Introductory Course in Neuroscience

Neuromorphic Engineering I

Neuromorphic Engineering

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http://www.ini.uzh.ch/~tobi/wiki/doku.php?id=introneuro

What is neuromorphic engineering?

Electronics that embody brain-like organizing principles of neural computation

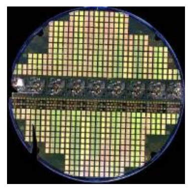
Part 1: Motivation & history

Part 2: Organizing principles

Part 3: The dynamic vision sensor silicon retina

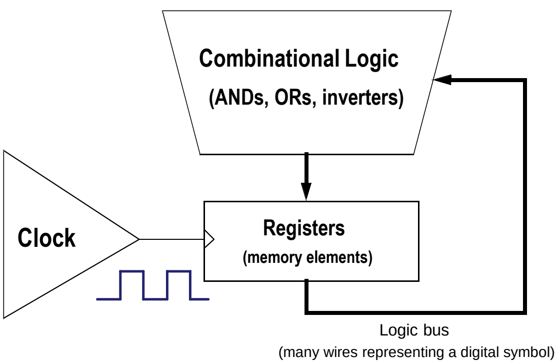
Artificial computation has been enabled by immense gains in silicon technology

1947	1997
1 transistor	10^9 transistors



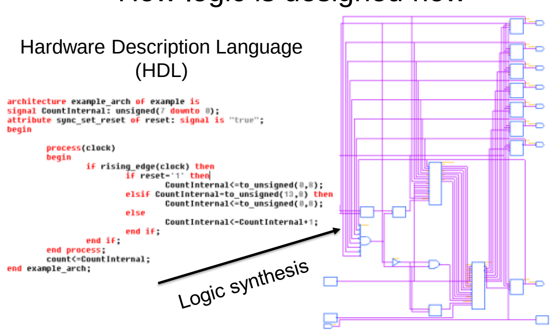
1. Moore's law: Number of transistors per chip doubles every 1.5 to 2 years
2. Cost/bit drops 29%/year
3. **True for last 45 years! Will continue at least another ~15y.**

Synchronous logic is ubiquitous



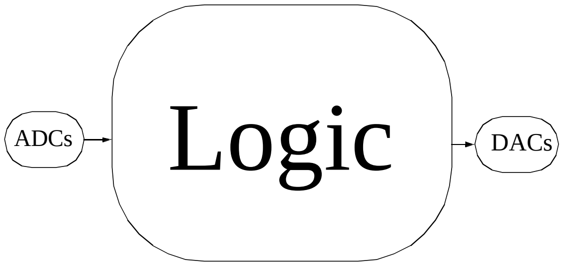
How logic is designed now

Hardware Description Language (HDL)



By using HDLs, industry can design complex chips with >100 million logic elements

How industry uses analog processing



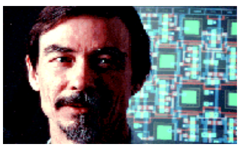
Natural computation

Flies acrobatically
Recognizes patterns
Navigates
Forages
Communicates

At least a million times as efficient as digital silicon

Physics of Computation Course

1982



1985 Carver Mead

Dick Feynman

John Hopfield

Computer vs. Brain

At the system level, brains are at least 1 million times more power efficient than computers. Why?	
Cost of elementary operation (turning on transistor or activating synapse) is about the same. It's not some magic about physics.	
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)
Mobility of electrons in silicon is about 10^7 times that of ions in solution.	

10/30

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)
- **Networks of spiking neurons** – with self-modifying adaptive synapses
- **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 systems** that use the *address-event representation* (spikes) for inter-chip communication

Part 1: Motivation, history
Part 2: Organizing principles
Part 3: The dynamic vision sensor silicon retina

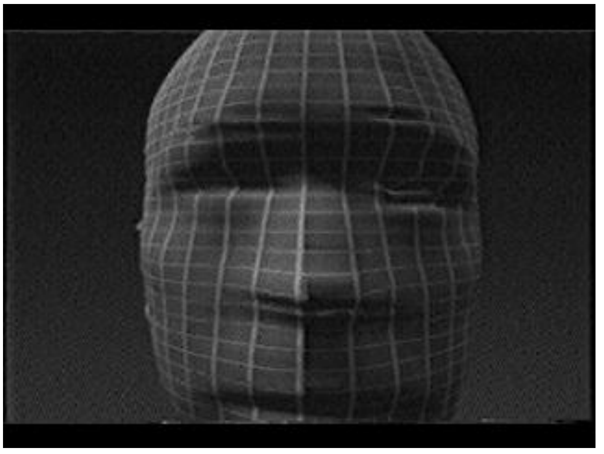
Part 2:
Some “organizing principles” as applied in neuromorphic engineering

The fact that we can build devices that implement the same basic operations as those the nervous system uses leads to the inevitable conclusion that we should be able to build entire systems based on the organizing principles used by the nervous system.

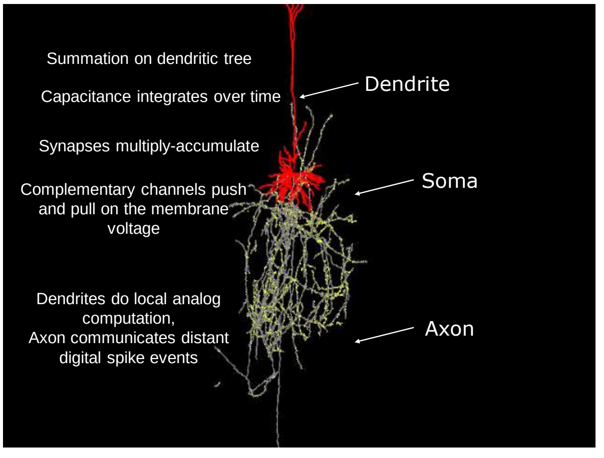
Carver Mead, 1990

Examples of these organizing principles

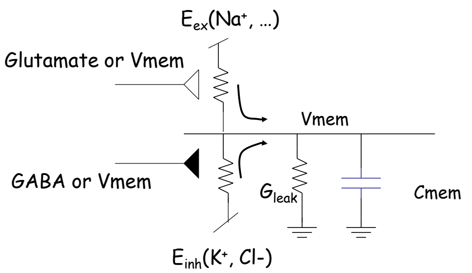
1. **Using device physics for computation**
   1. Using charge to add and subtract by summing currents onto nodes
   2. Using capacitance to integrate over time
   3. Using controlled energy barriers to amplify
2. **Using complementary devices to avoid burning static power**
3. **Averaging over space & time** to control noise and find signal context
4. **Using context to normalize** signals
5. **Representing signed quantities by rectifying** into ON and OFF channels
6. Using **adaptation** to **amplify novelty**
7. Computing **locally in analog** and **communicating remotely using events**



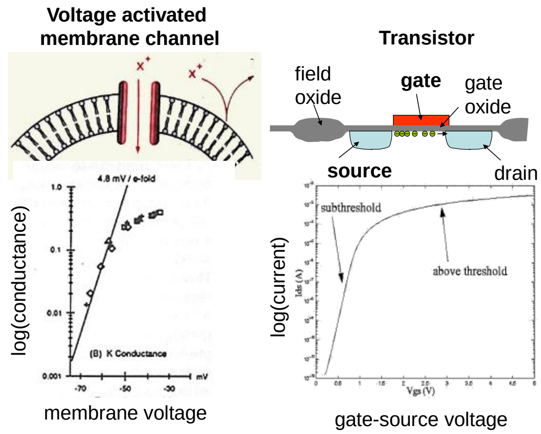
Complementary devices, amplification



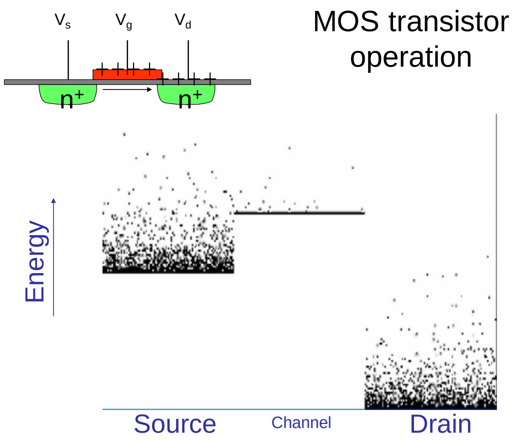
The membrane voltage is controlled by complementary voltage and neurotransmitter gated channels



Little power is burned when both channels are off.

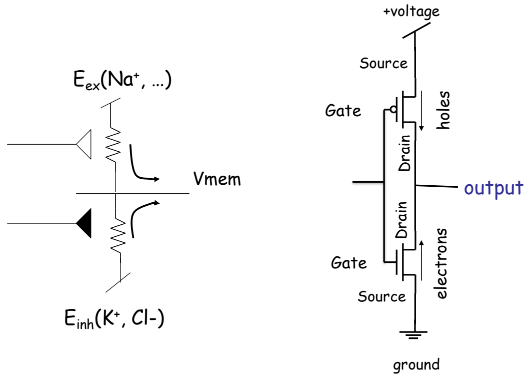


MOS transistor operation

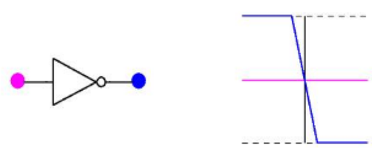


Mechanism of gain

Voltage sensitive channel conductance is exponential in membrane voltage	Transistor current is exponential function of gate voltage
Organizing principle: Use controlled energy barriers (with Boltzmann energy distributions) to amplify	

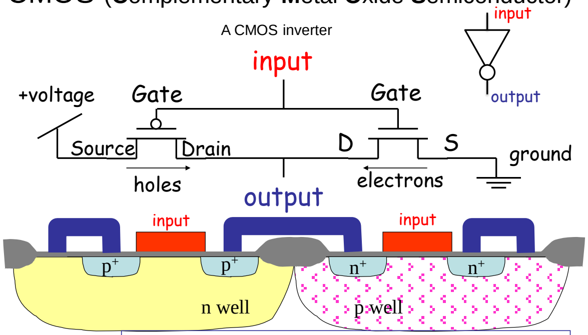


A digital inverter



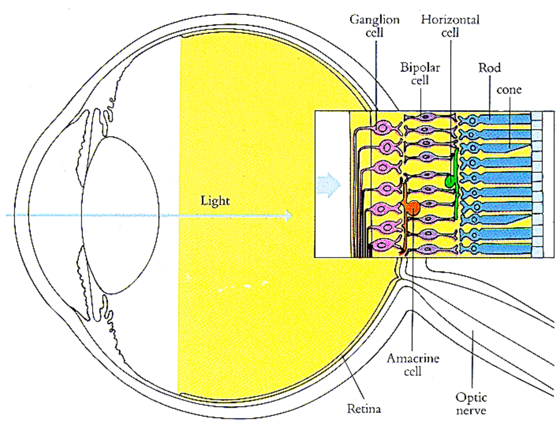
Combinational logic (AND, OR etc) built the same way

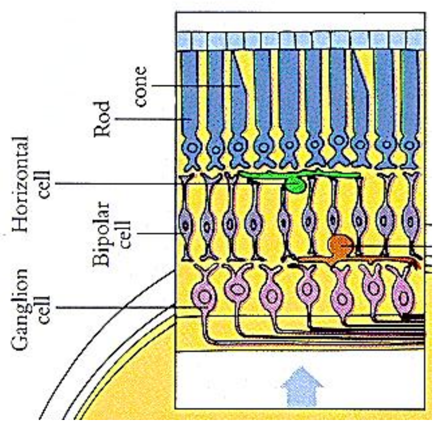
CMOS (**C**omplementary **M**etal **O**xide **S**emiconductor)

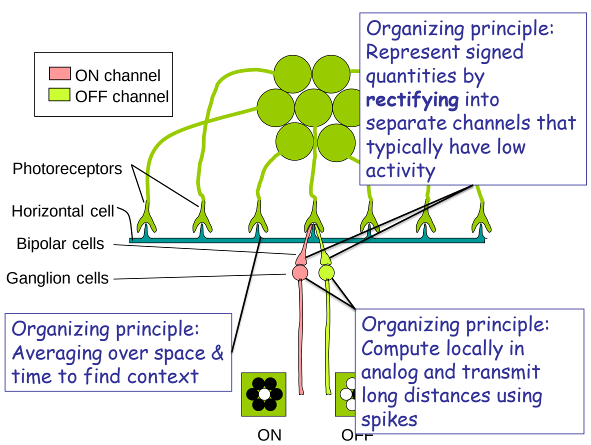


Organizing principle:
Use complementary devices to generate gain without burning static power

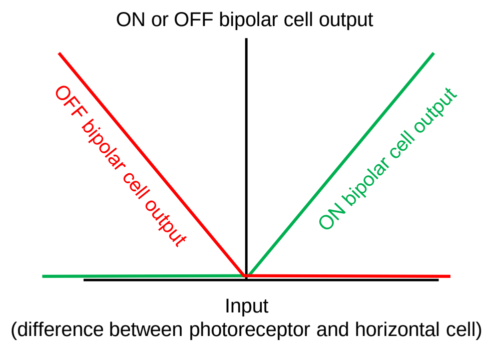
Part 1: Motivation, history, community
Part 2: Organizing principles
Part 3: The dynamic vision sensor silicon retina



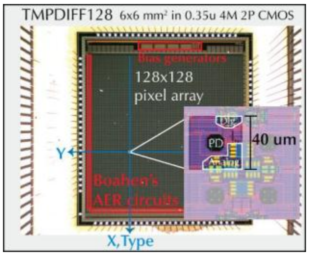




Rectification



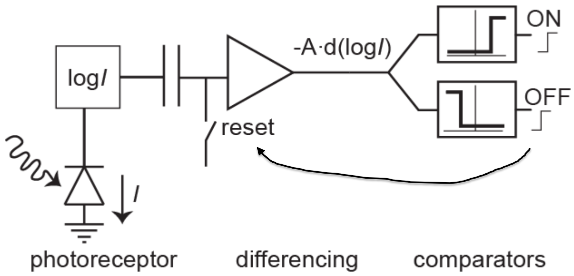
Dynamic vision sensor



1. This silicon retina ***asynchronously*** outputs ***address-events.***
2. The events represent to ***temporal contrast*** , like transient ganglion cells.

Lichtsteiner et al. ISSCC 2006

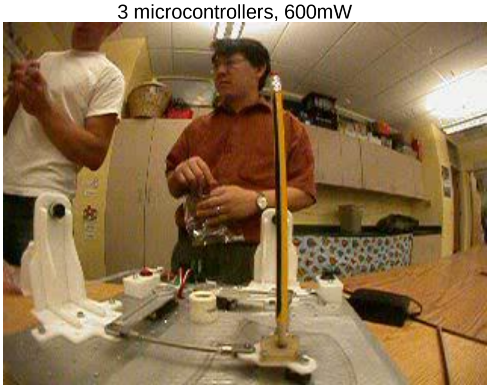
Simplified DVS pixel architecture



Embedded DVS Pencil Balancer

Jorg Conradt, Matt Cook

3 microcontrollers, 600mW



Review of “organizing principles” in neural and neuromorphic electronic systems

1. **Using device physics for computation**
   1. Using charge to add and subtract by summing currents onto nodes
   2. Using capacitance to integrate over time
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7. Computing **locally in analog** and **communicating remotely using events**

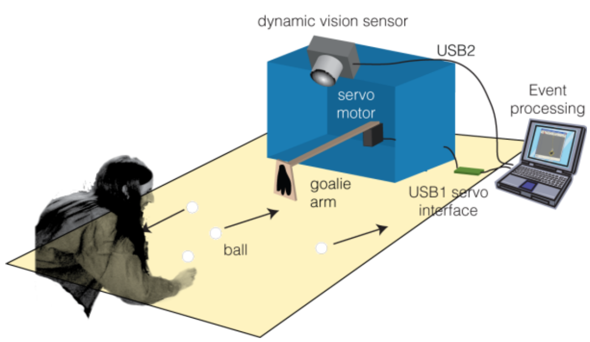
Your exam question will be based on this lecture

Additional reading background

1. Mead, **Neuromorphic Electronic Systems**, *Proc. IEEE*, 1990
2. Liu and Delbruck, **Neuromorphic Sensory Systems**, *Curr. Opinions in Neurobiology*, 2011
3. Web page on the silicon retina DVS

You can find this material via the ZNZ Neuroscience Course web page.

Robot Goalie



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

Resources

Background reading for the material:

- 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.*
- Dynamic Vision Sensor - *Describes the dynamic vision sensor silicon retina demonstrated in the lecture.*

Yet more historical material:

- Original silicon retina paper from Scientific American, Misha Mahowald and Carver Mead, 1991

Yet more background:

- 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.*
- 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).*
- The Physiologist's Friend Chip - *The electronic model of the early visual system demonstrated in the lecture (not in 2011).*
- Jorg Conradt's Pencil Balancing Robot