I, Robot:
Blurring the Lines between Mind, Body and Machines

Ralph Etienne-Cummings

Dept. of Electrical and Computer Engineering and Computer Science

Johns Hopkins University

The Motivation

- Fully neurally integrated prosthetics
  - Thoughts to action (decoding of intent)
  - Sensors to feeling (encoding of reaction)
  - Knowing location of limbs (representing joint space)

Lucas Films, 1978

The Motivation

- Enhancing Human Capabilities
  - Memory Extensions (Storage/Retrieval of Memories)
  - Perceptive Extension (Hyper Spectral Optics/Acoustics)
  - Direct Brain-Brain Communications

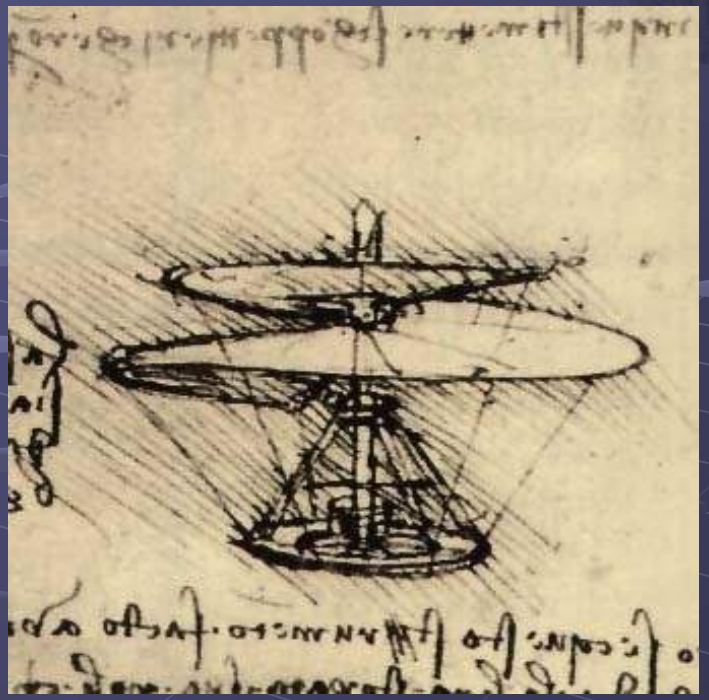
Johnny Mnemonic, TriStar Pictures, 1995

Star Trek, Next Generation , Paramount Studios, 1987

Nature Inspires Machines

Antoni Gaudi, *Casa Mila*, 1906 – 1910

"Form"

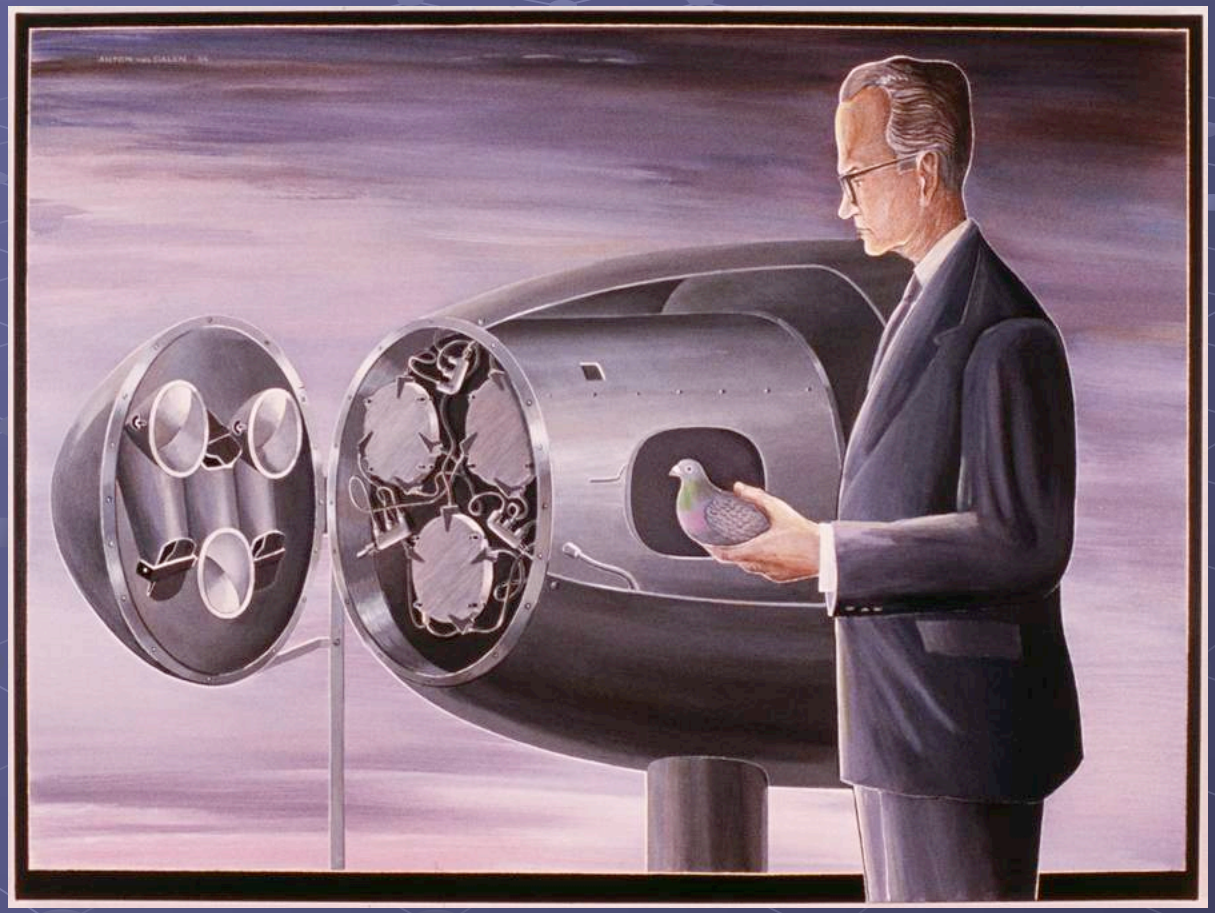


Leonardo da Vinci, *Helicopter*, 1452 – 1519

"Function"

After wikipedia.com

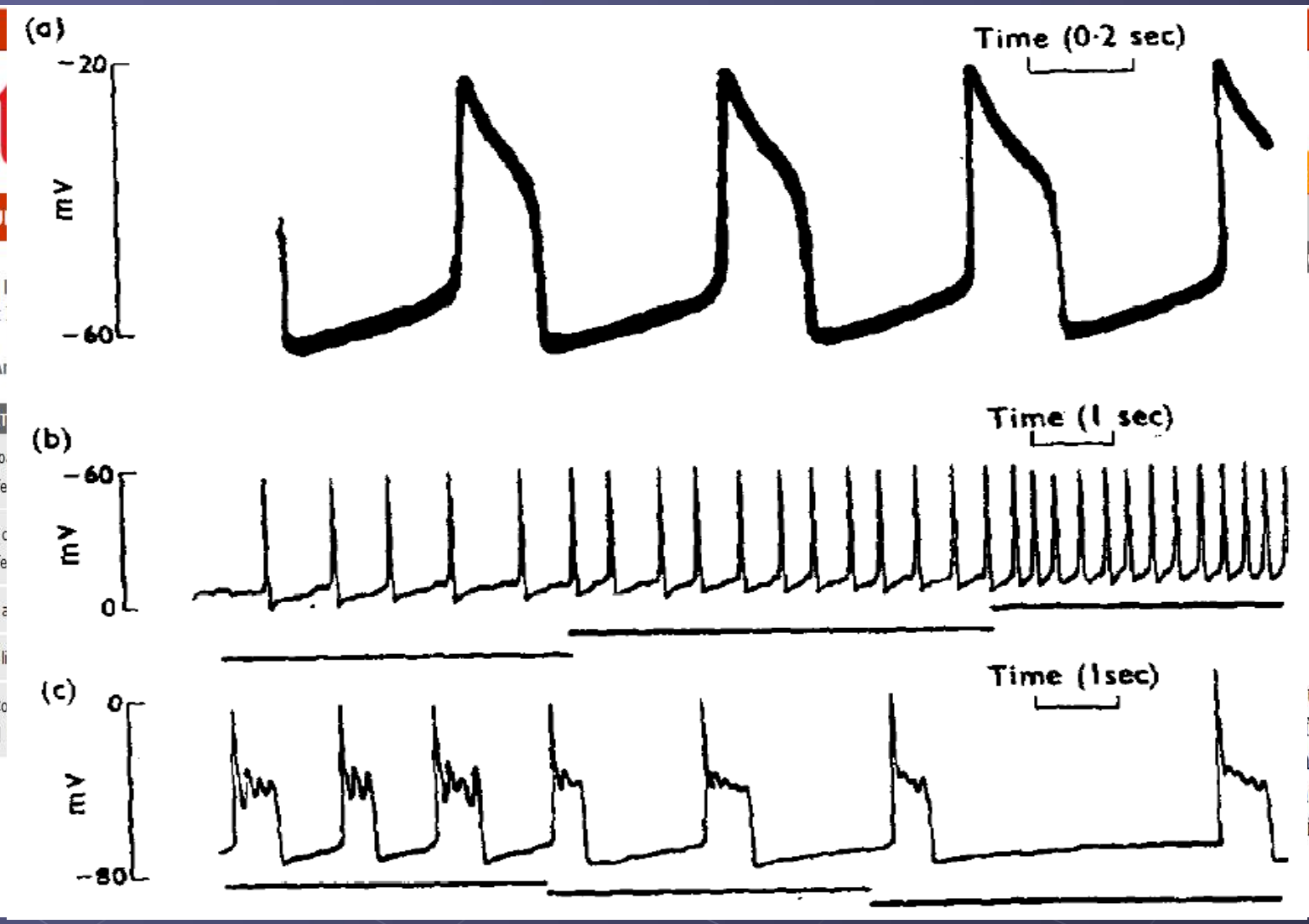
Nature in the Loop with Machines



B. F. Skinner by Anton van Dalen

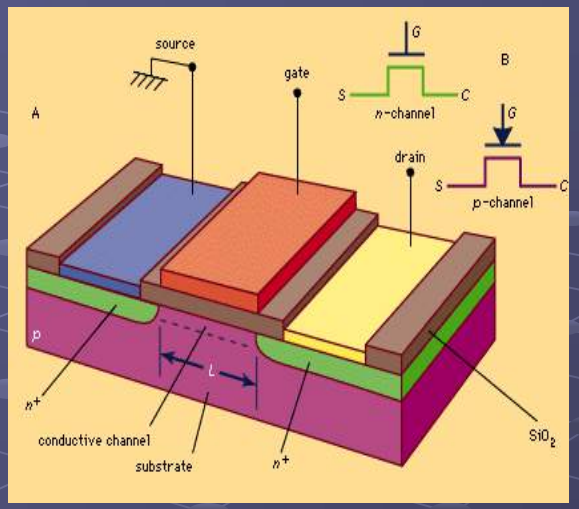
Smithsonian Institute

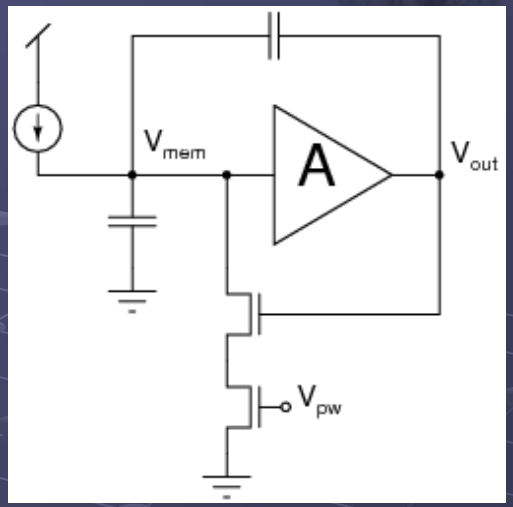
Nature's Inspiration ....

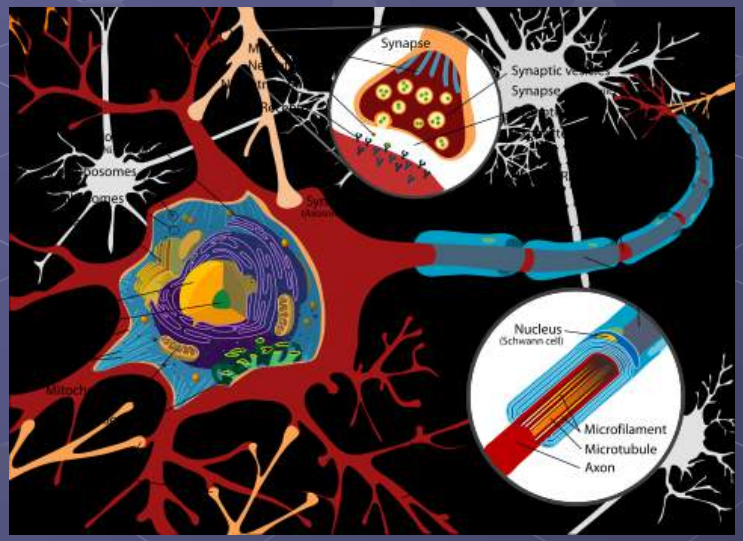


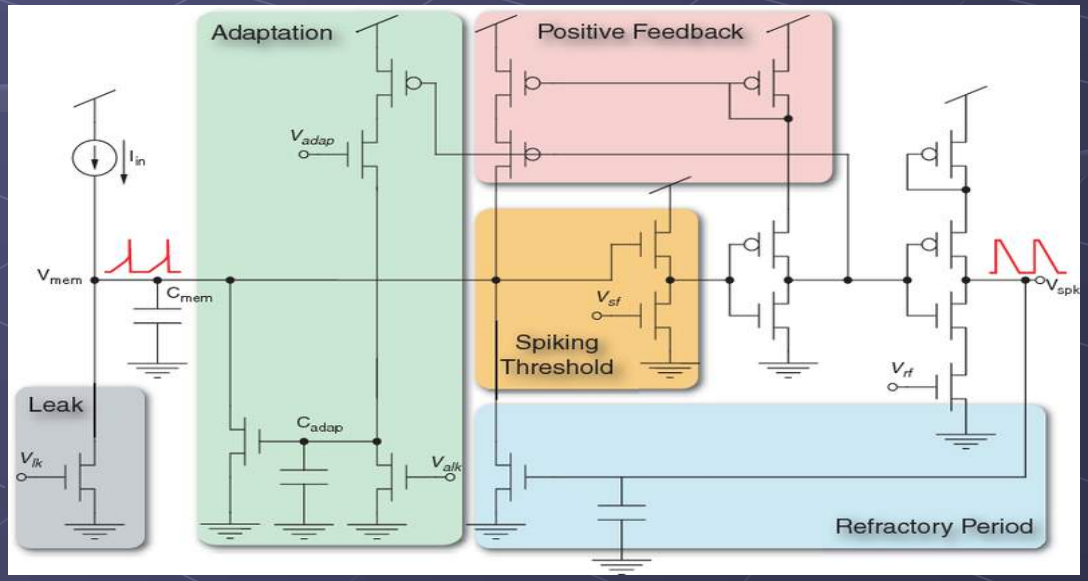
After wikipedia.com

Nature's Inspiration ....









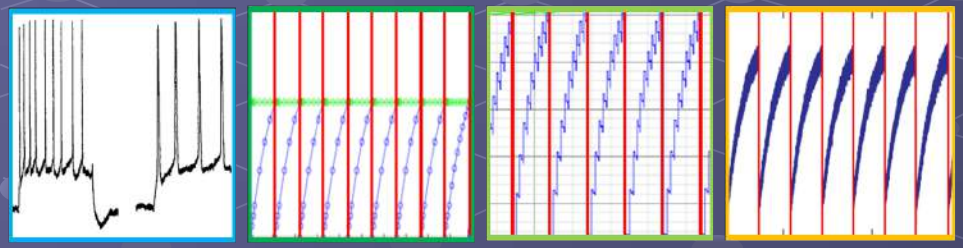
Paul Mueller, Carver Mead, *Neuromorphic Circuits*, 1986 - 1990

After wikipedia.com

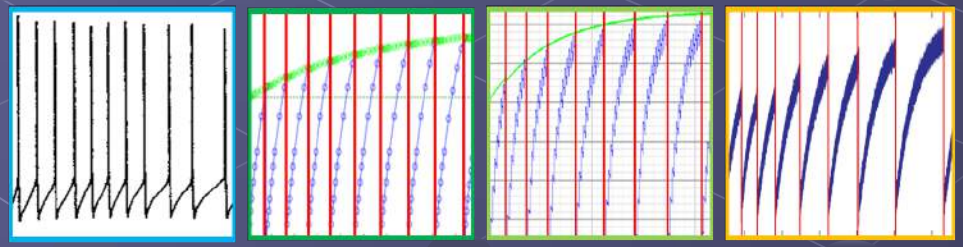
Large Scale Brains in Silicon

Neuron in Biology → MatLab Simulations → Cadence Simulations → Neuron on Chip

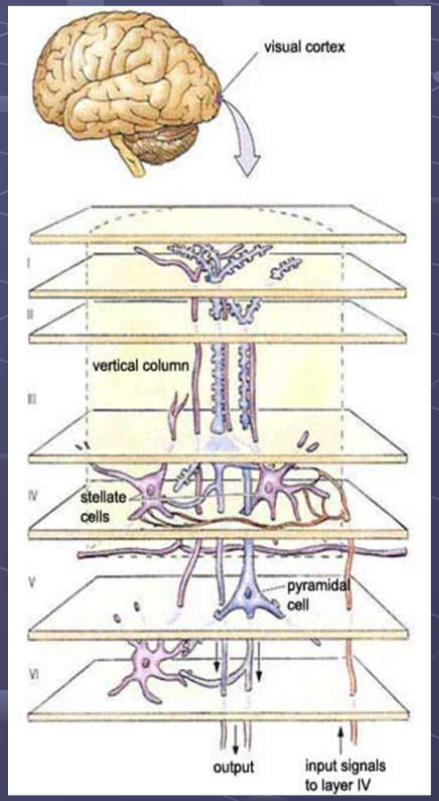
- Tonic Spiking

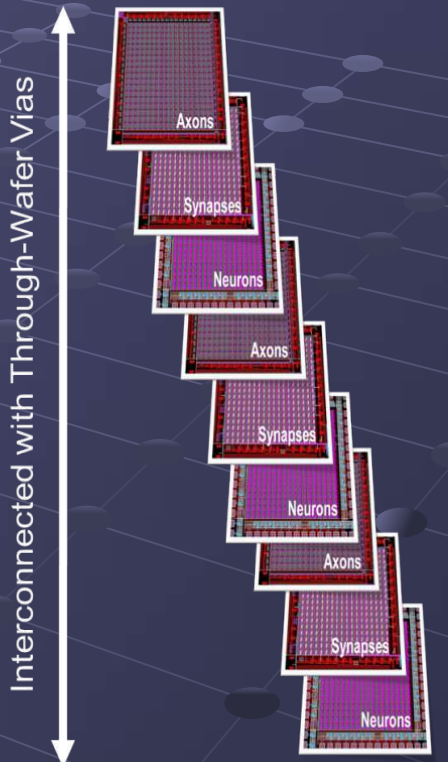


- Spike Frequency Adaptation



F. Folowosele et al., *IEEE TNN*, 2011



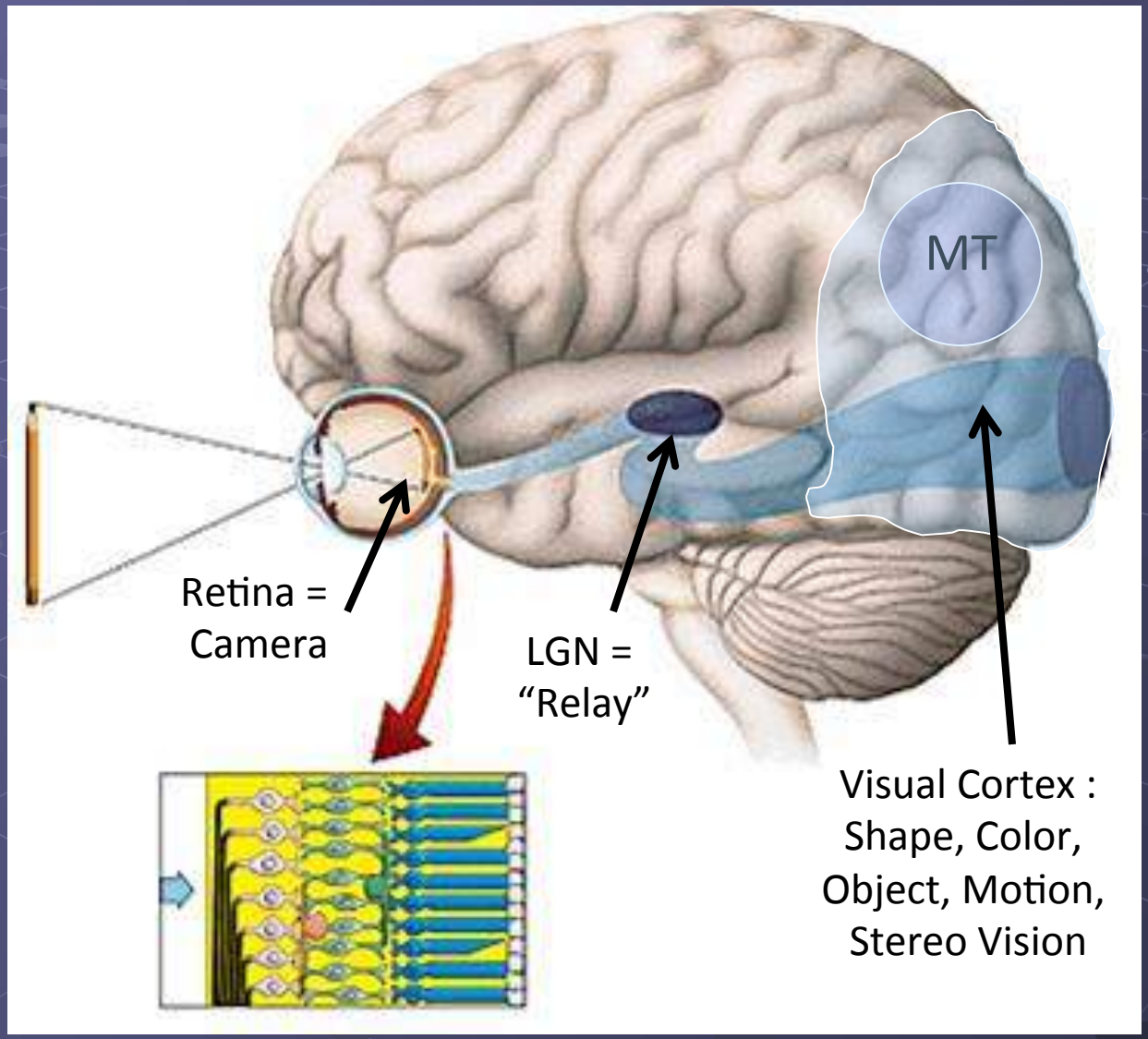


3D IFAT (Johns Hopkins), 2008 - present

Presentation Outline

- Cameras That Work Like Our Eyes
  - The biological visual system
  - Silicon eyes
  - Making the Blind See
- Restoring Walking After Spinal Cord Injuries
  - The biological locomotion system
  - Silicon model of spinal cord circuits
  - Making the Paralyzed Walk
- Replacing Limbs with Neurally Integrated Prosthetics
  - High degree of freedom prosthetic limbs
  - Closed loop control
- Conclusions

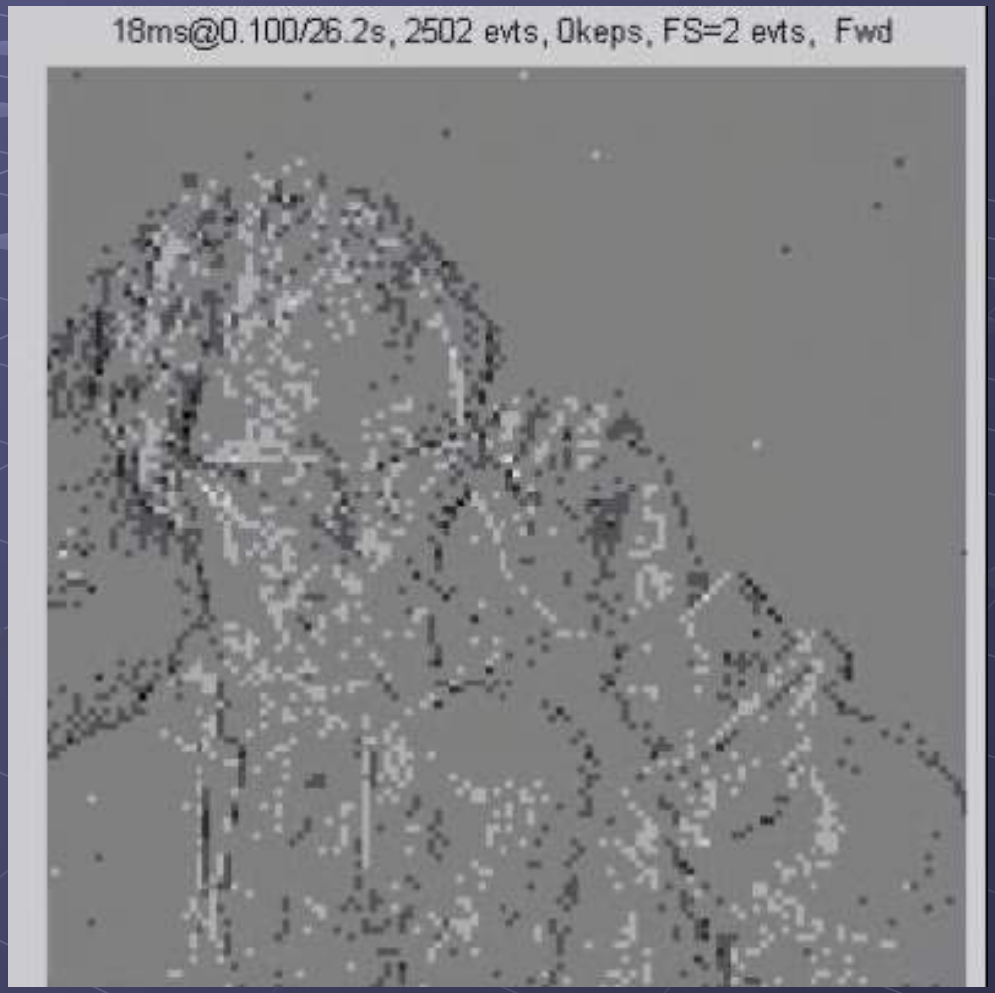
Visual Processing in Humans



After wikipedia.com

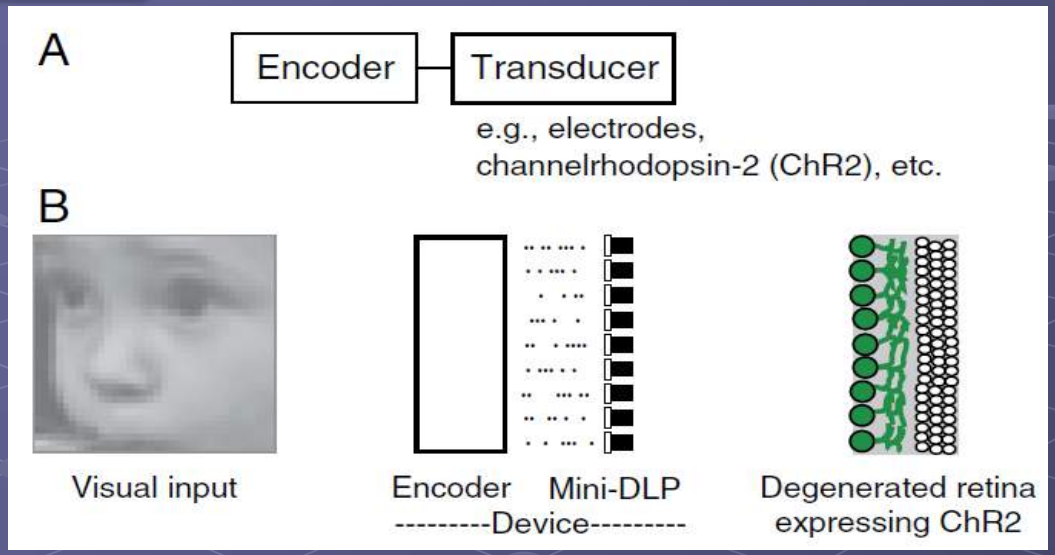
Retinal Prosthetics and Retinomorphic Image Sensors

Argus 2.0 (FDA Approved)

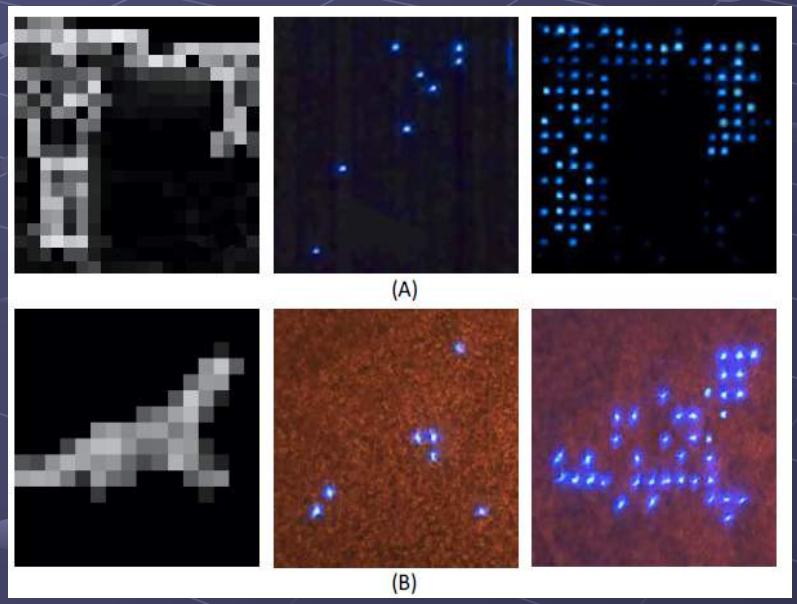


Delbruck et al, ETHZ, 2008

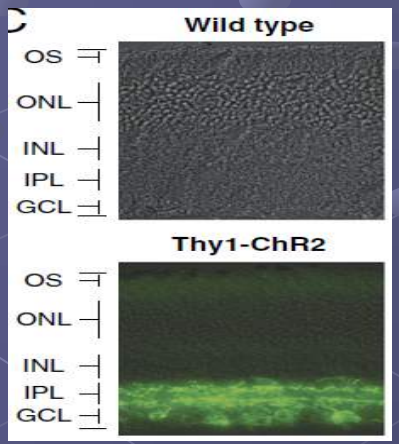
Retinal Prostheses of the Future

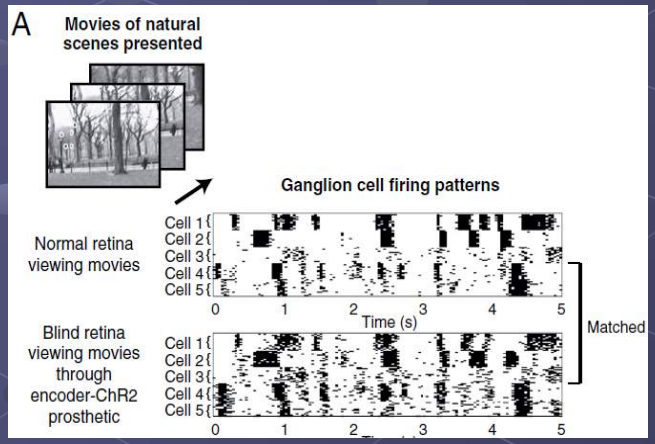


LED Chip for Optogenetic Stimulation



Deganaar et al., *IEEE TBME*, 2013
U. Newcastle, UK



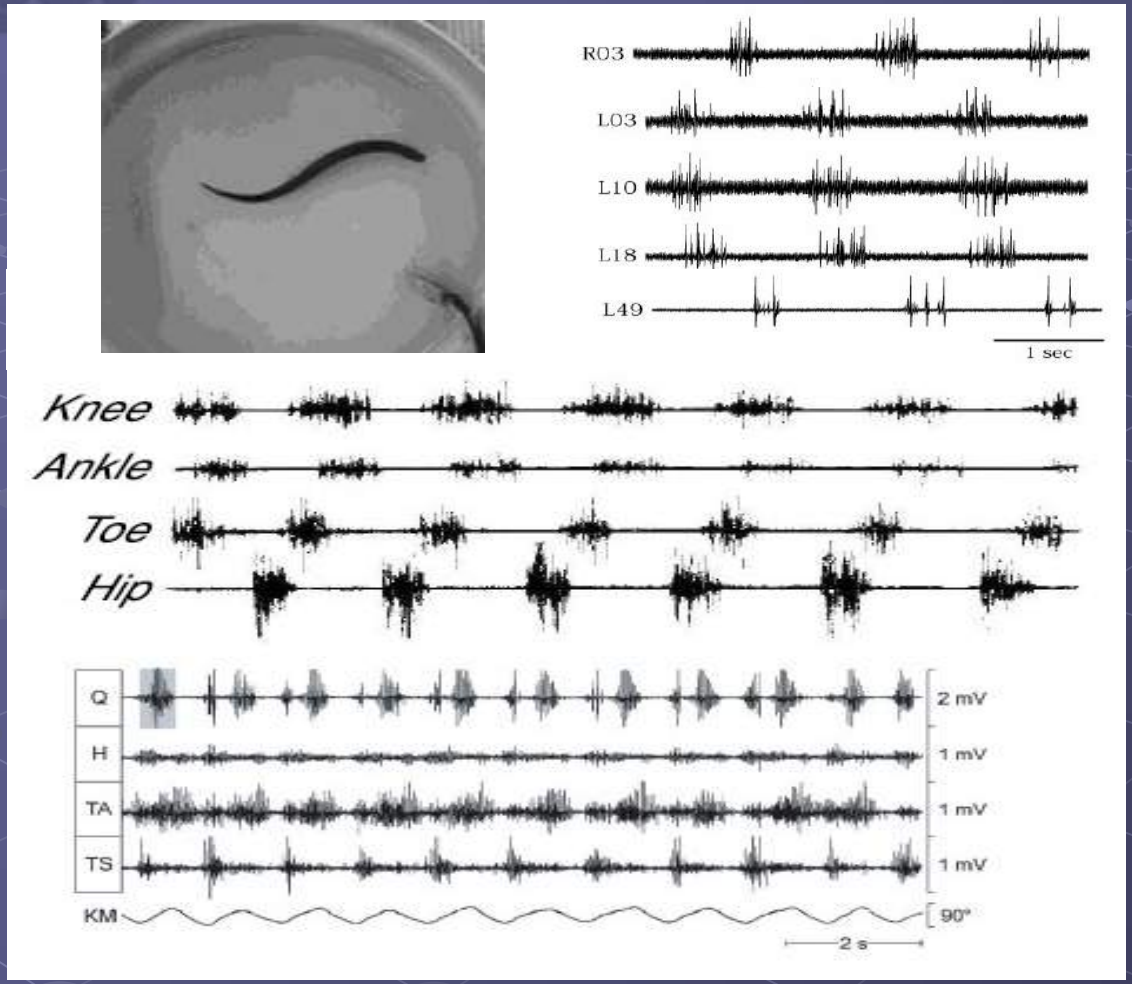


Nirenberg & Pandarinath, *PNAS*, 2012
Cornel U.

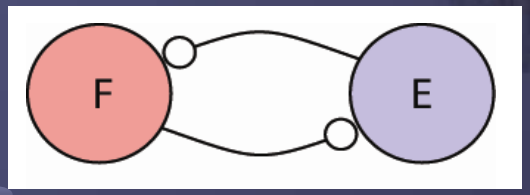
Presentation Outline

- Cameras That Work Like Our Eyes
  - The biological visual system
  - Silicon eyes
  - Making the Blind See
- Restoring Walking After Spinal Cord Injuries
  - The biological locomotion system
  - Silicon model of spinal cord circuits
  - Making the Paralyzed Walk
- Replacing Limbs with Neurally Integrated Prosthetics
  - High degree of freedom prosthetic limbs
  - Closed loop control
- Conclusions

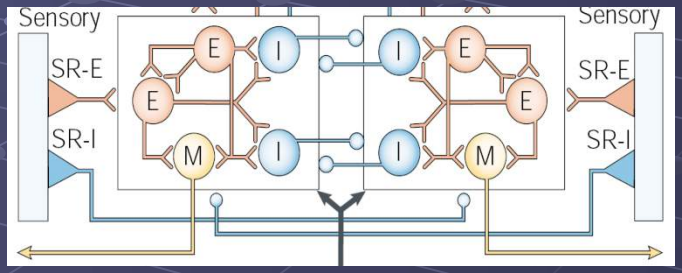
Central Pattern Generation (CPG) in Action



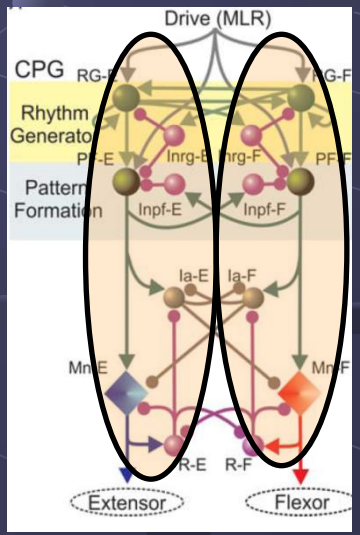
Source: Mellen et al., 1995;
Grillner & Zangger, 1984; Dimitriavic & Minassian et al., 2004



Source: T. Graham Brown, 1911



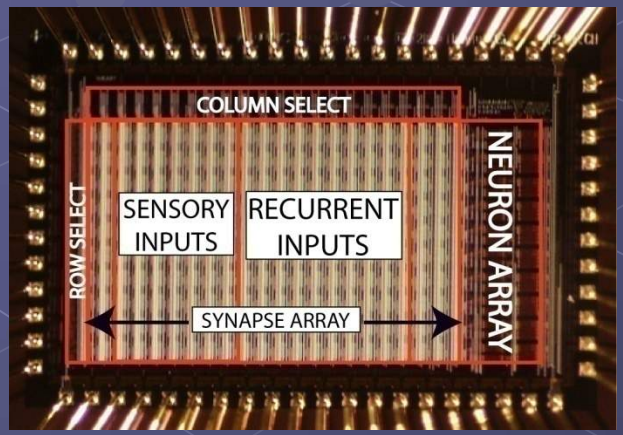
Source: Grillner, Nat Rev Neurosci, 2003



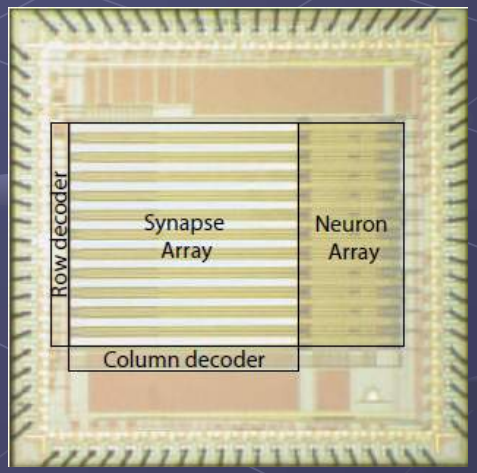
Source: Rybak et al., J Physiol, 2006

A Piece of the Spinal Cord on a Computer Chip

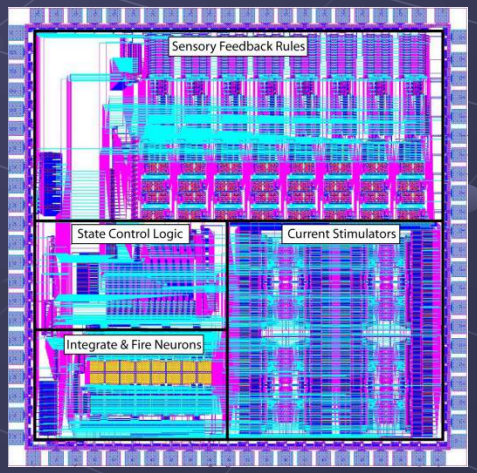
- Prescribe motor output based on pre-defined gait and current sensorimotor state
- Measure biological motor circuits all times and predict next desired state in order to effectively control it
- Build a silicon model of biological spinal circuits: neuromorphic silicon CPG chip (SiCPG) or Locomotion Processor Unit (LPU)



CPGv2 (Tenore et al., 2004)

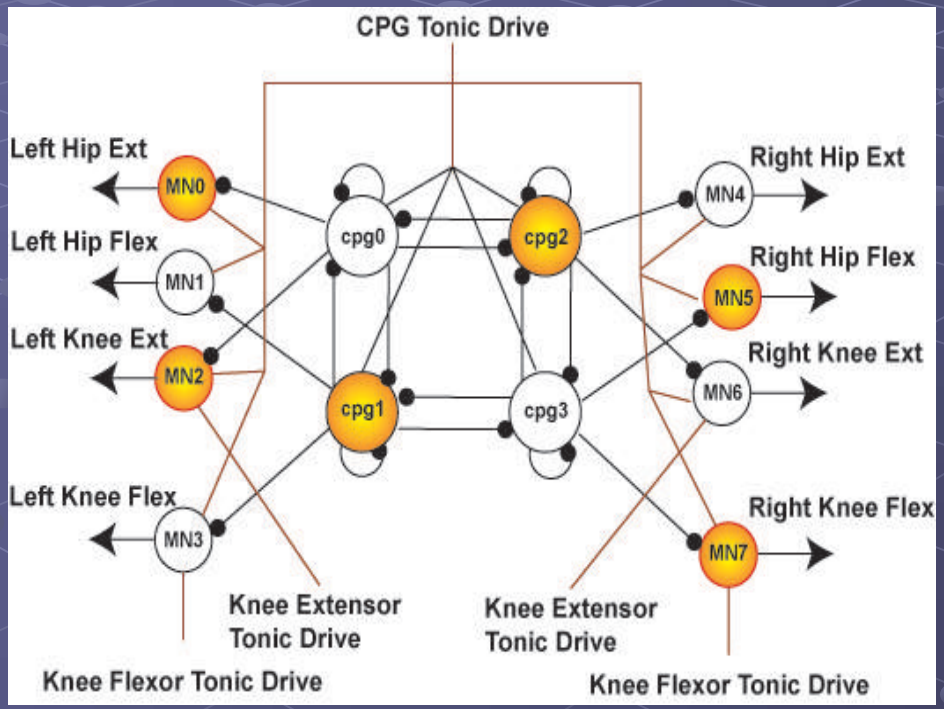


CPGv3 (Tenore et al., 2006)

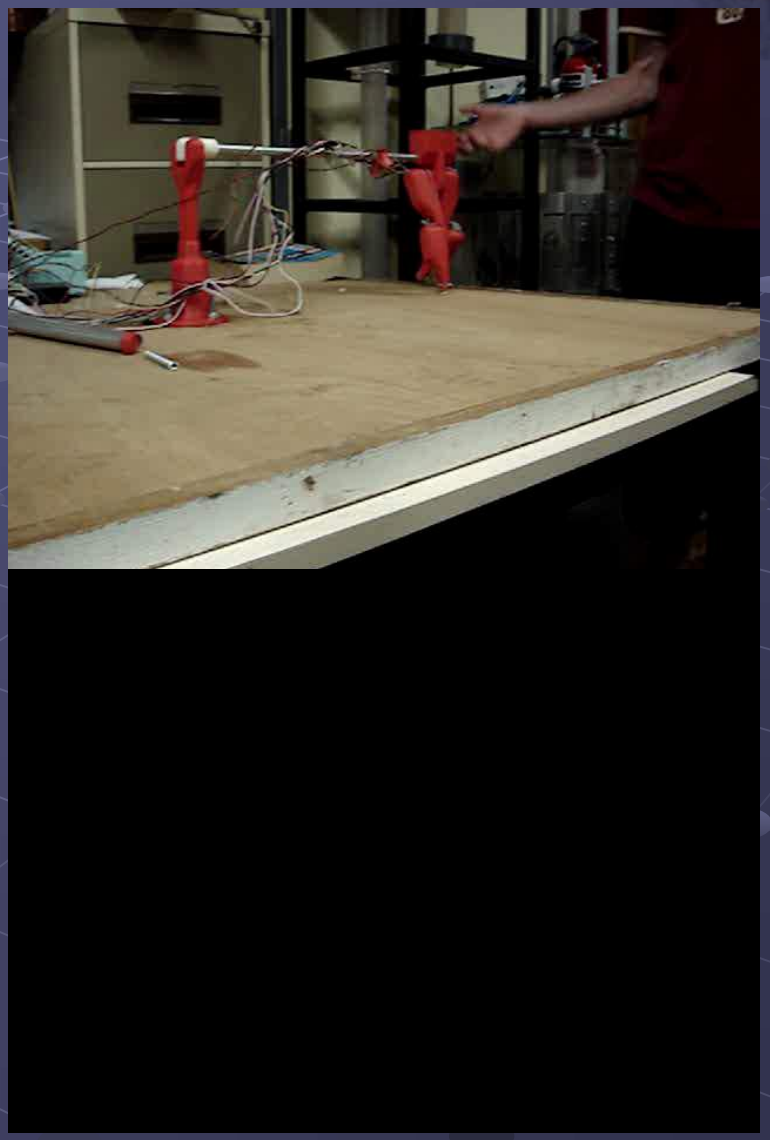


LPU (Mazurek et al., 2011)

Making a Robot Walk with CPG Chip

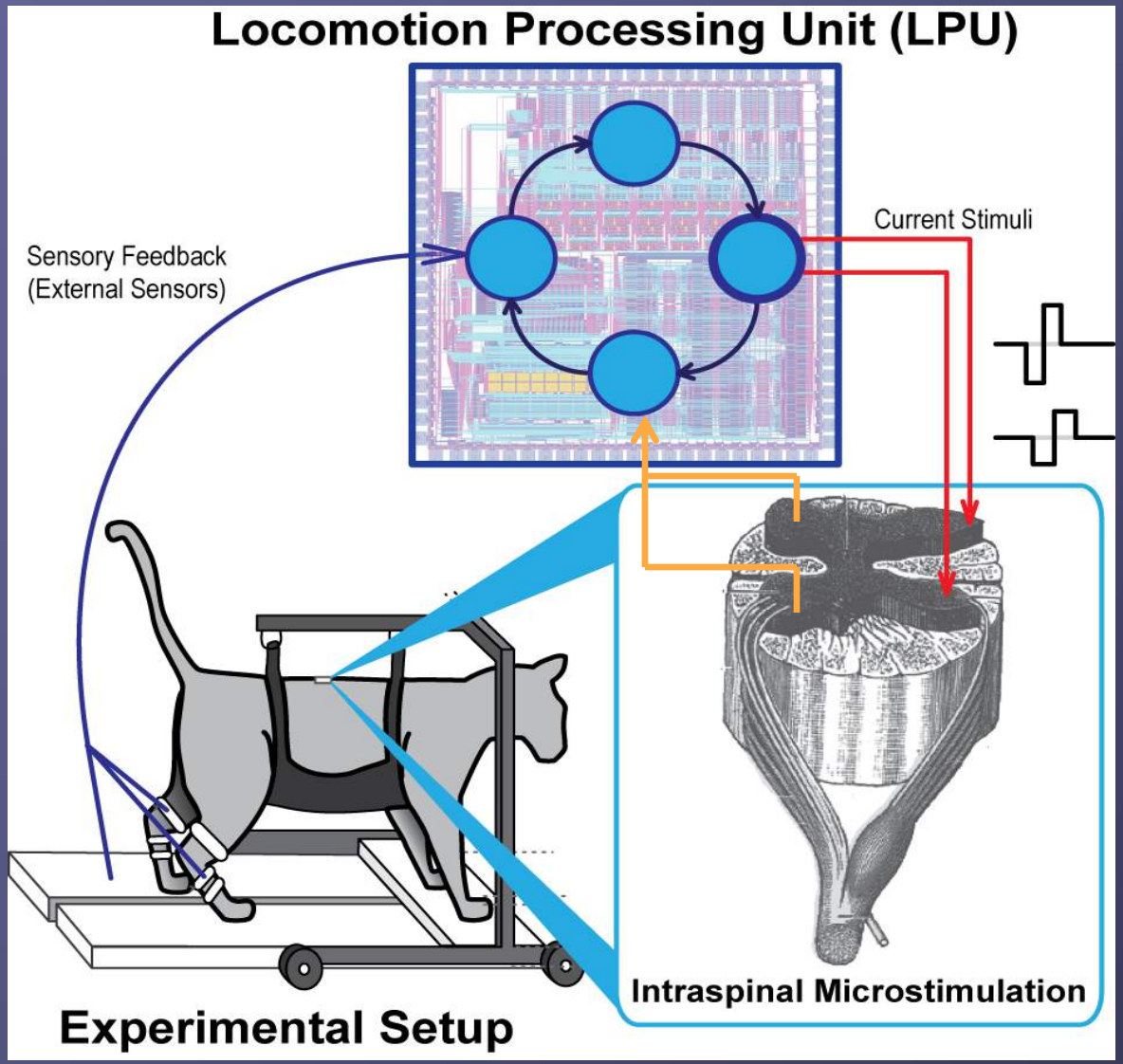


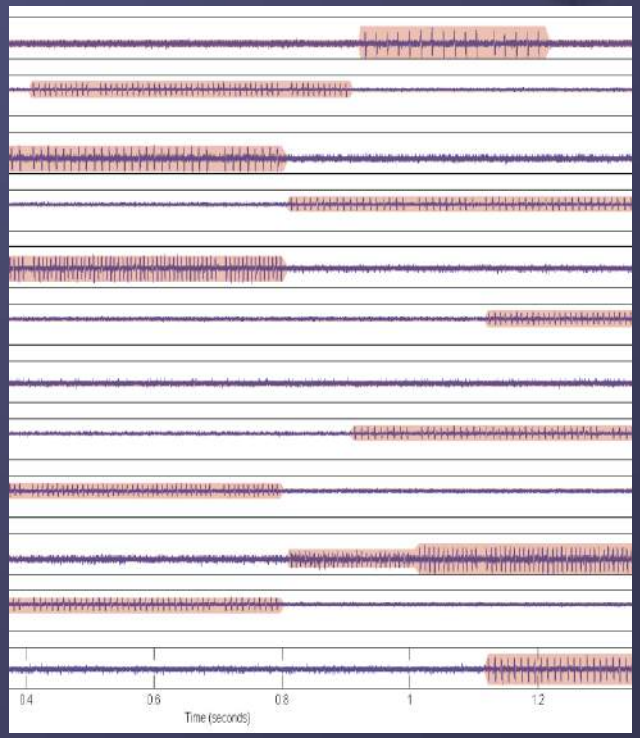
Lewis et al., 2005

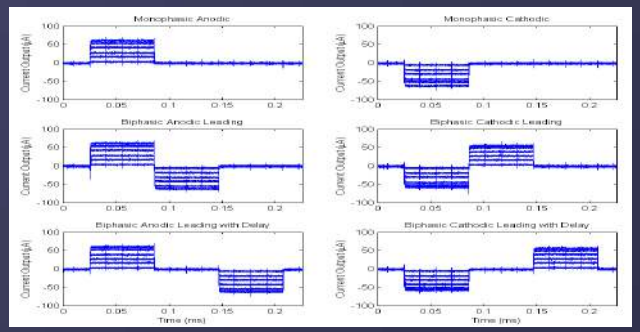


Lewis et al., 2005,2012; Russell, Orchard et al, 2007

Reactivating the Spinal Cord after Injury

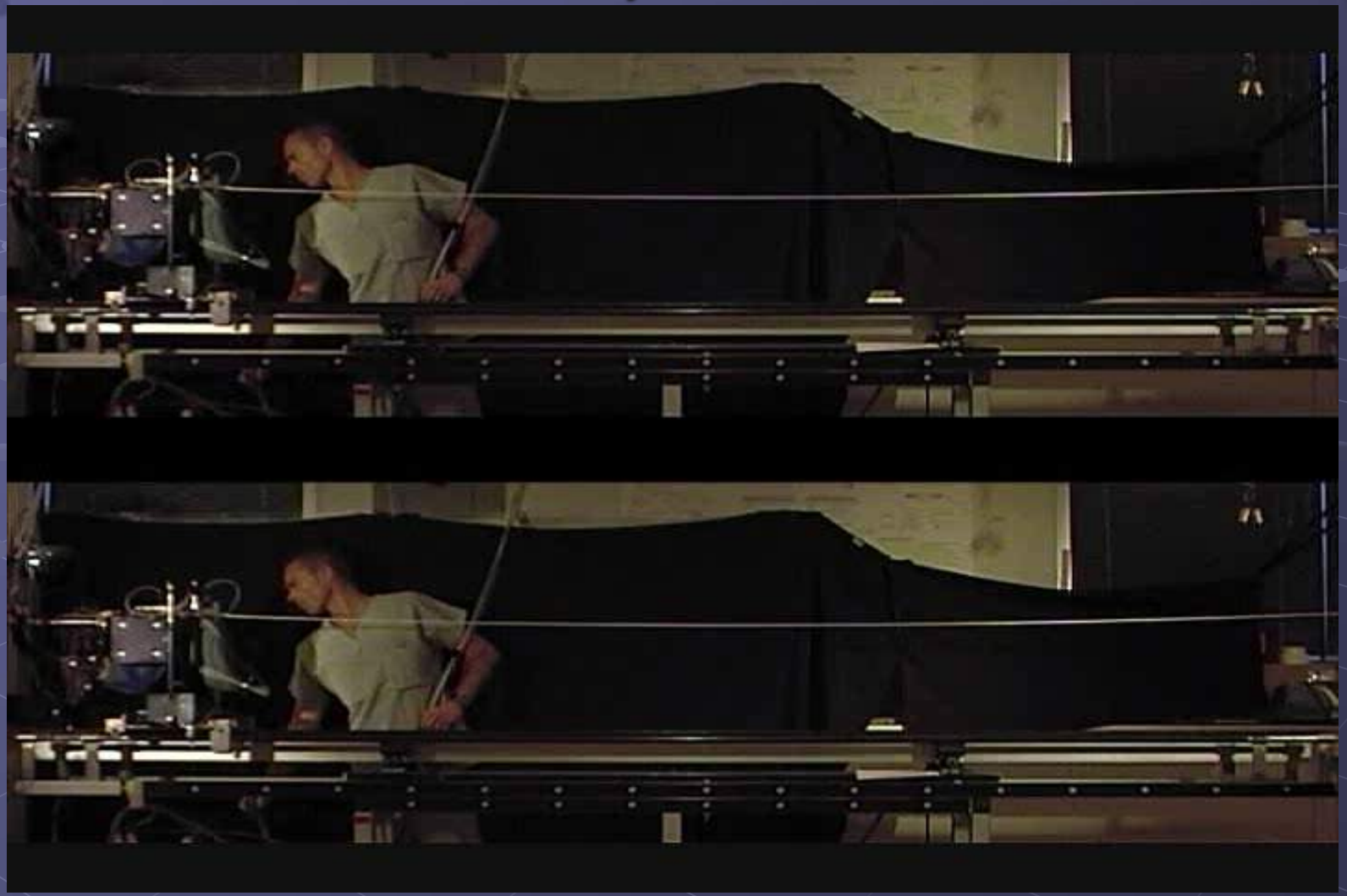






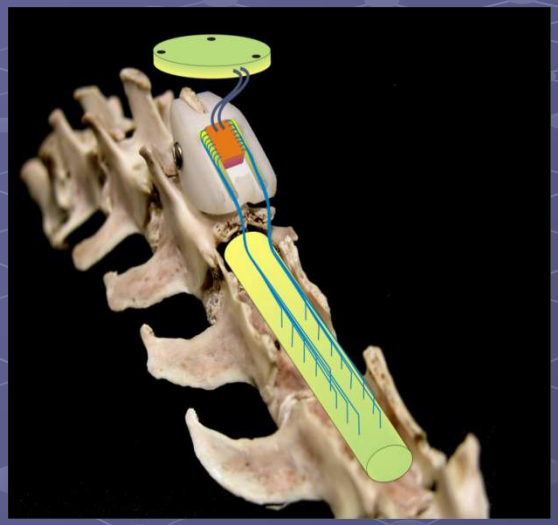
Mazurek et al., 2011

Results: Restoring Locomotion in a "Paralyzed" Cat



Mazurek et al., 2011
Mushahwar et al, 2011

Implanting the Controller onto The Spinal Cord



Mushahwar et al., 2011

Cyberdyne, Inc.

Presentation Outline

- Cameras That Work Like Our Eyes
  - The biological visual system
  - Silicon eyes
  - Making the Blind See
- Restoring Walking After Spinal Cord Injuries
  - The biological locomotion system
  - Silicon model of spinal cord circuits
  - Making the Paralyzed Walk
- Replacing Limbs with Neurally Integrated Prosthetics
  - High degree of freedom prosthetic limbs
  - Closed loop control
- Conclusions

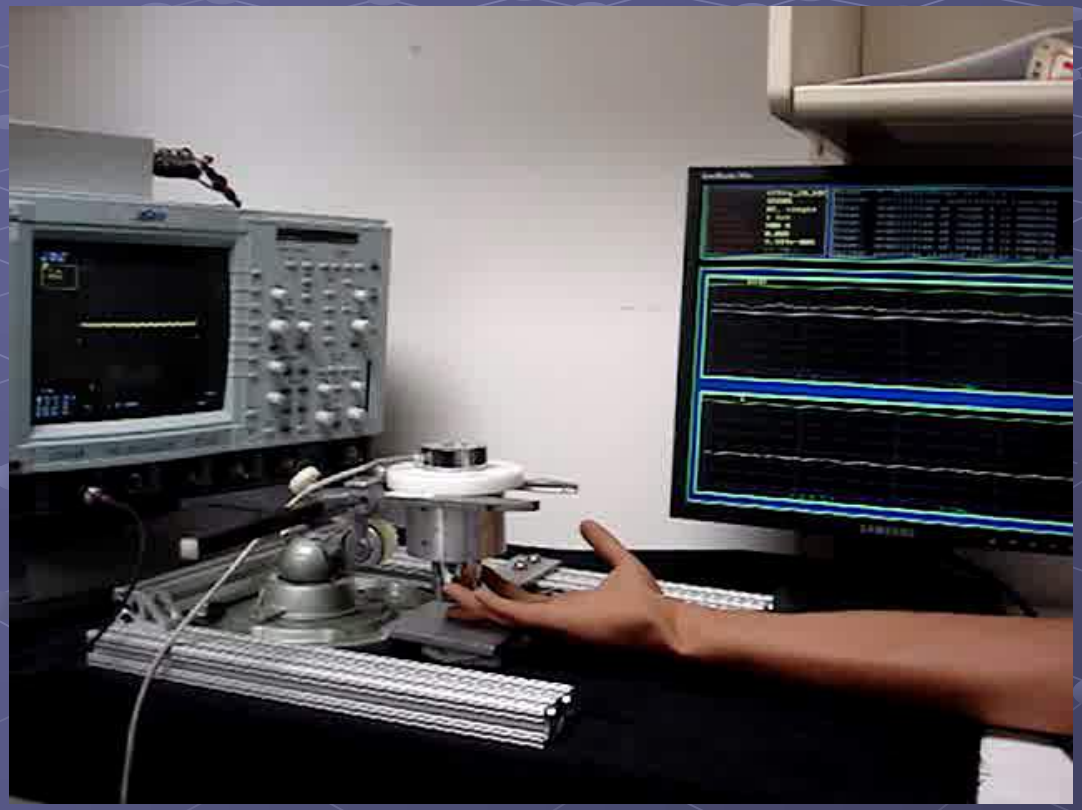
Replacing Limbs: Nerve Reinnervation Prosthetic Arm

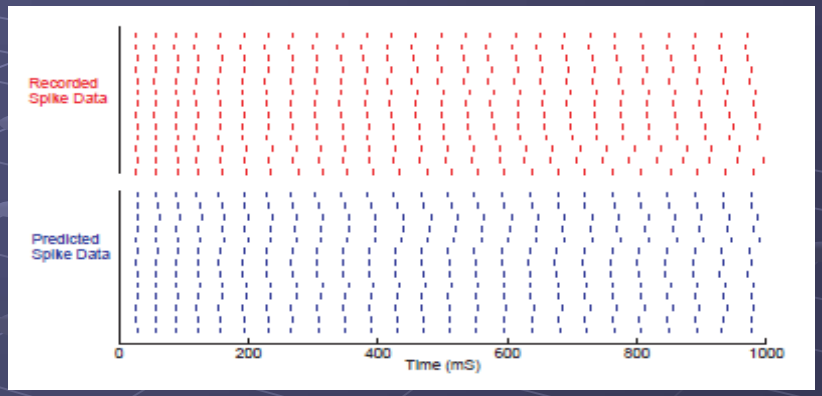
Source: Johns Hopkins U., Applied Physics Lab, RP 2009

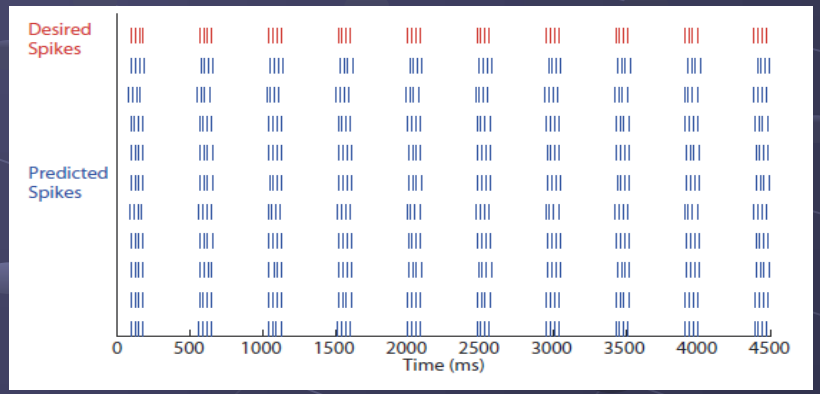
Replacing Limbs: Neurally Integrated Prosthesis

Source: Etienne-Cummings & Thakor Labs (Johns Hopkins), Schieber Lab (Rochester) RP 2009

Encoding Sensory Feedback to the Peripheral Nerve







Modeling the SA-1 Peripheral Nerve Fiber *in silico*
Source: Etienne-Cummings (Johns Hopkins) & Bensmaia (Chicago) Labs

Bensmaia et al., IEEE TBioCAS, 2009
Russell et al, IEEE TBioCAS, 2010 – 11
Russell et al, IEEE TNN, 2010
Russell et al, Neural Comp., 2011

Replacing Limbs: Neurally Integrated Prosthesis

- Acquisition of electrophysiological signals involved in generation of movement
- Extraction of movement-related information from biosignals
- Provide sensory information to the nervous system

Source: Johns Hopkins U., Applied Physics Lab, RP 2009

Conclusion

- The line between mind, body and robotics are quickly blurring and may be disappearing
- In the future we will be able to use electronics and robotics to **seamlessly** mitigate injuries and enhance human capabilities
- Requires basic, computational and applied scientific research in neuroscience and psychology
- **Collaborations** between engineers, biologist and clinicians needed to realize the dream

Acknowledgements

- Various ONR Awards
- Various NIH Awards & Neuroengineering Training Grant
- Various individual NFS Awards
- NSF Graduate Research Fellowships
- DARPA Revolutionizing Prosthetics
- Telluride Neuromorphic Engineering Workshop
- NSF ERC CISST at JHU
- Various AFRL and ARL Awards
- Alberta Heritage Foundation for Medical Research