Introductory Course in Neuroscience

Neuromorphic Engineering

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What is neuromorphic engineering?

It consists of embodying *organizing principles* of neural computation in electronics

Part 1: Motivation & history

Part 2: Modeling the neuron in silicon

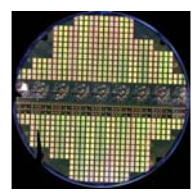
Part 3: Modeling vision in the dynamic vision sensor (DVS) silicon retina

Part 4: Modeling audition in the AEREAR2 silicon cochlea

Artificial computation has been enabled by immense gains in silicon technology

1947
1 transistor

1997
10^9 transistors



1. Moore's law: Number of transistors per chip doubles every 1.5 to 2 years
2. Cost/bit of memory drops 29%/year
3. **True for last 45 years! Will continue at least another ~10y.**

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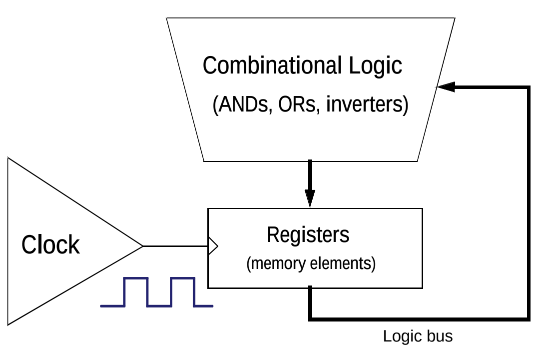
Synchronous logic is ubiquitous



Logic bus
(many wires representing a digital symbol)

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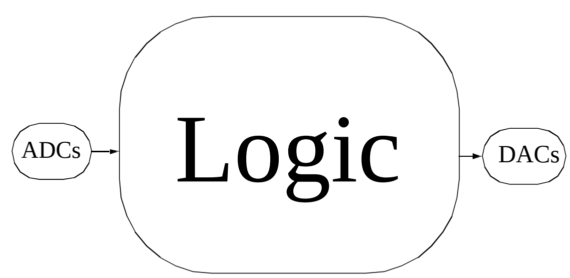
How industry uses analog processing



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Computer vs. Brain

Computer	Brain
Fast global clock	Self-timed, data driven
Bit-perfect deterministic logical state	Synapses are stochastic! Computation dances digital→analog→digital
Memory distant to computation	Synaptic memory at computation
Fast, high resolution, constant sample rate analog-to-digital converters	Low resolution adaptive data-driven quantizers (spiking neurons)

Differences are currently possible because mobility of electrons in silicon is about 10^7 times that of ions in solution

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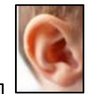
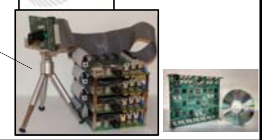
Types of neuromorphic systems

- **Neuromorphic Sensors** —electronic models of retinas and cochleas
- **Smart sensors** (e.g. tracking chips, motion sensors, presence sensors, auditory classification and localization sensors)
- **Central pattern generators** – for locomotion or rhythmic behavior
- **Models of specific systems:** e.g. *bat sonar echolocation*, lamprey spinal cord for swimming, lobster stomatogastric ganglion, electric fish lateral line
- **Multi-chip large-scale systems** that use the *address-event representation* (spikes) for inter-chip communication and are used for studying models of neuronal (cortical) computation and synaptic plasticity for learning

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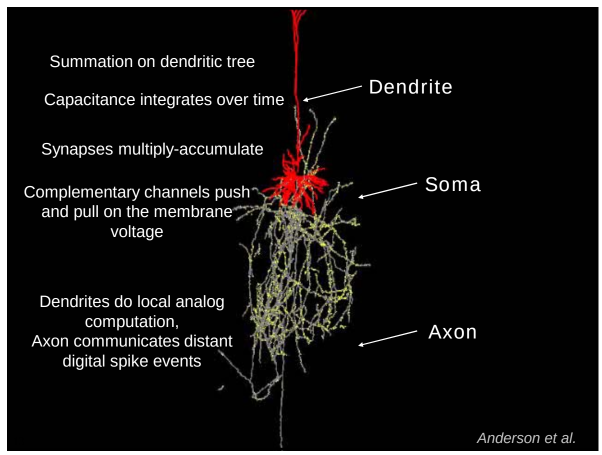
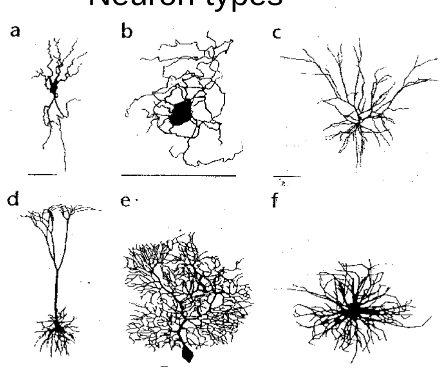
Part 2: Modeling the neuron in silicon

Part 3: Modeling vision in the dynamic vision sensor (DVS) silicon retina

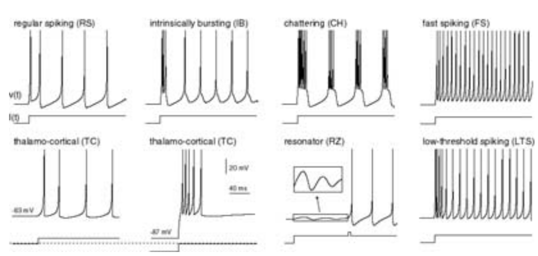
Part 4: Modeling audition in the AEREAR2 silicon cochlea



Neuron types



Firing patterns



Izhikevich 2002

Hodgkin-Huxley (1952) model

$$C_m \frac{\partial V}{\partial t} = -[I_{NA} + I_{K1} + I_{K2} + I_L] + I_{ext}$$

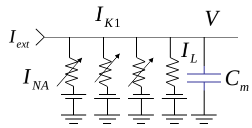
Example:

$$I_{NA} = g_{NA} m^3 h (V - E_{NA})$$

$$\dot{m} = \alpha_m(V)(1-m) - \beta_m(V)m$$

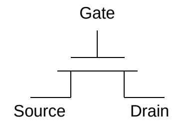
$$\dot{m} = -\frac{1}{\tau_m(V)}[m - m_\infty(V)]$$

$$m_\infty(V) = \frac{\alpha_m(V)}{\alpha_m(V)+\beta_m(V)}; \tau_m(V) = \frac{1}{\alpha_m(V)+\beta_m(V)}$$



How to model neurons in silicon technology

Basic element is the transistor.



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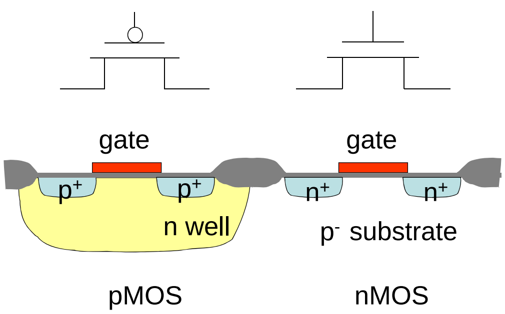
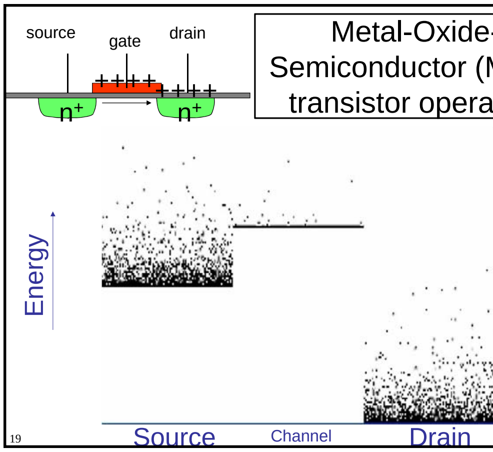
Symbol and cross-section of transistors



Metal-Oxide-Semiconductor (MOS) transistor operation



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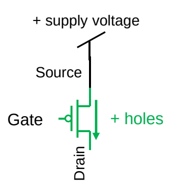
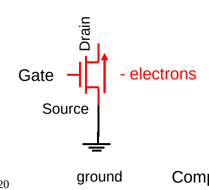
Transistors in silicon come in two **complementary** types n-type and p-type



- p-type transistors conduct positive *holes* from a positive supply
- They are turned on by negative charge on the gate, producing negative voltage between gate and source
- They act like current **sources**



- n-type transistors conduct negative *electrons* from a negative supply
- They are turned on by positive charge on the gate, producing positive voltage between gate and source
- They act like current **sinks**

This leads to the name **CMOS**
Complementary Metal Oxide Semiconductor

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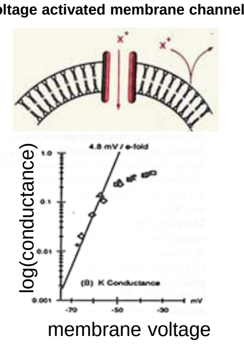
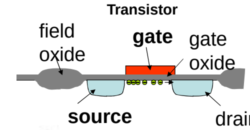
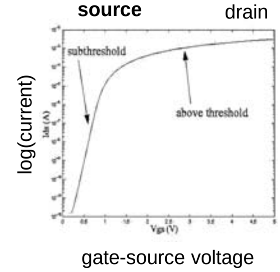
The physics of voltage activated membrane channels and transistors is closely related

Voltage activated membrane channel



Transistor





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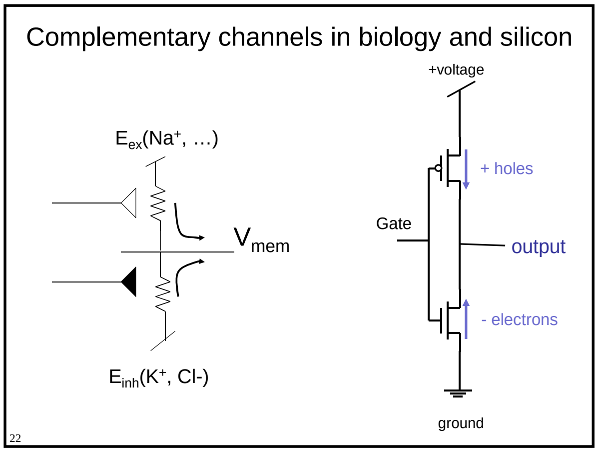
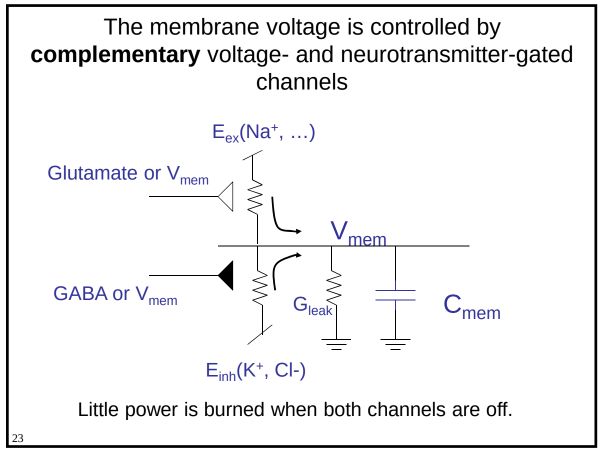


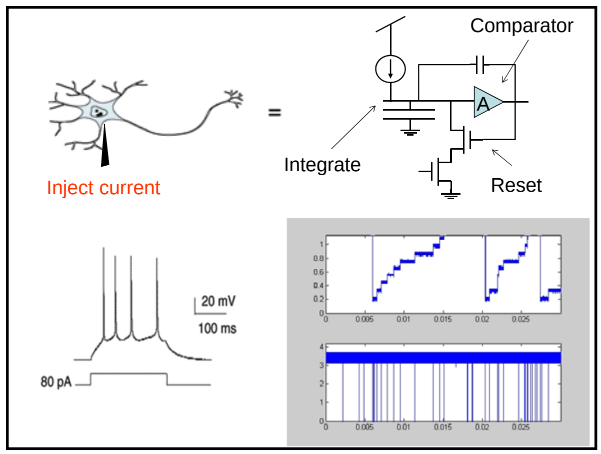


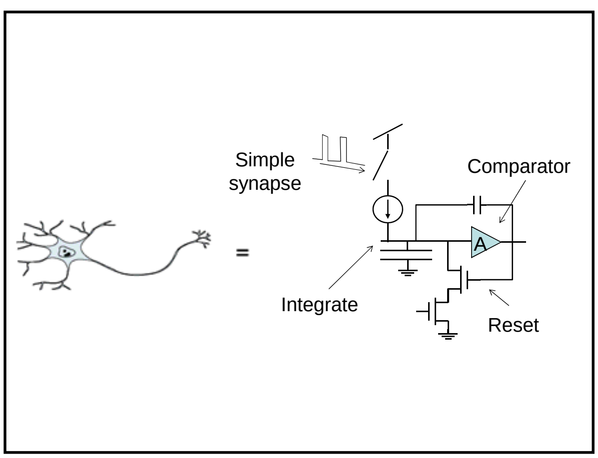
Simpler Soma Model: I/F model

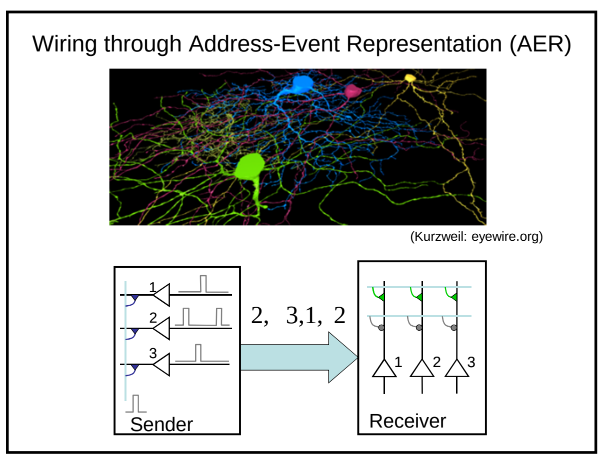
• Integrate-and-fire model (Hill 1936, Stein 1965):

$$C_m \frac{\partial V}{\partial t} = I \qquad \text{When } V > \theta; \quad V = 0$$

Integration Comparator Reset

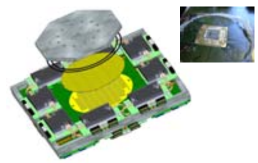




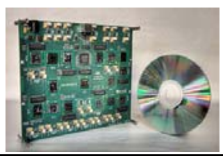


Neuromorphic Event-Based Cortical Simulators

SpiNNaker
(Manchester)



Brainscales/HBP
(Heidelberg, Lausanne)



Neurogrid
(Stanford)
Power: 5W
Neurons: 1 million

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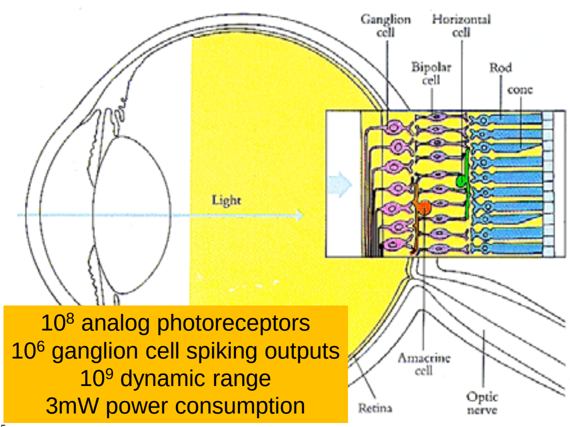

10^8 analog photoreceptors
10^6 ganglion cell spiking outputs
10^9 dynamic range
3mW power consumption

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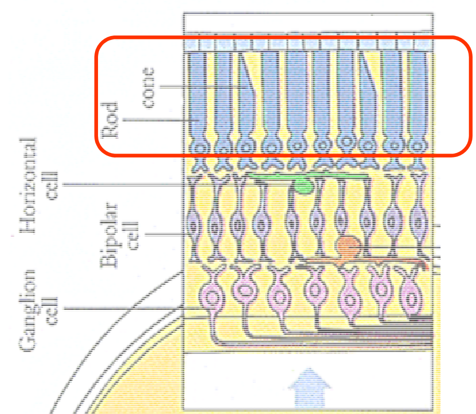

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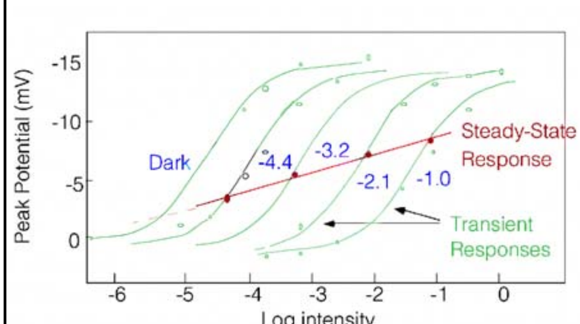
Biological photoreceptors adapt their operating point and gain



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Norman & Perlman 1979

A logarithmic (or self-normalizing) representation of intensity is useful for representing object reflectance differences, rather than the illumination conditions.

- Two objects of different reflectance produce a ratio of luminance values.
- The difference of two log values represents this ratio, independent of the illumination.

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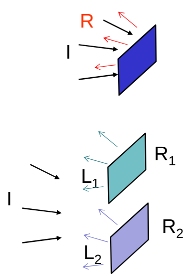

I is Illuminance
L is Luminance
R is reflectance

$L_1 = I*R_1$
$L_2 = I*R_2$
$L_1/L_2 = R_1/R_2$

$\text{Log}(L_1/L_2) = \text{Log}(L_1) - \text{Log}(L_2)$

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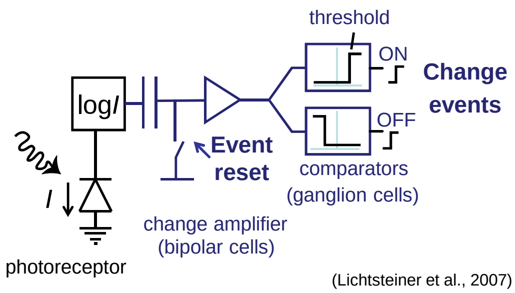
The dynamic vision sensor
silicon retina

Dynamic Vision Sensor (DVS) pixel



(Lichtsteiner et al., 2007)

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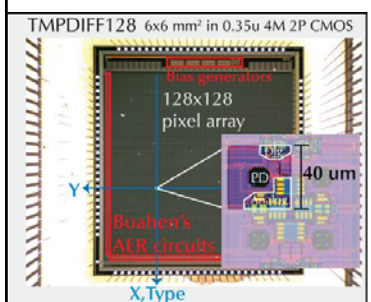
Dynamic Vision Sensor Silicon Retina (DVS)



1. The DVS ***asynchronously*** transmits ***address-events.***
2. The events represent ***temporal contrast*** , like transient ganglion cells.

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Lichtsteiner et al. ISSCC 2006

Demo of DVS

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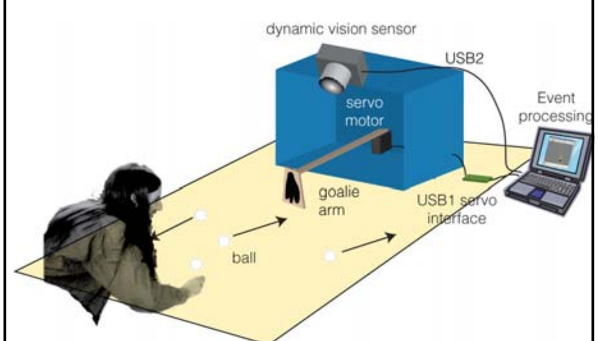
Robot Goalie



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Achieves 550 "FPS" and 3 ms reaction time at 4% processor load

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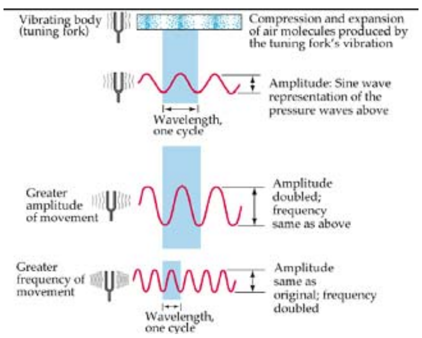
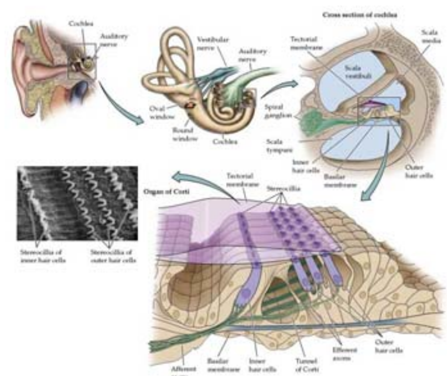
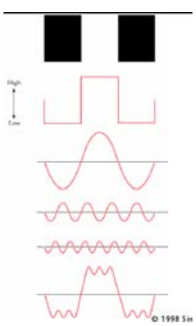
The physics of sound





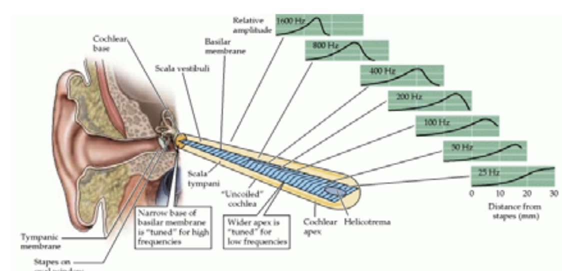
•(Neuroscience. 2nd edition.
•Purves D, Augustine GJ, Fitzpatrick D, et al., editors.
•Sunderland (MA): Sinauer Associates; 2001)

Fourier analysis



- •Any complex waveform can be
- •represented as the sum of a series
- •of sine waves of different
- •frequencies and amplitudes

•Kiper, system neuroscience, fall 2009



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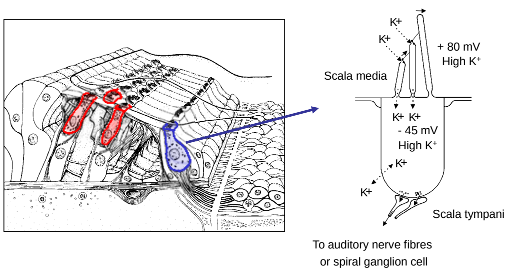
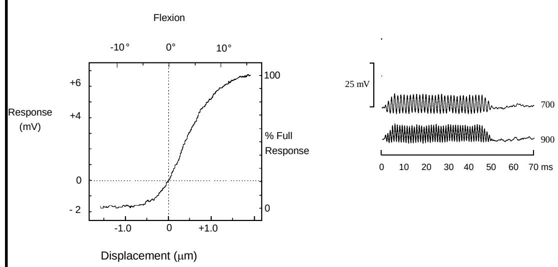
•Sunderland (MA): Sinauer Associates; 2001)

The Inner Hair Cells



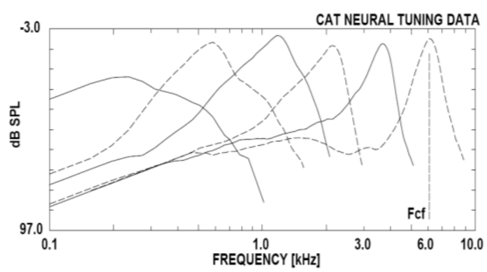
(Kelly, 1991) (Pickles, 1988)

IHC response



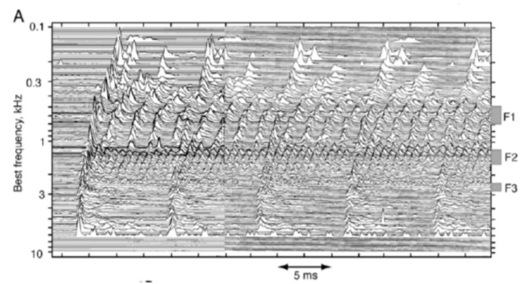
(Hudspeth and Corey, 1977) (Palmer and Russell, 1986)

Auditory nerve fibre (ANF) responses



SPL (sound pressure level) = 20 log (pm/pref) dB
pref = 20 uPa (rms)

ANF Response to Speech

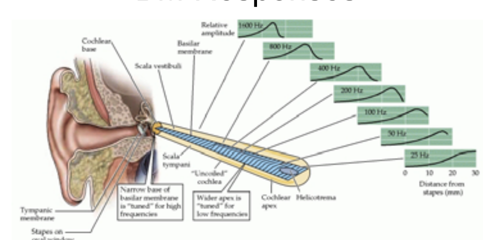


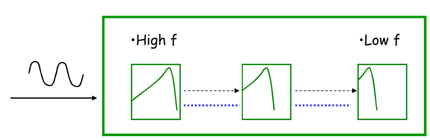
•Response from 275 fibres from an anesthetized cat to first 50 ms of syllable 'da'

•(Miller and Sachs, 1993,
•Shamma, 1985)

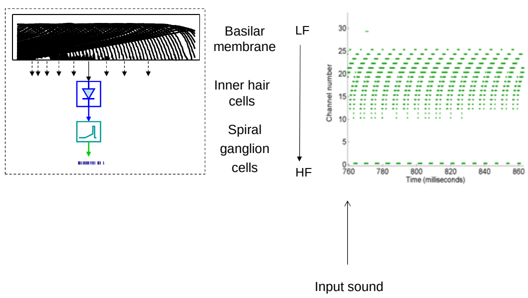
The AEREAR2 silicon cochlea

BM Responses





AEREAR2 cochlea



Possible applications

- Auditory tasks like speaker verification and speech recognition.
- Front-end for exploring ideas about neural-inspired speech processing.
- Binaural information used for source localization.
- Spike-based multi-modal motor system.

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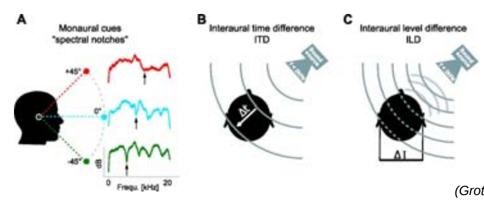
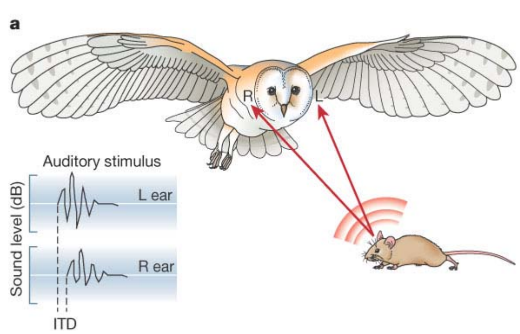
Spatial Auditory Cues

- Two basic types of head-centric direction cues
  - binaural cues
    - Interaural time difference cues (ITD)
    - Interaural intensity difference cues (IID)
  - spectral cues

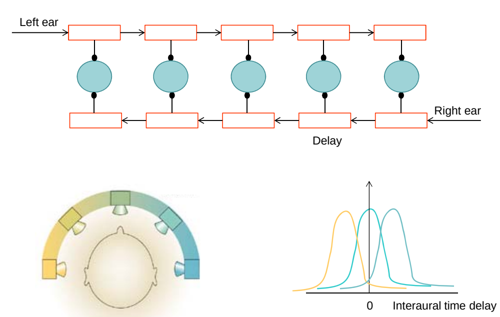


(Grothe, 2010)



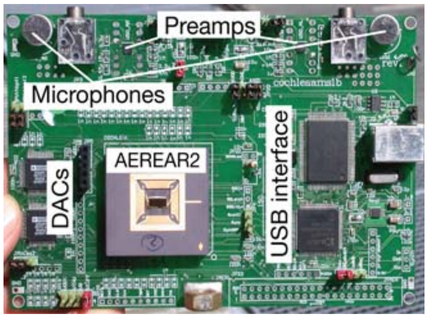
(Knudsen, 2002)

Jeffress localization model



(Grothe, 2003)

Demo of AER-EAR2



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Summary

1. Neuromorphic Engineering: Motivation
2. Modeling the neuron in silicon
3. Modeling vision in the dynamic vision sensor (DVS) silicon retina
4. Modeling audition in the AEREAR2 silicon cochlea

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Resources

Background readingl:

- C. Mead (1990) **Neuromorphic Electronic Systems**, Proceedings of the IEEE, vol 78, No 10, pp 1629-1636 - *Carver Mead's summary paper on the rationale and state of the art in 1990 for neuromorphic electronics.*
- S.C. Liu, T. Delbruck (2010) **Neuromorphic Sensory Systems**, Curr. Opinions in Neurobiology - *Our recent review paper on neuromorphic sensors.*

Demonstrations

- T. Delbruck, S.C. Liu., **A silicon visual system as a model animal**, (2004). Vision Research, vol. 44, issue 17, pp. 2083-2089 - *About the electronic model of the early visual system demonstrated in the some class lectures (not in 2011).*
- **Dynamic Vision Sensor** - *Describes the dynamic vision sensor silicon retina demonstrated in the lecture.*
- Liu et al 2010 - *Event-based 64-channel binaural silicon cochlea with Q enhancement mechanisms*

Yet more historical material and background:

- **Original silicon retina paper** from Scientific American, M. Mahowald and C. Mead, 1991
- K. Boahen (2005) **Neuromorphic Microchips**, Scientific American, May 2005, pp. 56-63 - *Kwabena Boahen's paper on the state of the art (in his lab) in 2005 in neuromorphic multi-chip systems.*
- **The Physiologist's Friend Chip** - *The electronic model of the early visual system.*

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