Learning From Nature to Make Machines See and Robots Walk

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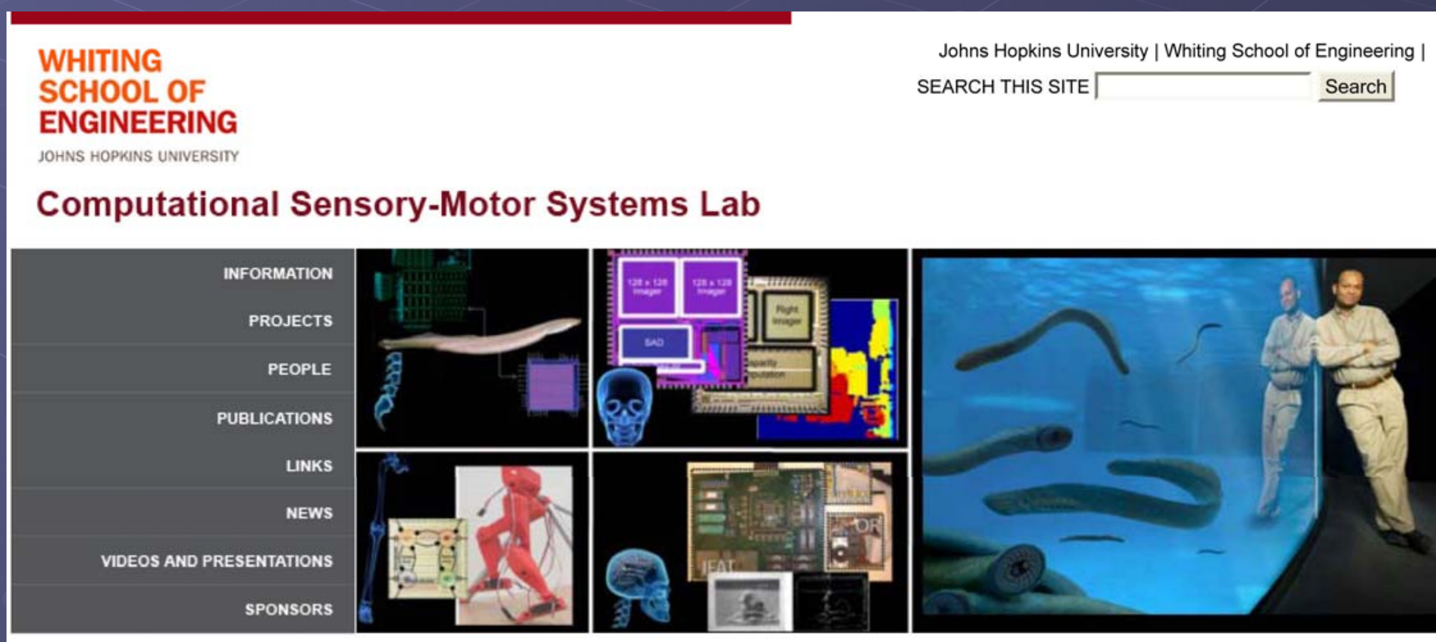
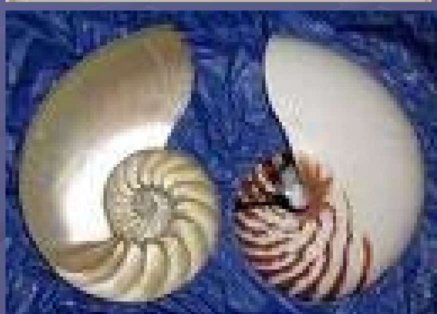
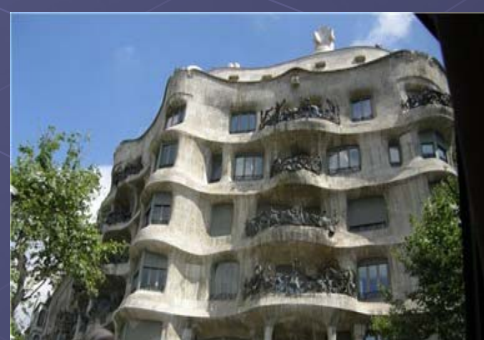
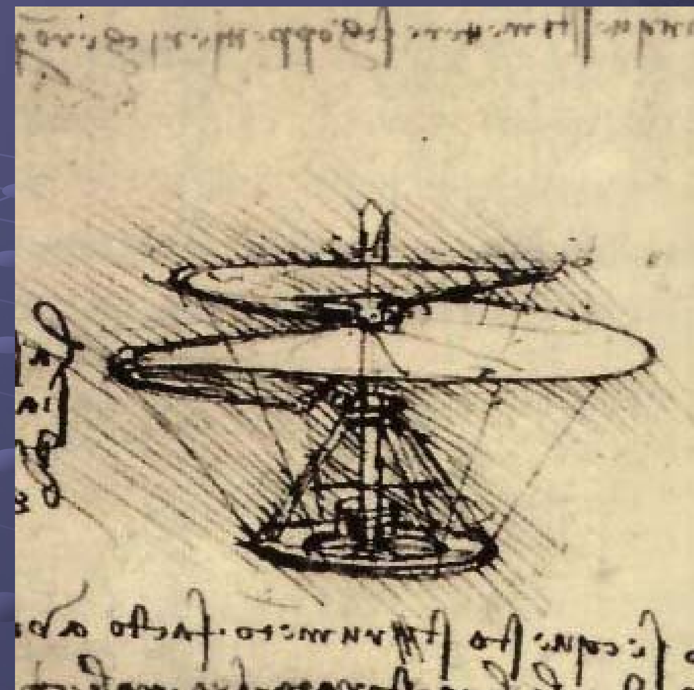


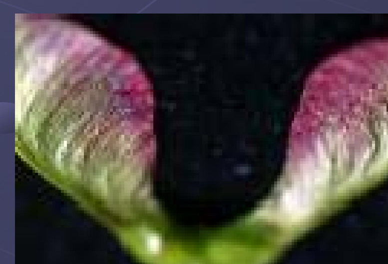
Nature's Inspiration ….

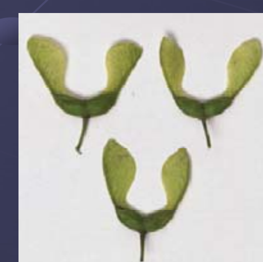




Antoni Gaudi, *Casa Mila*, 1906 – 1910
"Form"



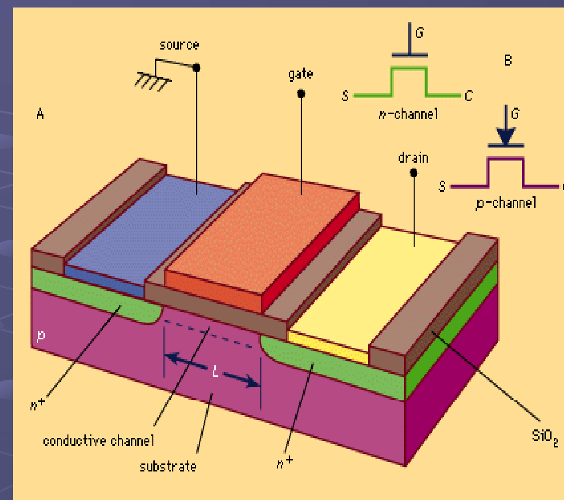


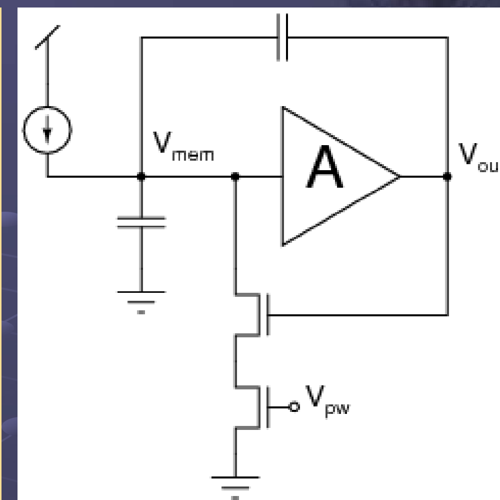


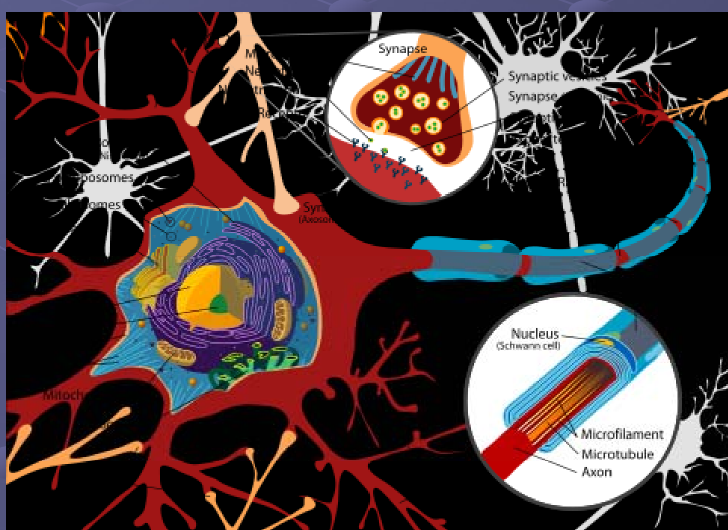
Leonardo da Vinci, *Helicopter*,
1452 – 1519
"Function"

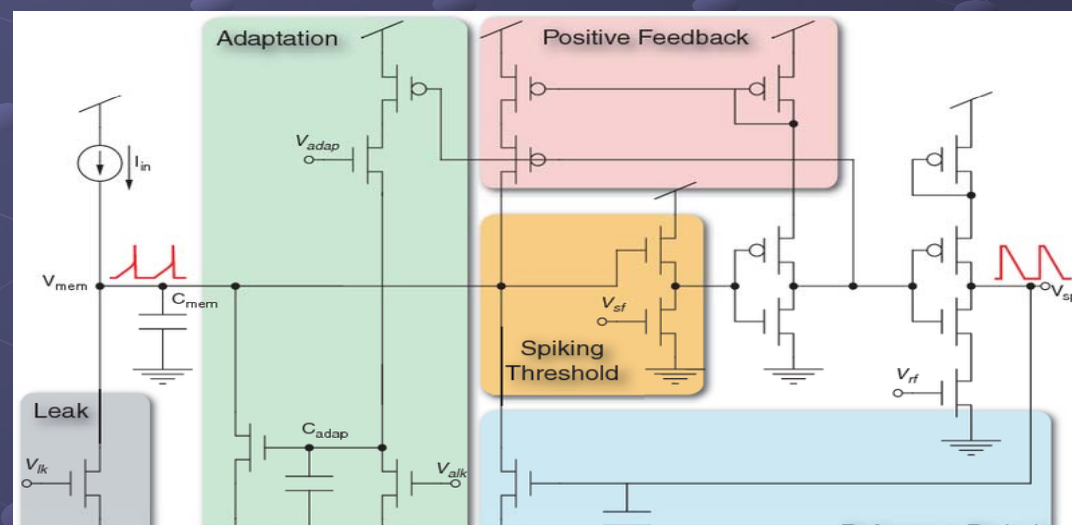
After wikipedia.com

Nature’s Inspiration ….









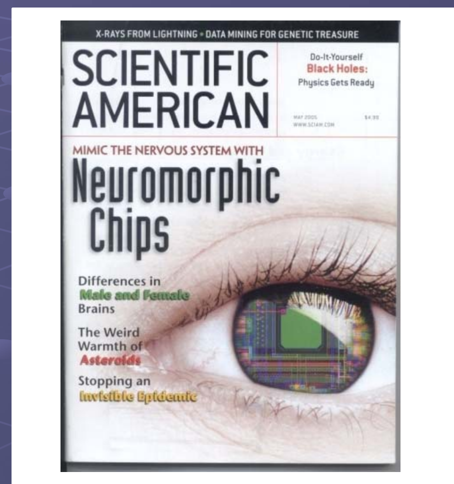
G. Indiveri *et al*, 2007

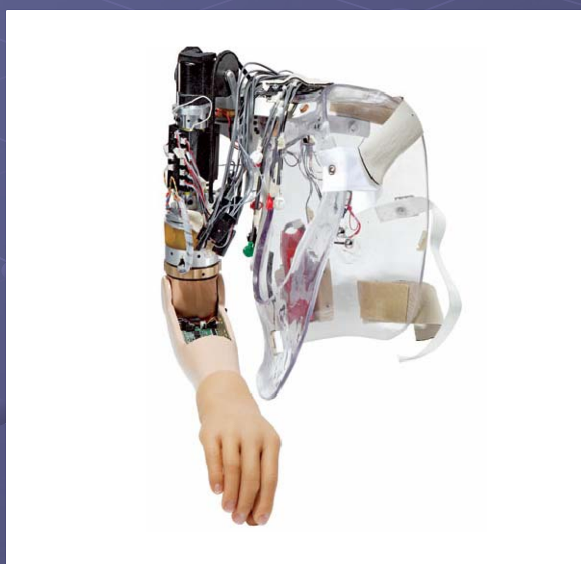
Carver Mead, *Neuromorphic Circuits*, 1986 - 1990

After wikipedia.com

The Big Picture: Motivation

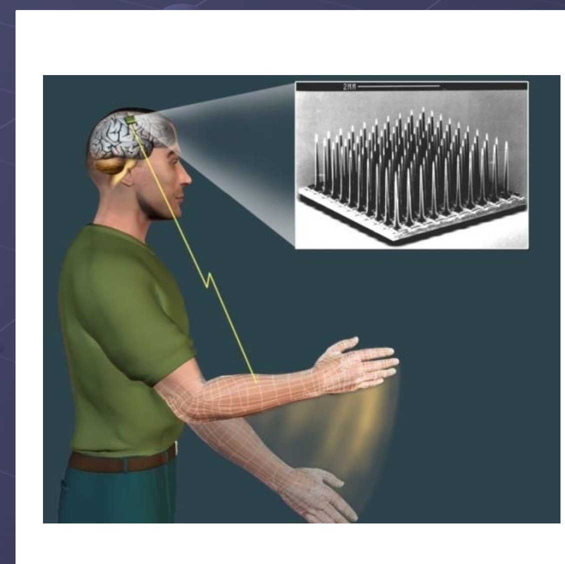
Developing Biomorphic Robotics





Restoring function after limb amputation

Adaptive Biomorphic Circuits & Systems



Restoring function after severe spinal cord injury

Presentation Outline

- Making Machines See
  - The biological visual system
  - Silicon eyes and brains
- Making Robots Walk
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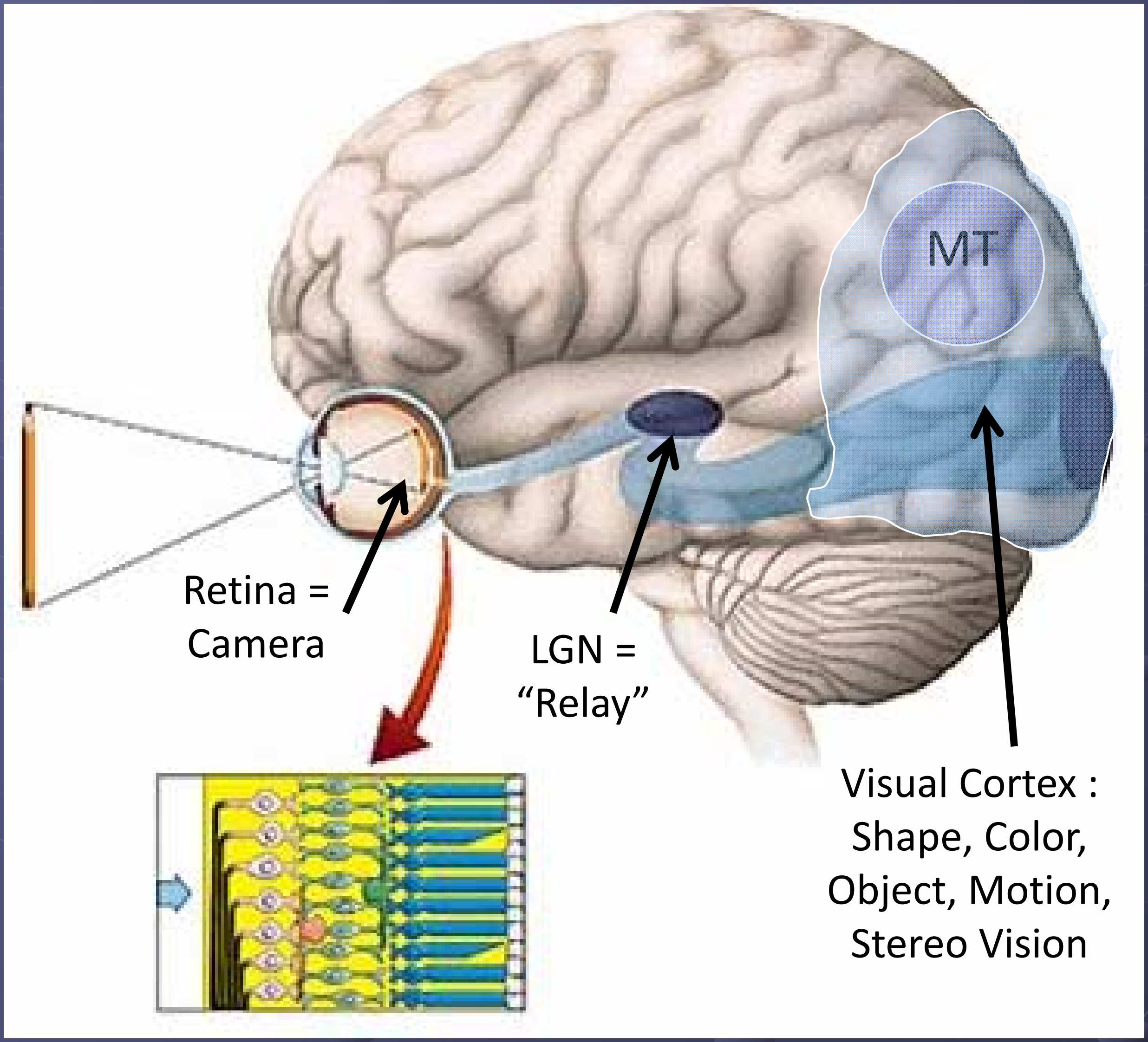
  - Silicon spine and Walking robots
- Restoring Function to the Impaired
  - Spinal cord injury and locomotion prosthesis
  - Gait controller: *silicon model of spinal cord circuits*
  - Phase controller: *controlling Behavior*
- Future and Conclusion
  - High degree of freedom prosthetic limbs
  - Sensory feedback and haptics

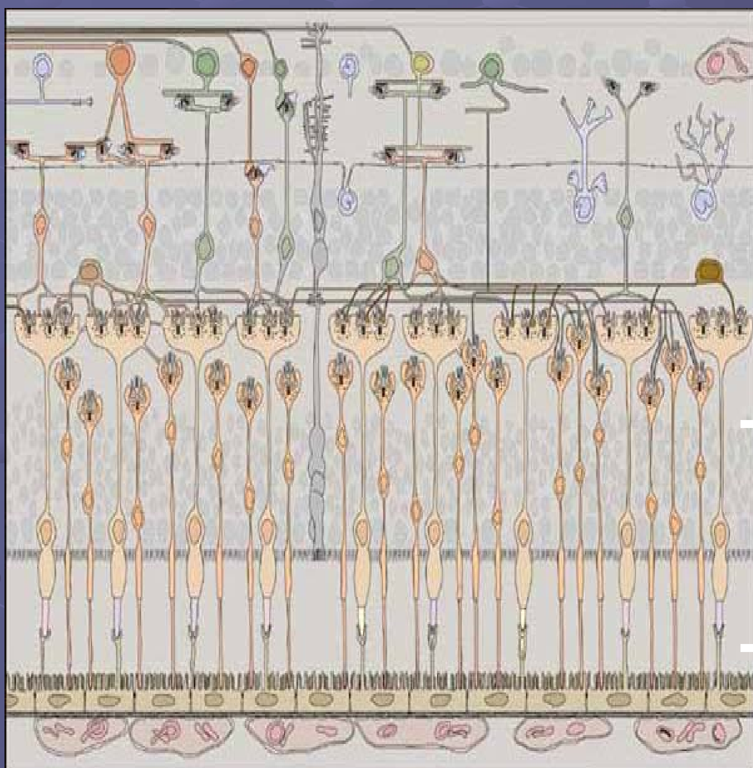
Learning from Nature to Make Machines See

Visual Processing in Humans

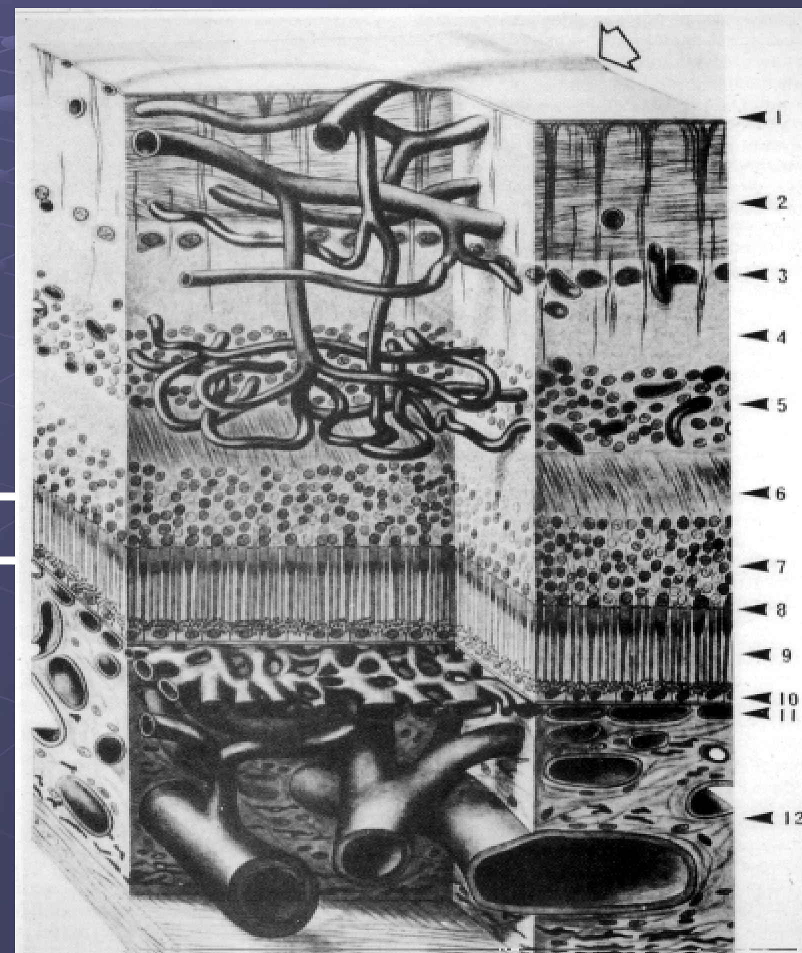


After wikipedia.com

Front-End of Vision System: The Retina Built for Perception



Rods
and
Cones



Source unknown

Conventional CMOS Cameras: Making Pretty Pictures

Camera phones are driving the CMOS camera market

150 million sold in 2004, 55% annual growth rate to >1 Billion by 2009

Power consumption is relatively low (~ 10's of mW for VGA)

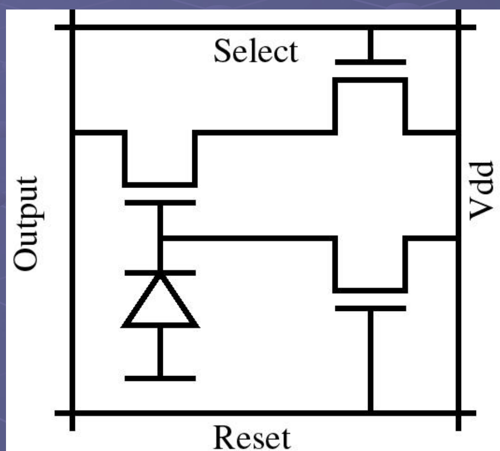
2 Mega Pixels is probably the limit of usefulness

Download bandwidth is a problem (service providers would like more people to download their pictures)

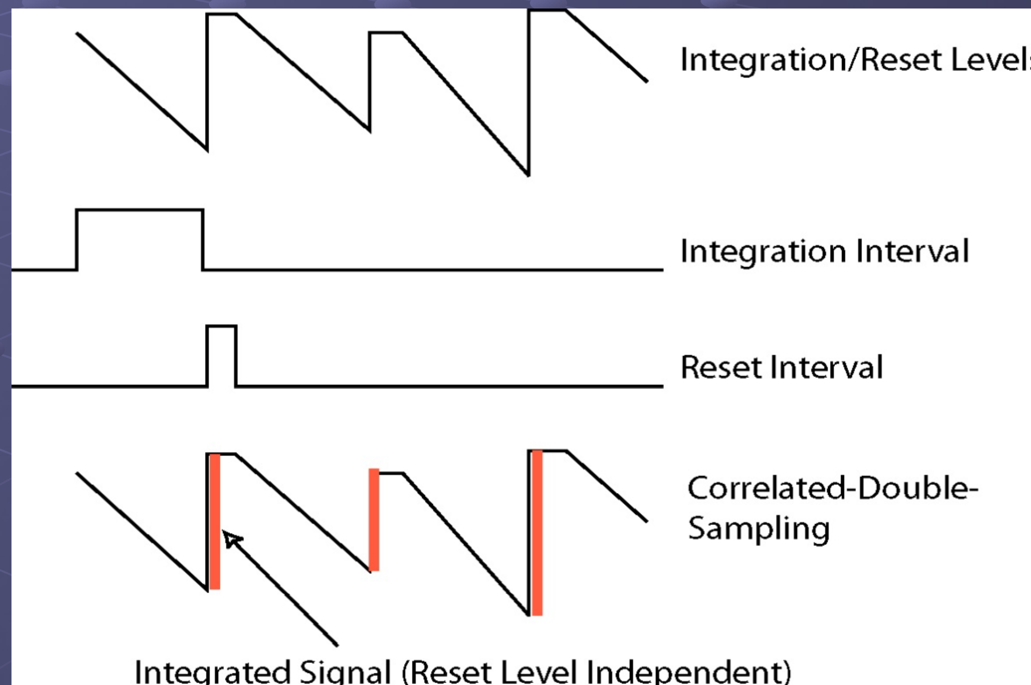
There is a fear that it will represent the next technology bubble …. So much hype, legal problems …

Small (~ 100 x 100 pixels) imagers, with smarts (e.g. motion, color processing) have market in toys, sensor networks, computer optical mouse …

Conventional CMOS Cameras: Voltage Mode Active Pixel Camera



Simple APS:
Fossum, 1992



Integrative Imagers:
Voltage domain; Dense arrays; Low Noise;
Low dynamic range, Not ideal for computation

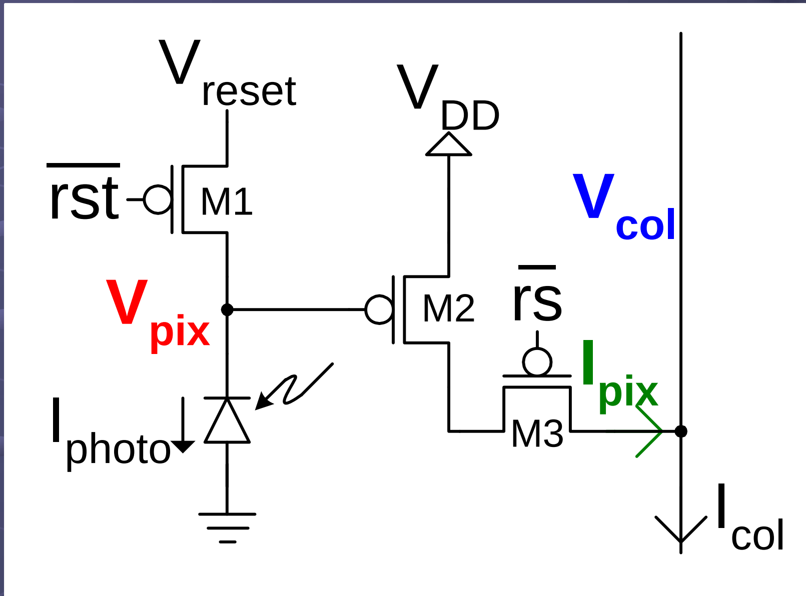
Current Active Pixel Sensor

Integrating

Current output

$V_{reset} \leq V_{DD} - |V_{tP}|$

$V_{col} \approx V_{DD} - 0.2\text{V}$



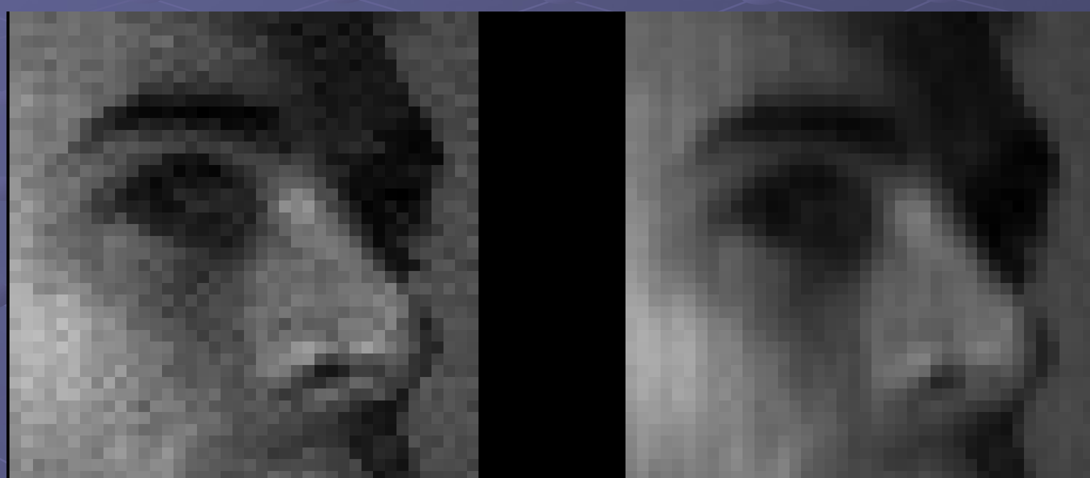
$$I_{pix} \approx \frac{W_2}{L_2} k_p \left(V_{DD} - |V_{tP}| - V_{pix}\right)\left(V_{DD} - V_{col}\right)$$

$$I_{pix} \propto -V_{pix}\left(V_{DD} - V_{col}\right)$$

$$I_{pix} \propto -V_{pix} \propto \text{Light} \times \text{Time}$$

Philipp et al, 2008

Improved Current Mode Photodetection



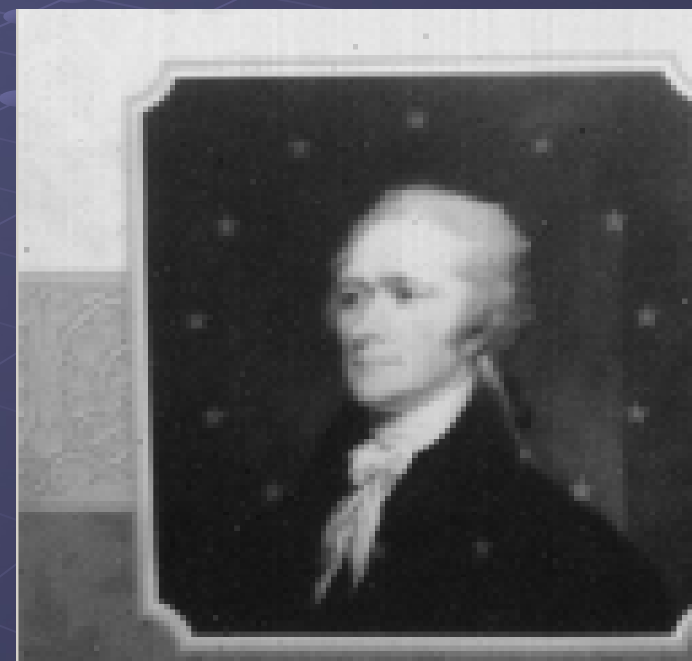
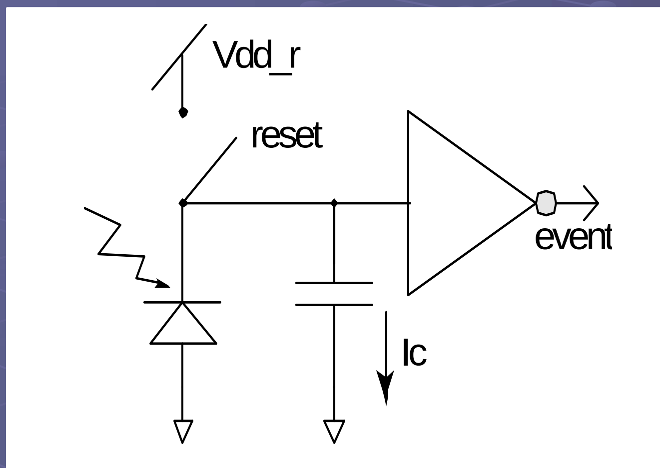


Image quality has been improved

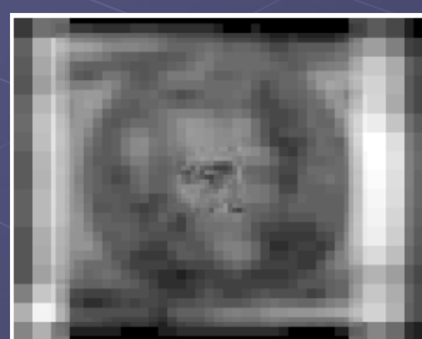
Non-linearity due to mobility degradation degrades performance under bight light

Philipp et al, 2008

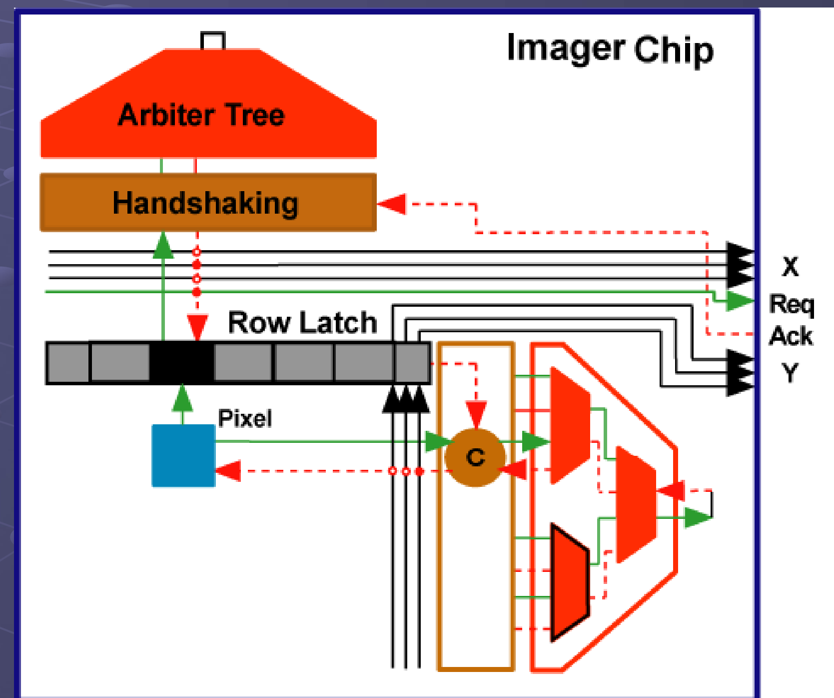
Spike-Based CMOS Cameras: Octopus



Imaging Concept



Sample Image



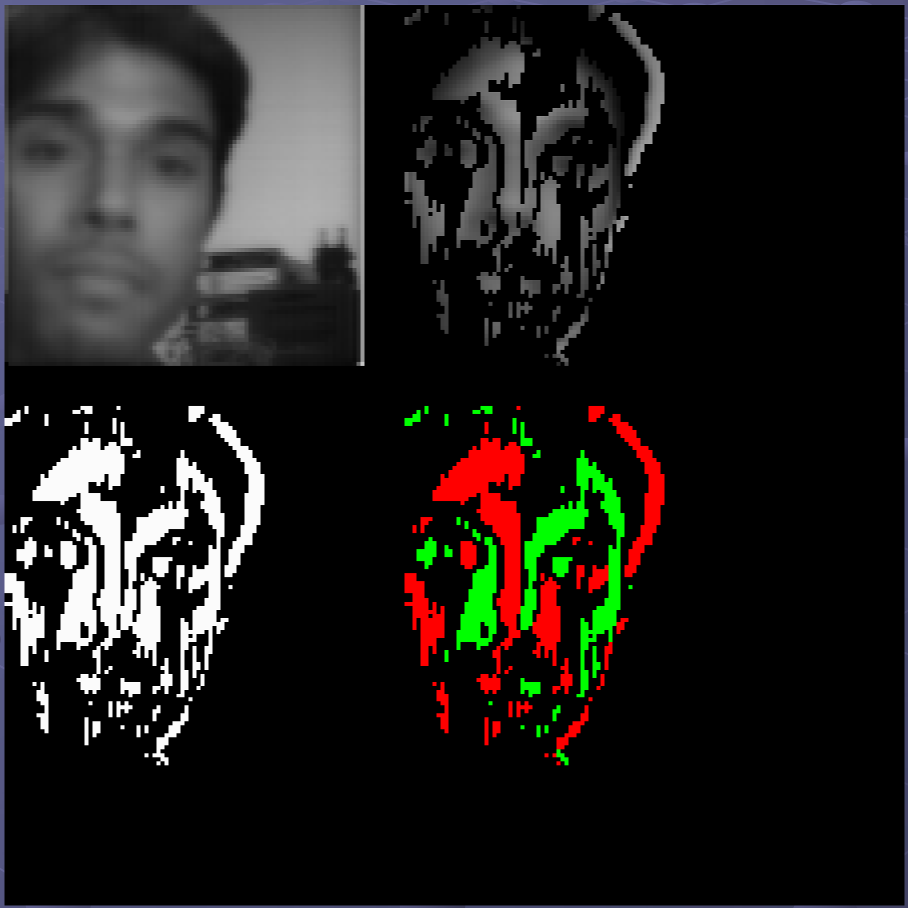
Other Approaches:
- W. Yang, "Oscillator in a Pixel," 1994
-J. Harris, "Time to First Spike," 2002
- A. Bermak, "Arbitrated Time to First Spike," 2007

Culurciello, Etienne-Cummings & Boahen, 2003

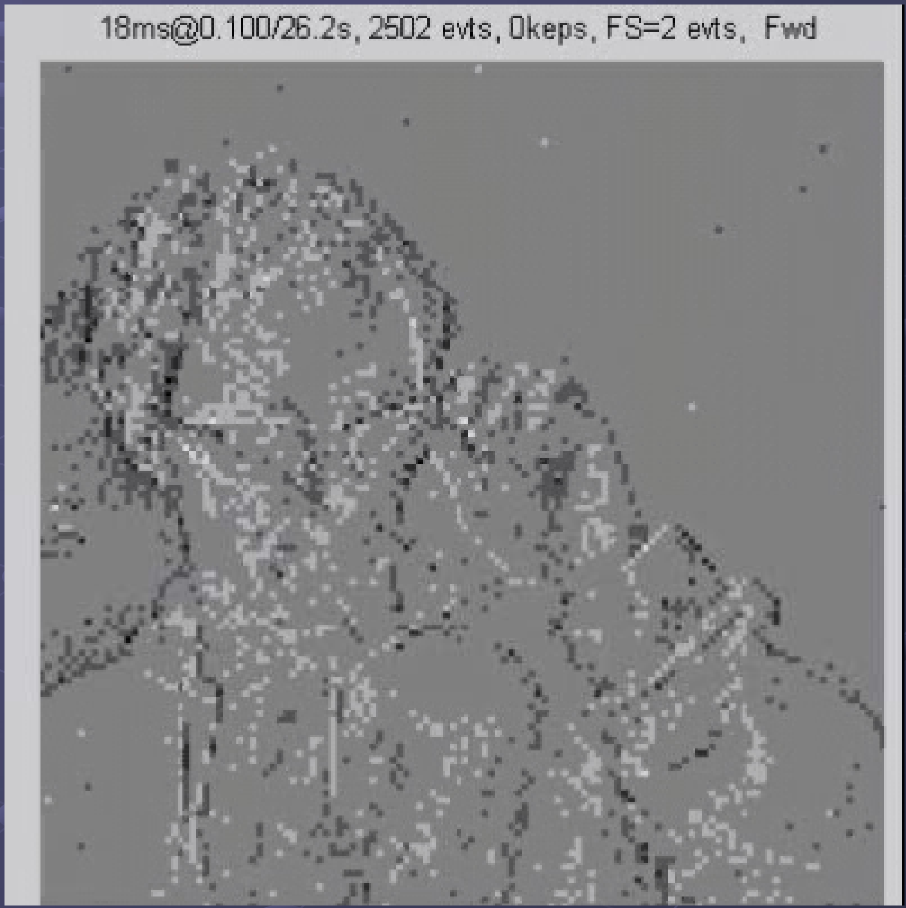
APS-Based Difference Imagers

Gruev & Etienne-Cummings, 2004

On-Set and Off-Set Imaging

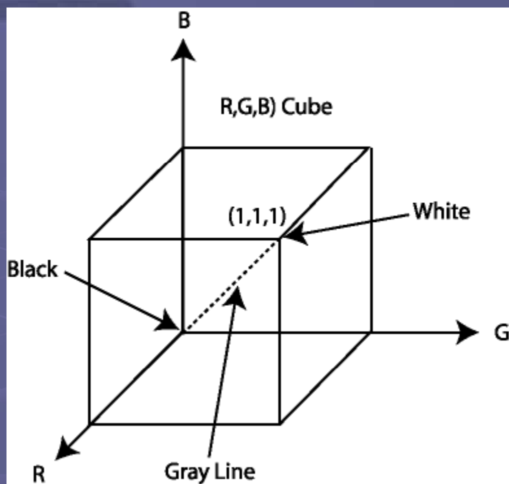


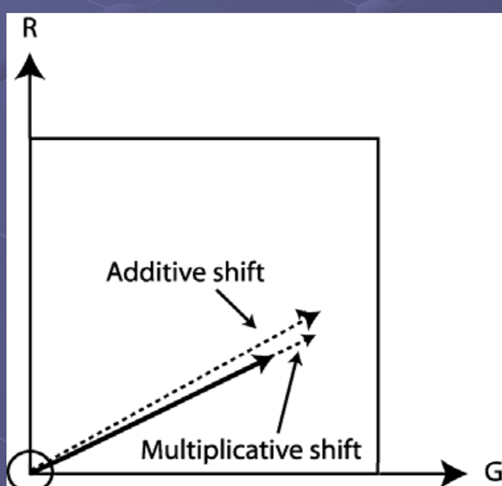
Chi et al., 2007

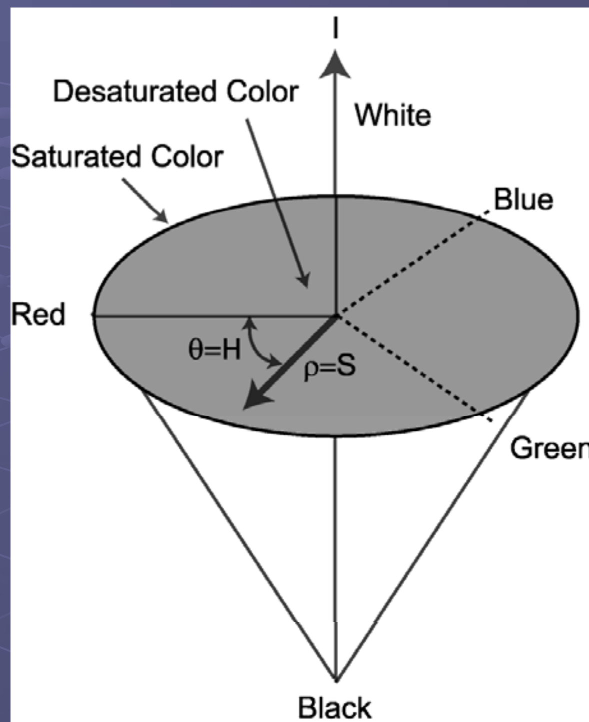


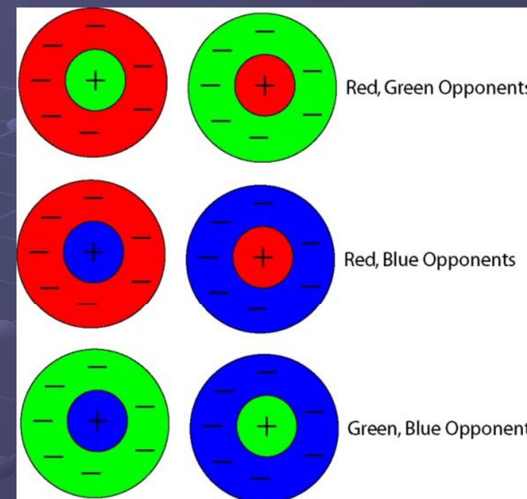
Delbruck et al., 2008

Color Processing: RGB to HSI: Why?









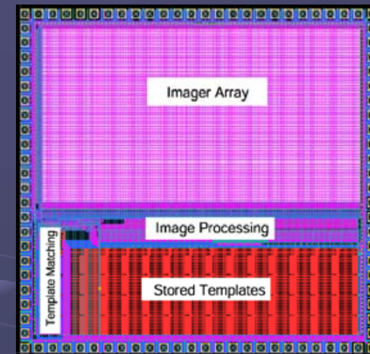
$$r = I\_bias\frac{R}{R+G+B}; g = I\_bias\frac{G}{R+G+B}; b = I\_bias\frac{B}{R+G+B}$$

$$Sat(R,G,B) = I\_bias[1-\min(r,g,b)]$$

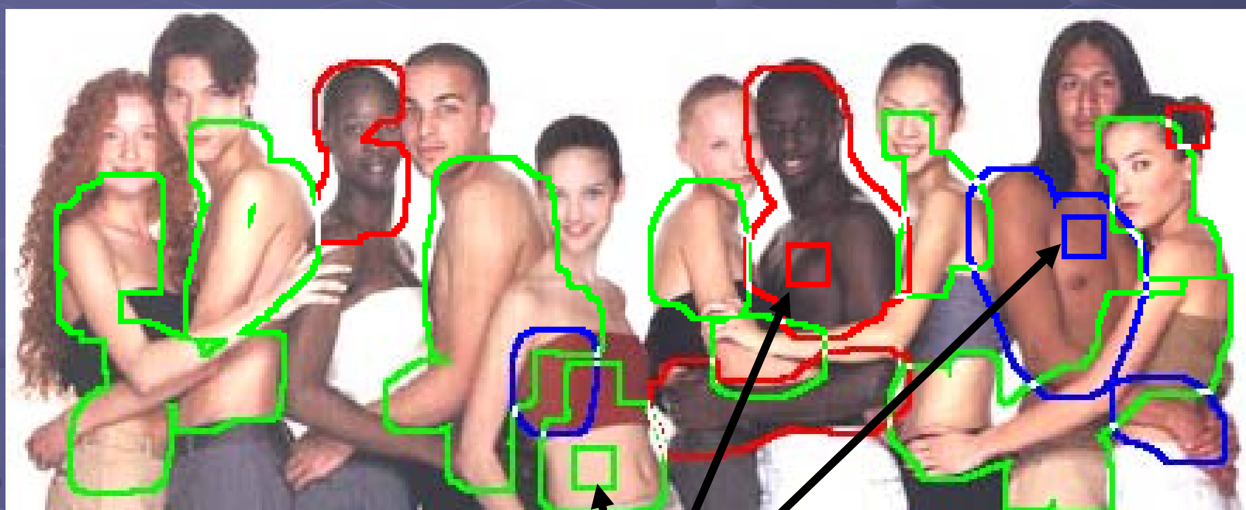
$$Hue(R,G,B) = \arctan(X/Y) = \arctan\left(\frac{0.866(G-B)}{2R-G-B}\right)$$

Etienne-Cummings et al., 2002

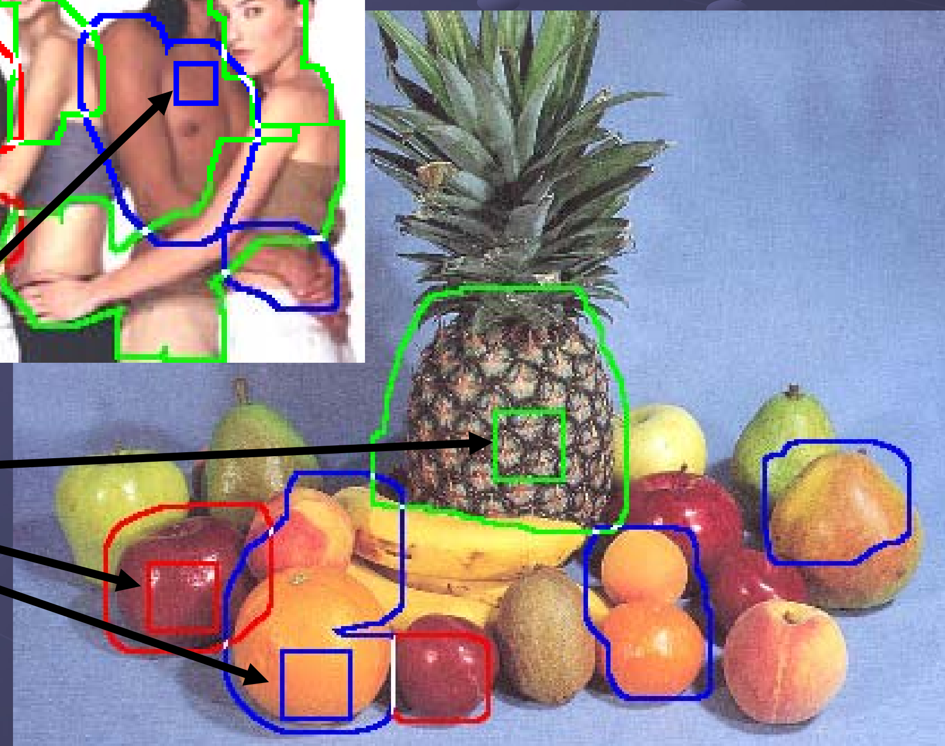
Examples: Chroma-Based Object Identification



Skin Identification



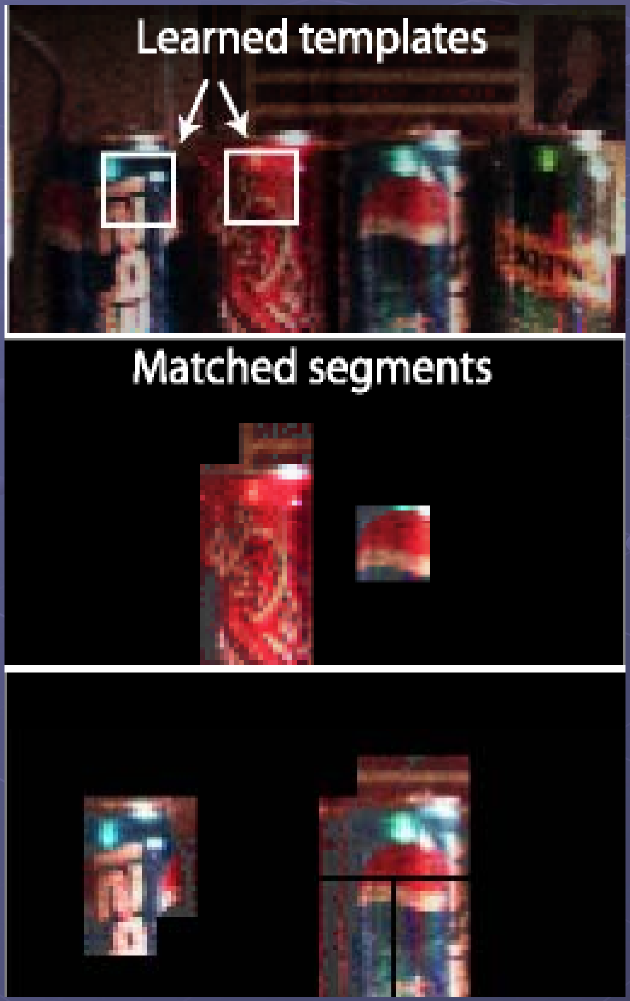
Fruit Identification

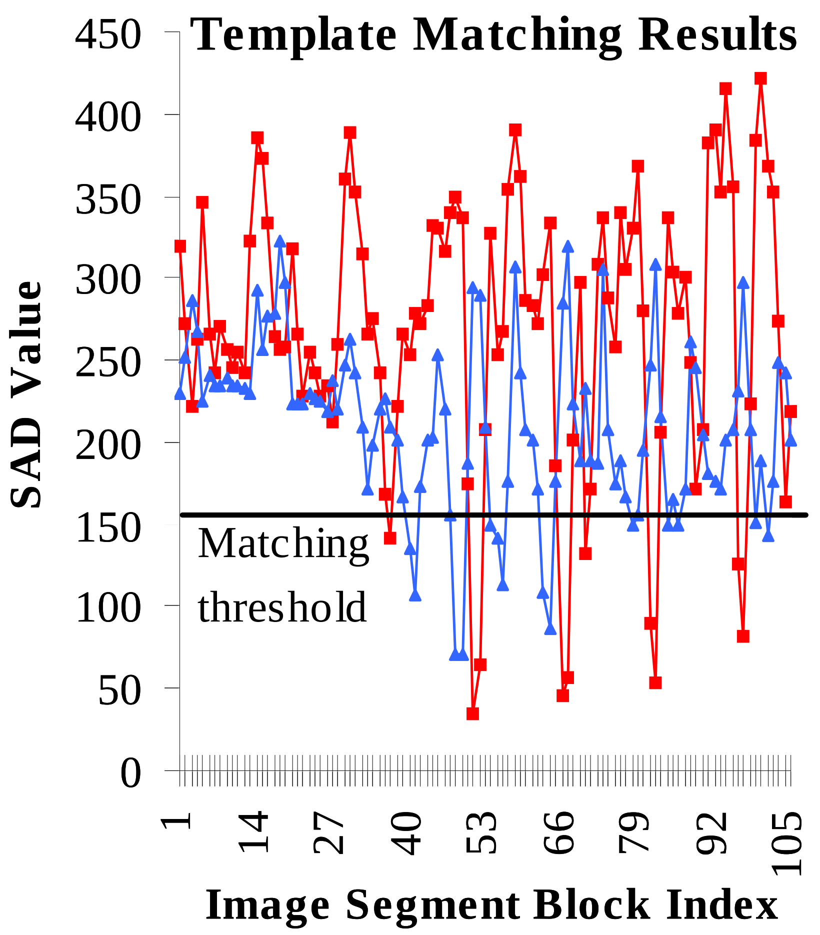


“Learned” templates

Etienne-Cummings et al., 2002

Coke or Pepsi?





$$SAD = \sum_{\Theta} \left| I_{i,j} - T_{i,j,k} \right| < \lambda_k$$

Etienne-Cummings et al., 2002

Two Eyes: Stereo Vision

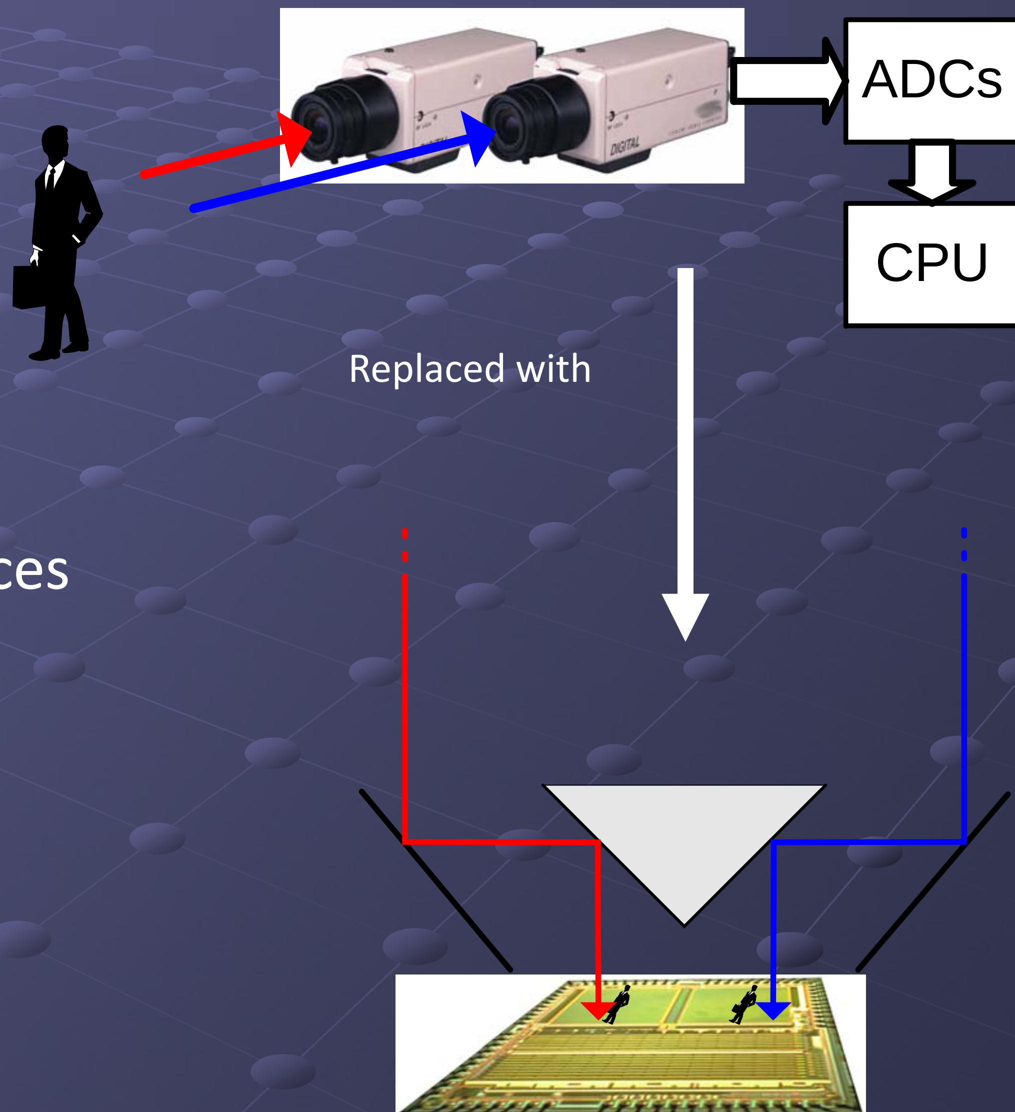
Single-chip stereo (3D) vision system

For use in:

- Autonomous systems
- Vehicle navigation
- Man-machine interfaces

Requirements

- Fully integrated
- Digital output
- Low power



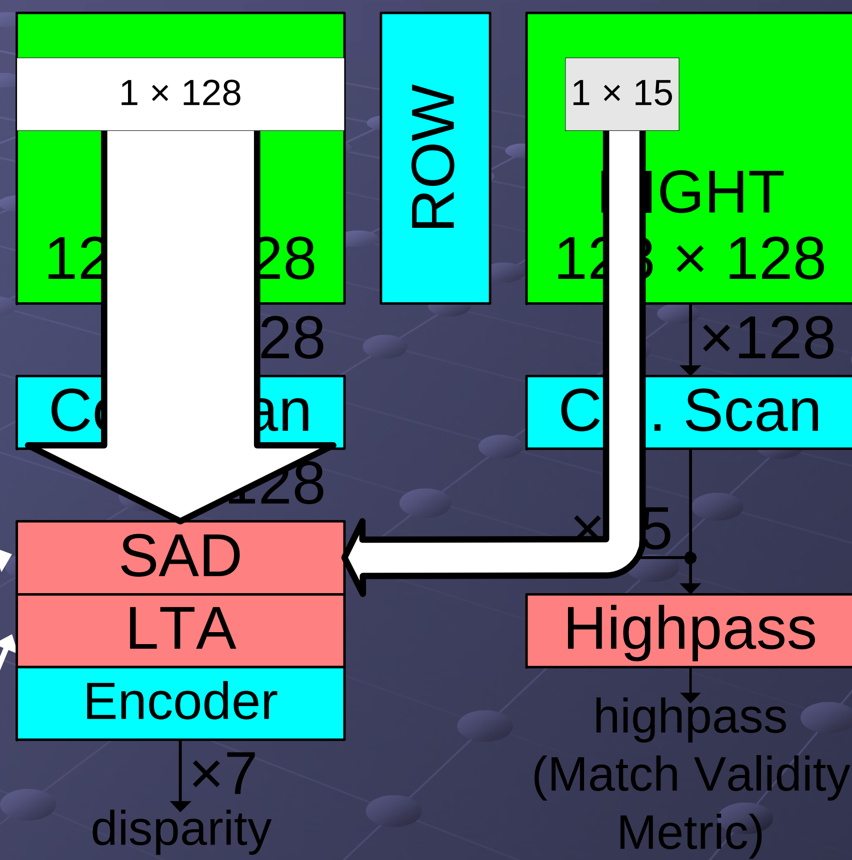
Philipp et al., 2006

Chip Architecture

- Vertical averaging
  - Select multiple rows
- Parallel computation SAD matching metric
- Loser-Take-All
  - Smallest SAD value

$$SAD(x,y,d) = \sum_{i=x}^{x+14} \left| r_{sum}(i,y) - l_{sum}(i+d,y) \right|$$

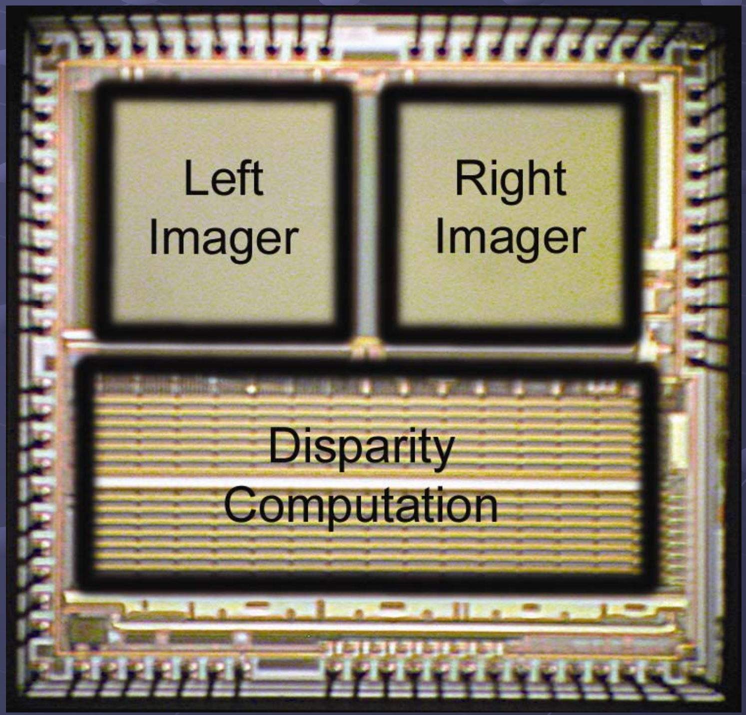
$$\Delta x(x,y) = \underset{d \in D}{\operatorname{argmin}} SAD(x,y,d)$$



Philipp et al., 2006

Chip Characteristics

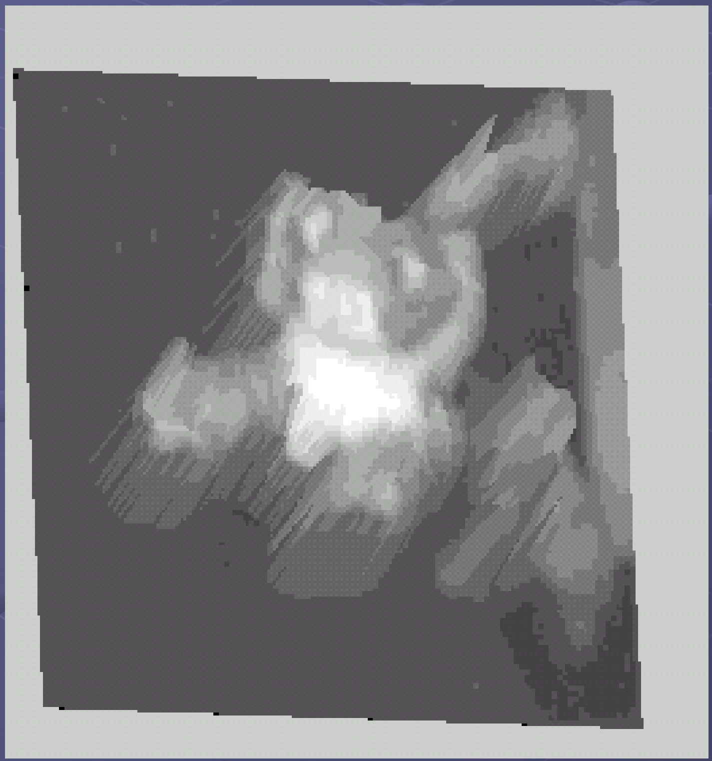
Technology	0.35µm 4M2P
Die Size	3.5mm x 3.3mm
Pixel Size	10µm x 10µm
Fill Factor	26%
Image FPN	1.2% (no CDS)
Imager Size	128 x 128 x 2
Depth Map Size	114 x 124
Frame Rate	30fps (40fps max)
Power Consumption	33.2mW (3.3V, 30fps)

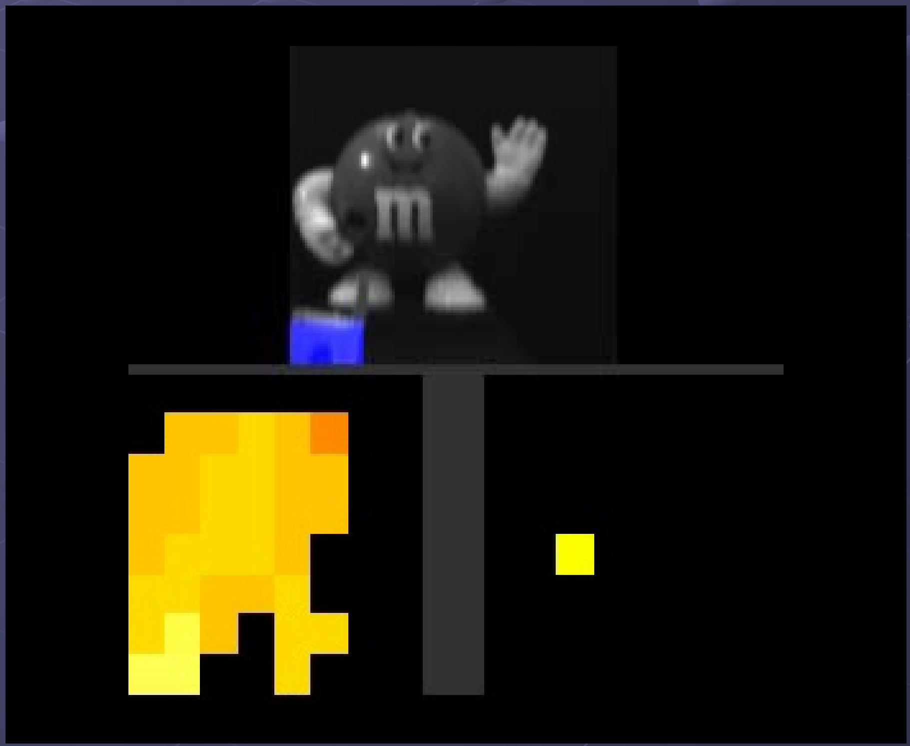


Philipp et al., 2006

Results

- Movie: 30fps @ 33.2mW
  - Right imager output texture mapped to depth results
  - Color (at lower right) corresponds to depth
  - Note: Plateau under the tiger is a black table





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Learning from Nature to Robots Walk

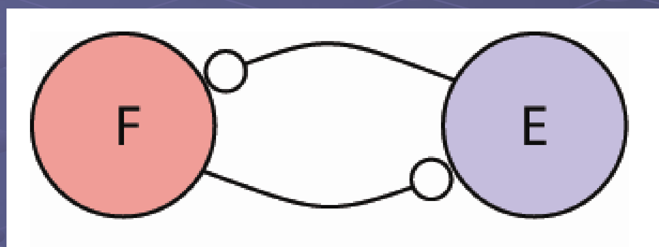
Central Pattern Generator (CPG)

- In the spinal cord of vertebrates
- Generate patterned outputs to activate muscles
- Motor systems with regular, periodic activity (breathing, chewing, locomotion, etc.)
- Architecture is preserved across species [Cohen et al., 1988]
- CPG is used for “*periodic*” not specialized, locomotion

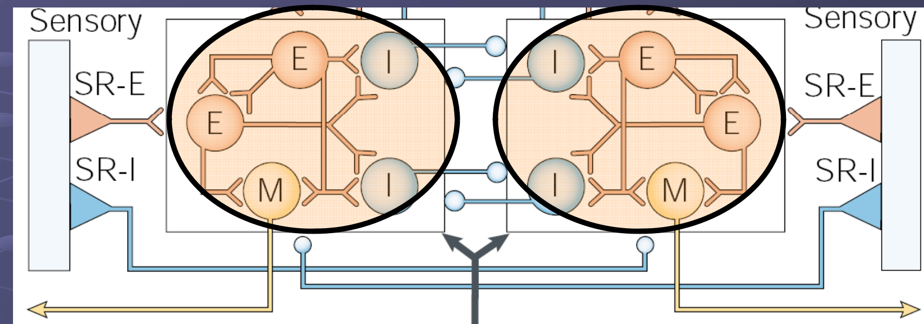
Source: J. M. Cleese, MPFC, 1970

CPG Architecture

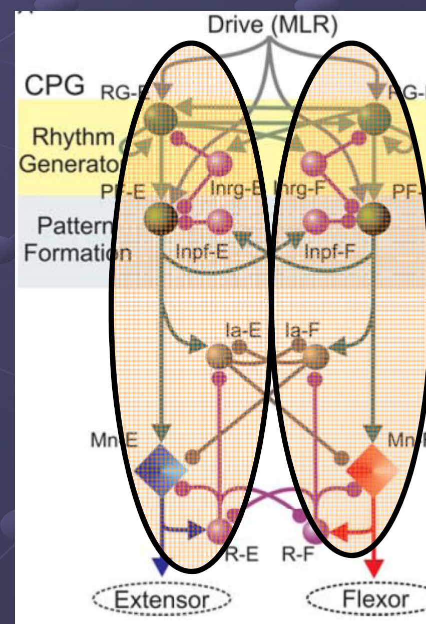
- First conceptual "model" in 1911 by T. G. Brown: half-center oscillator



- HCO structure preserved in modern models
- Cellular models in primitive vertebrates
- Models in higher vertebrates are less detailed; designed to match behavioral data

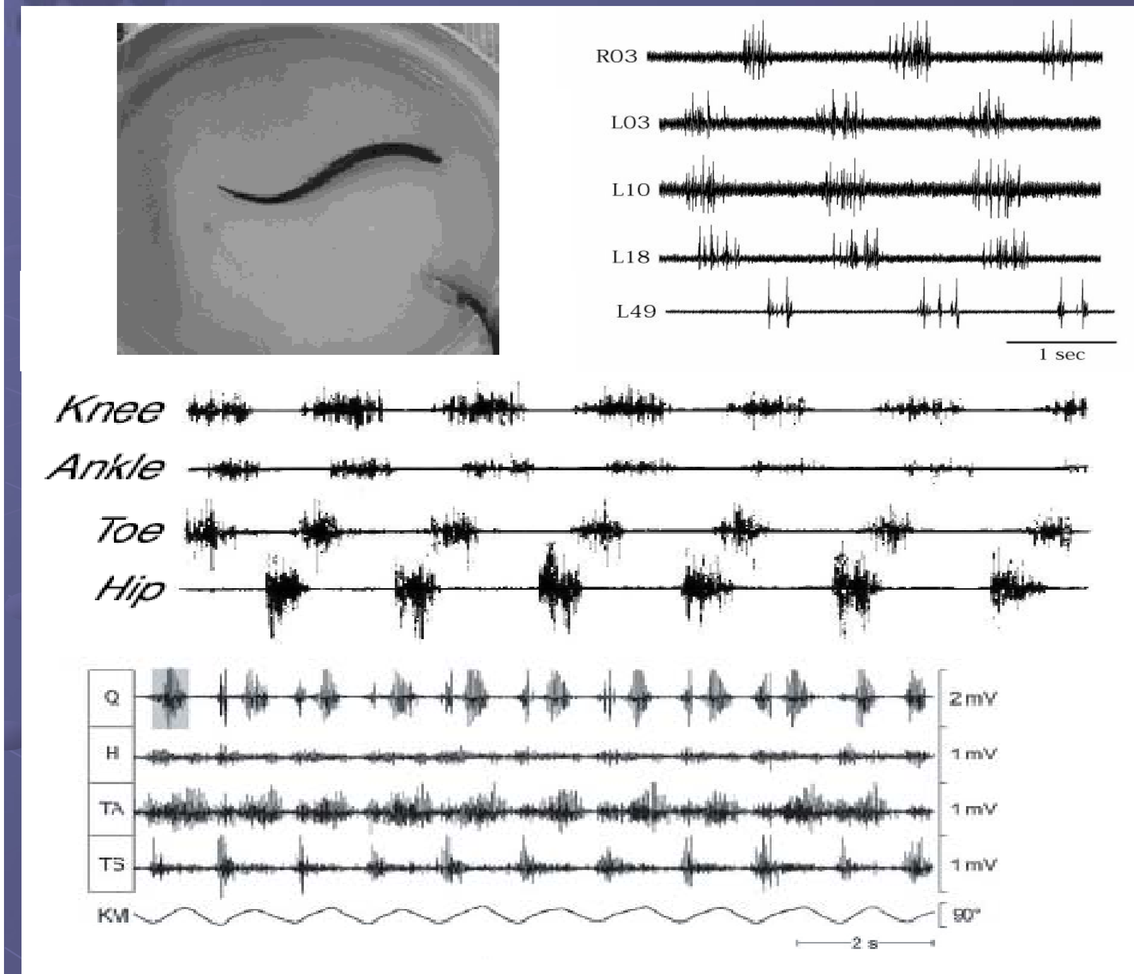


Source: Grillner, Nat Rev Neurosci, 2003



Source: Rybak et al., J Physiol, 2006

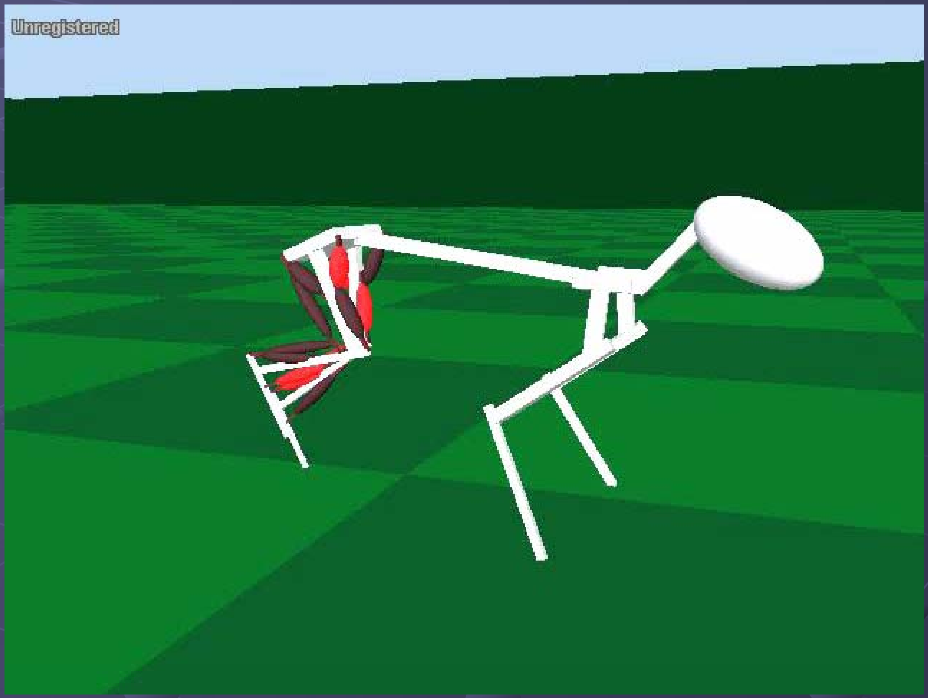
CPGs in Action



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

Cat Walking

- IF-THEN formulation of "rules" governing hind limb stepping in cats:
  - Stance-to-swing transitions:
    IF ipsilateral hip is extended
    AND ipsilateral limb is unloaded
    AND contralateral limb is bearing weight
    THEN initiate flexion in the ipsilateral limb
  - Swing-to-stance transitions:
    IF ipsilateral hip is flexed
    THEN initiate extension in the ipsilateral limb

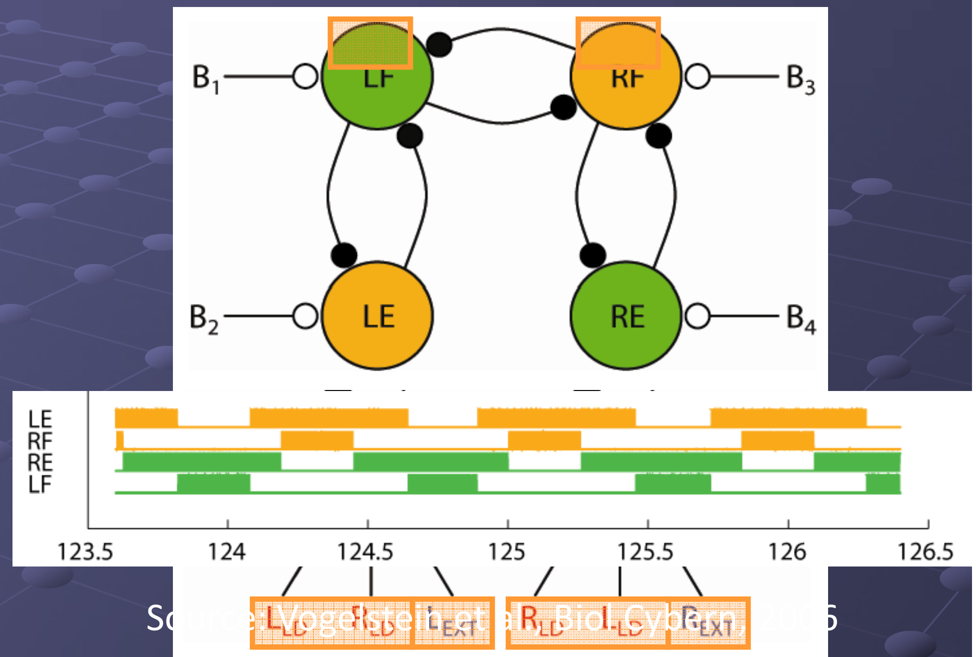


Ekeberg and Pearson, J Neurophys, 2005

Saigal et al., 2004; Prochazka, 1996; Guevremont et al., 2007

Designing the Gait Controller's CPG Network

- Patterns in normal walking and IF-THEN formulation provides basis for CPG network
- Incremental design process
  - Extensors and flexors in counterphase
  - Alternate between stance (extension) and swing (flexion) phases ~ 70-30 duty cycle
  - Stance to swing and vice-versa triggered by two main proprioceptive inputs
    - Hip angle
    - Ankle load
- Extensible: replace flexor and extensor neurons with hip/knee/ankle subpopulations
- Structure similar to biology-based models [Pearson, personal comm.]

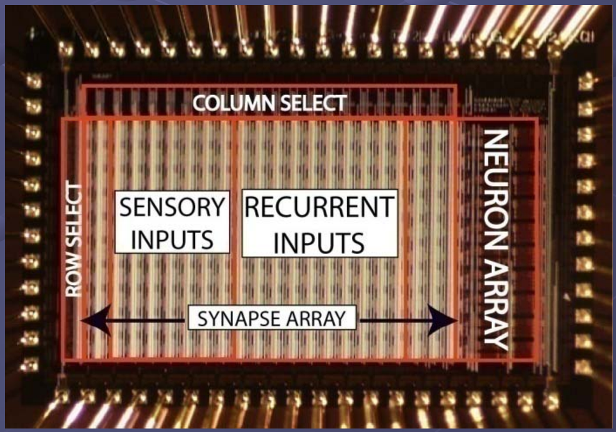


Source: Vogelstein et al., *IEEE TBioCAS*, 2008

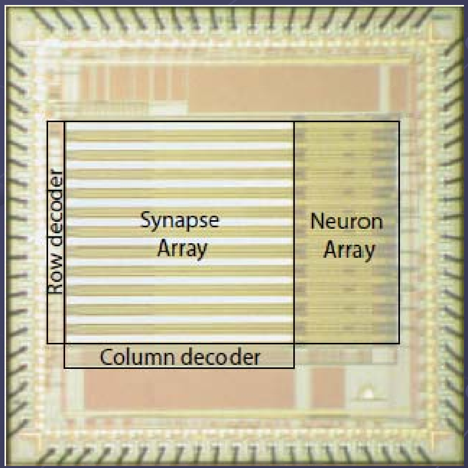
- Synaptic weights, sensory, and lateral inhibitory inputs, adaptation, control timing between swing/stance transitions or sensory-driven

Hardware Development: Gait Controller

- Develop hardware system to prescribe motor output based on pre-defined gait and current sensorimotor state
- Need to know what the biological CPG is doing at all times and what we want it to do next in order to effectively control it
- Build a silicon model of biological CPG, i.e. a neuromorphic silicon CPG chip (SiCPG)

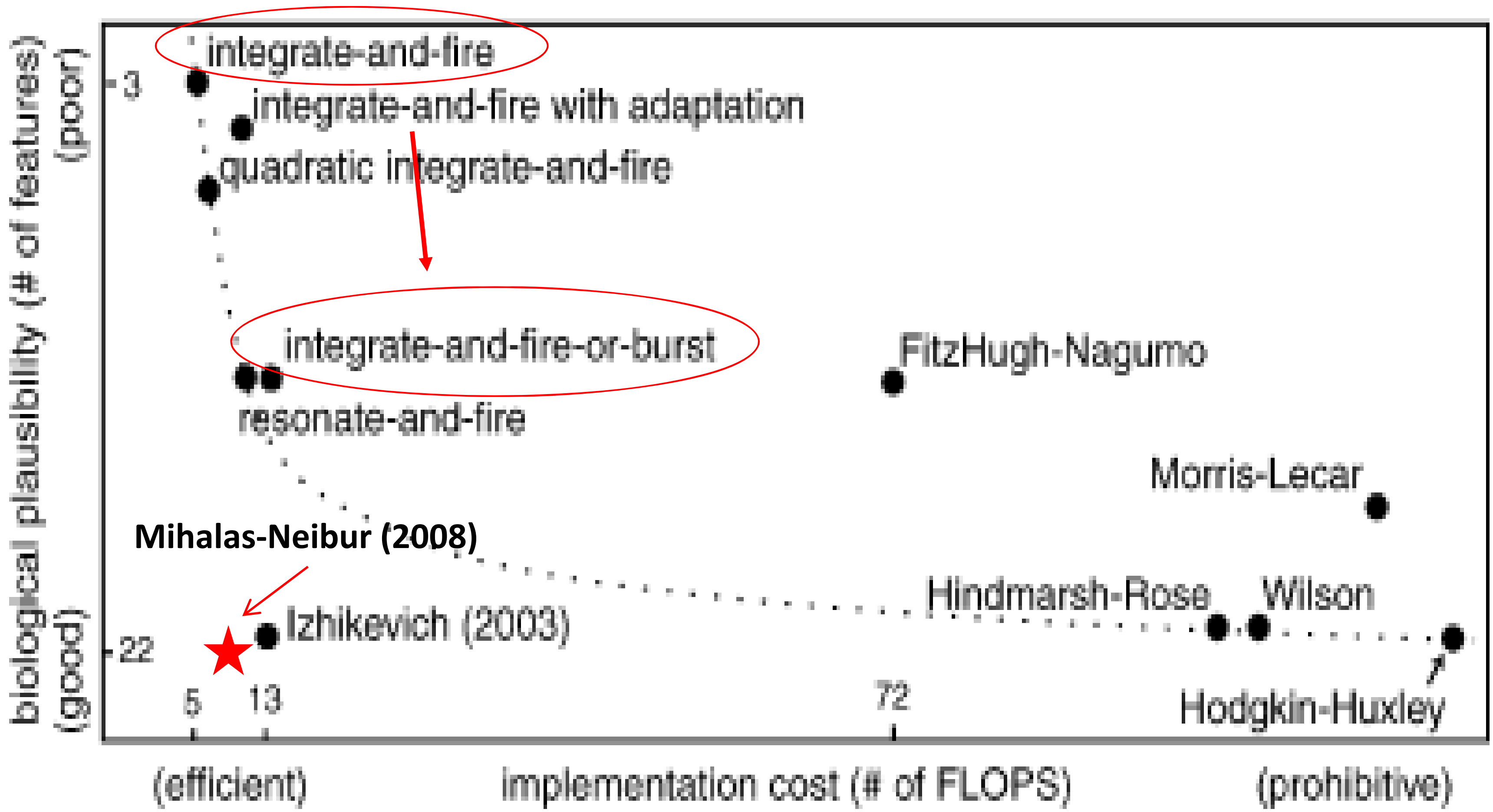


CPGv2 (Tenore et al., 2004)



CPGv3 (Tenore et al., 2006)

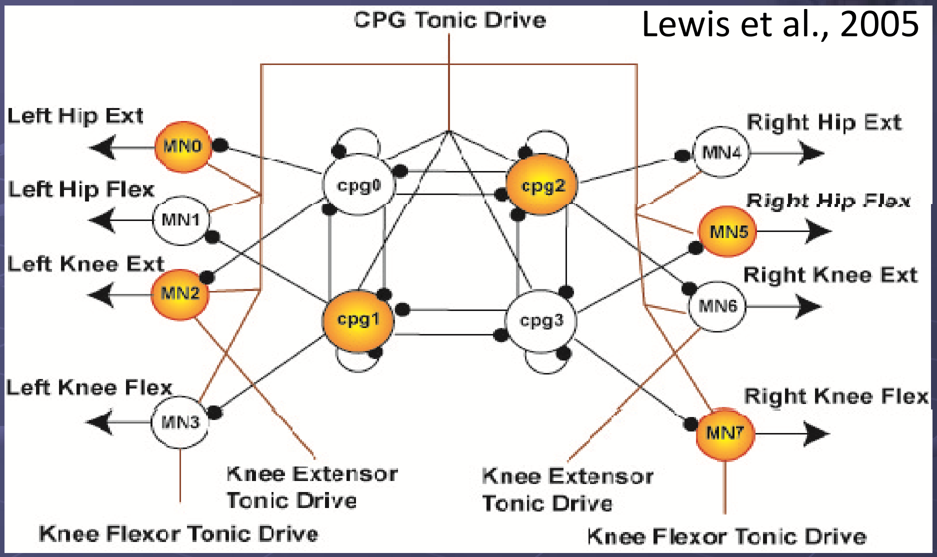
Which Neuron Model?

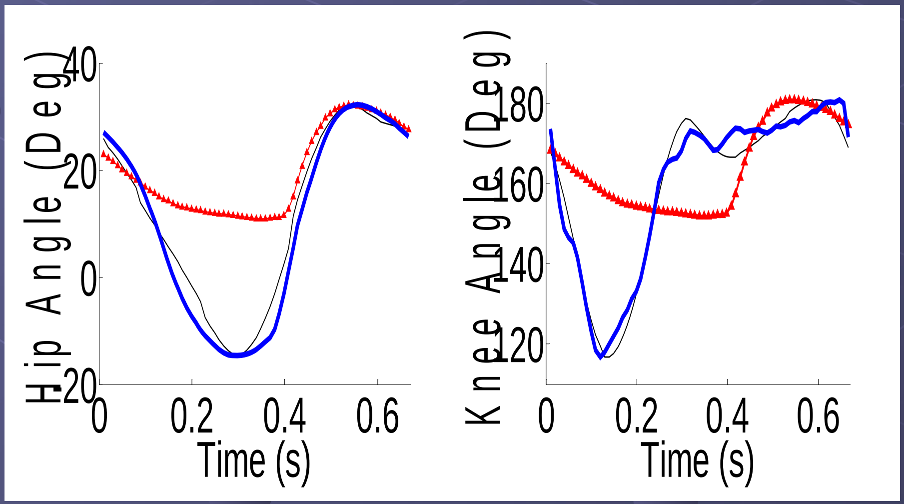


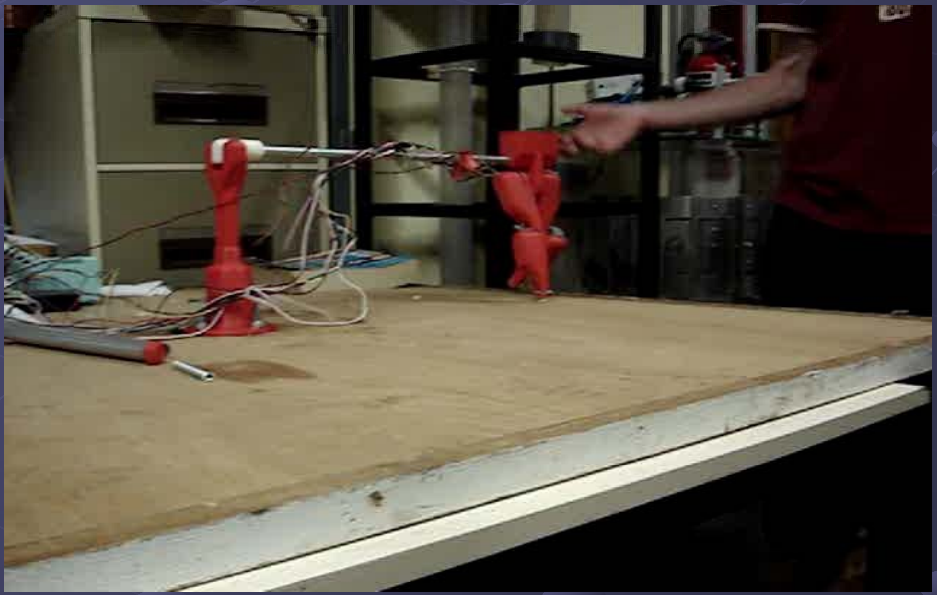
Izhikevich, EM, **Which model to use for cortical spiking neurons**? *IEEE Trans. Neural Networks*, **15**:5, 1063-1070 (2004)

Making a Robot Walk with CPG Chip

- Use artificial motor system to develop on-line phase control infrastructure
- Materials:
  - Partially-supported bipedal robot ("RedBot") or RoboCat
  - Reconfigurable silicon CPG chip
    - CPG controls hip movements, knee/ankles are passive

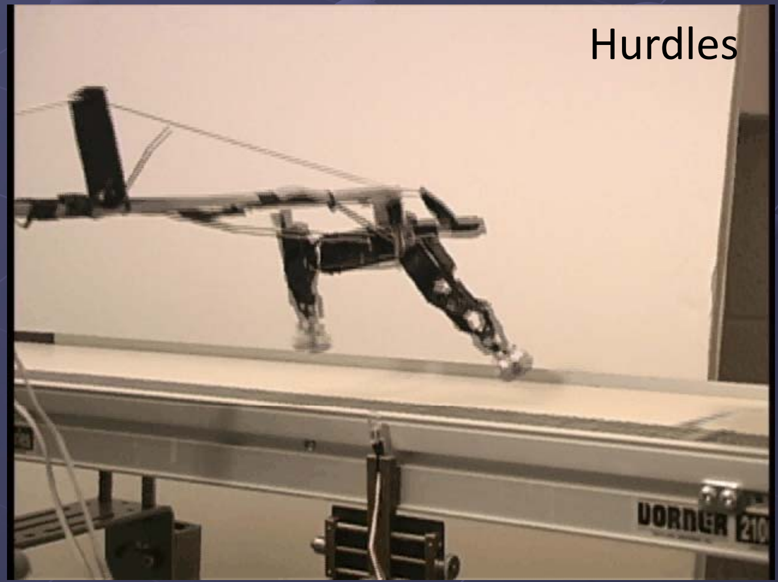






Lewis et al., 2005; Russell, Orchard et al, 2007

When Coupling Goes Good & Bad



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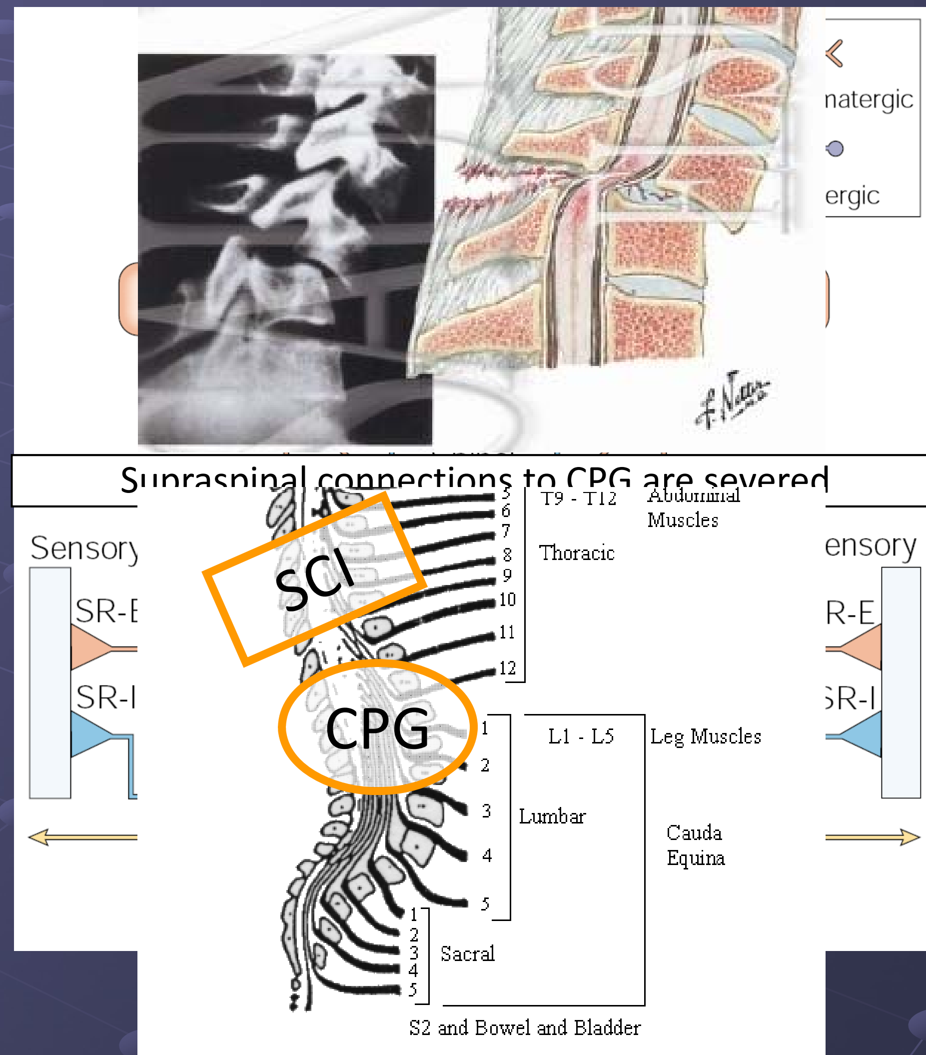
  - Sensory feedback and haptics

Restoring Function to the Impaired

Spinal Cord Injury (SCI)

- SCI is usually a focal injury: vertebral body dislocation → spinal cord contusion
  - Kills spinal cord cells at lesion site
  - Severs connections
  - Leaves cells above/below lesion intact
- In most cases (~65%), lower limb CPG is intact after SCI
- Paralysis is caused by loss of descending control of the CPG, not by loss of CPG itself
  - Tonic & phasic inputs to CPG are disconnected
  - Efferent inputs required to activate CPG and control locomotion

→ Paralysis



Responsibilities of Locomotion Controller

1. Select Gait

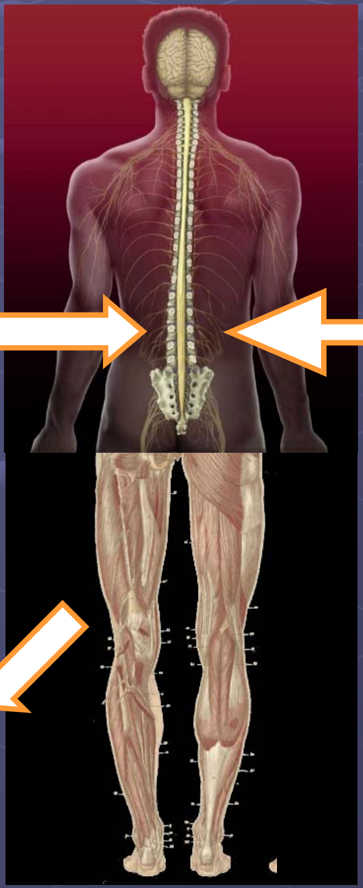
+ specify desired motor output
  - phase relationships
  - joint angles

4. Control Output of CPG

+ phasic stimulation (efferent copy required for precisely-timed stimuli)
  - convert baseline CPG activity into functional motor output
  - correct deviations
  - adjust individual components
  - adapt output to environment

3. Generate "Efferent Copy"

+ monitor sensorimotor state
  - external sensors on limbs
  - internal afferent recordings



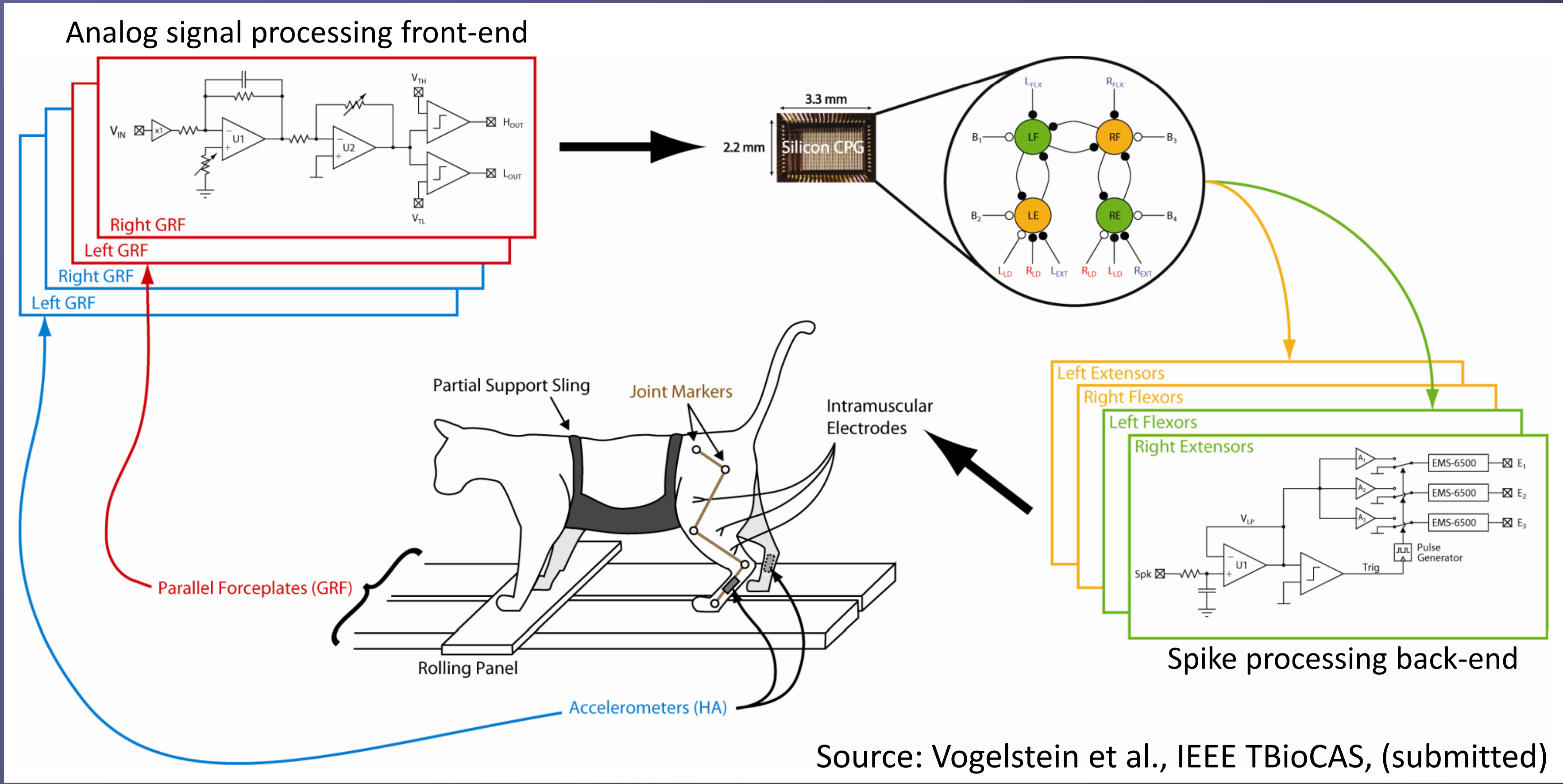
2. Activate CPG

+ tonic stimulation initiates locomotion
  - epidural spinal cord stimulation (ESCS)
  - intraspinal microstimulation (ISMS)

Select gait ~ brain
Activate CPG ~ brainstem (MLR)
Efferent copy ~ efferent copy
Enforce/adapt output ~ phasic RS

Vogelstein et al., 2008

Gait Control System



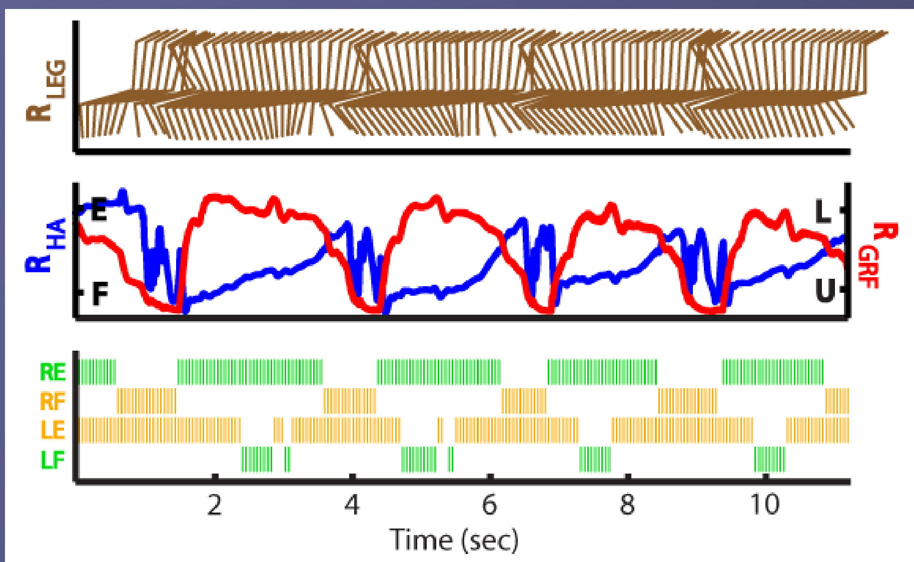
- 12 pairs of IM electrodes: 3 each for left/right hip, knee, and ankle extensors/flexors
- Two types of sensory data were collected for each leg
  - Hip angle (HA)
  - Ground reaction force (GRF)

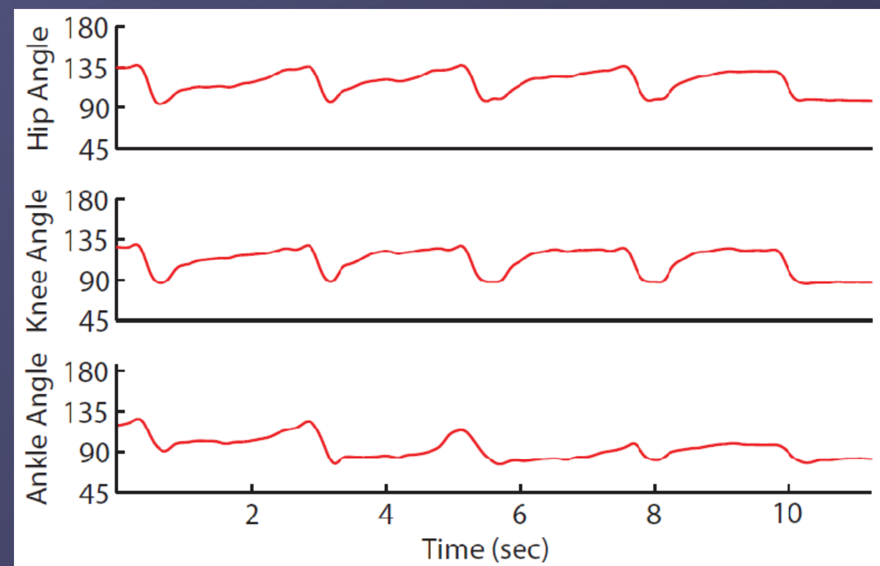
Vogelstein et al., 2008

Results: SiCPG Chip Controls Locomotion in a Paralyzed Cat

Vogelstein et al., 2008

Results: SiCPG Chip Controls Locomotion in a Paralyzed Cat





- We have also shown that turning control is possible using phasic stimulation of biological CPG
  - Use error between desired activity = “efferent copy” and measured activity to stimulate spine

Vogelstein et al., 2008

Presentation Outline

- Making Machines See
  - The biological visual system
  - Silicon eyes and brains
- Making Robots Walk
  - The biological locomotion system
  - Silicon spine and Walking robots
- Restoring Function to the Impaired
  - Spinal cord injury and locomotion prosthesis
  - Gait controller: *silicon model of spinal cord circuits*
- Future and Conclusion
  - High degree of freedom prosthetic limbs
  - Sensory feedback and haptics

Control paradigm

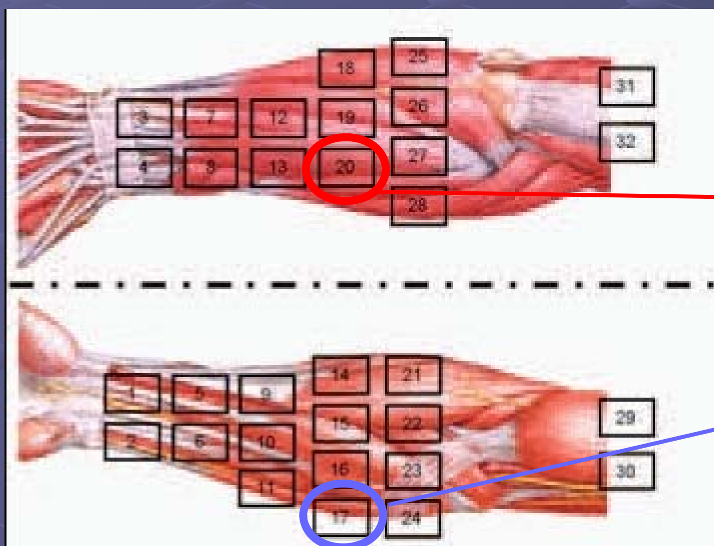
- Acquisition of electrophysiological signals involved in generation of movement
- Extraction of movement-related information from biosignals
- Provide sensory information to the nervous system

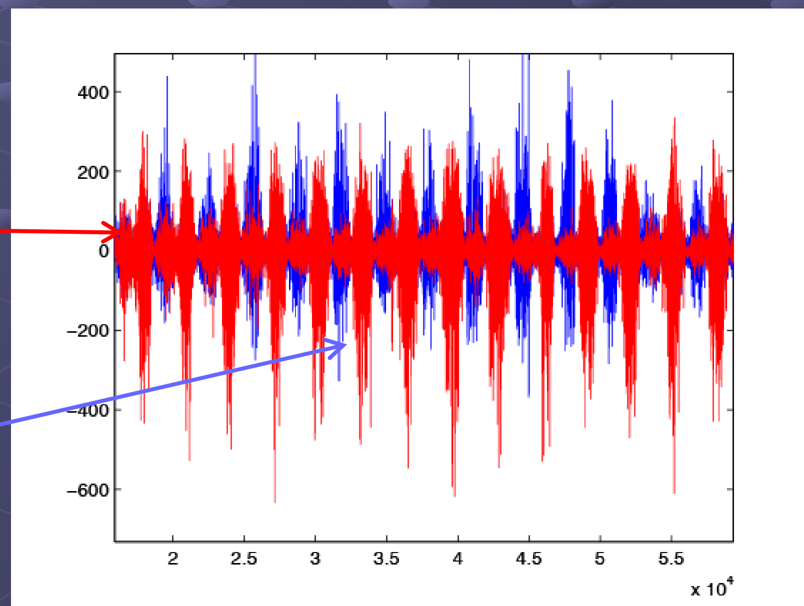
JHU/APL RP2009

State-of-the-art of Prosthetic Hands

JHU/APL RP2009 Prototype II Hand

Repetitive movements : Hand opening/closing

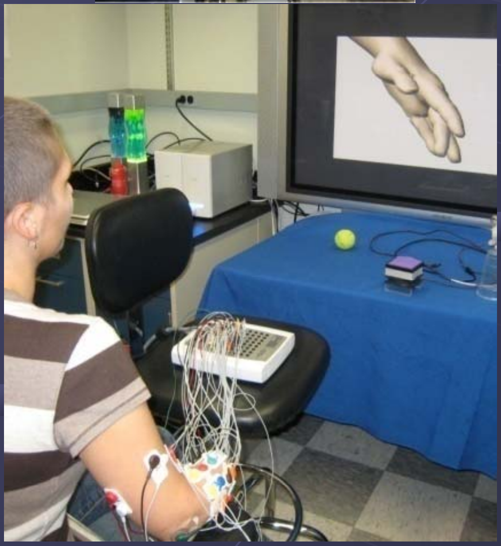




Tenore et al., 2008

Experimental protocol

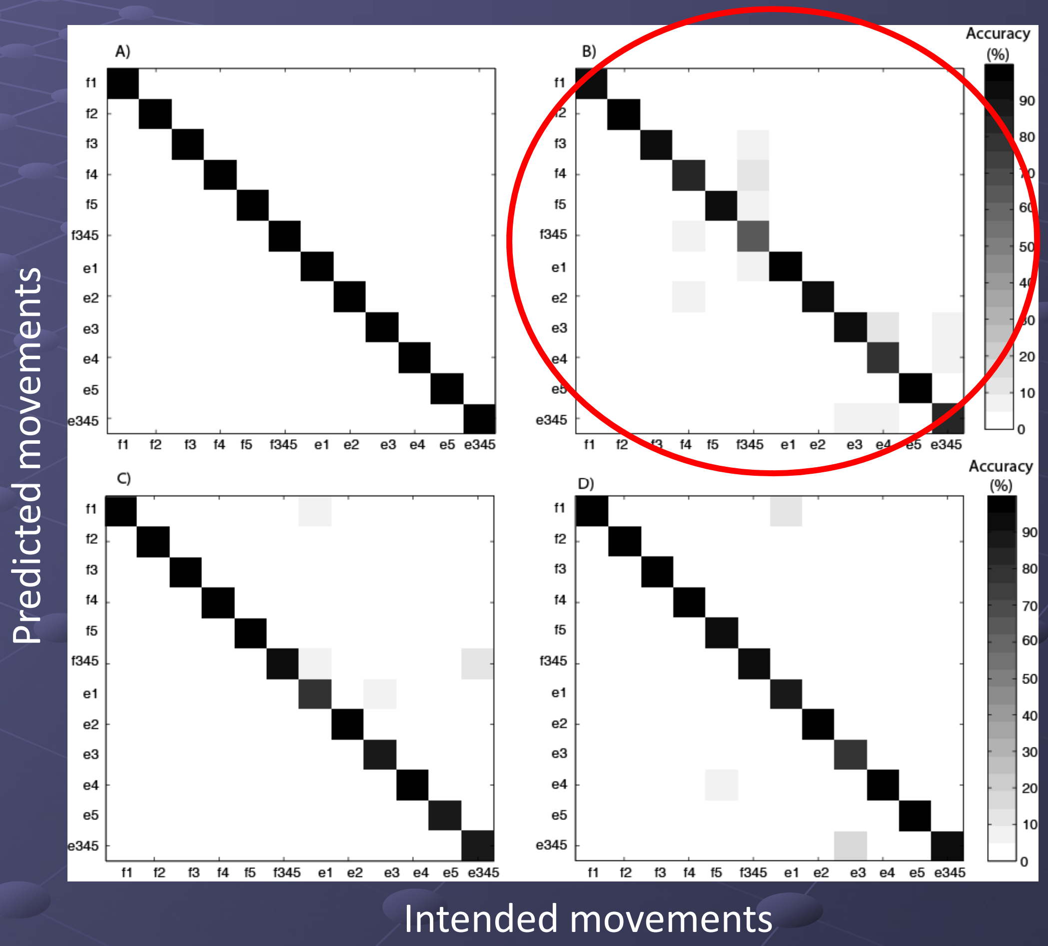
- Acquisition of non-invasive surface EMG signals from forearm (and upper arm)
- Subjects perform finger and hand movements on cue (audiovisual) – 18 total
- Transradial amputees perform movements also with intact hand simultaneously



Tenore et al., 2007

Results

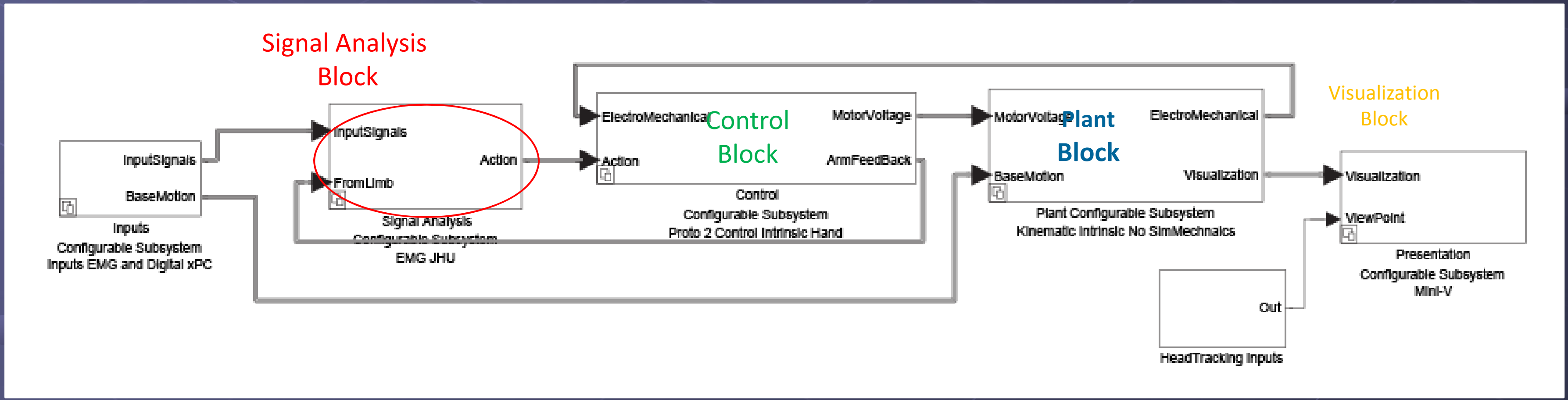
- 4 subjects, 12 movements
  - 32 electrodes able-bodied subjects,
  - 19 electrodes on transradial amputee
- Confusion matrices: allow identification of misclassified movements
- Transradial amputee is?



Tenore et al., 2008

Visualization on Virtual Integration Environment

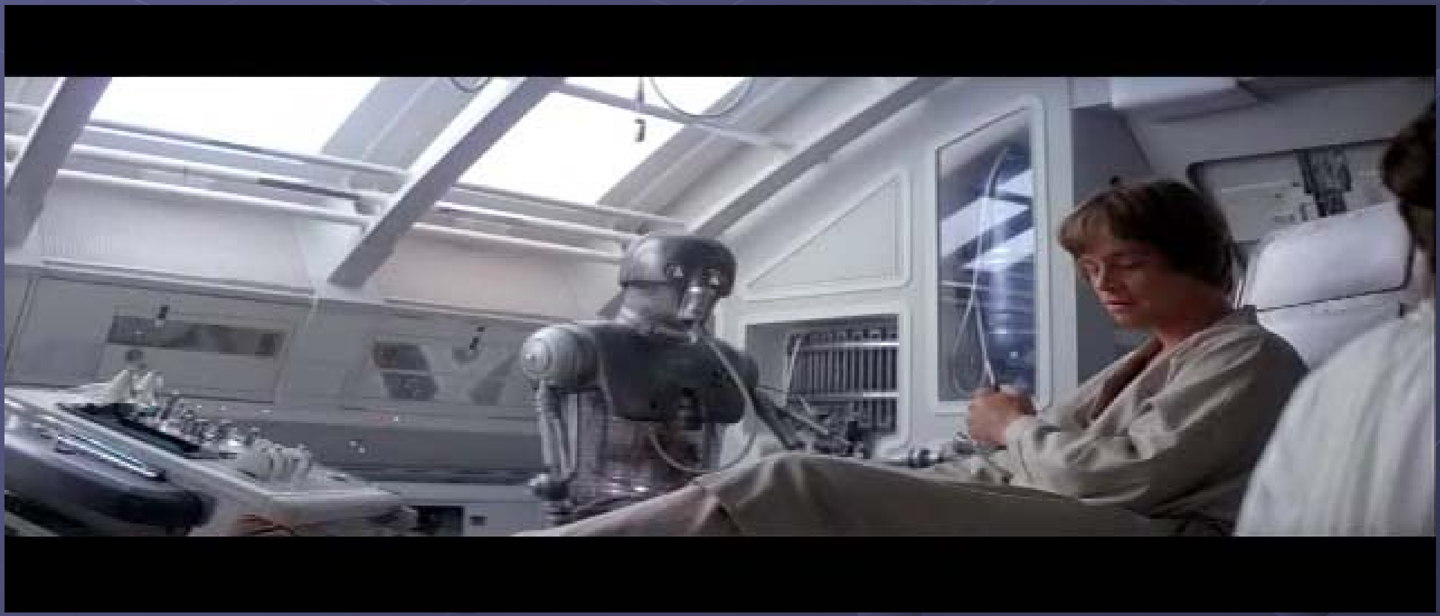
- VIE provided by JHUAPL for fast prototyping of decoding algorithms
- VIE in action
- Real Time Decoding



Tenore et al., 2008

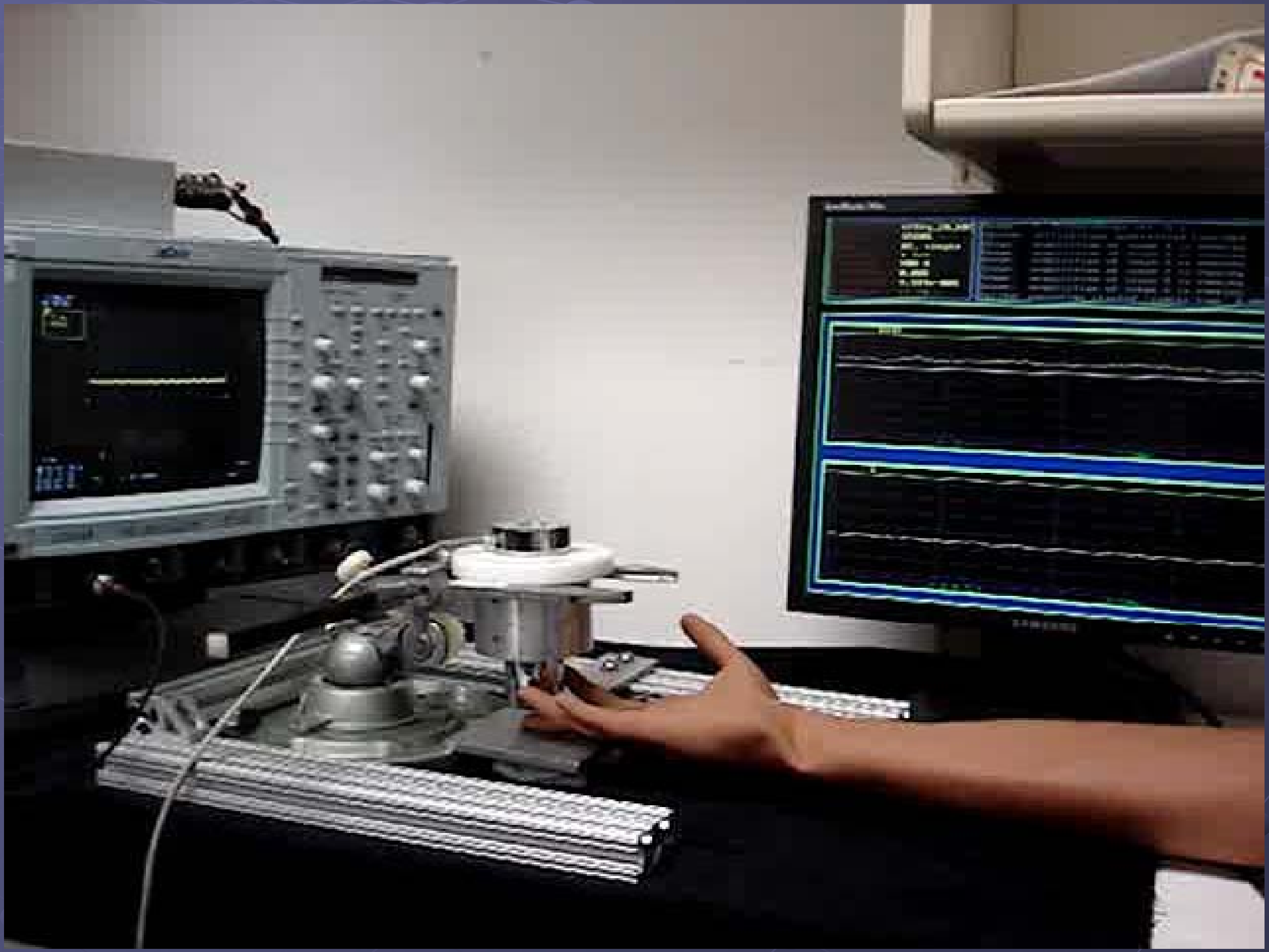
Conclusions and Future

- Fully neurally integrated prosthetics
  - Thoughts to action (decoding of intent)
  - Sensors to feeling (encoding of reaction)
  - Knowing where is the limb (representing joint space)



Lucas Films, 1978

Conclusions and Future (Preliminary Results)



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

Mentors, Collaborators and Students

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