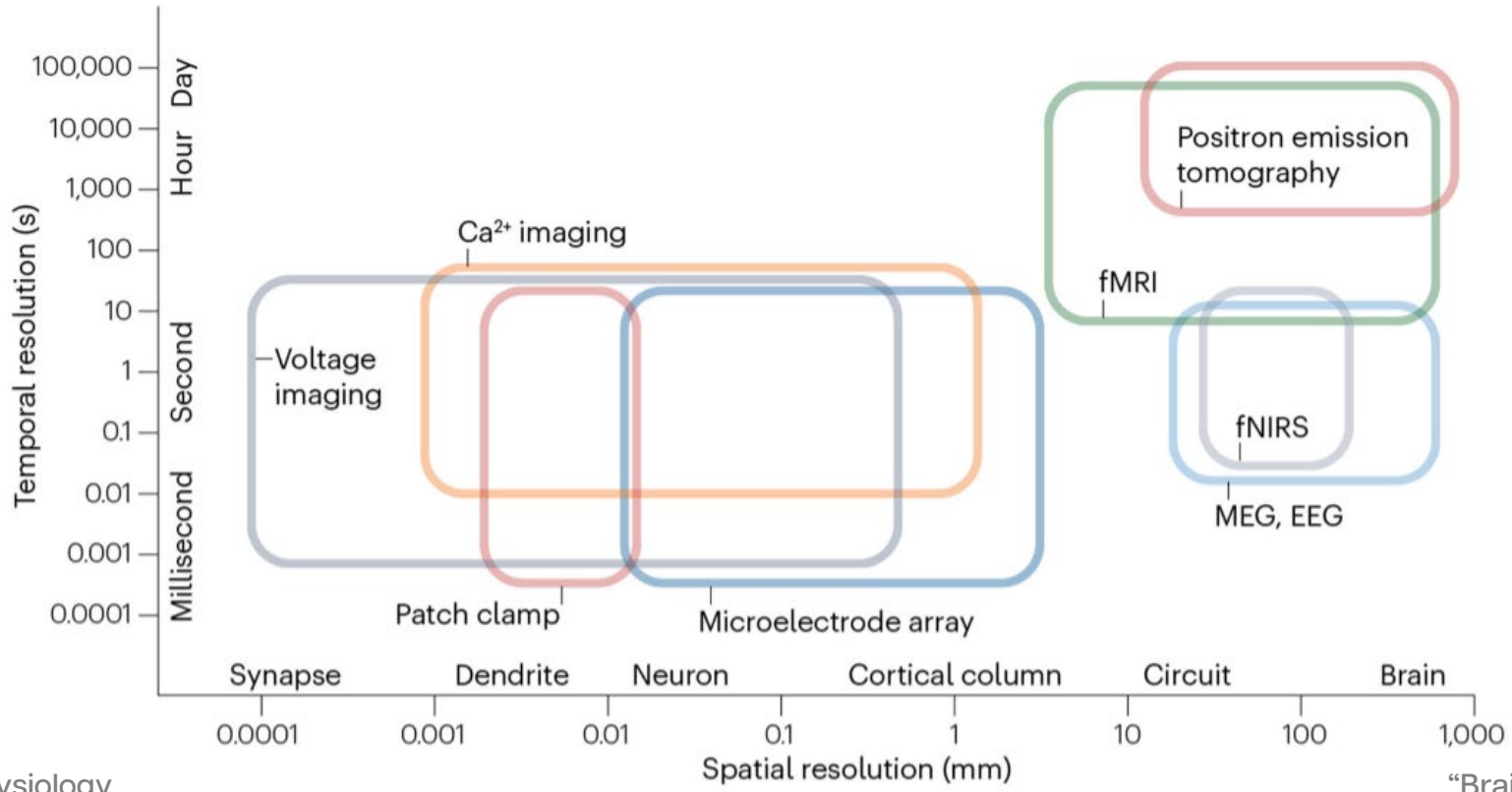
EEG: Electroencephalography
fMRI: functional magnetic resonance imaging
fNIRS: functional near-infrared spectroscopy
MEG: magnetoencephalography
ECoG: Electrocorticography
s/i EEG: stereotactic/intracortical EEG





TAMs and scope

What's In a Name?



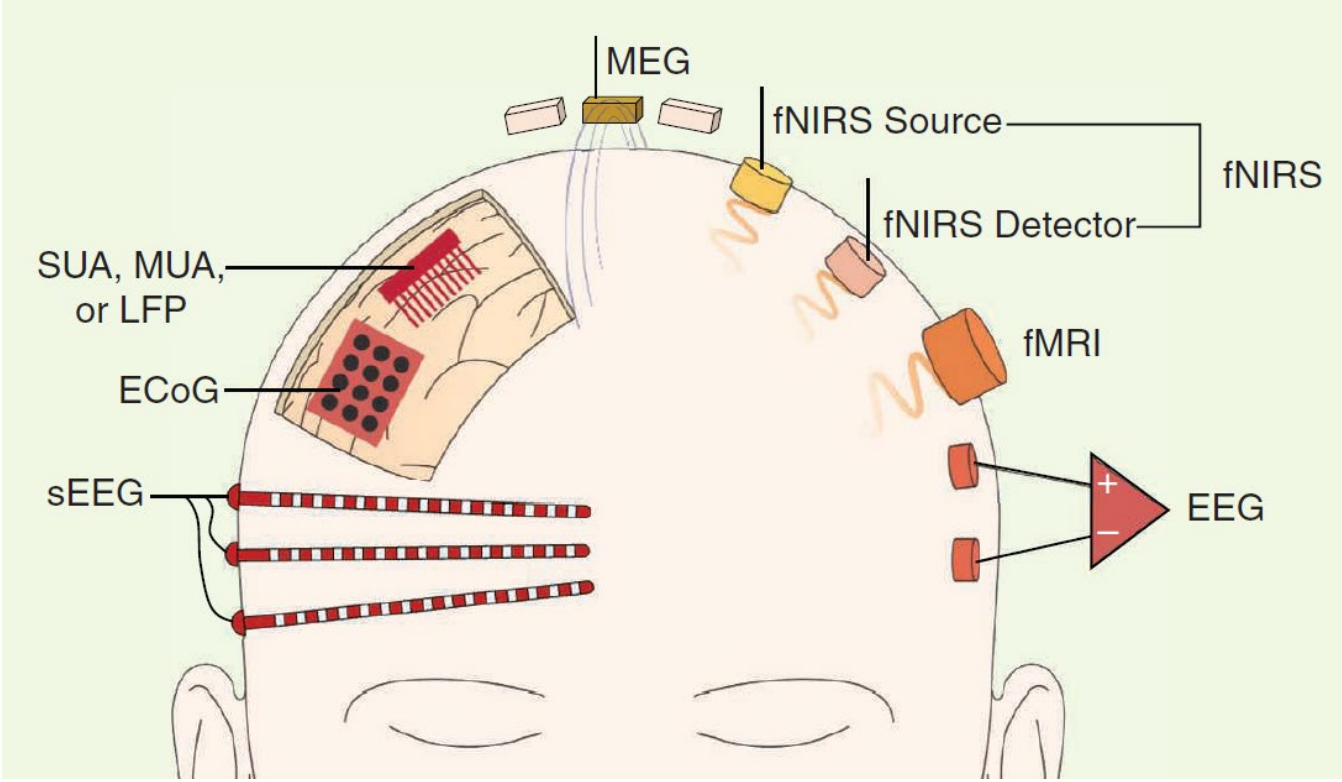
"Innovating beyond electrophysiology through multimodal neural interfaces"

"Brain–computer interfaces for communication and rehabilitation"

What's In a Name?

"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."

Designated pathways

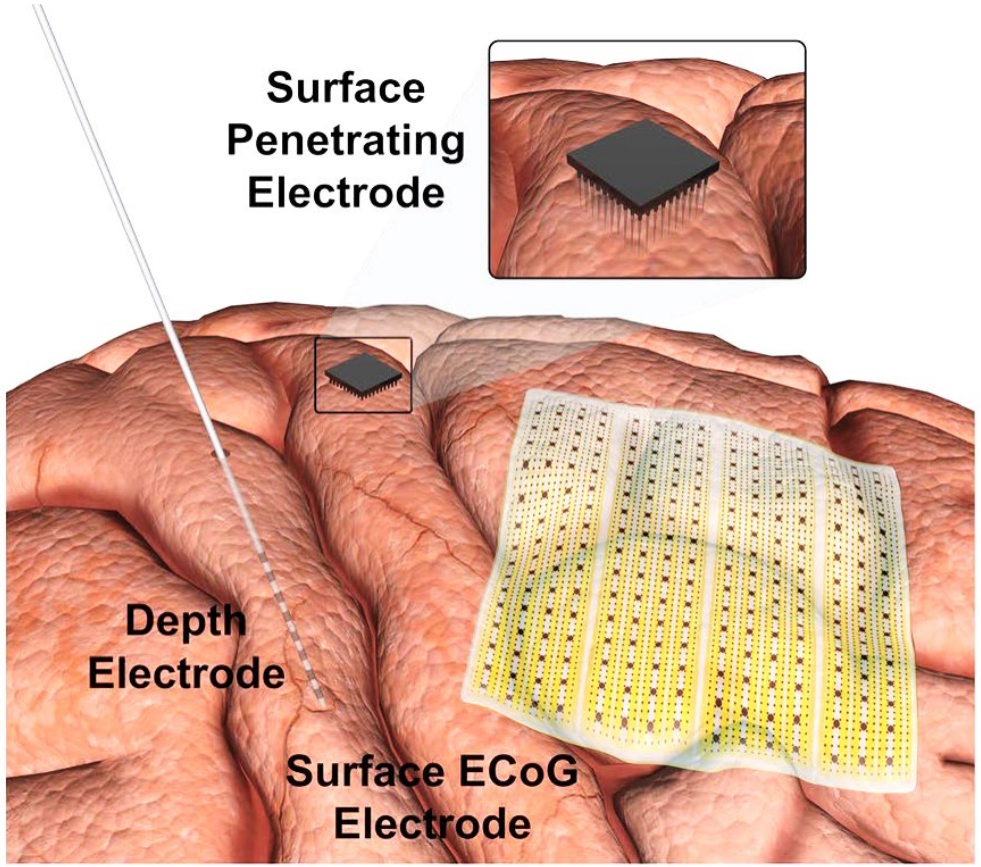


TAMs and scope

BCI Hardware

$\Delta T \leq 1\ °C$

$< 50\ mW$



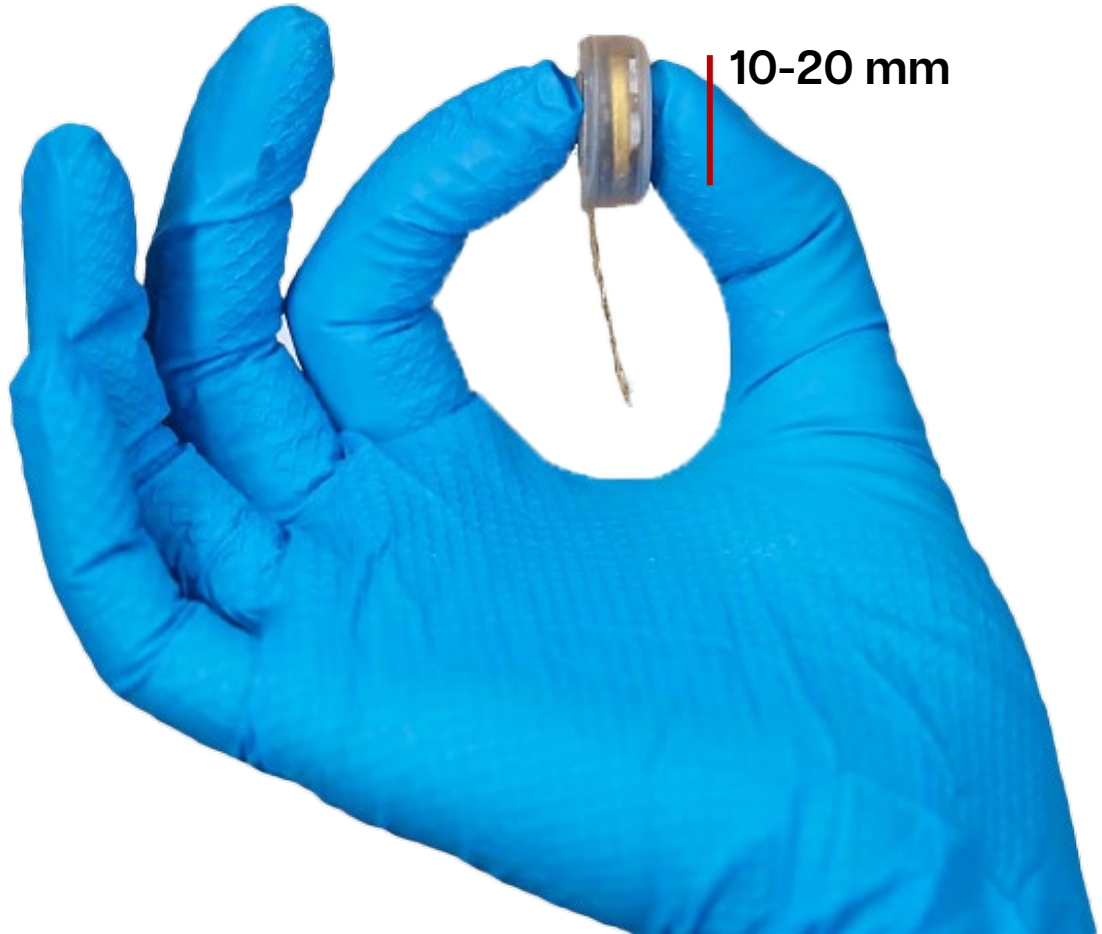
Illustrative BCI system

- Battery, Wireless
- Processing
- Digitization
- Electrodes

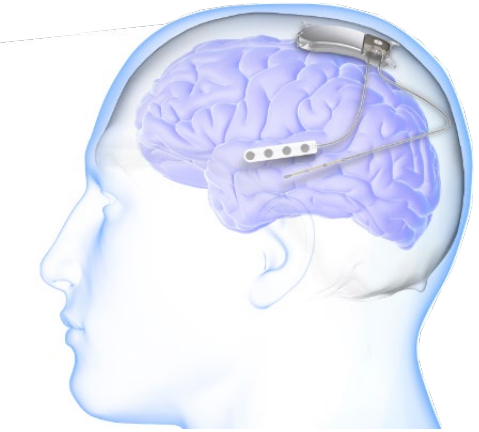
BCI Hardware

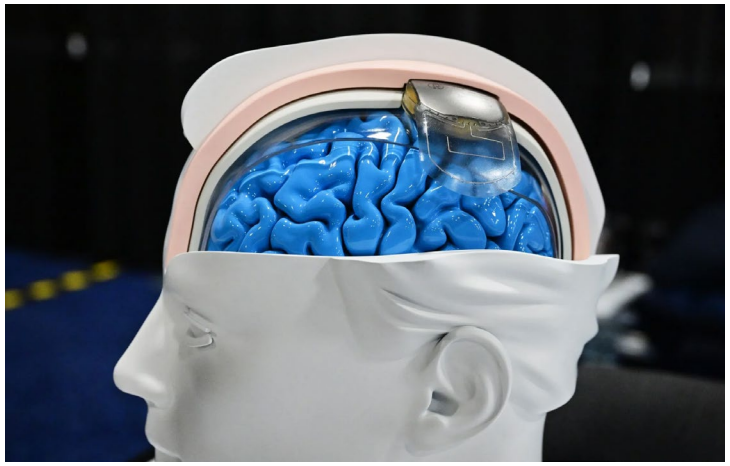
$\Delta T \leq 1\ °C$

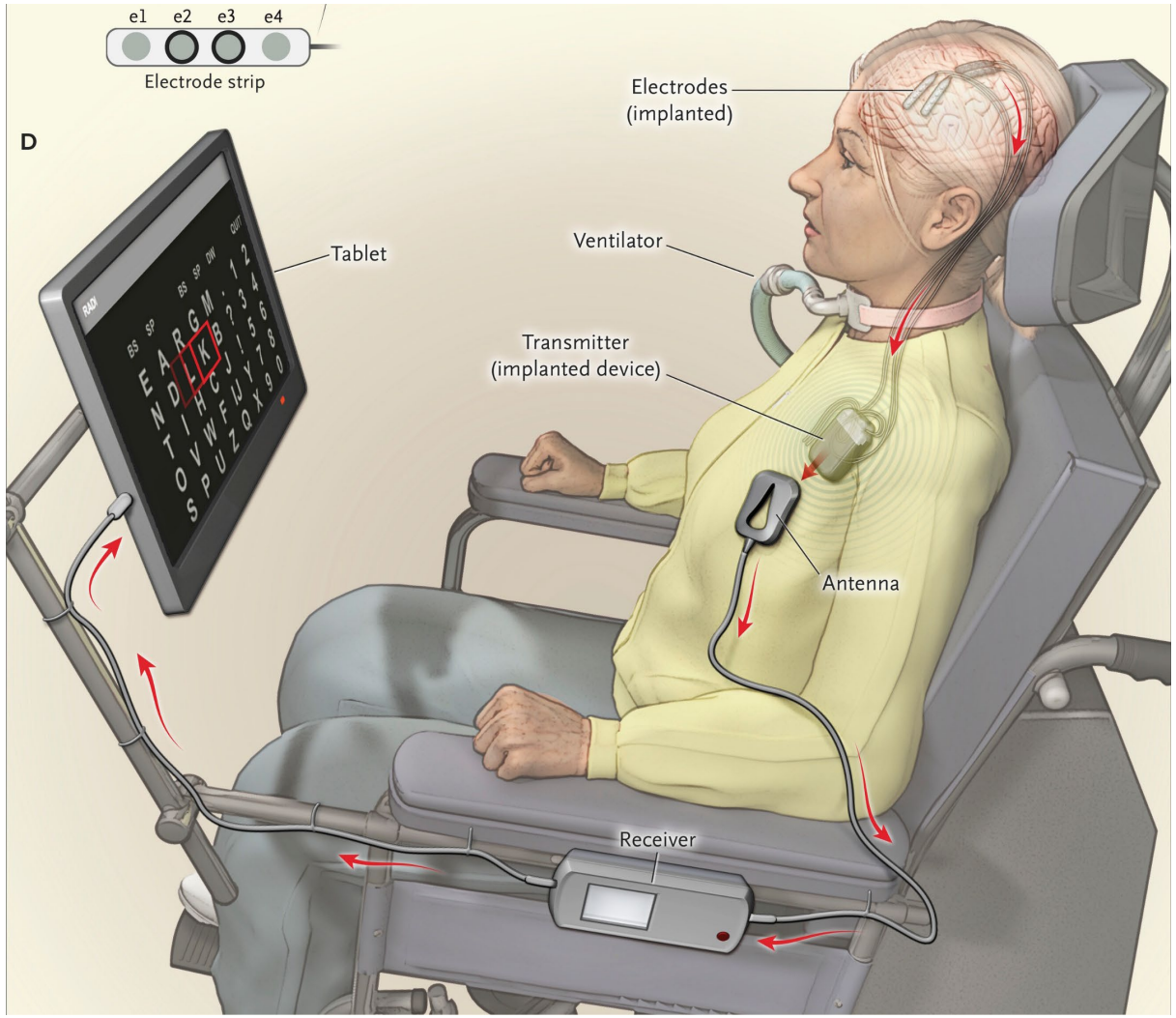
$< 50\ mW$



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)

"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."

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

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

More Recent Examples

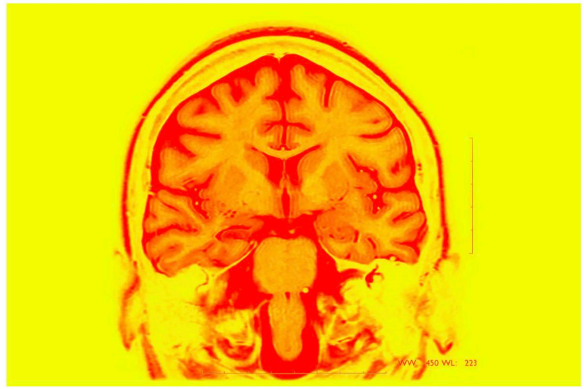
The New York Times

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

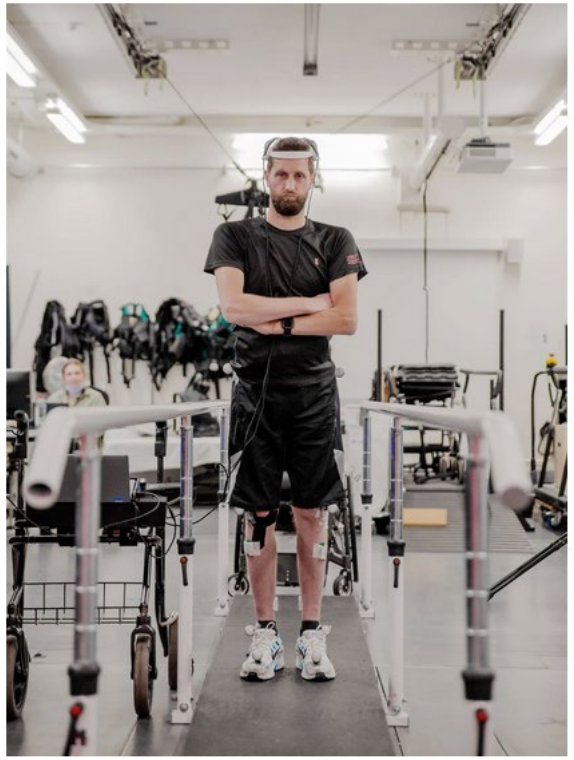
Give this article | 12



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

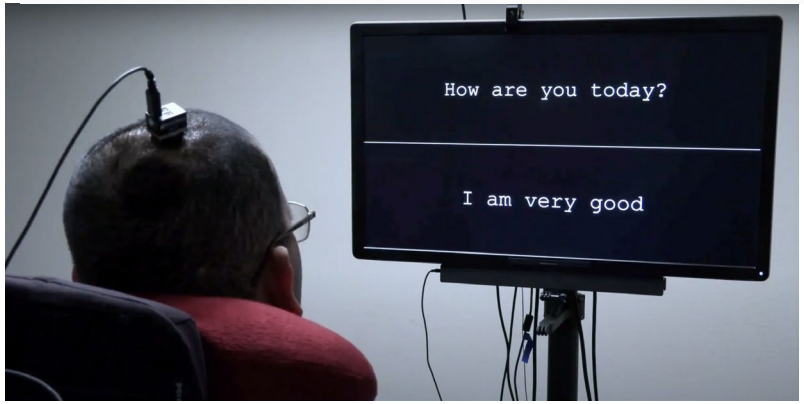
HEALTHCARE

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

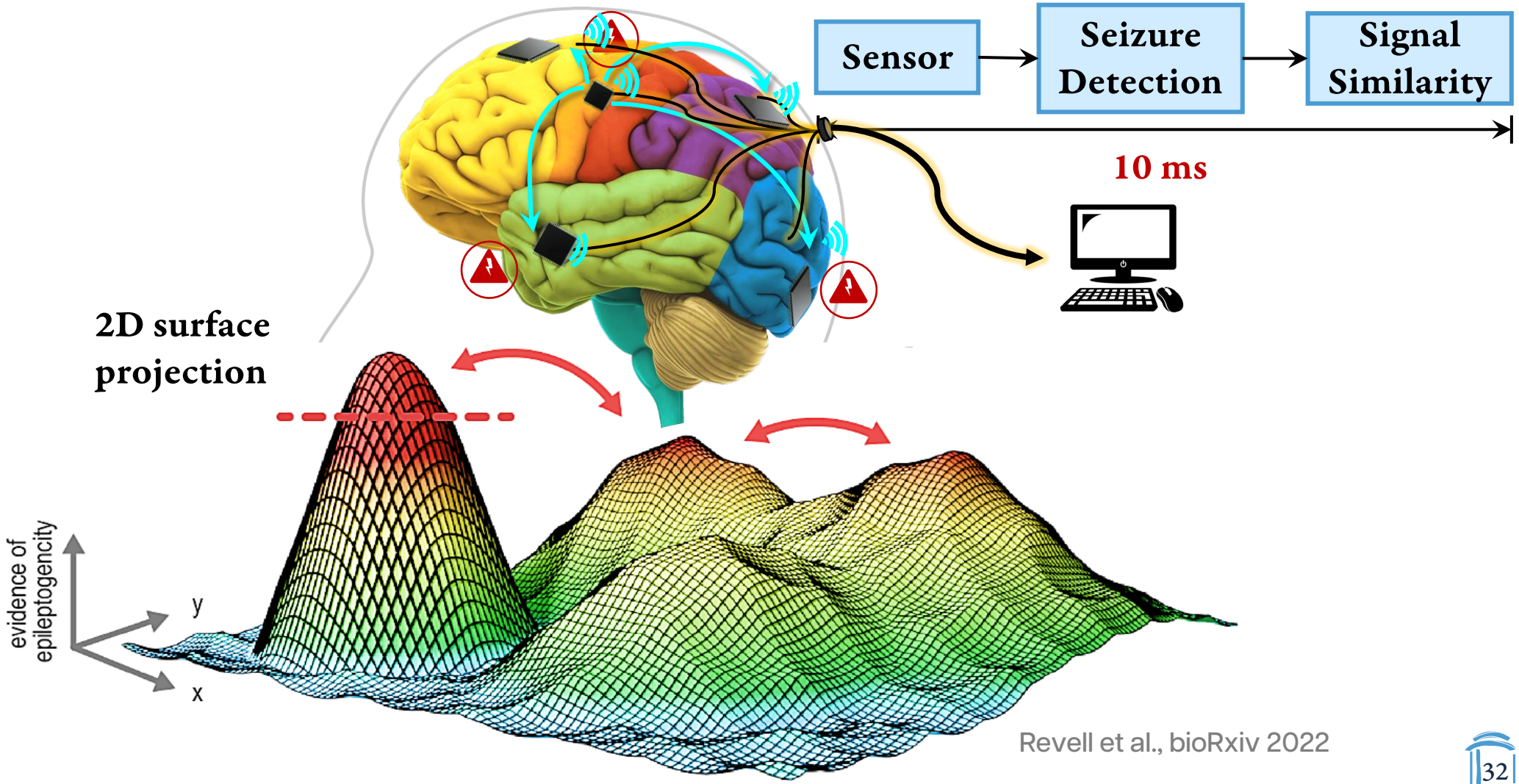
What Are The Computational Challenges?

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

BCI Applications

Distributed, on-device

Seizure network detection



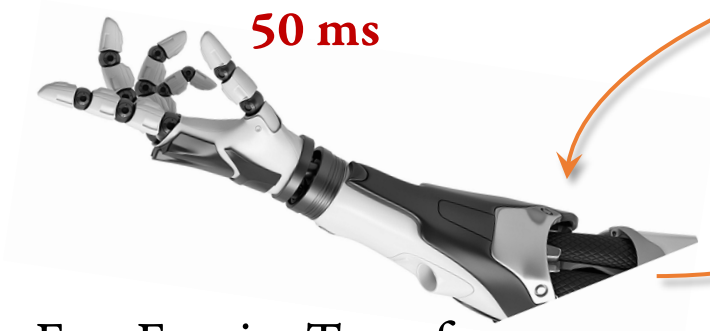
Revell et al., bioRxiv 2022

BCI Applications

Movement intent decoding

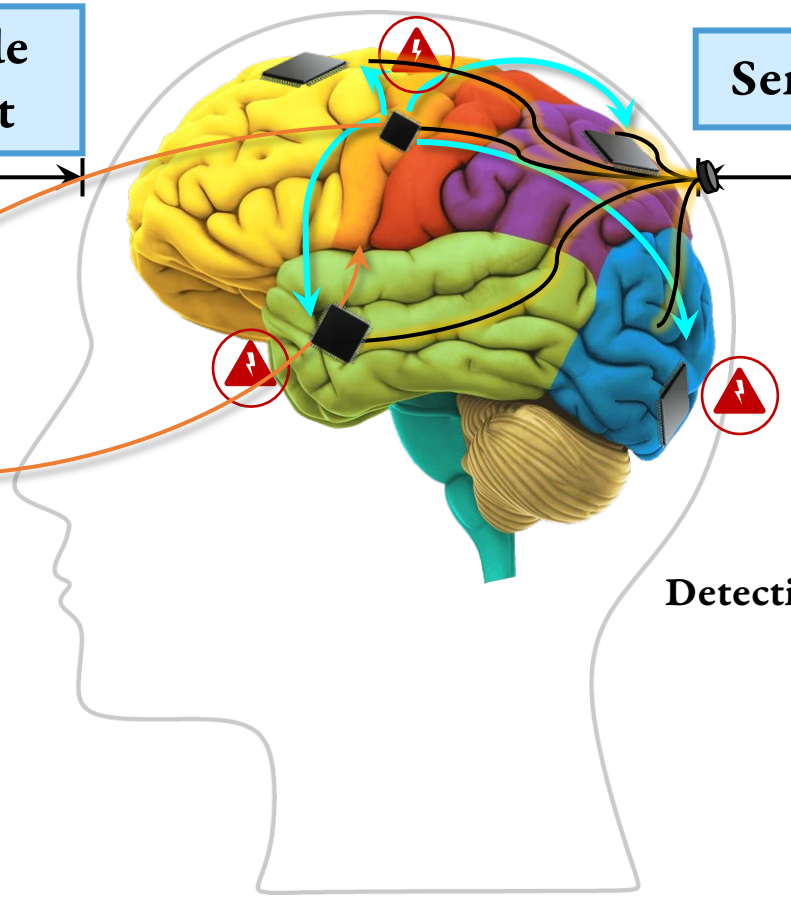
Sensor → Feature Extraction → Decode Intent

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, ...

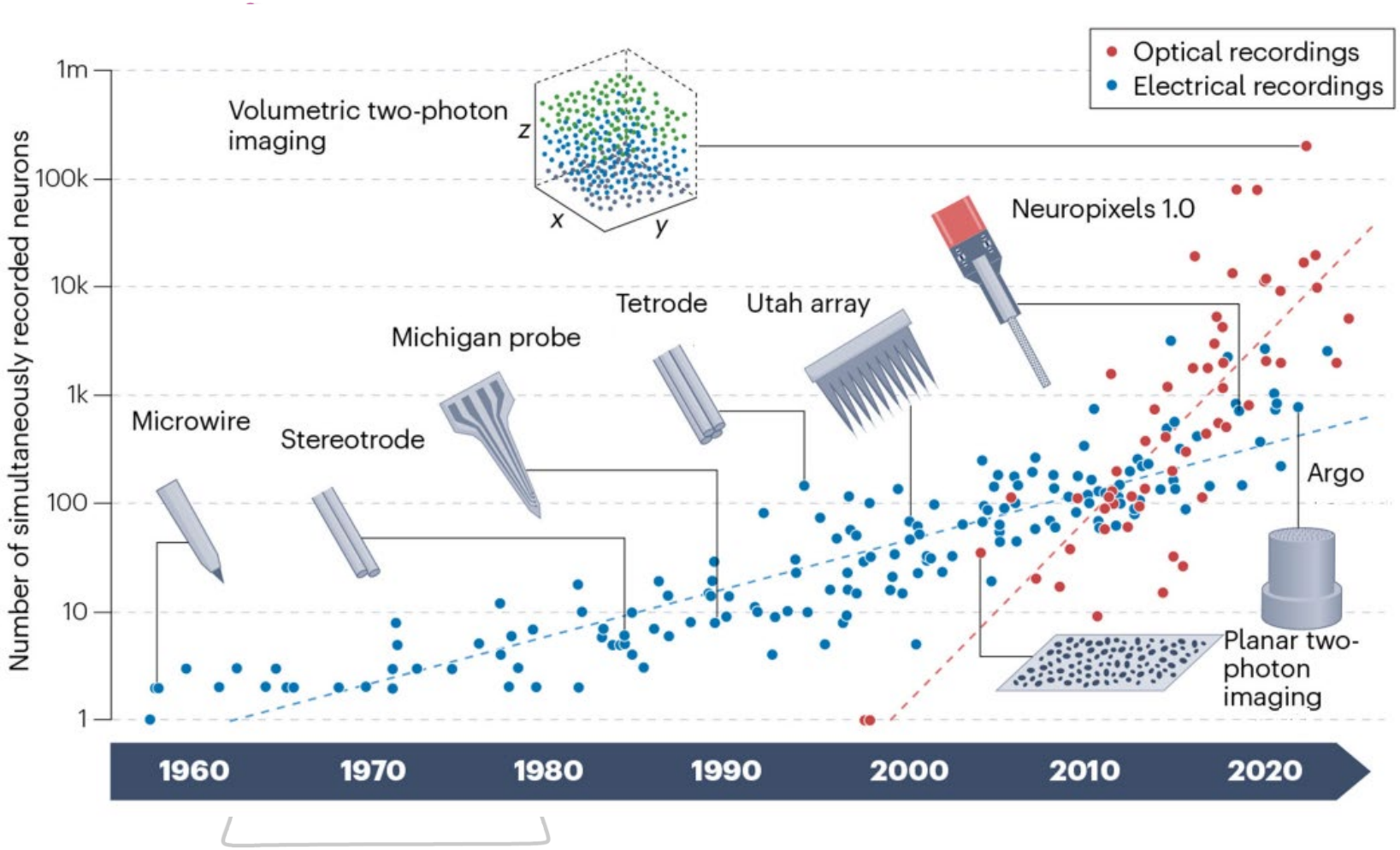
Similarity

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

Summary of Design Challenges

High Throughput

100-1000 Mbps

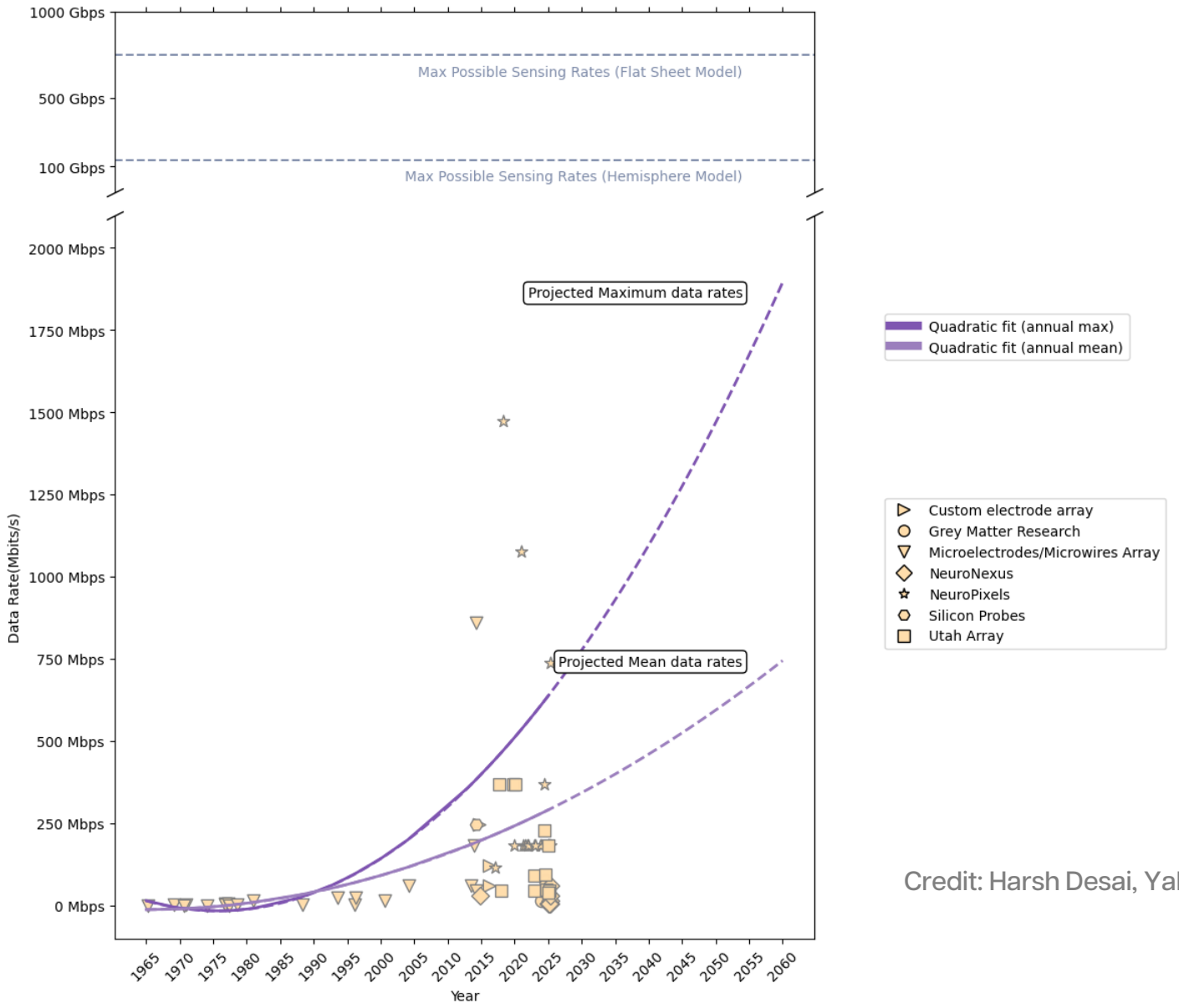


"Innovating beyond electrophysiology through multimodal neural interfaces"

Summary of Design Challenges

High Throughput

100-1000 Mbps



Credit: Harsh Desai, Yale

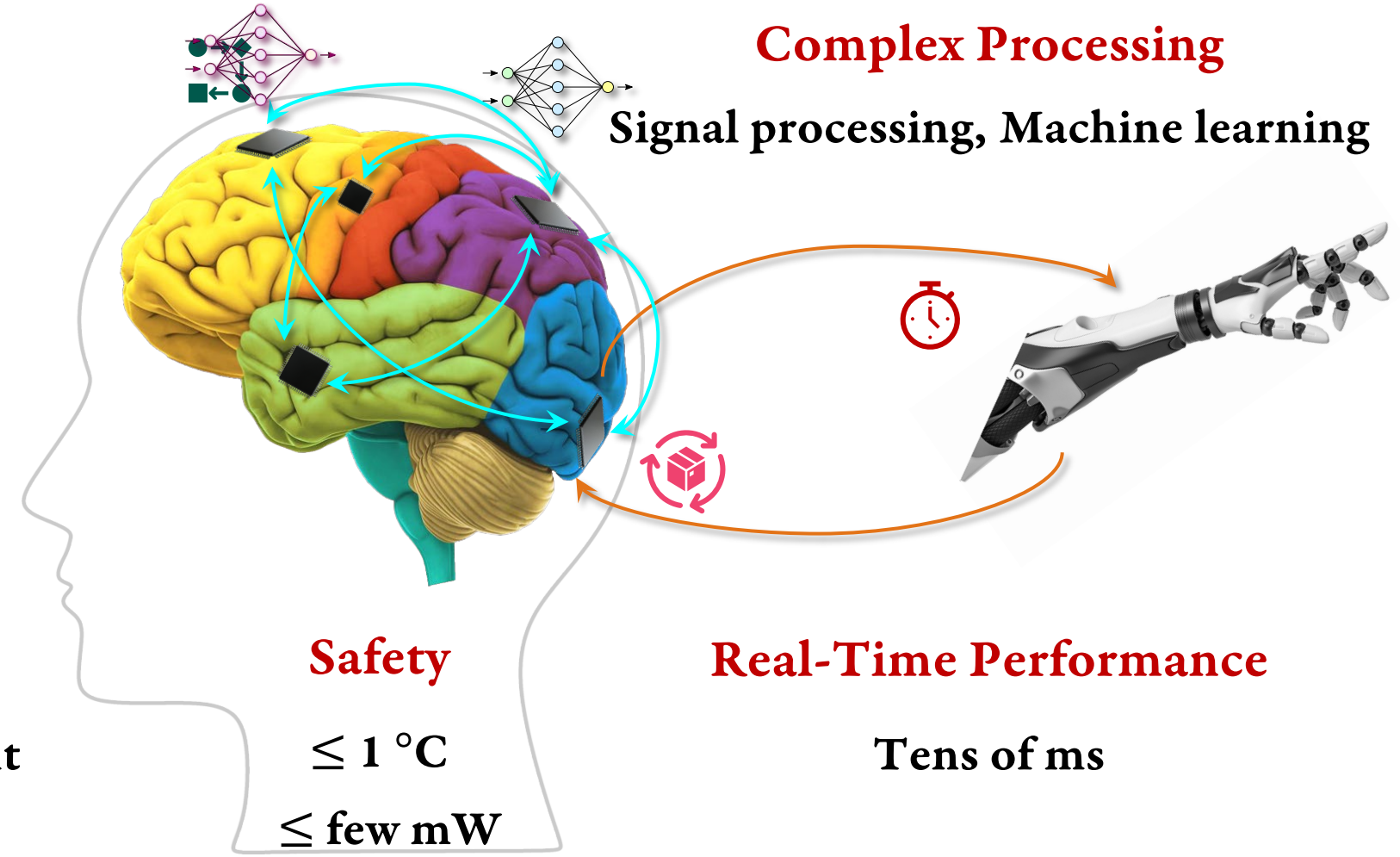
Summary of Design Challenges

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?

Neuralink…

Efficient but not flexible

Analogy: deliver a canned speech

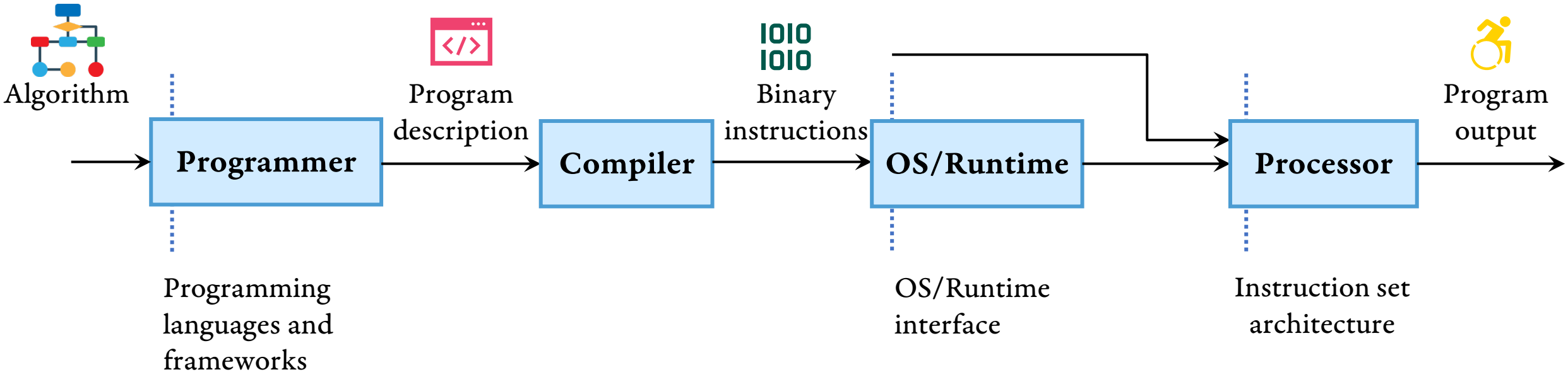
Low power CPUs/GPUs/FPGAs?

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

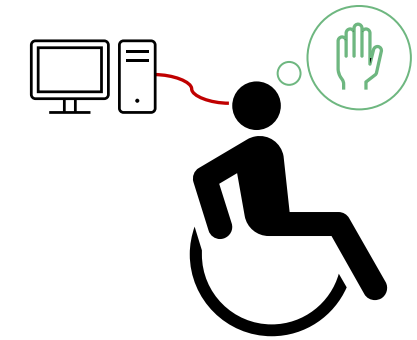


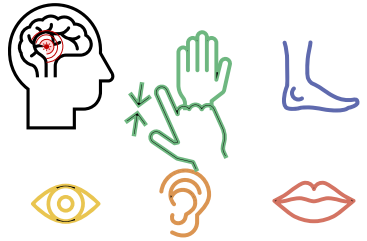
Revisit what abstractions, design, methods and implementations are ideal, and create new as needed

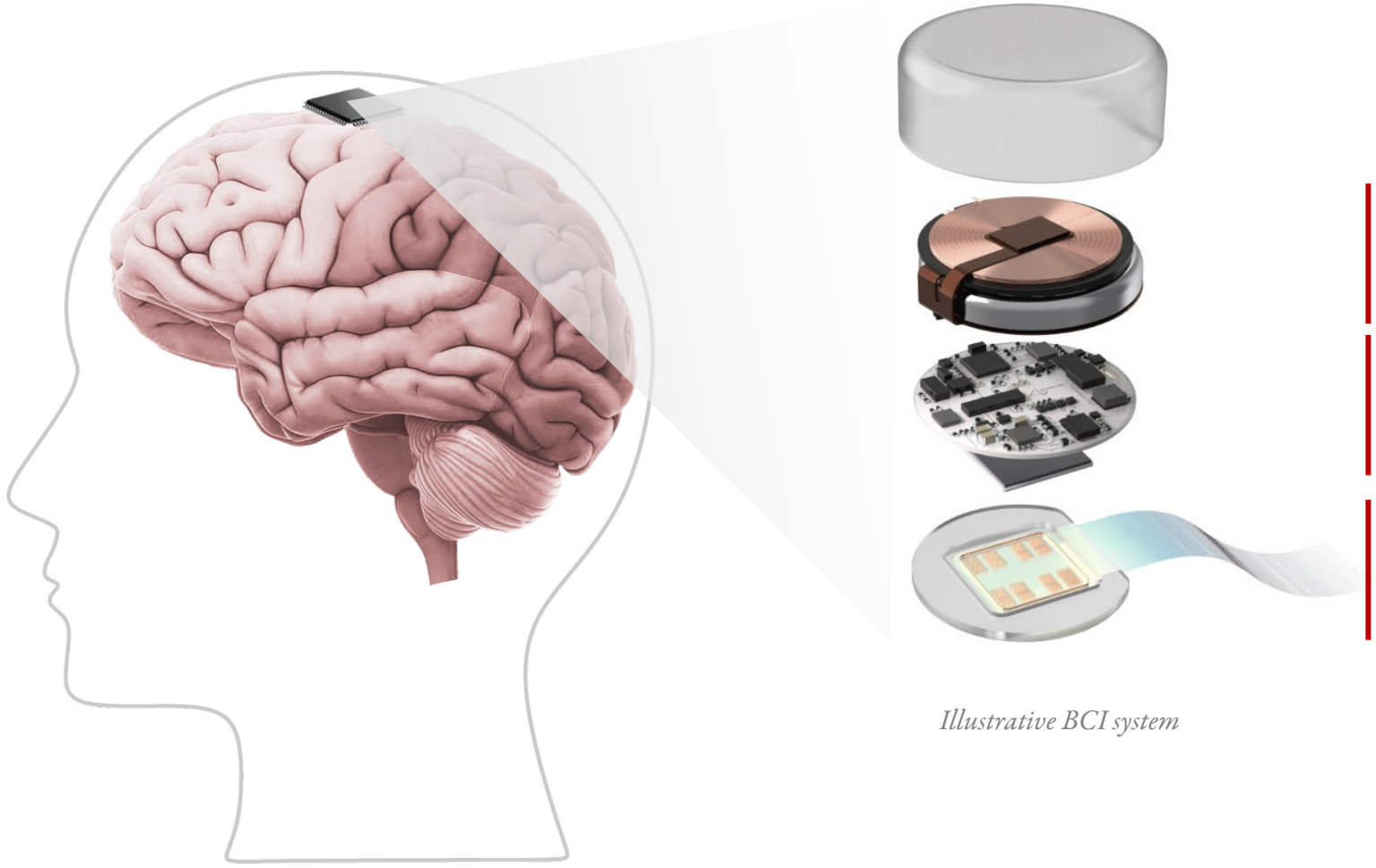
Co-design: Harmonious composition of the joint design of multiple components

What Happens Without Capable BCI Processing?

Lose autonomy **Lose functionality**







Battery, Wireless

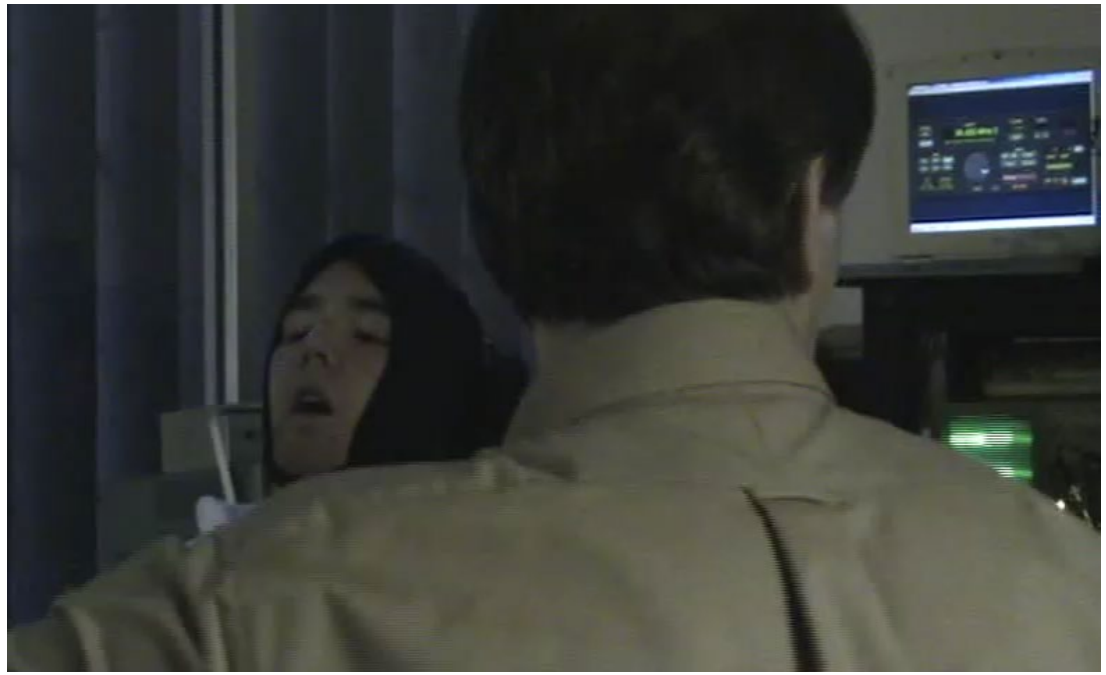
Processing **Inadequate**

Digitization

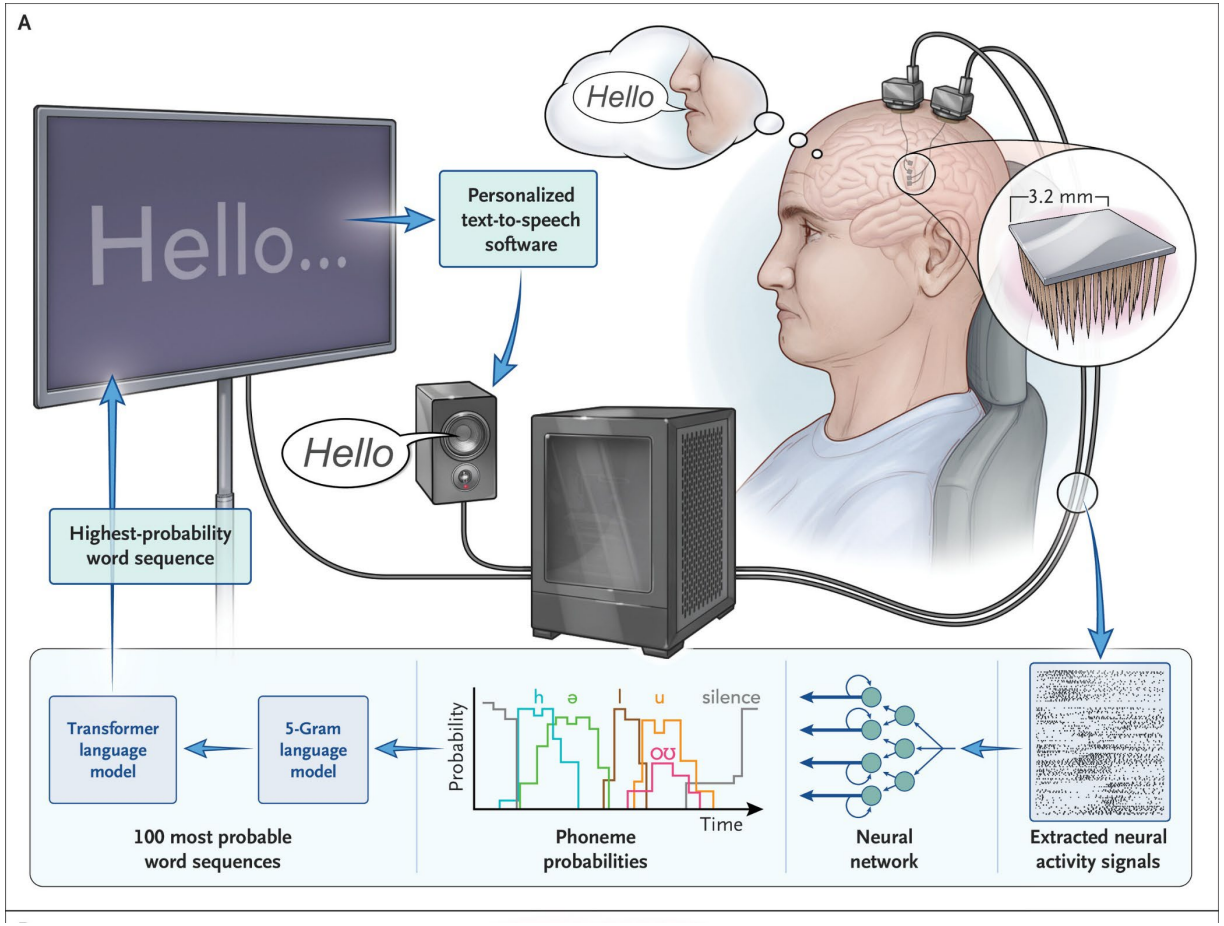
Electrodes

Illustrative BCI system

The Need for Computing in Perspective

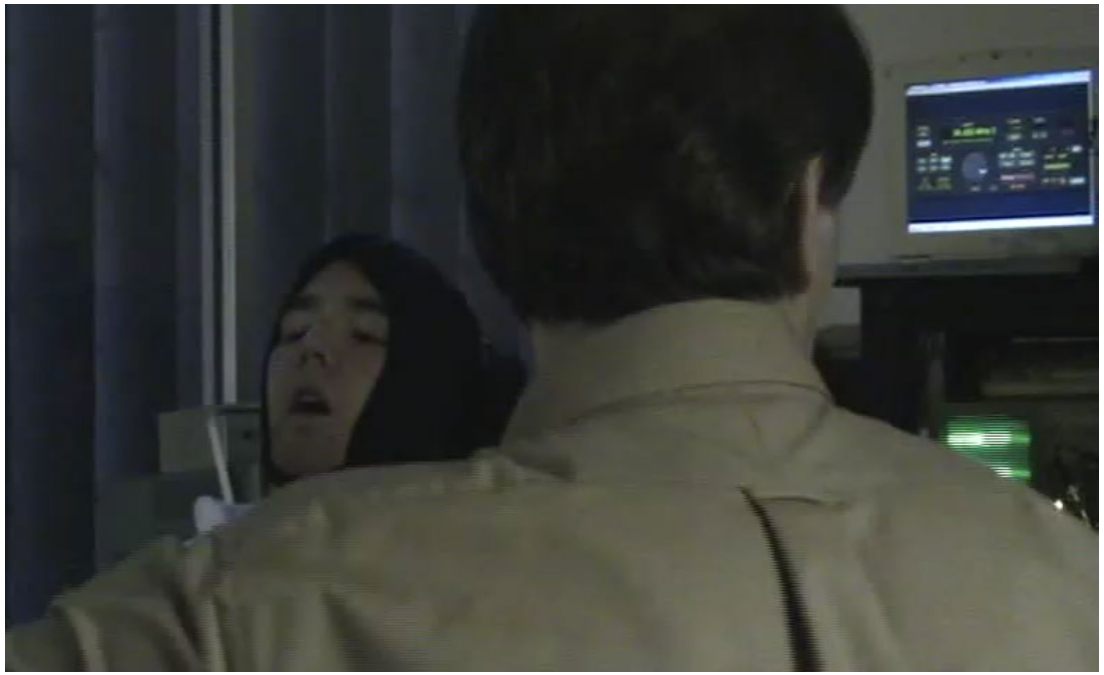


Phil Kennedy with patient Erik Ramsey, around 2004



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

The Need for Computing in Perspective



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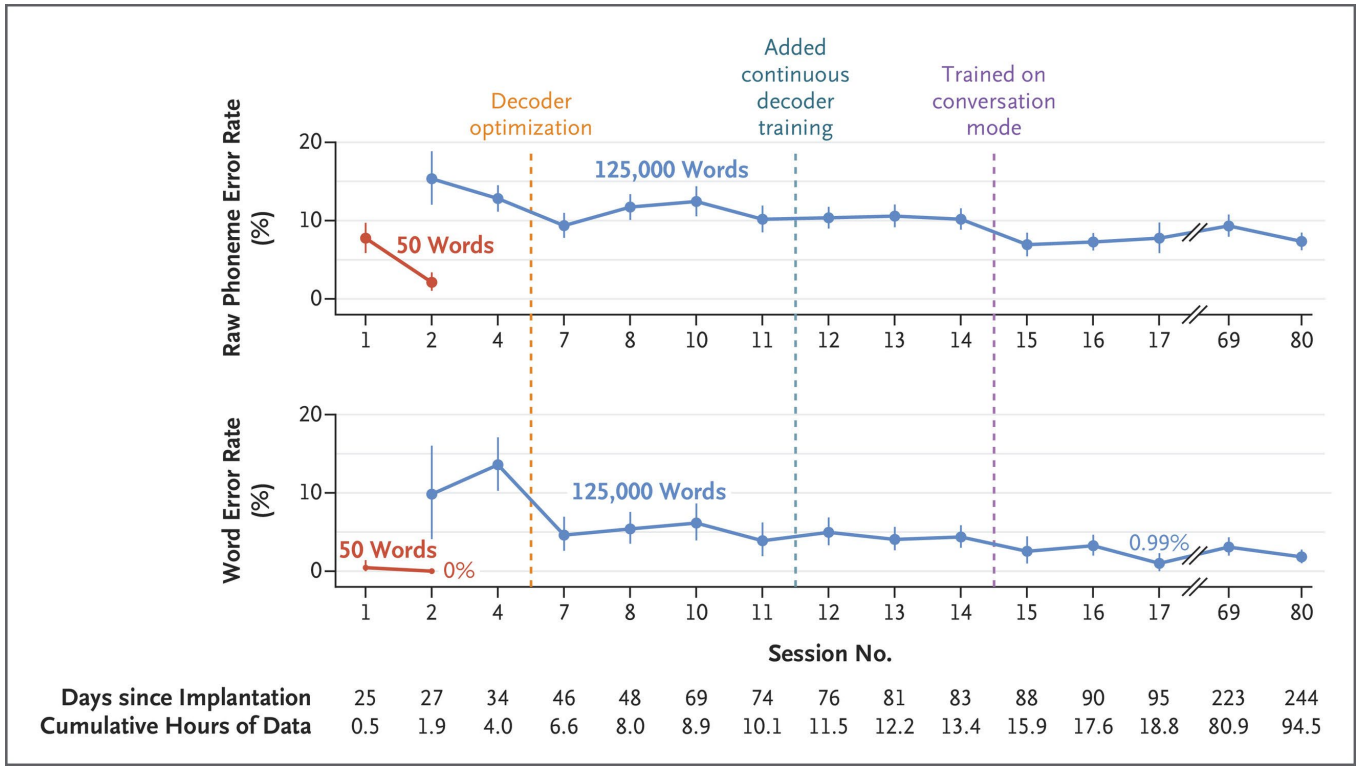
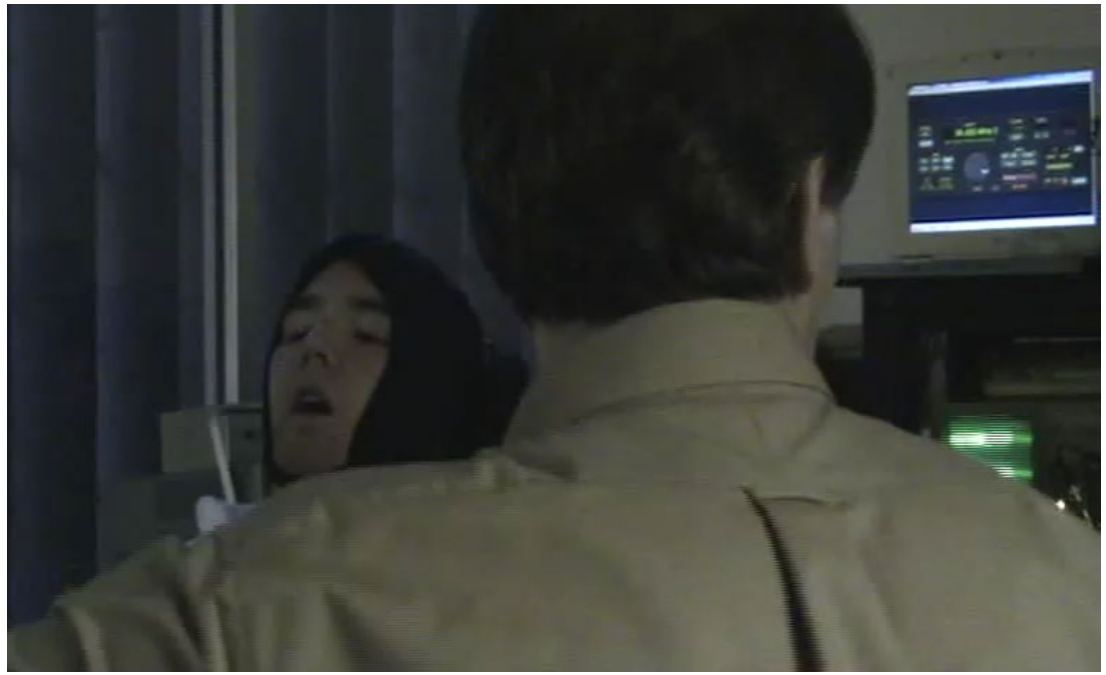


Running on "BRAND: a platform for closed-loop experiments with deep network models"

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

The Need for Computing in Perspective



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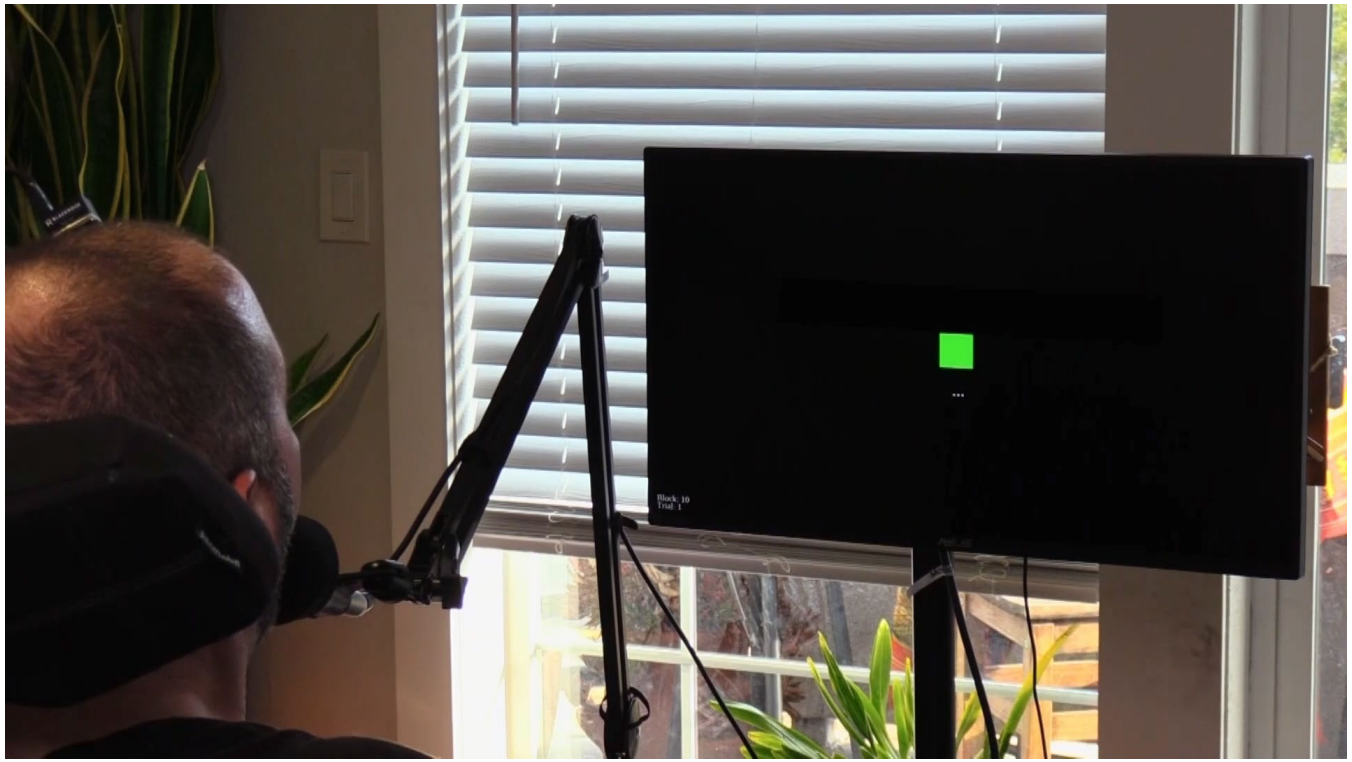

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The Need for Computing in Perspective

LOCAL NEWS

IBM's Smallest PC Designed In Triangle

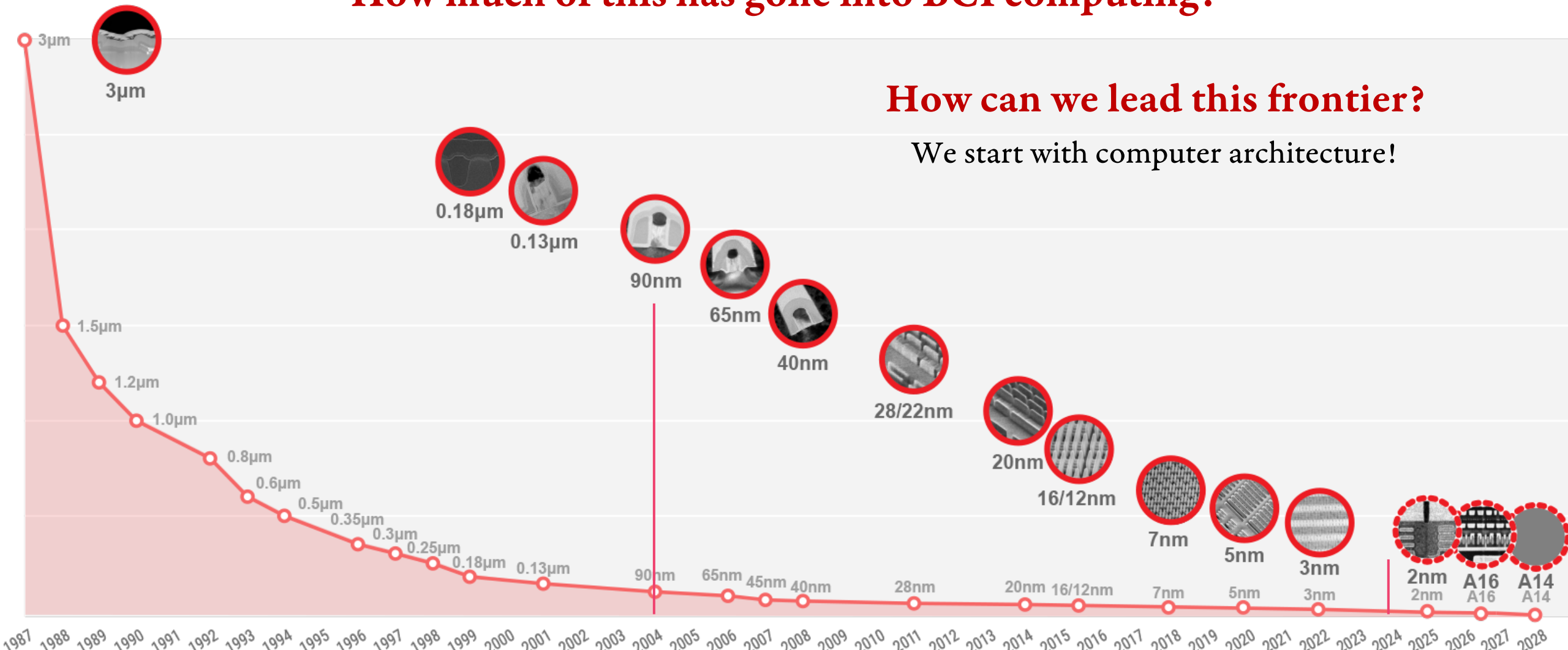
Posted 5:06 p.m. Aug 3, 2006 - Updated 5:16 a.m. Jun 11, 2004

"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 due on Gradescope by 1/16

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

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 on GradeScope on 1/16

Introductions!

Name

Grad/undergrad

Focus area

Why are you taking the course?

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- Infinite brain: Science wonder stories, May 1930, Illustrator: Frank R Paul, Editor: Hugo Gernsback
- Brain color, ICs, cloud server, black rat: No attribution required (Hiclipart)
- 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)