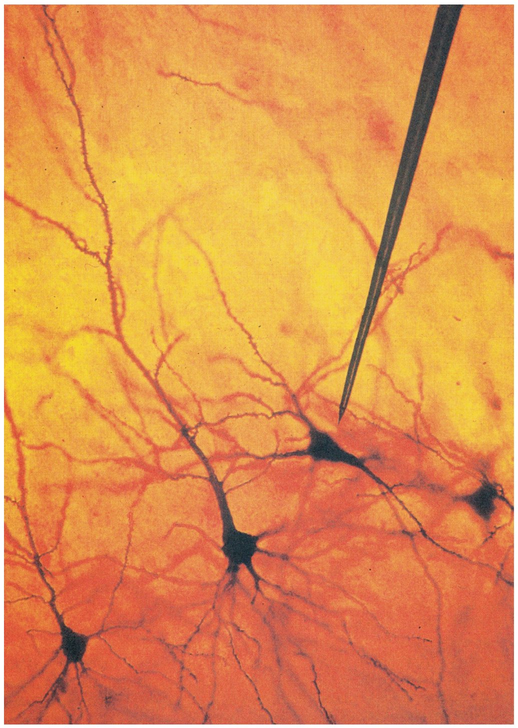
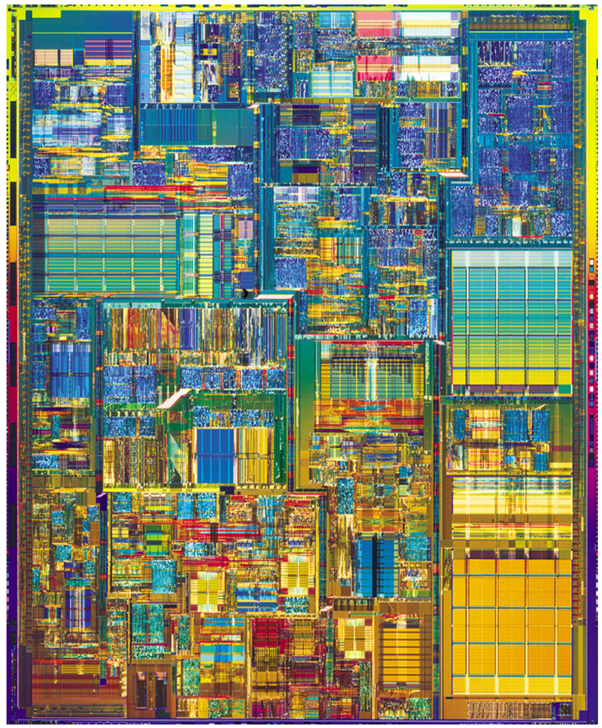
18-698 / 42-632 Neural Signal Processing



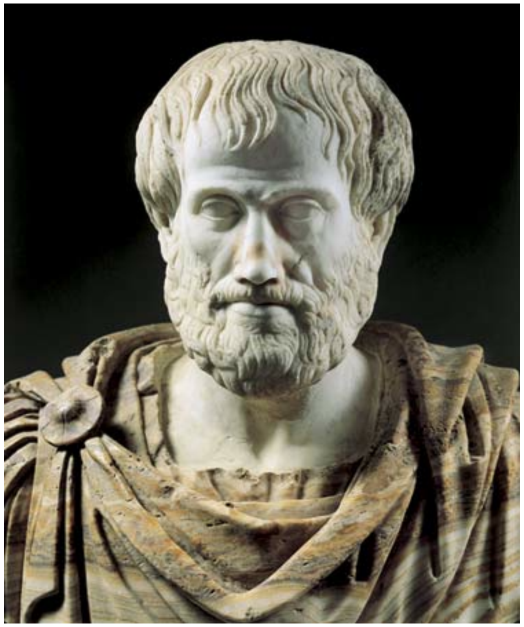


Prof. Byron Yu
Electrical & Computer Engineering / Biomedical Engineering
Carnegie Mellon University
Spring 2013

What is Neural Signal Processing?

For centuries, people have sought to understand what gives rise to our ability to perceive, to reason, and to act.

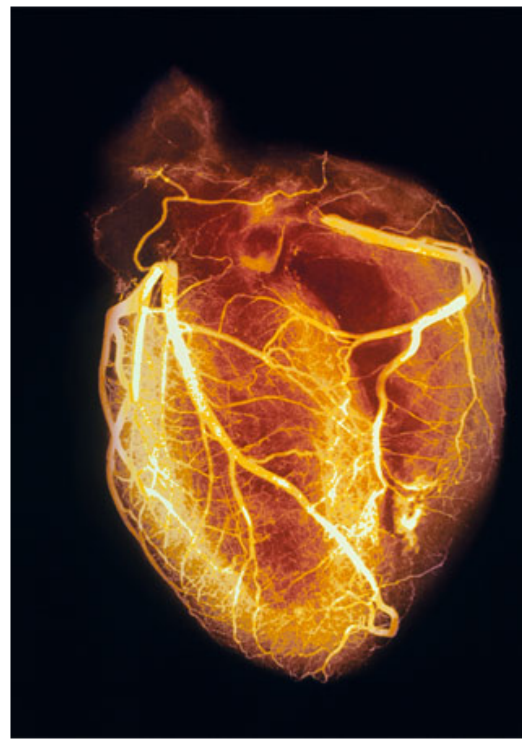
4th century BC: Aristotle identified the heart as the seat of intelligence and thought.



What is Neural Signal Processing?

We've learned a lot since then:

- It's the brain, not the heart.



http://science.nationalgeographic.com

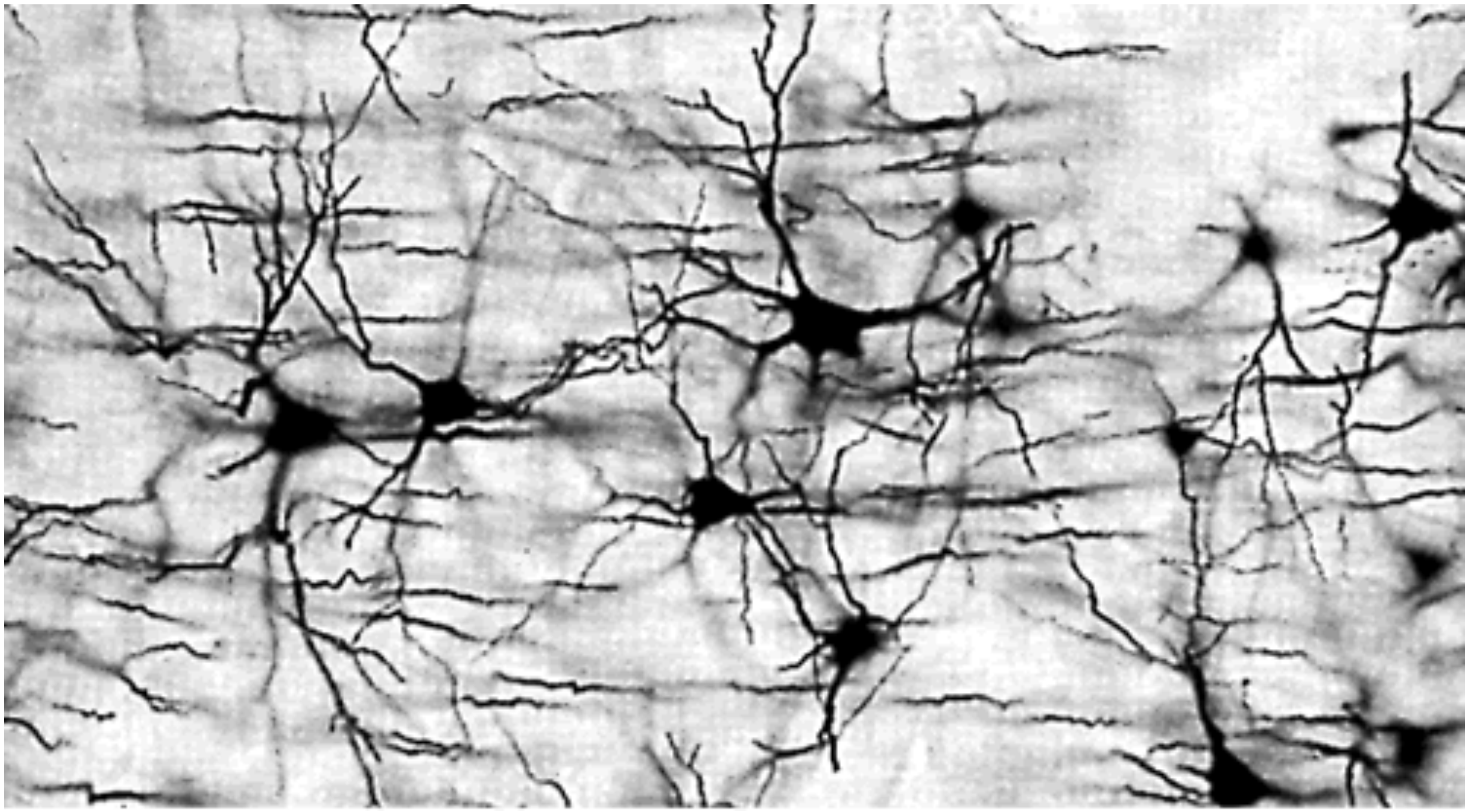
What is Neural Signal Processing?

- Nerves conduct electrical signals, rather than conveying fluids secreted by the brain.

http://science.nationalgeographic.com

What is Neural Signal Processing?

- Nervous system is a network of discrete cells called *neurons*, rather than a continuous web.



http://www.alanturing.net

Analogous to transistors

What is Neural Signal Processing?

There are many important neuroscience discoveries that I haven't listed here.

However, we're still only scratching the surface today. There's *way* more that we don't know about the brain than we do know.

How are we to further our understanding of the brain?

$\Rightarrow$ We must monitor the activity of its constituent elements: neurons.

Holy grail: Monitor the activity of every neuron in the brain.

What is the best that we can do today?

One end of the spectrum…

Single-electrode recordings

Pro: single-neuron resolution

Con: can only monitor one (or a small number of) neurons at a time

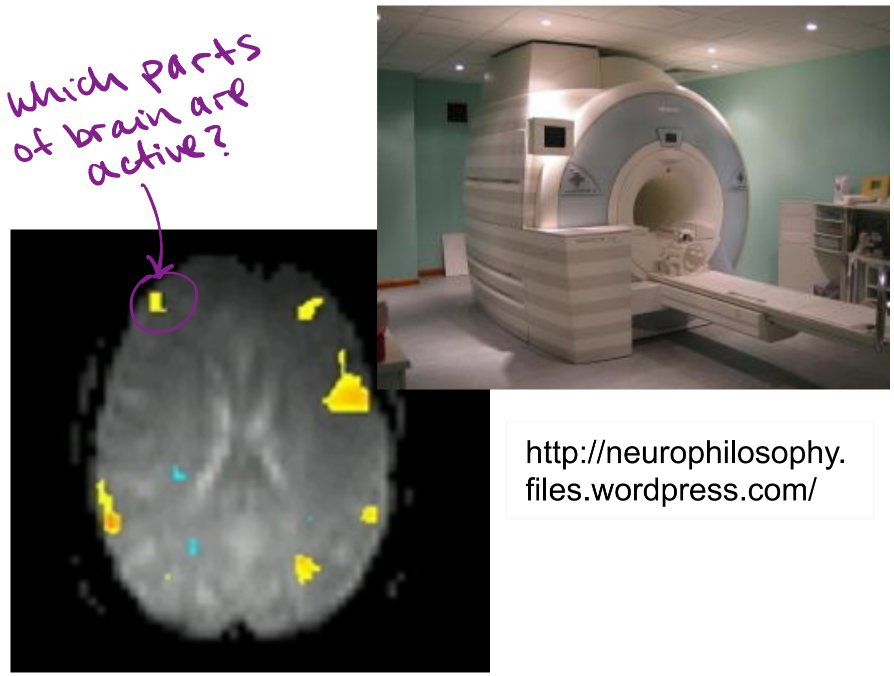
…the other end of the spectrum

Electroencephalography (EEG)

http://people.brandeis.edu/~sekuler

Functional magnetic resonance imaging (fMRI)

which parts of brain are active?



http://neurophilosophy.files.wordpress.com/

Pro: can monitor entire brain

Con: no single-neuron resolution

Different neural recording technologies: it's all about tradeoffs

Stadium analogy

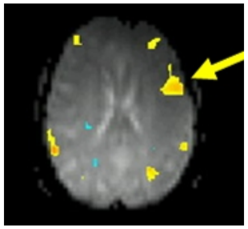
Stadium is the brain.
Each person is a neuron.

Stadium analogy

Single electrode recording is like
listening in to what <u>one</u> person is saying.

Stadium analogy

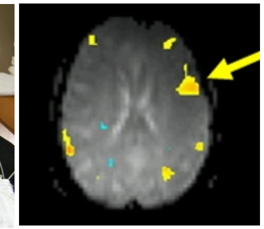
EEG and fMRI are like listening to the collective roar of the crowd.



Stadium analogy







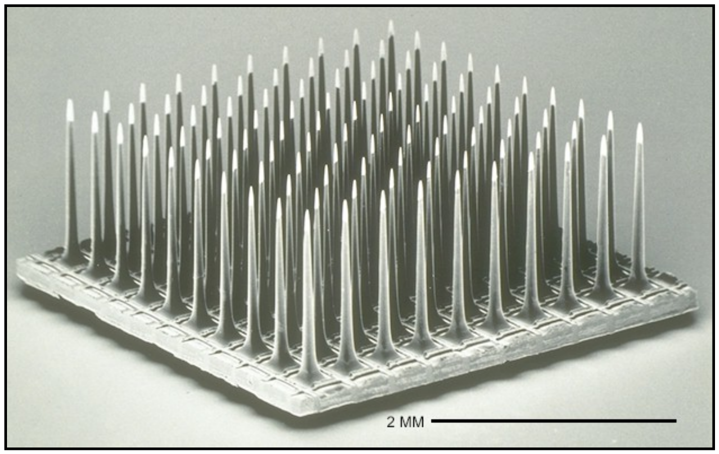

Stadium analogy

Ideally, we'd like to monitor what each individual person is saying.

More recent neural recording technologies

Only in last 15 years or so, we've been able to monitor many neurons at single-neuron resolution.

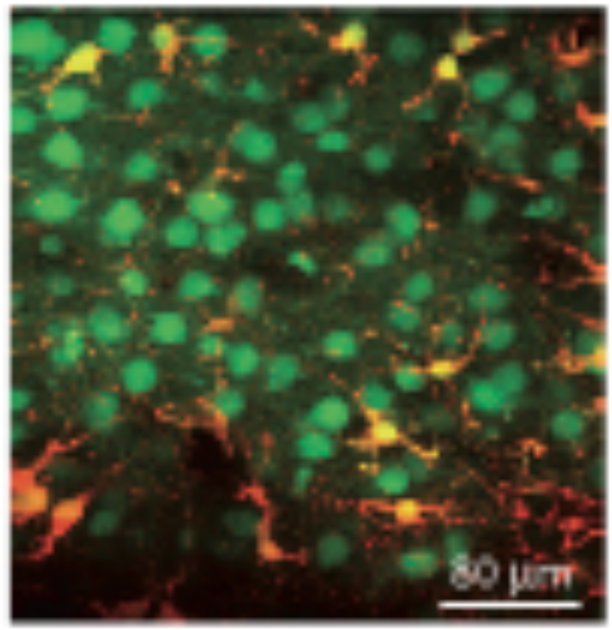
Multi-electrode arrays



~100 electrodes at a time

Cyberkinetics, Inc

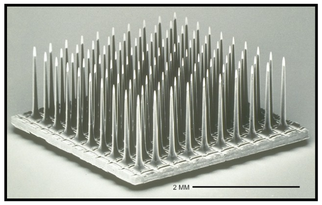
Optical imaging



inject dye into each neuron, when activates it changes fluorescence

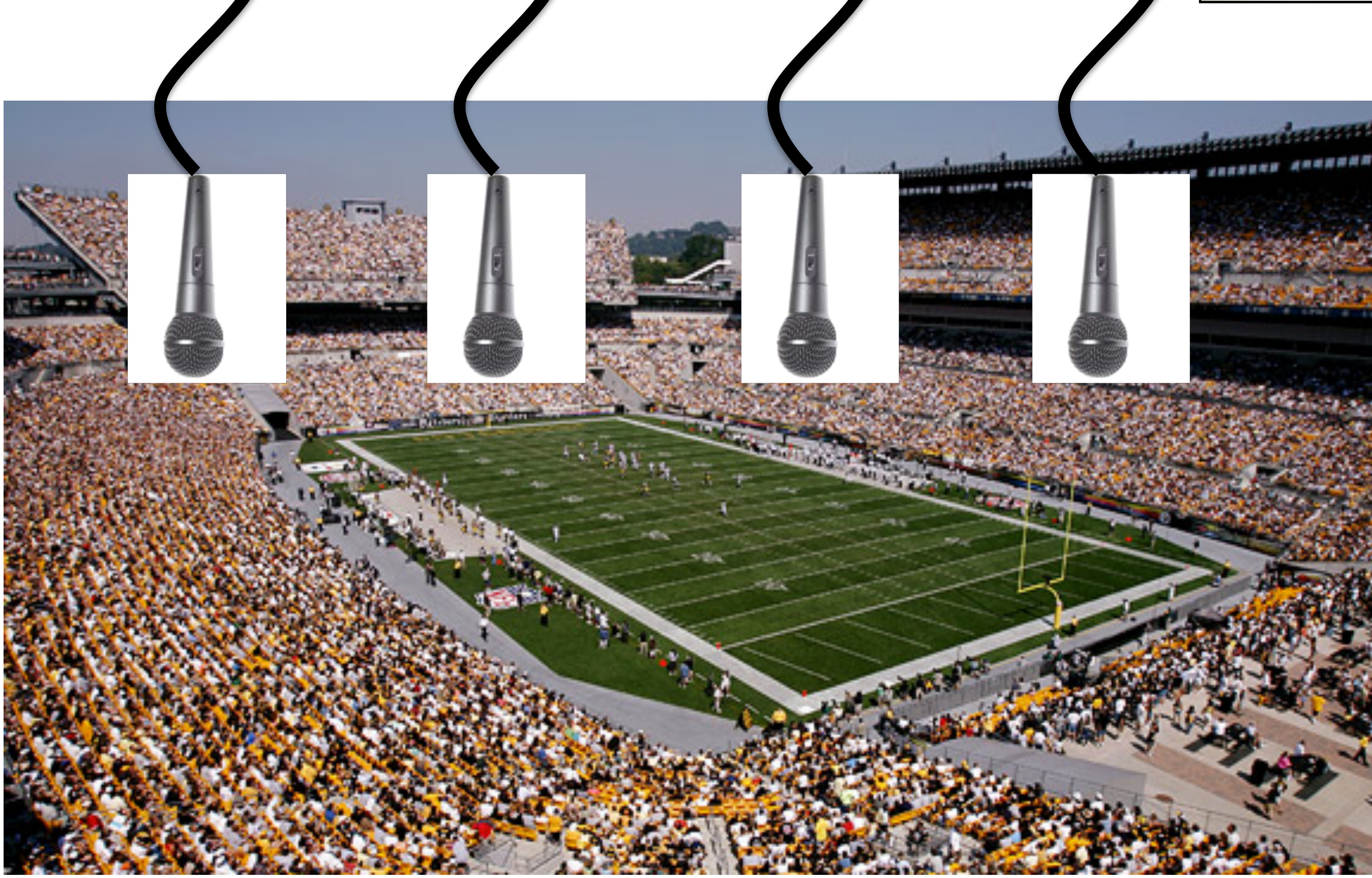
Kerr and Denk, 2008.

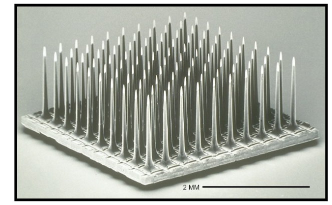
Stadium analogy



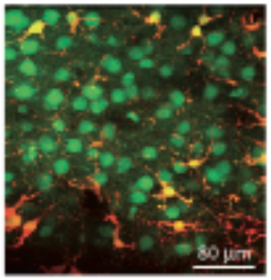
Multi-electrode array recording is like listening in on <u>multiple</u> <u>individual</u> conversations.

Stadium analogy



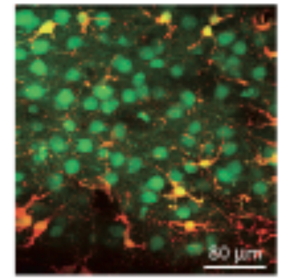


Stadium analogy



Optical imaging is like watching multiple individual mouths moving, from which we can deduce what each person is saying.

Stadium analogy



What is Neural Signal Processing?

Technologies like multi-electrode arrays and optical imaging are providing unprecedented views of the brain's activity.

Even though we're far from monitoring every neuron in the brain, we now have more data than we know what to do with it.

We need powerful statistical methods to make inferences about what the brain is doing from sparse sampling.

What is Neural Signal Processing?

What we have

Novel experimental paradigms

animals & humans
fancy tasks

New neural recording technologies

EEG, arrays, fMRI, etc...

Huge and rich data sets

Goals

Further our basic understanding of brain function

Develop biomedical devices that interface with the brain

Missing link

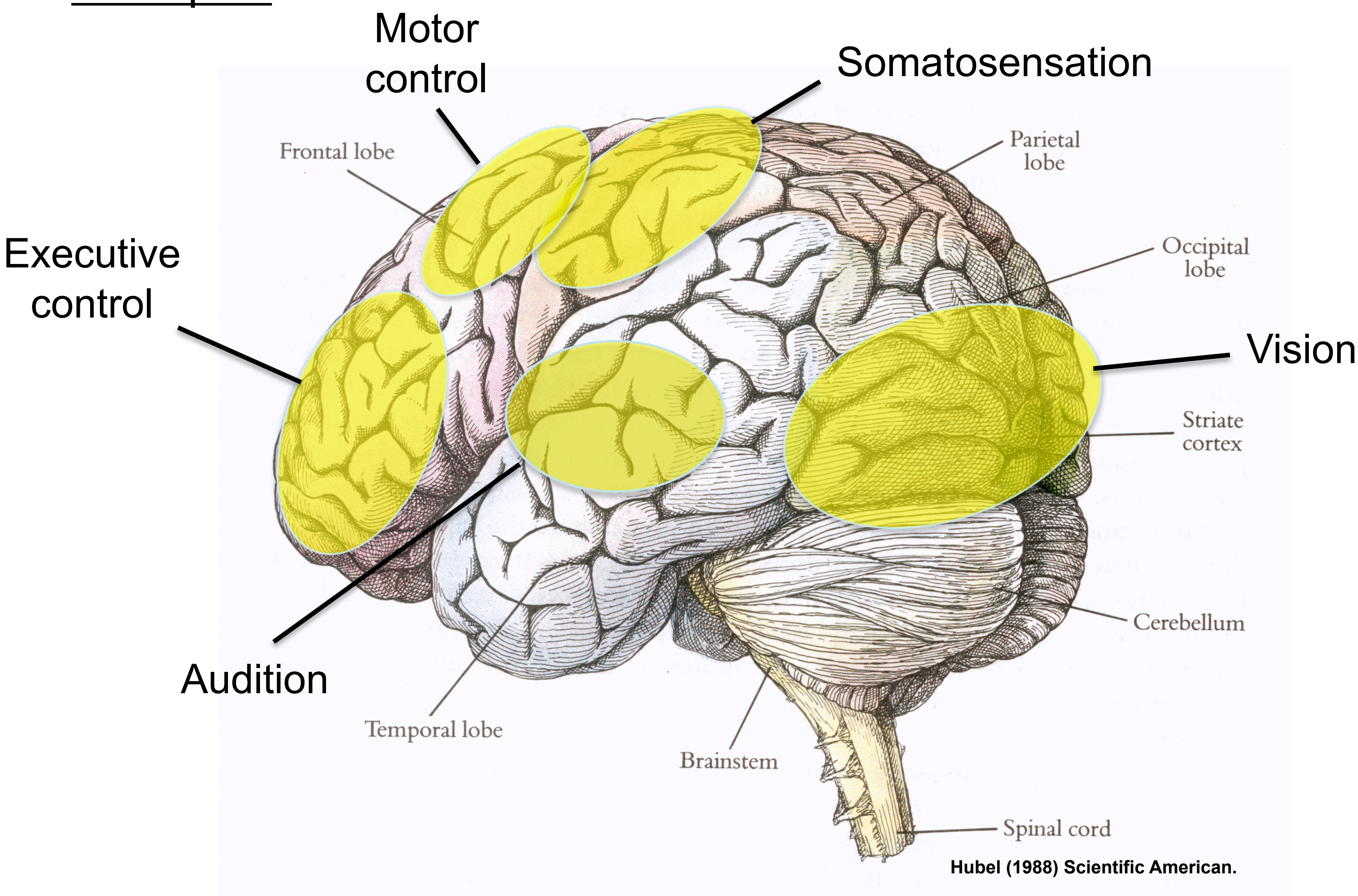
Signal processing methods appropriate for neural data

Creative ways of extracting meaningful features from huge data sets

Topic of this course!

Further our basic understanding of brain function

Examples:



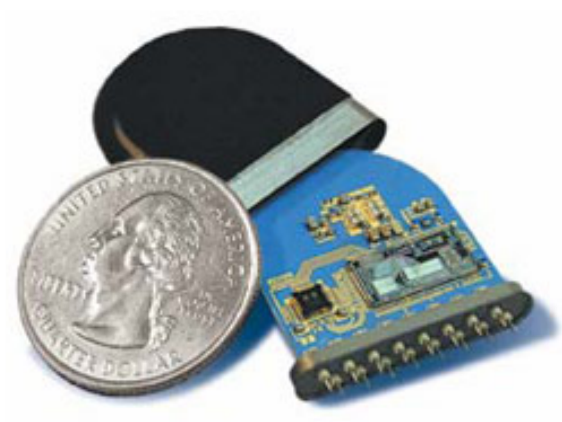
Develop biomedical devices that interface with the brain

Examples:

Deafness

Cochlear implants

Captures sounds to stimulate auditory nerve



Advanced Bionics Corp.

Motor disorders (Parkinsons)

Deep brain stimulation

Pass small current to deep part of brain, able to make coordinated movements

Medtronic, Inc.

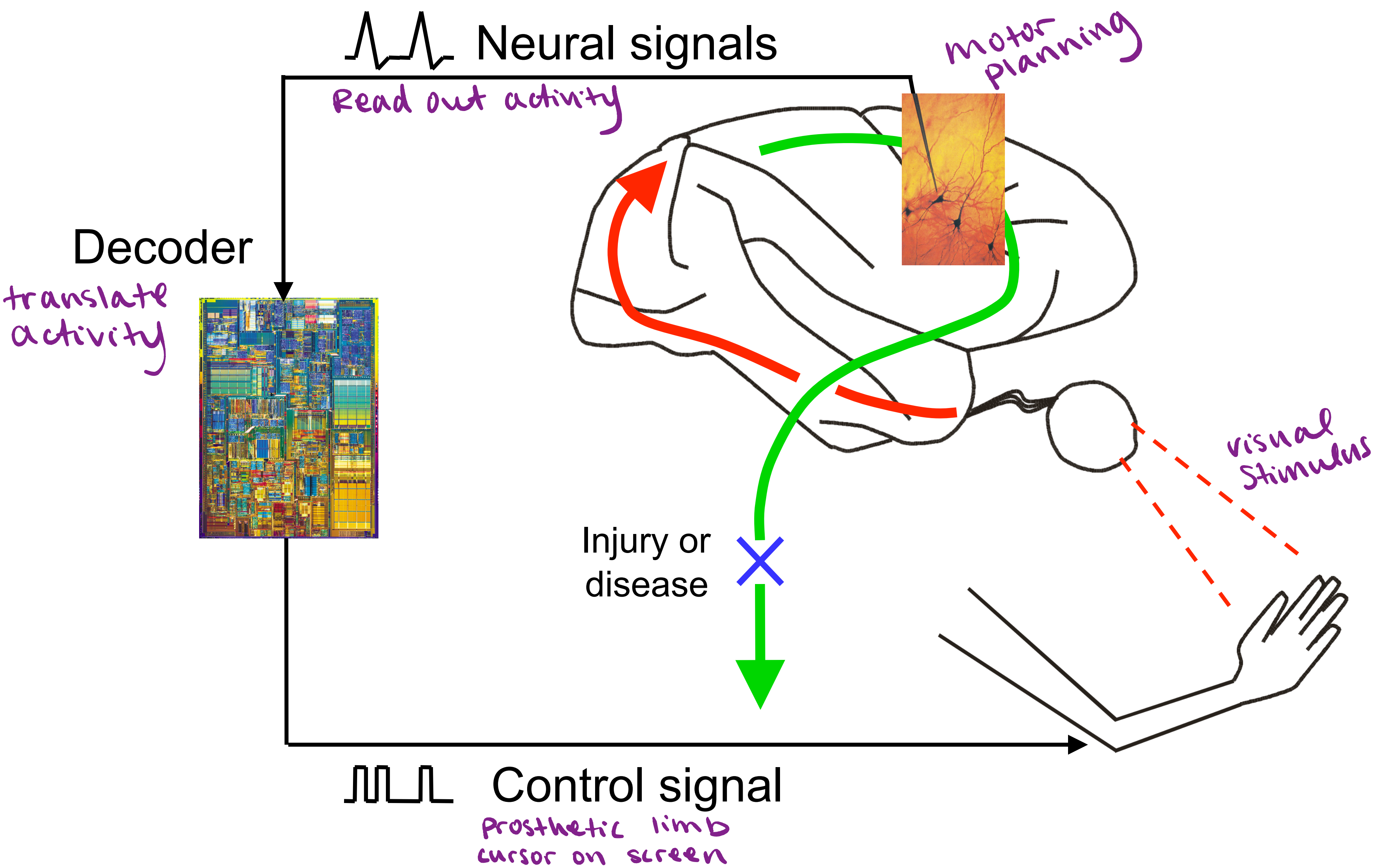
Paralysis

Motor prostheses

Read out neural activity & transfer to prosthetic

Cyberkinetics

Neural prosthetic systems



Motor prostheses

Ultimately, we want to help human patients.

Cyberkinetics, Inc.

Motor prostheses

Basic research on prosthetic systems is done with monkeys.

Schwartz Lab, U Pitt

Motor prostheses

There is still much work to be done to get decoded movements to rival natural movements.

Monkey **hand-controlling**
a virtual cursor

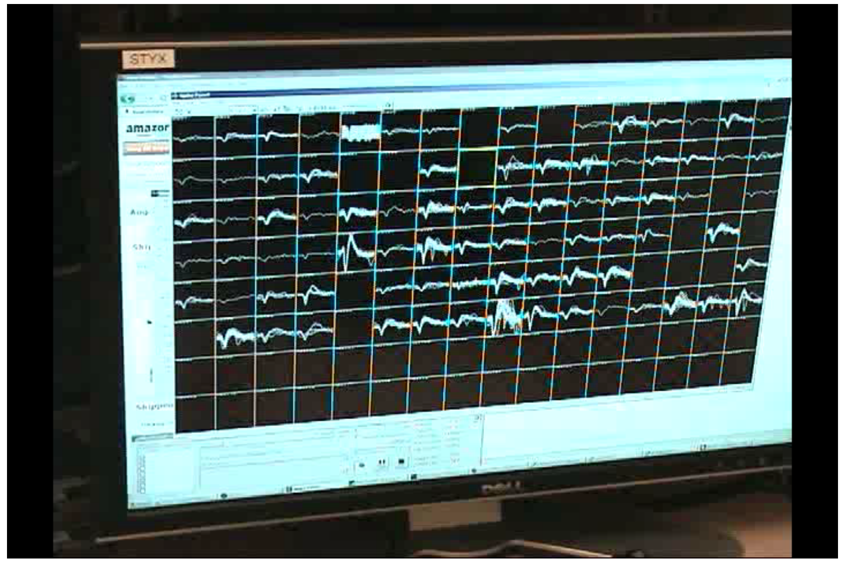
Credit: Churchland, Kaufman, Shenoy

Motor prostheses

There is still much work to be done to get decoded movements to rival natural movements.

Monkey **hand-controlling**
a virtual cursor

Credit: Churchland, Kaufman, Shenoy



Monkey **brain-controlling**
a virtual cursor

Credit: Chestek, Gilja, Nuyujukian, Cunningham, Shenoy

Why this course is timely

- Neuroscience, as a field, used to be data-limited. Although more data is always nice, we're rapidly becoming limited by the available signal processing methods.

- CMU and Pitt together form a neuroscience hotbed. There are over 100 faculty members across the two universities that work on neuroscience-related topics. You are at the center of the action!

Syllabus

Course staff

Instructor: Byron Yu

byronyu@cmu.edu
(412) 268-9658
B204 Hamerschlag Hall
Office hours: Tues / Thurs 3-4pm

About me

- Undergraduate in Electrical Engineering and Computer Sciences at UC Berkeley

  (didn’t take a single biology class there)

- Graduate school in Electrical Engineering at Stanford

  (research group included neuroscientists and engineers; did neural recordings and worked with animals)

- Post-doc at Stanford and UCL

  (experimental / computational collaboration)

- Started at CMU in January 2010

Syllabus

Course goals:

(1) to introduce the statistical tools used to study large-scale neural activity

(2) to bring out the real-world challenges of working with experimental data

By the end of the course, students should be able to ask research-level questions in neural signal processing, as well as develop new statistical tools for problems in their own research. In short, this course serves as a stepping stone to research in neural signal processing.

Syllabus

<u>Course outline</u>:

<u>Motivation</u>: doing neural signal processing requires some intuition for how neural signals are generated and how neurons communicate with each other.

First ~~3~~ 2 weeks -- basic neuroscience from the ground up

Rest of course – signal processing and machine learning methods as applied to neural signals

Note: First 3 weeks is not representative of rest of course, which is quite mathematical.

If you're already familiar with basic neuroscience, hold tight for first 3 weeks!

Syllabus

Course outline:

1. What is neural signal processing?

2. Neuroscience basics. Membrane potential. Action potential. Synaptic transmission.

3. Spike train analysis. Spike histogram. Tuning curve. Poisson process.

4. Classification. Naive Bayes.
Neuroscience application: discrete neural decoding

5. Graphical models.

6. Mixture models. Expectation-maximization.
Neuroscience application: spike sorting

Syllabus

Course outline (cont):

7. Model selection. Cross-validation.
   Neuroscience applications: spike sorting, dimensionality reduction

8. Principal components analysis. Factor analysis.
   Neuroscience applications: spike sorting, dimensionality reduction

9. Kalman filter.
   Neuroscience application: continuous neural decoding

Syllabus

Prerequisites:

This course is ideally suited for students with a solid background in basic probability and linear algebra. Prior knowledge of neuroscience is welcome, but not required.

Students should already be familiar with concepts such as:

Probability -- independence, conditional probability, Bayes rule, multivariate Gaussian distribution, Poisson distribution, Poisson process

Linear algebra -- basic matrix operations (sums and products), matrix inversion, eigenvectors and eigenvalues, singular value decomposition

For those unfamiliar with the concepts above, I would recommend Probability Theory and Random Processes (36-217).

If you are unsure whether this class is for you, please talk with me.

update yourself on these concepts

Syllabus

<u>Prerequisites</u>:

You should be comfortable using Matlab.

Syllabus

Relationship to other courses:

Machine Learning (10-601 and 10-701)

If you've taken Machine Learning already, Neural Signal Processing should be sufficiently different that it could be worth taking. Even if it may be the same textbook, many of the chapters are non-overlapping. Most of my examples will come from neuroscience.

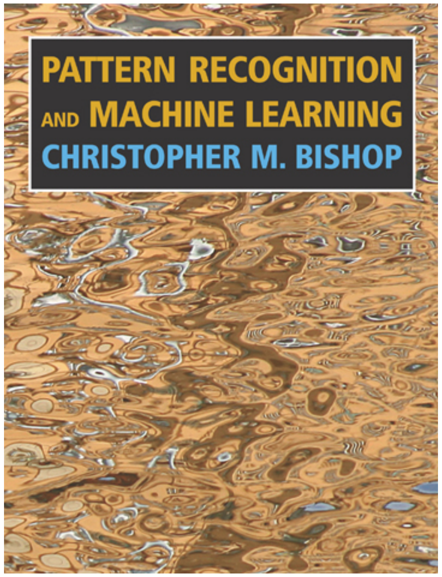
Neural Data Analysis (42-699B / 86-595)

Neural Signal Processing is a natural follow-up course after Neural Data Analysis, although I will not assume that you've taken Neural Data Analysis.

Syllabus

Required textbook:

Pattern Recognition and Machine Learning
Christopher Bishop. Springer, 2006.

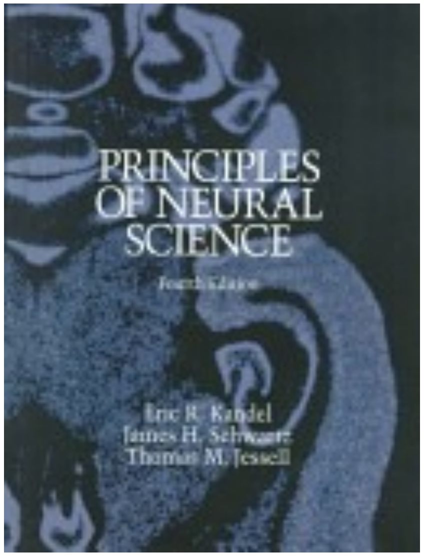


Syllabus

<u>Optional textbooks</u>:

Principles of Neural Science
Eric Kandel, James Schwartz, Thomas Jessell.
McGraw-Hill Medical, 2000.
Available at bookstore.

I will be photocopying sections of PNS needed for the course, but I highly recommend that you buy the book, especially if you plan to continue in neuroscience. This is the definitive neuroscience textbook and reference.



Syllabus

<u>Optional textbooks</u>:

Theoretical Neuroscience
Peter Dayan and L.F. Abbott. MIT Press, 2001.
Chapter 1 will be made available to you electronically.

Information Theory, Inference, and Learning Algorithms
David J.C. MacKay. Cambridge University Press, 2003.
Entire book is available online at:
http://www.inference.phy.cam.ac.uk/mackay/itprnn/ps/

Matlab for Neuroscientists
Pascal Wallisch, Michael Lusignan, Marc Benayoun, Tanya I. Baker,
Adam S. Dickey, and Nicholas G. Hatsopoulos. Academic Press, 2009.

Syllabus

Assignments and exams:

There will be approximately 9 problem sets during the semester and regular reading assignments.

Thursday, March 3

Midterm exam: in class on ~~**Thursday, March 7**~~.
Final exam: week of May 6-14, date TBD.

Most problem sets will have a Matlab component, in which students will implement various algorithms and apply them to neural data. Matlab is available on most campus machines and can be downloaded for free by CMU students.

Students may discuss problem sets, but each student must turn in his/her own work. *You may not simply copy another student's work*. All students are bound by the CMU Academic Integrity Code.

Late policy for problem sets: Each student is allowed two late problem sets during the semester (up to 24 hours after the deadline to ECE Course Hub). Problem sets that are turned in outside of this grace period will receive zero credit.

Syllabus

<u>Grading breakdown</u>:

Problem sets	30%
Midterm exam	30%
Final exam	40%

You are encouraged to speak up in class and ask questions!

Course Feedback

• This is the fourth time this course is offered.

• I welcome any feedback you might have about how this course is taught.

• Feel free to send me email or talk with me.