Introductory Course in Neuroscience
Neuromorphic Engineering I

Neuromorphic Engineering

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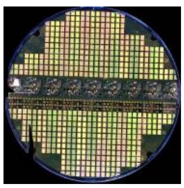
Part 1: Motivation, history, community
Part 2: Organizing principles
Part 3: The physiologist's friend chip and dynamic vision sensor silicon retina

Artificial computation has been enabled by immense gains in silicon technology

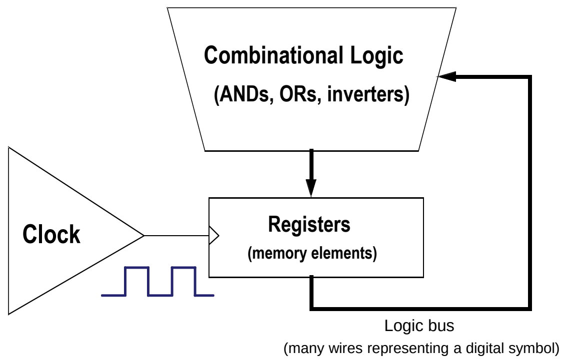
1947
1 transistor

1997
10^9 transistors



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

Synchronous logic is ubiquitous

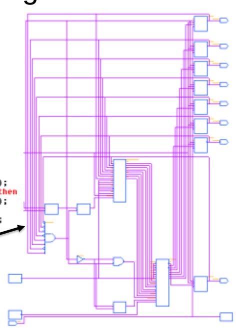


How logic is designed now

Hardware Description Language (HDL)

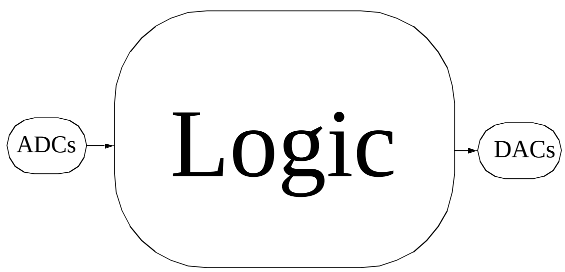
```
architecture example_arch of example is
signal CountInternal: unsigned(7 downto 0);
attribute sync_set_reset of reset: signal is "true";
begin

	process(clock)
	begin
		if rising_edge(clock) then
			if reset='1' then
				CountInternal<=to_unsigned(0,8);
			elsif CountInternal=to_unsigned(13,8) then
				CountInternal<=to_unsigned(0,8);
			else
				CountInternal<=CountInternal+1;
			end if;
		end if;
	end process;
	count<=CountInternal;
end example_arch;
```

Logic synthesis



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

How industry uses analog processing



Natural computation

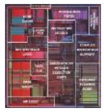
Flies acrobatically
Recognizes patterns
Navigates
Forages
Communicates

10^8 to 10^4 times as efficient as digital silicon

Computer vs. Brain

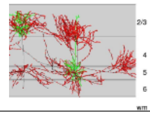
Anderson et al. 2003

Pentium 4



Cortex

1mm

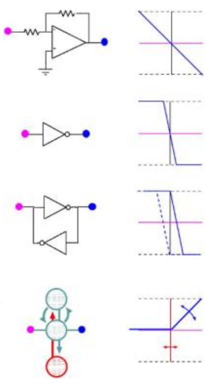


At the system level, brains are about 1 million times more power efficient than computers. Why?

Cost of elementary operation (turning on transistor or synapse) is about the same.
It's not some magic about physics.

Computer	Brain
Fast global clock	Self-timed
Bit-perfect deterministic logical state	Synapses are stochastic! Computation dances: digital→analog→digital
Memory distant to computation	Memory at computation
Fast high precision power hungry ADCs	Low resolution adaptive data-driven quantization
Devices frozen on fabrication	Constant adaptation and self-modification

styles of processing



analog — constant **precise** analog gain by negative feedback

digital — **binary** signal restoration by high feedforward gain

digital — multi-stability by positive feedback & limits

cortex ? — variable analog gain, analog signal restoration, & multi-stability

Douglas 2001

The community of neuromorphic engineering

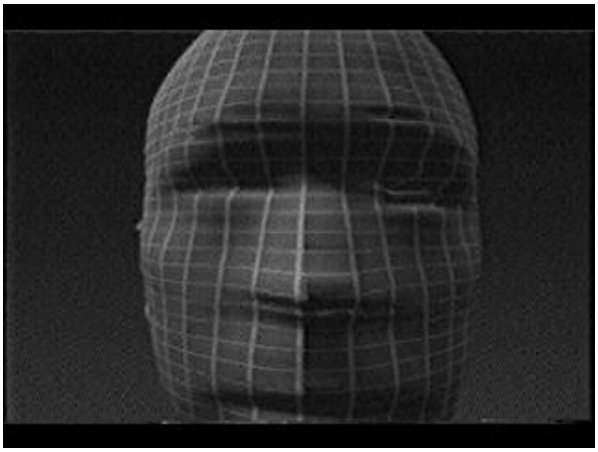
The World of Neuromorphic Electronic Engineering

2010

Liu/Delbruck

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, community
Part 2: Organizing principles
Part 3: The physiologist's friend chip and dynamic vision sensor silicon retina

Part 2:
What are "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.

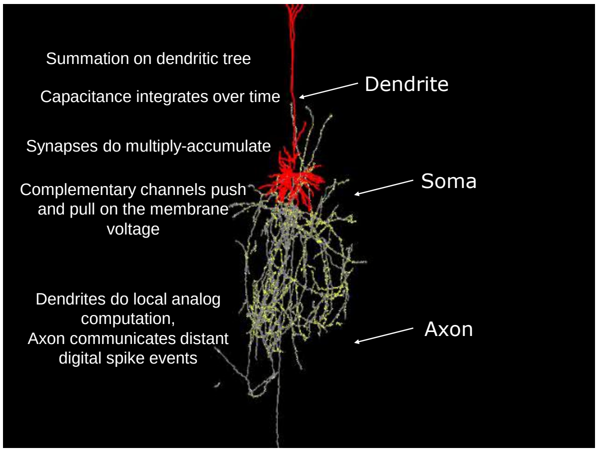
Mead, 1990

Examples of organizing principles demonstrated today

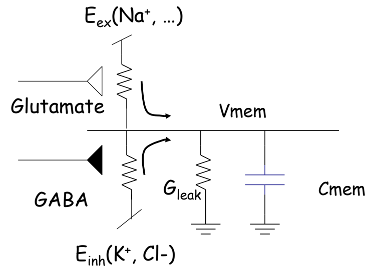
1. **Using device physics for computation**
   1. Summing currents onto nodes
   2. Using capacitance to integrate over time
   3. Using controlled energy barriers to amplify
2. **Using complementary devices to amplify without burning excessive static power**
3. **Averaging over space (& time)** to optimally use dynamic range to and to reduce noise
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

(Example #1)



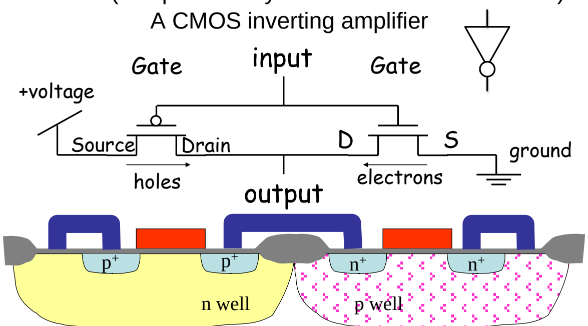
The membrane voltage is controlled by complementary voltage gated channels



Almost no power is burned when both channels are off!

CMOS (complementary metal oxide semiconductor)

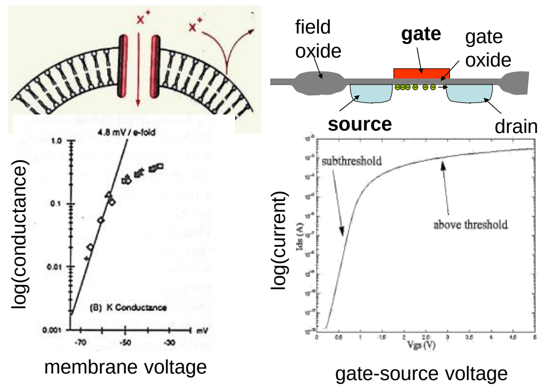
A CMOS inverting amplifier



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

Voltage activated membrane channel

Transistor



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	

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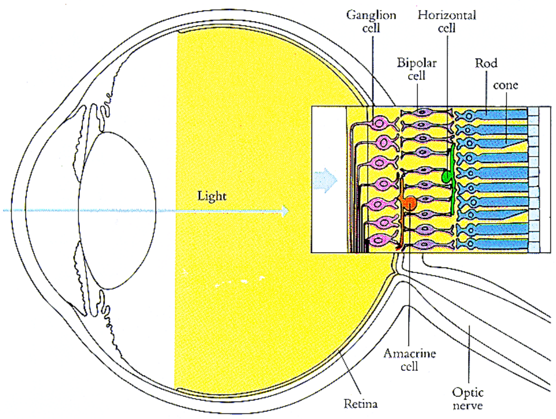
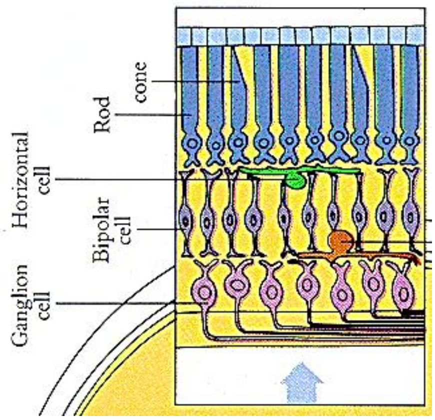
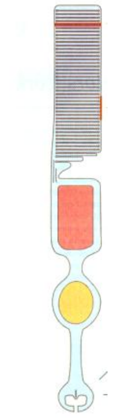
Part 3a:
Structure and function of the retina, as expressed in the
"Physiologist's Friend Chip"

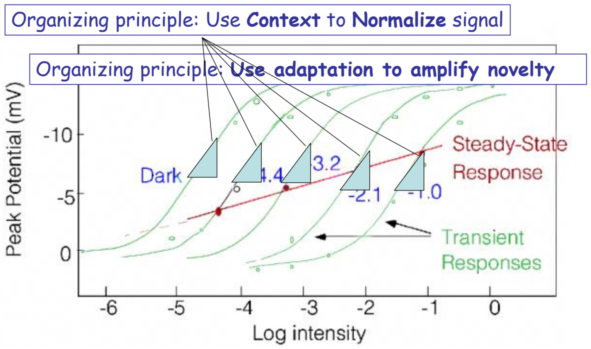




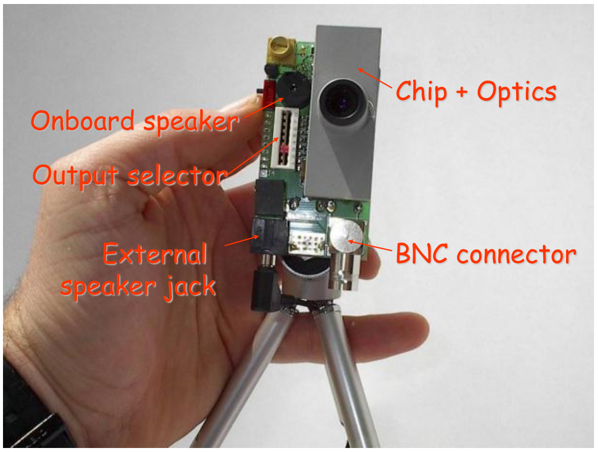


Rodieck 1998
The first steps in seeing

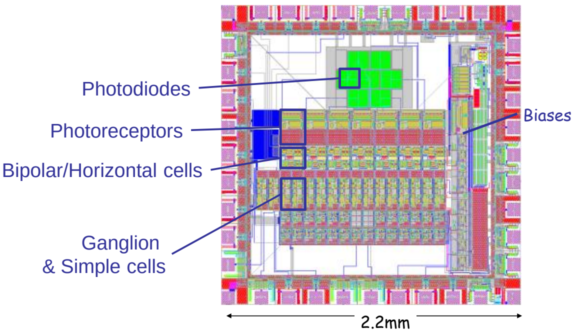
Biological photoreceptors adapt their operating point and gain



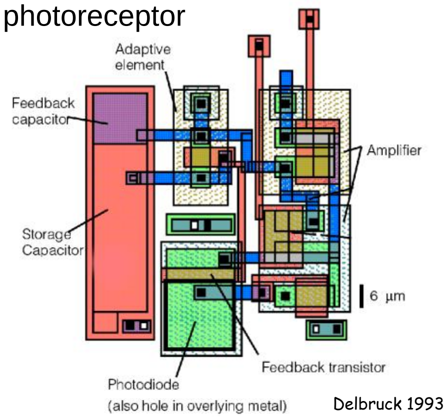
Norman & Perlman 1979

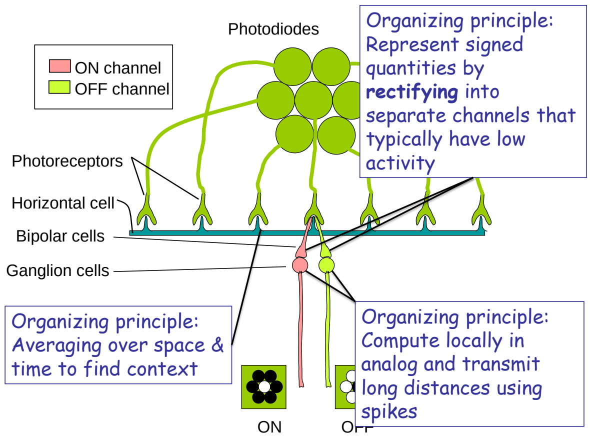


Physiologist's Friend Chip

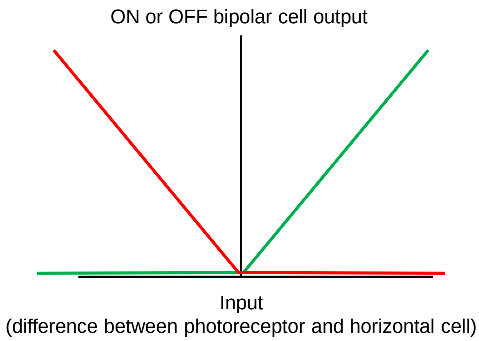


A silicon photoreceptor



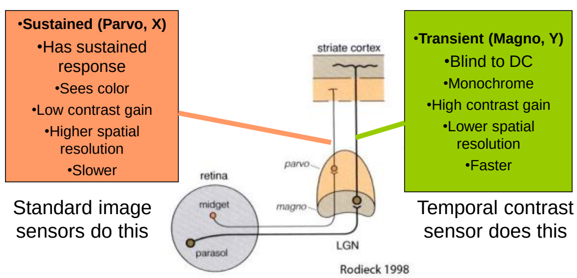


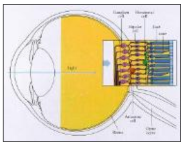
Rectification

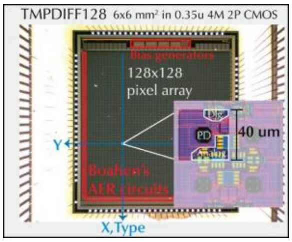


Part 3b:
Structure and function of the visual system's **transient pathway**, as expressed in the dynamic vision sensor (DVS)
(an asynchronous temporal contrast silicon retina)

All animals (from insects to us) partition vision into sustained and transient visual pathways





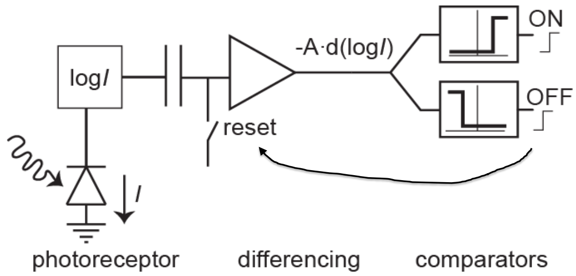


Dynamic vision sensor

1. This silicon retina ***asynchronously*** outputs ***pixel addresses (spikes)***.
2. The pixels respond to ***temporal contrast*** , like transient ganglion cells.

Lichtsteiner et al. ISSCC 2006

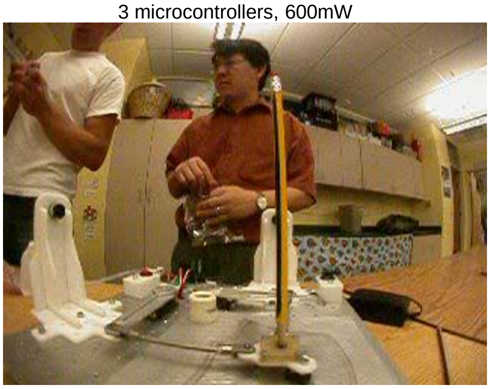
Simplified DVS pixel architecture



Embedded DVS Pencil Balancer

Jorg Conradt, Matt Cook

3 microcontrollers, 600mW



Review of "organizing principles" in neural and neuromorphic electronic systems

Examples of organizing principles demonstrated today

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   1. Summing currents onto nodes
   2. Using capacitance to integrate over time
   3. Using controlled energy barriers with Boltzmann physics to amplify
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Your exam question will be based on this lecture

Additional reading for interested parties

1. Mead, **Neuromorphic Electronic Systems**, *Proc. IEEE*, 1990
2. Delbruck & Liu, **A silicon visual system as a model animal**, *Vision Research*, 2004
3. Liu & Delbruck, **Neuromorphic Sensory Systems**, *Curr. Opin. Neurobiology*, 2010
4. Web pages on the Physiologist's Friend Chip and DVS

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