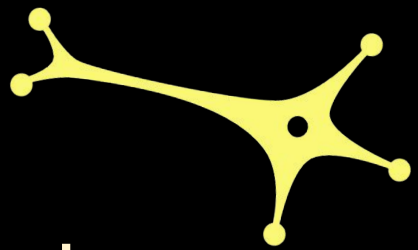


Neural Interfaces and How They Use Signal Processing

Sarah Felix

May 12, 2016

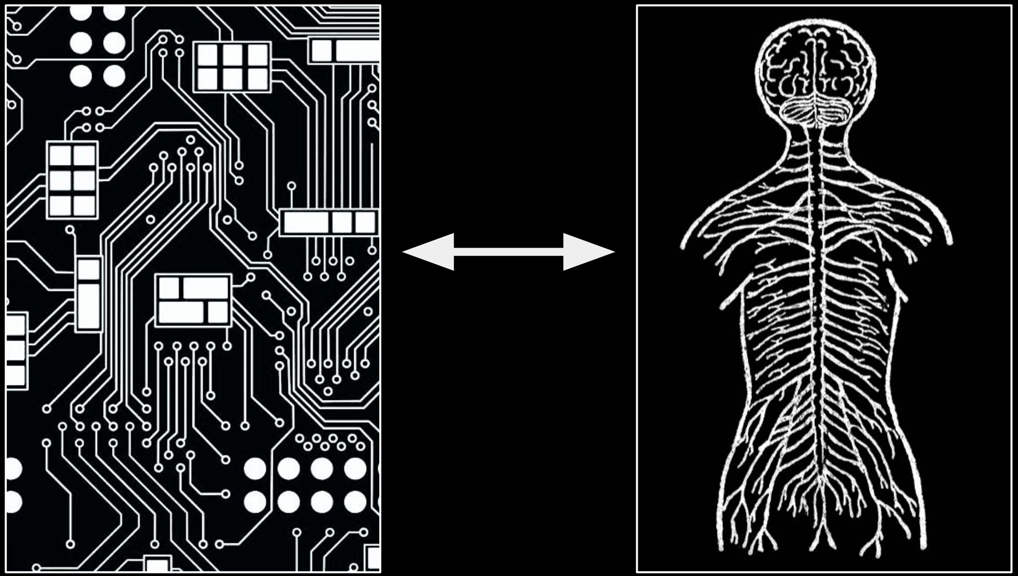
IEEE Signal Processing Society, Santa Clara Chapter Event

Outline

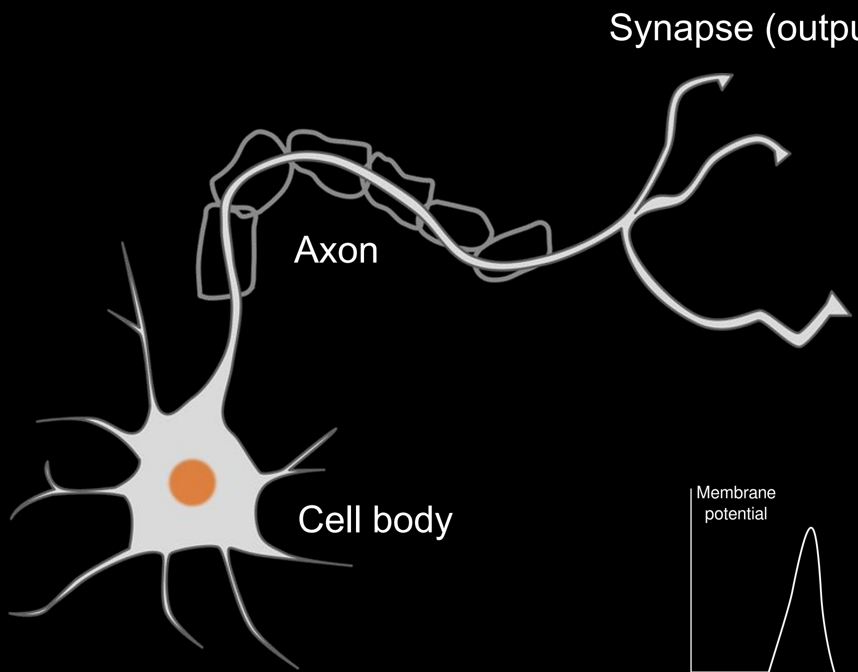
- What is a neural interface?
  - Case study: Artificial retina
- Perceiving neural recordings
  - Case study: Brain-machine interface
  - Case study: Combining ECoG with other information
- Stimulating the senses
  - Case study: Encoding sound in a cochlear implant
  - Case study: Prosthetic limb with sensory feedback
- Closing the loop

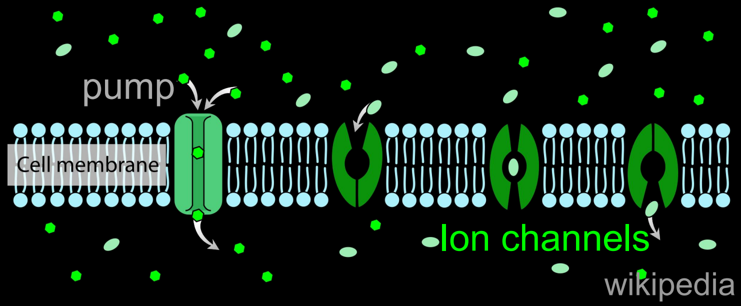
Neural Interface: biology + technology

Engineered system that interacts with the brain and/or peripheral nerves

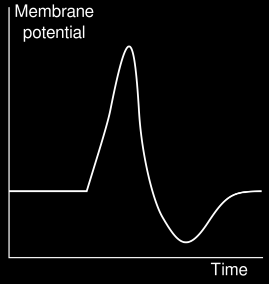


Neuron 101

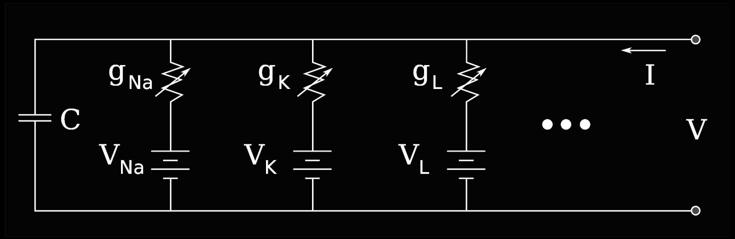




Cell membrane

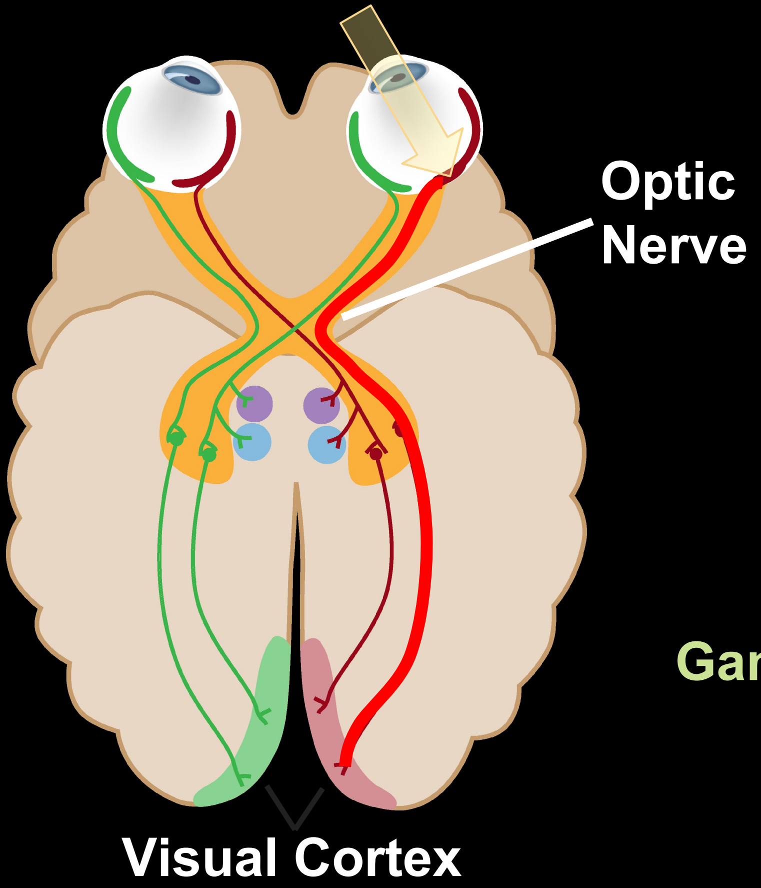


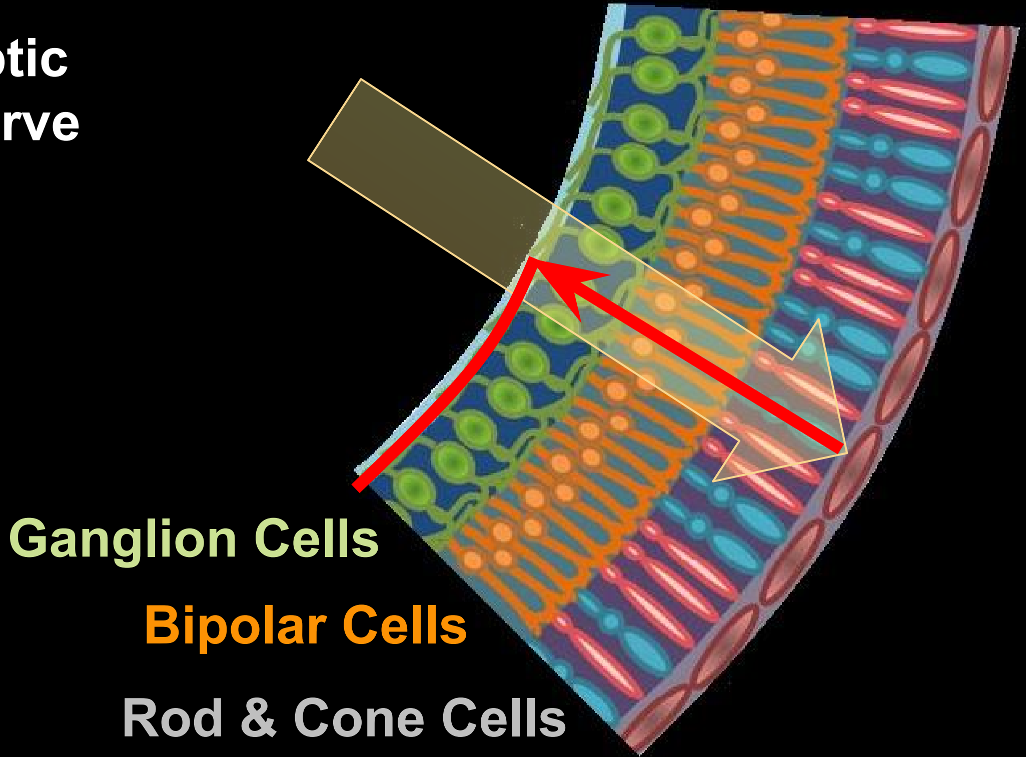
Action potential



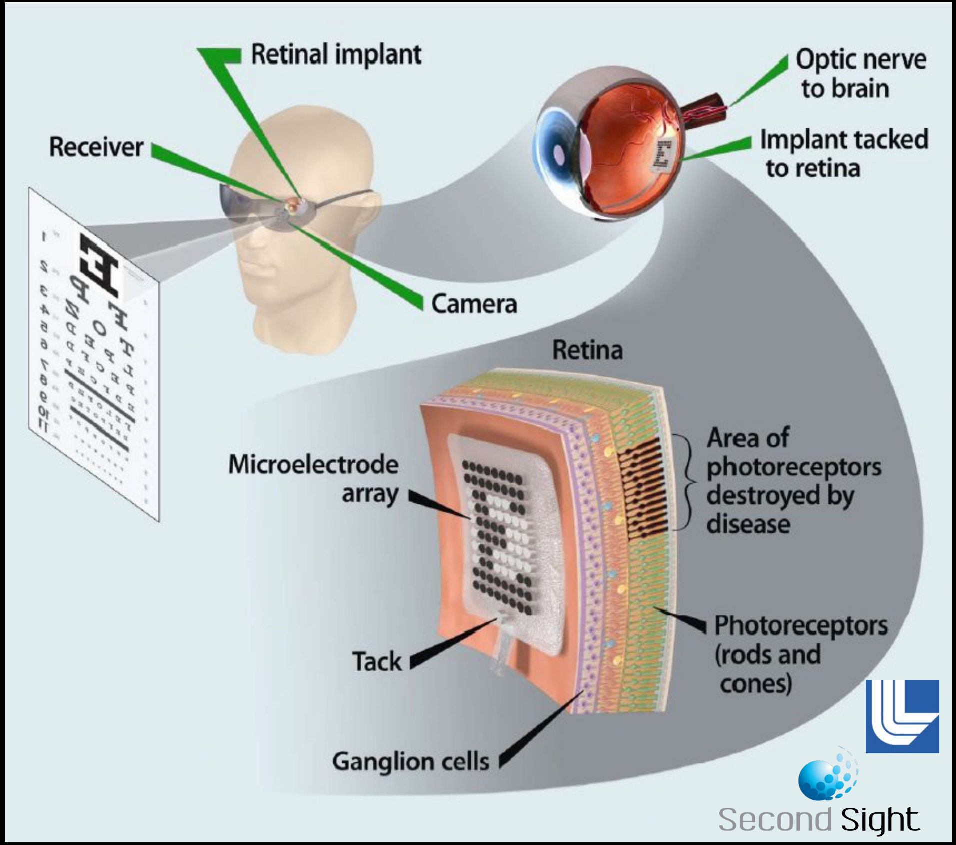
Hodgkin & Huxley model (1952)

Retina

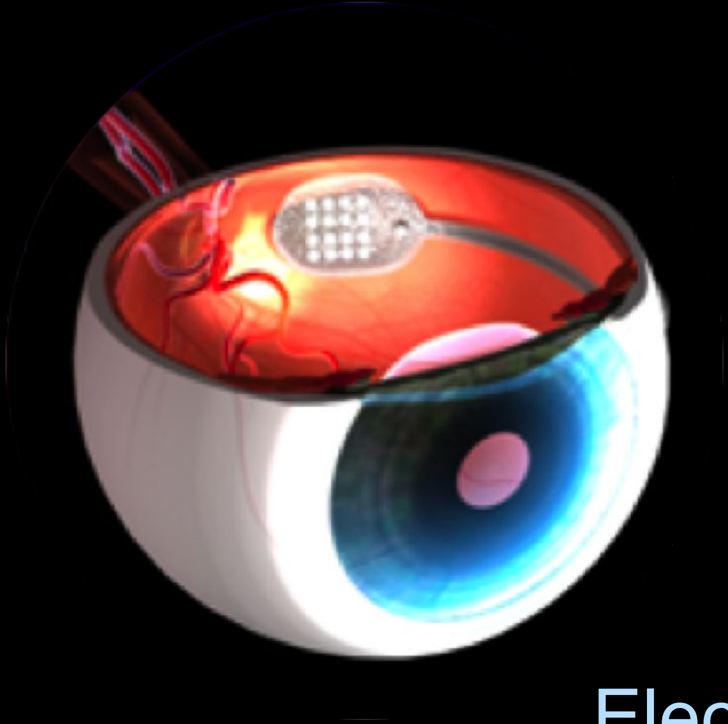

Optic
Nerve
Visual Cortex

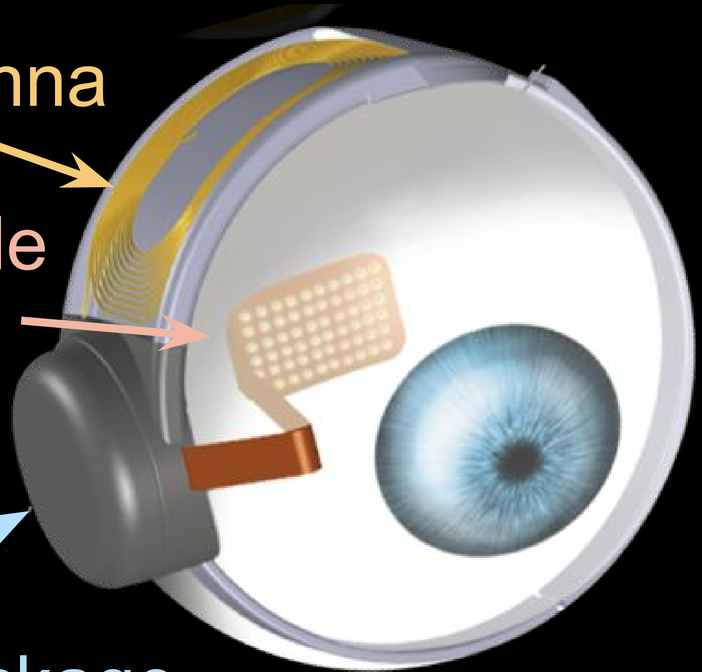

Ganglion Cells
Bipolar Cells
Rod & Cone Cells

Artificial Retina

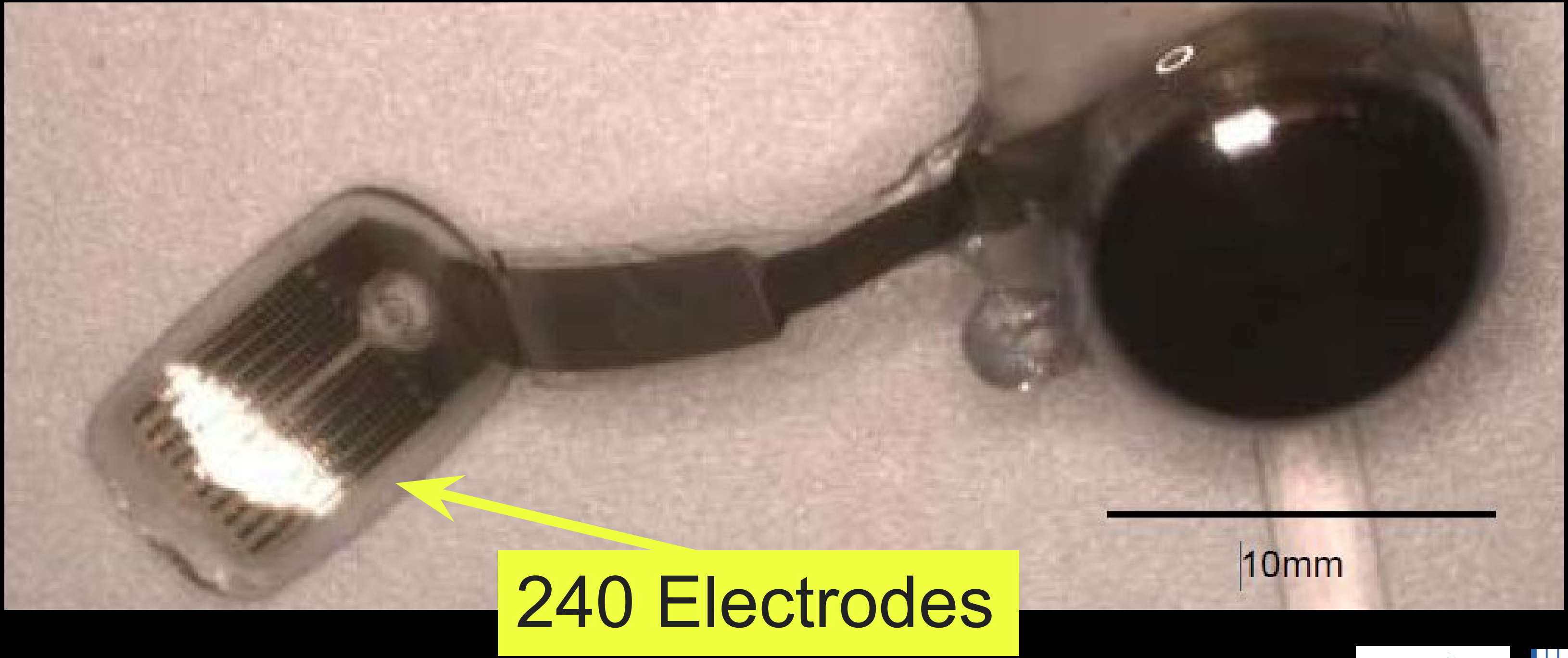


Implant Components





Thin film technology enables neuron-sized electrodes



It takes a large team to develop a full system

Lawrence Livermore National Laboratory

California Institute of Technology

Argonne National Laboratory

Second Sight

Doheny Eye Institute

Brookhaven National Laboratory

Los Alamos National Laboratory

Keck School of Medicine USC

Sandia National Laboratories

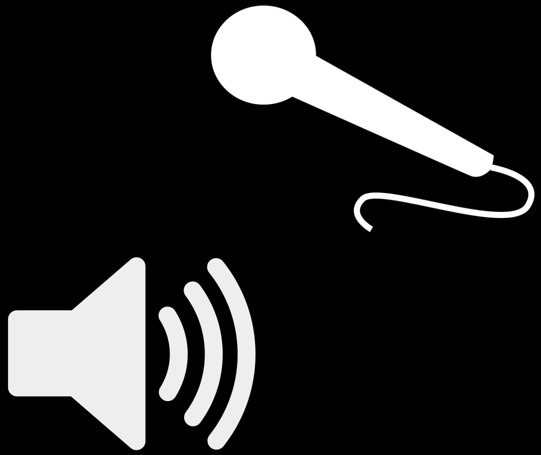
NC State University

UC Santa Cruz

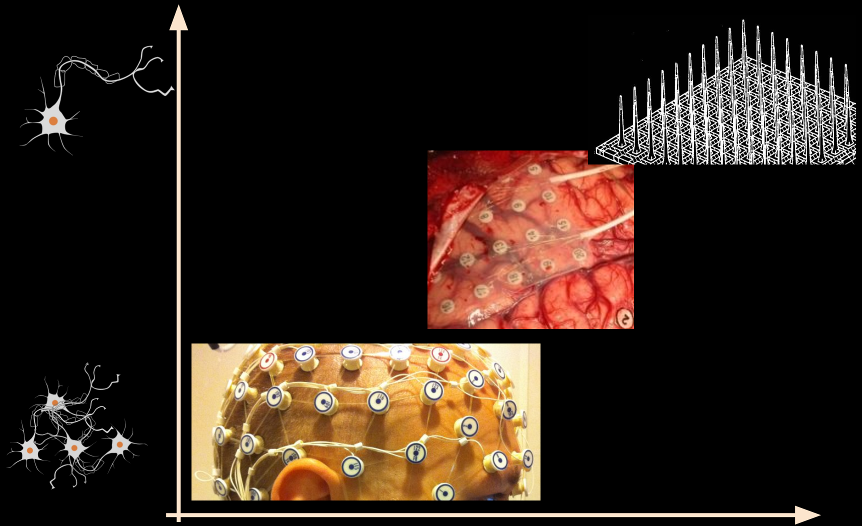
Oak Ridge National Laboratory

Considerations for choosing an interface

Recording vs. stimulation

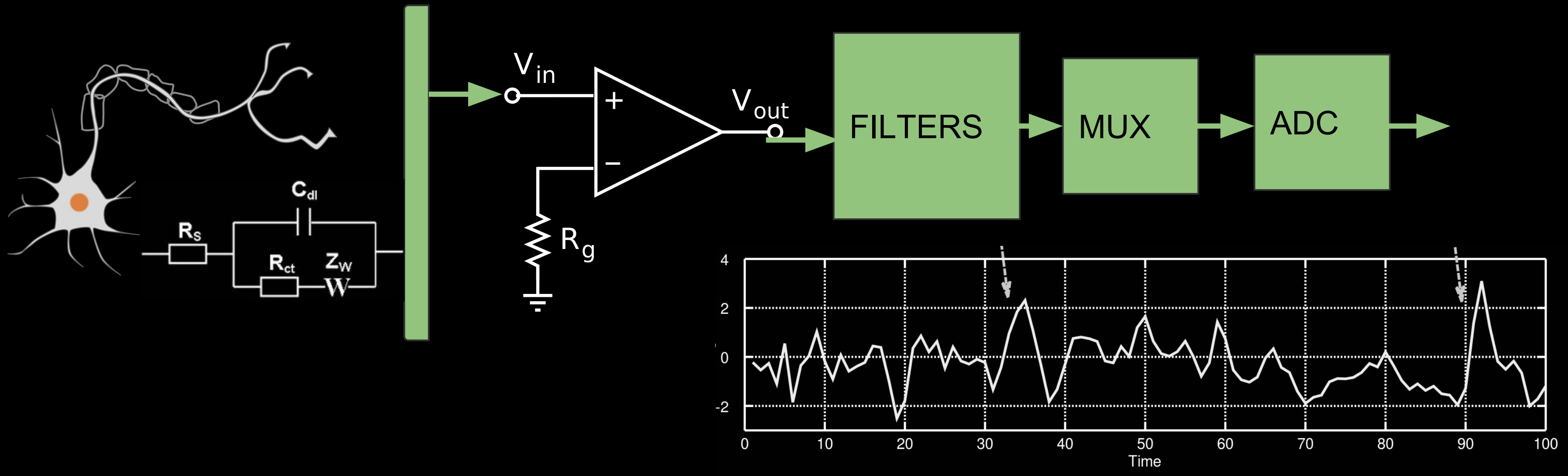


Selectivity vs. invasiveness

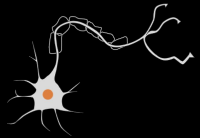


Making sense of neural recordings

Electrodes detect voltage fluctuations from neurons



Tradeoffs of different recording types



Single neuron
Spikes
More Invasive
Spatially localized
Time domain analysis
Time series, probabilistic

Many neurons
Oscillations
Less invasive
Spatially aggregated
Frequency domain analysis
Wavelet, time-frequency

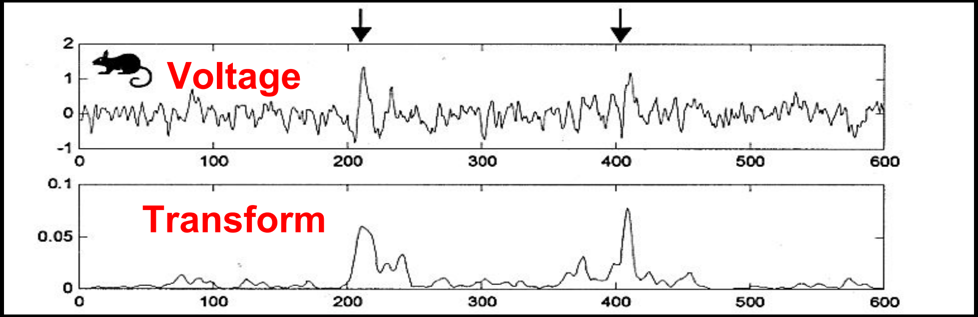
Depends on the goal

Understanding neural circuitry?
Classifying signals corresponding to brain states?
Inferring stimuli or inputs?
Controlling a prosthetic (BMI)?

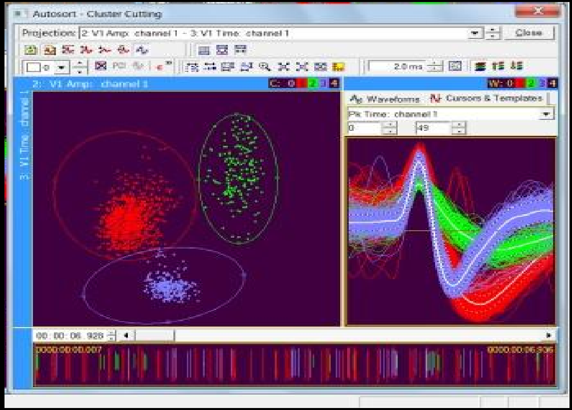
Single unit recording

- Detection
  - Step 1: Transformation, e.g:
    - Simple band pass filter
    - Wavelet transform
    - Likelihood test
  - Step 2: Threshold or criteria
- Classification (“spike sorting”)
  - Principal component analysis
  - Template matching

OUTPUT: Event times



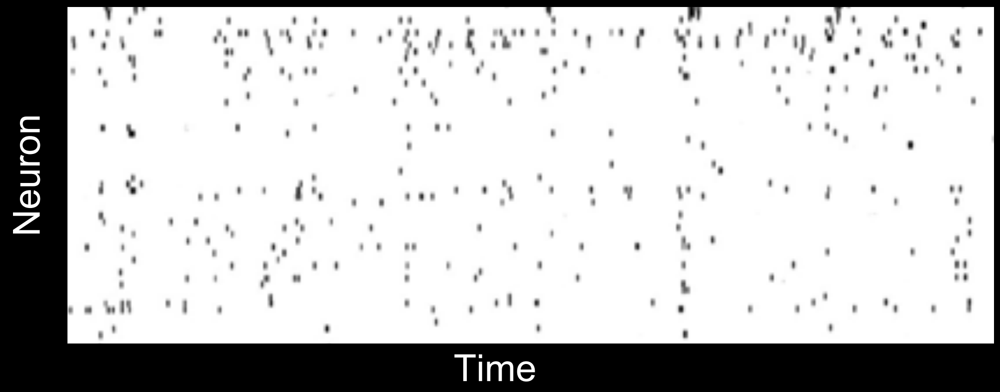
Kim, K. H. and Kim, S. J., “A wavelet-based method ..."*Biomed. Eng., IEEE Transactions*, 2003.



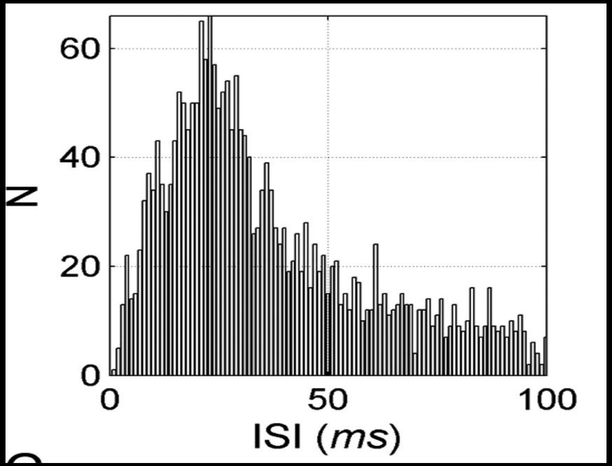
Software from DataWave Technologies

Single unit recording

- Analyze *spike trains*
  - Extract features: firing rate, burst rate
  - Characterize interspike interval (ISI) distribution
  - Map spatial and temporal correlations
  - Model as a point process



Raster plot of spike activity from 35 neurons



Histogram of inter-spike intervals

Decoding for Brain Machine Interface

1. Statistical model of neural spiking

$$Pr(\text{spike in } [t, t+\Delta]|\text{history}) = \lambda(t)\Delta$$

$$\lambda_i(x_k) = exp(\alpha_i + \beta_i \cdot x_k)$$

Firing rate, neuron *i*

2. State evolution model

$$x_k = F x_{k-1} + \epsilon_k$$

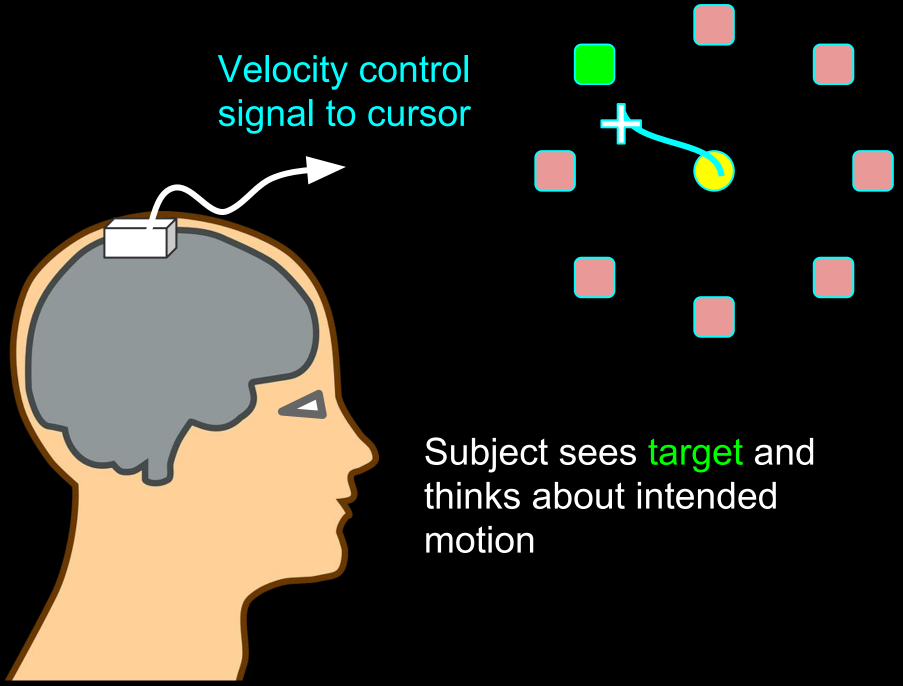
Intended Velocity

3. Fit parameters to the model
4. Bayesian estimation algorithm

(e.g. Koyama, Eden, Brown, Kass, 2010)

Spike sorting may not be necessary

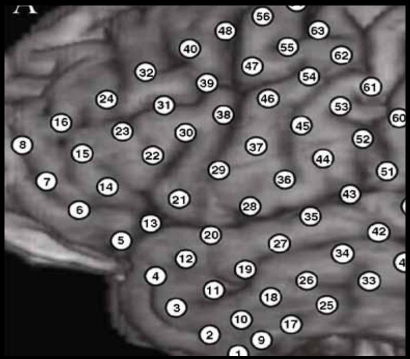
(Fraser, Chase, Whitford, Schwartz, 2009)

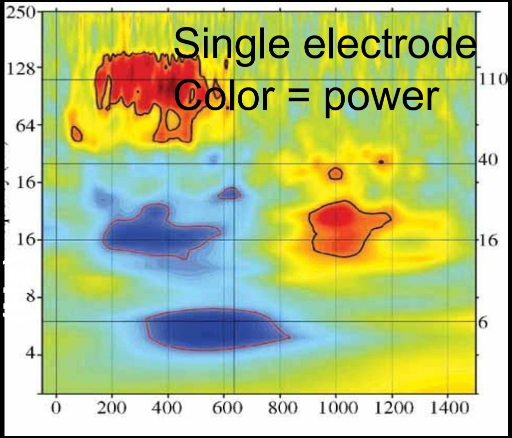


Field potentials and oscillatory signals

Time-frequency analysis

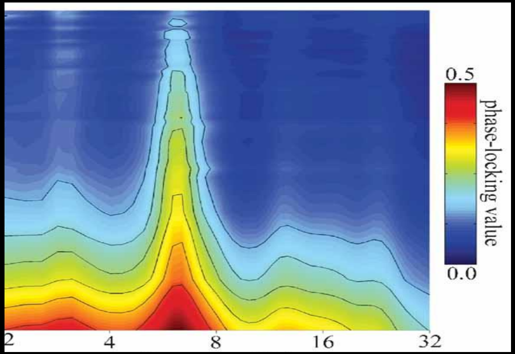
ECoG electrodes





e.g. Gabor transform

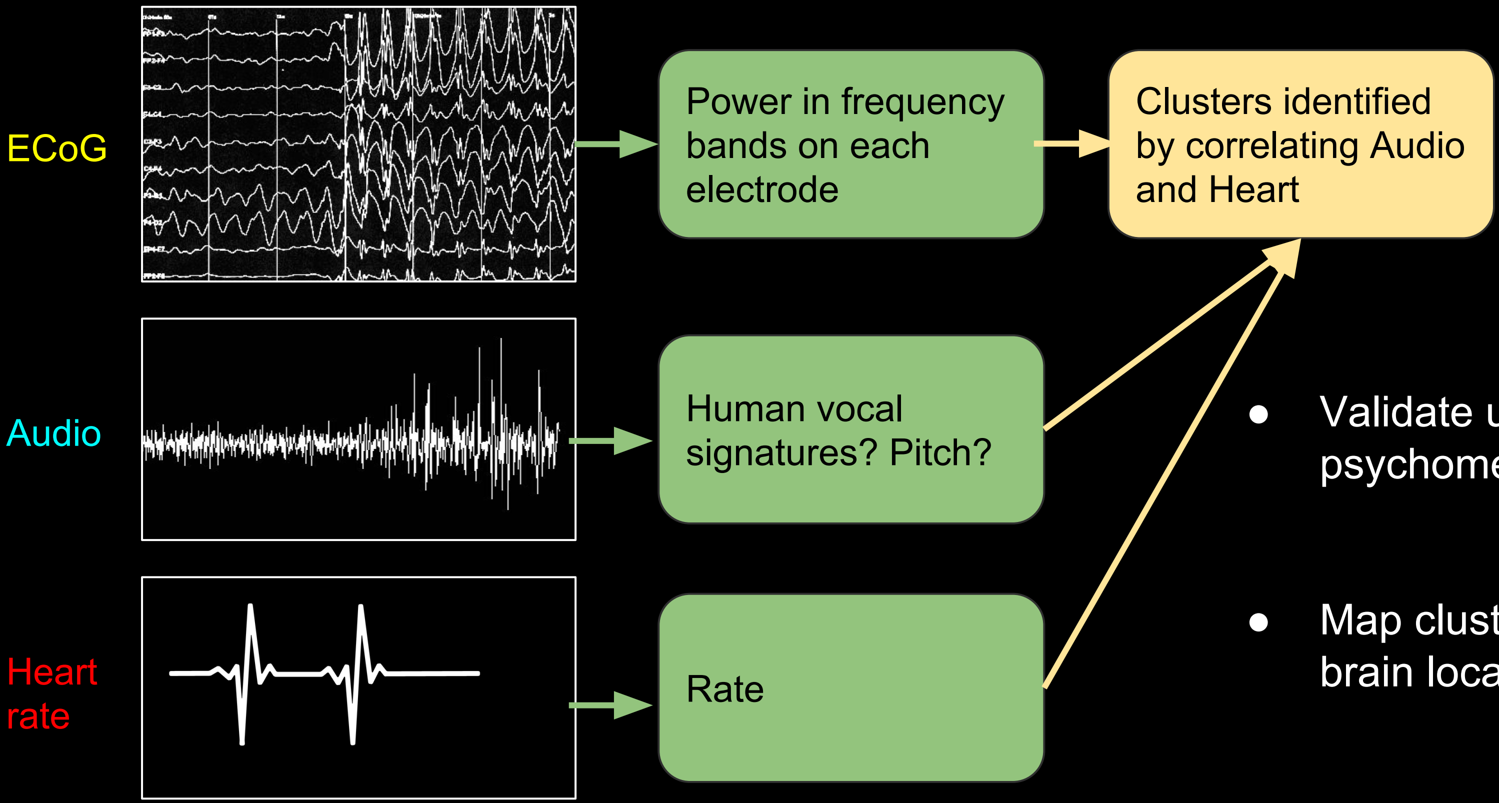
Coherence and spatial correlation



e.g. Mean Phase Locking Value

“Spatiotemporal dynamics of word processing in the human brain,” Conolty et al., *Frontiers in Neuroscience*, 2003

Multimodal decoding of...fear?

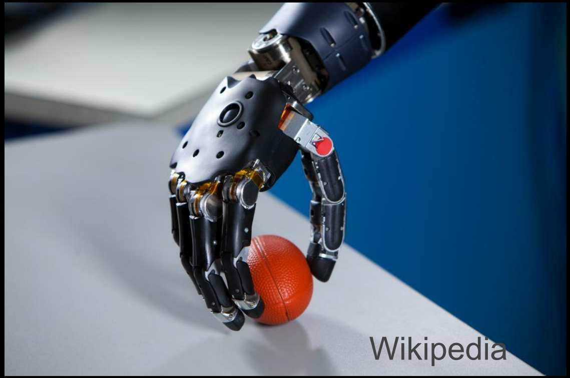


- Validate using psychometrics
- Map clusters back to brain location

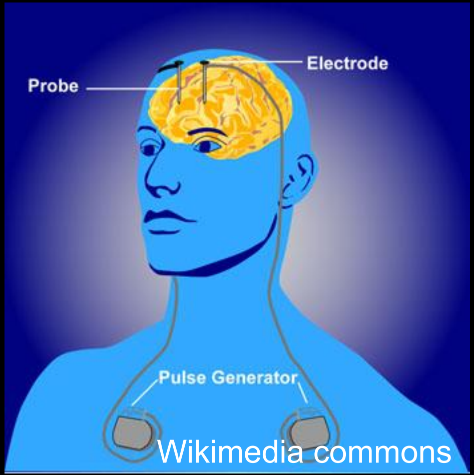
Stimulating the senses

Examples of neural interfaces that use stimulation

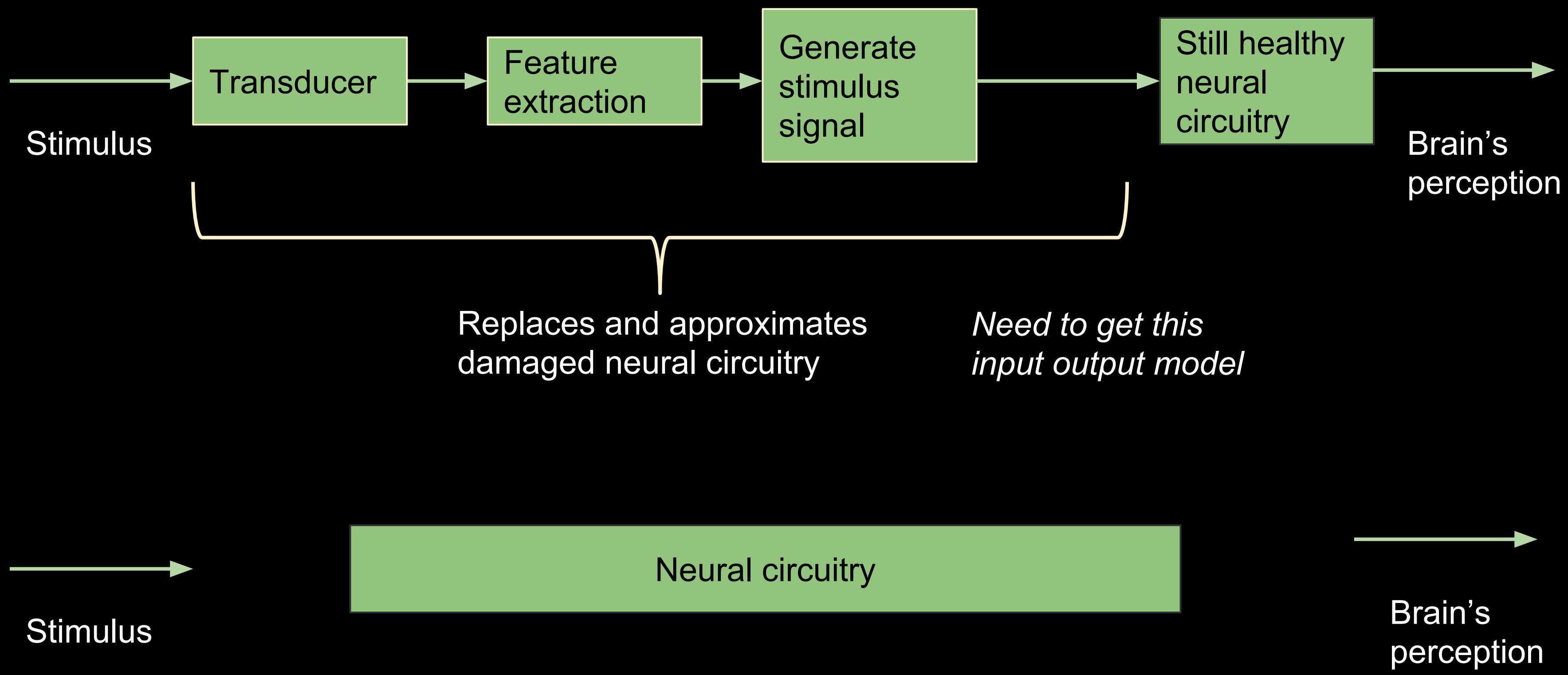
- Sensory prosthetics
  - Cochlear implant
  - Artificial retina
  - Vestibular implant
  - Upper limb prosthetic



- Therapeutic stimulation
  - DBS
  - Vagus nerve stimulation
  - TMS and tDCS

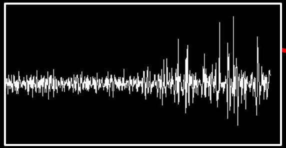


Schematic of a neural prosthetic



Encoding sound in the cochlear implant

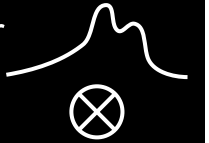
MICROPHONE



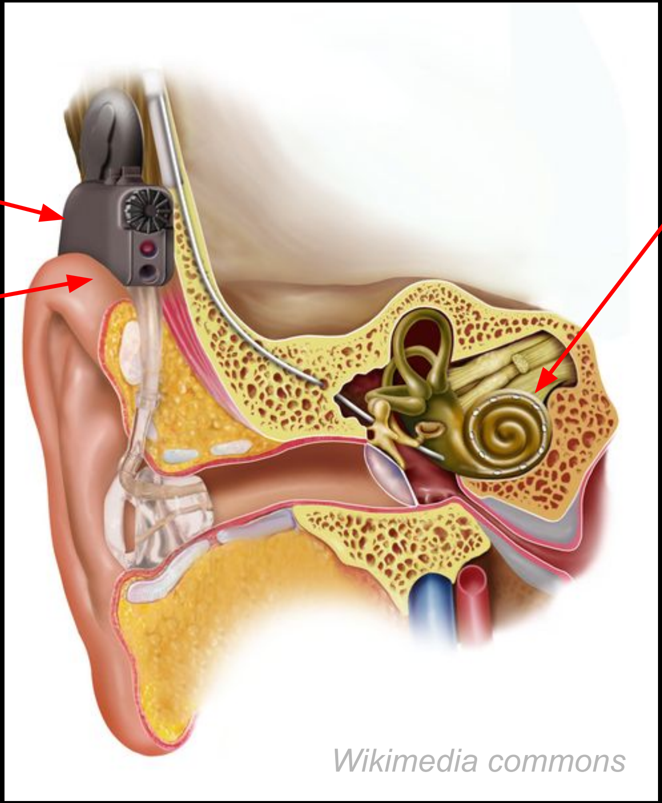
PROCESSOR

Filter bank → separate frequency components

Rectifying low pass filter → amplitude envelope



Pulse generator



ELECTRODES

Series of biphasic "charge balanced" pulses

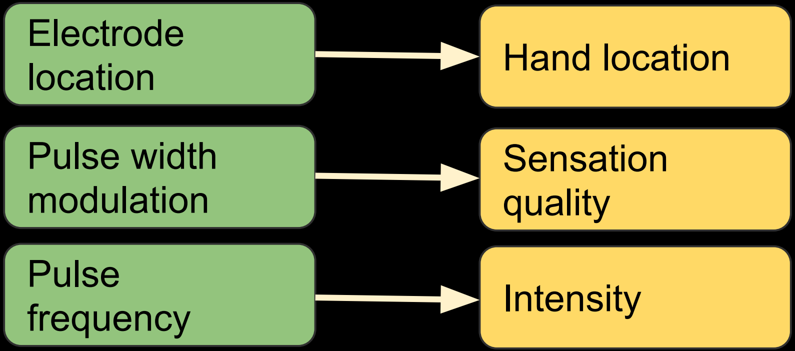
Different locations on the cochlea are tuned to different frequencies

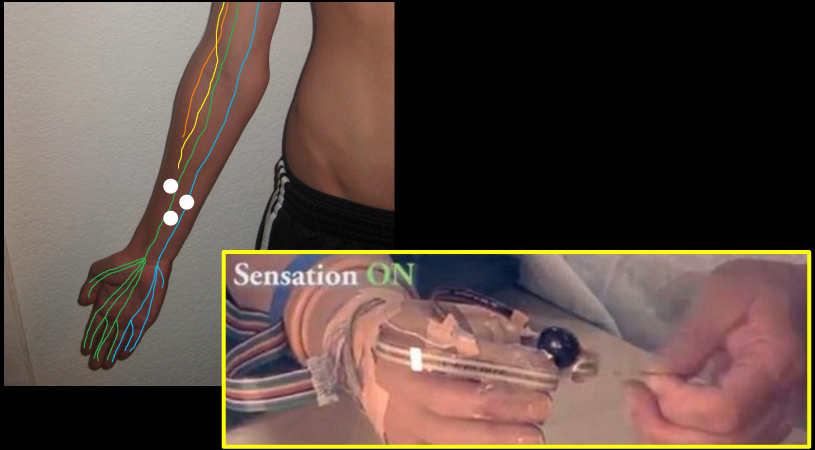
Active area of research to improve perception of:

- speech with background noise
- music

Relaying touch from a prosthetic hand

- Input/output model based on descriptive feedback from amputee volunteers
- Stimulation frequency proportional to force sensor output allowed patient to handle delicate objects



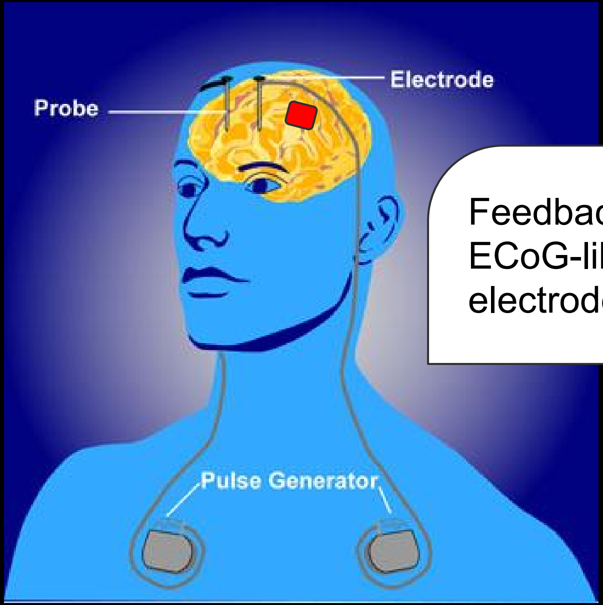


http://engineering.case.edu/Tyler-prosthetic-sensation

Tan, Daniel W., et al. "A neural interface provides long-term stable natural touch perception." *Science translational medicine* 6.257 (2014): 257ra138-257ra138.

Closing the loop

Smart deep brain stimulation

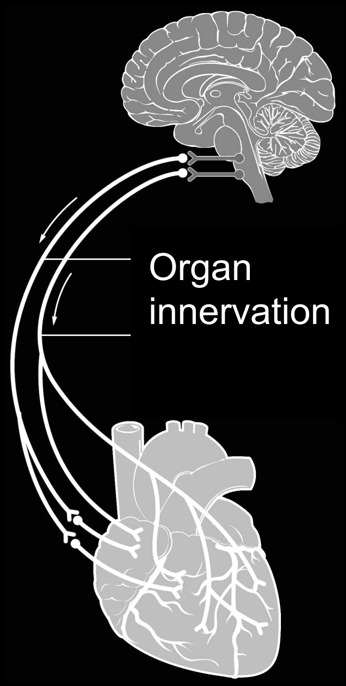


Feedback from ECoG-like electrodes

- Epilepsy suppression
- Mood disorders

See: “Smart neural stimulators listen to the body,” T. Dennison, M. Morris, F. Sun, *IEEE Spectrum,* Jan. 2015.

Bioelectronic medicine - a new frontier



Vagus nerve stimulation

Feedback from biochemical signatures…?

- Cardiac regulation
- Gastro-intestinal health
- Inflammation and pain management

Summary

- Neural interfaces leverage the electrical and network characteristics of human + machine
- Neural recordings present a plethora a SP problems for brain machine interfaces and basic neuroscience
- Sensory prosthetics stimulate neurons to restore lost function - identifying the right I/O model is critical
- Closed loop interfaces are a new frontier promising therapies for hard-to-treat conditions

Acknowledgements and other references

Thank you to Sat Pannu at Lawrence Livermore National Laboratory
neurotech.llnl.gov

- Articles and texts not listed in slides
  - Rubinstein, Jay T. "How cochlear implants encode speech." *Current opinion in otolaryngology & head and neck surgery* 12.5 (2004): 444-448.
  - Gibson, Sarah, Jack W. Judy, and Dejan Markovic. "Spike Sorting." *IEEE Signal processing magazine* 29.1 (2012): 124.
  - *Statistical Signal Processing for Neuroscience and Neurotechnology*, Karim Oweiss
  - *Signal Processing for Neuroscientists,* Wim van Drongelen
  - *Analyzing Neural Time Series Data*, Mike X Cohen
- Coursera: *Computational Neuroscience,* Rajesh Rao & Adrienne Fairhall